Final report

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1. Project details

Project title	EUDP 2019-II IEA Wind Task 32
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Name of the funding scheme	EUDP
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CVR number (central business register)	30 06 09 46
Project partners	
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2. Summary

Summary in English:

This project supports the participation of DTU Wind Energy in the IEA Task 32. The main objective of IEA Wind Task 32 – Wind Lidar is to identify and mitigate the barriers to the use of lidar technology in wind energy applications such as site assessment, wind turbine power performance, loads and control, complex flow measurement, and lidar data digitalization.

DTU will push the barriers further for the wind turbine power performance verification application in this project. The main objective of this project is to demonstrate the ability of nacelle mounted Lidar for wind turbine power performance in challenging conditions, especially in complex terrain (hills and forest) and in large offshore wind farm arrays, so that it becomes the new default instrument for power performance testing in areas where the use of traditional meteorological masts is impractical.

The project's focus has been to understand what to measure concerning power curve measurement to utilize lidars in a unified method for characterizing power curves. This has been done through advanced high-fidelity simulations of turbines in complex flow and wind farm arrays applying a Lidar as a sensor in the flow simulations. The project has revealed several weaknesses in the current standards based on an oversimplified view of power curve validation based on the concept of a turbine in a reference flow based on flat and homogenous terrain. The investigations have shown that there can be significant differences in the power curves due to inhomogeneous flow conditions. The flow behind the turbines is affection the power curve due to terrain effect or blockage from turbines in a wind farm. The results call for a controversial redefinition of power curves, including more information to include turbines models in the Annual Energy calculations. The stakeholder

analysis also supports this statement. OEM's currently uses advanced tools such as Aerodynamic turbine tools to characterize the power curves in which they have high confidence but these tools need a general acceptance within the standards and acknowledging that the reference power curves are insufficient to perform advanced AEP calculations. The developers are asking for these advanced tools in their search for precise prediction tools of AEP.

Opsummering på dansk:

Dette projekt støtter DTU Vindenergis deltagelse i IEA Task 32. Hovedformålet med IEA Wind Task 32 – Wind Lidar er at identificere muligheder for brug af lidarteknologi i vindenergiapplikationer såsom vurdering af vindmøllers effektkurver, belastninger og brug til styring, vha. flowmåling og lidar-data digitalisering.

DTU vil skubbe barriererne yderligere for vindmøllens effektstyringsapplikation i dette projekt. Hovedformålet med dette projekt er at demonstrere nacelle-monteret Lidars evne til måle vindmøllers effektkurver under udfordrende forhold, især i komplekst terræn (bakker og skov) og i store havvindmølleparksystemer, så det bliver det nye standardinstrument til test af "power performance" i områder, hvor brugen af traditionelle meteorologiske master er upraktisk.

Projektets fokus har været at forstå, hvad man skal måle i en effektkurvemåling for at udnytte lidarer bedst muligt, og definere en metode til at karakterisere effektkurver. Dette er sket gennem avancerede high-fidelity simuleringer af turbiner i komplekse flow og vindmøllepark arrays hvor Lidaren er anvendt som sensor i flowet fra simuleringerne. Projektet har afsløret flere svagheder i de nuværende standarder baseret på et forenklet syn på validering af effektkurven baseret på begrebet " fristrøms reference- flow" baseret på fladt og homogent terræn. Undersøgelserne har vist, at der kan være betydelige forskelle i effektkurverne på grund af inhomogene flowforhold. Projekt har vist at strømningen bag møllerne har en betydning for effektkurverne på grund af terræneffekt eller blokering fra vindmøller i en vindmøllepark. Resultaterne kræver en kontroversiel omdefinering af effektkurver, som kræver flere oplysninger end specificeret i standarderne i dag. Eksempelvis inkludere at avancerede møllermodellerne til beregning af energien. Interessentanalysen støtter også denne erklæring. OEM's bruger i øjeblikket avancerede værktøjer som aerodynamiske turbineværktøjer til at karakterisere de effektkurver, hvor de har stor tillid disse, men disse værktøjer har brug for en generel accept inden for standarderne og en anerkendelse, at referenceeffektkurverne ikke er tilstrækkelige til at udføre avancerede AEP-beregninger. Udviklerne beder om disse avancerede værktøjer i deres søgen efter præcise forudsigelsesværktøjer til AEP.

3. Project implementation

Due to the COVID-19 situation, the project did not evolve as expected. The main impact of the COVID-19 outbreak was that all the planned meetings and workshops had to take place online. The online meeting turned out to be a reasonable substitute for the in-person meetings with respect to knowledge sharing and presentation of results but not suitable for discussions, planning, and networking. Another consequence of the COVID-19 situation was that the Wind Energy Conference 2020 was canceled, and therefore DTU could unfortunately not present the project results there as planned. However, the Torque, WESC conferences took place online, and thus, the project results could still be disseminated to a broader audience at these conferences as planned initially

A the same time, it became clear that round-robin exercise was not possible to perform due to no dedicated experimental campaigns with a sufficient amount of both high-quality inflow measurements data and turbine measurement. Therefore the scope has of the projects was changed with the focus on delivering the following

A Stakeholder analysis: How should power curves be measured in the future. Here a short report will be delivered which specifies the demand for measurement of power curves from the industries point of view by interviewing OEM's and developers

An analysis of a unified measure for Power curve validations using inflow measurements and turbine data, based on CFD simulations

Except for the above-described setbacks, the project developed more or less according to plan, and DTU realized most of the objectives of the project and milestones as outlined in the next section.

4. Project results

DTU has contributed with activities and publications during the project period and has achieved the objectives and milestones listed below. However, CFD calculations have shown that the initial goal of coming up with recommendations to the IEC standards to reduce the uncertainty for on power curve validation measurements has shown to be more complicated and requires a substantial research effort to establish better methods than today with the current standards. This is also reflected in the stakeholder analysis. The significant findings of the projects are:

The conclusion from the stakeholder analysis

- Both OEMs and developers find that the standard reference of power curves are defined too simplistic for being able to characterize the performance of turbines in complex flows
- The OEMs have a wish to validate their power curve tools to be able to create site-specific power curves.
- The developers are keen to obtain more details of the power performance in ord to estimate the site-specific energy yield
- The OEMs do not believe developers can adequately handle all the turbine information and which, due to complexity, will lead to larger uncertainties in the estimates of power performance. The data from the OEMs are often susceptible as it also includes the control of turbines and their aerodynamic performances

Conclusions from simulations:

- The aim of providing a unified method of calculation of a power curve in complex terrain is demonstrated to be very difficult as the advanced simulations show that it is not enough to measure Infront as the conditions behind the turbine also influence the power from a turbine. Here increased accuracy and closer measurements will not reduce the uncertainty on the power curve. This calls for revision of the definitions of power curves in the standards for complex terrain. It is aligned with the manufacturer's wish to validate the power curve tools for the turbines.
- The simulations of the blockage effect show there is a higher correlation with the measure performed closer to the turbines
- The nearby turbines will create blockage and speed-up, causing biases in the free windspeed in the order of the 1% in power.
- Blockage in a wind farm from a turbine in the wake of the front turbines are likely to influence the power curves creating increased inductions and thereby biased power curves

The overall conclusion from the work performed is that the errors and uncertainty of the power curve validation steaming from the interaction with complex flows and the definition of non-existing free stream velocity. The current simplifications in the standards need to be rethought to include new technologies such as remote sensing advanced power curve tools combined with new technologies such as advanced flow models.

DTU has participated in the following meetings and conferences where the work related to the IEA task 32 project has been disseminated:

- IEA Task 32 meeting (took place online)
- Torque conference, September 28 – October 2, 2020 (took place online)
- IEA Task 32 annual meeting,   2021 (took place online)
- WESC conference, May 25-28, 2021 (took place online)

As described in section 4, the COVID-19 situation blocked all in-person meetings, and therefore all meetings had to take place online. Fortunately, most of the conferences and events managed to carry through online. Consequently, the project results could be disseminated to stakeholders from the Danish and international wind energy industry and research institutes. An exception was the Wind Energy Conference 2020, which, as mentioned above, unfortunately, was canceled.

4.1 Stakeholder analysis

In the stakeholder analysis, we interviewed large OEMs and developers and talked with instrument developers and test engineers working with power curve validations. Finally, researchers in aerodynamic modeling and performance have also been interviewed. As a supplement to interviews, the information from the power curve working group: https://pcwg.org has been used.

The focus interviews have been kept anonymous not to comprise the individuals, and the interpretation of the is solely made by the authors of this report.

In the interviews, the participants were asked to identify some of the major challenges that they experienced working with power curve validations and power performance.

4.1.1 OEMs

- The OEMs have advanced aerodynamic tools to calculate the power curves based on measured and simulated inflow measurements, including the controls system of the turbines. The manufacturers have large confidence in their power curve tools based on their long experience with them (i.e., Flex5 and other internal tools). The OEM has capabilities to provide climate-specific power curves based on turbulence, shear, veer, and the control system. These extended power curves are seldomly shared with the consultancies and developers due to their complexity.
- The OEM often finds large discrepancies from the consultancy's estimated power curves, which nearly always is due to the site-specific climate conditions.
- The information about the aerodynamic performance and control system, which is basically the background for the power curves, is considered very sensitive information for the OEM.
- In general, the OEM is interested in validating their Power curves tools for estimating the energy yield both as a single turbine and also in the wind farm.
- In general, the OEMs wish to move towards a site-specific warranty test with additional information that is not covered in the IEC standards.
- In some parts of the world, the power curves are not as important as the investments, primarily is CAPEX- driven (anonymous contribution)
- The power curve warranty is currently very important as an under-performance of the turbines will release a claim from developers and turbine owners against the OEM's
- The OEM has a clear wish to be able to separate the performance of the wind turbines from the actual wind resource. It is indicated by a wish to measure the whole wind field in front of the rotor and use this together with their advanced power curve tools

4.1.2 Large developers:

The large developers have two main reasons for performing power curve validations

1) Warranty test to evaluate the single turbines live up to specification of the turbines

2) To give the most precise description of the power performance of a turbine to be able to estimate the Energy yield as close as possible with the purpose to reduce investments risk of their projects

The developers are, in general, most interested in the energy yield of the wind farm, And there is an anticipation that Met towers will disappear as the reference for the background wind speed measurements. Therefore all power performance measurements have to be rethought using Lidar-based technologies.

The developers want more information than given in the existing power curves, preferable as a multidimensional power curve for different climate situations (turbulence, veer, etc.). The reasoning behind this is to be able to estimate the Annual energy yield for all cases and not just a reference case and thereby de-risk their investment in a wind farm.

The large developers are interested in the transparency of the different tools and would like as much information as possible from the OEMs. This is reflected in the Power curve working group https://pcwg.org.

The large developers are looking into ML techniques, including SCADA data together with inflow measurements to support a power performance validation of individual turbines and also for being able to perform a better postconstruction of the energy yield from a wind farm.

4.1.3 Test engineers

Experience differences on the measured power curves depending on seasons, indicating that the inflow characteristics are changing. REWs can be a possible way to mitigate this, but the response to the turbulence is not included.

There is a doubt that the concept of one reference power curve is possible to identify.

4.1.4 Researchers

The interactions of the turbine and its control with the flow need to be considered to understand the physics of the power curve validation and power curve performance and thereby mitigate the uncertainties.

The inhomogeneities in the flow are considered larger as larger rotors are installed. More basic physics needs to be included, and we should be able to model all the different cases with aerodynamic tools with advanced flow interactions

Dedicated experiments are needed to validate the performance of turbines to establish a complete validation of the turbine performance. Both detailed measurements of the inflow, turbine data (SCADA), and wake measurements need to be undertaken here.

In general, the viewpoint is that the current standards are insufficient, and the simplifications where focus on inflow measurements are not sufficient. The aerodynamic performance of the turbine needs to be included.

Methods based on both inflow measurements and SCADA data need to be established to gain higher precision of the power curves in complex flows. Here the complexity is created wakes and complex terrain and significant roughness changes.

4.2 Numerical investigation of power performance in complex terrain

The standard way of verifying the power performance of a wind turbine is to relate its power output to the free-stream wind speed, i.e., the wind speed at the rotor location if there was no turbine. In flat homogenous terrain, the free-stream wind speed can be well approximated by measuring sufficiently far upstream of the rotor (typically 2.5D). However, this is not possible in complex terrain because the velocity is not homogeneous in this case.

To overcome this issue, it is common practice to perform a site calibration in which the relation between the wind speed at the location of the turbine and the wind speed at some upstream location is established before erecting the turbine. Typically, a site calibration is performed by erecting two met masts but can also be established via lidar measurements. In any case, the idea is to establish a transfer function that can be used to correct the upstream measurements to account for the fact the mean inflow changes upstream of the turbine. Most work on wind turbine power performance verification in complex terrain focus on how to establish a robust and accurate transfer function and thereby reduce the scatter in the power curve.

The power performance of wind turbines and wind farms in complex terrain has also been studied via Computational Fluid Dynamics (CFD). The wind turbines are typically represented as actuator disks (Sessarego 2018, Tabas 2019). Many of these studies find that the simulations can predict measured power outputs reasonably well.

However, very few studies exist where it is investigated whether a turbine in complex terrain performs in the same way as if it was in flat terrain. Usually, a power curve is considered as a characteristic of a wind turbine, and, in this respect, the power curve should not change when for example, placed on top of a hill. However, Hyunseok et al. (Hyunseok 2015) compared the guaranteed and actual power curves of a turbine in a complex site and found that the actual power production was lower than expected from the guaranteed power curve. No explanation for the difference was given. Therefore, the objective of this work is to study the characteristics of the power curve of a wind turbine in complex terrain via Large Eddy Simulations (LES).

4.2.1 Numerical setup

In the following, we consider the flow over the complex site of Perdigao in Portugal, where we have placed a DTU 10MW turbine on top of one of the ridges, see Fig. 1.

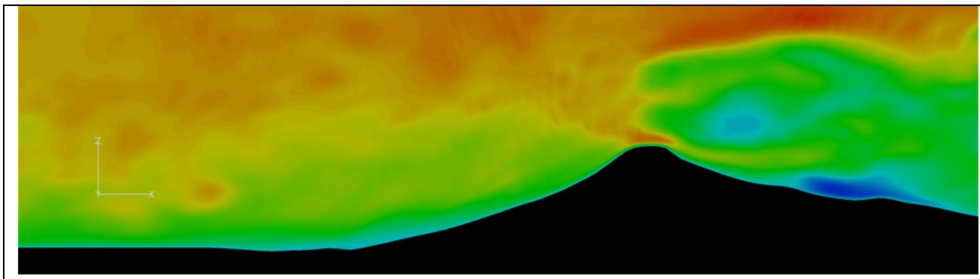

Figure 1: Snapshot of streamwise velocity in a vertical cross-section through the rotor center of a turbine placed on top of a hill.

The grid used to resolve the terrain is as described by (Berg et al. 2018), but it is extended with a flat region after the terrain. Instead of periodic conditions in the flow direction, we use prescribed inlet upstream and zero-gradient conditions at the outlet. The dimension of the numerical grid is 8480m x 2560m x 3320m (streamwise, spanwise, and vertically), and the number of grid cells is 512 x 256 x 256. In the terrain region, the grid cells have dimensions dx=dy=2dz=10m, and the cells are stretched towards the flat region's outlet.

The flow field is simulated as LES using the sub-grid scale model by (Deardorf 1972). The inlet to the simulation is determined in a separate precursor simulation where the flow is driven over a flat surface by a constant pressure gradient, and the flow is assumed fully neutral. In this simulation, the friction velocity is 0.3 m/s, and the roughness height was 2e-4 m. The precursor grid had dimension 5120m x 2560m x 3320m and 512 x 256 x 256 grid cells. To obtain different flow field realizations, the precursor flow field was scaled according to the scaling laws (Castro 2007, Jimenez 2004, Townsend 1975).

The wind turbine is modeled as an actuator disk combined with the aeroelastic model Flex5 (Øye 1996). The inflow to the wind turbine is established by running separate simulations without the turbine and sampling the wind field at the position of the rotor.

All simulations were carried out using the incompressible Navier-Stokes solver EllipSys3D (Sørensen 1995).

4.2.2 Results

Figure 2 compares the power curves of the turbine in complex and flat terrain using both LES coupled to Flex5 and standalone Flex5. The predictions of standalone Flex5 in complex terrain are obtained by extracting the full inflow to the rotor from the LES simulations and using it as an input to the Flex5 model. The prediction in flat terrain is obtained by running separate simulations in steady uniform inflow using both Flex5 standalone and CFD. The CFD simulations in uniform inflow are conducted with the same resolution as in the terrain simulations to avoid any impact from grid resolution.

In flat terrain, there is generally a good agreement between AD-LES and Flex5 standalone, but in complex terrain, it is seen that the power is significantly lower in the AD-LES. This is a surprising result but can be explained by looking at the free-stream velocity along the centreline of the turbine, as shown in Fig. 3.

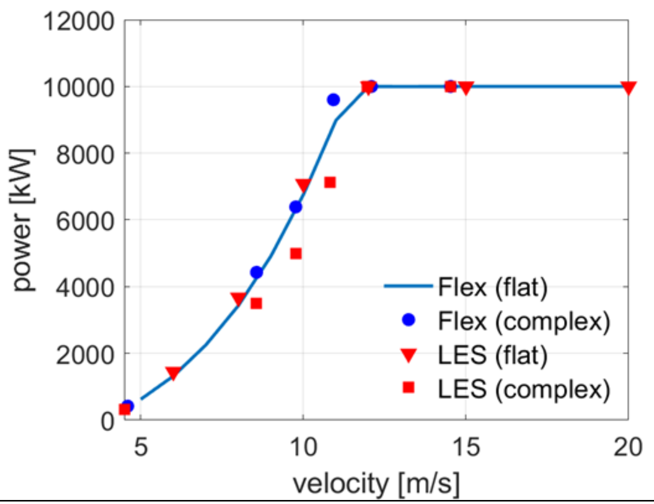

Figure 2: Power curve of DTU 10MW in flat and complex terrain. Predictions are shown both for standalone Flex5 and the coupled LES-AD-Flex simulations.

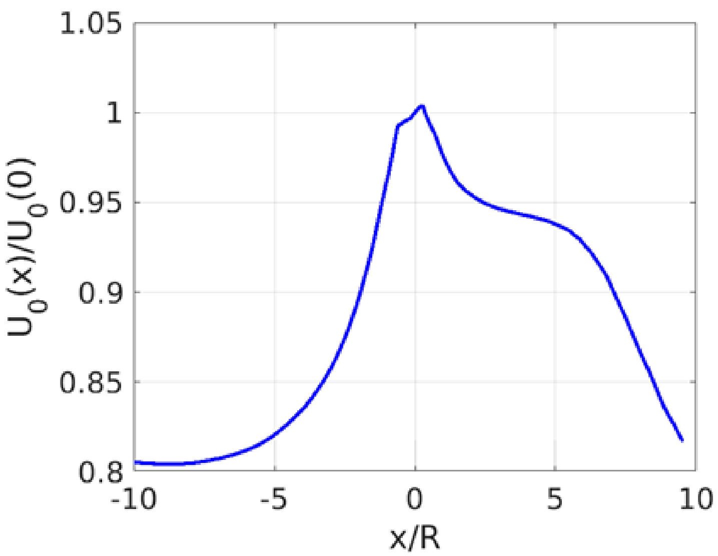

Figure 3: Free-stream velocity along the centreline of the wind turbine. The rotor is placed at x=0.

From Fig. 3, it is evident that the free-stream velocity decreases behind the rotor. This is in contrast to a homogenous flat flow where it would be constant. A consequence of the decreasing free-stream velocity is that the wake vorticity is transported at a slower velocity, thereby inducing a higher velocity in the rotor plane, producing less power than in an equivalent homogenous case.

4.2.3 Conclusion

The simulations have shown that the power curve in complex terrain may be significantly different than for the same turbine in flat homogeneous terrain. The reason for this is that the free-stream velocity varies behind the rotor, and therefore the velocities induced by the wake at the rotor plane are different. In the considered case where the turbine is placed on top of a hill, it causes the power production to be in the order 20% lower than what should be expected for a turbine in flat terrain which experiences the same inflow conditions. A direct consequence of this finding is that it questions the usefulness of a standard site calibration for power curve verification in complex terrain. Future site calibrations should, therefore, not only aim at establishing a transfer function for the inflow but also the backflow. Combined with a wake model, a backflow correction could be used to predict how the power curve is changing for a turbine in complex terrain.

4.3 Power curve assessment with close-range lidar measurements

As mentioned earlier, power curve assessment tries to correlate a wind turbine's power output with the available wind resource. Usually, the wind resource is determined from wind speed measurements taken at turbine hub height at least 2.5R away from the turbine. At this distance from the rotor, the influence of the turbine on the measurements is assumed negligible. Any closer and the deceleration originating from the extraction of energy from the wind by the turbine would be noticeable. The wind speed measurements are usually performed using met masts equipped with cup anemometers. Considering that in the 2000s, the largest wind turbine rotors reached 50m in radius, using a wind speed measurement of 125m from the turbine might still have been representative of the turbine's available resource, however nowadays radii are exceeding 100m, so measurements are conducted 250m from the rotor and still at a single point, although there are over 200m from tip to tip. At a common mean wind speed of 8 m/s, it takes an air particle over half a minute from met mast to turbine leading to decorrelation between measured resource and the one finally interacting with the turbine, due to time and spatial evolution of the wind field. Measurement in a single point neither represents the spatial variability of the wind field across the wind turbine rotor, which is ultimately driving power production. Nacelle-based lidars, on the other hand, are capable of measuring the upstream wind field over a larger part of the rotor area at a sufficiently high temporal resolution for power curve assessment; however, they can only measure with difficulty beyond 150m from the rotor. Whilst this places the measurement well inside the wind turbine's area of influence, measuring closer to the rotor increases the correlation between the measured and driving wind resource. Although this would not constitute power assessment in its classic form, it could present a viable future alternative to current practice. In this section, we briefly present a feasibility study of this approach by extracting wind measurements from numerically generated wind farm flow data by virtual lidars and correlating them to turbine power production.

4.3.1 Method

The wind farm flow data was generated by DTU Wind Energy and is openly available from data.dtu.dk, where the simulations are also described in more detail. The specific case analyzed as part of this study is the Large Eddy Simulations (LES, a form of Computational Fluid Dynamics (CFD) resolving larger turbulent structures) of a numerical reference wind farm with 32 wind turbines. The latter were DTU10 MW reference turbines (R=89m), modeled in the fluid domain as actuator lines (a geometrically simplified representation of a turbine in CFD) and fully coupled to the structural solver Flex5 to compute the blade deformations and forces. By also incorporating the wind turbine controller in the modeling framework, the wind turbines are operating - with respect to loads and power production - similar to real turbines in wind farms. The numerical wind farm was intended to represent offshore conditions, and thus the surface is modeled as flat with a low homogenous roughness of 3mm, and the atmospheric boundary layer was taken as conventionally neutral. After a certain spin-up phase, the last 600s of turbine sensory (20 Hz) and velocity data (1 Hz) are analyzed. Velocities are extracted over vertical planes parallel to the rotor plane, two rotor radii ($x/R = \hat{x} = -2$) and one radius in front of it ($\hat{x} = -1$). The velocity planes are furthermore processed by sampling them in a circular manner, centered at the hub location, with different radii ($r/R = \hat{r}$) as a nacelle-lidar would potentially do. Finally, data is aggregated over different time spans for all 32 turbines, and power output is correlated with the different available velocity signals.

4.3.2 Results

Figures 4 and 5 summarize the impact of wind speed measurement location on power curve assessment in wind farms. Colored lines indicate velocities sampled by virtual lidars in planes upstream of the rotor, either two rotor radii ($x/R = \hat{x} = -2$) or one radius ($\hat{x} = -1$) in front of the rotor. Lidars are extracting velocities over circles centered at the hub location, with different radii ($r/R = \hat{r}$). The integral denotes the area-weighted average of all circular lidar measurements. As a reference, the nacelle anemometer values are also given, extracted at the rotor center. Data from all 32 wind farm turbines are aggregated in this analysis. In the first row of Figure 4, power curves are shown for the different velocity reference signals. Columns show the variation with time-averaging window size. The power curves differ, as the turbine influences the velocities to different extents, depending on where they are taken. At the nacelle, the wind speed reduction is stronger than at the upstream locations at which the lidars are measuring, making the power curve shift to the left. Whilst the amount of time-averaging changes the power curve shapes relative to each other, they change little, with the order clearly preserved. The measurements taken at $\hat{r} = 0$ falling furthest to the left at lower wind speeds, moving to the right as the measurement radius increases towards $\hat{r} = 0.83$. Approaching rated wind speed, little dependency on measuring radius remains. Interestingly lines are crossing when different measurement distances from the rotor are compared for the same measurement radius. In the second row, the standard error of the mean power curve is shown. It is defined as the standard deviation divided by the square root of the number of samples. For time-averaging above 1s, the standard error is largely unchanged, as only 600s of data was available. With a longer time series, these would reduce. With very short time-averaging shown in the first column, the number of samples is extremely large, even for our short time series, decreasing the standard error. The lower row shows the standard deviation of power in each wind speed bin to demonstrate the variability in the power curve as a function of wind speed. Generally, the shape of the curves is similar across the different measurement locations; however, the magnitude differs and diminishes with averaging time. There is a clear tendency for the power variation to diminish as the sampling radius increases towards $\hat{r} = 0.83$, showing a better power and velocity signal, as a greater region of the incoming flow is sampled. This is reinforced by averaging the different lidar measurements, thereby effectively getting a rotor-disc averaged wind speed. There also seems to be a benefit from measuring closest to the turbine, which is also indicated by the reasonable results obtained with the point measurement in the rotor plane at the nacelle. An overview of the conclusions from Figure 4 is given in Figure 5 by averaging the quantities over the wind speed bins.

4.3.3 Conclusion

Accurate power curve assessment relies on obtaining a velocity measurement that is well correlated with a wind turbine's power production. The velocity thus needs to be representative of the wind field with which the turbine interacts. Measuring this reference wind speed far from the turbine in a single point as it is current practice results in spatial and temporal decorrelation between wind speed and power production. There is a clear benefit it measuring as close as possible to the wind turbine, even as close as one radius in front, and measuring over the largest fraction of the rotor area possible at high frequency; something wind lidars could potentially do. Measuring closer than 2.5 rotor radii to the rotor – putting the measurements inside the turbine's area of influence - would not satisfy current industrial standards for power curve assessment; however, due to the improved correlation, precision would increase whilst measurement time could decrease. This only requires the publication of reference power curves using new measures for the velocity reference (close-range with large rotor area coverage). The added benefit of using nacelle-lidars in this context would be the possibility to determine the shear and veer of the incoming wind field, allowing to create multidimensional power curves that make the comparison between measured and reference curves more precise.

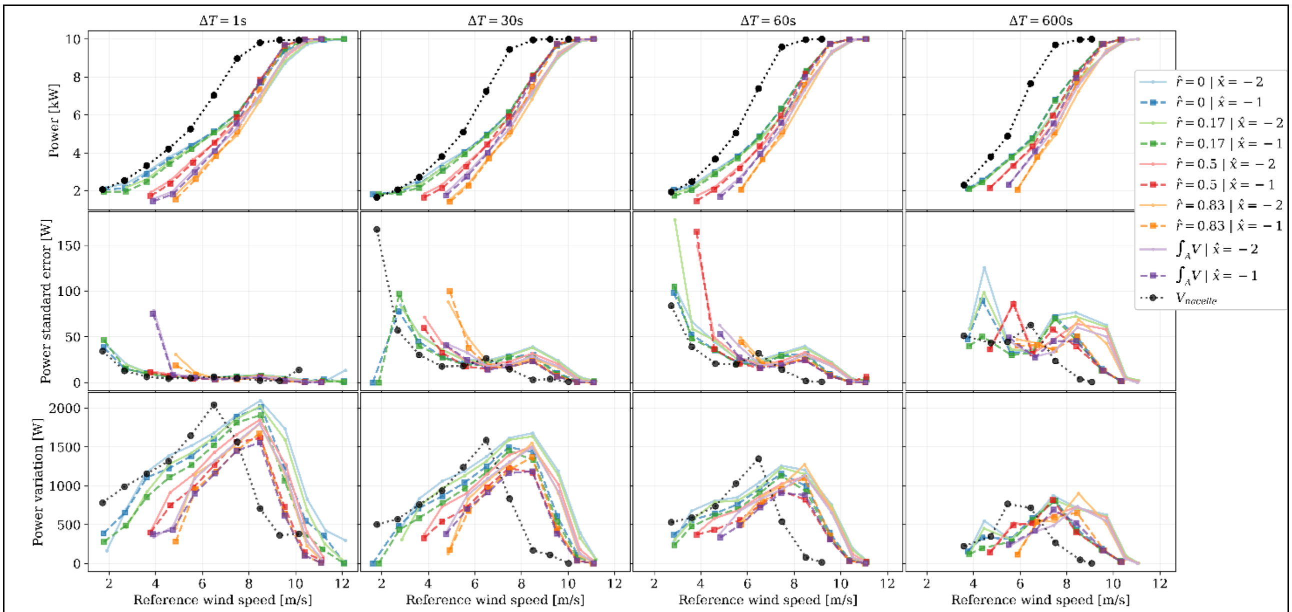

Figure 4: The impact of wind speed measurement location on power curve assessment in wind farms indicated by CFD farm simulations. Colored lines indicate velocities sampled by virtual lidars in planes upstream of the rotor, either two rotor radii ($x/R = \hat{x} = -2$) or one radius ($\hat{x} = -1$) in front of the rotor with radius, R. Lidars are extracting velocities over circles centered at the hub location, with different radii ($r/R = \hat{r}$). The integral denotes the area-weighted average of all circular lidar measurements. As a reference, the nacelle anemometer values are also given, extracted at the rotor center. Results are shown for different time averaging (ΔT); the sequence is 600s long.

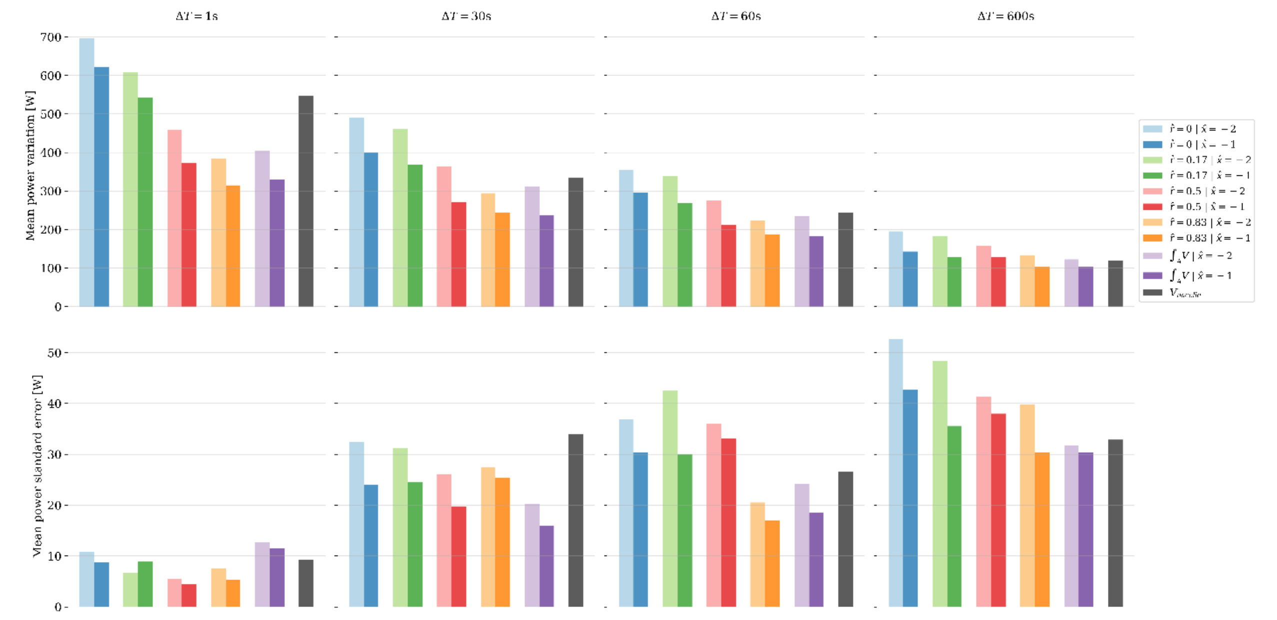

Figure 5: Quantities from Figure 4 averaged over the wind speed range. Detailed description in caption of referenced figure.

4.4 Numerical study of blockage effect of two turbines

Traditional engineering wake models disregard the blocking effect that downstream turbines have on upstream turbines because this effect is considered very small compared to the wake effect. However, as wind farms get bigger, the consequence of neglecting blockage is a significant bias in the predicted power output of wind farms (Bleeg 2018). Blockage effects are hard to investigate from field measurements because it is a small effect but also because it requires knowledge of what the wind speed seen by a given turbine would have been if the surrounding wind turbines had not been there. In the present work, we therefore use simulations to investigate blockage effects. To keep the problem as simple as possible, we consider only two turbines that are aligned along the wind direction.

4.4.1 Numerical setup

The numerical setup is illustrated in Fig. 6. We consider two DTU 10MW turbines placed ten rotor radii apart in a uniform inflow of V_∞ = [8, 10, 12, 14, and 16] m/s. The rotors are simulated as actuator disks. The flow is simulated as RANS using the incompressible flow solver EllipSys3D (Sørensen 1995). The used grid is Cartesian and has a resolution of dx=dy=dz=R/16 in the region around the rotors.

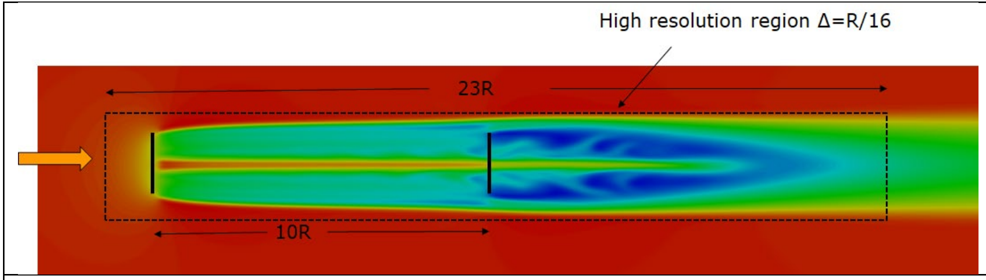

Figure 6: Sketch of numerical setup used for studying the global blockage effect on two turbines

The pitch and rotational speed (RPM) of the rotors are determined using a simplified controller based on the rotor averaged wind speed U_D (Laan 2015). The idea is to establish a relation between U_D and the pitch and RPM from known tables of pitch and RPM as a function of U_∞. The relations pitch(U_D) and RPM(U_D) are obtained from simulations of a single rotor in uniform inflow. Fig. 7 shows the rotational speed, pitch, power, and free-stream velocity of the turbine as a function of U_D obtained from the single rotor simulations.

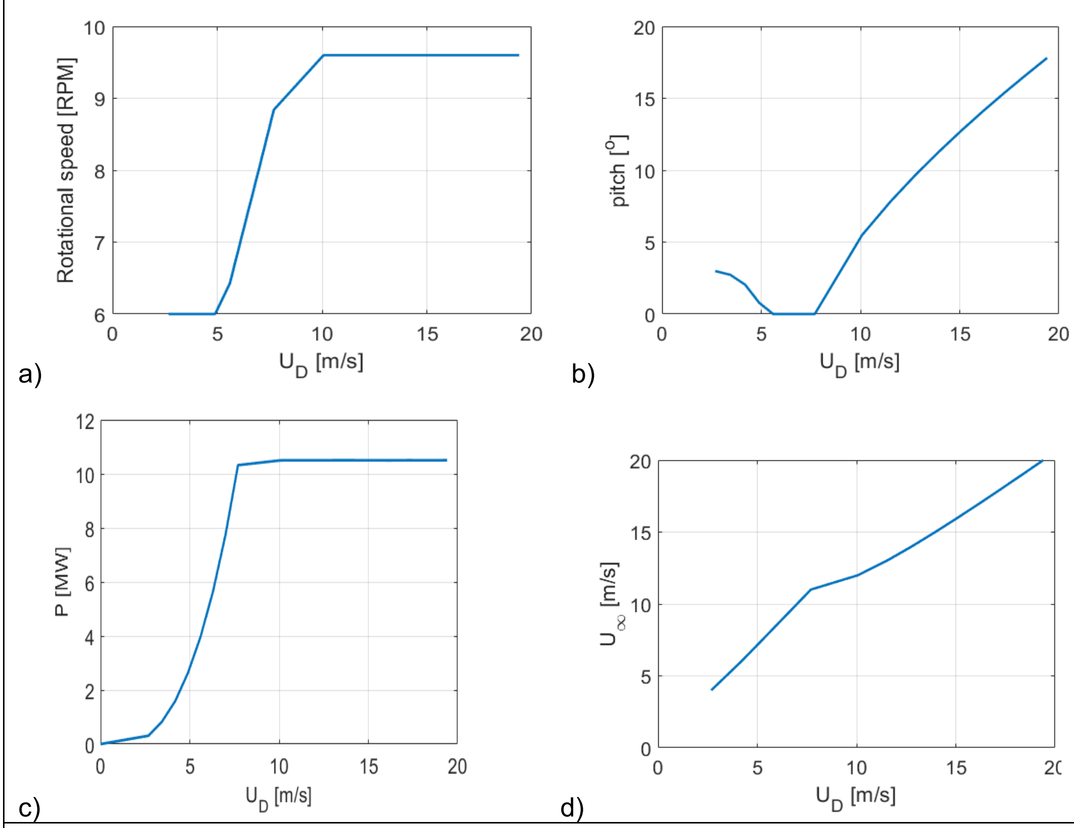

Figure 7: Rotational speed, pitch, power, and free-stream velocity as a function of rotor averaged disk velocity

From the tabulated data in Fig. 7 it is possible to get the pitch, RPM, and local free-stream velocity from the known velocity at the disk. It should be noted that the tabulated data are obtained in uniform inflow and therefore is strictly only valid for an isolated turbine in uniform inflow. When applied in a two-turbine setup, then the local free-stream velocity is no longer uniform. This is most apparent for the downstream turbine, which experiences the wake of turbine 1. However, the induction from turbine 2 also produces a vague shear at the position of turbine 1. In the following, we will use $U_{\infty i,loc}$ to denote the local free-stream velocity found from interpolation based on the disk velocity. When the local free-stream velocity is estimated using $U_{\infty i,loc}$ it is inherently assumed that the free-flow is uniform.

The "true" local free-stream velocity for each rotor is found by running separate simulations where that rotor is removed from the domain and extracting the velocity at the rotor plane. Thus, to get the free-stream velocity for the downstream rotor (turbine 2), we make a simulation where only the upstream turbine is present and extract the velocity at the position where turbine 2 is located. Similarly, the free-stream velocity for turbine 1 is found by running a simulation without rotor 1 included. The "true" local free-stream velocity at each rotor is denoted by $U_{\infty,loc}$. It should be noted that the $U_{\infty,loc}$ is not a perfect estimate of the free-stream velocity because by removing one rotor, the other rotor will inherently perform differently than in a two-turbine setting.

4.4.2 Results

Fig. 8 shows the power of the two turbines as a function of the local free-stream velocity in comparison to the corresponding curves when in isolation. In Fig. 8 P and Pi refer to the power curve versus the true and interpolated local free wind speed, Fig. 8 also includes the estimated power curves when the blockage is neglected. These estimates are denoted by "wo" for wakes only. The "wakes only" estimates are found by extracting the $U_{\infty,loc}$ and using it to estimate U_D from the tabulated input plotted in Fig 7d and then from U_D get the power from the tabulated input in Fig. 7c.

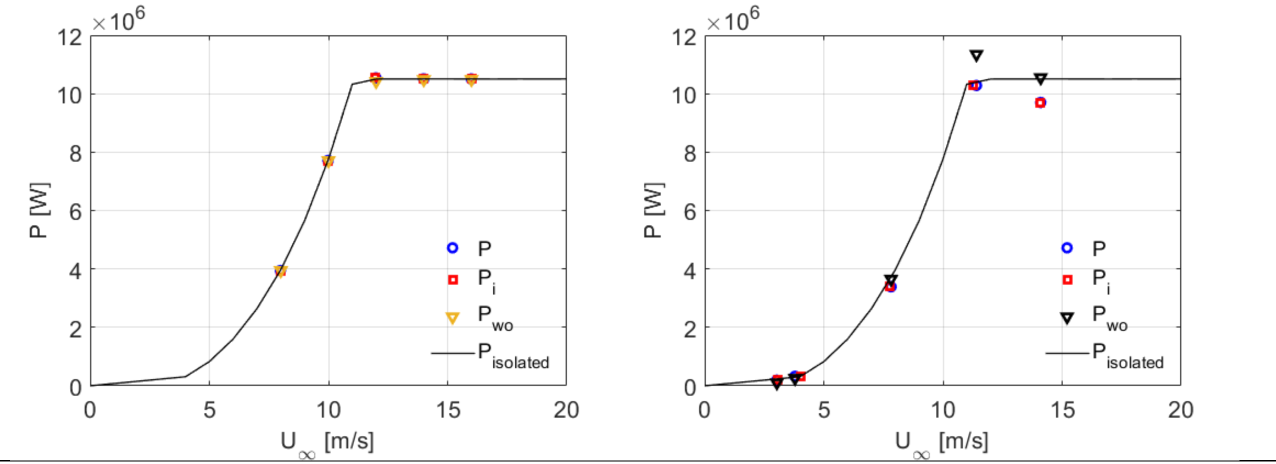

Figure 8: Power curve for the upstream (left) and downstream (right) wind turbine. "P" is the actual power vs. $U_{\infty,loc}$, "Pi" is the power vs. $U_{\infty i,loc}$, and Pwo is the estimated power when neglecting blockage (wakes only).

The power curve of the upstream turbine is, as expected, not very affected by the presence of the downstream turbine. However, a closer inspection reveals that if the induction of the downstream turbine is neglected, then it leads to an overprediction of the power in the order of 0.5% because the available wind resource is overpredicted.

The power curve of the downstream turbine shows bigger deviations from its standalone counterpart. It should be noted that the power of the downstream turbine is, of course, lower than for the upstream turbine but what is shown in Fig. 8 is the power as a function of the local free-stream velocity at the rotor. The biggest differences occur above rated wind speed, but these are due to limitations in the simplified controller. The controller is purely based on the rotor averaged disk velocity and does not respond to the actual torque as a real controller. Below rated, it is seen that the downstream turbine is less effective than its standalone counterpart. For example, when the free-wind speed for the downstream turbine is 7.8 m/s, then it produces about 5% less energy than the same turbine in a uniform inflow of 7.8 m/s. This result may not be perfectly representative of a real rotor because the present results are obtained with a simplified controller. Looking at Fig. 6 it is seen that the highest velocity at the downstream turbine occurs in the center from where no energy will be extracted, and therefore there will be a bias towards underprediction when the power is plotted against rotor averaged free-stream velocity. Nevertheless, it suggests that the power curve of a turbine changes when it is in a wind farm setting, just as the power curve changes in complex terrain.

4.4.3 Conclusions

We have performed simulations on a simple setup consisting of 2 DTU 10MW turbines aligned along the wind direction. The results show that neglecting the blockage of the downstream turbine leads to an overprediction of the power of the upstream turbine by an order of 0.5%. The power curve of the downstream turbine was seen to be quite different from its standalone counterpart. Below rated, we found that the power at a given local free-stream wind speed is in the order 5% less than its standalone counterpart. The reason for this is due to the shear imposed by the upstream turbine. The 5% difference is probably not perfectly representative of a real turbine, which uses a more advanced controller than applied in this study.

4.5 Global blockage effect for wind turbines in a test site setup

Figures 9-10 show representative plots from some recently published work (https://wes.copernicus.org/preprints/wes-2021-105/) on global blockage effects for a row of five turbines placed in a setup which is representative for a typical test site for power curve verifications (see Figure 9a). Fig. 10 shows the computed power of each turbine as a function of wind direction in comparison to their standalone counterparts. When the wind is perpendicular to the turbine row (0°), all turbines produce slightly higher power than in isolation. For wind directions 30° and 45°, the power production increase with the downstream position. The most downstream turbine may produce up to 4% more than in isolation, while the most upstream turbine produces less than in isolation. The reason for the power variation is the blockage effect which shows that the power curve measurements at a typical test site may be subject to unexpected bias.

Figure 10 shows a qualitative comparison of the simulations with full-scale measurements from a real test site. The figure shows the power of a turbine equivalent to T1 in Figure 9. As seen, the trend is the same as shown in Figure 10, but also, the simulations are in very good agreement with the measurements and show that the simulations are reliable for predicting the blockage effect.

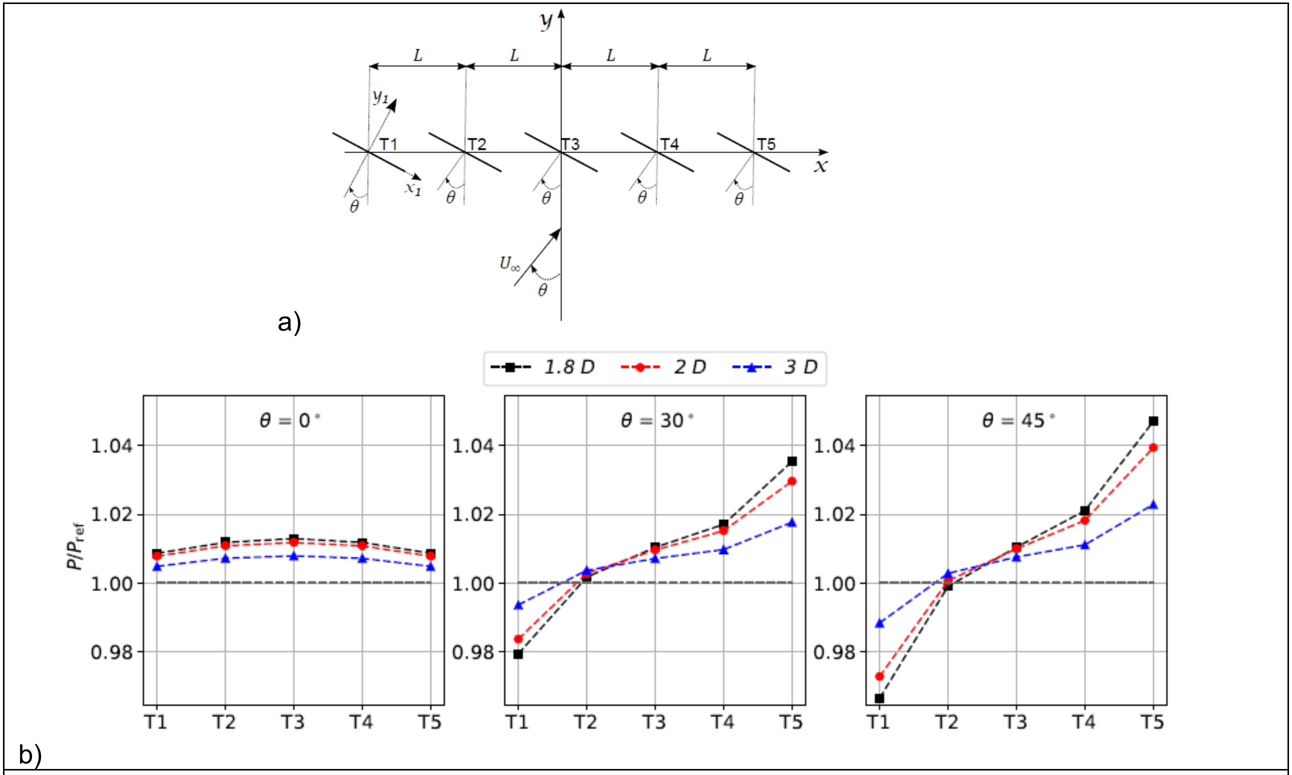

Figure 9: Power output of the five turbines for different wind directions and spacings.

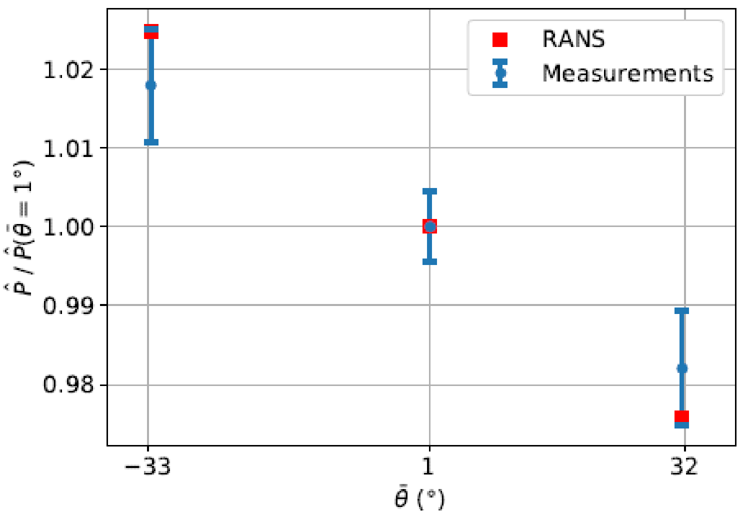

Figure 10: Comparison of measured and simulated power production for an edge turbine at a test site.

5. Utilisation of project results

The present project is contributing to an improved understanding of what is necessary to measure with lidars to obtain better power curve performance. DTU wind energy is in constant dialog with OEM and developers to improve and introduce Lidar based power curve performance under complex flow conditions. The increase in rotor size will introduce complex flow patterns even in the expected reference case due to turbulence and sheer falling outside the reference case.

The advanced simulations performed of the interactions between the flow and the turbine performance is now possible to be performed in a standard approach as described herein this report working towards site-specific power curves.

The results are currently being included in new research proposals on flow around turbines, sofar the results are not mature enough to include in the standards.

Project conclusion and perspective

By supporting the international collaboration IEA-Task 32, this project have contributed to improving the understanding of the physics in the interaction turbines and the project results may therefor lead to

1) Site- specific power curves
2) Suggestion for new methods of using lidars closer to the rotor
3) Include advanced aerodynic tools in the power curve validations

6. Appendices

Publications

[1] Sebastiani, A., Peña, A., Troldborg, N., and Meyer Forsting, A.: Evaluation of the global-blockage effect on power performance through simulations and measurements, Wind Energ. Sci. Discuss. [preprint], https://doi.org/10.5194/wes-2021-105, in review, 2021.

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