International Energy Agency (IEA)
Implementing Agreement for Co-operation in the Research and Development of Wind
Energy Systems (IEA Wind)

IEA Task 32:
Wind Lidar Systems for Wind Energy Deployment (LIDAR)

Final report
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Operating Agent
Martin Kühn and Davide Trabucchi
ForWind – University of Oldenburg
Germany

in cooperation with

Andrew Clifton
NREL – National Wind Technology Center
USA

Mike Courtney
DTU – Wind Energy Department
Denmark

Andreas Rettenmeier
SWE – University of Stuttgart Germany
Executive Summary

When IEA Wind Task 32—Lidar for Wind Energy Deployment—was established in May 2012, the wind energy community had just discovered the possible advantages of using remote sensing for wind resource assessment. At that time, new lidar technologies (e.g. nacelle-based systems and floating systems) as well as new applications (e.g. power curve measurements, measurements in complex terrain, and turbine control) were under development.

The topical expert meeting entitled *State of the art of Remote Wind Speed Sensing Techniques using Sodar, Lidar and Satellites* was organized within IEA Wind Task 11—Base Technology Information Exchange— in January 2007, forming the basis of Task 32. The main objective of Task 32 was to make recommendations for the use of lidar in the fields of lidar calibration (on- as well as offshore) and application for wind resource and turbine assessment.

The Task 32 activities were coordinated by ForWind at the University of Oldenburg (Germany) as Operating Agent assisted by Technical University of Denmark Department of Wind Energy (DTU Wind, Denmark), the National Wind Technology Center at the National Renewable Energy Laboratory (NREL, U.S.), and Stuttgart Wind Energy (SWE), University of Stuttgart (Germany).

Nine IEA Wind member countries joined Task 32. Several other member and three non-member countries expressed interest in the task. Experts from these countries attended one of the progress meetings as guests and occasionally participated in the task activities. Overall, at least 120 individuals from more than 50 institutions worked together under Task 32.

Task 32 lasted about three and a half years during which five plenary meetings were organized. A range of topics under the themes of lidar calibration, site assessment, and turbine applications were investigated in ten individual work packages, and seven reports documenting the results of the work packages have been published or are expected by early 2016. IEA Wind reports recently published include *Recommended Practices for Floating Lidar* [1] and *Expert Group Study Report on Turbulence Characterization Based on Lidar Measurements* [2]. Other reports published through participating institutions include [3] [4] [5] [6].

Although many institutions have cooperated within Task 32 to gain a better understanding and facilitate the application of lidar instruments, there is still a great need to define new or revise existing reliable procedures for taking accurate lidar measurements in standard and advanced applications. For these reasons, Task 32 should be extended.
# Table of Contents

Executive Summary ............................................................................................................. 2
Table of Contents .................................................................................................................. 3
1 Introduction .......................................................................................................................... 4
2 Objective of Task 32 ............................................................................................................. 4
3 Review of Task 32 Activity .................................................................................................. 5
   3.1 Coordination .................................................................................................................. 5
   3.2 Work Plan and Milestones ............................................................................................ 6
   3.3 Cooperative Activities ................................................................................................. 6
   3.4 Participants .................................................................................................................... 8
   3.5 Task 32 publications .................................................................................................... 9
4 Work Description and Accomplishments .......................................................................... 10
   4.1 Subtask 1: Lidar Assessment ....................................................................................... 10
   4.2 Subtask 2: Site Assessment ........................................................................................ 16
   4.3 Subtask 3: Turbine Assessment ................................................................................... 20
5 Conclusions ......................................................................................................................... 24
6 References .......................................................................................................................... 25
1 Introduction
Wind lidar is a remote sensing technology that uses laser light backscattered from aerosols in the atmosphere to remotely measure wind speed in the line of sight. This information can be used to estimate wind characteristics such as wind speed, direction, and turbulence. This technology has opened new frontiers to the wind energy community since the first commercial lidar instruments became available in the early 2000s.

Since then, research has shown that lidar instruments may be used as an alternative to conventional anemometry to measure the mean wind speed. Compared to anemometers and wind vanes mounted on a meteorological tower, ground-based lidar instruments are very flexible as they can be installed more quickly and easily to measure the wind vertical profile from the ground up to the rotor tip of the tallest turbine on the market or beyond. Consequently, the use of ground-based lidar instruments for wind resource assessment has increased.

New lidar technologies, such as nacelle-based and floating systems, have also been developed recently. In addition, researchers have proposed new procedures for assessing wind turbine power curves using ground-based lidar measurements.

There are some inherent differences between the measurement principles of lidar versus cup anemometry. First, lidar uses several volumetric-averaged measurements to estimate wind characteristics, while cup or sonic anemometers make point measurements of wind. This can lead to differences in measurements of mean or turbulent wind characteristics, which can increase in complex terrain or turbine wakes.

Under the International Energy Agency Wind Implementing Agreement (IEA Wind) Task 11, researchers started examining novel applications for remote sensing and the issues around them during the 51st topical expert meeting about remote sensing in January 2007. The 59th topical expert meeting organized by Task 11 in October 2009 was also dedicated to remote sensing, and the first draft of the Task’s recommended practices (RP) on remote sensing was published in January 2013 [7].

The results of the Task 11 topical expert meetings provided solid groundwork for a new IEA Wind Task 32 on wind lidar technologies. Members of the wind community identified the need to consolidate the knowledge about wind lidar systems to facilitate their use, and to investigate how to exploit the advantages offered by this technology. This was the motivation that led to the start of IEA Wind Task 32 “Lidar Application for Wind Energy Deployment” in November 2011. The kick-off meeting was held in May 2012.

2 Objective of Task 32
The general aim of IEA Wind Task 32 was to address the very fast development of wind lidar technologies and assess their applicability for more accurate measurement of wind characteristics, which is relevant to the more reliable deployment of wind power systems.

The objectives of the IEA Task were threefold:
1. Provide an international open platform for a continuous exchange of experience with lidar technologies, including progress in research on the performance of lidar devices and associated measurement techniques under different operational and site conditions.

2. Continue the development of the "IEA Wind Recommended Practices 15. Ground-based Vertically-profiling Remote Sensing for Wind Resource Assessment" [7], and investigate the possibility of refining and extending the content to address wind lidar concerns.

3. Identify areas for further research and development as well as standardization needs.

3 Review of Task 32 Activity

3.1 Coordination

ForWind, University of Oldenburg (Germany), was the Operating Agent of Task 32. DTU – Wind Energy (Denmark), Stuttgart Wind Energy (SWE), University of Stuttgart (Germany), and The National Renewable Energy Laboratory (NREL) (United States) assisted in the coordination of the project.

The members of Task 32 identified three main areas of interest and dedicated a subtask to each of them. The activities within the subtasks were organized in work packages (WPs); each had a specific scope. The organization of the work packages in the subtasks was discussed and revised during the course of the project resulting in the structure described in Table 1.

Table 1: Subtasks and Work Packages (WP) of Task 32

<table>
<thead>
<tr>
<th>Subtask I - Calibration and classification of lidar devices</th>
<th>Coordinator: Michael Courtney, DTU – Wind Energy, Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP 1.1 Ground-based lidar calibration</td>
<td></td>
</tr>
<tr>
<td>WP 1.2 Classification and uncertainty (merged into WP 1.1)</td>
<td></td>
</tr>
<tr>
<td>WP 1.3 Calibration of nacelle-based lidars</td>
<td></td>
</tr>
<tr>
<td>WP 1.4 Calibration in complex terrain (merged into WP 2.2)</td>
<td></td>
</tr>
<tr>
<td>WP 1.5 Application of floating lidar systems</td>
<td></td>
</tr>
<tr>
<td>WP 1.6 Novel idea: Line of sight calibration (on hold, to be addressed in the future)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subtask II: Procedures for site assessment</th>
<th>Coordinator: Andrew Clifton, NREL – National Wind Technology Center, USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP 2.1 Creation, dissemination and revision of recommended practices for the use of ground-based vertically profiling remote sensing for resource assessment</td>
<td></td>
</tr>
<tr>
<td>WP 2.2 Evaluation of wind field reconstruction methods in complex flows for wind lidars</td>
<td></td>
</tr>
<tr>
<td>WP 2.3 Measurement of wind turbulence</td>
<td></td>
</tr>
<tr>
<td>WP 2.4 Using lidar as a part of wind resource assessment</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subtask III - Procedures for turbine assessment</th>
<th>Coordinator: Andreas Rettenmeier, SWE – University of Stuttgart, Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP 3.1 Exchange of experience in power performance testing using a ground-based lidar according to 61400-12-1 2nd edition Committee Draft [8]</td>
<td></td>
</tr>
<tr>
<td>WP 3.2 Wind field reconstruction from nacelle-based lidar measurements</td>
<td></td>
</tr>
<tr>
<td>WP 3.3 Nacelle-based power performance testing</td>
<td></td>
</tr>
<tr>
<td>WP 3.4 Load estimation using a lidar system (on hold, to be addressed in the future)</td>
<td></td>
</tr>
</tbody>
</table>
Additionally, a fourth subtask coordinated by DTU–Wind Energy was established to coordinate the online communication among participants, the exchange of information, and data management. A project website, http://www.forwind.de/IEAAnnex32/, was established to facilitate internal and external communications. Working documents were shared within groups directly.

### 3.2 Work Plan and Milestones

The IEA Executive Committee approved the Task 32 3-year plan (see Table 3) in October 2011. The project kick-off meeting was held in May 2012 at DTU Risø campus. The project schedule, shown in Table 2, included six milestones and five plenary meetings.

#### Table 2: Project Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Achieved</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M1: Confirmation of participants, agreement on the work plan</strong></td>
<td>7 12/12</td>
<td>5-month delay</td>
</tr>
<tr>
<td><strong>M2: Data exchange platform operational</strong></td>
<td>12 05/13</td>
<td>9-month delay</td>
</tr>
<tr>
<td><strong>M3: IEA Recommended Practices (RP), 1st edition</strong></td>
<td>9 02/13</td>
<td>Published</td>
</tr>
<tr>
<td><strong>M4: IEA RP for Floating Lidar System and collection of technical reports (draft version)</strong></td>
<td>36 05/15</td>
<td>Documents currently in final review</td>
</tr>
<tr>
<td><strong>M5: IEA RP for Floating Lidar System and collection of technical reports (final version)</strong></td>
<td>42 11/15</td>
<td>12-month delay</td>
</tr>
<tr>
<td><strong>M6: Final reporting</strong></td>
<td>40 9/15</td>
<td>4-month delay</td>
</tr>
</tbody>
</table>

Some of the milestones were delayed for two main reasons:

1. The large number of topics considered in parallel the academic approach proposed within the work packages, and the efforts required were often an obstacle for participants with limited time resources.
2. The writing and review process of the final documents for the work packages lasted longer than expected.

### 3.3 Cooperative Activities

After the kick-off meeting, four progress meetings were organized to present intermediate results of the work packages to the full audience of Task 32. Information about the plenary meeting is provided in Table 4. The presentations given during the meetings as well as the meeting minutes are available on the Task 32 website (www.forwind.de/iea-annex32).
### Table 3: Task 32 Project Schedule and Milestones

<table>
<thead>
<tr>
<th>Activity/Milestone</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
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<tr>
<td></td>
<td>41</td>
<td>42</td>
<td>43</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Duration**

68th ExCo: Expected Task approval
Meeting 1: Initial Workshop (Roskilde)

**Subtask I: Calibration and classification**
Meeting 2: Progress meeting (Oldenburg)
M1: Confirmation of participants, agreement on the work plan

**Subtask IV: Data management**

**Subtask II: Proc. for site assessments**
M2: Data exchange platform operational

**Subtask III: Proc. for turbine assessment**
Meeting 4: Progress meeting (Stuttgart)
Meeting 5: Progress meeting (Glasgow)
M4: IEA RP Floating lidar system and reports of WPs (draft documents)
M5: IEA RP Floating lidar system and reports of WPs
M6: Final reporting
The operating agent and the work package leaders constituted the coordination team. They participated in 15 teleconferences to discuss the overall organization and progress of Task 32. Additional calls were organized within the individual work packages.

The work package activities included literature review, comparative exercises, and experience exchange. A virtual working space, including a web forum, was established to support these activities.

### Table 4: Task 32 Plenary Meetings

<table>
<thead>
<tr>
<th>Dates/Place</th>
<th>Host</th>
<th>Number of participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-31 May 2012</td>
<td>DTU – Wind Energy</td>
<td>41</td>
</tr>
<tr>
<td>Roskilde, Denmark</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-6 November 2012</td>
<td>ForWind – University of Oldenburg</td>
<td>31</td>
</tr>
<tr>
<td>Oldenburg, Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-15 May 2013</td>
<td>NREL – National Wind Technology Center</td>
<td>33</td>
</tr>
<tr>
<td>Boulder, Colorado, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-7 March 2014</td>
<td>SWE – University of Stuttgart</td>
<td>45</td>
</tr>
<tr>
<td>Stuttgart, Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-6 November 2014</td>
<td>University of Strathclyde</td>
<td>50</td>
</tr>
<tr>
<td>Glasgow, UK</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.4 Participants

Task 32 was initiated with four member countries; Denmark, Germany, Japan and the United States. During the course of the project, five more countries (Canada, China, The Netherlands, Norway, and the United Kingdom) joined Task 32.

Countries that were in the process of joining Task 32 but not yet officially part of the task were also allowed to participate. This enabled Belgium and France to take part in the task.

Austria, Greece, Israel, Spain, Switzerland and Sweden also expressed interest in joining Task 32. Institutes from these countries were therefore invited to attend a progress meeting.

Task 32 participants are listed in Table 5. Overall fifty-one institutions from 17 countries participated in Task 32 activities, including research centres, universities, wind measurement companies, and lidar and wind turbine manufacturers.
Table 5: Task 32 Participants

<table>
<thead>
<tr>
<th>Country</th>
<th>Partner</th>
<th>Participation Task 32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>Energiewerkstatt</td>
<td>Interested</td>
</tr>
<tr>
<td>Belgium</td>
<td>3E</td>
<td>Interested</td>
</tr>
<tr>
<td>Canada</td>
<td>AXYS Technologies, Technocenter Eolien</td>
<td>Committed (2013)</td>
</tr>
<tr>
<td>France</td>
<td>Avent Lidar, Epsiline, Institut Français du Pétrole Energies Nouvelles, Leosphere</td>
<td>Informally committed</td>
</tr>
<tr>
<td>Israel</td>
<td>Pentalum Technologies</td>
<td>Interested</td>
</tr>
<tr>
<td>Japan</td>
<td>ITOCHU Techno-Solutions, Mie University, Mitsubishi Electric</td>
<td>Committed (2012)</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>Energy research Centre of the Netherlands</td>
<td>Committed (2014)</td>
</tr>
<tr>
<td>Norway</td>
<td>Christian Michelsen Research, Meventus, Norwegian Centre for Offshore Wind Energy, University of Bergen</td>
<td>Committed (2013)</td>
</tr>
<tr>
<td>Sweden</td>
<td>WindVector AB</td>
<td>Interested</td>
</tr>
<tr>
<td>Switzerland</td>
<td>École polytechnique fédérale de Lausanne, Meteo Swiss, Meteotest</td>
<td>Interested</td>
</tr>
<tr>
<td>United States</td>
<td>AWS Truepower, CRES, Cornell University, National Center for Atmospheric Research, National Oceanic and Atmospheric Administration – Earth System Research Laboratory, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, University of Colorado</td>
<td>Committed (2012)</td>
</tr>
</tbody>
</table>

3.5 Task 32 publications

Task 32 deliverables included technical reports and a second edition of the IEA Wind RP15; “Ground-Based Vertically-Profiling Remote Sensing for Wind Resource Assessment” with a section dedicated to lidar. Because of the lack of firm answers on specific issues within the lidar community, Task 32 members decided not to publish a second edition of the IEA Wind RP 15. Instead, they decided a number of technical reports would be compiled that could contribute to a plan for this document in the future. These documents will be published by the lead authors’ institutions in the near future.
Work package 2.3 prepared an IEA Wind Expert Group Study Report on “Estimating Turbulence Statistics and Parameters.” Work package 1.5 will also submit a draft of the Recommended Practices for “Floating Lidar Systems” for approval by the IEA Wind Executive Committee soon. Table 6 provides a detailed list of the documents published within Task 32.

<table>
<thead>
<tr>
<th>Title</th>
<th>Work package</th>
<th>Document type</th>
<th>Publication/submission</th>
</tr>
</thead>
</table>

4 Work Description and Accomplishments

This chapter presents the three different subtasks of Task 32 on lidar applications and outcomes of the individual work packages. Examples and results and references to documents written within Task 32 are also provided.

4.1 Subtask 1: Lidar Assessment

At the outset of Task 32, ground-based lidar calibration was already established as a commercial activity with a foundation in journal articles [10] as well as in draft standards [8] and recommended practices [7]. However, this was true for ground-based measurement in flat terrain only. A reliable procedure for novel applications such as nacelle-based and floating lidar was still under investigation. Nonetheless, it was also quite clear from discussions among three or four of the practitioners in Task 32 that results of ground-based lidar calibration were limited in their repeatability.

\footnote{Document based on activities of the IEA Wind Task 11}
In subtask 1, two groups were formed to consider issues concerning lidar calibration for ground-based (WP 1.1 and WP 1.2) and nacelle-based (WP 1.3) applications. A third group considered floating lidar systems (WP 1.5) and extended the scope beyond calibration to include other aspects of offshore deployment of floating lidar systems. The activities and the results produced by the three groups are summarized in the following sections.

4.1.1 Calibration of Ground-Based Lidar (WP 1.1 and WP 1.2)
This work package was managed by Michael Courtney at DTU Wind Energy, Roskilde, Denmark.

The variation of lidar calibration results
Typically calibration of the same lidar at the same location can give a variation in the gain value, i.e. the slope of the linear calibration curve, of between 0.5% and 1%. Figure 1 (left) [11] shows the values in gain (for an offset forced to zero) for one lidar over a 4-month period. Here, a “moving window” technique was used where a long dataset was split into a number of shorter datasets, each representing a valid calibration dataset. We can see a ±0.5% variation for this period. As part of the same study (a joint DONG Energy and DTU project that forms much of the basis of the work in package 1.1), lidar systems were calibrated before and after a period of field service. The results are shown in Figure 1 (right). We can see the same order of magnitude of variation but with no evidence of any long-term drifting. The goal of work package 1.1 was to investigate the causes of the variation in calibration results and what can be done to reduce it.

![Figure 1. Left: Variation of calibration results for one lidar at one site, Right: Pre- and post-calibration results for one lidar after a period of service.](image)

The activity of this work package was based on the exchange, discussion, and review of the scientific publications, white papers, and technical reports that were collected and made available on the virtual work space. These documents are listed in Table 7.
Table 7: Working documents of Work Packages 1.1 and 1.2

<table>
<thead>
<tr>
<th>No.</th>
<th>Document name</th>
<th>Organisation/author</th>
<th>Purpose/relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WP1_1_Kickoff.pptx</td>
<td>DTU/Courtney</td>
<td>Presentation from kick-off meeting.</td>
</tr>
<tr>
<td>2</td>
<td>Kick_off_meeting_minutes.docx</td>
<td>DTU/Courtney</td>
<td>Minutes from kick-off meeting.</td>
</tr>
<tr>
<td>3</td>
<td>Shear_error_action1.docx</td>
<td>DTU/Courtney</td>
<td>Suggested common shear error action.</td>
</tr>
<tr>
<td>4</td>
<td>Vector_scalar_action2.docx</td>
<td>DTU/Courtney</td>
<td>Suggested common vector/scalar averaging action.</td>
</tr>
<tr>
<td>6</td>
<td>DTU-Wind_Energy_E-0061_Shear_and_Turbulence_effects_on_lidar_measurements.pdf</td>
<td>DTU-DONG/Courtney-Nygaaard-Sathe</td>
<td>Study of how shear and turbulence effects can influence lidar measurements with some additional observations about cup anemometers.</td>
</tr>
<tr>
<td>7</td>
<td>Shear_error_report_Mitsubishi.pdf</td>
<td>Mitsubishi/Kameyama</td>
<td>Mitsubishi response to the shear action.</td>
</tr>
<tr>
<td>8</td>
<td>VectorScalarAve.pdf</td>
<td>DONG/Mann</td>
<td>A note about the difference between scalar and vector averaging.</td>
</tr>
<tr>
<td>9</td>
<td>NRELScalarOrVector.pdf</td>
<td>NREL/Clifton</td>
<td>NREL response to the scalar/vector averaging action.</td>
</tr>
<tr>
<td>11</td>
<td>ZZ ZephIR 40 months operation.pdf</td>
<td>ZephIR/Mangat</td>
<td>Long-term stability of Z300 calibrations.</td>
</tr>
<tr>
<td>12</td>
<td>Z3 Guidelines for siting and comparison of ZephIR against a met mast June2014.pdf</td>
<td>ZephIR/Harris-des Roziers</td>
<td>ZephIR guidelines for ZephIR testing.</td>
</tr>
</tbody>
</table>

The effect of wind shear and sensing height error

One probable cause of the variation in calibration results was identified as the variation of wind shear at the test site. Wind shear has two effects on the wind speed reported by the lidar; an averaging error if either the shear is nonlinear or the probe weighting function is asymmetric and a “sensing height” error if the interrogation height also has an error. Figure 2 [12] shows the combined effect of these errors for various values of power law shear exponent and sensing height error calculated for the case of a Windcube lidar measuring a 15 m/s wind at 100 m.
It can be seen that although both effects are significant, the error introduced by even a modest (1 m) sensing height error is usually much more significant than the curvature effects of the nonlinear shear. This general trend was confirmed from the simulations of Mitsubishi Electric Corporation, using a model for their own lidar.

In [12] an attempt was made to correct for the effects of a sensing height error known from the calibration using the three parameter (3p) regression method. The calibration results from Figure 1 were re-run with this correction included. However, the scatter between the actual calibration results increased slightly. It was tentatively concluded that a good estimation of the sensing height error requires a much higher density of vertical measurement points than was (and is normally) available.

The conclusions from this work presented at the Glasgow workshop of Task 32 in November 2014 were as follows:

- Sensing height errors matter
- We need to increase confidence in the three parameter (3p) regression method (or find an alternative)
- The International Electrotechnical Commission (IEC) 61400-12-1 standards committee has also identified this as an issue.
- Errors caused by asymmetric probe volumes and shear curvature are also well worth evaluating

**The effect of turbulence on the lidar speed measurements**

Another cause of variation of calibration results was suspected to be from effects of varying turbulence intensity. In particular, we were concerned that a mechanism observed with a two-beam nacelle lidar, where the scalar average was significantly biased by inhomogeneity effects [13], could also play a significant role for ground-based lidar systems.

The activity conducted in the task mainly dealt with the difference in the average wind speed evaluated either as an average of the wind speed values calculated from the instantaneous
lidar measurements (scalar averaging), or averaging first the instantaneous lidar measurements and then calculating the wind speed (vector averaging). The work included both analysis of experimental results using scalar and vector averaging (in work package document 9) and a theoretical analysis (contained in work package document 6). Figure 3 attempts to summarise these results. In this figure, the actual differences between scalar and vector averages are shown both as modelled and as measured. The results for the sonic represent the ideal case where there is no error caused by inhomogeneity. For the lidar, both the modelled and the measured difference between the scalar and vector averages are slightly higher than for the sonic, and it is this difference that represents the error in the lidar scalar mean. We concluded that the error in the scalar mean is rarely larger than 0.1%. This is much smaller than observed for the 2-beam nacelle lidar and this can thus be discounted as a significant cause of calibration variation. On the other hand, Figure 3 demonstrates the importance of using a consistent averaging method as we can see that the actual difference between vector and scalar averaging can be on the order of 1% at low wind speeds.

![Figure 3. Modeled and measured differences between the scalar averaging error (the difference between the red and blue lines and markers).](image)

A general and important observation from this work is that errors on the reference instruments caused by the direction (mast/boom flow distortion) and in particular the sensitivity of cup anemometers to turbulence are much larger than scalar averaging errors. Indeed, at the Glasgow workshop we concluded that the main problem is the sensitivity of the reference cup anemometer to turbulence. This is poorly understood and not corrected for.
4.1.2 Calibrating Nacelle Lidar (WP 1.3)
This work package was managed by Michael Courtney at DTU Wind Energy, Roskilde, Denmark.

Work on a calibration procedure and uncertainty scheme was already well underway at the kick-off of Task 32 in May 2012. A finalised report on the work (specifically for the two-beam Avent IRIS nacelle lidar) [14] was uploaded to the Task 32 web site in October 2013 with a request for comments. To date, there has been no feedback on this document from the participants of Task 32. This is probably because, until recently, the authors (DTU) have been the only institute offering calibrations of this type.

The current status is that a significant number of commercial calibrations have been carried out using [14], and this has formed the basis of the uncertainty evaluation for a number of commercial power curve tests [15].

In the meantime, the nacelle lidar industry is moving towards multibeam systems capable of measuring the wind shear in front of the rotor to a certain degree. DTU – Wind Energy has initiated the new project Unified Turbine Testing (UniTTE) in which calibration of multibeam nacelle lidar systems is included as a work package. This work is currently being reported.

4.1.3 Application of Floating Lidar Systems (WP 1.5)
This work package was managed by Julia Gottschall at Fraunhofer IWES, Bremerhaven, Germany.

Floating lidar systems have emerged as wind resource assessment tools for offshore wind farms, with the potential for greatly reduced installation costs compared to fixed meteorological masts in some cases. The challenges that floating lidar systems have to overcome to be considered as effective wind measurement options can broadly be grouped in two categories:

- The movement of the sea imparting motion on the lidar, and the subsequent challenge of maintaining wind speed and direction accuracy;
- The remoteness of the deployed system necessitating robust, autonomous, and reliable operation of measurement, power supply, data logging, and communication systems.

The development of floating lidar systems towards a (pre-)commercial technology for use in site assessment campaigns coincides to a large extent with the duration of IEA Wind Task 32. At the time of the Task’s kick-off, the first systems were already introduced and their capabilities demonstrated, but a regulatory framework for their application, including pre-testing of the system, was not available.

The “Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating Lidar Technology” [16] (often referred to as the Roadmap) was published in November 2013 as the first guideline of this kind made available to the industry by a consortium of different partners active in the field. The Roadmap offers details on a possible classification of the systems according to their stage of maturity as well as a procedure for the accordant testing and evaluation prior to an application. Although the document is
comprehensive and was accepted by the industry more or less immediately, it is obvious that it does not cover all the relevant topics, and that there is a definite need for a follow-up or additional document.

In this context, work package 1.5 was not only initiated, but also the compilation of a draft RP document (IEA Task 32 Work Package 1.5 Recommended Practice on Floating Lidar Systems) was defined as a target already in an early phase of the project.

A corresponding initial draft was completed in late summer 2015 and given to a broader group for a Task-internal review. The next steps are to revise the draft based on the reviewers’ comments and to submit the revised document to the IEA Wind Executive Committee for review and approval.

This RP is meant to facilitate the application of lidar for offshore wind energy resource assessment. It aims to codify existing industry and academic best practices to help ensure that the best quality floating lidar systems data are made available for use. Therefore, the document includes sections on:

- Configuration
- Characterisation
- Assessment of site suitability
- Licensing
- Trial campaign design
- Trial results assessment
- Wind resource assessment campaign design
- Wind resource assessment.

The individual sections are in sequence according to a project’s timeline, but they can also be considered separately for guidelines in a specific field. For example, the document may address the needs of system suppliers, measurement institutes, and consultancies engaged in testing as well as users that wish to apply the technology in a wind resource assessment. The draft RP’s focus is on resource assessment; however, it may also be used as a reference for other applications of floating lidar systems. Although future work may include this and additional relevant topics, we believe the current draft RP reflects the state of the art.

4.2 Subtask 2: Site Assessment

Subtask 2 investigated the use of lidar for site assessment activities. Site assessment is the process of measuring wind and other conditions at a wind plant site. Site assessment is typically carried out before a wind plant is built, but can also include investigations on an operational site, if, for example, that site is not performing as well as expected.

In 2011, prior to the start of Task 32, site assessment was usually conducted using fixed meteorological towers, and data were extrapolated vertically and horizontally from those towers to estimate the wind resource on a site. The role of remote sensing was typically to check the vertical extrapolation (as lidar can measure at greater heights than meteorological...
towers) and to move around the site to check the horizontal extrapolation. However, there were clear areas in which lidar could be beneficial:

1. To replace meteorological towers in general
2. To measure winds at multiple heights across the rotor disk to enable the use of the rotor-equivalent wind speed
3. To measure the spatial variability of the wind, either across wide swathes of the wind plant or locally to confirm wind models
4. To target specific flow features or turbines in measurement campaigns.

The objectives of subtask 2 were to identify how lidar was being used in 2011 for site assessment, show how lidar could be used throughout site assessment, and identify why lidar was not being used more widely. The goal of subtask 2 was to set the groundwork for later actions to overcome barriers to the use of lidar.

Four individual work packages were established to look at issues around site assessment. These work packages included:

- WP 2.1: RP 15 ground-based vertically profiling remote sensing for site assessment—tasked with getting this RP (arising from a Task 11 Topical Expert Meeting) edited, reviewed, and adopted
- WP 2.2: Lidar wind measurements in complex flow—tasked with documenting how lidar was used in complex flow, and what the issues were with using lidar in those situations.
- WP 2.3: Turbulence measurements using ground and nacelle-based wind lidars—tasked with documenting the use of lidars to measure turbulence and identifying issues
- WP 2.4: Using lidar as part of wind resource assessment—tasked with documenting how lidar can be used in resource assessment.

The activities and results from the work packages are summarized in the following pages.

4.2.1 RP 15 Ground-Based Vertically Profiling Remote Sensing for Site Assessment (WP 2.1)

This work package was managed by Andrew Clifton at the National Renewable Energy Laboratory, Golden, Colorado.

Getting reliable and trustworthy data from any measurement device requires careful set up and maintenance of the equipment. Much of the required information can be found in owners’ manuals, but recommended practices that consolidate many years of experience from many people can also help reinforce good practice. For this reason, the 51st IEA Topical Expert Meeting (TEM) in 2007 suggested the development of recommended practices for remote sensing, and the 59th TEM in 2009 placed a high priority on completing those recommended practices. Two draft documents for the use of sodar and lidar respectively were consolidated in 2011 into draft recommended practices for ground-based systems using vertical profiling. The recommendations were limited to deployments for resource assessment on land.

At the kick-off meeting in Roskilde, Denmark, in May 2012, Task 32 supported the review and editing of the proposed RP, including several rounds of revisions. The RP document
was approved by the ExCo in 2013 and published online at [http://www.ieawind.org](http://www.ieawind.org) as *IEA Wind RP 15: Ground-Based, Vertically Profiling Remote Sensing for Wind Resource Assessment*, or RP15 [7].

RP15 covers the characterization, installation, operation, analysis, validation, and maintenance of a ground-based remote sensing device used for wind resource assessments. The recommended practices are intended to help users obtain low-uncertainty data from a remote sensing device used for site assessment. RP15 contains 41 recommended practices and describes the motivation behind each practice.

Since publication, RP15 has been downloaded more than 2,000 times and was used as the template for the Recommended Practices for Floating Lidar Systems developed under work package 1.5. Feedback from the user community has been positive, and experience with RP15 helped inform the development of the forthcoming revision to IEC 61400-12-1 (2005) [17].

### 4.2.2 Lidar Wind Measurements in Complex Flow (WP 2.2)

This work package was managed by Andrew Clifton at the National Renewable Energy Laboratory, Golden, Colorado.

A key goal of the site assessment subtask in Task 32 was to investigate how lidar can be used to measure winds in complex flows. Lidar measurements in complex flow are challenging to interpret and compare to traditional cup measurements, as the cup makes a point measurement, and the lidar makes a volumetric measurement.

Work package 2.2 developed a working definition of complex flow based on a combination of terrain and atmospheric indicators (Figure 4). The presence of any one of the indicators found in Figure 4 means that a lidar may be used for measuring in a complex flow, and that appropriate measures should be taken to ensure the quality of the final data.

![Diagram](image-url)

**Figure 4.** Indicators of complex flow that may be important for comparisons of lidar and point measurements [18] [19].
Recognizing complex flow and the effects that it has on a lidar system enables the user to choose an appropriate measurement method to acquire the data that they require. Work package 2.2 documented the combination of conditions, data, and methods in a report published by NREL [3]. The report documents use cases for lidar in complex flow, and identifies several preliminary recommendations for the use of lidar in complex flow conditions. These recommendations may form the basis for future recommended practices for the use of lidar in complex flow situations.

4.2.3 Turbulence Measurements Using Ground- and Nacelle-Based Wind Lidars (WP 2.3)

This work package was managed by Ameya Sathe at DTU Wind Energy, Roskilde, Denmark.

Information about turbulence is required for turbine selection and siting. However, turbulence measured using a single lidar system is different than that measured by a cup or sonic anemometer on a meteorological tower. This difference stems from the fundamentally different measurement techniques used by lidar systems and cup anemometers.

Work package 2.3 investigated the use of lidar for turbulence measurements and produced an IEA Wind Expert Group Study Report [2] that details the challenges of measuring turbulence with lidar, different measurement configurations, and the state of the art. The report also summarizes past experimental campaigns.

The major conclusion of the report is that the observed difference in measurements between lidar and cup or sonic anemometers is generally due to the measurement configurations that are used, and the methods used to recover turbulence information from the measurements. The report also suggests adjustments to configurations and post-processing that could provide better turbulence measurements and help overcome a significant barrier to the use of lidar for site assessment.

4.2.4 Using Lidar as Part of Wind Resource Assessment (WP 2.4)

This work package was managed by Rozenn Wagner at DTU Wind Energy, Roskilde, Denmark.

The use of lidar systems can potentially add significant value to a wind resource assessment because they can take measurements at greater heights and distances than a meteorological tower.

At the start of Task 32, there was a lack of information about the different ways in which lidar systems were being used in resource assessment.

Work package 2.4 was initiated to document the ways in which lidar systems are used in the resource assessment process. Members of Task 32 prepared a report documenting approximately 10 different use cases, ranging from standalone, vertically-profiling lidar systems to multiple scanning lidar systems [6]. The report will be used in the future to educate users and to identify potential recommended practices.
4.3 Subtask 3: Turbine Assessment

Subtask 3 comprises smaller topics including ground- and nacelle-based lidar applications, as well as power performance and wind field reconstruction issues.

In addition to using lidar for site assessments, the technology may be used for a variety of applications directly linked to wind turbines and the certification process. When using a lidar system as a wind profiler from the ground, it can be linked to power performance testing according to the IEC 61400-12-1 standard [8] and its Annex L, which is currently under further development.

Furthermore, when installed on the nacelle or in the spinner of a wind turbine, lidar can measure the wind field approaching the rotor—even during yaw maneuvers. This information can be used for various novel developments in terms of predictive control strategies, load estimation, and power performance testing, and could be especially advantageous for performing nacelle-based lidar measurements onshore and offshore to determine the power curve of a wind turbine.

Considering the state of the art of the developments previously described, three main work packages were established within subtask 3:

1. WP 3.1: Power performance testing using a ground-based lidar. The objective of this WP was to acquire feedback from several companies, certification offices, and research institutes that have already worked with the draft of the forthcoming edition of the IEC standard.
2. WP 3.2: Wind field reconstruction from nacelle-based lidar measurements. This WP was dedicated to investigating the different approaches to estimate wind speed, wind direction, and shear based on the “raw” radial wind speed measurements provided by the lidar. This topic is relevant for control and power performance applications.
3. WP 3.3: Nacelle-based power performance testing. The WP objective was the collection and documentation of different approaches to determine a power curve from nacelle-based lidar measurements.

4.3.1 Power Performance Testing Using a Ground-Based Lidar According to IEC 61400-12-1 Edition 2 Committee Draft (WP 3.1)

This work package was managed by Rozenn Wagner at DTU Wind Energy, Roskilde, Denmark.

Wind turbine power curves are currently measured using cup anemometers and wind vanes mounted on meteorological towers as recommended in the IEC 61400-12-1 Power Performance Testing standard [17].

Lately research results have demonstrated the need for more comprehensive measurements of the power curve of wind turbines and of the induced loads. It has been shown that the wind shear has an important effect in the uncertainty of power curves, and that this becomes more important for large wind turbines in regards to loads. The objective of WP 3.1 was to evaluate Annex L of the committee draft of IEC 61400-12-1 Power Performance Testing standard 2nd edition [8]. This section describes how to use the combination of a reference
meteorological mast (smaller than hub height) and a lidar system. Based on this standard it
will be possible to measure the wind speed at hub height or to estimate the so-called rotor
equivalent wind speed (REWS), i.e. an equivalent wind speed calculated on the basis of
measurement points over the swept rotor area [20].

The activity in WP 3.1 dealt with some tests of the REWS method as proposed in [8].

Eight organizations from five countries participated in the exercise. Each member of the
group derived both the power curve based on the wind speed at hub height and the power
curve based on the REWS. This yielded results for different wind turbines located in diverse
types of terrain with the wind speed profile measured with different instruments (mast or
various lidars). The participants carried out two preliminary steps to reach a consensus on
how to implement the REWS method. First, they all derived the REWS for one 10-minute
wind speed profile. Second, they all derived the power curves for one dataset. The exercise
highlighted that the definition of the segment area used as weighting for the wind speeds
measured at the various heights in the calculation of the REWS was unclear. Results also
showed that the REWS method led to a significant difference compared to the standard
method using the wind speed at hub height in conditions with large shear and low turbulence
intensity. Results were presented at the Science of Making Torque from Wind conference in
2014 and are summarized in [9].

4.3.2 Wind Field Reconstruction from Nacelle-Based Lidar Measurements
(WP 3.2)
This work package was managed by David Schlipf, SWE, University of Stuttgart, Germany.

Wind field reconstruction is the procedure used to calculate the three-dimensional wind
vector, or any other wind characteristics such as rotor effective wind speed, shears or
direction, out of the line-of-sight wind speed vector by using assumptions or an estimator.
The knowledge of the wind field is necessary for several lidar applications such as site
assessment, power performance testing, lidar-assisted control, or detection of complex
flows. Traditionally, ground-based lidar systems use the assumption of homogeneous flow
for each measurement height. In flat terrain, very good agreement can be achieved for
ground-based systems over 10-minute average values [21]. However, new algorithms need
to be found, where the assumption of homogenous flow is not adequate (complex terrain,
[22]), where the lidar system is not measuring from the ground or moving (floating and
nacelle-based lidar systems, [23]), or where higher temporal resolution is needed (lidar-
assisted control, [24]). Usually, new algorithms use static [25] or dynamic models [26]
tailored to the application.

The main activity in WP 3.2 was a blind comparison exercise. The objective was to
reconstruct the three-dimensional wind components from raw lidar data and obtain values as
close as possible to the measurements from three sonic anemometers on a meteorological
mast (see Figure 5). Only the coordinates of the 10 measurement points and the 10-minute
average values of the line-of-sight wind speeds of 11 days were provided. The evaluation
criteria were the absolute mean error over the three wind components of all three sonic
anemometers.
Before the comparison exercise, the model-based approach [25] was used to estimate a baseline absolute mean error value. Five researchers from three organizations participated in the exercise. It is important to note that the three best results have been very close and showed higher accuracy than the baseline error, showing that the methodologies used for wind field reconstruction can be improved.

A technical report is planned in WP 3.2 with more details from the exercise.

![Diagram of a Nordtank turbine with a Scanning SWE lidar](image)

**Figure 5. Scanning SWE lidar on a Nordtank turbine with a rotor diameter of 41 m at Risø DTU (left). Trajectory (center: front view, right: side view).**

### 4.3.3 Nacelle-Based Power Performance Testing (WP 3.3)

This work package was managed by Andreas Rettenmeier at SWE – University of Stuttgart, Stuttgart, Germany.

The use of a nacelle-based lidar system allows for measuring turbine inflow and wake in a very high spatial and temporal resolution. The new measurement techniques to be developed have direct applications on- and offshore for the verification of wake models, predictive control strategies, and new methods for power curve determination and load estimation. Installation of the lidar system on the nacelle of a turbine is advantageous because

1. The lidar yaws with the turbine and the laser beam is always orientated along the up- or downstream wind direction
2. No information about the horizontal wind speed is lost due to the vertical inclination of the pointing direction of the lidar, which is otherwise needed using ground-based lidars to set the target point at the wind turbine hub height.

Different nacelle-based lidar systems have been developed as commercial products with several beam directions by companies such as Zephir, Avent Lidar, and Mitsubishi. Different lidar systems were also developed by research institutes for nacelle applications, such as the spinner lidar developed by DTU – Wind Energy (continuous-wave lidar, flexible scan pattern) and at the University of Oldenburg (pulsed lidar with a fixed pointing direction).
Several experiments were performed to estimate the possibility of nacelle-based lidar applications. In one experiment, one of the first continuous-wave lidar systems developed by QinetiQ was used to investigate wind turbine control [27]. In a second experiment, a continuous-wave lidar was mounted in the rotating spinner of a wind turbine [28]. In the third, the lidar system of the SVE – University of Stuttgart, based on the pulsed lidar device "Windcube" by Leosphere enhanced with a two degrees of freedom scanner, was applied for the reconstruction of a wind field approaching a wind turbine [29].

**Nacelle-Based Power Performance Testing**
A very promising approach for on- and offshore power performance testing and validation is to measure the wind field from the nacelle. By using a nacelle-based lidar system that yaws with the turbine, it is possible to measure the incoming wind field. The measurement comprises a spatial measurement of the radial wind speed distributed on discrete points over the swept rotor area. Applying specific assumptions, information about the wind shear could be derived. As a result, the power performance testing becomes far more accurate than with any conventional method as long as the wind parameters can be determined in a satisfactory way.

Procedures regarding the calculation of a wind speed representative for the rotor, such as the rotor effective wind speed and the previously mentioned rotor equivalent wind speed (REWS), are still a matter of the ongoing research. For example, a specific field of investigation is the definition of the points in space that should be used for an accurate assessment of these wind speeds.

Within WP 3.3, participants collected and reviewed scientific papers about nacelle-based lidar for power curve estimation. For example, they considered [30], [31], [32] and [33], along with the well documented results of the Danish Energy Technological Development and Demonstration Program (EUDP) project: "Nacelle lidar for power performance measurement" [34]. On this basis, they compiled a technical report [4] describing the possible choices for the type of installation and scanning pattern. This document also describes issues concerning the accuracy of the results and reports on the practical experience collected by the participants who deal with nacelle-based lidar power performances.

All the chapters of the report have not yet been finished as results will be included from ongoing research and projects such as the Danish UniTTe project started in January 2014.

During Task 32, a novel lidar system was presented by a participant Mitsubishi Electric Corporation has released the commercially available wind lidar product series named "DIABREZZA." This instrument is designed for installation on the nacelle of a wind turbine specifically for power performance testing and wind turbine control. In Figure 6, it is possible to see the 9-beam configuration implemented in the device.

**4.3.4 Concluding Remarks on Turbine Assessment**
In the near future, ground-based lidar measurements should be further developed for load estimation regarding a prospective implementation into IEC 61400-13 "Wind turbine generator systems—Part 13: Measurement of mechanical loads" [35]. Here, it is important to
determine not only the wind speed but also the turbulence intensity because the measured loads have to be filtered according to both wind parameters into a capture matrix. This activity is tightly connected with WP 2.3 “Turbulence measurements using ground and nacelle-based wind lidars.”

Furthermore, the development of applications for nacelle-based lidar measurements should be supported and continued in the future because of the advantages they provide. Currently, there are several ongoing nationally funded research projects such as the “UniTTe” project in Denmark and the “Lidar complex” project in Germany (FKZ 0325519) where nacelle-based lidar measurements are dealing with power performance testing of wind turbines in flat as well as complex terrain. Both projects also focus on load estimation. Hence, several papers and reports will be published in relation to these projects during the next months. They will feed into the final technical report for WP 3.1 and into the work plan of the proposed extension of Task 32.

The promising predictive lidar-assisted turbine control was not directly included in the current phase of Task 32 because of confidentiality issues with the turbine manufacturers. But this topic will be included in parallel to the aspect of turbine loading in the proposed extension of the task.

5 Conclusions
With the 10 work packages and 3 subtasks, Task 32 tackled several open issues affecting the deployment, operation, and analysis of data from wind lidar systems. Specifically, topics such as lidar calibration, resource assessment, and wind turbine related applications were considered. Important conclusions were reached in the field of floating lidar systems, ground and nacelle-based applications, deployment in complex flows, and measurement of turbulence. In particular, a recommended practices document for the use of a floating lidar system is about to be submitted to the IEA Wind Executive Committee, and a conference paper on the application of the rotor equivalent approach for wind turbine power
performance testing was published. An IEA Wind Expert Group Study Report on Estimating Turbulence Statistics and Parameters from Ground-Based Lidar Measurements was produced as well.

Also, Task 32 provided assistance in the review and promotion of the IEA Wind RP 15: Application of Ground-Based Remote Sensing for Wind Resource Assessment written within Task 11. During the course of Task 32, there was the hope that a second edition of RP 15 or another recommended practice on wind energy resource assessment with lidar measurements in complex flow could be completed. However, the subject turned out to be so complex that such a consolidated and comprehensive document could not be published.

The participants set ambitious objectives at the beginning of the project. Some had to be reconsidered to fit the resources of the 51 participating institutions. In addition, the number of work packages and topics addressed in parallel represented a considerable inertia, which slowed the progress of Task 32 as a whole.

Nonetheless, Task 32 was successfully concluded. Some good achievements were gathered and areas for further research and development as well as standardization needs were identified when it was not possible to find conclusive answers.

One valuable result of Task 32 was the establishment of an international community that is devoted to the joint discussion of and improvement to the state of art as well as the perspective of lidar applications. The momentum of this community should be further energized and directed to release lidar technology from the constraints still restraining its application. For this purpose a continuation of Task 32 in a second phase will be proposed to the IEA Wind Executive Committee.

6 References


