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IEA Wind Task 32: Best Practices for the Certification of Lidar-Assisted Control Applications

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Abstract. Lidar-assisted control is a promising technology for reducing structural loads on wind turbines. Guidelines for certifying wind turbines with this technology are important for its widespread adoption. As a first step, an IEA Wind Task 32 workshop was held, bringing together wind turbine manufacturers, lidar suppliers, certifiers, consultants, and researchers to identify barriers to certification with lidar-assisted control and ideas for mitigating the barriers. This paper builds on the outcome of the workshop by providing an analysis of the areas affected and the remaining challenges. Further, initial best practices are given to address the challenges, covering the lidar system, control and protection systems, design loads, and type testing.

1. Introduction

Lidar-assisted control (LAC) of wind turbines has been an active area of research for over a decade [1]. Both simulation-based studies and field-testing campaigns show promising reductions in structural loads as well as increases in energy production using feedforward control relying on preview measurements of the approaching wind field. However, LAC has not become widely adopted by the wind industry yet. One of the most significant barriers to the widespread adoption of the technology is that guidelines for certifying wind turbines with LAC have not been established. Without clear design standards for wind turbines using LAC, it is difficult for wind turbine manufacturers to fully assess the value creation of the control technology and move forward with including it in a commercial turbine design.

The general objective of the International Energy Agency (IEA) Task 32 extension is to identify and mitigate barriers related to the use of lidar for wind energy applications including loads and control by organizing topical workshops with tangible outcomes. While the first workshop focused on how to optimize lidar systems for LAC [2], the workshop "Certification of Lidar-Assisted Control Applications" of Task 32 in January 2018 at the DNV GL office in Hamburg brought together lidar manufacturers, wind turbine manufacturers, research organizations, and certification bodies to develop suggestions for guidelines for type certification of wind turbines with LAC. This paper builds on the main results of the workshop to provide a first step toward the development of standards for LAC.

First, an overview of type certification and an analysis of the areas affected by LAC is provided, along with a discussion of how these areas are related to existing standards. The

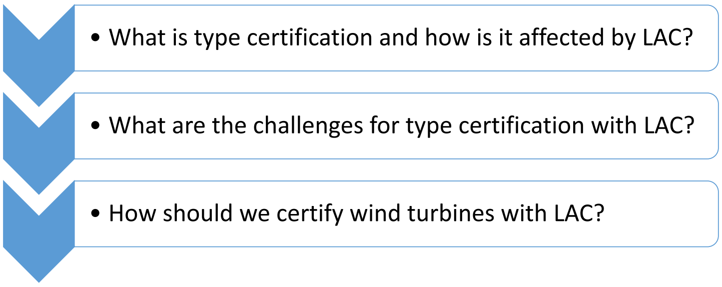

Figure 1: Key questions for the certification of lidar-assisted control, which served as the session themes for the IEA Wind Task 32 workshop and represent the main sections of this paper.

second subsection is devoted to the feedback from the four relevant stakeholder groups (lidar manufacturers, turbine manufacturers, consultants, and researchers), all answering the question: What are the challenges for type certification with LAC? This section is intended to alert the community to open issues. In the final section, initial best practices are given, based on information on how to certify wind turbines with LAC in the identified areas gathered during a discussion round with experts at the workshop. This section is intended to serve as the starting point in the development of a dedicated standard to certify turbines with LAC.

The work is structured into three main sections similar to the workshop organization (see Figure 1).

2. What is type certification and how is it affected by LAC?

Certification is the confirmation of design requirements by an accredited party (certification body) to a third party (authorities, financiers, insurers, etc.) based on accepted standards. This process supports the confidence in technical integrity, assists in satisfying health and safety requirements, and helps with securing investment.

Type certification of wind turbines is typically performed according to well-known standards, such as International Electrotechnical Commission (IEC) 61400-22 [3] or DNV GL-SE-0441 [4]. Beside further details both standards have in common that the following three modules form the basis for a wind turbine type certificate:

- Design evaluation
- Manufacturing evaluation
- Type testing.

During design evaluation, it is confirmed that the respective wind turbine design complies with requirements set up by applicable design standards. These design standards address all components of the wind turbine and represent the state of the art in wind turbine technology. Manufacturing evaluation intends to ensure that the production of components proceeds under consideration of the requirements assumed for the component design. Type testing closes the link between the real wind turbine and the theoretical design by confirming the model assumptions using measurements from the wind turbine in the field. LAC will mainly affect the design evaluation and type testing modules, with no significant relevance for manufacturing evaluation.

Today, wind turbines with LAC can be certified based on individualized interpretation of the standards and assessment of the specific lidar system and wind turbine type. However, existing standards do not contain explicit guidance and requirements for wind turbines with LAC. Certification of wind turbines with LAC thus currently relies on an interpretation of the standards and employs risk-based mechanisms, such as technology qualification DNVGL-RP-A203 [5].

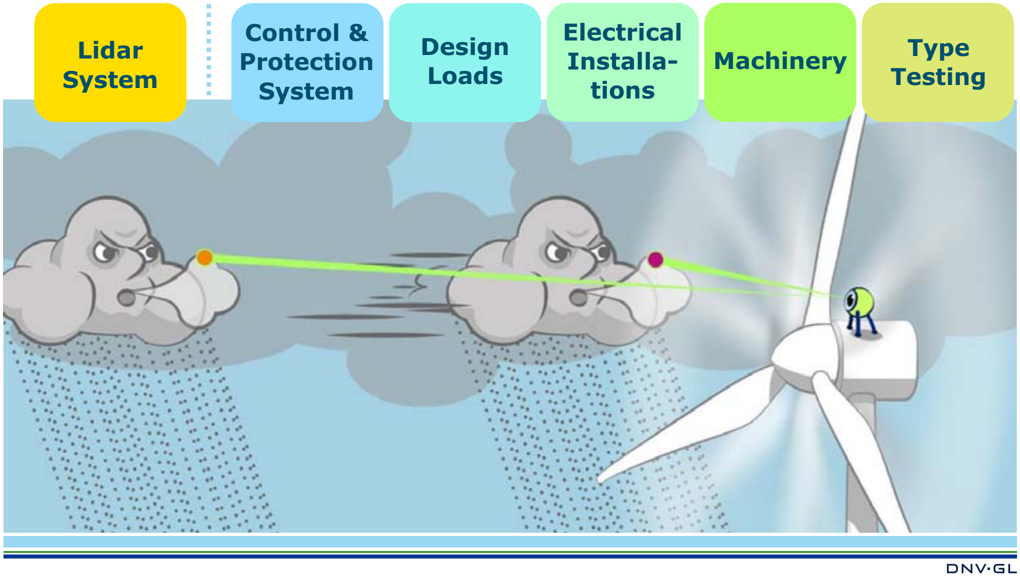

Figure 2: Lidar-assisted control in certification context.

Developing new standards considering LAC involves identifying requirements that ensure that a wind turbine with LAC meets the same safety level as the design standards for customary wind turbines. LAC uses a feedforward control loop for load reductions. Undetected faults in the lidar or in other parts of the LAC may cause the load reduction to fail or result in a load increase, thus possibly causing damage to the wind turbine. As a consequence, appropriate requirements need to be set up for a wind turbine with LAC to ensure safe operation. Proposals for best-practice requirements will be described in Section 4.

To comply with these requirements, the lidar manufacturer has to provide documentation on the lidar system to the wind turbine manufacturer. This documentation is the basis for integrating the lidar system with the wind turbine and its control and protection system. The wind turbine manufacturer analyzes the integrated design and documents the design and test results for the certification body. For LAC, the assessment by the certification body will typically focus on the areas given in Figure 2.

2.1. Lidar system

For the lidar system, the following features are considered relevant. They require documentation by the lidar manufacturer:

- Measurement uncertainty
- Data processing
- Data availability
- Failure mode and effects analysis (FMEA) or similar
- Lightning protection
- Electromagnetic compatibility (EMC)
- Personal safety.

Although it may be difficult to determine measurement uncertainty, it is important to do so when the measurement uncertainty could influence the loads. Depending on the integration of the lidar system and wind turbine controller, the measurement uncertainty needs to be determined by the lidar and wind turbine manufacturer together. For the lidar system, no specific design standard exists. For FMEA and personal safety, recourse can be taken to DNVGL-ST-0438 [6], whereas lightning protection and EMC is addressed in DNVGL-ST-0076 [7].

2.2. Control and protection system
For the control and protection system, the following features are considered relevant. They require documentation by the wind turbine manufacturer on the integrated system wind turbine with LAC:

- Control system
- FMEA or similar
- Manuals
- Analysis of failure probability
- Sanity checks
- Maintenance plan.

Within the documentation of the control and protection system, clarification is required regarding how the turbine reacts to unavailability and malfunctioning of the lidar. A special focus on sanity checks is needed as they ensure that a malfunction—which is undetected by the lidar—is detected by the wind turbine's control and protection system. For further guidance, refer to the design standard DNVGL-ST-0438 [6].

2.3. Design loads
For the calculation of the design loads a simulation model needs to be set up. It appropriately has to reflect the dynamic behaviour of the wind turbine with LAC regarding loads. The model requires input according to the following aspects:

- Wind evolution model
- Lidar model
- Controller model
- Load case definition.

The load case definition must consider cases of lidar system unavailability and malfunctioning within fatigue and extreme load calculations. Careful interpretation of deterministic design load cases is required to ensure that they match well with LAC and still fulfil the targeted safety level. For further guidance, refer to the design standards IEC 61400-1 [8] and DNVGL-ST-0437 [9].

2.4. Electrical installations and machinery
The lightning protection of the lidar system requires integration with the wind turbine's lightning protection system (see DNVGL-ST-0076 [7]). The mounting of the lidar system is assessed in context with the machinery components (see DNVGL-ST-0361 [10]).

2.5. Type testing
Type testing is of special importance because the simulation model of a new turbine type with LAC features several additional model uncertainties compared to a customary wind turbine. These model uncertainties are addressed by load measurements and the safety and function test. General validation is performed by direct one-to-one comparison of measurements with simulations (refer to DNVGL-ST-0438 [6] and DNVGL-ST-0437 [9]).

Besides fatigue load measurements, the extreme load behaviour must be evaluated, especially if the LAC design reduces extreme loads. During the safety and function test, it is relevant to investigate additional stops as well as error cases that are evoked by the lidar system. If the wind turbine with LAC changes to a baseline control mode when the lidar system is not available, then transitions between these control modes require testing, too. If extreme loads are reduced significantly, example events must be investigated where the load-reducing feature is active.

3. What are the challenges for type certification with LAC?

Building on the general requirements for certification with LAC proposed in Section 2, challenges identified by the four stakeholder groups at the workshop (lidar manufacturers, turbine manufacturers, consultants, and researchers) are discussed here. Note that the challenges presented by the stakeholders are occasionally augmented with the authors' observations.

3.1. Challenges for lidar manufacturers

From the lidar manufacturers' perspective, the two main challenges for certification with LAC are (1) properly assessing and simulating the atmospheric conditions and other variables that affect availability and measurement accuracy, and (2) including potentially proprietary lidar and wind field reconstruction methods in the certification process. As explained by Davoust *et al.* [11], atmospheric conditions such as very clean air, snowfall and extreme fog can cause availability to decrease due to either low aerosol density or high optical attenuation. Furthermore, variables such as the lidar sampling time and rotor speed affect availability due to blade blockage. Therefore, (1) the atmospheric conditions that will be experienced by a wind turbine should be characterized so that lidar availability can be estimated, and (2) the impacts of atmospheric conditions and blade blockage on availability and measurement noise should be included when simulating lidar measurements during the design evaluation stage. Two strategies for reconstructing wind field variables from raw lidar measurements (e.g., accounting for the induction zone [12]) can be used in LAC. Line-of-sight velocities can be used to reconstruct the wind field variables of interest in the controller, giving the wind turbine manufacturer more freedom in the design process, or the reconstructed wind field variables can be output directly by the lidar. If the latter strategy is adopted, methods for including the lidar manufacturer's wind field reconstruction algorithms in controller simulations while respecting their potentially proprietary nature need to be devised. One solution is compiled software with a defined interface (raw lidar data to derived signals) e.g., in the form of a dynamic link library (DLL) similar to the controller DLL usually used for aeroelastic simulations. This software should be identical to the software used on the real lidar system.

3.2. Challenges for turbine manufacturers

For wind turbine manufacturers, the primary challenge in certifying turbines using LAC lies in the application of LAC to extreme load reduction. In contrast to fatigue load assessment, many design load cases (DLCs) used to determine extreme loads during design evaluation include unrealistic deterministic wind conditions (e.g. gusts, direction changes) that present challenges when incorporating lidar measurements [13]. Depending on one's interpretation of the design standards, these extreme wind events could be measured almost perfectly by lidar—but this is clearly not justified. However, it is not reasonable to exclude the use of LAC for these DLCs completely. Therefore, clear guidelines for simulating lidar measurements in extreme wind fields should be established. An additional challenge for wind turbine manufacturers is proving that the extreme loads made possible by the use of LAC can be achieved even when the lidar is unavailable (for example, by detecting when lidar measurements are unavailable and switching to a derated mode of operation).

3.3. Challenges for consultants

For consultants, there are several open aspects that exist regarding the type certification of LAC. Consultants mainly provide their knowledge to lidar and turbine manufacturers to accompany the process of type certification, deriving their own recommended practices for realizing LAC. Thus, consultants can play a significant part in helping shape future design standards for type certification with LAC (for example, by helping determine if additional DLCs are needed). Another challenge identified by consultants is the need to develop a standard realistic lidar simulator that is general enough to be used with a variety of wind turbine simulation tools in the certification process. In doing so, consultants can help standardize elements of lidar simulation including the range-weighting functions used for spatial averaging [14], wind evolution modeling, the influence of nacelle motions on measurement locations and measured velocities, and the impact of the induction zone via the reduced velocities upstream of the turbine [15].

3.4. Challenges for researchers

The research community has identified LAC certification challenges based on field testing of LAC as well as theoretical work on wind field simulation. From field experiments performed by the research community using LAC, reliability was found to be an issue. In order to ensure the safety of the turbine, a robust control design should not look solely at the normal operation of the wind turbine, but also consider fall-back solutions for when lidar signals are lost or determined to be of poor validity. In general, LAC methods need to be developed, which account for the changing measurement quality. In order to account for this, a FMEA should be included in the certification process for LAC. On the simulation side, an important challenge for researchers is the creation of realistic wind field models through the integration of wind evolution into load simulations and the addition of turbulence to extreme wind event simulations. Although several wind evolution models exist, additional validation and re-tuning of the models is needed [16, 17]. Additionally, there are several open research questions with implications for the effectiveness of LAC for extreme load reduction. For example, how can gusts, direction changes, and other extreme deterministic wind events be embedded in turbulence to allow for the realistic simulation of lidar measurements while preserving the intent of the DLC? How does a change in wind direction evolve and from which direction does it propagate? In essence, can it be detected by a forward-measuring lidar? Further, wind field reconstruction methods for complex flow situations (complex terrain, measurements within wakes) and a simulation environment for testing these methods need to be developed.

4. How should we certify wind turbines with LAC?

During the workshop, the participants were split into four working groups based on the areas identified in Section 2: lidar system, control and protection system, design loads, and type testing. Electrical installations and machinery have been considered to be already sufficiently covered by existing standards. The participants were rotating through four different stations, each hosted by an expert moderator. This section summarizes and elaborates on the discussion results.

4.1. Lidar system

The lidar system is the key measurement device in LAC. Hence, it must be considered as part of the safety and control system and therefore treated according to the regulations of the safety and control system. Quantifications on mean time to failure, the probability of failure, and the probability of failure on demand need to be provided for the lidar sensor to analyze the safety system properly. Furthermore, the following guidelines on quantifying data availability and measurement uncertainty are needed. Practical aspects like personal safety in use, maintenance,

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and mounting procedures of the lidar as well as electrical and lightning protection standards must be ensured. In the following, the different aspects are discussed in more detail.

4.1.1. Failure mode and effects analysis for LAC In order to certify wind turbines with LAC, the theoretical consideration of the failures at the lidar sensor need to be considered. The FMEA method is an analytical methodology that takes the reliability of a system into account and displays the impact on other components and the overall system. The general intention in implementing security features that observe the lidar sensor is that a failure in the sensor should not lead to a worse situation than without it. Self-monitoring capabilities of the lidar system can help to minimize the impact of a failure to the overall safety chain. However, not every failure mode can be covered with a self-monitoring. Altogether, the FMEA serves as an analysis tool but can be used to quantify a critical limit that the system should not exceed.

4.1.2. Personal safety Personal safety is a necessary aspect that needs to be answered before realizing LAC. Mainly, three aspects are included: (1) eye safety, (2) electrical safety, and (3) handling safety.

Eye safety needs to be ensured. A guided use regarding installation, operation, and failure cases is necessary and should be provided in the documentation. Here, an adaption of a standardized certification procedure can be used.

Electrical safety is a requirement. Ensuring safety to the equipment from a lightning hazard is necessary as well.

Installation of lidar sensors on the nacelle offers the potential of higher risk for the technicians. Here, safety procedures for installation, service, and dismounting are needed to ensure that turbine manufacturers comply with requirements.

Altogether, adhering to the personal safety aspect is crucial. With clear procedures and the adoption of standardized processes, the health and safety of all personnel can be ensured.

4.1.3. Data availability Data availability is an important aspect when considering the lidar sensor in the safety and control system. There is no standardized definition of data availability of lidar systems for LAC. This challenges the comparability of lidar systems for LAC. A request would be to deliver a meaningful availability measure for each provided signal. Here, a clear link to measurement uncertainty is given, which will be discussed in Subsection 4.1.4.

4.1.4. Measurement uncertainty Several aspects influence the measurement uncertainty of a lidar system (e.g., external aspects like atmospheric and weather conditions, handling aspects like the exact orientation and alignment of the system and its components, or internal aspects like the uncertainty of the data processing algorithm or real-time properties). Altogether, a clear guideline is needed for a specified uncertainty analysis that standardizes the quantification. Furthermore, a guideline is needed on how to perform or verify the uncertainty analysis in the type certification.

4.1.5. Data processing For data processing, the turbine manufacturer asks for a standardized metric of signals that are provided by the lidar sensor. This implies that dedicated signals, such as the rotor-effective wind speed, need to be defined and specified in the guidelines. Then, they can be directly used in the controller. If unspecified signals are used or the data processing is included in the wind turbine controller, this aspect needs to be included in the type certification by the certifying body.

4.2. Control and protection system

During the workshop, ideas were generated for how LAC should be addressed in the certification of the control and protection systems, which keep the turbine within its operating limits and protect it when safe operating conditions are exceeded. Here, the contribution to both systems needs to be distinguished, because different requirements need to be fulfilled. In the near future, lidar will probably mainly improve control functions. Later, lidar assistance might be used to reduce extreme loads and will become part of the protection function.

Further, a turbine with LAC should have a traditional feedback control system to rely on when lidar measurements are not available. Due to the importance of reliable wind measurements for LAC to properly regulate and protect a wind turbine, a lidar quality signal should be required from the lidar, indicating the trustworthiness of the measurement so the turbine can switch to feedback control when necessary. Additionally, "sanity checks" should be performed by the controller to determine lidar measurement accuracy; for example, by comparing the lidar measurement with the wind speed estimated from turbine sensors. To accomplish this, a possible method is the calculation of the measurement coherence bandwidth (wavenumber at which the coherence between both wind speed estimates drops below 0.5).

It was concluded that for LAC no special requirements on a maintenance plan are necessary. A standard operation and maintenance manual that includes a maintenance plan is sufficient.

4.3. Design loads

Recommendations for including LAC in load simulations during the design evaluation stage were made in the following four categories: lidar modeling, wind field modeling, fatigue load calculations, and extreme load calculations.

4.3.1. Lidar modeling

It is generally agreed that lidar models should include the limitation to line-of-sight velocity measurements (i.e., the ability to measure only the wind velocity aligned with the beam direction), spatial averaging (weighting of the wind speeds along the beam according to an appropriate range-weighting function [14]), and realistic modeling of the scan pattern measurement sequence. Additional details that should be modeled include the impact of nacelle motions on the measurement locations and the relative velocities measured by the lidar, the consequences of blade blockage on lidar availability, and the effects of the induction zone. The induction zone model should include the reduced velocities upstream of the turbine where the lidar measures the wind as well as the additional preview time afforded by the reduced velocities.

Two methods for realistically simulating lidar measurements were discussed. The first approach is to include blade blockage and atmospheric conditions, such as visibility and aerosol density, in a detailed simulator meant to recreate the impacts of these parameters on availability and measurement noise [18]. This would require site-specific knowledge of the atmospheric conditions or at least a conservative estimate of them. The second approach uses knowledge of the scan pattern, range-weighting functions, wind evolution and spectral properties of the wind field to generate random realizations of the lidar measurements that adhere to the calculated theoretical measurement coherence (e.g., see [19, 20]). While this approach misses the direct impact of variables, such as visibility or aerosol density on measurement error, it can capture their impact in a statistical sense through the identified measurement coherence. Regardless of the method used, there should be a clearly defined interface between the lidar model and the controller/wind turbine simulator so that lidar manufacturers can supply potentially proprietary lidar models that can be used with a variety of simulation codes (e.g., as a DLL).

Because of the importance of atmospheric conditions, such as visibility and aerosol density, in determining lidar availability and measurement noise, a suggestion was made to create different atmospheric condition "classes" that are analogous to the mean wind speed and turbulence classes that currently exist in the standards [8]. This atmospheric condition class system would provide standardization in the determination of lidar availability, although work is needed to define a small representative set of atmospheric conditions that are likely to be encountered. Well-known methods for including wind evolution in lidar measurement simulations for stochastic turbulent wind fields have been established, relying on longitudinal spatial coherence functions to describe the evolution of turbulence as it advects downstream [19, 21]. While several longitudinal coherence models for wind evolution have been used in the LAC community [22–24], more work is needed to validate the models against field observations [16, 17].

4.3.2. Load simulations

Participants agreed that methods for determining fatigue loads using LAC are relatively straightforward. When calculating fatigue loads, imperfect lidar availability can be accounted for by performing separate load simulations with and without LAC, weighting the resulting damage based on the percentage of time the lidar is assumed to be available. However, loss of the lidar signal due to unfavorable atmospheric conditions is expected to occur frequently enough that DLCs capturing the transition from LAC to baseline control (or vice versa) should factor into the fatigue load calculations.

Calculating extreme loads using LAC is more complicated, especially if the controller relies on lidar measurements to mitigate the impact of extreme gusts or other events on loads. A chief concern is the possibility of lidar unavailability when extreme events occur. Therefore, extreme load DLCs should be simulated with and without LAC, including operation in a safe mode if necessary when the lidar is unavailable. Furthermore, DLCs should be developed to simulate the transition to a safe mode of operation when a lidar fault occurs. For rare events, such as extreme gusts and direction changes, it may be determined that the likelihood of lidar unavailability or of a lidar fault occurring simultaneously with an extreme event is low enough that it does not need to be considered or that the safety factor can be reduced. However, first it must be determined if such extreme events occur during weather conditions that increase the probability of unavailability (e.g., heavy rain).

While performing extreme load simulations with LAC in extreme turbulence (DLC 1.3 in the IEC 61400-1 Ed. 3 standard [8]) is relatively straightforward, deterministic extreme events, such as the extreme operating gust, extreme coherent gust with direction change, and extreme wind shear [8] are problematic because (1) they do not contain turbulence (and can therefore be measured accurately by a lidar, which is unrealistic) and (2) they are only defined at the turbine location (the speed and direction of propagation toward the turbine is unclear).

A solution to the first obstacle is to redefine the extreme events as stochastic turbulent wind fields where the rotor-averaged wind parameters of interest match the intended deterministic event. Wind evolution can then be introduced to the turbulent realizations of the extreme wind fields [21]. At least two methods have been developed for generating stochastic turbulent wind fields with constraints imposed on rotor-averaged quantities. First, Bierbooms and Cheng [25] discuss a statistical method for combining a random unconstrained stochastic field with the most likely residual field such that constraints imposed on a linear combination of points in the field are met. Alternatively, Schlipf and Raach [13] present an engineering approach in which the phase angles of the Fourier coefficients of a stochastic wind field are optimized so that the resulting rotor-averaged time series matches the intended extreme event. Dimitrov and Natarajan [26] developed a method, which fits turbulent wind fields to lidar measurements and which might be used for extreme event simulations as well.

Finally, uncertainty in the propagation speed and direction of extreme events can be addressed by including several different realizations of the parameters in the appropriate DLCs. For example, the extreme operating gust and extreme wind shear events can be simulated with a range of advection speeds toward the turbine while the extreme coherent gust with direction change can be simulated with the wind direction change propagating from a range of directions, from straight ahead to approaching from the side.

4.4. Type testing
Groups also met to discuss the topic of type testing, and their feedback is summarized here. In considering type testing for certifying LAC, a load performance test should be performed on a wind turbine with LAC. The following guidelines were produced from the four working groups.

4.4.1. Test matrix
A test matrix should include wind speed bins over the operational range of LAC. Typically, this is a subset of the operational range of a wind turbine as LAC has been used in above-rated wind conditions. The test matrix should also look to include various atmospheric conditions (e.g., various turbulence intensities, shears/veers, lidar backscatter conditions, etc.) and weather conditions (e.g., sunny skies, cloudy, fog, rain, snow, etc.) in order to show robust performance. In order to evaluate the LAC performance, data should be collected without the LAC portion of the controller as a baseline to compare against.

4.4.2. Instrumentation
An independent meteorological mast and/or lidar would be useful for the type testing to better quantify the wind speed and atmospheric conditions. Additionally, the wind turbine would need to be outfitted with strain gauges in the wind turbine tower at multiple stations/directions to assess the tower loading. Similarly, strain gauges would need to be installed on the wind turbine blades, again at multiple stations/directions in order to assess the blade loading. Instrumentation to measure the nacelle motion and blade tip deflection would also be useful.

4.4.3. Other considerations
Fault cases should also be included in the test matrix to show the control design performs well in the event of the loss of LAC. The type testing should only consider simple terrain and simple flow conditions where the wind can be considered homogeneous. Finally, in assessing the performance of LAC, 10-minute-averaged data points may be insufficient to effectively evaluate the performance as the control happens in real time and the wind disturbance can vary greatly over a 10-minute period. Instead, smaller averaged data points ($\sim$1 minute average) may be of more use. Data analysis in the frequency domain would also be useful to show the LAC performance at different operational frequencies of the wind turbine.

5. Conclusions
The lack of standards for the certification of wind turbines using lidar-assisted control (LAC) is a main barrier for the wide adoption of the technology by the wind industry. This paper presents the results of an IEA Wind Task 32 workshop that brought together experts from research and industry and thus is a first step toward a "best practices" document, providing solutions both to practical and research questions.

First, the areas of type certification impacted by LAC are identified to be the lidar system itself, the control and protection system, design loads, and type testing. Although turbines with LAC can be already certified by interpretation of existing standards, there are still several challenges to overcome for lidar and turbine manufacturers, consultants, and researchers before a dedicated standard can be issued. These challenges are described in this paper. Despite these challenges, the paper already presents discussions and first ideas on how to certify wind turbines with LAC.

The IEA Wind Task 32 will continue to bring experts together to foster lidar-assisted control and help make it an accessible and beneficial technology for the wind community.

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