Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology

Version 2.0
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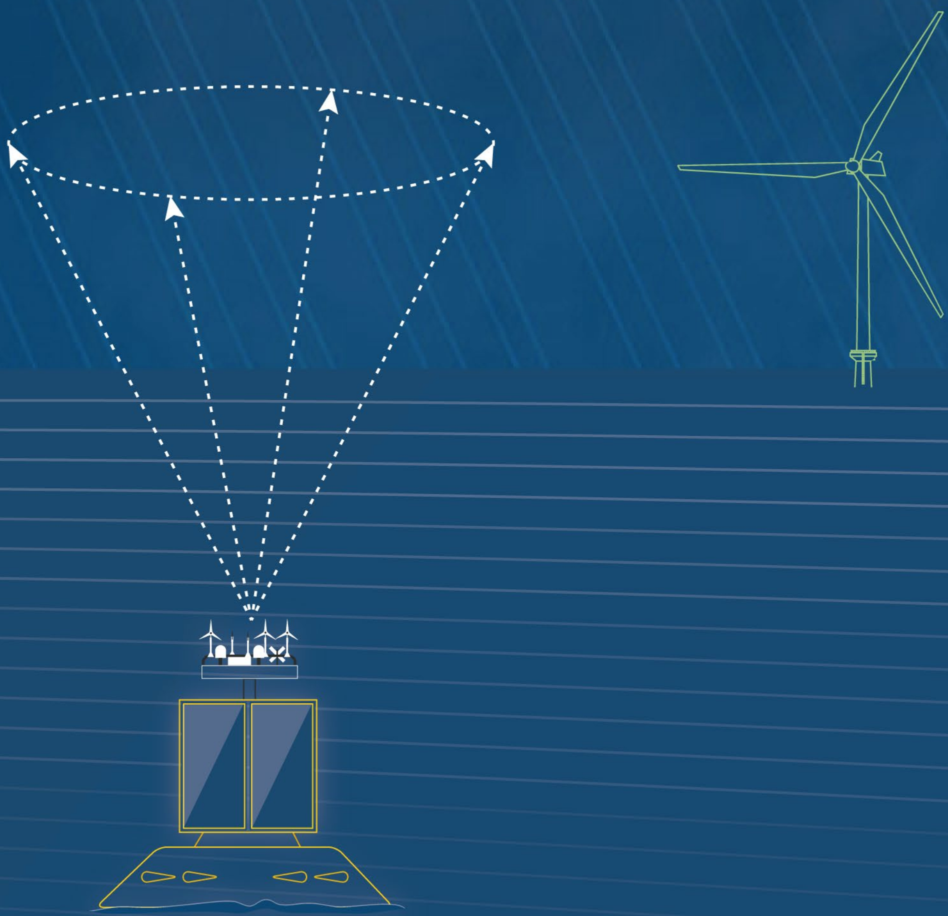

Foreword

Floating LiDAR has the potential to replace meteorological met masts for the measurement of primary wind resource data – wind speed and wind direction.

The purpose of this document is to present a roadmap for floating LiDARs to become commercially accepted as a source of data to support financial investment decisions. The roadmap was originally published in 2013 and this version has been published in 2018 to reflect industry experience gained in the interim period with clarifications, updates, extensions and new material included based on industry engagement to ensure the roadmap continues to be fit for purpose for several user groups in to the future. The progress made in successfully adopting floating LiDAR technology since 2013 is underpinned by a recent OWA review of system deployments worldwide[1]. Since that time, a number of systems have been accepted by the industry as attaining Stage 2 maturity status; the inclusion in this version of the roadmap of more definition to Stage 3 requirements is therefore timely as the industry seeks to develop confidence further.

The roadmap has been prepared by the Carbon Trust Offshore Wind Accelerator (OWA), a joint industry project involving nine developers representing over three-quarters of the UK's licenced capacity – Ørsted, E.ON, innogy, ScottishPower Renewables, SSE Renewables, EnBW, Statkraft, Equinor and Vattenfall – in close collaboration with DNV GL, Frazer-Nash Consultancy, Multiversum Consulting and Fraunhofer IWES.

An important element of ensuring trust in data from floating LiDAR systems continues to be a comparison to an IEC compliant meteorological mast, or alternatively in comparison with another trusted reference source (e.g. a fixed LiDAR) of similar measurement uncertainty, by an independent third party, and according to the guidelines set out in this document. In order to support floating LiDAR suppliers to achieve this, the OWA has previously facilitated trials of floating LiDAR systems compared to meteorological masts within their portfolio of projects[2].

[1] "Deployments of Floating LiDAR Systems", 2018

2 Carbon Trust press release: Carbon Trust drives industry acceptance of new floating LiDAR systems to deliver low-cost bankable wind data (May, 2017).
https://www.carbontrust.com/news/2017/05/carbon-trust-drives-industry-acceptance-of-new-floating-lidar-systems/

Document history

Version	Date	Authors
1.0	21 November 2013	Garrad Hassan & Partners Ltd, DNV KEMA, Mott MacDonald, ECN, Frazer-Nash Consultancy
2.0	9 October 2018	DNV GL, Frazer-Nash Consultancy, Multiversum Consulting, Fraunhofer IWES

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List of abbreviations

Abbreviation	*Meaning*
CNR	Carrier-to-Noise Ratio
FLS	Floating LiDAR System
KPI	Key Performance Indicator
NaN	Not a Number (IEEE symbol)
OEM	Original Equipment Manufacturer
OWA	Offshore Wind Accelerator
QA	Quality Assurance
QC	Quality Control
WRA	Wind Resource Assessment

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DNV GL, Frazer-Nash Consultancy, Multiversum Consulting, Fraunhofer IWES

In the development of Version 2 of this document a wide range of industry stakeholders have been consulted via a questionnaire process and a dedicated 1-day workshop in London on 23 January 2018. The authors would like to thank those contributors for their invaluable contributions, those contributors being floating LiDAR system developers (9 different organisations), research organisations and universities (3), LiDAR suppliers (1), consultancies/banks' engineers (8), as well as the OWA partner organisations (11) and other wind farm developers (2).

The Carbon Trust would like to acknowledge the significant prior research into the development of LiDAR for offshore application[3].

[3] Papers including

Oldroyd, A; Kindler D: Wind Measurements using floating LiDAR Best Practice June 2011

IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

1 Introduction

1.1 Background

As part of the Offshore Wind Accelerator (OWA) programme, The Carbon Trust, along with a consortium of industry partners, previously developed a guide or "roadmap" for the steps required for floating LiDAR technology to become commercially accepted within the industry. Since the original version (Version 1.0) of the roadmap was published in 2013, floating LiDAR technology has been seen as a maturing technology within the industry, observing an increasing number of deployments globally as part of commercial offshore wind farm developments.

The Carbon Trust has commissioned an update to the original roadmap to reflect the latest status of floating LiDAR systems using input from stakeholders across the industry, as reported in this document (Version 2.0). The document has been prepared in close collaboration with DNV GL, Frazer-Nash Consultancy, Multiversum Consulting and Fraunhofer IWES, building on the work from authors of the first version of the roadmap with edits made throughout to make clarifications, updates, extensions and introduce new material.

In this context, "commercial acceptance" is defined as the stage at which measurement data recorded using a particular floating LiDAR technology is accepted by funders of commercial scale offshore wind projects. In broad terms, the following stages are envisaged:

1. **Baseline:** As a pre-requisite, the LiDAR measurement unit itself should have achieved wide-spread acceptance within the onshore wind industry as "proven" in the field of wind resource characterisation for non-complex terrain sites at least. Industry-proven LiDARs are LiDAR types that are commercially available and have a widespread accepted track record in the wind industry onshore, reliably and repeatedly producing wind data in benign terrain conditions at an accuracy comparable to that of classical anemometry.

2. **Pre-commercial:** Following a successful Type Validation trial, the **floating** LiDAR technology may be utilised commercially in limited circumstances - specifically in conditions similar to those experienced during the trial. In this application, where the performance and sensitivities of the device in certain environmental conditions has previously been captured in a trial, accuracy can, in principle, be considered to be approximate to that of a conventional meteorological mast, albeit with a level of residual uncertainty relating to site-specific deployment conditions. Where the environmental conditions at a deployment site are different from those during the Type Validation trial, elevated measurement uncertainty assumptions may be expected given the lack of evidence regarding sensitivity of performance to difference environmental conditions at this stage.

3. **Commercial:** At this stage, a significant body of operational evidence and verification has been accumulated across a range of environmental conditions leading to a good understanding of any environmental performance sensitivities thus increasing certainty in the performance of the FLS. Furthermore, the floating LiDAR system has consistently demonstrated significantly more demanding reliability performance and data availability.

In this roadmap document, the above stages are described qualitatively in greater detail in Section 3. Version 2.0 of the roadmap also includes consideration of Health, Safety and Environment (HSE) guidelines for FLS deployments in Section 2. The industry experience gained since the original version of the roadmap has highlighted the importance of HSE aspects and hence warrants some discussion in this roadmap. A discussion of other considerations relating to application of FLSs in offshore wind resource assessments is also given in Section 3. Finally, conclusions and recommendations are drawn regarding the guidance provided and the application of floating LiDARs to future deployment of this technology at the pre-commercial and commercial stages in Section 4.

Users of floating LiDAR systems are also directed towards the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR System[4]. The current roadmap document and the recommended practice document are consistent but serve different purposes: the current document defines a roadmap towards commercial acceptance, with associated acceptance criteria; whereas the recommended practice document compiles recommended practices in the use of floating LiDAR systems to help ensure that the best quality data can be obtained for use in wind energy resource assessments.

1.2 Note on use of this document

Version 1.0 of this document was widely used and referred to by the wind energy industry, and it is anticipated that this will continue to be the case for this version, Version 2.0. Experience with Version 1.0 is that assertions of maturity stage claims are most effective when carried out by independent, experienced, and trusted third party organisations. It is also expected that this will continue to be the case for the use of this version. Where the requirements to achieve a maturity stage are set out in this document, there is in some cases flexibility in how these requirements are met and evidenced, which must be left to the judgement of the participating third party organisation.

For clarity, although this roadmap document is provided by the Carbon Trust on behalf of the Offshore Wind Accelerator research partnership, the Carbon Trust nor the other partners expect to act as the third party evaluators of maturity claims. It is noted that some industry groups may use this roadmap document to inform procurement procedures and tender requirements for floating LiDAR measurement campaigns. As outlined in the following sections of this document, whilst industry should expect a higher reliability performance and significant operational experience across a range of environmental conditions from Stage 3 devices, this document is not intended to close the door on consideration of Stage 2 or even Stage 1 devices in commercial deployments. This roadmap sets out expectations with regards to wind speed measurement accuracy, availability and reliability for each maturity stage. On the basis of this framework, Stage 2 devices can achieve similar wind speed accuracy as Stage 3. This roadmap does not intend to provide instruction for procurement based decisions. However, as for any commercial decision, it is strongly recommended that consideration is given to the risks associated with the use of FLSs at different maturity stages on accuracy, reliability and acceptance of results.

1.3 Cautionary note

It is important to note that this roadmap was designed to focus on the capabilities of floating LiDAR technology to replace met masts in measuring primary wind data, namely wind speed and wind direction. There are other secondary but important parameters required for a comprehensive offshore wind resource assessment such as hub-height turbulence intensity, air temperature, air pressure, relative humidity, air density (not measured directly but derived from atmospheric measurements) etc. Additionally,

[4] IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

complementary oceanographic measurements are also required to achieve a full met-ocean measurement campaign. Therefore, while some floating LiDARs currently feature additional measurement capabilities and while future developments might add even more comprehensive measurement capabilities, it is important to bear in mind that this document is only a roadmap towards replacing primary wind data measured from offshore met masts with floating LiDARs, and that secondary wind data and met-ocean measurements are still very likely to be required to complete a comprehensive offshore wind resource and met-ocean measurement campaign.

Additionally, although system availability is one of the KPIs used in this roadmap, this document does not directly address or cover the seaworthiness of the floating LiDAR devices.

Lastly, the geographical context of the body of work and experience leading to this document should be understood. Most floating LiDAR deployments, as trials or in support of wind resource assessments, have been in Northern Europe. Wave climates and sea state conditions in other parts of the world, for example in southeast Asia, could be different and could offer additional challenges as the system performance may not be enveloped by the existing body of experience. Therefore, in employing the roadmap outside Northern Europe it is recommended to review how similar or otherwise the metocean conditions are, and how this may modify interpretation of the roadmap in general and reliability maturity in particular. At the time of writing, the authors do not believe that more specific regional aspects can be stipulated as the body of experience does not exist, but this may change in future.

2 Health, Safety and Environment guidelines

The following sections in this roadmap focus on the definition of criteria for an FLS to demonstrate the device's capability of accurately recording wind data. It should be recognised that an important aspect of FLSs is the survivability and maintainability of the supporting structure, regardless of maturity stage.

As a minimum the design of FLS hydrostatic buoys and supporting structure should comply with the *International Association of Marine Aids to Navigation and Lighthouse Authorities* (e.g. IALA Guideline No. 1099 on the hydrostatic design of buoys, May 2013, and IALA Guideline No. 1066 on the design of floating aid to navigation moorings, June 2010). The *HSE/MCA regulatory expectations on moorings for floating wind and marine devices, August 2017*, provides valuable design principles and specifications for new mooring systems that draw on the established good practice for long term reliability in the Oil & Gas and renewables sectors. These give high level guidance and point to key international references that cover design, hardware, installation, operation, monitoring and verification of the floating renewable energy device mooring system. On a case-by-case basis, and considering the project criticality of the FLS deployment, it is recommended that these HSE/MCA regulatory expectations are followed as guidance.

To improve reliability of the FLS supporting structure and ensure safe and repeatable operations during the deployment phase, a robust and tested methodology should be implemented for the deployment and retrieval of the FLS that manages risk of the marine operations. *DNVGL-ST-N001 Marine Operations and Marine Warranty, June 2016*, provides guidance to ensure marine operations are designed and performed in accordance with recognized safety levels and describes "current industry good practice". These interactive guidelines can be used to help plan the marine operations and mature transportation and installation procedures for FLD deployment. The safety management system for the design, fabrication/manufacturing, installation, operation, maintenance and decommissioning of the FLS and its mooring system should demonstrate compliance with the applicable local safety legislations covering the health and safety of persons either at work or affected by work activities.

Where appropriate, the above guidelines should be supplemented by user experience in the region in which the deployment is underway (e.g. the FLS OEM or the wind farm developer). Consideration should also be given to identifying vessels for FLS installation, maintenance or retrieval that comply with the health and safety standards of validating parties.

It is an expectation that all FLSs, regardless of maturity stage, will satisfy these minimum requirements.

3 Stages of maturity

Floating LiDAR Systems (FLS) are based on laser anemometry known as LiDAR (Light Detection and Ranging) technology which has been developed for various industries, including the wind energy industry. In addition to a body of onshore verification data for the type of LiDAR employed on a floating structure itself, it is also important that the performance of the complete FLS is rigorously validated within the offshore environment to demonstrate that it can operate effectively across a range of dynamic conditions.

There are potentially significant issues requiring careful consideration regarding the accuracy of the measurements when the device is deployed on a moving support structure. From an engineering perspective, there appear to be three main approaches to address these issues. The first is to minimise the movement of the support structure such that all, or at least the majority, of the measurements are made when the amplitude of device movement is sufficiently small so that the impact on the accuracy of the measurements may be negligible. The second approach is to measure that movement and correct for its impact on the measurements using numerical algorithms. A third approach is simply to allow such movements and to demonstrate that the system produces sufficiently accurate data nonetheless. Although some FLS have shown that their 10-minute wind data accuracy does not seem very sensitive to movement, for limited evidence this cannot yet be assumed valid for all systems available on the market.

The use of FLSs in place of or in combination with conventional offshore meteorological masts offers potential benefits for the industry in terms of development costs, consenting timescales and the uncertainty associated with wind resource estimates. However, a significant body of supporting verification data must be established for each FLS to enable the confidence to be gained in measurement accuracy and reliability to move through the 3 stages of maturity defined in this roadmap document: Baseline, Pre-commercial and Commercial. The following subsections provide definitions, application limitations and milestones for each of these stages.

It is recognised that effort and investment is required to progress through these maturity stages, so it is useful here to summarise the advantage attained should progressive stages be reached:

- The advantage of the **Pre-commercial** maturity stage over the **Baseline** stage is that a user of that system will have a significant additional degree of confidence on the accuracy and reliability performance that the FLS has demonstrated, and therefore can be expected to achieve, in a manner which is possible to compare with the performance of other measurement systems.

- The advantage in attaining the **Commercial** stage over the **Pre-commercial** stage consists of accuracy, reliability, uncertainty and cost of deployment aspects. To attain the Commercial maturity stage, the FLS has to demonstrate the Best Practice accuracy criteria associated with Stage 2; and the minimum accuracy performance criteria are no longer applicable. With regards to reliability, the FLS has to demonstrate significantly more demanding reliability performance, in terms of repeatedly proving high system and data availability during shorter or longer pre- and post-deployment verifications and in particular during early commercial project applications typically lasting at least 12 months. With regards to uncertainty, a key aspect which has been considered since the earliest days of FLS technology is how to understand the uncertainty of FLS data in a deployment environment which will be different, and quite possibly more demanding, than the environment which it experienced during verification. This is addressed through the Stage 3 maturity requirement that the FLS must have been subject to 3 Classification Trials, which therefore provides a rational route to uncertainty assessment. Lastly, for Stage 3 systems, the pre-deployment verification requirements are less onerous in that a risk-based approach may be followed and in some cases this will reduce the overall deployment costs as there may be no requirement for a full floating LiDAR system pre-deployment verification. Further discussion of this risk-based approach is given in Appendix 3.

3.1 FLS type related considerations

It should be recognized, in general, that all statements, prerequisites and rankings related to the maturity stage of an FLS as treated and prescribed in this Roadmap document shall be understood as being assigned to a specific "type" of an FLS and hence be valid for each FLS "unit" of this "type". This means for example, that the prescribed Stage 2 type verification trial needs to be performed only once and for a single unit for each "type" of FLS.

In this context considerations have to be made as to when a design change to an FLS type constitutes a different type. A type verification of a certain type of FLS refers to a suite of devices that are effectively identical in design as manufactured by an OEM. It is therefore important to understand whether any applied design changes constituting a new FLS design will invalidate the type verification that has been undertaken for the original FLS design. If this was the case, then the new design would effectively be considered as a new FLS type and would require a further type verification for a period of 6 months as prescribed in this roadmap.

Typical type-critical design changes seen in the past, and that have the potential to constitute a new FLS type, are primarily considered to be related to the following fundamental components and aspects:

- type of LiDAR device;
- type of buoy/floating platform employed by the FLS;
- power supply, fuelling capabilities and related change in buoyancy distribution;
- the dynamic response of the whole FLS buoy to various sea states and weather conditions (for example related to weight distribution, centre of gravity, centre of buoyancy etc);
- the reliability of the overall system.

In principle, the FLS must be considered of a new type if a design change has occurred including where a component (such as, but not limited to, those listed above) previously used is exchanged for an alternative component of a different specification. If there is a reasonable case to assert that the risk of such a change invalidating the previous type verification is so small as to be negligible, this can be asserted by a suitably qualified and experienced, independent 3rd party organisation, taking consideration of:

1. The specific design changes that have occurred;
2. The results of previously declared type verifications;
3. An examination of whether the design changes would invalidate the accuracy or reliability of the system, taking into account any margins available from the previous type verification and the specific requirements of the type verification.

In principle, it does not matter which stakeholders action this process, although in practice it is more likely to be practicable for the FLS OEMs to do so, as it is considered they will own the FLS configuration control process.

As the type of LiDAR device used is fundamental, such a change must be considered as a type change and is not subject to the above concession process. Any other change which may result in a change to the dynamic response of the buoy (e.g. to the Response Amplitude Operator) could be similarly fundamental, or in fact may be quite minor, so needs to be properly assessed in detail.

It is further noted that in the case of any changes made to the FLS during a measurement campaign (e.g. replacement of a LiDAR device), further recommendations are given in Section 3.4.4 (Need for pre- or post-deployment verification trials).

3.2 Summary

The prerequisites, possible modes of application, requirements for and limitations of deployment for each maturity stage, as part of a future Wind Resource Assessment (WRA) measurement campaign, are summarised on the following page. This roadmap diagram in Table 2.2 serves as a summary guide to the remainder of this section, which provides the detailed rationale.

An important aim of this document is to increase confidence in the wind industry with regards to the performance and accuracy of floating LiDAR technology, in the context of wind resource assessment campaigns, when used to support final investment decisions for proposed offshore wind farms. A key metric here is the uncertainty associated with the measurements from the FLS. At the time of writing, the authors consider there is currently an insufficient body of evidence to support the indicative range of measurement uncertainties previously presented in Version 1.0, although this is anticipated to change in the future. Therefore, in this version, no indicative measurement uncertainties are presented and a strong recommendation is made that case specific uncertainty calculations are performed for each deployment. The reader's attention is drawn to further discussion of this topic at the end of this section.

Indicative scenarios of plausible FLS deployments as part of a WRA are summarised below in Table 2.2.

Table1.1: Summary of FLS scenarios examined

WRA Deployment Type	Maturity Stage		
	Baseline	Pre-commercial	Commercial
One FLS unit replacing a met mast	N / A	Scenario B	Scenario E
Multiple FLS units replacing a met mast	N / A	Scenario C	Scenario F
Fixed met mast supplemented by one or more floating LiDAR	Scenario A	Scenario D	Scenario G

Table 1.2 Summary of Roadmap

Maturity Stage	Pre-requisites (type verification)	Wind Resource Assessment Campaign Requirements	
		Possible Applications	Limitations
Baseline	> LiDAR type considered as "proven technology" in onshore wind industry.	**Scenario A** Fixed met mast supplemented by one or more FLS deployments	> FLS data used only in a relative sense to support wind flow modelling used to estimate horizontal and vertical variation in wind resource across site.
Pre-commercial	> As above, plus: > Pilot verification trial for FLS type completed successfully including independent scrutiny and confirmation of Acceptance Criteria.	**Scenario B** Single FLS deployment	> 2-Phase FLS Validation[5] required. > Metocean conditions during campaign must be demonstrated to be within the Unit Validation and Type Validation. > Independent and reliable wind data source (regional measurements or modelling) and / or high level of industry experience of wind resource in region required to cross-check results.
		Scenario C Multiple FLS deployments	
		Scenario D Fixed met mast supplemented by one or more FLS deployments	> 2-Phase FLS Validation[5] required. Phase 2 can be carried out on target site.
Commercial	> As above, with elevated Acceptance Criteria, plus: > Good operational experience and accuracy achieved across a number of pre-commercial deployments. > Residual environmental sensitivities well	**Scenario E** Single FLS deployment	> Scenario B and C limitations recommended for lowest uncertainty, although not essential. > For 2-Phase FLS Validation, ideally at least Phase 2 to be performed, or Phase 1 plus a risk-based approach as described in the IEA Recommended Practices[6], see also Appendix 3.
		Scenario F Multiple FLS deployments	
		Scenario G Fixed met mast supplemented by one	> 2-Phase FLS Validation[5] recommended for lowest uncertainty, but not essential.

[5] 2-Phase FLD Unit Validation is described further in Section 3.4.2.

[6] Pre-deployment verification defined in the IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

	understood and documented.	or more FLS deployments.	Phase 2 can be carried out on target site.

Important notes

It is stressed that for each scenario a case-specific uncertainty is to be estimated following the procedure and principles outlined in Appendix 2. Past studies have shown that FLS measurement uncertainties are generally dominated by the uncertainty of the reference device used in the unit verification test and a classification uncertainty that may be applied if environmental conditions at the verification and the application site are not sufficiently similar. For Scenario D and G the classification uncertainty can be neglected completely if the unit verification is carried out at the target site and concurrently with the target application.

As detailed in Table 2.2, Scenarios C and F differ not with respect to their limitations. The benefit of using multiple FLS deployments may be in making use of the data redundancy (and the fact that one system may still be available if the other fails) or the potential to assess horizontal variation in wind resource if the systems are further distributed over the target site. Both items may have a beneficial effect on the overall confidence in a final wind resource or energy yield estimate.

Further note that the achievement of Stage 3 (Commercial) does not in itself necessarily entail a lower uncertainty than Stage 2 (Pre-commercial) as this will depend on the magnitude of the classification uncertainty which may or may not be available for a Stage 2 device (see Section 3.4.5). However, it is expected that the FLS types that are pushed to Stage 3, are likely to be those systems that are characterized by a lower uncertainty – and generally better performance in terms of measurement accuracy – than other types.

In either case, measured uncertainties should be estimated following a well defined procedure (as the one outlined in Appendix 2). Requirements for Stage 3 (see Section 3.5) include an advanced assessment of the FLS type under consideration – with further shorter verification trials as well as more detailed classification tests – and with this potentially a better understanding of the system performance across a range of environmental conditions. It can be expected that this improved understanding, evidenced through the requirements listed in Section 3.5.2 and independently verified by a 3rd party as described in Section 1.2, may result in less conservative uncertainty estimates and lower 'penalty' values for so far non-observed system behaviour.

For a particular FLS unit which has been verified for a first WRA deployment, the question arises as to whether verification for a second WRA deployment needs to be as stringent or required at all. It is recommended that on this topic the advice from Section 6 of the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[7] is followed.

[7] IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

3.3 Stage 1: Baseline

3.3.1 Definition

At this stage, operational devices are available and some preliminary demonstration tests have been carried out or are in progress. An FLS is considered to be within the Baseline stage as long as no independent and thorough offshore verification test as defined in Section 3.3.2, has been successfully completed.

3.3.2 Prerequisites

As a pre-requisite, the LiDAR product used in the FLS – including its hardware and firmware – should have achieved wide-spread acceptance within the onshore wind industry as "proven technology" in the field of wind resource characterisation for non-complex terrain sites. Currently, not all LiDAR types are considered as proven technology while a few have indeed reached this stage and therefore individual units of the LiDAR product in question can be deployed for wind resource measurement with a reasonable level of confidence.

To be considered as proven technology for onshore applications, the LiDAR must be commercially available and have a widespread accepted track record for being capable of routinely providing measurements of wind speed and direction with height. More precisely, multiple independent reports should be available supporting its successful verification against high-quality mechanical anemometry in benign terrain/flow under various atmospheric conditions and at measurement heights relevant to modern wind turbines at an accuracy comparable to that of classical anemometry.

A milestone is reached when one or more production units have been successfully tested at one or more suitable and recognized test facility(ies) against data recorded from a high-quality conventional wind measurement met mast, or alternatively against a trusted reference LiDAR (so-called Golden LiDAR), whose accuracy is traceable to high-quality conventional anemometry over a range of heights, operational, atmospheric and simple flow/terrain conditions relevant to wind energy applications. The tests will have demonstrated that the accuracy achieved through remote sensing is similar to that which would have been achieved with conventional anemometry for measuring 10-minute average wind speed and wind direction. The results of the test must be published in a suitable technical paper.

Once the above-mentioned milestone is reached, the LiDAR type gains wide use and an increasing number of production units are deployed on a range of sites with different meteorological characteristics. Additionally, more operational experience is gained and more is learned about the set-up, robustness and consistency of the measurement equipment when comparing various units. Confidence is gained that LiDAR units provide robust, continuous and accurate data over the full spectrum of operational conditions. Alternatively, specific conditions where the LiDAR type, and its individual units, do not provide robust data become well understood and can be excluded from analyses. Data from individual units of the LiDAR type may be used quantitatively within an onshore formal wind speed and energy assessment in non-complex terrain/flow although, in some instances, site-specific verifications for a given unit against conventional anemometry data may be required. At this stage, the LiDAR type is considered as proven technology and it is common that in onshore non-complex terrain and flow, the error bars associated with measurements provided by individual LiDAR units are similar to those of high-quality mechanical anemometry.

3.3.3 Offshore application

Data from FLS at this stage are not deemed reliable enough to be used quantitatively in the context of a formal wind resource assessment. However, it is expected that they can provide qualitative information to supplement fixed offshore wind measurement sensors and these circumstances are assessed quantitatively under Scenario A (Section 3).

3.3.4 Limitations of offshore application

There are no formal requirements for FLS at this stage as they are not expected to provide acceptably validated wind data. However, it is recommended that metocean conditions be measured and documented to help build a body of knowledge on the performance of the technology and its sensitivity to external and operational parameters.

3.3.5 Expected levels of measurement uncertainty

At this stage, the FLS data shall only be utilised in a relative sense, to support wind flow modelling and potentially other sources used to estimate horizontal and vertical variation in wind resource across the site. Absolute wind resource estimates will be anchored to analysis of the primary source of on-site wind data which is assumed to be from a trusted reference system[8] and therefore uncertainty levels shall be primarily driven by this primary source.

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[8] Section 5.4: IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

3.4 Stage 2: Pre-commercial

3.4.1 Definition

At this stage, FLS units are commercially available in the sense that FLS units can be purchased from OEMs, have fulfilled the Baseline stage requirements and an independent third-party has published a Type Validation document for the technology (as described below). However, operational requirements and limitations may be insufficiently studied and documented so that there is a significant level of uncertainty as per their performance on any given offshore site, especially where the expected environmental conditions differ significantly from those experienced during the pilot verification trial(s), which in the end may result in a higher uncertainty estimate.

3.4.2 Prerequisites

For a floating LiDAR technology at Baseline stage, a milestone is reached when at least one unit has successfully completed at least one pilot verification trial. The FLS is then said to have achieved Type Validation. For the pilot verification trial, a 2-phase protocol as described below is required.

The 2-phase protocol is designed to:

- Validate the LiDAR performance onshore in a fixed frame of reference and in the absence of any motion; and,
- To validate the floating LiDAR performance offshore under dynamic conditions and under wind and sea conditions representative of its future deployment locations.

The onshore verification of the unit should be performed against high-quality conventional anemometry, or alternatively against a trusted reference LiDAR whose accuracy is traceable to high-quality conventional anemometry. Indeed, at this preliminary stage, it is considered that despite the fact that the LiDAR unit belongs to a proven LiDAR type; the specific performance of the unit at hand should be precisely determined before any offshore test is undertaken.

The offshore verification would need to be undertaken at an actual offshore site against a reliable and traceable fixed offshore meteorological mast designed in accordance with relevant industry standards and best practice, or against another suitable trusted reference system[9]. However, caution is noted that the use of a LiDAR as the trusted reference source is not currently considered a reliable source to assess the performance of the FLS in accurately measuring Turbulence Intensity (TI) as discussed further below. The offshore verification test is to determine the accuracy achieved by the FLS is traceably referenced ultimately to that achieved with fixed cup-anemometry already accepted for formal wind resource and energy yield assessments. Metocean conditions should be documented and relevant sensitivity analyses should be undertaken to show the extent to which external parameters and conditions affect remote sensing device performance[10]. However, suggested Acceptance Criteria have previously been developed by the Carbon Trust and the OWA industry partners in collaboration with DNV GL, and these are reproduced in Appendix 1. It is

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[9] Section 5.4: IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

[10] Sections 5.5 and 7.3: IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

noted that independent scrutiny of trial design and execution is recommended and that the performance of FLS units over the trial be clearly validated against “minimum” and “best practice” Acceptance Criteria.

The results of the Type Validation test must be published in a suitable technical paper to serve as a reference document for the FLS technology.

It is noted that in some circumstances detailed turbulence and gust information may be a formal requirement of certification bodies or turbine manufacturers for site feasibility assessment and structural design; therefore careful consideration should be given to this point in the specification of a measurement campaign. Turbulence Intensity (TI) is also of relevance for wake modelling when assessing Annual Energy Production (AEP).

This roadmap focusses on the capabilities of floating LiDAR technology to replace met masts in measuring primary wind data, namely wind speed and wind direction. Currently, there is insufficient evidence to confirm the reliability of turbulence intensity measurements from LiDAR technology. However, some further discussion regarding consideration of turbulence intensity measurements from FLSs is given in Section 3.6.

The above pre-requisites are summarised in tabular form in Appendix 1.

3.4.3 Offshore application

Once the above-mentioned milestone is reached and the FLS is considered to have achieved Type Validation, it is expected that it could be deployed on offshore sites to supplement fixed offshore wind sensors (Scenario D) or as a stand-alone source of wind data (Scenarios B and C) provided the requirements of the next subsection are met.

3.4.4 Limitations of offshore application

2-phase verification of each unit

During this stage, FLS units to be deployed for offshore wind resource assessment are to follow the 2-phase verification protocol (see Section 3.4.2) before the actual measurement campaign may begin. The purpose of the preliminary 2-phase verification is twofold:

- To avoid tracing back the performance of all units to a single test, namely the Type Validation trial results; and,
- To gain confidence that different units provide consistent, robust, continuous and accurate data over a variety of operational, atmospheric and sea conditions.

Metocean conditions are to be accurately measured and documented during the 2-phase verification protocol to help understand FLS performance during the tests and later during the actual offshore measurement campaign.

If the outcome of the 2-phase verification protocol is not consistent with previous such tests, notably those of the Type Validation (pilot) trial, the FLS unit may not be suitable for use in the context of a formal uncertainty analysis. In such circumstances, the causes of unexpected performance should be investigated and explained.

Metocean conditions

For stand-alone applications (Scenarios B and C), it is required that the metocean conditions which have prevailed during the 2-phase verification described above be *representative* of those expected on site during the measurement campaign. More precisely, it is expected that the external and operational parameters which are deemed to affect the FLS performance do not significantly exceed the envelope of these environmental parameters observed during the 2-phase verification trial. Otherwise, it must be demonstrated that either the impacts of these parameters on wind speed error are negligible or that they can be reliably quantified based on evidence from available FLS Type Classification, where available. This should be backed by literature or acceptable data analyses.

A list of parameters which may affect the performance of the FLS is provided in the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[11]. Measurement of these quantities is recommended to perform sensitivity analyses of the statistics of the FLS errors as a function of the listed parameters to drive conclusions. It is recommended that on this topic the advice from Section 7 of the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems is followed.

As a first approximation, verification test conditions may be deemed representative of site conditions if the magnitudes of environmental parameters potentially impacting the wind data quality during the measurement campaign (referred to above) remain within the envelope observed during the verification tests. Recorded wind data during periods where such tertiary parameters fall outside of the verification envelope should be considered with care, and potentially rejected.

Independent source of site wind data

During the Pre-commercial Stage, it is important to monitor the consistency of the performance of the FLS during the measurement campaign. It is therefore required that an independent and reliable source of site wind data be available to perform periodic and regular sanity checks. This could be from on-board ancillary measurement equipment providing secondary wind speed and direction measurements, as recommended in Section 2.6 of the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[12].

The presence of such an independent source of wind data would also serve to mitigate risks associated with a lack of redundancy, risks of systematic errors and other issues such as those related to measuring on-site Turbulence Intensity (TI) with a LiDAR – provided the said source of wind data does indeed provide this information.

In case a stand-alone application is sought (Scenarios B and C), it is required that a good level of regional wind climatology knowledge be available. Such a body of knowledge may be based on previous studies and modelling or come from nearby reliable sources of fixed wind data sources.

[11] Section 5.5: IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

[12] Section 2.6: IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

Need for pre- or post-deployment verification trials

Should an inconsistent performance of the FLS be observed during a measurement campaign, a post-deployment verification trial of the FLS unit is required to determine the cause, explain the observations and, if possible, attempt to salvage the measurement campaign in case a serious anomalous behaviour is detected.

Those inconsistencies may consist in failure and replacement of the employed LiDAR device or the whole FLS buoy, incidents of impact to the buoy during deployment and operation (e.g. collision with drifting debris or fisheries), extreme weather and sea states, longer lasting outage of power supply for example. It is recommended that on this topic of whether pre- or post-deployment verifications of an FLS unit are required, the advice from the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems is followed.

3.4.5 Assessment of uncertainties for Stage 2 FLS

The measurement uncertainties of an FLS (irrespective of which stage it has achieved) are to be assessed by following the procedure outlined in Appendix 2 and in accordance with the guidelines mentioned herein. As discussed in Appendix 2 there are a number of uncertainty components that are to be assessed; the main ones being a verification/calibration uncertainty and a classification uncertainty.

The Type Validation trial that is required to achieve Stage 2 may (at this stage) be evaluated as a verification test in order to derive a verification/calibration uncertainty. Unit verification trials (i.e. pre-deployment verifications) can also be used to derive the verification/calibration uncertainty.

If the covered ranges of environmental conditions are broad enough, the Type Validation trial can also be interpreted as a classification trial and the corresponding uncertainties be derived for it. Note that for a complete classification test, several trials at different locations and with different units are required which is a pre-requisite for achieving Stage 3. A classification test and the corresponding uncertainty which is based on fewer trials and related evidence should include some added uncertainty.

In principle, a Stage 2 FLS can have the same uncertainty as a Stage 3 FLS. However, it is expected that the assessment for a Stage 2 FLS is typically based on less evidence in terms of performed trials and that uncertainty values, particularly relating to the classification uncertainty, are estimated or assumed on another basis which may lead to an elevated (and more conservative) level due to the lack of evidence at this stage.

3.5 Stage 3: Commercial stage

3.5.1 Definition

At this stage, the FLS type is considered to have achieved commercial acceptance with respect to formal wind resource and energy yield assessment reports, incorporating uncertainty analyses and quantification of confidence limits in terms of energy yield expectations at various levels of probability such as 90% (P90), 95% (P95) and 99% (P99) commonly used for project financing. Wind data from FLSs at this stage may be used quantitatively with only limited or even in the absence of site-specific verification. Expected error bars should be comparable to those assigned to conventional offshore met masts provided best practice are followed and robust data quality control and uncertainty analyses have been undertaken and documented. In addition, FLSs at this stage have demonstrated significantly more demanding reliability performance, to a criteria higher than Stage 2, and in a range of metocean conditions, supported by a sufficient body of evidence. The reliability performance, number of trials and duration required for each maturity stage are summarised in Appendix 1.

3.5.2 Prerequisite

At this stage, units of a specific FLS type, such as using a specific LiDAR type and being sufficiently similar in technical configuration to the type tested version as discussed in Section 3.1, are commercially available. Furthermore, an independent third-party has published a Type Validation document for the technology as described in Section 3.4.2, fulfilling the requirements for Stage 2 maturity.

In addition, a body of evidence is available that demonstrates the capability of the particular FLS type to achieve higher levels of availability and reliability beyond that expected of Stage 2 devices and across a range of conditions. This is evidenced through further successful trials as well as early commercial deployments as part of wind resource assessments covering a range of operational, site and metocean conditions. As discussed in Section 1.2, it is expected that Stage 3 maturity claims will be independently verified by a suitably qualified and experienced third party organisation.

In particular, an FLS is considered to reach Stage 3 maturity when the following specific requirements are fulfilled in addition to the Stage 2 Type Validation:

1. A number of at least six (6) trials of this FLS type, consisting in three (3) longer trials of at least 3 months continuous duration and three (3) shorter pre- or post-deployment verifications have been completed against a suitable trusted reference, successfully meeting:
    a. all data accuracy KPIs at best practice AC level (see Appendix 1), for heights above sea level that are representative of typical offshore hub heights (i.e. at least 100 m, with next generation turbines predicted to reach up to 150 m).
    b. all availability KPIs at stage 3 AC level, see KPI tables in Appendix 1.
2. A number of three (3) FLS type Classification Trials have been completed, as recommended in the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[13] and in

[13] Section 7.6: IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

compliance with the IEC Standard for Power Performance Measurements of Electricity Producing Wind Turbines[14]. These should be performed for a minimum of two devices of a specific type of FLS at a minimum of two different sites for a sufficiently long period. A period of between 3 to 6 months is anticipated to be sufficient, although this will be dependent upon the range of conditions captured during the trial. These Classification Trials shall provide consistent results for FLS error sensitivity to offshore typical environmental variables, covering a sufficient significant range of sea states.

3. A number of at least five (5) early commercial project deployments (using the same FLS type as discussed in Section 3.1) covering an un-interrupted duration of 12 or more months have been completed successfully, meeting all availability KPIs at Stage 3 Acceptance Criteria level as defined in Appendix 1[15].

4. For all of the above (a) to (c), evidence on logistical management should be collected, documented and provided. This should comprise scheduled and unscheduled service visits, any occurring issues or faults and related risk mitigation measures as part of an operations management plan to assure maximum reliability and maintainability, all whilst maintaining the KPI for availability in order to prove the logistical capabilities of the FLS.

The above pre-requisites are summarised in tabular form in Appendix 1. It is noted that the trials listed for requirement (a) above could include the Stage 2 Type Validation trial and Classification Trials as defined in requirement (b).

For devices that have reached maturity Stage 3, it is recommended that availability requirements for overall system availability campaign average (OSA_{CA}), monthly system availability (MSA_{1M}) and overall post-processed data availability ($OPDA_{CA}$) are fulfilled by all trial or project deployment campaigns.

Furthermore, the envelope of operational, site and metocean conditions covered by these trials and deployments is considered sufficient and the performance of the FLS in a range of conditions becomes well understood. In particular, from the body of evidence gathered, certain environmental conditions may be identified in which the FLS is known not to perform correctly. In these specific conditions where the technology is known not to provide robust data, these can be excluded from analyses either through removing affected periods entirely, or through filtering the dataset for the specific conditions.

An FLS which has reached Stage 3 maturity is expected to have demonstrated a track record for serviceability during deployments of varying durations. This requires a documentation of collected evidence on logistical management as recommended above under item (d).To ensure safe and repeatable operations during the deployment phase, a robust and tested methodology should be considered and adopted for the deployment and retrieval of the FLS. This should include operations for transport, repair and servicing strategies in order to meet the required KPI criteria for data availability as described in Appendix 1.

It is expected that the OEM of a Stage 3 FLS will clearly outline which relevant Health and Safety standards will be complied with as part of any tender. Further information is given in Section 2.

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[14] Annex L of IEC 61400-12-1, Ed. 2, 2017.

[15] It is acknowledged that the maintenance strategy can strongly influence the achieved availability KPIs. For example, a maintenance strategy ensuring highly responsive service vessels could achieve significantly greater availability KPIs than a less responsive service, where the underlying reliability of the FLS may be identical. To avoid this affecting the criterion unduly, in evaluating this criterion adjustments can be made to account for varying maintenance strategy, so long as the principle of attaining availability KPIs is retained.

3.5.3 Offshore application

It is expected that at this stage, FLS data can be used quantitatively as a stand-alone data source (Scenarios E and F) or to supplement data from offshore meteorological mast(s) (Scenario G), provided the requirements below are met. For stand-alone applications, as previously mentioned, attention should be paid to such concerns as redundancy, performance consistency, potential systematic errors and TI measurement.

3.5.4 Limitations of offshore application

It is expected that for the FLS technology to continue on track to become a mature and widely accepted means of offshore wind resource assessment, a set of best practice will be needed to ensure a consistent and high level of quality. It is intended that this document, in conjunction with the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[16], shall form such industry best practice.

As a general rule, the following recommendations are seen as best practice rules which would bring additional confidence in the reliability and accuracy of the FLS data:

- FLS sanity or consistency checks using an independent source of wind data during the campaign. Typically referred to as Site Acceptance Tests – see Section 3.6.4 for further details.
- 2-phase verification trial before an offshore wind resource campaign begins is recommended for lowest uncertainty. Alternatively, a single-phase verification trial (ideally offshore) in addition to a risk based approach as described in Section 6.2 of the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[9] may be sufficient, see also Appendix 3.
- Additional confidence in the reliability and accuracy of the FLS when operated within metocean ranges where its performance has been proved.

The same comments as made previously in Section 3.4.4 regarding pre- and post-deployment verification trials of the FLS unit as part of a wind measurement campaign still apply.

3.5.5 Assessment of uncertainties for Stage 3 FLS

It is expected that following the recommendations presented in the previous subsection, an increased level of confidence would be gained in the results and the related uncertainty levels of FLS wind data. It is expected that under ideal conditions, the FLS measurement uncertainty could be similar to those of a proven LiDAR device deployed onshore in benign terrain. However, the actual uncertainty levels will be site-specific and would eventually need to be evaluated based on available information and data and by following industry standards.

As for a FLS that has achieved Stage 2, the measurement uncertainties of an FLS that has achieved Stage 3 are to be assessed by following the procedure outlined in Appendix 2. A pre-verification is required for each individual FLS unit, independent from which maturity stage has been achieved by the type. The type classification is based on a larger number of trials (cf. Stage 2 with only one trial available in some cases), which may result in a better knowledge of the device performance and most likely less conservative estimates of the uncertainty contribution according to type classification. If the FLS is deployed in connection

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[16] IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

with a met mast (Scenario G in Table 2.2) the verification can, again, be obtained from the application campaign itself.

3.6 Other considerations

3.6.1 Length of measurements and power supply

Regardless of the level of maturity or acceptance of the technology, the length of the data set and achieved data coverage rates at hub height are key considerations in measurement campaigns. Remote sensing campaigns should span a similar period as those undertaken with conventional masts and both should also take account of the availability of suitable long-term reference data for use in Measure-Correlate-Predict type analyses (i.e. at least 12 months but ideally more than 24 months).

In particular, care should be given to circumstances, if any, where specific operational or metocean conditions may reduce data availability or reliability and therefore result in systematic errors or uncertainties. Also, it is important to deploy a device with a sufficient power supply and an appropriate O&M program such that it can be expected that data coverage rates up to hub height will be high (see appendix for availability KPIs).

In addition, it is important that the equipment and power supply are such that the FLS may operate for extended periods without interruption in very challenging environments. Given the substantial cost of offshore platform installation, consideration should be made as to how data redundancy might be achieved through the installation of conventional anemometry, a second remote sensing device, or any other scenario which might be appropriate given the site-specific conditions prevailing at the offshore project site in question.

3.6.2 Reliability of turbulence intensity measurements from FLS units

Although this roadmap focusses on the FLSs ability to accurately measure wind speed and direction, there are other secondary measurements, such as turbulence intensity and gusts, which are of importance to site suitability and energy production assessments.

Use of FLSs for the measurement of Turbulence Intensity and gusts is currently at a far lower level of maturity than for wind speed and direction as discussed in this roadmap. However, at the time of writing, it is acknowledged that efforts are being made within the industry to develop a better understanding on how to confidently obtain such measurements from FLSs.

In building a body of evidence to demonstrate the performance of FLSs in a range of conditions, and thus improve confidence in the technology, it is considered prudent to undertake steps to improve the understanding of the performance of FLSs in recording such measurements. For TI in particular, it is recommended that the data available from the FLS demonstrate that turbulence data are sufficiently representative, or alternatively, they can be complemented or corrected to measurements from cup anemometry, notably by using an on-site independent source of data, to provide the inputs required for site feasibility assessment, structural design and wake modelling purposes.

It is noted that design standards IEC 61400-1 and IEC 61400-3 make no specific reference to the use of LiDAR data for site assessment, which currently refer to measurements from cup anemometry as a metric. It is further noted that ground based, commercially available LiDAR devices cannot provide all the parameters required for site assessment under the current version of the design standards. Two sources of systematic error, spatial averaging and contamination of the horizontal turbulence statistics by vertical flow components, affect the ability of current commercial LiDAR devices to accurately replicate turbulence intensity measurements as produced by cup anemometry.

It is noted that some LiDAR and FLS OEMs use algorithms internally in their devices for calculating, processing and filtering the raw measured data to calculate TI. It is therefore expected that clarity will be provided by the OEM regarding any processing algorithms implemented by the FLS. Where refinements and developments have been made by the OEM, it is expected that the impact of such changes be demonstrated as part of a trial.

As a minimum, it is expected that the profile of TI with wind speed and direction is measured by the FLS and compared to the TI measurements obtained at the reference source as part of a verification trial. Given the reliance of existing design standards on measurement from cup anemometry, it is recommended that, where possible, the reference source is a meteorological mast. It is recommended that the verification trial be performed under similar atmospheric stability conditions as expected in the wind resource assessment campaign in order to identify any trends or conditions which impact the accuracy of the TI measurements.

Reference is made to the IEA Recommended Practices which includes related notes and advice regarding the measurement of TI by FLSs.

3.6.3 Replacement of faulty components or system during a wind resource assessment campaign

In cases where a key component such as the LiDAR device needs to be replaced during a WRA campaign (for example due to an observed failure or malfunction) specific measures should be taken to mitigate the risk of losing wind data traceability and increasing uncertainty. Those measures may consist of checks to ensure the correct function of the replaced component in conjunction with the whole FLS such as:

- onshore sanity check against a suitable reference (typically referred to as Site Acceptance Tests – see Section 3.6.4 for further details);
- onsite in-situ comparisons against a suitable on-board or external reference sensor;
- where a pre-deployment verification of the replaced configuration has not been performed, then undertake a post-deployment verification of the whole FLS.

3.6.4 Site Acceptance Tests

It is recommended that a Factory Acceptance Test (FAT) and Site Acceptance Test (SAT) are undertaken as part of any successful FLS deployment to ensure that the device has been configured correctly and thus mitigate the risk of lost time or wind data associated with correcting any erroneous configurations during a deployment.

The Site Acceptance Test should be undertaken prior to commencement of the campaign deployment and with both the FLS OEM and the project developer to which the deployment pertains in attendance. To ensure transparency and traceability of the deployment, it is further recommended that the SAT is witnessed and documented, ideally by a suitably qualified and experienced independent 3rd party although not exclusively.

Site Acceptance Tests should include an inspection of the main components of the FLS, testing of the equipment and plausibility checks of the measurements recorded by all sensors on the FLS. The serial numbers of all equipment sensors should also be documented for transparency (for example, buoy, LiDAR device, data logging equipment, on-board meteorological and metocean sensors etc).

SAT checklists can vary between FLS OEMs, however, it is recommended that as a minimum the following topics are assessed and tested as part of a SAT:

1. Visual inspection of the buoy to include, but not limited to:
    a. Buoys, sensors and equipment;
    b. Mooring;
2. Power systems like batteries, solar panels, wind turbines and the fuel powered generator;
3. Meteorological and ocean state instrumentation;
4. Communication systems like telemetry, location systems (GPS) and on-board compass;
5. LiDAR System:
    a. Installation position, mounting and orientation;
    b. Measurement height configuration;
6. Calibration of the compass heading.

4 Conclusions

The Carbon Trust OWA has produced this roadmap for the steps required for Floating LiDAR System (FLS) technology to become commercially accepted within the offshore wind industry. Version 2.0 of this document was developed in 2018 and is highly consistent with Version 1 from 2013. An important material difference is that an appropriate trusted wind speed reference (which is not an anemometer mounted on a mast) is now explicitly permitted. The major development of Version 2.0 is to provide much more information on Stage 3 requirements, which are centred on the consistent demonstration of very good levels of system reliability and data availability.

Broad guidance is provided for the three stages envisaged for an FLS product to reach commercial acceptance. On the basis of this work, the following conclusions are drawn.

- Prior to the deployment of FLS technology, the LiDAR measurement unit itself should be considered as proven technology and have broad commercial acceptance within the onshore wind industry. At this "Baseline" stage of maturity, no formal verification trials have been completed, but the FLS technology still may be used to contribute to a commercial energy production assessment in a supporting role, when deployed in parallel to a conventional offshore meteorological mast.

- An FLS product may be considered to have reached a second stage of maturity ("Pre-commercial") once a pilot verification trial has been successfully completed, including independent scrutiny and confirmation of appropriate acceptance criteria and trial design. At this stage, FLS technology may be used with or without an onsite met mast, but should minimally undertake a pre-campaign 2-phase (i.e. onshore and offshore see Section 3.4.2) unit verification to prove the accuracy of the LiDAR unit and FLS system against a trusted reference source prior to full deployment. If deployed without an onsite met mast, the FLS wind data can only be considered valid for periods when metocean conditions remain within the verification envelope experienced in the type and unit trials.

- Commercial maturity is considered as a third stage for FLS products and is reached once a significant body of operational experience and verification has been established across a range of environmental conditions. Any residual environmental performance sensitivities are assumed to have been well documented and are understood by the manufacturer and the broader industry at this stage. With regards to reliability, the FLS has to demonstrate significantly more demanding reliability performance. At this stage FLS accuracy can be considered to approximate that of conventional fixed onsite met masts, albeit with a marginal level of residual uncertainty relating to site-specific deployment conditions.

It is important to note that this roadmap was designed to focus on the capabilities of floating LiDAR technology in measuring primary wind data, namely wind speed and wind direction. There are other secondary but important parameters required for a comprehensive offshore wind resource assessment such as hub-height turbulence intensity, temperature, air density, relative humidity etc. Additionally, complementary oceanographic measurements are also required to achieve a full met-ocean measurement campaign. Therefore, while some floating LiDARs currently feature additional measurement capabilities and while future developments might add even more comprehensive measurement capabilities, it is important to bear in mind that this document is only a roadmap towards replacing primary wind measured from offshore met masts with floating LiDARs, and that secondary wind data and met-ocean measurements will still need to be taken to complete a comprehensive offshore wind resource and met-ocean measurement campaign.

Additionally, although system availability is one of the KPIs used in this roadmap, this document does not directly address or cover the seaworthiness of the floating LiDAR devices.

Appendix 1

Suggested acceptance criteria for type verification trials and for pre- or post-deployment verification trials

Recommended guidelines are presented below for the assessment of the performance of the floating LiDAR units under trial against a suitable reference[17], or during project deployments. They are based on the following definitions:

- Key Performance Indicators (KPIs), being the parameters derived from analysis of the data gathered, which will specifically be used to assess performance.
- Acceptance Criteria (ACs), being specific benchmark values defined for a sub-set of the KPIs which constitute the required minimum level of performance for each floating LiDAR system to be considered as achieving Maturity Stage 2 (pre-commercial) or Maturity Stage 3 (commercial).

These parameters are divided into those representing the Availability / Reliability and Accuracy of the systems in question.

The reliability of an FLS is to be assessed in conjunction with data accuracy for all verification trials against a suitable trusted reference, be it for a Stage 2 Type Validation trial, or for any post- or pre-deployment trial of a Stage 2 or Stage 3 FLS. When looking at reliability measures during project deployments, system and data availabilities may be treated in isolation from the data accuracy, if no wind data reference is available.

Note, that for FLSs that have reached Stage 3:

- Best practice acceptance criteria for data accuracy KPIs are to be applied, only; and
- Higher acceptance criteria for system and data availability KPIs are imposed.

Generally, it is expected that the KPIs are evaluated for heights being representative for a typical state-of-the-art offshore wind turbine covering a height range over the full rotor disk. This means covering heights of modern turbine's upper tip heights of some 200 m. If this is not possible the upper measurement key height shall – as minimum requirement – be representative for a typical offshore hub height (i.e. at least 100 m, with next generation turbines predicted to reach up to 150 m), and several other lower heights down to 40 m (if feasible even 30 m above mean sea level) shall be taken into account.

The performance assessment of the given KPIs and respective acceptance criteria regarding Availability and Accuracy shall be executed at each reference level present, in this case at each of the trusted reference source's measurement levels.

All data collected from the date of commissioning of each FLS until its decommissioning shall be taken into account in the overall data processing scheme, regardless of the environmental conditions.

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[17] Section 5.4: IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef.

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Finally, the duration of the campaign should be considered. The conclusions will be valid for the metocean conditions experienced during the trial(s), and so longer trials may be preferred to increase the probability of experiencing rougher sea states.

For a Stage 2 Type Validation trial it is recommended that at least six (6) months of continuous offshore data are available from a single campaign to provide confidence with respect to the measured KPIs described below. It is expected that this total of six (6) months of data are gathered within a single, uninterrupted trial campaign.

Availability / reliability

The KPIs and Acceptance Criteria relating to availability, all of which are applicable to all measurement heights under consideration, are defined in the following tables.

Attention is drawn to the footnote within Section 3.5.2 regarding consideration of the influence of maintenance strategy in assessing the availability Acceptance Criteria in the context of wind resource assessment campaigns, listed as pre-requisite (c) for Maturity Stage 3.

Availability KPIs are listed for both Overall System Availability and Post-processed Data Availability. It is acknowledged that in the context of wind resource assessments, the Post-processed Data Availability KPI will be of most interest. The Overall System Availability KPI is included to inform the industry on the capability of an FLS to be fully functional and ready to collect data in an offshore environment. Distinction is made between overall and monthly availability KPIs to allow for seasonal effects.

KPI	Definition / Rationale	Acceptance Criteria Across total campaign length
MSA_{1M}	**Monthly System Availability – 1 Month Average** The LiDAR system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the given month. The Monthly Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10 minute) data entries including periods of maintenance (regarded as 100%) within the respective month.	≥90% for Stage 2 ≥95% for Stage 3
OSA_{CA}	**Overall System Availability – Campaign Average** The LiDAR system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the pre-defined total campaign length. The Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10 minute) data entries including periods of maintenance (regarded as 100%) within the pre-defined total campaign period.	≥95% for Stage 2 ≥97% for Stage 3

KPI	Definition / Rationale	Acceptance Criteria Across total campaign length
$MPDA_{1M}$	**Monthly Post-processed Data Availability – 1 Month Average** The Monthly Post-processed Data availability is the number of those data entries remaining > after system internal (unseen) filtering, i.e. excluding (NaN or 999) flagged data entries > and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of LiDAR contractor guidelines relative to the maximum possible number of (here 10 minute) data entries (regarded as 100%) within the respective month, regardless of the environmental conditions within this period.	≥80% for Stage 2 ≥85% for Stage 3
$OPDA_{CA}$	**Overall Post-processed Data Availability** The Overall Post-processed Data availability is the number of those data entries remaining > after system internal (unseen) filtering, i.e. excluding (NaN or 999) flagged data entries > and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of LiDAR contractor guidelines relative to the maximum possible number of (here 10 minute) data entries (regarded as 100%) within the pre-defined total campaign period regardless of the environmental conditions within this period.	≥85% for Stage 2 ≥90% for Stage 3

The following KPIs are considered to have an impact on the overall reliability of the FLS. However, due to their nature it is not considered appropriate to assign Acceptance Criteria to these KPIs. However, it is recommended these KPIs be reported on and their impact included in availability KPIs listed in the tables above.

KPI	Definition / Rationale	Considerations
MV	**Number of Maintenance Visits** Number of Visits to the floating LiDAR system by either the supplier or an authorised third party to maintain and service the system. This is to be documented and reported by the supplier and confirmed by an independent 3rd party.	See pre-requisite (c) given in Section 3.5.2 for further discussion. Although listed as a pre-requisite for Stage 3 Maturity, it is considered good practice to follow the approach outlined regardless of maturity stage.
UO	**Number of Unscheduled Outages** Number Unscheduled Outages of the floating LiDAR system in addition to scheduled service outages. Each outage needs to be documented regarding possible cause of outage, exact time / duration and action performed to overcome the Unscheduled outage. This is to be reported by the supplier and independently confirmed and checked by an independent 3rd party.	
CU	**Uptime of Communication System** To be documented and reported by the supplier and independently checked/confirmed by an independent 3rd party.	See Section 2.5 in the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems for further guidance on this topic, specifically RPs 9, 10 and 11.

In the above tables, during periods of maintenance; the system is deemed unavailable.

Preconditions for accuracy assessment

All comparisons and regression analysis are to be based on 10-minute average values returned from the sensors on the trusted reference measurement system.

The data from both the FLS and the trusted reference measurement system are to be filtered for external parameters such as:

- wind flow distorting effects from the ground / terrain (in the case of an onshore / coastal reference system) or from platform structures potentially influencing the undisturbed wind flow up to a certain height at the trusted reference measurement system;
- wind direction in order to avoid non-valid wind speed measures from sectors where either the trusted reference measurement system or the floating LiDAR itself is influenced by mast wake effects. Final valid sectors are to be defined by taking into account:
  - boom directions for the side mounted cup anemometry at the reference mast, where used;
  - Any lightning protection components that may wake effect top mounted cups on the mast, where used; and,
  - each floating LiDAR position relative to the mast, where used.
- wind speed: application of clipping below 2 m/s. The rational for such low wind speed cut-off is that remote sensing techniques are known to suffer from weak signals in low wind speed conditions. Therefore, such wind speeds should be excluded from the analysis to prevent the relation between floating LiDAR and reference being biased in a rather unimportant wind speeds range.
- air temperature taken from on-board measurements in order to avoid unpredictable conditions like icing of cups that could violate the representativeness of the reference measurements. Hence the data should be clipped for air temperature with $T < 0.5°C$.

Data coverage requirements for accuracy assessment

The data coverage requirements set-out below, prescribes the minimum required number of valid data points after the final filtering for allowable conditions required for data quality assessment, i.e. after clipping for wake affected wind direction sectors, ground or structure effected height levels, low wind speeds and low temperatures. By defining such data coverage requirements, it shall be assured that results from the performance assessment are statistically relevant.

The requirements on data coverage are based on 10-minute average values as returned from the floating LiDAR system.

The following data coverage definitions are prescribed as follows:

1. minimum number of 40 data points required in each 1 m/s bin wide reference wind speed bin centred between 2.5 m/s and 11.5 m/s, i.e. covering a range between 2 and 12 m/s.
2. minimum number of 40 data points required in each 2 m/s bin wide reference wind speed bin centred on 13 m/s and 15 m/s, i.e. covering a range 12 m/s and 16 m/s.
3. minimum number of 40 data points in each 2 m/s bin wide reference wind speed bin centred on 17 m/s and above, i.e. covering a range above 16 m/s only if such number of data is available. This is not mandatory.

Those data coverage requirements are regarded as achievable for the planned 6 months deployment period but also for considerably shorter verification tests.

It is accepted that at certain test sites filling all of the bins at lower wind speeds can be challenging, without necessarily there being a deleterious impact on the accuracy assessment. Subject to review and approval of a suitably qualified and experienced independent 3rd party, these data coverage requirements can be waived if the LiDAR itself has been verified at the missing wind speed bins (in the case of a fixed LiDAR as the trusted reference source), and if the data which has been obtained can be demonstrated to have sufficient coverage to assure that the overall accuracy requirements are met. It is noted that the impact of any unfilled bins will have a bearing on measurement uncertainty estimation.

Accuracy assessment

The KPIs and Acceptance Criteria relating to accuracy are defined in the following table. To assess the accuracy a statistical linear regression approach has been selected which is based on:

1. a two-variant regression y = mx+b (with m slope and b offset) to be applied to wind direction data comparisons between floating instrument and reference measurement system (for the wind direction's circular nature the offset is to be understood as mean difference instead of intersection with Y-axis); or,

2. a single variant regression, with the regression analysis constrained to pass through origin (y = mx+b; b = 0) to be applied to wind speed, turbulence intensity and wind shear data comparisons between floating instrument and reference.

In addition, Acceptance Criteria in the form of "best practice" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on correlation coefficients returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

Note, that these "minimum" criteria are allowable for Stage 2, only. For Stage 3 judgements "best practice" criteria should be applied.

KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum Stage 2, only
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) all above 2 m/s given achieved data coverage requirements.	0.98 – 1.02	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Correlation Co-efficient returned from single variant regression A tolerance is imposed on the Correlation Co-efficient value. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) all above 2 m/s given achieved data coverage requirements.	>0.98	>0.97

KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum Stage 2, only
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of coverage requirements.	0.97 – 1.03	0.95 – 1.05
OFF_{mwd}	**Mean Wind Direction – Offset** In terms of mean difference between FLS and reference (between 0° and 360°) (same as for M_{mwd})	< 5°	< 10°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97	> 0.95

Consideration of other measurement parameters

Furthermore, there are parameters of secondary importance that are recommended to be measured (wind shear and turbulence intensity) as defined below, but without Acceptance Criteria. It is recommended to compare the measured wind shear and turbulence intensity from FLS measurements with the shear and turbulence intensity from the trusted reference source measurements given the importance of these measurements in site suitability and energy production assessments.

It is noted that due to the previously noted limitations of remote sensing devices (such as LiDARs) to accurately measure turbulence intensity, a comparison of turbulence intensity measurement against conventional anemometry is recommended until there is sufficient understanding in the industry on this topic.

See Appendix C in the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems for further guidance on this topic.

KPI	Definition / Rationale
X_{TI}	**Turbulence Intensity – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin.
R^2_{TI}	**Turbulence Intensity – Correlation Co-efficient** Correlation Co-efficient returned from single variant regression with the regression analysis constrained to pass through the origin.
A	**Wind Speed Shear – Shear Exponent Alpha related to Hellman's power law.** a) Alpha to be calculated using reference heights that are representative of turbine rotor tip bottom and top heights, where possible. If limited by the measurement heights available at the reference source, then ensure the height interval assessed is as large as possible.

Maturity stages: overview of pre-requisites and trial durations

The pre-requisites for attaining the respective stages of maturity are summarised in the table below. Note that this table does not indicate recommendations for subsequent pre-deployment verifications for an FLS unit in the context of a wind resource assessment. This topic is more appropriate for, and is covered in, the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[18]. To support the reader's understanding of this and the implication of the application of the recommended practices on pre-deployment verifications for FLS units which have reached Stage 3 maturity, a number of example scenarios are illustrated in Appendix 3.

The pre-requisites outlined in the table below are significantly more demanding for Stage 3 than for Stage 2. However, it is pointed out that deployments of Stage 2 devices in wind resource assessments will entail pre-deployment verifications, and if this continues successfully for a number of units then the requirements for Stage 3 will, in the main, mostly be accumulated as a matter of course.

[18]IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

Maturity Level	FL Type Verification[1] (1 long trial)	FL Unit Verification[1] (3 long and 3 short trials)	FL Offshore Classification[1] (3 long trials)	Early Commercial Project Deployments
Stage 1	Not required.	Not required.	Not required.	Not required.
Stage 2	Number: At least 1. Duration: At least 6 months. Continuous single campaign. Availability KPIs: > meet Stage 2 AC. > Data Accuracy KPIs: > meet minimum AC.	Not required.	Not required.	Not required.
Stage 3	Stage 2 Type Verification completed. May count as 1 of 3 long trials if KPIs meet: > Stage 3 AC for availability. > Stage 2 best practice AC for data accuracy. May count to classification trials.	Number: 6 (minimum 3 short and 3 long). Duration: At least 3 months for long trials. Continuous single campaign. Availability KPIs: > meet Stage 3 AC. > Data Accuracy KPIs: > meet Stage 2 best practice AC. May count to classification trials.	Number: At least 3. Duration: At least 3 months (typically). 2 individual units are trialled at the same test site. One unit trialled at two different test sites. Continuous single campaign. May count towards long trials if KPIs meet: > Stage 3 AC for availability. > Stage 2 best practice AC for data accuracy.	Number: At least 5. Duration: At least 12 months. Continuous single campaign. Availability KPIs: > meet Stage 3 AC.

Note 1: Assumes trial is undertaken against a trusted reference source as defined in IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017.

Appendix 2

Suggested procedure to estimate FLS measurement uncertainties

The purpose of this appendix is to outline the suggested procedure for estimating FLS measurement uncertainties from the available type and unit verification trials. The procedure is consistent with the recommendations given in Section 7.6 of the IEA Wind Expert Group Report on Recommended Practices for Floating LiDAR Systems[19] and in line with the IEC Standard for Power Performance Measurements of Electricity Producing Wind Turbines[20] approach to derive uncertainties of Remote Sensing Device (RSD) measurements.

For the specific application of an FLS (in the context of this document: WRA), the associated uncertainties of the measured and processed data are made up of the following components:

- A calibration/verification uncertainty that is derived from the results of a (relevant) unit verification trial – cf. RP 105 of the reference above[2],
- A classification uncertainty that is derived from the system classification defined on the basis of (ideally) a number of type verification trials – cf. RP 106 of the reference above[2],
- A mounting uncertainty that is considered to be negligible for an FLS or hidden by the sensitivity to sea motions and therefore covered already by the classification uncertainty, respectively,
- A further uncertainty related to terrain non-homogeneities that again is considered to be negligible or very small for most offshore sites.

Previous studies have shown that an FLS calibration uncertainty is typically dominated by the uncertainty of the used reference, in most cases an offshore meteorological mast. Observed deviations between FLS and reference become only relevant if they are outside the magnitude of the reference uncertainty. Furthermore, the impact of the distance between FLS and reference (which is typically at least an order of magnitude larger than the distance in onshore lidar trials) needs to be considered carefully.

The mentioned reference documents give guidance on how to evaluate a type classification test for a (floating) lidar system. It is noted that there are three ways to estimate the classification uncertainty for a specific application case: either by considering the FLS sensitivities to relevant environmental conditions based on the observed ranges of conditions, based on assumed ranges (based on solid experience or in terms of a conservative best-guess), or from the class number of the FLS type. From experience, the first option typically gives the least conservative and lowest uncertainty values (but at the cost of a higher effort in monitoring the detailed conditions during the application) and the last option the highest and rather exaggerated estimates.

In case the unit verification is undertaken at the same time (and location) as the application (cf, Scenarios D and G in Table 2.1 in this document), the classification uncertainty is per definition zero.

There are some aspects covered in this document that do not affect the FLS measurement uncertainty per se but rather have an impact on the uncertainty of the final wind resource estimate, one of these is the system and data availability. In this sense, system redundancy may be a desirable feature (cf. Scenarios C and F in Table 2.1) though not reducing the measurement uncertainty of the devices directly.

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[19] IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

[20] IEC 61400-12-1, Ed. 2, 2017.

Appendix 3

Examples of Pre-Deployment Verification Scenarios

Preamble, quoting RP91 in the floating LiDAR recommended practices document ("RPD")[21]:

"A risk-based approach is recommended in determining appropriate pre-deployment verification actions. The purpose of the pre-deployment check for the FLS unit is not to establish that the type is capable of good performance – this has already been examined in the FLS trial or trials. Rather, it is to establish confidence that the specific FLS unit performs as well as the one which was trialled. Table 3 Risk-based approach to pre-deployment verification summarises the risks to the FLS unit under-performing compared to the unit that was trialled. Depending on the maturity of the FLS, the FLS unit specifics (e.g. motion compensation or not, mooring design changed or not) and appetite for uncertainty in the final data, the user should use this table to be guided on which mitigations to perform based on how much the risk is reduced. This table also refers to RP 89 and RP 90 and allows them to be understood in a risk-based context."

It is noted that in the definition above, "trial" specifically refers to the Type Verification trial, whereas the meaning of trial in the table that follows refers also to pre- and post- deployment trials.

Key:

Parameter	Meaning
Stage	Refers to the maturity stage of the FLS Type to which the unit belongs as defined in previous sections of this roadmap.
Deployment conditions	Refers to the environmental conditions experienced at the deployment conditions – notably sea state (e.g. wave period, significant wave height).
FLS System Integration	Refers to the integration of all components into the complete system.
Dynamic Response of Buoy = *f*(Set Up)	Refers to the dynamic response of the buoy due to (known) difference in the set-up; for example moorings, buoyancy, gimbal settings, software differences.
Dynamic Response of Buoy = *f*(Sea State)	Refers to the dynamic response of the buoy due to differing sea states.
Comment on Traceability	Refers to the ability to trace the accuracy of wind measurements (wind speed and direction) back to a trusted reference source to inform uncertainty analysis calculations in the context of wind resource assessment deployments.

[21] IEA Wind, Expert Group Report on Recommended Practices, 18. Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef. https://community.ieawind.org/publications/rp

Risk based scenarios

ID	Stage	FLS Type (RP 90)	Deployment Conditions (See Mitigation 8 in Table 3 in RPD, which is assumed to have been applied)	Risk / Acceptable Mitigation (See Table 3 in RPD)			Comment on Traceability
				FLS System Integration	Dynamic Response of Buoy = f(Set Up)	Dynamic Response of Buoy = f(Sea State)	
S1	2	Not "fixed"	Much more severe (well outside envelope) than experienced in Type Verification.	FLS Verification Test and FLS Performance Sanity Check	FLS Verification Test	Expert assessment of Type B uncertainty, see Note 31.	FLS Verification Test provides traceability to known reference.
S2	2	Not "fixed"	Slightly different (just outside envelope) than experienced in Type Verification.	FLS Verification Test and FLS Performance Sanity Check	FLS Verification Test	Expert assessment that classification can apply. Apply Classification procedure RP 104.	FLS Verification Test provides traceability to known reference.
S3	2	Not "fixed"	Enveloped by Type Verification ranges.	FLS Verification Test and FLS Performance Sanity Check	FLS Verification Test	Apply Classification procedure RP 104.	FLS Verification Test provides traceability to known reference.
S4	2	"Fixed"	Much more severe (well outside envelope) than experienced in Type Verification.	FLS Verification Test and FLS Performance Sanity Check	FLS Verification Test	Expert assessment of Type B uncertainty, see Note 31.	FLS Verification Test provides traceability to known reference.

S5	2	"Fixed"	Slightly different (just outside envelope) than experienced in Type Verification.	FLS Verification Test and FLS Performance Sanity Check	FLS Verification Test	Expert assessment that classification can apply. Apply Classification procedure RP 104.	FLS Verification Test provides traceability to known reference.
S6	2	"Fixed"	Enveloped by Type Verification ranges.	LiDAR Verification Test and FLS Performance Sanity Check	FLS Performance Sanity Check	Apply Classification procedure RP 104, noting that sea state will not be significant.	LiDAR Verification Test provides traceability to known reference. Potential FLS influences are known to be negligible.
S7	3	Not "fixed"	Much more severe (well outside envelope) than experienced in Type Verification.	LiDAR Verification Test and FLS Performance Sanity Check	If the FLS has been modified e.g. to account for differing depth, and the current set-up has not been subject to a prior FLS Verification Test, then an FLS Verification Test is indicated. If an expert assessment indicates that there is negligible risk of a different response, then this is not required. The expert review is likely to recommend Mitigation 8.	Expert assessment of Type B uncertainty, see Note 31.	LiDAR Verification Test provides traceability to known reference, or FLS Verification test if carried out. For the former, potential FLS influences are considered invariant as both set-up and conditions are consistent with many prior Verifications.
S8	3	Not "fixed"	Slightly different (just outside envelope) than experienced in Type Verification.	LiDAR Verification Test and FLS Performance Sanity Check	As for S7.	Expert assessment that classification can apply. Apply Classification procedure RP 104.	As for S7.
S9	3	Not "fixed"	Enveloped by Type Verification ranges.	LiDAR Verification Test and	As for S7.	Apply Classification procedure RP 104.	As for S7.

				FLS Performance Sanity Check			
S10	3	"Fixed"	Much more severe (well outside envelope) than experienced in Type Verification.	LiDAR Verification Test and FLS Performance Sanity Check	As for S7.	Expert assessment of Type B uncertainty, see Note 31.	As for S7.
S11	3	"Fixed"	Slightly different (just outside envelope) than experienced in Type Verification.	LiDAR Verification Test and FLS Performance Sanity Check	As for S7.	Expert assessment that classification can apply. Apply Classification procedure RP 104.	As for S7.
S12	3	"Fixed"	Enveloped by Type Verification ranges.	LiDAR Verification Test and FLS Performance Sanity Check	As for S7.	Apply Classification procedure RP 104.	LiDAR Verification Test provides traceability to known reference. Potential FLS influences are known to be negligible.