Recommendations on potential standards changes for distributed wind: driving research via IEA Task 41

Mark Kelly, Ian Baring-Gould, and Trudy Forsyth

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By
Mark Kelly [DTU], Ian Baring-Gould [NREL], and Trudy Forsyth [NREL]

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Preface

This report acts as deliverable 1.1 in the Danish part of the IEA Task 41 on distributed wind. Much of it is based on two sources. The first was a document headed by Ian Baring-Gould of NREL (National Renewable Energy Laboratory, USA), entitled *Updating Domestic and International Standards for Distributed Wind Technology*, where 'domestic' refers to the USA's standards. A second 'distributed source' is the collected output and summary of 2019 workshops and industry/Task 41-participant expertise, cast as a 'catalog' of research priorities circulated within the IEA Wind Task. Mark Runacres helped to bring results on turbulence from Task 27 into these documents. Additional basis is found in Task 41 interactions and comparison with academic and industry views concerning the subject (including differences from work and references such as the previous Task 27), tempered by the professional experience of the author in topics connected with this subject and in creation of the emerging IEC 61400-15 standard.

Hvalsø, Denmark, March 2021

Mark Kelly
Assoc. Prof., DTU Wind Energy

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Summary

Aiming towards recommendation of updates to the standards that concern distributed wind systems, this report addresses ‘small’ wind turbines and associated technology, as well as larger turbines not covered by either the small wind or ‘large’ industrial standards. Via previous and ongoing discussions within the International Energy Agency’s Wind Technical Collaboration Program (IEA Wind TCP) and the current task (IEA Task 41), the need for such updates have been identified. Areas of research to support such updates are outlined, based on the joint experiences and interactions between Task 41 members and industry in IEA workshops. Beyond understanding issues with the existing standard, research is needed to document problems and concerns, and justify potential revisions. In the past, targeted research under the IEA Wind TCP produced results for experts to consider when (re-)writing standards, such as the previous (second) revision of the IEC 61400-2 on small wind turbines; here Task 41 also aims to do so. Finally, potential updates are given, as planned for deliverable 1.1 in the (EUDP funded part of the) IEA Task 41 project.

1. Introduction

The purpose of this report is to recommend potential updates to the standards that concern distributed wind systems; thus it is primarily concerned with 'small' wind turbines and associated technology. Through extensive discussions with industry, including North American and European workshops dedicated to this subject, members of Task 41 ("Enabling Wind to Contribute to a Distributed Energy Future") within the International Energy Agency's Wind Technical Collaboration Program (IEA Wind TCP) have established the need for such updates. That is, together they have noted that design and testing standards for distributed wind are a both barrier to development and innovation, as well as ultimately increasing the cost of energy for distributed (small) wind technologies. Here we identify the relevant standards and suggest updates. This document also outlines areas of research to support such updates, noting the priority of each area according to the experience and interactions between Task 41 members and industry in the targeted workshops under the current IEA project. Beyond initial understanding of key concerns with the existing standard, research is needed to (better) document problems and concerns, and to justify potential revisions. Additionally, it is important to get broad buy-in for proposed changes, promoting strong international effort to bring in stakeholders from around the world. In the past, targeted research under the IEA Wind TCP produced results for experts to consider when (re-)writing standards, such as the previous (second) revision of the IEC 61400-2 on small wind turbines; here Task 41 also aims to do so.

2. Standards for Distributed Wind: technical challenges and gaps

2.1 Background: standards, distributed wind, and small wind

To start, some context about distributed wind (DW), and standards applicable to it, should be given. Distributed wind can include micro-turbines, small turbines, and 'medium-sized' wind turbines; these are not necessarily limited to horizontal-axis types, particularly for the smallest devices. Within the United States, DW can also include large wind turbines installed in distributed applications, typically connected to distribution-level electrical infrastructure. The rated power of such turbines is basically smaller than what is covered by the standard for commercial turbines, the International Electrotechnical Commission (IEC) standard 61400-1. A related standard, the IEC 61400-2 entitled *Small Wind Turbines*, tends to be the primary reference for small wind turbines with a rotor-swept area of below 200 m^2. However, classifying what is "small" has itself been a challenge for distributed wind, as well as the treatment of turbine styles other than common horizontal-axis machines. Aside from the IEC 61400-2 standard, IEC 61400-13 (on loads measurements) has relevance, but like the 61400-1 it is intended for large turbines with rotor-swept areas exceeding 200 m^2 and has not yet been adapted for distributed wind. Conformity testing and certification had previously been covered by the IEC 61400-22, but this standard has since been rescinded. An IEC renewable-energy

(IECRE) stakeholder group (SG 554[1]) has been established to address conformity assessment for small wind turbines, with an official operational document (OD) expected to be released this year; a similar document (OD-501) has been released for large turbines. There is also a normative section in 61400-12-1 (annex H) for power-performance testing of small turbines, which may need to be modified. Due to differences internationally in priorities and rate of development, there are several relevant national standards in the United States which could also be relevant here: namely the American Wind Energy Association's 2009 reference guidance (AWEA 9.1) and the forthcoming update by the American Clean Power association[2] (ACP SWT-1), driven by the Distributed Wind Energy Association (DWEA) in the US.

Towards understanding the challenges being faced relating to the standards relevant to distributed wind, two international gatherings were held in 2019. The first was a half-day meeting held in conjunction with the DWEA business conference, in February 2019 near Washington, DC. This meeting included companies from across North America and focused on the U.S. standards (SWT-1 and AWEA 9.1). The challenges identified were the basis of much of the discussion within the International Standards Assessment Forum held in Dundalk, Ireland in June 2019. The latter was organized under the auspices of IEA Wind TCP Task 41 and included representation from Austria, Denmark, Germany, Ireland, Korea, Spain, and Taiwan. The European meeting was longer, lasting several days, and included more detailed conversations about specific issues relating to the 61400-2 standard. A third virtual meeting was held in the Fall of 2020 to gather further insight into the primary challenges identified by the previous discussions.

The primary goal of these meetings was to find the sections of the IEC 61400-2 standard which most need updating and areas in which near-term research results could be added, as well as to identify and prioritize future research efforts within IEA Wind TCP Task 41. To further broaden industry engagement and support of this effort, an Asia International Standards Assessment Forum was scheduled for 2020 in China[3], but postponed due to the Covid-19 pandemic.

2.2 Issues identified in the IEC standards concerning small wind

Based on the 2019 and 2020 meetings, ongoing discussions in Task 41 and review of the standards, we list the key aspects of the IEC standards which need to be addressed for small wind. These are presented in the table (and subsection) below. The table includes a column listing the importance of the issue (research priority, with 'H' denoting high, 'M' denoting medium, and 'L' denoting low), a column showing which standard is concerned (61400-2 is denoted by '*-2*', and so on, with IECRE subgroup 554 as *'SG 554'*), and a column indicating whether the issues arose at the North American or European forums (denoted by '*Am'* and '*Eu*'). A sub-subsection about each challenge, with explanations, follows below the table.

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[1] The IECRE SG 554 can be found at https://www.iecre.org/dyn/www/f?p=110:6:3386602070542::::P6_ORG_ID:26145 .

[2] The AWEA has merged with other American renewable energy trade groups to become the American Clean Power (ACP) association.

[3]The Asian standards forum was scheduled to be hosted by the Inner-Mongolia Technical University of China.

Key Technical Challenges and Gaps	Priority	Standard	Forum
Size limits / classifications are inappropriate or prohibitive	H	-2	Eu,Am
Certification and testing requirements	H	SG 554	Eu,Am
Conformity assessment is inadequate	H/M	SG 554	Eu
Validated aeroelastic modelling is lacking	H	-13 (-2)	Eu,Am
Loads testing and characterization	H	-13	Eu,Am
Turbulence prescription, characterization, and classes	H/M/L	-2	Eu,Am
Performance and conditions	M	-2	Eu
Tower dynamics/interaction	M	-2, -13	Eu
Limitations/applicability of simplified loads model (SLM)	M/L	-13 (-2)	Eu,Am
Blade testing	M/L	-23	(Am)
Acoustic/noise testing	L	(-11-2)	Eu
Safety and function testing	L	-2	(Am)

Table 1. Key technical challenges and knowledge gaps identified for distributed wind.

2.2.1 Size limits / classifications are inappropriate or prohibitive

The 61400-2 standard explicitly states that it does not cover so-called ‘medium’ sized turbines, i.e. those with rotor areas A_{rotor} greater than 200 m^2 (~55 kW given the specific power of small turbines on the market in 2020). Rotor area was originally selected by international industry as the key metric because of the common perception of it having relatively clear relationship with wind energy generation. However, rated power encompasses many variables and interpretations, making comparisons difficult; swept area has the drawback that for turbines with progressively lower specific power, the rated power of the turbines covered within the 200 m^2 limit under the 61400-2 certification are expected to continue to drop as turbine rotors continue to expand.[4] In general, size limits should cluster similar wind turbine characteristics in terms of control, RPM, electrical output, and market application. Turbines of vastly different sizes have quite different operational and design characteristics. From a design perspective, a dramatic change occurs around roughly ~3 kW. Above this power comes the ability to include more robust and reliable control methods in the design; some of these (such as stall) may yet be passive. Further, it may not be reasonably appropriate for ‘microturbines,’ with A_{rotor} <~5 m^2 (~2 kW), to undergo a full set of certifications to the 61400-2 standard—considering also that they have different design and market drivers as compared to larger wind turbines.

On the larger end, the 200 m^2 limit is merely an artifact of a study preceding—and used to justify—the current 64100-2 (edition 2), explicitly constraining its scope to below this rotor size. However, turbines larger than this (which share similar design principles) do exist, but fall under the 64100-1; the latter is significantly more expensive to implement. Italy and the United Kingdom had incentive policies for turbines up to 200 kW and 500 kW respectively, whereas the 200 m^2 limit corresponds to roughly 55 kW given the specific power of turbines currently on the

[4] In the previous version of the 61400-2 a rotor-swept area of 200 m^2 corresponded roughly to 65 kW; now this is approaching 50 kW, and will likely reduce further towards 30 kW in the coming years.

market. Turbines of such size have the same certification requirements as multi-MW scale turbines under the current standards, thus increasing the effective cost of their development and hindering entry into the wind turbine market.

On the small end, microturbines have little active control, relying on passive control and simple approaches. Wind turbines in this size category may produce AC or DC output, typically controlled by inverters if a permanent magnet alternator is used. Loads design methods include the simplified loads model (SLM), which uses high safety factors to overcome a relatively weak technical approach and lack of computer simulation models. China is the dominant manufacturer of microturbines, selling to the global market for rural battery-charging applications that are often part of hybrid systems. Manufacturers of microturbines focus on repeatable manufacturing, in an attempt to drive profit margin by high volume; thus the lifetimes, failure rates, and replacement costs of such turbines is markedly different than for the relatively larger 'small' turbines considered by the 61400-2. But with few exceptions, microturbines in 2021 must meet the same requirements[5] as those having A_{rotor} up to 200 m^2.

2.2.2 Certification and testing requirements

Overall, the process of testing and reporting has been seen to take up to 1–2 years (Whale *et al.*, 2013), particularly when duration testing is involved. Technical rigor and costs have yet not been scaled, relative to the size (or cost) of turbines. Micro- to medium-sized turbines are subjected to the same rules according to the 61400-2, despite differing operational and lifetime expectations. These differences are not yet reflected in the testing requirements, nor certification. This hinders development and market entry for microturbines, as noted for at least a decade (Sharman, 2010); however, global markets for microturbines are expanding, and manufacturers (and the market more generally) would benefit from global markets requiring certified microturbines. China may be seen to be moving somewhat in this area, with a set of 16 non-mandatory national standards for voluntary product certification, along with 23 industrial standards that also serve as guidelines and facilitate evaluation of manufacturing procedures (Wu *et al.*, 2019); these Chinese national standards on small wind turbines refer to the IEC, and may develop further.

A major issue involves updating *duration tests*, which were originally intended to address early failures and identify potential issues that are not apparent in simplified loads calculations. They also serve to verify designed/rated production based on samples of actual turbine operation over all expected conditions; they were not meant to cover specific loads testing and requirements. As Sharman (2010) noted: loads measurements are expensive and time consuming, with analysis of these being a costly specialized task; the small wind turbine community substituted a lengthy duration test (and simplified load calculations) as an alternative method to ensure a turbine would remain in safe operation, for cases where a manufacturer chose to avoid loads measurements as a route to certification. According to the 64100-2 duration tests require at least of 6 months (minimum 2,500 hours) of operation, including numerous hours of high-wind conditions and 90% reliable operation. The 61400-2 tests also

[5]Some simplifications from micro-turbines exist in the new ACPA (SWT-1) standard.

demand no significant wear, damage, or failure of components (based on operation and a post-test inspection), and no significant degradation in power production.[6]

2.2.3 Inadequate conformity assessment

Conformity assessment gives a common approach to wind turbine certification. It outlines the methods, procedures, and protocols for both certifying and reporting of certification results; further, it also identifies what is needed to update existing turbine certifications when there are design changes. But, as mentioned above, there is not a clear method to do (and report) this—both for 'medium' turbines with sizes beyond the 61400-2 limits, as well as for microturbines which have vastly different characteristics and usage cases. Further, definitions are somewhat lacking beyond horizontal-axis wind turbines (HAWTs); in addition to vertical-axis turbines (VAWTs) needing a certification protocol (Wu *et al.*, 2019), there are a wide variety of microturbine designs which also lack any unified methodology.

2.2.4 Validated aeroelastic modelling is lacking

Aeroelastic simulation modeling capabilities have helped wind turbine designers for all size turbines. Validated aeroelastic modeling is the most accurate method of understanding design loads, dynamics, and structural strength, but is not easy to develop (or potentially afford). The U.S. distributed wind industry has clearly indicated that all major manufacturers are now using and will continue to use aeroelastic models in turbine design if they remain available at a low cost, particularly for turbines producing more that ~3 kW.

A major challenge is the lack of refinement in aeroelastic models for smaller turbines (e.g., FAST in N. America) to reflect the needs of modern distributed wind turbine designs. A clear and documented methodology is needed that will allow aeroelastic models to be validated and meet IEC 61400-13 (and potentially 61400-2) requirements. A much larger variety of designs exists for small wind turbines, compared with larger turbines (typically three-bladed, upwind, actively yawed and pitched) commonly found in the market, which changes or complicates the modeling needed. Small, distributed wind turbines on the market have a number of different archetypes, with deviations from common large turbines including downwind rotors, active or passive yawing, and stall-regulated control; these simple examples do not even address turbine forms such as vertical-axis, ducted, or other more unique turbine designs. Aeroelastic models of directly coupled generators (a common Danish design) are needed, especially for fatigue loads on the drivetrain components. Turbine-specific models need validation from wind turbine measurements under operation.

2.2.5 Loads testing and characterization

The IEC 61400-2 requires compliance with IEC 61400-13, the loads testing standard. This very

[6]We note that there is no "pass/fail" criteria with these qualitative demands regarding the duration testing, with observations from post-test inspection noted in the duration test report.

detailed standard has been difficult to meet for manufacturers of smaller turbines, as it is also covers larger turbines that must meet 61400-1. Essentially the same requirements exist for a 3 MW onshore wind turbine and a small 3 kW distributed wind turbine. The value of loads testing lies chiefly in validation of aeroelastic models; when validated, the latter can be used as a tool to not only enable certification, but to also consider design changes.

The dominant issue with mechanical loads testing is the costs: these arise from a combination of the required instrumentation, data acquisition system, required expertise (often external personnel need to be contracted), and the amount of time needed to collect sufficient data. For smaller turbines the costs can increase yet further in a relative sense because they are harder to instrument, particularly due to the need for instrumentation with a smaller form factor.

Though it is possible that parts of the 61400-13 may be appropriate for (some) medium and perhaps small wind turbines, other parts may not apply; the parts that are applicable might also change from one turbine style/design to another. Microturbines are even less likely to be covered appropriately by the 61400-13, which is "*intended for onshore electricity-generating, horizontal-axis wind turbines (HAWTs) with rotor swept areas of larger than 200 m^2*"; we note that the 61400-13 does include an annex on vertical-axis wind turbines (VAWTs).

2.2.6 Turbulence prescription, characterization, and classes

Regarding turbulence, many of the current requirements found in the design classification and normal turbulence model of the 61400-2 do not reflect the commercial reality that micro- and small wind turbines are installed in locations that have high turbulence intensity. The latter is due to the limited hub heights of such turbines, and their installation near buildings and other obstacles which enhance turbulence. Preliminary research conducted under IEA Task 27 indicated that modifying the current standard design classes, using a different turbulence intensity range, would more accurately reflect consumer sites.

Further, turbulent velocity spectra tend to be modified by the landscape, particularly closer to the surface, as well as by obstacles. If the effective surface roughness of local terrain is high (e.g., urban, hilly, with high trees, buildings/built structures), the turbulence intensity of air flow increases. Such surfaces tend to generate turbulence with dominant sizes of the order of the characteristic scales of the structures themselves, increasing kinetic energy around the corresponding wavenumber—and thus frequency, depending on the wind speed (via Taylor's hypothesis). Depending on the blade size and construction, this shift in turbulent kinetic energy (from low frequencies corresponding to the atmospheric boundary-layer depth to higher frequencies) can have a detrimental effect on blade fatigue loads. Frequent occurrence of significantly unstable conditions (such as urban installations over asphalt/roofs), where the stability distribution deviates from universal forms (Kelly & Gryning, 2010), can lead to both larger turbulence length scales as well as stronger turbulence. Higher turbulence-induced loads, in aggregate (more frequent strong loads due to high turbulence intensity) typically shorten turbine lifetimes. Based on measurements from numerous country sites in an effort led by researchers in Belgium and Poland, a basis for a new wind class and Normal Turbulence Model adjustment were presented via IEA Task 27 (Forsyth & Baranowski, 2018).

Microturbines can also react differently to variations in characteristic turbulence length scales, depending on their size and topology. For example, a 'micro' blade that is 1 m long will 'see' 10 m wide turbulent eddies simply as varying wind speed, while a turbine with 400 m^2 area will sometimes experience them as high shear across the rotor. Thus, design sub-classes addressing turbulence for microturbines should also be considered.

2.2.7 Performance and conditions

The flow experienced by distributed wind turbines—particularly ones closer to terrain and obstacles—tends to be not only more turbulent than the flows experienced by large turbines that follow 61400-1, but also has other different key characteristics. First, the flow can have a significant vertical velocity component due to nearby obstructions (and to a lesser extent unstable stratification, as on sunny days); this can increase fatigue loads depending on the turbine design topology (e.g. VAWTs being affected differently than classic HAWT designs), the blade lengths, and the control system. Secondly, the flow can have radically different shear compared to the current IEC 61400-2 (and 61400-1) prescriptions, as also seen previously in IEA Task 27. The shear and its distribution[7] can vary widely according to wind direction, and also fluctuate significantly in time for a given wind direction due to obstacle-related turbulence.

Power performance test methods are well understood, and the IEC 61400-12-1 (Annex H) documents special requirements for small wind turbines. However, the highly variable and more turbulent inflow conditions which can occur for distributed wind, such as described above, lead to issues with both performance and loads. Power performance results are rarely matched at consumer sites, leading the public to believe that "small wind doesn't work." Strong turbulence and coherent motions lead to increased fatigue and failure as well (e.g. Kelley, 2011)[8], further affecting the (perceived) reliability of small wind.

2.2.8 Tower dynamics/interaction

Tower dynamics are not well addressed in IEC 61400-2, leaving turbine systems vulnerable to motions and system dynamics arising from the tower. This is generally a larger problem for smaller and microturbines, having less than ~50 m^2 swept rotor area, as small wind turbines have resonances that are likely to occur within the tower-rotor system. This is a result of the natural frequency of these structures (towers several meters high with a nacelle/rotor mass on top) often falling in the critical frequency range matched by the rotor at high wind speeds.

2.2.9 Limitations/applicability of simplified loads model (SLM)

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[7] The distribution of shear or shear exponent can also vary widely with height, as well as wind speed, such that a mean value may no longer suffice (e.g. Kelly *et al.*, 2014).

[8]Reviewing data from turbines at two sites, PDFs of root flap-wise blade damage equivalent loads and peak loads were compared to all velocity components, per stability. The results demonstrated the importance of coherent eddy structures in simulations of inflow to small wind turbines, including wave-induced structures ones caused by stable conditions (and the associated signature of vertical velocity variance in the latter).

The SLM was developed in the second (2006) edition of the IEC 61400-2. This method replaced the expensive requirement of aeroelastic simulations, with simpler equations and high safety factors. Based on a comparison of turbine measurements and aeroelastic models, it identified areas that needed high(er) safety factors, in order to be conservative. The current (edition 3) safety factors are quite high, which increases turbine cost due to 'overbuilding' according to such conservative estimates, and reduces how marketable wind turbines are compared to other distributed energy technologies. It has thus led many manufacturers of small to medium turbines to return to using aeroelastic models, as measured loads data are becoming more common; aeroelastic model use also allows further turbine system optimization, and is seen as being valuable for other reasons.

While safety factors tend to change over time and become less conservative as more knowledge is applied to standards, there has not yet been a focused effort towards their refinement within the SLM for small wind.

Since past international standards committees have had limited engagement from vertical-axis wind turbine experts, there is no SLM for vertical-axis wind turbines. Similarly, the SLM has not been generalized for different topologies which arise in micro-scale turbines.

2.2.10 Blade testing

Anecdotally, industry members have seen blade failures that could have been identified during the design cycle and component testing. In particular, small and micro turbines typically operate at higher rotation rates (RPM) than large wind turbines, which leads to centrifugal stiffening. Yet no blade tests have been developed to test this phenomenon, nor does the IEC 61400-23 (2014) does not address such issues with small turbine blades.

2.2.11 Acoustic/noise testing

Small wind turbines often produce audible sound, which can impact the market. Annex F of the IEC 61400-11 standard (*acoustic noise measurement techniques for wind turbines*) addresses small wind turbines, stating that it is "*appropriate to ease the demands on the noise measurement*"; however, it only applies to turbines below 100 kW, and also requires tonality testing that may not be informative for distributed wind turbine consumers. The tonal audibility portion of 61400-11 Annex (F) is an issue because the data processing is somewhat laborious, and the added value is questionable.

2.2.12 Safety and function testing

Though mentioned as a low priority in the Task 41 workshops, safety testing safety systems are key to development of safe turbines. This needs to be adapted for different turbine topologies, though it is not yet outlined for all configurations (e.g. microturbines); it also supports the duration test. It has not been documented whether simple RPM and power control are sufficient for microturbine function testing, though this is the current baseline requirement.

2.3 Research needed to support adjustment of standards, for small and distributed wind turbines

Standards are developed based on the scientific understanding of experts within the applicable fields in question. Although not everything within a specific standard needs to be backed by rigorous research and some educated judgement is required, it is important that to the extent possible, proposed changes or additions to existing standards are backed by such research. Given the challenges identified in the previous section, this section outlines research efforts that would help elucidate understanding to help improve the appropriate standards for small and distributed turbines during the next revision to 61400-2 or to be incorporated into appropriate national standards.

2.3.1 Expansion and adjustment of size, types and classes; conformity assessment

Technical justification is needed to determine and/or adjust turbine size thresholds and classes. Research to support this includes:

- Collecting detailed measurements (starting with speed, power, rotation rate, turbulence intensity) on more wind turbines with areas <~5 m^2 and >200 m^2;
    - secondarily, including (micro) turbines with different topologies.
- Conducting parametric studies, across turbine types and sizes, to inform power (size) limits.
- Surveying lifetimes and failure rates of different microturbine topologies. This includes both expected and measured statistics, as well as consideration of operation in different conditions, particularly turbulence. It also includes manufacturing aspects and variability, especially for very small turbines which are installed near each other or surfaces such as rooftops/edges.

Conformity assessment (CA) is also a key issue, as described in section 2.2.3, that is connected to research of turbine classes as well; it is not limited to addressing changes to turbine designs, but more importantly provides a common approach to certification, helping to stabilize the global market. Research needed towards CA of new classes is addressed by the above points, elucidating differences in key failure paths between different topologies and sizes. This should be done both for microturbines and turbines larger than 200 m^2, with the latter being compared to large 61400-1 turbines (as well as formerly 'large' turbines from previous decades of comparable topology, where applicable). Additionally, because their design drivers may be different, further investigation likely involves assessing the microturbine market(s) and dominant end-use cases, identifying potential sub-classes for microturbines.

The result of this work would be a scientific basis to update turbine size thresholds within the given standards, most specifically 61400-2 or other applicable referenced standards. Additionally, if different operational conditions are driving the expansion of the microturbine market, specific standards may need to be further defined and developed.

2.3.2 Scaling and update of certification and testing requirements

In addition to updating turbine sizes and classes, research is also needed the support the determination of specific requirements for these classes. In addition to the points of section 2.3.1 above, this would include, for example an evaluation of ‘how much’ duration testing is statistically relevant for microturbines, along with identification/verification of key metrics per different turbine topology.

For small turbines (roughly from 1–2 up to 10–15 kW), investigation and validation of less complex aeroelastic models (addressed in the following section) and simplified or targeted duration tests—as has been proposed in the new U.S. small wind turbine standard—can facilitate reduction of duration-test requirements for this turbine class; this should be done at multiple sites with different conditions.

For medium turbines, particularly larger than the current threshold of ~200 m^2, several things can be examined. For example, determining the reasonable upper limit of using validated aeroelastic models for HAWT conformity, and investigation of turbulence and loads with increasing turbine size.

2.3.3 Aeroelastic models and their validation

To facilitate the updated classification scheme discussed above there is a need to identify and document general measurement needs for key aeroelastic model inputs, as well as specific inputs needed for different turbine configurations—and for different turbine size/power classes. Further, a clearly documented methodology for validating aeroelastic models is needed that will allow such models to meet the 61400-13 requirements, for at least the most common configurations of distributed wind turbines. The measurement needs, model inputs, and validation methodology need to be linked and made consistent with the output of the joint workgroup between IECRE/IEC TC 88 regarding the validation process. This workgroup is expected to issue a document describing this process in 2021.

For medium turbines (particularly the larger ones beyond the previous 61400-2 limit), further research is needed to understand the extent to which aeroelastic models can be used without loads data validation. From detailed measurement data on wind turbines above 200 m^2 swept area (of different topologies), develop or adapt aeroelastic models (e.g. from larger or similar turbines) and compare results for each design load case, evaluating accuracy of loads predictions.

2.3.4 Loads testing and characterization

The 61400-13 states that its “*methods described may be applicable to other wind turbines (for example, "small wind turbines, ducted wind turbines, vertical axis wind turbines)*.” But the degree to which this is the case needs to be researched, as a function of size, control system family, and design topology/general configuration. In order to simplify the process of using aeroelastic models, a methodology needs to be developed to streamline the IEC 61400-13 measurement requirements specifically to smaller wind turbines. Research is needed to find the extent to which power curves can be used to reduce loads test requirements for medium turbines (larger than ~50–200 m^2), as well as how much the loads testing can be simplified compared to the 61400-13. Additional investigation includes reduction of requirements for yaw and pitch control, which are still common control processes used for small and medium scale wind turbines.

2.3.5 Turbulence prescription, characterization, and classes

Validation of a new high-turbulence class, previously proposed under the IEA Task 27 research for small turbines, would provide a more solid technical backbone for future standards-making efforts. Refining the Normal Turbulence Model (NTM) in the 61400-2 has also been identified as a potential step; this can be done based on comparison of past and current modelling as well as in situ observations, including wind tunnel observations for microturbines small enough to neglect unscalable atmospheric phenomena. Towards these ends and to allow assessment regarding the need for improved standards in this area, more research is needed; this is outlined via the list below.

- Re-examine the NTM comparing with 3D velocity (e.g. sonic anemometer) measurements at various *representative* sites affected by obstacles and/or terrain at heights common for distributed wind turbines.
- Determining what is '*representative*' is itself non-trivial: it requires synthesis/connection of different results, research, and theory on turbulent atmospheric flow as affected by obstacles.
- Evaluate select wind turbines (particularly medium size) using multiple aeroelastic codes (TurbSim, FAST, HAWC2, etc.) for fatigue damage calculations, with both NTM input and synthesized (modelled) turbulence driven by observational statistics.
- Comparing loads (observed and/or modelled) for turbulence spectra having different peak length scales (frequencies) as found in operational conditions, across turbine classes/sizes. I.e., finding key differences and turbulence metrics for input to both aeroelastic simulations (medium/small turbines) and simplified loads modelling (for small/micro turbines).
- Document the results of tests and modeling (such as the above).
- Validating preliminary results with more datasets.

2.3.6 Performance and conditions

The flow experienced by distributed wind—especially in the proximity of obstacles and/or terrain whose heights (vertical variations) are comparable to the turbines' hub heights—can be quite turbulent and non-uniform, as described in section 2.2.7 above. The breakdown of similitude, due to turbulent stability-influenced atmospheric flow, can limit the applicability of wind tunnel testing, particularly for larger turbines (but here including the proposed 'medium' size class). Simplified engineering models are available for treatment of the wind speed deficits caused by obstacles, as reviewed and updated in IEA Wind Task 27, though they require more validation over different sites and conditions. Further, such engineering models for turbulence and shear are not readily available (or perhaps possible for some applications); CFD models, such as the

RANS codes commonly used for large wind, tend to be too expensive for distributed wind use. However, continued research can help here, such as using RANS to update and inform engineering models to describe approximate mean flow conditions and their variability.

The performance of small and medium HAWTs, of varying sizes, also needs to be investigated in variable conditions at multiple sites, as affected by obstacles (and terrain) in different configurations. Such performance assessments need to be accompanied by three-dimensional turbulent velocity measurements in situ, with at least one 3D sonic anemometer at a representative location. For microturbines, similar studies need to be undertaken, but may be further facilitated by the ability to switch anemometry between the turbine(s) with measurement devices (using pairs of anemometers), to allow better characterization of inflow. Further, for some microturbines the mounting may be varied in order to change the conditions experienced, such as inflow angle. At any rate, the power curves of DW turbines need to be further researched in different conditions, coordinated with appropriate corresponding anemometry. This information could then be compared to the output of aeroelastic models to gain a better understanding of the likely loading of the different potential configurations of small to mid-scale distributed wind turbines in turbulent environments. Such analysis facilitates finding the extent to which current aeroelastic models capture the potential loading impact of turbulent flow, but also allows optimized turbine design, given a more accurate representation of true operating conditions.

2.3.7 Tower dynamics/interaction

Preliminary results from IEA Wind Task 27 work involving towers, led by researchers at the University of Applied Sciences in Vienna (UAS Technikum Wien), resulted in recommendation of the following approaches in order to reduce the risk of fatigue failure:

- Small wind turbine tower systems should be designed in a way that guarantees an overcritical mode of operation within the range of 70% to full rated power when the stimulated forces are relatively high. What is ‘high’ needs to be refined by research, for different turbine types and control systems.
- Small wind turbine tower systems should be designed to have as high a structural damping factor as possible; factors between 10% and 20% are desirable. To increase the structural damping and reduce natural frequencies, damping or decoupling elements may be used.

These approaches need to be validated, and lead to more research needs, which include:

- Performing modal tests of tower systems to identify structural damping factors for different tower sizes and types, also with different turbines;
- Developing a (simplified) method to model tower dynamics accurately for free-yaw turbines with tower resonance.

2.3.8 Limitations/applicability of the Simplified Loads Model (SLM)

If most small turbine manufacturers are moving to the use of aeroelastic models, the SLM could be revised to focus only on smaller turbines, below some threshold (on the order of ~1–10 kW, as mentioned in previous sections). Additionally, different modelling load cases and safety factor recommendations should be developed and documented. This includes the following investigation topics:

- Conduct a parametric study on the use of the “300 N·m method” (used in Denmark for quick assessment of structural strength).
- Develop a fatigue load case that addresses gyroscopic loads, based on turbulence intensity as an input. This would include yaw bearing (passive yaw), yaw error (active yaw), power production and fault, normal shutdown, parked (low cycle/high fatigue), as well as different fatigue thresholds for on and off-grid turbines.
- Develop a specific set of SLM parameters for downwind-rotor turbines.
- Reduce or eliminate SLM load cases, if they do not impact design.
- Develop new assumptions for yaw rate that more accurately reflect measurement data.
- Investigate the upper size limit and conditions for usage of the SLM.

2.3.9 Blade Testing

For small and micro-turbines, whose blades typically rotate with angular velocities higher than those for large wind turbines, blade tests need to be developed to test high-RPM effects such as centrifugal stiffening. Further, if the safety factor for blades could be reduced by blade fatigue testing, the result should be a technically viable lighter turbine. Research on a new testing regime could address this challenge. It includes development of a full-rotor testing method for micro turbines; establishing a strategy for reduction of safety factors based on blade (fatigue) testing; reviewing extant blade fatigue test results; investigation of why some blades fail in practice but not during tests; creation of an approach to centrifugal testing.

2.3.10 Acoustic/noise testing

Investigate and document technical rationale for lack of value added by determination of tonal audibility according to Annex F of the IEC 61400-11 standard. The development of a simplified acoustic assessment method is also needed for smaller turbines. Lastly, the methodology should be assessed for applicability to VAWT technology.

2.3.11 Safety and function testing

This aligns and supports the duration test, tailored for different turbine configurations. Dozens of small and mid-scale turbines have gone through safety and function testing since the last revision of the IEC 61400-2 standard. Analysis of the datasets available from these tests permits improved recommendations. To better understand if current safety and function tests can be refined, the following actions are required:

- document technical rationale based on measurements as to why only RPM and power control are needed for micro wind turbines;
- review multiple datasets to find patterns and trends, later identifying any needed changes to the safety and function test.

Further, the metric of *peak power* for turbine classification needs to be further investigated, in comparison with rotor/swept area. While the latter tends to be more indicative of loads-related issues, it might not be as useful as peak power ratings, especially considering an additional turbulence class.

3. Recommendations to improve standards for DW

Above we have documented gaps, limitations, and challenges in the standards associated with distributed wind energy, as well as the research needed to address such—particularly focused around wind turbines smaller than those covered by the IEC 61400-1 standard. To provide a starting point for dialog, recommendations are suggested below to improve the standards for distributed wind technology. These recommendations are (thus far) focused on turbine testing and classification as well as operational conditions, without consideration of electrical or grid-related aspects. Electrical requirements for distributed scale wind technology are being considered separately.

3.1 Update the turbine classifications to fairly address different sizes and types.

As discussed, the current size threshold of 200 m^2 rotor swept area—and standards assuming that all turbines under this size should be considered equally—has hindered innovation within the distributed wind industry. As was recently demonstrated by the adoption of the new American SWT-1 standard for small wind turbines, even the use of rotor swept area may not be the best metric for classification.

An initial recommendation would be to adopt a new classification for microturbines, with a rotor area less than 5 m^2 or power not exceeding several (crudely, 1–3) kW. This type can also encompass many different topologies, including turbines designed to interact with and/or benefit from the flow near adjacent turbines or other solid structures. However, more technical justification is needed to determine specific requirements for this turbine class, understanding that the design lifetime of these turbines may be different from larger turbine technologies.

A second recommendation is to add a classification for so-called ‘medium scale’ turbines: these currently fall outside the 61400-2 standard’s limit of 200 m^2 rotor area, but more closely resemble *smaller* turbines as opposed to the (much larger) multi-MW turbines currently covered within 61400-1. This would include turbines having swept areas above 200 m^2 and (potentially) up to 500 m^2. The new SWT-1 American standard identified this upper limit as 150 kW peak power. Such an increase in the effective maximum power (or size) of turbines to be covered by the 61400-2 is largely driven by two factors, the first of which is the expanded use of aeroelastic models. The second factor is the success of the 61400-2 methodology in identifying issues with turbines of similar configurations, which is a cost-effective alternative to the full 61400-1 certification process.

The third recommendation is to implement an intermediate type of turbines, denoted ‘small,’ which covers a range of turbines with rotors larger than microturbines (larger than ~5m^2), but for which a simplified approach to design loads (SLM) would be allowed, as well as less rigorous requirements than the ‘medium’ class. This threshold could fall around 50 m^2, or about 11 kW peak power. The size limits proposed here will likely change based on expanded research, international dialogue, and continued advances by the industry. An additional consideration is that the new American SWT-1 standard added another classification to provide slightly different requirements for turbines between nominally 30 kW peak power and the current 200 m^2 threshold (nominally 65 kW peak). The specification of a different set of requirements for turbines that are not using the SLM, which but still fall below the current size threshold, will require additional international consideration. the use of aeroelastic modelling has become common practice for smaller turbines than in the previous decades.

Table 2 shows the recommended classification updates, along with suggested elements for each, starting from the current 61400-2 standard.

Rotor swept area Nominal power	Micro < 5 m^2 < 2 kW	Small 5-50 m^2 2 – 11 kW	Medium 50-500 m^2 11-150 kW
PRINCIPAL ELEMENTS AND EXTERNAL CONDITIONS			
Streamline micro wind requirements	X		
Raise the size limit > 200 m^2 based on aeroelastic model and measurement data			X
Design class requirements	choose one	X	X
Normal Turbulence Model	X	X	X
STRUCTURAL DESIGN			
SLM	Use 300 N·m requirement	X	
Safety factors	investigate	X	
Aeroelastic model	NA	If aeroelastic model used, reduce duration test	Validated aeroelastic model required
Tower dynamics and interactions should be considered.	X	X	
TYPE TESTING			
Duration Testing	Reduced time with strength analyses	In different speed & turbulence ranges	Limited or no requirements
Power Performance	No site calibration, don't test past peak power	No site calibration	Can power curve be used to reduce loads test requirements?
Loads Testing		At a minimum, tower loads testing should be performed	Streamline requirements for aeroelastic model validation

Acoustics Testing	No tonality	No tonality	X
Safety and Function Testing	RPM and power control only	X	[Possibly]
Blade Testing	Fatigue full rotor	Static, if fatigue test reduces safety factor	Fatigue

Table 2. Recommended classification update, with suggested differing aspects per type.

3.2 Change certification and testing requirements, per appropriate turbine classes and types.

In addition to the recommendation of (re-)defining turbine types/classes, as written above, corresponding certifications will need to be adapted for each. For micro wind, it starts with reduced requirements for duration testing: this includes reduced test duration with strength analyses (relative to expected lifetime), not testing beyond peak power, conducting function/safety testing with RPM and power control only, implementing a full-rotor fatigue testing, and ignoring tonality in the noise testing. It is also possible that a mix of voluntary (informative) and mandatory (normative) standards could be merited here; one example is the Chinese (GB/T) guidelines for manufacturing procedures.

For the proposed ‘small’ category spanning roughly 5 to ~50 m^2 or ~2–11 kW, possible updates of testing requirements are to use static blade testing (if fatigue testing implies relatively low uncertainty), and reduction of the duration test where aeroelastic modelling is used; Table 2 shows more elements for this category.

For ‘medium’ turbines (rotor areas > 50 m^2), particularly larger than 200 m^2, the requirements for aeroelastic model validation need to be streamlined, i.e. relaxed to fit this turbine class relative to the large turbines covered by the 61400-1. Loads test requirements might also be reduced, depending on pending research regarding use of power curve analysis as an effective supplement (or partial proxy).

3.3 Conformity assessment

Recommendations on are pending, based on the forthcoming operational document from IECRE SG 554. The postponed stakeholder workshop/meeting in China may also motivate further recommendations.

3.4 Validated aeroelastic models

Given the general need to continue to reduce costs for wind technologies through design optimization, the expectation is that turbine manufacturers will continue to shift to using aeroelastic simulation tools that reflect their current designs. Aeroelastic models allow further investigation of expected ranges of inflow conditions, and permit more rapid innovation of turbine designs. Revising aeroelastic codes such as FAST and HAWC, to improve modeling capabilities for a wider range of turbine configurations, is one major path identified. More research and model capability assessments are needed before issuing recommendations, as shown in section 2.3.3 above. The other major path is to establish a clear and documented methodology that will allow aeroelastic models to be validated and meet IEC 61400-13 requirements, or else extend (or replace) the 61400-13 for the limited-size turbines (<~150 kW, <~500 m^2) associated with distributed wind. For either path, model enhancements and validation is likely to be needed, including different turbine configurations.

3.5 Loads testing and characterization

Addition of an annex to the IEC 61400-13, to address specific requirements for small wind, should be considered. But this requires more research as outlined in section 2.3.4—aside from potentially informative options being included, along with suggested reporting.

3.6 Turbulence prescription, characterization, and classes

A new, high-turbulence design class is recommended for distributed wind turbines; a potential candidate, with $I_{10} = 0.36$, has been suggested within the Task 41 group and carried from the earlier IEA Task 27. This is applicable to micro wind turbines, but needs to be investigated further for small turbines; it is not expected to be applicable to medium turbines. The new high-turbulence class will likely be reasonable when used with the normal turbulence model (NTM), though manufacturing turbines which satisfy it may yet be difficult. In Annex L of the 61400-2, one can also see the conditions implied by the new class can still be exceeded in real-world environments.

3.7 Performance and conditions

The IEC 61400-2 standard needs to be extended to accommodate multiple power curves depending on conditions, starting with HAWTs in each of the proposed (updated) design classes. Given the difficulty and cost of site calibration, as well as the research still required, a practical start is to informatively advise DW turbine manufacturers to provide power curves in obstacle-affected conditions, including high turbulence and mis-aligned flow (yaw error). Further, these new power performance reporting requirements need to be harmonized with the IEC 61400-12-1 and any emerging IECRE guidelines.

3.8 Tower dynamics/interaction

Ultimately more research is needed to make a solid recommendation for a normative update to address tower interactions seen with lighter guyed or dynamic free-standing towers. Given the current state of knowledge, an informative supplement to §11.2.3.2 of the IEC 61400-2, perhaps as an annex, can be added to suggest the tower damping recommended. An additional consideration could be reporting of the expected resonances for given tower masses and heights, as outlined above in sub-section 2.3.7.

3.9 Update Simplified Loads Model (SLM)

The SLM needs to be updated and streamlined for small wind turbines to minimize overdesign and overbuilding, which will reduce machine costs. Additionally, because the SLM will only be applied for turbines below approximately 10 kW in size, it should be more focused at these smaller turbine sizes. Vertical-axis wind turbines (VAWTs) also need to be addressed.

3.9.1 Development of SLM cases for VAWTs

An expanded set of SLM cases should be developed for small VAWTs, including a normal operation fatigue case.

3.9.2 Adapt SLM for microturbines

With an expanding array of modern microturbines, SLM cases should be developed for different classes of microturbines considering their expected design use (e.g. remote telecommunications, small recreational boats, remote charging of communications devices). More market clarification and research is needed, but the standard needs to be updated to handle such different structural loading and design lifetime cases. A preliminary proposal is to adopt the simple 300 N·m requirement used in Denmark for quick assessment of structural strength.

3.10 Acoustic/noise testing

Better explanation or simplification of §F.5 in the 61400-11 can be made, to help consumers and manufacturers check tonal audibility.

The forthcoming IEC standard 61400-11-2 (*Measurement of wind turbine noise characteristics in receptor position*) should also be informed by potential distributed wind deployment characteristics.

4. Conclusion

Since the release of the IEC 61400-2 Edition 3.0 in 2013, continued development of distributed-scale wind technology has identified a number of challenges in the implementation and usage of this valuable and industry-accepted standard. Through an international collaboration undertaken under the IEC Wind TCP Task 41, experts have worked with stakeholders to identify global concerns, towards conducting research to facilitate scientifically based revision of the standards.

This document summarizes the key challenges identified to date and gives recommendations for updating the relevant standards, though some recommendations (SLM and conformity assessment) have been reduced due to complications arising during the global pandemic (international travel bans and a cancelled workshop). Suggestions include refining the turbine size classifications in the IEC 61400-2 standard, consideration of different requirements based on turbine size such as those for duration testing, addressing operation in strongly turbulent conditions, and the use of aeroelastic models versus a SLM for turbine certification. Here we also expand upon the challenges identified, also for the purpose of continued dialogue towards research to support updating the standards. In addition to developing an international consensus on these topics, research needed for clarifying many of these issues was identified. The members of Task 41, in collaboration with universities and other international organizations, is spearheading a research effort to help inform potential revisions to the IEC standards relevant for distributed wind energy.

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Witold Skrzypiński, Lead Engineer, Siemens-Gamesa (formerly DTU Wind Energy)
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