Aeroelastic Modeling for Distributed Wind Turbines

March 11, 2021 – November 10, 2021

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1 RRD Engineering
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List of Acronyms

ACP	American Clean Power
ACP2020	American National Standards Institute/American Wind Energy Association Small Wind Turbine meetings
AHSE	aero-hydro-servo-elastic
AIAA	American Institute of Aeronautics and Astronautics
AM	aeroelastic modeling
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
AWE	airborne wind energy
AWEA	American Wind Energy Association
CVA	certification and verification agency
DEL	damage equivalent load
DLC	design load case
DLL	dynamically linked library
DOE	U.S. Department of Energy
DWAMW	Distributed Wind Aeroelastic Modeling Workshop
DWEA	Distributed Wind Energy Association
DWEA0227	DWEA Standards Forum held February 27, 2019
DWT	distributed wind technology
FMEA	failure modes and effects analysis
HAWT	horizontal-axis wind turbine
IEA Wind	International Energy Agency Wind Technology Collaboration Programme
IEA41	IEA Wind Task 41 meeting
IEC	International Electrotechnical Commission
ISA2019	European International Standards Assessment Forum 2019
JSWTA	Japan Small Wind Turbines Association
MLC	measurement load case
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PCMM	predictive maturity of the model
QoI	quantity (or quantities) of interest
RRD	RRD Engineering
ROSCO	Reference OpenSource Controller
RSA	rotor-swept area
SLM	simplified loads methodology
SWT	small wind turbine
TI	turbulence intensity
V&V	verification and validation
VAWT	vertical-axis wind turbine

Executive Summary

Aeroelastic modeling (AM) is the primary methodology for the structural and performance assessment of any wind turbine and provides an understanding of the impact of design parameters on wind turbine loading and power response before witnessing it in the field. Despite these advantages, the use of AM in the distributed wind technology sector is limited, especially by the less established manufacturers.

This project represents an in-depth assessment of the status of AM and its role within the standards for the distributed wind technology industry. The study gathered input and feedback from a large number of national and international stakeholders, reviewed technical strengths and weaknesses of the current edition of the design standards, analyzed the minutes from recent industry workshops and meetings, collected publicly available AM templates, and provided an evaluation of the existing AM codes.

The study achieved several goals, including providing strategies for the loads assessment categorization of wind turbines based on rotor-swept area and archetype, and guidance for AM verification and validation (V&V), which includes discussions of measurement requirements and a sample test plan for future V&V campaigns and design standards development.

This document summarizes the different tasks conducted in the course of the project and highlights the steps required to improve AM adoption based on a multifaceted approach that encompasses (1) augmenting AM software capabilities, (2) publishing AM best practices and design bases, (3) creating new model templates, (4) providing guidance for V&V of codes and specific wind turbine models leveraging field testing best practice, and (5) addressing weaknesses in the current standards. Many of the future objectives identified in this study could leverage the National Renewable Energy Laboratory's upcoming testing campaigns of three modern distributed wind turbines.

Recommendations within this study will advance the value and the ease-of-use of AM, thereby allowing the industry to better capitalize this underutilized tool, resulting in a more efficient design process, an easier path to certification, and overall better and more reliable distributed wind turbine products.

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1 Project Introduction

From the request for proposal from the National Renewable Energy Laboratory (NREL; NREL 2021b): "A primary objective of the U.S. Department of Energy (DOE) Wind Energy Technologies Office is to increase the number of certified small and midsize wind systems. Another DOE objective is to improve national and international technical standards that are used as the baseline for wind turbine certification. The U.S. distributed wind turbine industry is the global leader of installed capacity of distributed wind turbines but is a micro-capitalized industry that is under competitive pressure from non-U.S. manufacturers, some without certification. The Strategic and Technical Engagement effort has a specific focus to improve the certification process around small and midsized distributed wind technology. Of specific interest is understanding how better to utilize decades of distributed wind turbine modeling and measurement expertise to both improve and simplify the certification of small and midsized wind turbines."

The International Electrotechnical Commission (IEC) 61400-2 standard is up for revision in 2022. The American Wind Energy Association (AWEA) small wind turbine (SWT) standard 9.1–2009 has been revised into an American National Standards Institute (ANSI) standard. The International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 41 (IEA Wind 2020a) mentions that standards and certification are seen as obstacles to innovation and result in slow market penetration of small wind turbines.

NREL contracted RRD Engineering, LLC, (RRD) for support and guidance on the use of aero-hydro-servo-elastic (AHSE) codes (e.g., OpenFAST) for the distributed wind technology (DWT) sector. In particular, RRD was tasked with identifying the strengths and weaknesses of current standards (e.g., IEC 61400-2:2013 [IEC 2013]) and developing a plan to exercise and validate specific wind turbine aeroelastic models. The goal is to help NREL strategize, develop, and implement a research method to improve national and international standards.

RRD partnered with Windward Engineering, LC, to conduct this work and to leverage their knowledge of IEC 61400-2:2013 and other international standards, as well as their expertise in wind turbine testing and loads measurement to support an update of how aeroelastic models can improve the certification process.

In Section 2, a summary is presented of recent stakeholder meetings together with key conclusions on the matters of simplified loads methodology (SLM), aeroelastic modeling (AM), and duration testing. Section 3 presents the recommended steps to substantiate a breakdown of wind turbine categories for loads assessment following AM and SLM in particular. Section 4 discusses the turbine-specific aeroelastic models that were retrieved in the public domain, their strengths and weaknesses, and suggested general actions to improve AM codes and their widespread adoption. In Section 5, the role of testing to support the development of AM code and design standards is described together with a review of the verification and validation (V&V) framework and an in-depth account of typical best practices in field testing and measurements that can further facilitate these activities. At the end of the section, a summary of recommended actions is offered to leverage upcoming wind turbine testing opportunities at NREL's Flatirons Campus. Section 6 provides recommendations for the use and improvement of specific AM code capabilities and the use of the retrieved turbine AM templates. Technical strengths and weaknesses of the current design standards (focus is on IEC 61400-2:2013) as they pertain to AM and as perceived after conducting expert elicitations and a dedicated workshop are discussed in Section 7. In the same section, we describe a wind turbine category breakdown matrix based on the input received at the workshop, which uses both turbine size and archetype characteristics as primary differentiating parameters, and which can be used to specify minimum requirements for loads assessment and validation of AM. Section 8 proposes strategies for design standard improvements based on the analysis conducted in this project and feedback from the industry stakeholders. Concluding remarks and tables of recommended future work activities to improve the adoption of AM in the distributed wind energy industry are presented in Section 9.

2 Summary of Recent Discussions and Findings Among Stakeholders

This section constitutes a brief memo that summarizes the weaknesses in design standards for DWT as identified by national and international meetings that occurred in 2019 and 2020 as indicated in (NREL 2021a). The meetings include:

- **Standards Forum** held on February 27, 2019, (during the Distributed Wind Energy Association [DWEA] business conference) denoted as DWEA0227, with detailed notes provided by NREL in (Baring-Gould, Preus, and van Dam 2019)
- **ANSI/AWEA SWT-1** (to become ANSI/American Clean Power [ACP] 101-1) meetings collectively denoted as ACP2020:
    - In-person meeting held on February 13, 2020, in Denver, Colorado, with notes provided in (NREL 2020a)
    - In-person meeting held on February 28, 2020, in Arlington, Virginia, with notes in (NREL 2020b; Baring-Gould 2020; Forsyth 2020)
    - Virtual meeting held on April 9, 2020, with meeting minutes in (NREL 2020c)
- **European International Standards Assessment Forum** held June 26–28, 2019, in Dundalk, Ireland, denoted as ISA2019, with notes in (Forsyth, van Dam, and Preus 2019)
- **IEA Wind Task 41** meeting held on January 20, 2020, denoted as IEA41, with comments and recommendations in (IEA Wind 2020a; IEA Wind 2020b) and a comprehensive document being edited (Kelly, Baring-Gould, and Forsyth 2021).

General notes:

ACP2020 indicated that ACP SWT-1 (ACP 2021) will have a classification based on peak power, with the following ranges: Micro (≤1 kW); Small (1–30 kW), with AM and minimum model validation (power/RPM); Medium (30–65 kW), with AM and more validation, including natural frequency and yaw behavior; Large (65–150 kW), with extensive validation through IEC 61400-13:2015 (load measurements).

Table 1 is a proposed revision of the above-mentioned classifications but with a refocusing on rotor-swept area (RSA) as the key classifier.

Table 1. Rotor-Swept Area, Rated Power, and Classification of Distributed Wind Turbines

Swept Area [m^2]	Rotor Diameter [m]	Approximate Power Rating Expected at 11m/s [kW]	Load Assessment Category
1	1.13	0.245	Micro - XS
2	1.6	0.489	
5	2.5	1.22	
10	3.6	2.45	Small - S
50	8.0	12.2	
100	11.3	24.5	
200	16.0	49.0	Medium - M
300	19.5	73.4	
500	25.2	122	
>500	>25.2	120 < power < 600	Large - L

Furthermore, there seems to be consensus to limit the IEC 61400-2:2013 wind turbine classes to just Class II and S, while raising the reference turbulence intensity (TI) at 15 m/s from 18% to 20% (NREL 2020b; Summerville et al. 2021) and raising the reference annual energy production wind speed to 6 m/s from 5 m/s (Summerville et al. 2021).

In the following subsections, we identify the key comments and salient points that were extracted from notes and documents associated with the various meetings held.

2.1 Duration Testing

A general consensus from DWEA0227 and ISA2019 is that the duration testing (1) is too lengthy and (2) requires wind speeds that are too high.

There seems to be uncertainty about what has turned up as problems and failures during the duration tests, and there does not seem to be a clear understanding of what the benefits might be. As mentioned in Forsyth, van Dam, and Preus (2019), a dedicated study should be conducted to assess what the tests have shown so far and what could be done as an alternative to the duration testing, such as component structural testing plus a statistical assessment of operating wind turbines. In Summerville (2020), results and findings for 29 duration tests are presented. The results of that study can be summarized as follows:

1. The duration tests took about 8.8 months to complete, with some taking as long as 14 to 18 months.
2. When failures occurred, they were most often electrical/electronic issues or structural fatigue issues.
3. Of the 29 tests, 22 targeted a Class II rating, with a handful looking at Class III and Class IV.

ACP2020 targeted the averaging time associated with the duration testing, as it is a key aspect of the test that contributes to its lengthy nature. Whereas a firm physics basis for the revision of the overall time requirement for the test or the averaging time (1 minute vs. 10 minutes) has not been identified, the SWT-1 committee (NREL 2020b) is proposing to reduce the averaging time from 10 to 1 minute, which is in line with the power performance test requirements for SWTs (IEC 2017).

Additionally, during ISA2019, a tiered certification scheme was proposed, in which a limited certification could be issued without the completion of the duration testing. Along these lines, for large wind turbines and those with more traditional configurations, the duration testing could be replaced by component (structural) testing and fatigue modeling.

Finally, during the AWEA/ACP SWT-1 meeting in Colorado (NREL 2020a), it was proposed to lessen the duration test requirements—resulting in a shorter and less burdensome test—and to use a surveillance program to monitor several installed wind turbines (proposed 5) for 3 years, during which time the certification body can continue to evaluate the product's reliability and ultimately its certification status. In Summerville et al. (2021), a summary of the changes that will be implemented in ACP 101-1-2021 is provided together with a rigorous analysis of 31 duration tests conducted between 2007 and 2018. The reduction in duration test requirement is partially balanced by an expanded post-certification surveillance process, which will add a 3-year field inspection process to the current factory inspections and annual reporting of design changes and field failures.

2.2 Simplified Loads Methodology

DWEA0227 indicates that the SLM is only applicable to wind turbines rated below about 1 kW. Therefore, for certification, AM should be required for turbines with a power rating greater than about 1 kW. A problem with this threshold definition is that the rating is defined (wind speed, in particular). A threshold based on RSA may be more scientific. The argument here is that a larger rotor, although associated with small power ratings, would lead to larger aeroelastic effects. Yet, to arrive at a more defendable parameter threshold, a number of cases (with varying turbine configurations) should be evaluated via both SLM and AM.

In our experience, SLM captures the loads conservatively, up to relatively large RSAs (100 m^2) for typical three-bladed, upwind horizontal-axis wind turbines (HAWTs), thereby leading to overdesigned but safe components. Whereas a distinction between RSAs greater than 200 m^2 and RSAs less than or equal to 200 m^2 for AM to become mandatory makes sense, below this threshold the use of AM should be enforced only for "unusual" configurations, as already recommended by IEC 61400-2:2013.

The division proposed in ISA2019, however, is as follows:

- Micro wind turbine generator: 3–5 m^2 (<2 kW) battery-charging, small distributed energy resource microgrids, SLM
- Small wind turbine generator: 5–50 m^2 (2-11 kW), can use SLM or AM
- Medium wind turbine generator: 50–500 m^2 (11–150 kW), must use aeroelastic models validated by measurements.

Following the 2020 DWEA meeting in Washington, DC (NREL 2020b), the consensus is that the new ACP SWT-1 standard would only allow SLM for wind turbines below 10 kW. Furthermore, the turbine classification in the ACP SWT-1 looks to be verging on peak power, rather than rated power or RSA.

SLM for small and micro vertical-axis wind turbines (VAWTs) is not available in either the IEC 61400-2:2013 standard (IEC 2013) or American and European national standards, as evidenced in ISA2019. However, work had been conducted in Taiwan and Japan toward the development of an SLM for VAWTs, which culminated in an annex of the Japanese SWT standard (Japan Small Wind Turbines Association [JSWTA] 2013). At a minimum, an international validation of this VAWT simplified loads methodology may be required to inform future national and international standards development.

ISA2019 (Forsyth, van Dam, and Preus 2019) further discusses the need for the development of renewed SLM fatigue analysis methods that would account for different control archetypes and on-grid vs. off-grid turbines and include factors such as yaw bearing loads (for passive yaw control), yaw error (for active yaw control), and load cases such as power production plus fault, normal shutdown, and parked/idling (low cycle/high fatigue). In parallel, the SLM development effort would also require the acquisition of structural test data (e.g., blade fatigue testing results) and field measurements from different archetypes and site conditions.

2.3 Aeroelastic Modeling and Recommended Steps To Facilitate Its Use

Aeroelastic modeling should be the primary methodology for the structural and performance assessment of any wind turbine. AM allows the evaluation of:

1. The load and power behavior of the wind turbine before witnessing it in the field
2. Extreme loading events that would not be possible to capture in the field
3. Control parameters that have the highest impact on the design
4. The configuration's most efficient layout.

Whereas AM is well-tuned for traditional three-bladed HAWTs, it is not as well-tuned for downwind HAWTs, and is progressively less and less validated for passive yaw, pitch-to-stall, furling, and VAWT machines (Forsyth, van Dam, and Preus 2019).

Parallel to the validation of the software used to simulate these "less-than-typical" configurations, a model should be validated before results can be used for design certification. Therefore, the degree of validation of an individual model (code plus its specific input deck) shall be adjusted depending on the experience of the code and the modeled configuration.

Continued support for the aeroelastic code development should be guaranteed, along with a commitment to support VAWT and other less-than-typical configurations.

A few other concerns that were expressed during ISA2019 are:

- Recent development in OpenFAST has neglected the fixed-speed machines that are still being used in the midsized SWTs.

- Tower dynamics is not included in IEC 61400-2:2013 (IEC 2013), which is perceived as a safety gap.
- The normal turbulence model does not reflect the turbulent environment of DWT sites, and certified power curves are not representative of these sites and their performance. Additionally, vertical inflow is perceived as an important factor for DWT turbines.
- Considerations for conformity assessment are not well-defined.
- Acoustic testing is perceived as the most difficult of all the testing requirements and results in limited use for the consumer.

Summerville (2021), states that whereas AM is commonly adopted by the more established manufacturers and for the medium and large segments of small wind turbines, the modeling space is not well-defined. Furthermore, to guarantee certification, the AM models must be validated, and the procedure for validation is unclear and perceived as time-consuming and expensive.

One of the additional advantages of moving to an expanded use of AM for wind turbine certification is that it could simplify the conformity assessments following a change in the turbine architecture. The conformity assessment sets up methods, procedures, and protocols for certifying, reporting certification results, and identifying what is needed to update existing turbine certifications based on design changes.

A study of current practices would be needed to yield an official guide outlining the conformity assessment process.

Also discussed in (Baring-Gould, Preus, and van Dam 2019), the expanded use of AM will require:

- Turbine aeroelastic model templates for different archetypes, such as:
    - Passive yaw control with tail
    - Furling control
    - Tower dynamics
    - VAWT
- A refined understanding of how to validate an aeroelastic model with less data than is currently required for certification; this could be aided by the development of standard V&V approaches (including discussion of testing at the user's site vs. a certified testing site and statistical sampling of deployed turbines)
- More refined guidance on when one must use AM (turbine parameters); this also requires a clear distinction between IEC 61400-1:2019 and IEC 61400-2:2013 and RSA and other structural dynamics effects
- Guidance on how to use AM, including what key parameters must be validated by the user and under what archetype and within what ranges of parameters AM is reliable and accurate
- Assessing the potential for simplification of the conformity processes, possibly tied to other turbine parameters such as RSA
- Dedicated support from national laboratories and industry consultants to keep models up to date and verified as new technology gets developed or codes get updated.

3 Recommended Next Steps To Assess Load Categories

In the utility-scale sector, the wind turbine type certificate is routinely acknowledged by manufacturers and stakeholders as a requirement for both public safety and proof of performance to secure the financing of a wind power plant. The role of certification of SWTs for end-consumer applications is primarily useful in gaining access to incentives from local and federal governments. Some of the established DWT manufacturers claim there is no real need to certify for safety (Baring-Gould, Preus, and van Dam 2019), and that some of the certification requirements are unnecessarily lengthy and expensive and are hampering the market diffusion of SWTs.

Based on the review of the stakeholder meetings held in 2019 and 2020 (see Section 2), it appears that the most urgent need is to arrive at a substantiated assessment of the load categories for distributed wind turbines to allow for a rigorous differentiation of requirements for certification depending on the turbine category. A logical plan would envision data-gathering in the form of models and test data to assess the fitness of the aeroelastic modeling and SLM as a function of various turbine characteristics (such as size and archetype).

A similar effort was undertaken in (Jonkman et al. 2003) that led to a series of improvements to the first edition of IEC 61400-2. A collection of SWTs, including variations in rotor size, blade number, rotor location (upwind/downwind), hub type (rigid/teetered), and yaw mechanism (free/active), were investigated via combined modeling and test measurement efforts. As a result of that study, enhanced load models, new load cases, and improved safety factors were devised and included in the revision of the IEC 61400-2:2013 standard. More recently, (Evans et al. 2021) presented a modified method for calculating the fatigue spectra of small wind turbine blades, highlighting the current shortcomings of the SLM. However, these research efforts focused more on improving the SLM equations than on trying to identify a threshold of applicability of SLM vs. AM. Forsyth, van Dam, and Preus (2019) also discuss the need to improve SLM fatigue for micro- and mini-wind turbines. As mentioned in Section 2.2, SLM should be expanded based on the control architecture.

What is crucial, however, is providing a physical basis to determine when (turbine size) AM must be applied and, as mentioned in Section 2.3, how to assess the process of validating a numerical model to be accepted as a certifiable basis for the design.

Below are the recommended high-level tasks in order of priority that are envisioned as the next steps:

1. Overarching effort: assess SLM vs. AM with field tests to arrive at a load-based categorization of wind turbines (e.g., Table 1) and threshold factors for use of SLM
2. Model validation requirement document: How do we prove the aeroelastic model meets certain quality standards to capture the actual loads experienced by the turbine? (IEC 61400-2:2013 requires compliance with IEC 61400-13:2015 for load testing, not for compliance verification)
3. Development and validation of AM for VAWTs

4. Conformity assessment guidelines for DWT
5. SLM extension to VAWT
6. SLM extension for fatigue of mini- and micro-distributed wind turbines.

The recommended immediate next steps around aeroelastic codes and validation are listed below:

- Prioritize wind turbine archetypes that will benefit from AM in the short term.
- Update OpenFAST models for the most common SWT archetypes.
- Acquire validated aeroelastic models for VAWT archetypes, or generate new models.
- Develop a document on the requirements for specific turbine aeroelastic model validation to define what type of test data would be required for initial turbine AM validation and possible certification (this is part of the current project). This would include the condition through which validation data could be collected, for example, testing at a manufacturer's site or statistical sampling of deployed turbines vs. certification testing at a certified site.
- Determine what work/analysis would need to be done to better document a new RSA threshold given the current analysis and modeling techniques (part of the current project).

4 Publicly Available Aeroelastic Models

RRD researched and collected publicly available aeroelastic models for various wind turbine archetypes. The following institutions were also contacted: University of Newcastle (S. Evans), Technical University of Denmark (K. Dykes and D. Verelst), Polytechnic University of Milan (A. Croce), University of Florence (A. Bianchini), Delft University of Technology (R. Schmehl), Netherlands Organization for Applied Scientific Research (TNO)(G. Schepers), National Renewable Energy Center of Spain (CENER)(A. Gonzales), and University of Utah (M. Metzger).

The complete table of retrieved models is available at (RRD Engineering, LLC 2021). The majority of these wind turbine models make use of the open-source AHSE code OpenFAST (and its variant KiteFAST for airborne wind energy [AWE]). A HAWC-2 (proprietary code) model for a HAWT, a MegAWES (https://github.com/awegroup/MegAWES) model for AWE ground-gen kite, and a CSIM (https://github.com/google/makani) model for AWE lift-gen kite were also collected. Because HAWC-2 input files can be ported to the OpenFAST format, the remainder of this document will focus on the widely used open-source platform OpenFAST.

Eight models (plus some variants) are readily available and can be easily downloaded from open-access file repositories (Table 2). The models span RSA values from 1.82 to 572 m^2 for HAWTs and include two templates for AWE kites: a lift-gen (crosswind flight with airborne generation) and a drag-gen (figure-8 flight and ground-based generation). Additionally, the models span a good range of control archetypes, including stall and active pitch-to-feather and passive and active yaw, with either variable or fixed speed generators. These models received adequate validation in past research work (albeit associated with the specific machines they were simulating) and can be considered technically ready to be used as templates for new wind turbine loads analysis and certification. Yet some level of validation is needed to prove that they are still reliable for the modifications to the turbine models as well as the AM code. The models that include tail dynamics and furling are no longer supported by the latest version of the aeroelastic computer-aided-engineering tool OpenFAST. This represents a clear need for tool updating.

No VAWT model was retrieved. It is our understanding that Sandia National Laboratories own both an aero-hydro-servo-elastic code (OWENS plus CACTUS) as well as several wind turbine models that have been validated against past VAWT experiments conducted in the field. We were unsuccessful in obtaining either one, however.

No ducted turbine models were found. This is a small but not insignificant category for SWTs. That being said, we perceive the effort required to develop and validate this wind turbine category as high, and as a consequence, the “value” is lower than other industry needs.

Further SWT models are being generated by different institutions and should become available soon. The University of Florence is planning to release a 200 m^2 RSA model with active pitch and yaw that could represent a good candidate to investigate the current IEC 61400-2:2013 threshold RSA value and the boundary between small- and medium-sized turbines. The Technical University of Denmark is working on a ~500 m^2 RSA turbine model that could be used as a template for larger medium-sized turbines.

To assess whether the acquired models (assuming updates to OpenFAST are implemented) cover the turbine-plus-control-strategy configurations seen in the current market, we created Table 3 where individual cells are color-coded to signify the presence of a certain archetype in the market, and a checkmark symbol (✓) denotes the availability of its template aeroelastic model.

Table 2. Publicly and Readily Available Distributed Wind Technology Aeroelastic Models

Up/Downwind/Rotor Axis/No. of Blades	Rotor-Swept Area (RSA)	Power Regulation / Yaw	Secondary Control/ Variable vs. Fixed Speed/ Generator[a]	Notes
D/H/3	147 m^2	Stall/passive	Tip Brakes/FS/SCIG	Past validation
D/H/2	175 m^2	Stall/passive	Teeter/FS/SCIG	Past validation
U-D/H/2	78 m^2	P2F (pitch to feather)/active	Teeter/V-FS/IG	Validated in wind tunnel and field
U/H/3	26 m^2	Stall/passive+tail	Furling/VS/PMG	OpenFAST is missing tail dynamics
U/H/2	26 m^2	Stall/passive+tail	Dynamic Braking/VS/ SEIG	OpenFAST is missing tail dynamics
U/H/3	573 m^2	P2F/active	Mech. Brake/VS/IG+FPC	Unconventional blade aerodynamics
AWE/crosswind	-	stall/ moving surfaces	tether control-motor control/VS/PMG	KiteFAST model and M600 simulator available
AWE/ground-gen	-	NA/moving surfaces	Tether control-motor control	Rigid-body model

[a]FS = fixed speed; VS = variable speed; SCIG = squirrel-cage induction generator; IG = induction generator; PMG = permanent-magnet generator; SEIG = self-excited induction generator; FPC = full power converter

Table 3. A Spectrum of Distributed Wind Technology Archetypes and Available Aeroelastic Models

Active Yaw	Passive Yaw	Stall	Pitch	Variable Speed	Fixed Speed	Downwind	Upwind	
			✓	✓	✓		✓	Active Yaw
		✓		✓	✓	✓	✓	Passive Yaw
				✓	✓	✓	✓	Stall
				✓		✓	✓	Pitch
						✓	✓	Variable Speed
						✓	✓	Fixed Speed
								Downwind
								Upwind

Where:

Gray = N/A
Green = common in the current market
Orange = rare in the current market
White = not seen in the current market
✓ = aeroelastic model template available

4.1 Aeroelastic model needs and recommendations

As shown in Table 3, most configurations are covered. What is missing are models for wind turbines with:

- Active yaw with stall control (common in current market)
- Active yaw with downwind rotor (not seen in current market)
- Fixed-speed generator with active pitch control (rare in current market)
- Passive yaw with active pitch (rare in current market).

Given that the yaw dynamics of an active-yaw machine are generally slow enough to be considered not a significant contributor to loading, the first two bullets above are not an issue and models can be easily modified to introduce active yaw control.

The concern associated with the third bullet is not related to the fixed-speed generator model in and of itself, which, in fact, could be easily introduced into any of the other variable-speed-plus-active-pitch models. Instead, the problem lies with the current OpenFAST control interface development. FAST (up to version 7.2) used to rely on Bladed-style dynamically linked library (DLL) for pitch and torque control. However, the recent code development and support in OpenFAST has moved toward a new user-friendly controller platform named the Reference OpenSource Controller, or ROSCO (NREL 2021c). ROSCO and its associated toolbox allow for a streamlined pitch control implementation, where the user must only provide aerodynamic properties of the rotor, and ROSCO can derive tables of the power, thrust, and torque coefficients

(*Cp*, *Ct*, *Cq*, respectively) vs. tip-speed ratio needed to tune the controller. ROSCO, however, was simply not designed to manage fixed speed generators (i.e., induction generators), and there is no way to separate or discard ROSCO's torque controller (to simulate a simple squirrel-cage induction generator, for example) from the pitch controller. As such, the user must resort to the old DLL style, which requires coding a (Fortran) control algorithm for the pitch controller and then setting the option for no torque control in ServoDyn (controller interface module of OpenFAST). Ideally, ROSCO would be updated to allow for the possibility of controlling pitch alone, leaving the torque control to the ServoDyn options.

The fourth bullet addresses machines with passive yaw and active pitch. Although these configurations are not prominent in the market, a passive-yaw machine with active pitch and fixed-speed generator is being designed by RRD and Windward Engineering within the context of a recent NREL competitiveness improvement project. The main concern with the lack of a validated model in this space is also associated with what was mentioned above and in the previous section, which is the difficulty in handling pitch control with a fixed-speed generator and, more importantly, the uncertain ability of the model to capture passive-yaw rotor aerodynamics. Although some success was shown by previous validation studies of passive-yaw turbine models (see references in [RRD Engineering, LLC 2021]), the existing data (especially in a turbulent environment and not wind tunnels) is not sufficient to fully validate the AHSE code for multiple rotor/turbine geometries. The aspects that affect passive-yaw turbines are mostly associated with unsteady aerodynamics, which is difficult to fully capture with an engineering model without resorting to computational fluid dynamics.

Another aspect that is crucial when modeling wind turbines, especially SWT with high-frequency modal characteristics, is to confidently assess the forcing and response modes of the wind turbine. A Campbell diagram provides a quick assessment of the system response as a function of rotor speed and can be used to focus the analysis and the design toward avoiding possible resonance risks. Currently, OpenFAST cannot generate a Campbell diagram in stand-alone mode. Multiple linearization runs are required as well as relatively intense manual processing. A streamlined and documented procedure for the generation of a Campbell diagram would be needed to facilitate the use of AM for certification.

4.2 Areas of Concern in the Retrieved Aeroelastic Models and Recommended Actions

In Table 4, we summarize the main areas of concern that arose after reviewing the available aeroelastic models and suggest possible actions in light of the increased focus on aeroelastic modeling that the standards for SWT and the DWT industry at large are adopting.

In this project, a prioritization strategy will be recommended based on industry and stakeholder feedback to identify aeroelastic models that are most likely to be used in the largest number.

In partnership with NREL, the authors of this report and Wind Advisors Team hosted a workshop to gather further expert opinions on aeroelastic modeling development needs, the results of which are summarized in Section 7.

Table 4. Concerns Associated With Existing Aeroelastic Models and Codes

Area of Concern	Perceived Needs	Suggested Action
Tail aerodynamics and furling dynamics in the OpenFAST code	Whereas turbine models that propose passive yaw control with a tail and furling dynamics have been less prominent in the recent market, the lack of AM capability to capture these dynamic aspects inhibits validation or improvement of the SLM approach as well as certification of these archetypes via AM.	NREL or NREL + subcontract consultancy to update the OpenFAST software to reintroduce the tail dynamics and possibly furling. Validation to be performed following the update.
Yaw system friction	Friction in the yaw system plays an important factor in the passive-yaw dynamics of turbines, especially in the medium category. Friction is substantially independent of yaw rate and cannot simply be modeled with damping coefficients.	NREL or NREL + subcontract consultancy to update the OpenFAST software to introduce yaw system friction.
Model accuracy in predicting passive-yaw aerodynamics	Validation of the AM code should be performed on multiple configurations to reduce uncertainty in the passive-yaw dynamics.	NREL or NREL + subcontract consultancy to identify candidate turbines (to be installed or preexisting) to be instrumented and perform AM vs. load measurements studies on them in the field.
Controller interface when using OpenFAST's ROSCO controller	ROSCO should be updated to include handling of induction generators to reduce the difficulty to DWT modelers.	NREL or NREL + subcontract consultancy to update the ROSCO software.
Linearization and Campbell diagram in OpenFAST	A streamlined process to arrive at a modal analysis of the wind turbine is required to both validate the model and proceed to certification of loads analysis, including recent concerns brought forth about tower dynamics downplayed in the current standards.	NREL or NREL + subcontract consultancy to produce a linearization manual and semiautomated software to arrive at a Campbell diagram.
Need for a validated VAWT code	VAWTs are currently challenged to find a reputable AM. This makes design work and certification work difficult.	NREL or NREL + subcontract consultancy to support development of a validated VAWT AM code.
Ducted turbine AM capability	Shrouded wind turbines exist, and there is currently no AM capability to account for the effects of the shroud on the inflow and for the shroud aerodynamics and structural dynamics.	NREL or NREL + subcontract consultancy to support development of a validated ducted turbine AM capability.
Verification and Validation for less common archetypes	Aeroelastic models have not received definitive cross-verification and field validation for non-traditional turbines (e.g., downwind, passive yaw, furling, and vertical axis wind turbines)	NREL or NREL + subcontract consultancy to implement a V&V plan on multiple turbine models.

5 Testing Strategy and Planning

5.1 Testing Goals

There are at least three major areas where field testing of DWTs paired to AM would support the broader industry:

1. Certification testing (wind turbine model validation): For manufacturers, field testing and certification are expensive and time-consuming. Studies to determine the minimum number of measurement quantities required and the minimum required capture matrix[1] to validate a model will help reduce the burden on manufacturers. Confidence levels will be higher for more traditional topologies and lower for new and innovative and/or unconventional designs. Focused testing will help determine which topologies are most accurately modeled vs. those that require more measurements to confidently validate the models.
2. Aeroelastic code validation and development: As more test data are accumulated, the aeroelastic modeling codes are expected to become more accurate and able to accommodate more diverse topologies. Note that the aeroelastic code as well as the specific “model” (setup and usage of an aeroelastic model with specific input parameters) should be validated against specific measured data and acceptance criteria. Protocols including the variables to be measured, the environmental and operational conditions to be covered by the testing, and the basic criteria of acceptance should be codified into design standard prescriptions.
3. SLM development and validation: Field measurements along with aeroelastic modeling can be used to further refine and validate the SLM equations in the design and certification standards. This work will also better define the extent (size and topology) to which the SLM equations are applicable.

The first point targets the manufacturers, whereas points 2 and 3 primarily apply to the research community and stakeholders involved in the development of the design codes and design standards. In the following subsections, we address aspects pertaining to these goals, starting with an overview of the V&V framework, then transitioning to a description of what requirements should be adopted for field testing aimed at supporting AM. We further provide a sample test plan that can be used for these activities and suggest research and development opportunities associated with the upcoming testing campaigns of three distributed small wind turbines at NREL’s Flatirons Campus.

5.2 Aeroelastic Modeling Verification and Validation

For the results of an aeroelastic model to be used for design and certification, the aeroelastic code (the software), the turbine-specific inputs, and the aeroelastic model setup and usage with those inputs as well as the post-processing of the results must achieve a certain level of V&V.

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[1]The capture matrix defines the minimum required data for each measurement load case and can be used to report the test database to demonstrate the minimum data requirements have been fulfilled (IEC 2015)

5.2.1 Verification and Validation Framework

The following American Society of Mechanical Engineers (ASME) definitions of V&V are commonly adopted (AIAA 1998):

Verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.

Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

The verification process addresses both the mechanics of the software (consistency with the conceptual model and coding issues) and the numerical solution procedure (Draxl et al. 2019). The ultimate goal is to identify and minimize numerical errors associated with equation discretization and integration of partial differential equations. Verification of AM software usually relies on "benchmarking," in which either an analytical or highly accurate numerical solution of well-established configurations are used as the "gold standard" to verify the accuracy of the model.

In the validation process, the model results are compared to experimental data sets to ascertain the degree to which the model represents the actual physics. Hence, the validation data sets must be properly collected and quality assured. Validation, however, is not a binary statement about whether a model is valid or invalid, but rather a critical part in the overall assessment of the suitability of the computational model for the intended application (Hills, Maniaci, and Naughton 2015). Furthermore, model accuracy is difficult, if not impossible, to bracket a priori. Nonetheless, safety factors are indicated by the design standards, and the error in the model prediction, at a minimum, should not exceed the load safety factors. Perhaps more important than the actual acceptance ranges for the various measurement channels is the identification of what the model can and should capture well, with high priority and accuracy (for example, loads at blade roots or in the main shaft), and which other channels may not be as important to predict (for example, if power production is missed, the design may still be safe if key loads are accurately predicted). As such, the end user's needs are an important aspect of V&V, but the end user must also act responsibly while leveraging third-party inputs and reviews within a codified framework.

The V&V framework is a process to define the conditions and application domain where model predictions can be trusted. Trust is built when the code performance has been tested and quantified based on appropriate data sets agreed upon to cover a relevant range of applicability.

A formal V&V framework (Hills, Maniaci, and Naughton 2015) would entail the development and execution of coordinated modeling and experimental programs to assess the predictive capability of computational models of DWTs through focused, well-structured (codified) processes. The American Institute of Aeronautics and Astronautics (AIAA) guide (AIAA 1998) states that verification and validation are processes or ongoing activities without a clearly defined completion point. This implies that V&V involves the planning of activities and a constant exchange of information among the modelers, experimentalists, and subject matter experts to arrive at a consensus on the predictive capabilities of a numerical model.

Whereas a V&V framework is recommended in the DWT space, it is outside the scope of this project. Nonetheless, we want to highlight some salient aspects of V&V that will need to be incorporated in future work related to this topic that use well-established procedures developed by DOE (Oberkampf and Roy 2010; Hills, Maniaci, and Naughton 2015), the National Aeronautics and Space Administration (NASA), AIAA (AIAA 1998), and ASME (ASME 2009).

A V&V framework entails (1) careful planning based on expert elicitation of the modeling physics requirements, (2) design of experiments for model assessment, (3) uncertainty quantification for experimental observations and computational model simulations, and (4) assessment of the model predictive capability. The range of operating conditions and the variables of interest and their associated acceptance criteria should be defined in collaboration with subject matter experts. For this reason, there is a degree of subjectivity in model validation that cannot be simply taken as a pass/fail test. Several types of quantitative validation metrics are available—for example, in terms of a probability (i.e., the probability of the observed differences between model predictions and the experimental observations, given the modeled and measured uncertainty). The estimation of model error and its uncertainty reflects the accuracy of the model predictions relative to the experimental observations, independent of the accuracy requirements of the intended applications. This allows one to characterize the computational model error and uncertainty, and then evaluate acceptance or rejection of the usefulness of the computational model as a separate step as the design evolves and the design margins become more evident (Maniaci and Naughton 2019).

Uncertainty quantification plays a central role in the validation exercise, as both aleatory (irreducible due to statistical randomness) and epistemic (reducible, due to lack of knowledge about the process that can be improved) uncertainty are present in the measurements as well as the model. Measurement uncertainty includes that associated with the instrumentation, data acquisition systems, and the use of data reduction equations. Measurement and data reduction uncertainty can be estimated, for example, following guidance in (ASME 2009). Environmental or boundary condition uncertainty, however, could be considered as either a measurement or model uncertainty. Normally, boundary condition uncertainties are considered part of the model input parameter uncertainty. Other uncertainties associated with the model are those related to numerical aspects of the solution algorithm and the propagation of input uncertainties. It is easy to understand how the choice of the methodology to address these uncertainties is an open area of research and therefore requires good scientific judgment and the involvement of subject matter experts (Hills, Maniaci, and Naughton 2015).

Model credibility is established through robust identification and characterization of sources of uncertainty, the completeness of a sensitivity analysis to determine the primary contributors to uncertainty in the system response quantities, the accuracy of propagating uncertainties through the computational model, and the correctness of the interpretation of the resulting uncertainties in the system responses (Maniaci and Naughton 2019). For example, the sources of the uncertainties include environmental uncertainties such as those that affect the initial and boundary conditions of the system, model parameter uncertainties such as those used in material property, numerical uncertainties due to lack of grid convergence, and model form uncertainties identified through validation tests and expert judgment (Hills, Maniaci, and Naughton 2015). Differences between experimental data and model predictions are expected, even for "perfect" models, due to the presence of uncertainty in both the experiment and in the parameters of the model. However, any observation of trends in the validation differences over time and space would suggest that systematic effects may be present. Furthermore, grouping model uncertainties by wind turbine archetype may reveal other modeling weaknesses.

Whereas no rigorous criteria exist to declare a computational model as "valid," a rigorous characterization of the model error, δ_{model}, and its probability density function $P(\delta_{model})$, could be attained following established guidelines, for example (ASME 2009). With reference to Figure 1, with a total standard uncertainty, u_{val} (calculated from the square-root of the sum of the squares of the data uncertainty, numerical uncertainty, and model parameter uncertainty), the probability density, $P(\delta_{model})$, of the observed difference, E = S - D, between model output S and data D, can be approximated. Consequently, one could estimate the range of model error based on a probability level of exceedance of a given range (e.g., the interval $[E - u_{val}, E + u_{val}]$), and compare that to the partial safety factors to be used for the specific application. In the end, it is up to the analyst/customer/decision-maker/certification and verification agency (CVA) to use judgment as to whether the estimated computational model error, E, and the estimate for uncertainty in this model error, u_{val}, are significant relative to the intended application of the model (ASME 2009). The final acceptance criteria can be defined in terms of error metrics that should be ratified by the user community.

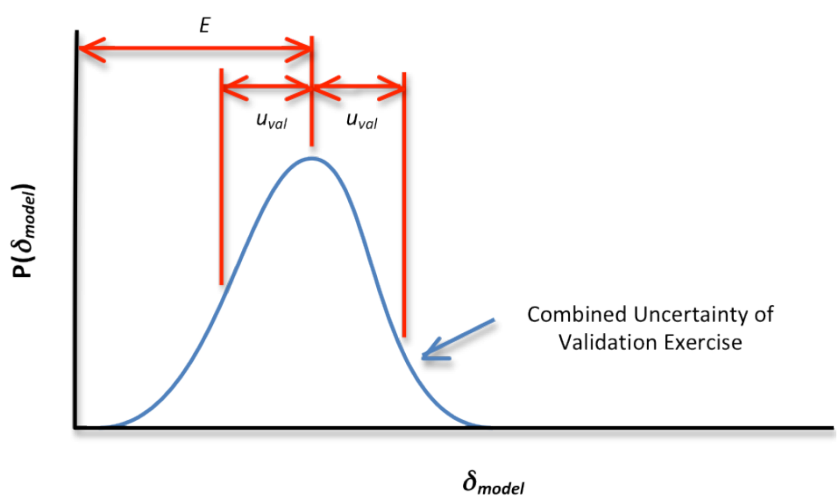

Figure 1. Estimate of model error δ_{model}. ***Illustration from Hills, Maniaci, and Naughton (2015)***

Finally, the complex and stochastic nature of the inflow and structural turbine response makes it practically impossible to validate the full range of operating conditions. Hence, a validated model will use inference methodologies to extrapolate performance from the validation space to the operational space (Wind Energy Model Evaluation Protocol [weMEP] 2021). Therefore, the main objective of the validation process is to develop and quantify enough confidence in the computer model (or code) so that it can be used reliably to predict the quantities of interest within acceptable limits. For this reason, validation is sometimes defined as the assessment of the predictive capability of a code. Consequently, there is a need for a formalized mechanism to infer the so-called predictive capability maturity of the model (PCMM), or the usability of the model for application conditions different from the validation conditions. PCMM is an elicitation tool (Oberkampf and Roy 2010) that formalizes the methodology to assess the maturity, or completeness level, of a computational model to judge its appropriateness for the intended application. It is based on expert judgment and ranking of the physical and mathematical rigor, correctness, experience, and relevancy of the model as it pertains to geometric fidelity, material and physical fidelity, code verification results, (mathematical) solution verification, and model validation together with uncertainty quantification and sensitivity analysis processes.

For more details on the V&V framework, refer to (Hills, Maniaci, and Naughton 2015).

5.2.2 Verification and Validation Codification

Currently, there is no real guidance in the design and certification standards on the procedure of V&V in the case of a new aeroelastic code, or aeroelastic model setup, when employed for certification of a new wind turbine. In this section, we offer some guidelines that could be incorporated into future standards and/or other documents.

As mentioned earlier, the aeroelastic model must (1) be verified for its accuracy in the software implementation and (2) be validated for its fidelity in the representation of the specific wind turbine model physics. Hence, the introduction of a new software or software capability must first be verified against established benchmarks. This activity could, and should, be performed by the end user. This will help the end user build knowledge and experience with the code and prepare it for the next phase of V&V. The review and approval of a CVA may still be required, but this should take minimal effort.

With the software verified, the validation phase can begin with the main objective being PCMM. In this phase, it is critical that a third-party entity (i.e., the CVA) review and approve the field-test planning before data are collected. Additionally, the CVA shall review (or independently run) the model against the measured data set. This would guarantee an independent assessment of the fitness of the model against acceptance ranges that can be established in partnership with the end user.

This process would guarantee that the acceptance ranges get deemed acceptable for safe design and certification; a formal conformity statement can then be provided by the CVA attesting to the predictions lying within the acceptance ranges.

The uncertainties in the quantities of interest (QoI) for both the experiment and the model prediction shall be estimated. The end goal of a validation exercise is generally to measure the discrepancy (bias) between the experimental results and the model prediction and the uncertainty of this bias (ASME 2009). Expert judgment (the CVA role) is used to evaluate whether the resulting discrepancy and associated uncertainty represent a risk in using the model for the intended goal (Hills, Maniaci, and Naughton 2015). If the model were to be considered invalid, a mitigation strategy shall be developed (e.g., additional model development, experimental characterization of the performance of the component, redesign of the component so that its performance is easier to predict using a model, and general model tuning).

It can be inferred that, when extending results of validation to QoI that were not within the validation space, the suitability of the model will need to be assessed on a case-by-case basis with the help of consultants, subject matter experts, and the CVA.

As a final remark, it should be obvious that a successful validation exercise requires close collaboration among the experimentalists, modelers, CVAs, and relevant stakeholders, throughout the conceptualization, design, execution, and post-processing phases of the experiments. Additionally, the computational model should be used to help design the details of the experimental campaign, which is, effectively, another (physical) simulation of the true behavior of the systems.

5.3 Simplified Loads Methodology Development and Validation

The expectation is that the only wind turbines that will use the SLM for load calculation are in the XS category (i.e., microturbines). Some turbines on the smaller end of the S (small) category might also consider the SLM as an option, but most larger turbines will find the SLM too conservative, resulting in an overdesign of components.

Any field data collected on XS and S turbines will be useful and would allow the following tasks to be performed:

1. The SLM can be evaluated against AM and load measurements to determine if there are calculations that are either too conservative or unconservative. This type of study was successfully carried out in the past and provided great insight into SLM validity and improvement (Evans et al. 2021; Jonkman et al. 2003). The same test-plan guidelines as shown in Section 5.5 could be employed. Of particular interest would be a study to verify the existence of operating characteristics that are being missed or underemphasized.
2. Similarly, the SLM can be evaluated to explore whether a size limit exists where the equations should no longer be used.
3. Japan has an active standard (JSWTA 2013) built around the simple loads model for VAWTs. This is one of the few viable options for certification of a VAWT. It would be useful to validate this standard to build confidence in its validity for certification. Having a validated SLM for VAWTs would be a great benefit to the vertical-axis community.

In the subsequent subsections, we address aspects pertaining to the field test planning that could be used for V&V, aeroelastic code development, SLM development, design standard development, and broader load measurements for certification that could be adapted for future certification standards.

5.4 Measurement Requirements

Before a field-testing campaign can commence, the measurement requirements must be laid out depending on the expected goals (Section 5.1). Among the various aspects to be considered are:

- What design load cases should be captured
- What environmental conditions (e.g., wind speeds, turbulence levels) should be collected
- What measurement parameters (also known as QoI) should be monitored, and the associated impact of the presence of sensors
- What spatial resolution, temporal frequency (need to capture the important eigenfrequencies and forcing frequencies for the system), and duration (for statistical significance as well for fatigue assessments or extremes) of data collection

- The methodology used to evaluate uncertainty in the measurements and the model predictions.

Depending on the testing goals, the above bullets can assume different meanings. For example, when direct-load measurements are used to certify a wind turbine, it is important that all historical design-driving load cases be captured, though extreme loads may be difficult to measure with reasonable testing windows, and some extrapolation will be required. For AM validation, however, a subset of operational and parked/idling conditions should suffice to present a good picture of the degree of model accuracy and validation space, especially when including power spectra and other derived QoI, besides time histories of direct measurement channels.

The sample test plan in Section 5.5 is comprehensive and appropriate for the research community for validation and development of codes and/or reference models. A simpler test plan, with fewer load and measurement channels and a smaller capture matrix, however, would be appropriate for the end user where sensitivity to time and costs are higher.

Table 5 proposes sets of minimum measurement channels for model-setup validation and for certification purposes on a prototypical HAWT (item 1 in Section 5.1). Table 5 does not apply to VAWTs, AWE kits, or other less common wind turbine topologies. In general, if a turbine topology can be modeled in OpenFAST, then it most likely could follow the guidelines in Table 5. By the same token, for appropriate code validation (item 2 in Section 5.1) the number of channels could be much larger and beyond what is shown in Table 5.

Table 5. Proposed Minimum Required Measurement Channels for a Prototypical Horizontal-Axis Wind Turbine for Use with Simplified Loads Methodology for Certification or for Aeroelastic Model Validation With the Purpose of Certification

Wind Turbine Category (RSA)	Load Calculation Model Used for Certification	Load/Performance Channels[a]
Micro – XS (<5 m^2)	SLM	P_{design},[b] n_{design}, Q_{design}, and n_{max}
Small – S (5 m^2 ≤ RSA < 100 m^2)	SLM	P_{design},[b] n_{design}, Q_{design}, and n_{max}
	Aeroelastic	Power, RPM, yaw angle, and any other parameter that will influence power or rotor speed regulation (such as furling)
Medium – M (100 ≤ RSA < 500 m^2)	Aeroelastic	Same as “Small” requirements plus blade-root bending moments (edge and flap), shaft bending moments (2), shaft torque, rotor azimuth, tower-base bending moments (2), and any other turbine-specific parameter such as pitch angle for a pitch-controlled turbine
Large – L (>500 m^2)	Aeroelastic	Full load campaign as described in IEC 61400-13:2015 (IEC 2015)

[a]In addition to the load/performance channels, meteorological measurements shall be captured such as wind speed, wind direction, and air density (calculated from temperature and pressure).

[b]Measurement of these parameters is a requirement for using the SLM and is outlined in IEC 61400-2:2013 (IEC 2013). The subscript “design” is defined as a wind speed of 1.4 V_{ave}, where P is power, n is rotor speed (RPM), and Q is torque (torque can be calculated from power and rotor speed). The measured data shall be binned into 0.5 m/s

wind speed bins. Each wind speed bin from 1 m/s below V_{in} to 2 V_{ave} shall contain at least 30 data points. A data point is based on a 1-minute average of samples recorded at a sample rate of at least 0.5 Hz.

5.5 Sample Test Plan

With a focus on HAWTs and VAWTs, in the next subsections, we present a typical test plan that could be used for aeroelastic model validation.

5.5.1 Measurement Quantities

5.5.1.1 Mass, Inertia, and Other Structural Properties

Mass, inertia, stiffness, or other modal properties need to be measured for model input validation and tuning. This is usually performed before the wind turbine is installed on the tower. At a minimum, critical components and subsystems (blades and nacelle) should be measured for mass, center of gravity, and rotational inertia. Inertia measurements of the tower are valuable, but less critical because most solid modeling programs provide accurate estimates. In the case of a turbine with a tail vane, it is recommended that the tail inertial properties be measured.

Different methods exist to arrive at good estimates of these properties; Windward Engineering has had success measuring blade inertia via both a pendulum method and a bifilar pendulum as seen in figure 2.

Figure 2. Measuring blade weight and center of gravity (left) and inertia with a bifilar pendulum (right). ***Photo courtesy of Windward Engineering***

Once the wind turbine is installed, it may still be possible to gather some system mass properties such as drivetrain and rotor inertia. As another example, Figure 3 shows how Windward Engineering derived rotor rotational inertia: a blade with a weight hung at its tip was rotated away from the vertical (6 o'clock) position and the rotor was allowed to swing back and forth. The rotor rotational inertia was then calculated by analyzing the frequency of oscillation.

Figure 3. Rotor rotational inertia is measured using a weighted blade and measuring the frequency of oscillation. ***Photo courtesy of Windward Engineering***

Yaw friction and structural damping are additional measurements that may be needed for model input validation. The yaw friction can be measured (easiest if on the ground, possibly while the nacelle is on a shipping pallet) simply by pulling on the nacelle (at a point where there is a moment arm) with a load cell and measuring the force needed to start and to keep it yawing. This will give a good value for the static and dynamic yaw friction for model inputs.

Structural damping can be determined experimentally for either a subsystem, a component, or an entire structure, through free-decay tests. An accelerometer can be used to measure the time series of oscillations; then, the data can be used to determine the logarithmic decrement from which a damping factor can be calculated. Figure 4 shows an example of free decay of a VAWT blade, initially displaced at the tip, which rendered information on the first flatwise eigenfrequency and damping ratio.

Blades and tower first natural frequencies can easily be determined by using accelerometers and free-decay tests. Alternatively, "low-frequency" components can be forced to oscillate at their first mode, by hand. Without the complication of a full modal test, higher modes can sometimes be extracted from the analysis of an accelerometer signal when the component/subsystem is excited via an impact hammer. The position of the accelerometer can be guided by a finite-element analysis that predicts the locations of antinodes (points of maximum deflections) for the various modes.

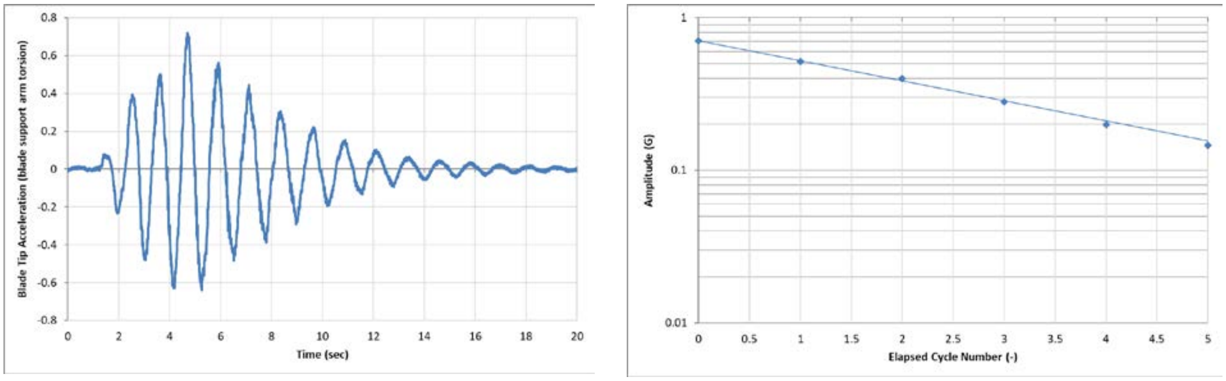

Figure 4. A vertical-axis wind turbine (H-rotor) blade tip oscillation (tangential lead-lag) in free vibration (left) and the logarithmic decrement plotted on a semilog plot (right). From this data, a damping factor of 5% was calculated.

5.5.1.2 Power Performance

The power curve is a fundamental characteristic of any wind turbine and a good foundation for model validation. IEC 61400-12-1:2017 (IEC 2017) gives details on minimum measurands (Table 6) that need to be measured for power performance.

Table 6. Fundamental Measurements for Power Performance

Measurement
Electrical power
Wind speed – hub height
Wind direction
Air density
Barometric pressure
Ambient temperature

In addition to the above measurements, additional measurands are recommended to better understand the turbine behavior with regards to its operation and power performance (Table 7).

Table 7. Additional Measurements for Wind Turbine Operation and Power Performance

Channel	Level of Importance
Rotor speed	Required for variable speed Recommended for constant speed
Yaw angle	Not applicable for VAWT
Yaw rate	Required for free yaw Not required for active or fixed yaw
Pitch angle	Required for variable-pitch rotors Not required for fixed-pitch rotors
Controller status	If available, such as brake status, freewheel or generating, etc.
Rotor azimuth	This will be used to resolve loads
Others	Such as furl, tilt, or any other turbine-specific parameter

The measurements would apply to either HAWTs or VAWTs, except for yaw angles that do not apply directly to VAWTs.

Other less-than-conventional configurations (e.g., AWE kites) will still require power-curve assessments, and most of the channels in Table 6 and Table 7 still apply, though with slight variations. For example, AWE kites may require wind measurements at different altitudes above ground. Other measurements specific to the configuration under investigation may include – but are not limited to – tether parameters, altitude, aircraft attitude and ground velocity, and control surface deflections.

5.5.1.3 Load Measurements

Measurands for a full loads campaign are specified in IEC 61400-13:2015 (IEC 2015) for a HAWT, with an informative guideline given for VAWT in Annex J. Capturing all of these measurands would be ideal for characterizing a wind turbine and to arrive at the PCMM but might be challenging for some smaller turbines or a company with a smaller field-testing budget. Depending on turbine topology and testing goals, fewer channels may be acceptable; for completeness, we list all the measurands that are perceived as the current "gold standard" in a load measurement campaign.

5.5.1.4 Horizontal-Axis Wind Turbine Loads

The fundamental loads to be measured for a HAWT are specified in IEC 61400-13:2015 and shown in Table 8. These load measurements correspond to the coordinate systems shown in Figure 5.

Table 8. Load Measurements for Turbines With a Rated Output Power Less Than 1.5 MW

Load Quantities	Level of Importance
Blade-root flatwise bending moment (M_{bf})	One blade mandatory, additional blade recommended
Blade-root edgewise bending moment (M_{be})	One blade mandatory, additional blade recommended
Rotor tilt moment (M_{tilt})	Mandatory
Rotor yaw moment (M_{yaw})	Mandatory
Rotor torque (M_x)	Mandatory
Tower-base normal (M_{tn})	Mandatory
Tower-base lateral moment (M_{tl})	Mandatory

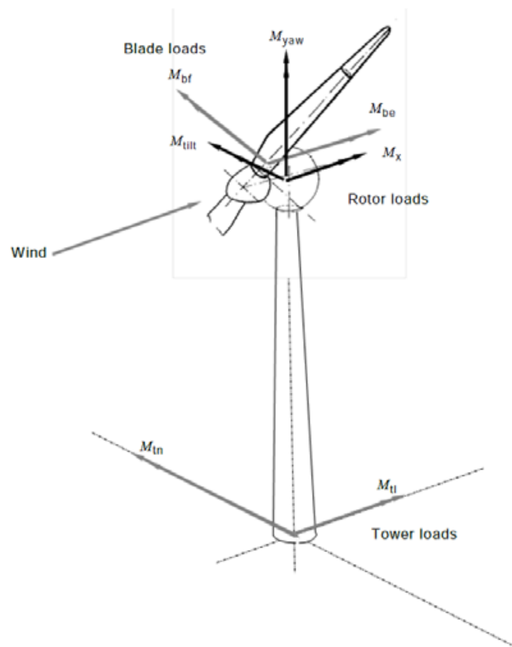

Figure 5. Coordinate systems used in IEC 61400-13:2015 for loads on horizontal-axis wind turbines (IEC 2015)

IEC 61400-13:2015 lists some additional load measurements for turbines with a rated output power greater than 1.5 MW (Table 9). This size is larger than any definition of a small wind turbine, but some of these measurands will be valuable for model validation—in particular, for validation of a modeling code or validation of a modeling code to a specific turbine topology. As one such example, the addition of tower-top bending moment allows the thrust load to be extracted as well as the tower drag loading.

Table 9. Additional Load Measurements for Wind Turbines With a Rated Output Power of Greater Than 1.5 MW But Which May Be Useful in the Validation of Models for Small Wind Turbines

Load Quantities	Level of Importance
Blade flatwise bending moment distribution	Two blades mandatory, additional blade recommended
Blade-root flatwise bending moment	Two blades mandatory, other blade recommended
Blade-root edgewise bending moment	Two blades mandatory, other blade recommended
Blade torsional frequency and damping	Recommended
Pitch actuation loads	One blade mandatory
Tower-top acceleration in normal direction	Mandatory when used for controller feedback
Tower-top acceleration in lateral direction	Mandatory when used for controller feedback
Tower-mid normal moment	Recommended
Tower-mid lateral moment	Recommended
Tower-top normal moment	Mandatory
Tower-top lateral moment	Mandatory
Tower torque	Mandatory

5.5.1.5 Vertical-Axis Wind Turbine Loads

The minimum recommended load channels for VAWTs from IEC 61400-13:2015 are shown in Table 10. These load measurements correspond to the coordinate systems shown in Figure 6.

Table 10. Minimum Load Measurements for Vertical-Axis Wind Turbines

Load Measurement	Measurement Location
Blade connecting point tangential bending moment (M_{bct})	On one blade
Blade connecting point vertical bending moment (M_{bcv})	On one blade
Blade midspan tangential bending moment (M_{bmt})	On one blade
Blade midspan vertical bending moment (M_{bmv})	On one blade
Connecting strut tangential bending moment (M_{st})	On one strut
Connecting strut vertical bending moment (M_{sv})	On one strut
Connecting strut axial force (F_{sa})	On one strut
Rotor torque (M_z)	
Tower-base normal moment (M_{tn})	
Tower torque (T_z)[a]	

[a]The standard lists "tower torque" as a measurand but this seems redundant to rotor torque. The standard does not list tower-base lateral bending, so "tower torque" could be interpreted as tower-base lateral bending moment instead.

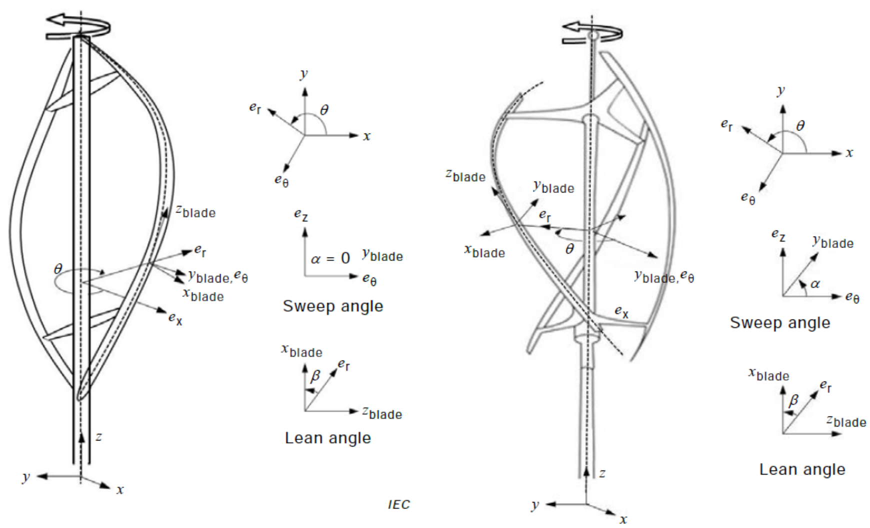

Figure 6. Coordinate systems used in IEC 61400-13:2015 for loads on vertical-axis wind turbines

5.5.1.6 Other Measurements

Certainly, other measurements will add value to either a unique turbine's model validation or to validate a specific attribute of an aeroelastic model. As an example, tip deflection of a blade might be a valuable measurement to assess the fitness of the model at capturing rotor deflections and centrifugal stiffening effects. Tip deflection can also be a critical and/or interesting measurement in the case of turbines with low initial tower clearance, flexible or hinged blades, and/or swept or asymmetrically laid-up blades where bend-torsion coupling exists. Tip deflection could be measured with a camera positioned on the hub and reflectors placed near the blade tip.

5.5.2 Calibrations

Non-load instrumentation such as those used in the power curve should be sent to a calibration laboratory for calibration. Calibration requirements can be found in the power performance standard IEC 61400-12-1:2017 (IEC 2017). Strain gauges for load measurements will need to be calibrated in situ. There are three common ways of calibrating these measurement channels.

1. **Gravity loading**: for blade, main shaft, and tower bending (the latter if nacelle overhang moment is sufficient)
2. **External load**: for blade, main shaft, and tower bending
3. **Analytical**: for tower and main shaft if beam theory is applicable (not recommended unless the other two options are not possible).

Note that it is critical that all load measurement locations be accurately defined; this will be required to match the locations in the aeroelastic model.

5.5.2.1 Gravity Loading Calibration Examples

Blade-edge moment: The blade-edge-root bending (in-plane) moment can be calibrated by rotating the rotor slowly in light or calm winds. Any offset can be determined from the mean of the sinusoidal signal, and the scale can be determined from the signal at the 3:00 and 9:00 positions. Shaft tilt will need to be known or measured.

Blade-flap moment: The blade-flap-root bending (out-of-plane) moment can be calibrated similarly to the blade-edge moment if the blade can be pitched to a full 90°.

Main shaft bending moments: The main shaft bending moments can be calibrated via a slow rotor rotation in calm or light winds. The distance from rotor center of gravity to gauge location and total rotor weight (with hub and partial main shaft) need to be known. The output signal will be a sinusoid where the mean should be zero and the maximum and minimums should be the calculated gravity moment.

Tower bending moments: The tower bending moments can be calibrated if the nacelle and rotor have a significant overhanging moment and if the turbine can be yawed around the tower. As the nacelle is yawed (in calm or light winds), the tower gauges will yield a sinusoidal signal, which should have a mean of zero, and the maximum and minimum moments are the center of gravity of the tower-top weight times the distance from the tower center.

5.5.2.2 External Loading Calibration Examples

Rotor torque: With a blade pointed at the 3:00 or 9:00 position and the brake applied, attach a cable (placed near the tip) with the other end lowered to the ground. Then, a known load can be applied (e.g., via calibrated weight), resulting in a known applied torque.

Blade-flap moment: The blade-root flapwise bending (out-of-plane) moment can be calibrated by pulling near the blade tip toward the tower. This will require either a climbable tower or the use of a manlift.

Tower bending: A cable can be attached to the tower top and tensioned from the ground at a generous distance from the tower base to ensure a good measurement of the angle. Both cable angle and tension must be measured with accuracy.

5.5.2.3 Analytical Calibration

If gravity or external loading cannot be accomplished, an analytical calibration can be performed. If the following information is known, then the output of the strain gauge signal can be converted to engineering units. This method is sensitive to small changes and will have a higher uncertainty compared with other calibration methods.

- Young's modulus, preferably from material test
- Poisson's ratio, preferably from material test
- Geometry of the part being gauged
- Gauge factor (of strain gauge)
- Strain gauge bridge factor
- Strain gauge cable lengths.

5.5.3 Measurement Load Cases

IEC 61400-13:2015 (IEC 2015) and IEC 61400-1:2019 (IEC 2019) give guidance for the measurement load cases (MLCs) and design load cases (DLCs) that should be captured both in modeling and during a measurement campaign. The MLCs and their corresponding DLCs are outlined in Table 11. It should be noted that most distributed wind turbines will fall under IEC 61400-2:2013 (RSA < 200 m^2), as opposed to IEC 61400-1:2019. Whereas IEC 61400-13:2015 is primarily focused on the testing of larger wind turbines, the MLCs are still relevant to smaller turbines associated with the equivalent DLCs that are required to be modeled/analyzed per IEC 61400-2:2013.

We expect these MLCs to be adequate for aeroelastic model validation. Specific variations will be required depending on the turbine configuration to be examined.

Table 11. Summary of Measurement Load Cases Outlined in IEC 61400-13:2015

Measurement Load Case SS = Steady State Trans = Transient Dyn = Dynamic Characterization	Design Load Case (from IEC 61400-1:2019)	Wind or Turbine State WS = Wind Speed	Comments
1.1 Power production (SS)	1.2	V_{in} < WS < V_{out} (or V_r + 4 m/s)	In this mode of operation, the wind turbine is running and connected to the grid
1.2 Parked (SS)	6.4	As high as possible	When the wind turbine is parked, the rotor may be either at a standstill or idling
2.1 Start-up (Trans)	3.1	V_{in} & V_r + 2 m/s	Capture loads on the wind turbine during the transients from standstill or idling to power
2.2 Normal shutdown (Trans)	4.1	V_{in}, V_r – 2 m/s, V_r + 2 m/s	Capture loads on a wind turbine during the normal transient caused by going from a power production situation to a parked condition
2.3 Emergency shutdown (Trans)	5.1	≥P_{rated}	Capture loads during an emergency shutdown
2.4 Grid failure (Trans)	2.4	≥P_{rated}	Capture loads during a grid failure
3.1 Power production (Dyn)		V_{in} ≤ WS ≤ V_{out}	Target frequencies: blade, tower, and drivetrain
3.2 Parked (Dyn)		As high as possible	Target frequencies: blade, and tower
3.3 Emergency stop (Dyn)		WS ≥ V_r	Target frequencies: blade, tower, and drivetrain
3.4 Yaw start/stop (Dyn)		Low or calm	Target frequency: blade—with an instrumented blade in a horizontal position, the blade gets excited by starting and stopping the nacelle yaw rotation. Test shall be conducted with blades in normal operating position (targeting the flatwise frequencies) and with blades feathered (targeting the edge frequencies).
3.5 Manual excitation (Dyn)		Low or calm	Target frequency: blade

5.5.4 Capture Matrix

IEC 61400-13:2015 (IEC 2015) gives guidance on how much data should be collected to acquire a statistically meaningful characterization of the wind turbine response.

5.5.4.1 Normal Power Production

The measurement campaign for normal power production is based on 10-minute time series data sets that are classified based on the average wind speed and TI. The data sets are then binned per wind speed and TI into 1 m/s and 2% TI bin-widths, respectively. The minimum capture requirements are different depending on the mean wind speed and the turbine's power regulation (see Table 12). All of the required 280 data sets (amounting to 48 hours worth of data) would likely require at least a few months of testing depending on the availability of high wind speeds at the testing site.

Table 12. Capture Matrix for Normal Power Production *(IEC 2015)*

Stall-Controlled Turbines		Non-Stall-Controlled Turbines	
Wind speed	Minimum data requirement	Wind speed	Minimum data requirement
V_{in} to 12 m/s	Twenty 10-minute data sets or 1 TI bin with six 10-minute data sets for each 1 m/s bin [TI must be >5%]	V_{in} to V_r – 2 m/s	Twenty 10-minute data sets or 1 TI bin with six 10-minute data sets for each 1-m/s bin [TI must be >5%]
12 to 16 m/s	Twenty 10-minute data sets or 1 TI bin with six 10-minute data sets for each 1 m/s bin		
16 to 20[a] m/s	Eight 10-minute data sets for each 1 m/s bin	V_r – 2 m/s to V_r + 2 m/s	Twenty 10-minute data sets for each 1-m/s bin
20[a] m/s to V_{out}	Eight 10-minute data sets (in total, not for each 1 m/s bin)	V_r + 2 m/s to V_r + 4 m/s	Ten 10-minute data sets for each 1-m/s bin

[a]If V_{out} is less than 20 m/s, data sets only need to be collected up to V_{out}.

5.5.4.2 Parked or Idling

The parked or idling load case will measure the loads in winds above V_{out} with and without yaw error. Three cases are outlined: (1) with a +30° yaw error, (2) with 0° yaw error, and (3) with a -30° yaw error. Although not required by IEC 61400-13:2015, capturing a data set with the turbine at 180° yaw error is recommended. This is a realistic MLC for either an active-yaw machine (due to a fault or a rapid wind direction change such as during a thunderstorm) or for a passive-yaw machine.

5.5.4.3 Transient Events

The transient load cases are performed in various wind conditions and require only a few data sets, as shown in Table 13.

Table 13. Capture Matrix for Transient Events *(from IEC 61400-13:2015 [IEC 2015])*

Event	Wind Speed	V_{in} to V_r – 2 m/s	V_r – 2 m/s to V_r + 2 m/s	>V_r + 2 m/s
Start-up	Minimum number of captures	3	-	3
Normal shutdown		3	3	3
Emergency shutdown	Target condition = P_{rated} Minimum number of captures = 3			
Grid failure	Target condition = P_{rated} Minimum number of captures = 3			

5.5.5 Data Post-Processing

One of the first steps in data processing entails calculating the required measurement quantities from the measured signals (e.g., air density from temperature and pressure, nonrotating rotor loads from rotating signals). The subsequent post-processing shall then be performed on the calculated channels and not necessarily the measured signals.

The time-series data shall be post-processed to provide summary statistics, damage equivalent loads, cumulative rainflow spectra, and power spectral densities. Fortunately, tools such as MExtremes or MLife have been developed to perform many of these calculations, and when combined with a dedicated spreadsheet, extensive measurements can be condensed into manageable and meaningful data. Details of how to post-process the data sets are not provided in this test plan but can be found in IEC 61400-13:2015 (IEC 2015).

5.5.6 Comparing Simulated Loads and Measured Loads

There are numerous ways to compare modeling and measured loads with the most typical shown in the next subsections. Other methods may apply to specific situations.

5.5.6.1 Statistical Binning

In this method, 10-minute statistics (such as mean, max, min, and standard deviation) from measurements are compared to statistically similar (in terms of wind inputs) modeling simulation results. The outcome of this method are scatter plots and/or bin/histogram plots.

5.5.6.2 Power Spectrum and Campbell Diagrams

Power spectral density, or power spectra, can be extracted from time-series data to compare the frequency content of the modeled data to that of the measured data. In particular, power spectral densities (Figure 7) can be used to verify how the power (in the various signals) is distributed within a range of frequencies between model and test measurements and whether matching of peaks occurs.

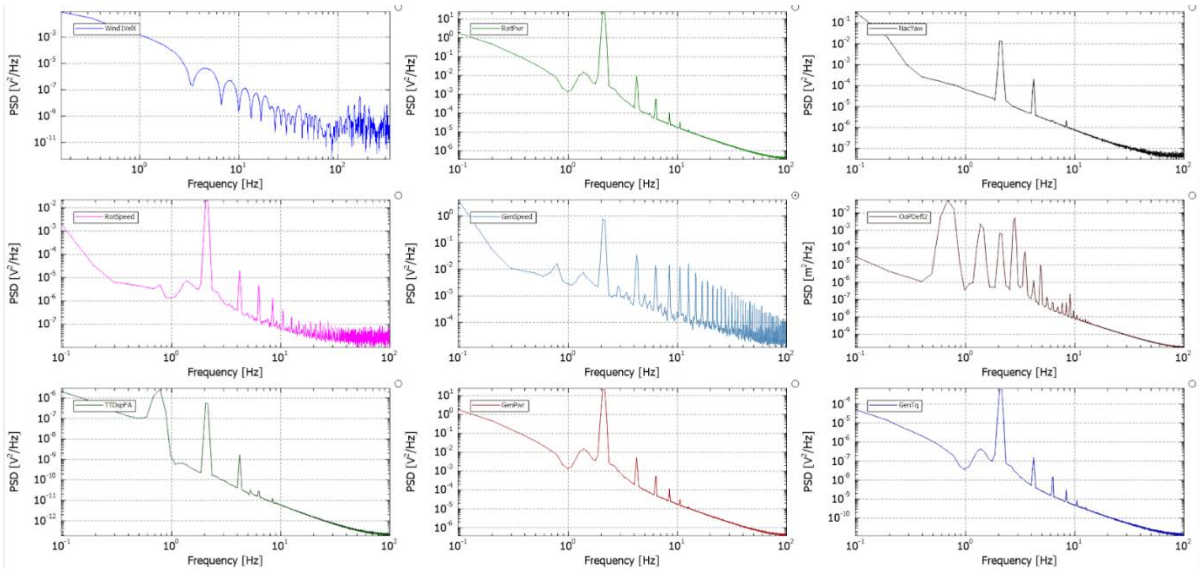

Figure 7. Typical channel power spectral densities (PSDs)

In parallel, a Campbell diagram (from model and/or modal tests; Figure 8) is used to both predict and justify observations. For example, analyzing Campbell data would help anticipate whether resonances could occur, assess dominant forcing frequencies, and determine whether instabilities are to be expected.

Comparing power spectral densities and Campbell diagrams from model and test data is very instructive of the predictive capabilities of the model across different operational conditions.

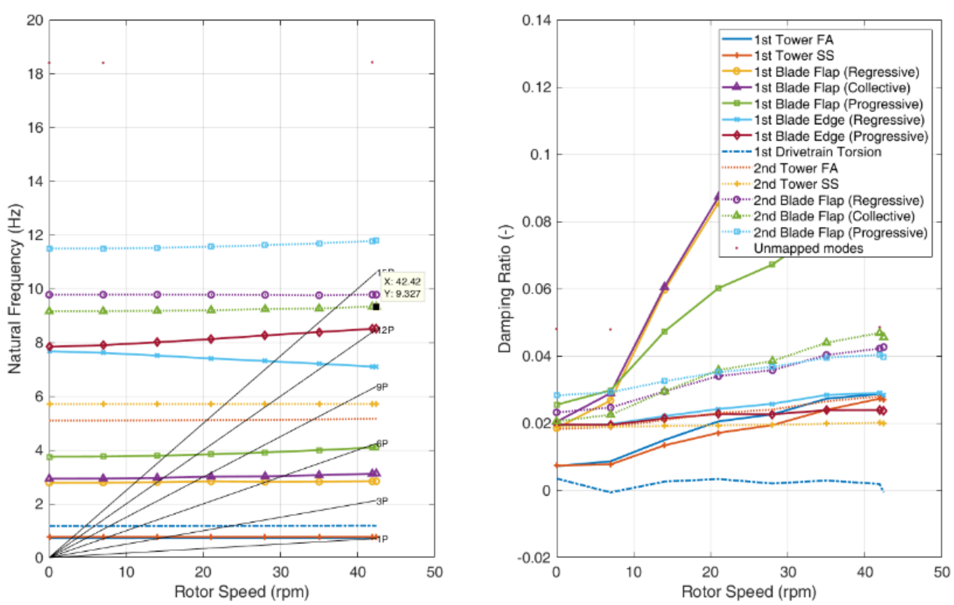

Figure 8. Example of a Campbell diagram

5.5.6.3 Fatigue Spectrum

In this method, a collection of 10-minute data sets covering a wide range of wind speeds and turbulence intensity is binned by wind speed, and then rainflow counted before being scaled by a Rayleigh distribution and transformed into a damage equivalent load (DEL). The DEL is the primary value for performing structural fatigue analysis on joints, welds, and other structural components.

Comparisons are then performed against model simulations using similar wind speed ranges and turbulence intensity values. Note that this is a validation procedure, whereas the actual fatigue analysis for design shall be performed based on turbulent wind field simulations as prescribed by IEC 61400-2:2013 and/or 61400-1:2019 standards (IEC 2013; IEC 2019).

Other DEL comparisons can be performed on a single data set or on a collection of data sets that have a common characteristic. For example, in the authors' experience, it was found useful to process DELs on 10-minute data sets (also known as "short-term DELs") and then plot these values against mean wind speed or TI. Often, the scatter plot will show higher DELs as the wind speed increases, but there may be multiple clusters of data showing multivalued DELs for the same wind speed due to differences in TI—Figure 9 shows one such example. Outliers within the scatter plot may also indicate particular environmental or operational conditions when more fatigue damage is occurring. Sometimes these high-fatigue damage events can drive a fatigue design, and they should be investigated further to make sure the model can accurately capture these unique situations.

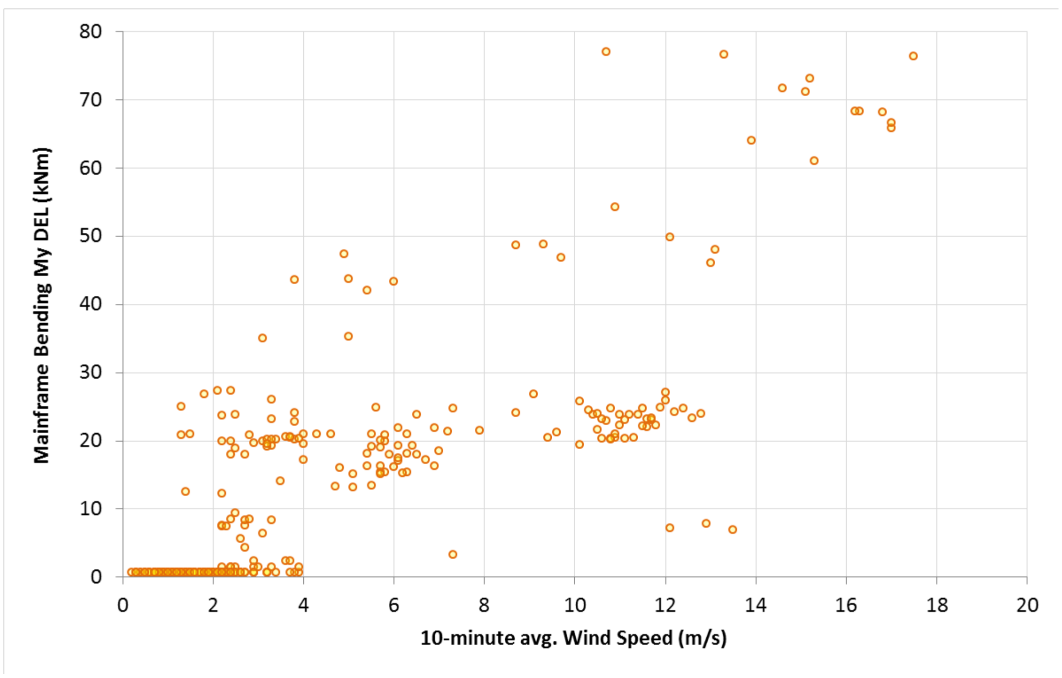

Figure 9. Example of measured 10-minute damage equivalent loads ('nodding' [My] bending moments of the turbine mainframe) scatter plotted against wind speed. Numerous data sets resulted in much higher fatigue damage even at the same wind speed. Further investigation showed a correlation to turbulence and yaw error where the bulk of the data was captured in lower turbulence typically showing DELs between 10 and 30 kNm.

5.5.6.4 Point-by-Point Comparisons

In point-by-point comparisons, the measured inflow conditions are input into the model simulation with the best approximation possible. This is especially useful for validating transient loads such as during start-up, shutdowns, fault conditions, or extreme winds. One challenge for this type of model validation is that the load measurements are based on the response to a three-dimensional wind field, yet the wind velocity is measured at a few locations or even a single location in space (i.e., hub height anemometer and wind vane). The simulated wind is therefore an approximation of reality even in the case of a fully three-dimensional inflow field, as it is based on relatively limited input information. The errors in load predictions will depend on the size and stiffness of the rotor blades, as well as the spatial coherence of the turbulence.

One example of a response to a gust event by a furling wind turbine is shown in Figure 10 as calculated by the AHSE code MSC Software ADAMS and as measured in the field.

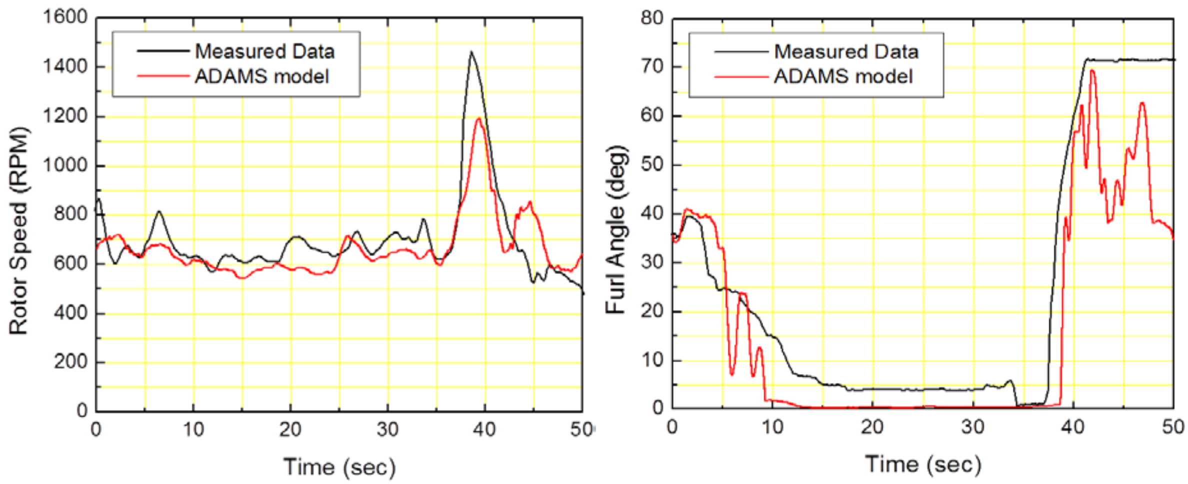

Figure 10. Example of point-by-point model validation for a 900-W furling wind turbine during a gust that resulted in a high rotor speed and rapid furling

5.6 NREL Planned Test Activities

NREL is installing three distributed wind turbines at their Flatirons Campus:

- A Bergey Excel 15, which is a tail-controlled, passive-yaw, upwind turbine, S category
- A QED PHX-20, which is an upwind, active-yaw machine, S category
- A Xant M-26, which is a 95-kW downwind, passive-yaw machine with a 26-m rotor, M category.

Data from these machines will be used for both SLM development and aeroelastic model validation. In particular, the Xant M-26 can be used to validate the OpenFAST model for downwind/passive-yaw dynamics, and potentially to validate the inclusion of new OpenFAST capabilities (e.g., yaw system friction). The Bergey Excel 15 could be tested to validate a future OpenFAST tail aerodynamics. All three turbines can be used to validate linearization capabilities in OpenFAST and for the identification of system eigenmodes.

Recommended test strategies and plans are given in Section 5.5.

6 Recommendations on General Improvements to Aeroelastic Modeling Codes and to Specific Wind Turbine Aeroelastic Models

6.1 General Recommendations on Improvements to Aeroelastic Code

To gather some feedback on the efforts brought forth by this project, interviews were carried out with original equipment manufacturers (OEMs) and consultants involved in DWT that have used AM in the recent past. The interview solicited inputs on their experience with AM, what works and what needs improvement, what key challenges they have faced, and what guidelines may be ideal to have for future efforts toward certification. The interviewees were Joshua Groleau (Pecos Wind Power), Tod Hanley (Bergey Wind Power), Jeff Minemma (former consultant), Sabina Auguscik (Eocycle), Scott Fouts (QED Wind Power), and Tim Olsen (consultant for QED Wind Power). These experts have experience with ADAMS, OpenFAST, Bladed, and other AHSE codes and several distributed wind turbine archetypes.

6.1.1 OpenFAST Recommendations

First, a common theme that emerged is the perceived need for a dedicated consultant with experience in AM and in AHSE codes. Though OpenFAST is an open-source code, learning a new code with a highly dispersed set of documentation (partially updated manuals, GitHub website open and closed issues, and fundamental know-how distilled into several forum posts on a different website) is an arduous proposition for DWT companies, even in the case of "in-house" availability of experienced structural and wind turbine engineers. Even in the case of other commercial codes, such as HAWC2, the level of knowledge required for their proper use is considered extremely high.

A series of obstacles associated with the open-source OpenFAST tool that make it difficult to create models and debug them when time is of the essence has been highlighted:

- The need to track multiple input files, at times with different reference frames to define properties of the various components
- The need for different preprocessors to generate the input parameters (e.g., tower eigenmodes, drivetrain, and yaw mechanism properties)
- The lack of an easy visualization of the assembled model or graphical interface
- The lack of an induction generator model in the latest controller interface
- Lattice tower modeling is cited as being extremely difficult to handle in OpenFAST, and folks have resorted to decreasing the degrees of freedom of the model (e.g., by including only the first tower eigenmode) to get a reasonable output from the simulations
- Airfoil data, especially the unsteady aero data, are very difficult to attain, and it would be ideal if OpenFAST could automatically handle some of the needed extrapolations or extensions of the airfoil polars. Additionally, the industry would benefit from publicly available collections of validated airfoil data for DWT applications. Note that existing databases exist (e.g., Tangler and Somers 1995; Timmer and Rooij 2003; Bertagnolio et al. 2001; Ramsay, Hoffmann, and Gregorek 1995), but a dedicated repository for DWT-scope airfoil data would be valuable.

Other commercial tools (sold under license) (e.g., Bladed) offer a graphical interface and the possibility of calculating some of those needed inputs directly within the main software program, so they are considered more user-friendly while offering an easier interface to debug models. Whereas some of these codes (e.g., HAWC2) are further supported by a direct line available to the users to call and receive immediate assistance and possibly on-demand modifications or improvements to the code, there still exist difficulties associated with running the tools on multiple-core CPUs or creating user-defined coordinate systems for the definitions of components (e.g., reference line for the blade fixed in HAWC2), thereby leading to inefficiencies in the workflow.

With furling or passive-yaw turbines, the difficulties increase, and there is general skepticism on the capability of OpenFAST to accurately capture the dynamics involved. The lack of a tail model in the current version of OpenFAST is felt as a serious problem because modelers resort to imposing an artificial yaw rate to simulate the effects of the tail on the yaw dynamics. Some of the OEMs stated that furling was complicated to model, and now that they have moved away from furling, they still face difficulties associated with estimates of the yaw rates and tail unsteady-aerodynamic drag coefficients for tailed turbines. The fact that the center of pressure on the tail would change with yaw angle is a serious issue that can, in the end, invalidate the simulations run with artificial yaw rates and either lead to dangerous underestimations of the loads or costly conservative estimates. For example, some interviewees stated that they would likely adopt a larger rotor if they could reliably simulate the blade-to-tower clearance in all DLC scenarios involving their passive-yaw, tailed design. Some others mentioned that they purposely moved away from a passive-yaw configuration to avoid "modeling nightmares."

Finally, if OpenFAST had a simpler linearization process to arrive at Campbell diagrams, that would crucially help the industry toward faster and more reliable design evaluations and validation. If visualization was also simpler, it would be useful as well, though it is not felt at the same level of priority as the ability to easily produce Campbell diagrams or other above-mentioned aspects.

6.1.2 Other AM Challenges

Besides comments on the AHSE codes, interviewees remarked that the AM prescriptions in design standards appear difficult to follow, even by experts. More information is requested, for example, on the number and input variation types of numerical realizations needed for fault cases, or on how to properly simulate drivetrain and rotor imbalances based on manufacturing tolerances. Overspeed is perceived as a "lurking" threat for SWTs, yet there exists wavering confidence in both the capability of AM to capture overspeed worst-case loading scenarios and on guidance from standards for fault cases that may lead to them. More advice on the selection of critical vs. non-design-driving load cases is also desirable, and when faced with a new configuration, it becomes essential. The scope of the output channels that should be monitored and investigated is also somewhat uncertain.

Overall, a detailed guidance document aimed at creating a design basis for DWT (e.g., similar to [Hansen et al. 2015]) is desired by many.

Additionally, some interviewees commented that the factors of safety in the standards are too large when AM is not used, especially when AM is not capable of capturing the physics (yaw dynamics in particular) much better than other methods (e.g., SLM or analytical treatments).

There is a general consensus that validation is an arduous and expensive exercise for distributed wind OEMs. Achieving meaningful and repeatable measurements is almost impossible for these companies. It seems like this is an effort that folks in the industry would ask NREL to perform at least on some commonly used archetypes.

Also important to many interviewees is understanding the failure modes that SWTs have encountered in the industry's experience to guide new designs away from known failures. Completing a failure modes and effects analysis (FMEA) before delving into specific DLC analyses is the preferred route to prioritize AM simulations and save engineering costs. However, the FMEA process is challenging, especially with entirely new designs, and some design aspects that seem critical at first turn out to be only secondary when tested or simulated, and vice versa. Some of the more established OEMs commented that they can benefit from their own experience on previous-model fleets. However, when a new model is introduced for a new turbine class, that historical experience is lost, and guidance on how changing the turbine class changes the design-driving load cases is highly valuable. It was stated that, ideally, NREL would provide a document with that kind of information for turbines that have failed in the past. NREL has published at least one report in that direction (Summerville et al. 2021), in which failed duration tests have been cataloged, though more detail could be provided on the modality of failures, component failures, and environmental conditions as well as load histories and fatigue spectra, if available.

An answer to some of the perceived needs is being addressed by this project, which is assembling AM templates of DWT archetypes that could guide the creation of new proprietary models by different stakeholders. Nonetheless, the consensus is that it would be very useful to have libraries of results associated with those AM templates, such as a library of DLCs and associated outputs. Time series, or at least statistics for the key output channels (for both performance and more importantly loads), provide a solid basis for validation of one's own model results. This is considered valuable and applicable even in the case where the turbine size differs between the actual model and the template model. A fundamental scaling guide with recommended best practices could help bridge the gap. In some cases, there is no basis at all against which to confirm a load level in a component, so this route is highly sought after.

6.2 Recommendations on Specific Wind Turbine Models

In this section, we focus on the specific archetype AHSE models that have been collected and that could be used by the industry to develop proprietary models for wind turbine analysis, design, and certification. Based on the assessment carried out in Section 4, we concentrated on high-priority models based on market presence and knowledge of current in-progress designs. This analysis may need to be updated in time as new archetypes become more prevalent in the market.

Based on our analysis and industry feedback, it is evident that even with well-established template models, there is a need for an expert to modify the template as appropriate for the specific characteristics of the wind turbine to be modeled, and that the technical effort is nontrivial. Yet starting from a template can provide guidance when specific input values are in question or unknown.

6.2.1 Upwind Horizontal-Axis Wind Turbine With Active Pitch and Active Yaw (L and M Categories)

The first model to be reviewed is the Sandia National Laboratories (Sandia) National Rotor Testbed (https://github.com/ckelley2/NRT/tree/main/FAST_v7). This model is based on a Vestas V27, a geared, active-pitch, active-yaw, upwind HAWT with an RSA of about 573 m^2 (rotor diameter is 27 m). The glass fiber reinforced polymer (GFRP) and balsa composite blade was redesigned to try to produce a wake similar to that of a downscaled GE37c blade (employed on the GE 1.5SLE) (Kelley and White 2018; Resor and LeBlanc 2014), and thus differs slightly from the OEM blade. This model is ideal from an engineering perspective because it benefits from a dedicated measurement campaign data set available at the DOE Data Archive and Portal (Naughton, Schreck, and Wright 2018). Not only was the model validated against data at the Scaled Wind Farm Technology (SWiFT) facility, but it also underwent an update in terms of airfoil polars to better represent the as-built conditions of the turbines. Although the model is provided in FAST v7.x, it can be easily ported to the latest OpenFAST version (currently 3.x) by NREL and/or consultants and can be used as an ideal template for turbines with a variable-speed, variable-pitch (to feather) control strategy in the L (>500 m^2) category (see Section 2, Table 1).

At the time of writing, the University of Florence and the Technical University of Denmark have not released their OpenFAST and HAWC-2 models of their respective upwind, active-pitch, active-yaw machines. We expect these models will provide good bases for the development of models in the M (200–500 m^2) category. Until these announced models become available, however, the Sandia National Rotor Testbed model could still be used as the template of choice for this machine archetype in the M category as well.

Examples of machines on the market that could use this AM template are the NPS 100X, Norvento nED100, Tozzi Nord Victory 60 and Victory 20, and Pecos Wind Power PW85.

Pros: Model extensively validated.

Cons: Model needs to be translated into latest OpenFAST.

6.2.2 Upwind Horizontal-Axis Wind Turbine With Fixed Pitch and Passive Yaw (S Category)

Two models are available to simulate upwind HAWTs with stall-controlled rotors. The two models are based on the Bergey Excel 10 (small wind research turbine) (Corbus and Meadors 2005) and the Aerogenesis 5-kW (Evans, Bradney, and Clausen 2018). Both machines are based on a passive-yaw control via a tail vane and are characterized by an RSA of approximately 26.4 m^2 and 19.6 m^2, respectively (S [10–100 m^2] category). The small wind research turbine makes use of furling in addition to stall control, whereas the Aerogenesis employs generator dynamic braking as a second control method for overspeed protection. The Bergey uses a direct-drive permanent-magnet generator, whereas the Aerogenesis uses a self-excited induction generator. OpenFAST currently does not have either furling or tail aero/structural dynamics; therefore, these models are better suited to be run in FAST v7.x. These models underwent extended validation at NREL and at the University of Newcastle. For both turbine models, the validation efforts demonstrated that while the models were generally capturing the overall behavior of the respective machines, the lack of torsional modes in the blades (not available in FAST v7.x) limited accuracy, especially at high yaw errors. These models are very well detailed—beyond what would normally be expected—in the aerodynamics of the rotor blades and structural dynamic parameters of all components, yet they primarily suffer from the difficulties associated with capturing passive-yaw aerodynamics and the lack of description of torsional stiffness and inertia in the blades.

The current OpenFAST version has a more advanced treatment for induction-factor calculation under yaw offsets, and it is capable of better handling unsteady effects in both the near- and mid-distance wake (unsteady aerodynamics and dynamic stall effects, and dynamic wake adjustment to inflow and rotor conditions in the dynamic blade element momentum theory or dynamic blade element momentum theory models, respectively). Additionally, OpenFAST's BeamDyn (blade structural dynamics module) is now capable of handling torsional stiffness in the blades and associated coupling between shear, torsion, and bending. OpenFAST also has a new erodynamic model to calculate induction factor based on a free-wake vortex method (OLAF) that should be verified in passive-yaw turbulent conditions. Furthermore, it is our understanding that OpenFAST will soon reintroduce the tail aerodynamics, although without furling. Machines with furling capabilities are still being manufactured, especially in the Chinese SWT market, but most Western manufacturers are moving away from that concept. Therefore, it is our opinion that furling is a lower priority (as discussed in previous sections as well), but that tail aerodynamics and structural dynamics are still critical for the modeling of a large swath of the distributed wind turbine market.

With a renewed tail aero-structural-dynamics in AeroDyn and ElastoDyn (aerodynamic and structural dynamics modules in OpenFAST) and a better description of the blade properties in BeamDyn, it is conceivable that an AHSE model could be tuned to accurately represent the turbine's dynamic yaw behavior in the turbulent environment. This is a validation effort that is best suited to be carried out at NREL with support from consultants. The Bergey Excel 15 scheduled to be installed at NREL's Flatirons Campus represents a great opportunity to develop a new, validated model for stall-controlled turbines with passive yaw in the S category. Even if the OEM does not allow for a public disclosure of the model as installed, the input set could be modified to depart sufficiently from proprietary information, while still retaining the nature of the archetype and confidence in the output. This new template would then replace the older models based on FAST v7.x.

Examples of machines on the market that could use this AM template as a starting model are: Bergey Excel 15 and Lely Aircon 10 and 30.

Pros:

- FAST v7.x models are available with extensive validation.

Cons:

- Fast v7 to OpenFAST conversion required
- Still missing tail aerodynamics in OpenFAST.

6.2.3 Upwind or Downwind Horizontal-Axis Wind Turbine With Fixed or Active Pitch and Active Yaw (S Category)

The UAE Phase VI model has been extensively validated in experimental campaigns in a wind tunnel (Hand et al. "Unsteady Aerodynamics Experiment Phase VI" 2001) and in the field at NREL (Hand et al. "Unsteady Aerodynamics Experiment Phase V" 2001). The standard machine has a two-bladed, 10-m rotor (RSA of 78.5 m^2) and can operate in either an upwind or downwind configuration. The UAE Phase VI had a special hub that allowed for a variable pre-cone angle and rotor teetering, yet the collected models (for upwind and downwind layouts, respectively) present a 0° pre-cone and do not contain any teetering parameter information. Additionally, the models have a simple induction generator, although the machine was capable of variable speed as well. Finally, in the models, no pitch controller is available, whereas the original machine was capable of fully independent pitch. Of course, modifications to the model inputs are relatively simple, based on the extensive literature available on the machine, except for the pitch controller, which would require some design effort.

The UAE Phase VI was a research wind turbine, therefore the nacelle and drivetrain components are rather unconventional when compared to current OEM products. Yet the blade design is representative of a 20-kW SWT, and the OpenFAST Aerodyn module has been tested and validated against the UAE Phase VI data in several inflow conditions—as recently as 2015 (Ning et al. 2015)—that can represent the actual inflow experienced by SWTs of this archetype. Consequently, the model is illustrative of certain characteristics of turbines of this size (S Category) and archetype (especially in terms of aerodynamic loading and blade structural response), but attention should be placed on how to best represent the actual characteristics of the nacelle and drivetrain. Nonetheless, scaling results for a specific wind turbine model AHSE campaign should be relatively straightforward.

Examples of machines on the market that could use this AM template are: QED PHX-20 and Lely Aircon 10 and 30.

Pros:

- OpenFAST model is available with extensive aerodynamic validation; detailed blade structural and aerodynamic information
- Validation data are available for different configurations in terms of pre-coning, yaw angles, and upwind vs. downwind configurations.

Cons:

- An unconventional architecture of the nacelle and drivetrain, with extra mass and features not commonly found in current market products.

6.2.4 Downwind Horizontal-Axis Wind Turbine With Fixed Pitch and Passive Yaw (M Category)

Two models were gathered for downwind turbines in the M category. They are representative of the old AOC-15/50 (Atlantic Orient Corporation 1994) and AWT-27 (Poore 1998) machines, both based on simple induction (fixed-speed) generators, stall controlled, and with RSAs of 147 and 175 m^2, respectively. The AWT-27 features a two-bladed rotor mounted on a teetered hub, whereas the AOC-15/50 features a three-bladed rotor with tip brakes or plates. Both models were studied by NREL in dedicated projects in the 1990s and were used to verify the capabilities of the AHSE FAST tool (precursor to the current OpenFAST tool) against other higher-fidelity codes such as MSC-Software ADAMS. As such, these models are considered well-suited to represent valid templates for downwind HAWTs in the M category. The templates can be easily edited to remove the teetering and tip-brake features, thereby simulating slightly different archetypes. Analogously, the generator model can be simply modified to simulate a variable-speed configuration, and the gearbox ratio can be set to unity in the case of a direct-drive unit.

Examples of machines on the market that could use this AM template are: XANT M-21 and M-26 and CWE Model 300-30.5 and Model 500-36.6.

Pros:

- OpenFAST models available.

Cons:

- Older architecture with fixed speed generator.

6.2.5 Downwind Micro-Horizontal-Axis Wind Turbine With Passive Yaw (XS Category)

One more model is currently available to the public in the XS (1–5 m^2) category. The model is for a three-bladed, stall-controlled, 1.82 m^2 RSA machine with a variable-speed, permanent-magnet generator. The model is available for the AHSE code HAWC-2 but could be translated to an OpenFAST input format. The value of this model resides in the associated validation data collected in a wind tunnel experiment with a focus on the passive-yaw dynamics (Verelst, Larsen, and van Wingerden 2016). Note that the data demonstrate how friction may be responsible for varying degrees of yaw error, which confirms the need for its accounting in AHSE models of passively yawing turbines.

Examples of machines on the market that could use this AM template are: Xzeres Skystream.

Pros:

- Model validated in wind tunnel
- Good set of data that could be scaled to slightly larger sizes to be used for validation.

Cons:

- Very few machines in the XS category will likely undergo a rigorous AM loads analysis; therefore, this model may not be widely used
- Need to convert to open-source OpenFAST code format.

6.3 Concluding Remarks on the Available Aeroelastic Modeling Templates

From a review of the available templates, and from the feedback received from experts involved in the AM of DWT-class machines, we can formulate a few concluding remarks:

1. Regardless of the accuracy and completeness of any given template, there is no substitute for an expert engineer to critically review the model and dedicate significant time to the building of a new model that captures the specific structural, inertial, and aerodynamic properties of the various components of the turbine under design and/or analysis.
2. Whereas model input templates can be useful to have a starting point and to check flag and switch settings in the model, the much greater value resides in the possibility of having the output of simulations carried out for these templates as a reference for comparison. Having detailed modal (Campbell diagrams), load (all major components, but blade, hub, shaft, tower top, and tower base at a minimum), and performance (rotor and generator power, torque, and rotor thrust at a minimum) reports for all the relevant DLCs in the standards would help significantly for both the building and troubleshooting of a new model as well as the model validation exercise. For example, having tables with statistics for all the major load channels and associated graphs (e.g., Figure 11) would quickly offer a good picture of the load entities and trends against which the individual OEMs could check their results.
3. In addition to templates and the reports in item 2 above, a document that could cover "good practice" in AM for DWT would be ideal. The document could be a refined tutorial on how to set up a new model based on a template, for example, with guidance on where particular attention should be placed. Additionally, the document could provide lessons learned based on the experience accumulated thus far in terms of witnessed failures, and what aspects of AM are most critical and where accuracy is crucial. Furthermore, the document could outline how to perform a typical loads analysis and how to set up the various DLCs as a function of different archetypes (i.e., it would be a companion to design standards such as IEC 61400-2:2013).

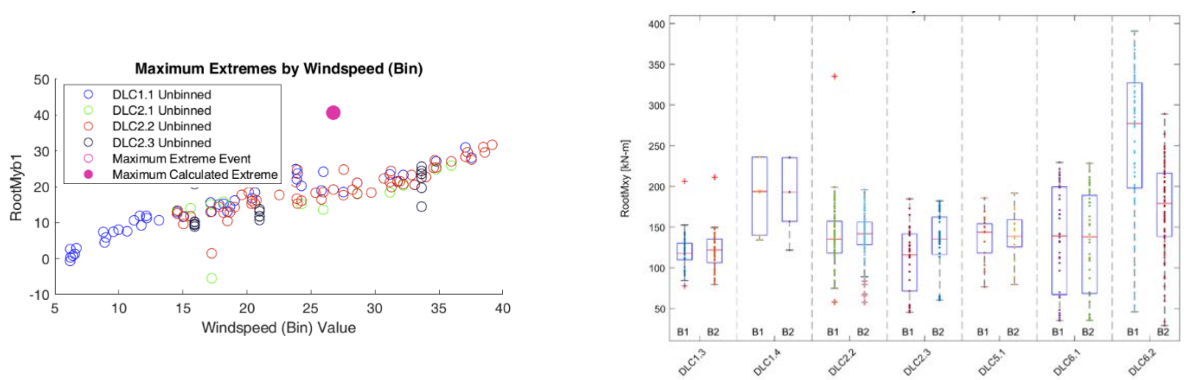

Figure 11. Examples of load statistics summary plots. Left: distribution of load (in this case, blade-root flapwise bending moment) maxima as a function of wind speed for different design load cases (DLC). Right: distribution of load (root-bending moment resultant for blade one [B1] and blade two [B2]) in terms of median (central mark), 25th and 75th percentiles (the bottom and top edges of the box), extremes (whiskers) and outliers (crosses), for various DLCs.

4. Except for the archetype that most closely resembles utility-scale turbines (upwind HAWT, with variable pitch and active yaw), all the other model templates suffer from some pitfalls. Some are in an outdated version of FAST but could be ported to the latest OpenFAST version once the code receives needed updates (e.g., to account for tail aerodynamics). Others could be replaced by more modern configurations, as is the case of downwind, passive-yaw turbines. The upcoming tests at NREL on a passive-yaw,

downwind machine are a valuable opportunity to both provide a new model for this archetype and to validate or improve and validate new physical models in OpenFAST (e.g., improved rotor aerodynamics under large yaw errors or yaw tracking).

5. The acquired models have been well validated, overall. Available reports have shown the largest discrepancies are associated with some of the missing features (e.g., yaw friction and tail aerodynamics) in AHSE codes, and/or poor code performance at capturing some of the more complicated fundamental physics (e.g., passive-yaw dynamics), which have already been listed in Section 4. Consequently, we recommend establishing a plan to both augment and improve the current physics in the codes (e.g., OpenFAST) and carry out new validation while also producing up-to-date template models and associated reports (per item 2 above) for the industry to use. The plan can take advantage of the new turbines being installed at NREL's Flatirons Campus as discussed in the previous subsections.
6. The most critically missing template, in the authors' view, is a VAWT AM template and associated load/performance reports. Efforts should be dedicated to the extension of OpenFAST toward VAWT modeling, possibly leveraging the efforts at Sandia with their Owens code.

7 Technical Weaknesses and Strengths of IEC 61400-2:2013 Aeroelastic Modeling Section

In this section, we identify weaknesses and strengths of the current edition of IEC 61400-2:2013 (IEC 2013) as perceived by the authors of this report and by stakeholders in the distributed wind industry that were interviewed in the course of this project. In particular, RRD Engineering, Windward Engineering, Wind Advisors Team, and NREL hosted a 4-hour workshop over 2 days to discuss the effort within this project as well as to elicit input from the distributed wind community on AM and its linkage to the standards. The workshop (called the Distributed Wind Aeroelastic Modeling Workshop, DWAMW) made use of an online survey software (Mentimeter) to get real-time feedback from the participants. There were 47 participants on Day 1 and 44 on Day 2. Most of the survey questions received more than 30 responses, resulting in about two-thirds of the participants providing feedback to each specific question, though an assessment was not completed to determine if the responses came from the same 30 individuals. These results will be presented within the following subsections where appropriate. The breakdown of the participants in terms of their role within the distributed wind industry is given in Figure 12.

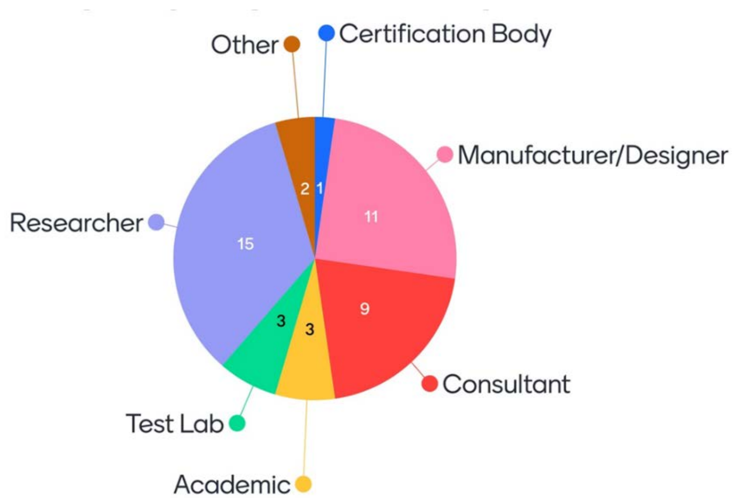

Figure 12. Distribution of Distributed Wind Aeroelastic Modeling Workshop (DWAMW) participant roles in the distributed wind industry

7.1 IEC 61400-2:2013 Loads Analysis Background

7.1.1 Loads

Concerning loads, the current standard (IEC 2013) addresses the following: (1) vibration, inertial and gravitational loads, (2) aerodynamic loads, (3) operational loads, and (4) other loads. These loads are defined as follows:

- Inertial and gravitational loads are static and dynamic loads acting on the SWT resulting from inertia, gyroscopic, vibration, rotation, gravity, and seismic activity (or motion of the support structure such as boats, etc.). Attention should be paid to the excitation of the natural frequencies of the turbine system.

- Aerodynamic loads are static and dynamic loads, which are caused by the airflow and its interaction with the stationary and moving parts of the SWT. The airflow shall be considered to be dependent upon the rotational speed of the rotor, the wind speed across the rotor plane, turbulence, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including aeroelastic effects.
- All loads that may occur due to special operating environments specified by the manufacturer shall also be considered (for example, wave loads, wake loads, ice loads, transport, assembly, maintenance, and repair loads).

7.1.2 Load Cases

History and experience have shown that the following DLCs most often determine the structural integrity of a SWT (IEC 2013):

- Turbine operation without fault and with normal external conditions
- Turbine operation without fault and with extreme external conditions
- Turbine operation with fault and appropriate external conditions
- Transportation, installation and maintenance, design situations, and appropriate external conditions.

If a significant correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a design load case.

Within each design situation, several DLCs shall be considered to verify the structural integrity of SWT components. As a minimum, the DLCs indicated by Table 2 and Table 4 in the IEC 61400-2:2013 standard (IEC 2013) shall be considered. In those tables, the DLCs are specified for each design situation by the description of the wind, electrical, and other external conditions.

7.1.3 Design Methodology

IEC 61400-2:2013 (IEC 2013) allows for three methodologies for determining the design loads, as stated below:

- Simplified load equations (SLM)
- Aeroelastic modeling (AM)
- Mechanical loads testing.

The focus in the following sections will be on AM.

7.2 Perceived Strengths of the IEC 61400-2:2013 Aeroelastic Modeling Sections

Based on the outcome of interviews with various stakeholders and feedback received during the DWAMW, the strengths of the IEC 61400-2:2013 AM sections (IEC 2013) seem to lie primarily on three pillars:

1. Wide community support for its development
2. Well-organized and defined DLCs including wind and control/safety system conditions
3. Adequate load factors used in AM.

Note that the DLCs are also seen by some stakeholders as too numerous (with redundant or superfluous cases) and not entirely clear (see Section 7.3).

The continued development of the IEC 61400-2:2013 standard should therefore maintain stakeholder involvement to receive feedback on new aspects that will be covered or modifications/additions to the DLCs and partial safety factors.

7.3 Perceived Weaknesses of the IEC 61400-2:2013 Aeroelastic Modeling Sections

DWAMW participants listed several weaknesses in the current edition of the standards. Some are tied to the definition of the DLCs, which are indicated by some as incomplete, especially when it comes to fault load cases. A better or more explicit definition of failure events to cover in simulations is requested.

Some participants commented on the possibility of providing more guidance or data to help avoid high safety factors associated with materials with minimum characterization. Furthermore, the current IEC 61400-2:2013 (IEC 2013) does not provide information on the required number of realizations, or on how to average peak loads to arrive at the estimate of the extreme, or on how to extrapolate the statistical probability of exceedances to arrive at high return period loads.

Specifics concerning VAWTs are not covered by the standards (as far as SLM and AM are concerned), and that is felt as a major deficiency by OEMs and consultants that support design, testing, and certification of VAWTs.

SLM, and especially the associated high partial safety factors are thought to be a significant weakness in the standards, as they are perceived to hamper cost-effective designs (see Figure 13). Furthermore, research and more data are still needed to address fatigue issues, especially in SLM, for both HAWTs and VAWTs.

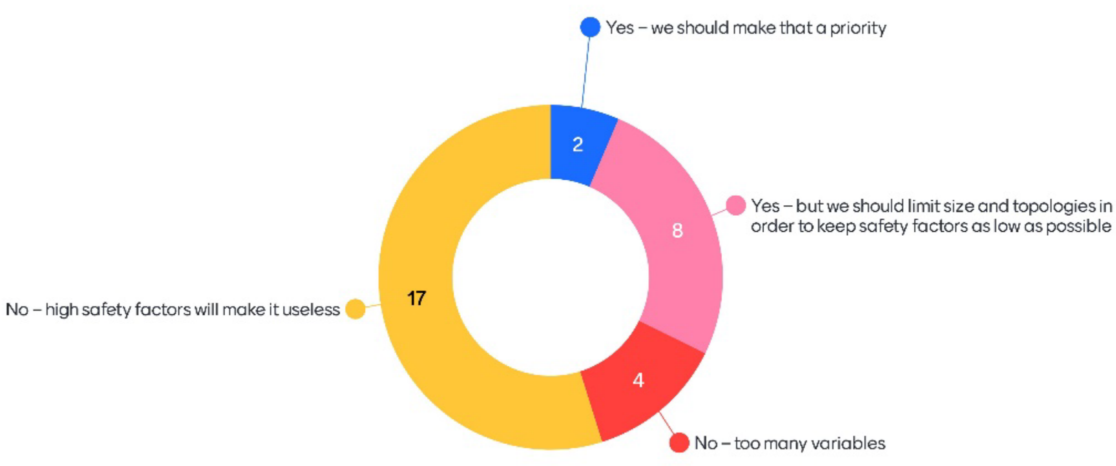

Figure 13. DWAMW participant feedback to a question on whether or not to expand the simplified loads methodology to different wind turbine sizes or archetypes

Many interviewees stated that the standards should be simplified to streamline and accelerate the certification process, albeit without reducing safety, reliability, and consumer protection.

The biggest weakness perceived by the participants of the DWAMW, however, is the lack of V&V requirements and guidance. This applies to both code verification (in the case of a new code used) and validation of the specific wind turbine model. During the DWAMW, it was stated that the standards are expected to continue balancing development – based on new physics and research – with the availability of new methods and tools, but the onus of demonstrating the viability of new tools should rest on the user.

The V&V guidance is also related to the categorization of SWTs as proposed in Sections 2 and 5 (Table 1 and Table 5). Currently, the lack of SWT categories is also a recognized weakness of the standards, as there exists no clear boundary for loads assessment requirements between turbines of different archetypes or sizes. In the following sections, we address aspects associated with V&V and turbine loads assessment category organization.

7.3.1 Wind Turbine Archetypes and Sizes for Loads Assessment and Validation and Verification

The distributed wind industry is made up of a vast array of wind turbines with respect to sizes as well as archetypes. Limiting the analysis to those with an RSA of less than 200 m^2, sizes vary from microturbines installed on sailboats or motorhomes (outputting DC) to grid-connected 150-kW turbines powering farms or businesses and outputting three-phase AC. Archetypes (see Section 4) encompass a large spectrum, from a traditional three-bladed, upwind, rigid-hub HAWT to a Darrieus VAWT, to a fly-gen tethered aircraft (AWE). Consequently, the design standard needs to move beyond the one-size-fits-all model and address some of this variation.

When asked whether Table 5 (based on RSA) is adequate to differentiate turbine models in terms of loads assessment and V&V requirements, DWAMW participants showed some neutrality (Figure 14).

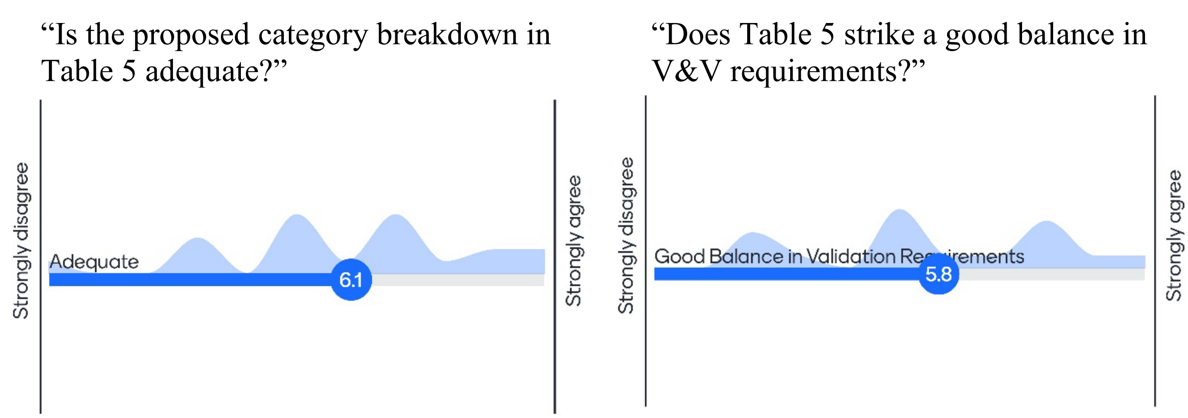

Figure 14. Distribution and average ratings provided by workshop participants to survey questions are shown at the top of the figures. The ranking scale was between 0 (strongly disagree) and 10 (strongly agree).

One concept that surfaced during the DWAMW was the idea of having a tiered partial safety factor structure, where validated models could benefit from lower partial safety factors and vice versa. Additionally, it is apparent that the archetype should be a factor, where a well-established archetype (e.g., HAWT with active yaw and pitch) with historically validated data should not be required to undergo the same validation efforts as archetypes of a more complex nature with less-understood or code-captured physics (e.g., downwind with passive yaw and stall controlled). Requiring a full loads campaign (similar to IEC 61400-13:2015) is viewed as too restrictive and burdensome unless no AM or SLM is performed.

7.3.1.1 Wind Turbine Sizes in IEC 61400-2:2013

In IEC 61400-2:2013 (IEC 2013), there are only a few references to wind turbine size. All references are based on RSA and not on rated or peak power, as follows:

1. Which design standard to use (RSA < 200 m^2): turbines with an RSA > 200 m^2 shall use IEC 61400-1:2019.
2. Manual shutdown button (RSA ≥ 40 m^2): For turbines with a swept area greater than or equal to 40 m^2, there shall be a manual shutdown button/switch, and shutdown procedures. The manual shutdown button/switch shall override the automatic control system and result in a parked machine for all normal operating conditions. For turbines with a swept area less than 40 m^2, the manual stop button/switch is not required, but shutdown procedures shall be specified. For these turbines, a manual stop button/switch is still recommended.
3. Support structure (RSA > 2 m^2): The support structure is a critical component for the SWT, as it carries the loads from the turbine down to the ground. If the RSA is greater than 2 m^2, then the support structure shall be included as part of the SWT system. Support structures shall also meet local codes and regulations. It is recommended that any wind turbine and tower that cannot be safely lowered to the ground for maintenance should have a fall-arresting system for ascending, descending, and working atop the tower.

7.3.1.2 Wind Turbine Sizes: Rotor-Swept Area vs. Power

While still not capturing the variability in archetypes, rotor size does account for—sometimes indirectly—the wind turbine's use, development and manufacturing costs, end customer's investment cost, and overall financial risk to all parties involved. In terms of the safety risk, however, size may not be the best differentiator, as smaller turbines that appear less dangerous at first glance are often installed and operated in more turbulent and structurally challenging conditions and much closer to people and buildings.

The distributed wind industry is still debating on how to best parameterize the size of a wind turbine while, as discussed above, the only differentiating metric used in the current standard (IEC 2013) is RSA. During the DWAMW, a question was asked on how to best break down categories for loads assessment (Figure 15). Most respondents (56% of them) picked RSA as the metric of choice, but, somewhat surprisingly, peak power was selected by about one-third of the respondents.

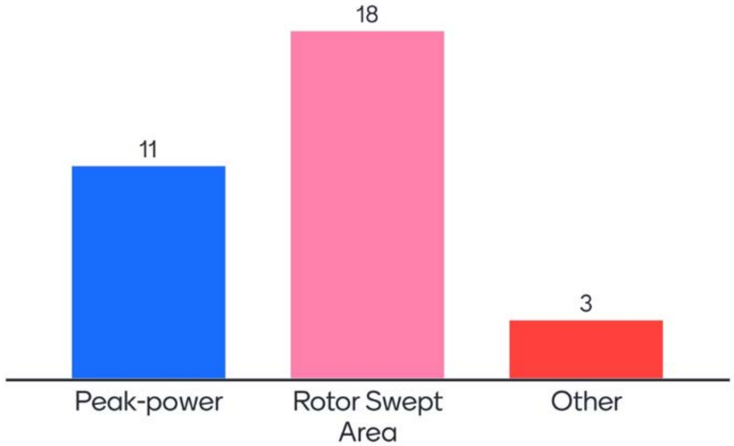

Figure 15. DWAMW participants' response to: "How would you break down categories for loads assessment?" The question was multiple choice (with three options), and 32 participants responded.

When trying to evaluate to which load category a turbine belongs or, in a broader sense, to categorize the financial costs and risk of a turbine, we argue that RSA is the preferred metric to use. The following example highlights this by comparing three distributed wind turbines: the Kenetech 100 kW (RSA = 227 m^2), the Micon 65 kW (RSA = 200 m^2), and the Eocycle 25 kW (RSA = 196 m^2) (see Figure 16). The three models have approximately the same RSA, yet the rated power varies by as much as a factor of 4.

Figure 16. Three turbines with similar rotor-swept area but different rated power. Left: Kenetech 100 kW (227 m2); Center: Micon 65 kW (200 m2); Right: Eocycle 25 kW (196 m2).

From a structural point of view, rotors of a similar size (in the same turbine Class, e.g., Class II per the new IEC recommendations for distributed wind turbines) are likely designed for similar ultimate loading and therefore are likely characterized by similar mass and stiffness properties. From an aeroelastic point of view, they can be considered similar, which suggests that they, indeed, belong to the same loads assessment category. Assuming these machines were not installed in an extremely high-wind resource area, they would also have similar annual energy production. From a financial perspective, these turbines would require similar balance-of-systems investments, and whereas generator and interconnection costs may be different, overall financial risks (rates of return on investment) can be considered comparable. In contrast, using a peak-power-based metric, during loads assessment, the smallest-capacity turbine in the above example would likely undergo less scrutiny than the largest-capacity one, and important aeroelastic coupling effects would be captured in one case but might be missed in another.

With the current IEC 61400-2:2013 (IEC 2013) upper bound of RSA ≤ 200 m^2, the Kenetech 100-kW turbine does not fall within the scope of the SWT standard. Given the above reasoning, this further suggests that the RSA limit for the SWT standard should be increased. A constraint that has been known to dictate the maximum RSA is associated with the maximum length of the blade that can fit in a standard shipping container—12.2 m (40 ft). Assuming the typical hub radius to be approximately equal to 15% of the blade length, the rotor radius that satisfies the shipping constraint is 14 m (46 ft) (diameter of 28 m [92 ft]). Many M-category distributed wind turbines currently cluster about this value, as shown in Table 14.

Larger distributed wind turbines exist that use some sort of blade segmentation (e.g., blade tips, blade-root extenders) and that can still fit in a standard shipping container. Nonetheless, because a boundary needs to be established in the standards, setting an RSA limit just beyond the natural break seen in the current industry may be preferred.

An additional benefit of using RSA as the primary metric is that RSA is defined early in the design process, whereas rated (or peak) power may vary and change after testing. This allows the wind turbine to be assigned a loads assessment category early without the concern that it may have to be reassigned after the design is completed and tested. Although the current trend is to upgrade a given turbine model toward larger and larger rotors with newer versions of the same machine, the repercussions on the system are nontrivial, and it is not always possible to remain within the same load envelope. Therefore, it seems reasonable that even though the power rating is unchanged, the aeroelastic nature of a turbine with a larger RSA changes sufficiently to potentially push the turbine into a different category.

Table 14. A Collection of Contemporary "Large" Small Wind Turbines and Associated Rotor Radius and Rotor-Swept Area. Photo credits from left to right: Endurance Wind Power, Eocycle, Tozzi Nord, Northern Power Systems, and Pecos Wind Power

					
Turbine	Endurance E4660	Eocycle EOX M-26	Tozzi Nord Victory 26-60	NPS 100C-28	Pecos PW85
Rotor Radius	12 m (39.5 ft)	13 m (42.7 ft)	13 m (42.7 ft)	14 m (45.9 ft)	15 m (49.2 ft)
RSA	433 m^2	531 m^2	531 m^2	616 m^2	707 m^2

Other DWAMW participants advocated for a power density metric (ratio of rated power to RSA) or rotor thrust density (ratio of rotor thrust to RSA). While these metrics try to account for both physical and electrical size in one metric, the difficulty lies in the fact that two turbines at either end of the spectrum (e.g., the sailboat battery-charging turbine and the grid-connected farm turbine) may have the exact same metric value, but, obviously, they would be affected by very different physics, and the requirements for loads assessment and V&V would (and should) be very different.

7.3.1.3 Wind Turbine Archetypes

From the arguments brought forth in the previous sections, it is apparent that a new classification of SWTs in the upcoming standards editions should account for both rotor size and archetype. On the one hand, the rotor size is linked to eigenfrequencies, eigenmodes, aeroelastic properties, and financial cost and risk of the machine. On the other hand, the archetype is tied to physics and the verification and validation of these physical characteristics in the AM codes.

Based on the authors' experience and the feedback received in this project, AM is well-tuned for traditional three-bladed, active-pitch, and active-yaw HAWTs, but less for passive-yaw HAWTs, and progressively less for models where even more degrees of freedom are present, as in the case of furling and teetering configurations (Forsyth, van Dam, and Preus 2019). VAWTs and AWE turbines are challenged by the limited number of AM codes and less documented effort and experience around V&V.

The archetypes that the standards could reference are:

- HAWT, with active pitch and yaw
- HAWT, with fixed pitch and passive yaw
- HAWT with shroud or teeter hinge or morphing coning or tilt

- VAWT
- AWE.

7.3.2 Verification and Validation

The current design standard (IEC 61400-2:2013) does not provide any guidance for V&V of an aeroelastic model. The only constraints provided (limitations concerning AM) are:

1. The RSA must be 200 m^2 or less to use the -2 standard
2. When using the SLM, the turbine must fall within the following configurations:
   - Horizontal axis
   - Two or more bladed propeller-type rotor
   - Cantilever blades
   - Rigid hub (not teetering or hinged hub).

V&V was a key discussion topic during the DWAMW, and below are some survey results demonstrating that it is regarded as a primary need by the distributed wind energy community. The majority of participants agree on the use of some load measurement as required for validation of an aeroelastic model (Figure 17). Furthermore, the majority of respondents agree on the importance of V&V to the entire industry, and that seems to be more consensus-driven than "improving physics of AM codes" or "simplifying their use," as can be ascertained from Figure 18.

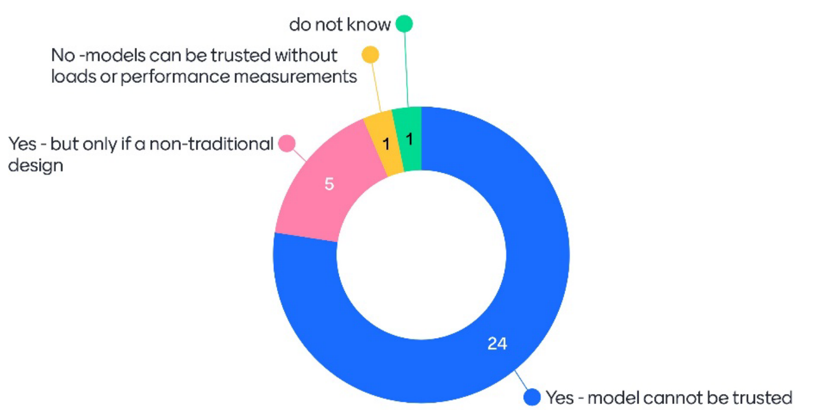

Figure 17. Distribution of DWAMW participant responses to a question on whether load measurements (V&V) are required to validate aeroelastic models

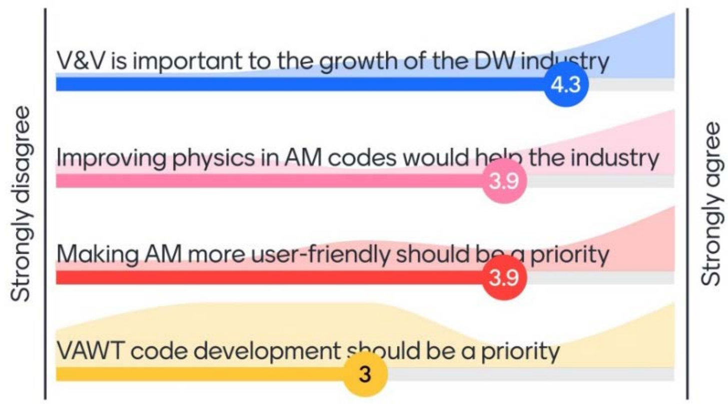

Figure 18. DWAMW survey: participants rated the above statements (1 = strongly disagree to 5 = strongly agree). The highest ranking was around the importance of V&V to the distributed wind industry.

Another survey question explicitly asked: "What are the biggest weaknesses in the standards when it comes to aeroelastic modeling?" Forty-two percent of the respondents answered: "the lack of V&V guidance/requirements." The remaining 58% were divided as follows: 21% said the standard was confusing or unclear, 21% were most concerned with the standard's inability to address nontraditional archetypes, and 16% were in the "Other" category.

7.3.2.1 Recommendations on Verification and Validation

Comments from stakeholders highlighted that a simple category organization as in Table 5 is not sufficient. We believe that an approach based on both size and archetype is the best approach to defining requirements for V&V as well as loads assessment.

To define the minimum requirements for V&V, the templates and associated load reports (see Section 6) could be used to create a validation grid that would report the prediction capabilities of a model based on different archetypes. As mentioned in previous sections, the collected publicly available templates have been sufficiently validated in the past. Yet most of the models are associated with older rotor geometries designed for higher mean wind speeds. It is advisable to arrive at new templates that better reflect contemporary designs for both aerodynamics and structural properties.

To this end, we also recommend leveraging the upcoming opportunities represented by new wind turbines being installed at NREL's Flatirons Campus (see Sections 5.6 and 6). The availability of new turbine archetypes that can be fully instrumented for loads, natural modes, and performance measurements constitutes an opportunity to further validate OpenFAST and possibly other AM codes (e.g., HAWC2, Bladed). In fact, the turbine test campaign may provide an additional opportunity for code-to-code verification of new physics, such as passive-yaw dynamics (tail aero-structural-dynamics, yaw friction, and rotor mid-wake). Furthermore, a modal test can be performed to confirm the prediction capabilities of the aeroelastic codes for the system eigenmodes and frequencies. Finally, if the intellectual property of the turbine models can be protected by slightly modifying the key properties of the machines, new AM templates could be generated together with associated load reports to be available to the entire industry and to provide guidance for revisions to the standards.

This V&V work would complement what has been done in the past and reviewed in this document, where we highlighted problematic areas of the codes, suggested remediation actions, and revisited specific AM turbine models and validation data (Sections 3, 4, and 6). This recommended campaign can also be an opportunity to improve the AM codes specifically for distributed wind use.

DWAMW participants mentioned some specific topics for V&V in addition to those already mentioned in this document:

- Stall and post-stall aerodynamics: This primarily involves stall-controlled rotors, but it would allow both understanding the current code capabilities and developing new aerodynamic models. Consequently, progress in this direction could open the door to pitch-to-stall control approaches (Bianchi, de Battista, and Mantz 2010), useful to the entire wind industry.
- Investigation of yaw rates in passive-yaw configurations.
- Best practices on how to measure yaw rates, rotor speed, and other quantities.
- Relationships of component loading to yaw errors and turbulence levels: This involves further aerodynamics and structural dynamics validation of the codes under yaw offset, turbulent winds, and unsteady rotor-wake dynamics.
- Lattice structure dynamics: In the distributed wind market, a large number of towers are of the lattice type. Further analysis is sought on the eigenmodes and on how to best represent them in the AM modal inputs.
- Structural damping: Damping is often guessed at in AM, and understanding the various contributions, including structural damping for different blade, tower, and drivetrain topologies would benefit the entire industry.

7.3.3 Revised Turbine Category Breakdown for Loads Assessment and Verification and Validation

A preliminary categorization for loads assessment and minimum required load measurements (for V&V) was proposed based on RSA (Table 5). Especially when evaluating the minimum requirements for V&V, RSA is still the fundamental metric but, as already mentioned, the archetype should also be considered. For this reason, we have expanded Table 5 into Table 15 to allow some well-verified aeroelastic models and well-validated archetypes to require less validation (regardless of their size). Conversely, aeroelastic models for less validated archetypes now have more onerous V&V requirements, even if they are small in size. In Table 15, a V&V ranking is assigned at the intersections of turbine categories and archetypes and is defined with the minimum field measurements, as described in the legend.

Table 15 condenses the various archetypes (see Section 4) into six key ones based, in part, on the study conducted in the course of this project. The six archetypes summarize various levels of uncertainty in AM's ability to capture the key load drivers. Active pitch-to-feather vs. stall control, or active vs. passive yaw are examples of key load driver characteristics, as opposed to upwind vs. downwind rotor configurations. Additionally, less common archetypes can still be captured in the Table 15 matrix. For example, a furling turbine (Category S, M, or L) lies within the passive-yaw archetype, resulting in at least a level 2 V&V ranking for AM validation.

Table 15. Category Breakdown for Loads Assessment and Verification and Validation Requirements

Turbine Category	RSA	Load Calculation Model used for Certification	Turbine Archetype: HAWT, Pitch Reg., active yaw	HAWT, Stall Reg., active yaw	HAWT, Pitch Reg., passive yaw	HAWT, Stall Reg., passive yaw	VAWT	AWE
Micro - XS	< 5 m^2	None	1	1	1	1	1	1
		SLM	1	1	1	1	1[a]	
Small - S	5 m^2 ≤ RSA < 100 m^2	SLM	1	1	1	1	1[a]	
		AM	1	2	2	2	2	4
Medium - M	100 m^2 ≤ RSA < 500 m^2	AM	2	2	3	3	3	4
Large - L	> 500 m^2	AM	2	3	3	3	3	4

LEGEND

1	Performance testing only: – power, RPM – environmental conditions: wind speed and direction, air density – key control parameters such as: yaw angle, furl angle, teeter angle, trajectory, and attitude quantities, as applicable.
2	Performance testing plus tower base loading.
3	Performance testing, tower base loading, and blade-root[b] bending moments (flap and edge).
4	For AWE: Performance testing, tether/bridle loading, and wing-root bending moments.

Note: measurement of shaft loads, tail boom loads, strut loads, as applicable, are encouraged.

It is recommended that component and system natural frequencies and modes should be measured as applicable to validate the model.

[a]Any SLM for VAWTs will need to be verified for use.

[b]Other span locations may be instrumented if they are expected to show higher loading levels (e.g., central span for VAWT simply supported blades).

Note also that Table 15 includes AWE archetypes. With AWE kites, aeroelastic models should also be able to capture both the trajectory described in space and the orientation (or attitude) of the aircraft, as these are fundamental performance quantities that are additionally linked to vehicle dynamics, safety, and loading aspects.

In support of the actual boundaries of the various categories and to verify the ranking assigned in Table 15, data from actual turbine models should be collected both in the field and through dedicated AM simulations to arrive at a data-driven consensus for codification in future editions of the standards.

7.4 Challenges and Priorities for Enhancing Aeroelastic Modeling Use

In this section, we summarize feedback received during the DWAMW in terms of perceived challenges and priorities to enhance the use of AM.

Figure 19 shows that the majority of the problems highlighted from workshop participants are associated with setting up or using the model (75%), with a smaller number (25%) saying they cannot use AM due to either cost or other issues.

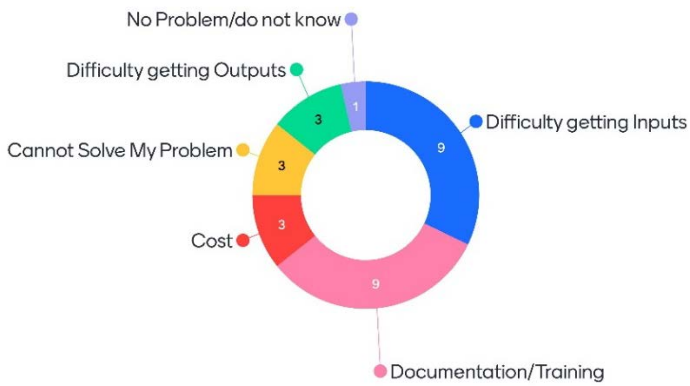

Figure 19. DWAMW responses to: "What are the biggest challenges in aeroelastic modeling?"

Twenty-four percent of the DWAMW participants stated that they had difficulties generating the modeling inputs, 38% struggled with not having a turbine feature available in the model, and 38% were challenged by either the difficult use of the code or some aspect of model refinement (see also the open-ended responses captured in a word cloud in Figure 20).

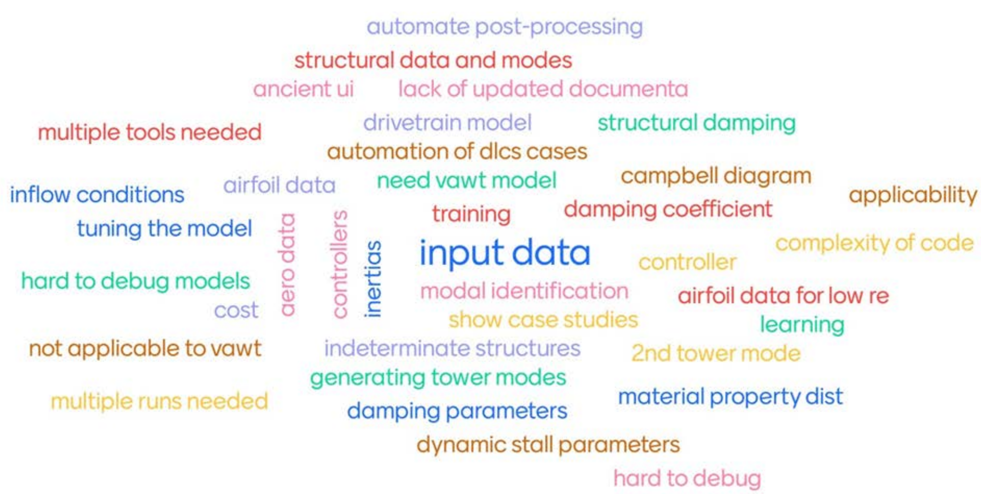

Figure 20. DWAMW responses to: "What are the pain points in aeroelastic modeling?"

In Figure 21, we show the ranking resulting from a survey on code advancements/features. Stakeholders voted as the top three priorities: better support for control tuning and design, improved documentation including code best practices guides, and improved "yaw features" such as tail dynamics and yaw friction.

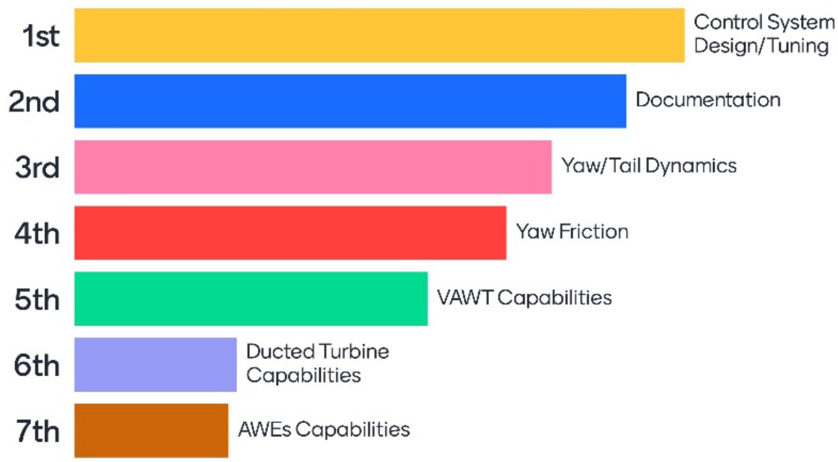

Figure 21. Results of DWAMW survey on code-advancement priorities

Figure 22 shows that the top R&D priorities to facilitate the widespread use of AM should include new guidelines for the use of aeroelastic codes, physics improvements to OpenFAST that reflect modern turbine design, tutorials based on collected turbine model templates, and validation guidance for loads assessment category (see Section 7.3.3).

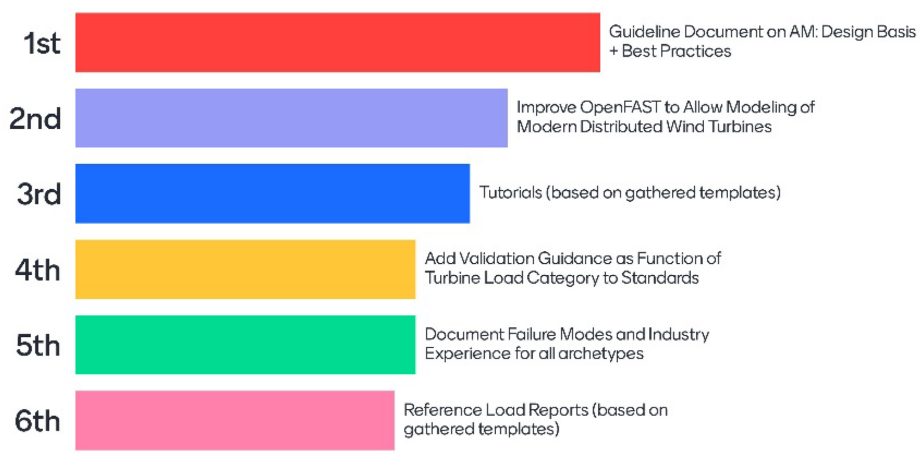

Figure 22. Results of DWAMW survey on overall aeroelastic modeling priorities to facilitate aeroelastic modeling adoption in distributed wind

8 Strategies To Redefine Standards Requirements

Based on the information gathered in the course of this study and through dialogs and interviews with relevant stakeholders, this section seeks to summarize the key strategies for design standards development.

For aeroelastic modeling to become more widely employed in the industry and to support distributed wind turbine certification, the requirements in the design standards should be clearly identified with regard to several aspects that are discussed in the next subsections, including loads assessment category and V&V prescriptions, turbulence modeling, and VAWT design. In addition to these facets, we address three more points related to SLM—duration testing, conformity assessment, and acoustic noise testing—that are still tied to AM, though indirectly. In the last subsection, further activities are mentioned around outreach to educate, engage, and attract new audiences to the field of AM.

8.1 Loads Assessment Category and Aeroelastic Modeling Applicability

The classification of the loads assessment category should be revisited and expanded given additional stakeholders' inputs. Three methods are currently available—within the current design standard—for wind turbine structural design (SLM, AM, and mechanical load testing). These methods are available to the entire spectrum of small wind turbine sizes up to an RSA of less than 200 m^2 (IEC 2013) with additional restrictions for use of the SLM. For the SLM, the wind turbine shall meet all of the following requirements: horizontal-axis, two or more bladed propeller-type rotor, cantilevered blades, and rigid hub.

The proposed loads assessment category and AM applicability would follow the current standard (IEC 61400-2:2013) with the following changes:

- The SLM will only be allowed for micro (XS) and small (S) turbine sizes, with encouragement to use AM for all turbine sizes
- The RSA threshold will be increased to 500–700 m^2 to better accommodate the current distributed wind turbine market, as discussed in Section 7.3.1.2
- Minimum requirements and guidance to be included on V&V as described in the following section.

8.2 Verification and Validation Requirements for Aeroelastic Modeling Use Toward Certification

The requirements for V&V of an aeroelastic computational tool and a specific turbine model for certification purposes should be clearly indicated in the design standards. Verification of the code ensures that the tool is deemed free of gross physical errors, whereas the validation of the specific turbine computational model guarantees that the AM process is acceptable for design and certification. The challenge lies in striking a balance between guaranteeing the safe use of AM, and therefore achieving safe designs, and preventing an unnecessary validation expense on the OEMs and CVAs. In the course of this project, with inputs solicited from several experts in the field, including opinions of OEMs, academia, national laboratories, and consultants, we arrived at Table 15 as a proposed solution to this challenge. Table 15 addresses both loads assessment classification and requirements for V&V for different archetypes, from HAWTs to AWE kites. Whereas AWE kites will likely require the development and publication of a dedicated standard given the additional challenges and constraint issues of airborne devices, IEC 61400-2:2013 should offer some guidance for CVAs and OEMs in the interim.

Table 15 proposes a minimum validation scheme for certification that is progressively more onerous the larger the scope of the machine or the more unconventional its configuration. For the smallest machines (XS and S) with conventional archetypes, only performance testing is required, whereas tower-base load measurements are recommended for the S category with archetypes different from the canonical pitch-controlled, active-yaw HAWTs. For larger machines (M and L) with archetypes other than the canonical one, blade-root (or central-span for vertical-axis turbine simply supported blades) bending moment validation is also required. AWE kites will require additional validation channels (e.g., tether/bridle loading, and wing-root bending moments).

The aeroelastic code used for AM should be verified according to the prescriptions indicated in Sections 5.2.1-5.2.2 and cited references. Based on the same material presented in this study, the standard should provide language for the CVA to be able to qualify as "verified codes" those that may be proposed by OEMs for certification.

We recommend that a dedicated V&V for small wind turbine certification guide be published, which can be referenced as an informational annex in updated international design standards. The document may encompass principles of the V&V framework (e.g., extracting them from Section 5.2.1), but point to practical aspects that both OEMs and CVAs could refer to (e.g., extracting them from Section 5.2.2–5.5). Furthermore, this document could also address conformity assessment criteria, as discussed in the next section.

8.3 Turbulence Model and Wind Turbine Classes

The normal turbulence model should be revised following the latest research on inflow characteristics in the DWT environment (Forsyth and Baranowski 2018), and the wind turbine classes may be revised following new definitions for urban or rural applications. As mentioned in Section 2, consensus exists in the DWT technical community to limit the IEC 61400-2:2013 turbine classes to just Class II and S and to raise the reference turbulence intensity at 15 m/s to TI15 = 20%. Class S would be used to cover open-country (rural) environments where the current TI15 = 18% is more appropriate. This aspect has been extensively covered by IEA Wind meetings and other stakeholder meetings and could be proposed to the IEC TC88 committee without further analysis.

8.4 Vertical-Axis Wind Turbine Guidance

VAWTs are only mentioned in the current standard (IEC 2013), yet there is an obvious need for more guidance in the standards. Given the situation with no publicly available code or model to calculate both VAWT aeroelastic loads and performance, the next revision of the standards will likely not cover VAWTs in any significant detail beyond the current version. Future strategy for standards development requires developing at least one representative VAWT aeroelastic model. Commercial codes exist that can simulate Darrieus VAWTs. A recommended multiyear pathway is to approach the VAWT treatment with a multipronged approach:

1. Identify and procure a commercial VAWT turbine that has reached some reputable level of deployment and/or certification.
2. In collaboration with the VAWT original equipment manufacturer, develop a numerical model based on an aeroelastic software code capable of simulating VAWTs.
3. Install the VAWT at an accredited testing facility for loads and performance measurements.
4. Perform validation of the software and input deck.
5. In collaboration with the OEM, modify the numerical model to represent a publicly available template for the community.
6. Assess whether additional DLCs and MLCs should be devised based on what is observed in the field and from focused interviews with stakeholders and experts in VAWTs (Sandia and other research institute staff).
7. Develop an open-source tool for the aeroelastic simulation of VAWTs. Verify the model against the commercial software and provide new model input.

With an aeroelastic model of a VAWT, SLM could also be developed starting from the efforts in the Japanese national standard (JSWTA 2013), as discussed in the next subsection.

8.5 Role of Simplified Loads Methodology and Applicability

SLM is a structural verification procedure that can be used to quickly assess loads in conceptual and preliminary design stages. Based on Table 15, SLM can be used for XS and S categories. The new ACP SWT-1 standard would only allow SLM for wind turbines below 10-kW peak power. In Table 15, the S category includes turbines up to 100 m^2, which approximately translates to a ~30-kW rated power; conversely, a 10-kW turbine would be around 35 m^2. This discrepancy does not pose a big problem because the high safety margins used in the SLM tend to discourage larger turbines from using SLM due to the required overdesign requirements. Yet to arrive at a defendable threshold for the use of SLM for certification, studies should be conducted on several different turbines to be evaluated with both SLM and validated aeroelastic models to assess differences in component loading. Similar studies have been performed in the past, but the new emphasis on larger and larger rotors demands a renewed effort to qualify the range of applicability of the simplified equations used in the SLM and to eventually modify them as needed. In particular, load cases should be checked for validity on several archetypes and control system strategies (see Section 2.1.2), and the fatigue verification of SLM, which is perceived as inadequate for modern wind turbines, should be revised. Some of this research can be performed in parallel to aeroacoustic modeling V&V studies (as, for example, those proposed at NREL's Flatirons Campus and discussed in Section 5.6), by simply cross-checking SLM loading levels against those measured in the field and those attained through AM. This work could also evaluate and possibly ameliorate the concern that the safety factors are too high to make the SLM useful.

This would require dedicated studies that can also leverage accelerated fatigue testing of components (e.g., blades, shafts, tail connections, yaw joints). Another extension for SLM is toward the inclusion of VAWTs. An SLM model exists in the Japanese national standard (JSWTA 2013), but an international coordinated effort could be leveraged together with field testing and modeling capabilities described earlier to arrive at a physically based and validated SLM model for VAWTs.

8.6 Duration Testing

The duration testing is viewed by many stakeholders as an unnecessary burden toward market diffusion (see also Section 2.1.1). Efforts have been carried out (Summerville et al. 2021) to extract lessons learned from 31 separate duration test outcomes, and the proposed modification is to reduce the length of the duration test by:

1. Removing the requirement of a minimum number of months
2. Reducing the required number of hours of power production from 2,500 to 1,000
3. Removing specific requirements to operate at given wind speeds (e.g., greater or equal to 1.2 V_{ave}, or 2.2 V_{ave})
4. Changing the requirement of 25 hours of power production in wind speeds greater or equal to 1.8 V_{ave} to at least 10 hours at wind speeds greater or equal to 15 m/s
5. Removing the operational time fraction requirement
6. Removing the power degradation analysis requirement
7. Removing the requirement of dynamic observations in favor of a Campbell diagram analysis
8. Changing the average period from 10 minutes to 1 minute.

The reduction in duration testing length and overall specific requirements is balanced by the introduction of a 3-year in-field surveillance to track operational experience as part of the post-certification surveillance. This new approach to duration testing was virtually applied to the 31-case database (in a hindcasting fashion) and proved to be effective, leading to similar outcomes for the various tests within a shorter time frame. Based on these results and the consensus received within the DWT community, the new duration testing requirements could be proposed to IEC for the next revision to IEC 61400-2:2013. Alternatively, if more data were to become available, the hindcasting approach could be expanded to other test cases to gain further insight and consensus for this proposal for changes in the IEC 61400-2:2013 standard.

Another pathway that has been proposed is that of a tiered certification scheme, wherein a limited certification could be issued without the completion of the duration test. Additionally, for conventional configurations (upwind, fixed-yaw HAWTs), the duration testing could be replaced by component structural testing and/or fatigue modeling. These various proposals are not mutually exclusive and can coexist, and this multipath approach should be proposed to IEC TC 88/MT02.

8.7 Conformity Assessment

The conformity assessment sets up methods and procedures for certification and for reporting certification results; furthermore, it defines what is needed to update existing turbine certifications based on design changes. AM can help and drastically simplify conformity assessments following the changes in turbine architecture and recertification of a turbine. Starting from an AM-validated package, the model can be further validated with minimal or no additional testing depending on the changes carried out on the turbine design. A dedicated study of current best practices would be needed to yield guidelines and methods to support the conformity assessment process. We recommend that this study be conducted with the final outcome of a document that can be both the project deliverable and an official guide.

8.8 Acoustic Noise Testing

Acoustic noise testing is considered the most difficult of all testing requirements and with limited value to the consumer (ISA2019). AM codes are increasingly more powerful at capturing aeroacoustic noise (Bortolotti et al. 2020), and other noise sources could be cataloged and ranked in terms of expected pressure levels and tonality. Consequently, AM may help address some of the concerns related to the current noise and acoustic testing, and reduce the burden on OEMs, especially for typical archetypes. The upcoming field-testing campaign at NREL (see Section 5.6) is an opportunity to further validate the aeroacoustic models in AM codes and to devise a strategy to supplement the data returned by the AM code to satisfy new labeling requirements.

8.9 Outreach

Another area that could help the industry would be an outreach program to educate, engage, and attract new people to the value of AM standards and testing. The following is a list of topics that could be addressed:

- The standards, what they are used for, and their role in certification
- Aeroelastic modeling
    - What tools are available
    - How AM can help in design and certification
    - Workshops, online courses, or YouTube videos on getting started with AM
- Certification education
    - Requirements of certification
    - Time, costs, and challenges
    - Sample documents such as test reports and a design evaluation
- Testing
    - Role in certification
    - Value in design
    - Best practices
    - Workshops, online courses, or YouTube videos on setup, collecting, and post-processing of data (both performance and loads)
    - Information on accelerated fatigue testing—how to perform and its value.

9 Conclusions

In this project, we conducted an in-depth assessment of the status of aeroelastic modeling (AM) and its role within the standards for the distributed wind technology (DWT) industry. The study gathered input and feedback from a large number of national and international stakeholders, reviewed technical weaknesses and strengths of the current edition of the design standards, analyzed recent industry workshop and meeting minutes, collected publicly available AM templates, and provided an evaluation of the existing AM codes.

Aeroelastic modeling is the primary methodology for structural and performance assessment of any wind turbine, providing an understanding of the impact of design parameters on its loading and power response before witnessing it in the field. AM also provides an efficient means to perform trade-off studies for design optimization. Finally, AM can help define the conformity process in the standards and simplify conformity assessments following any changes in architecture and recertification of a turbine. Despite these advantages, the use of AM in the DWT sector is limited, especially within the less established original equipment manufacturers (OEMs). Recommendations within this study will advance the value and the ease of use of AM, which will allow the industry to better capitalize this underutilized tool, resulting in a more efficient design process, an easier path to certification, and overall better and more reliable wind turbine products.

AM is well-tuned for active-yaw and active-pitch horizontal-axis wind turbines (HAWTs), but less for stall-controlled, passive-yaw HAWTs, and progressively less and less for less-than-conventional archetypes (e.g., teetering hubs, vertical-axis wind turbines [VAWTs], and airborne wind energy kites). In this project, we collected eight (plus some variants) publicly available aeroelastic models that could be used by researchers and OEMs as starting templates to create new models. These public aeroelastic modes could also aid in the verification and validation of new AM code capabilities and less validated archetypes. The templates cover the most widely seen turbine archetypes in the market, spanning a large range of sizes, and even include some airborne wind energy archetypes. Most notably, however, is the absence of a VAWT model. No open-source aeroelastic code exists that can simulate VAWTs, and this is viewed as a fundamental obstacle to the certification of distributed wind VAWTs.

This study highlighted the steps required to improve AM adoption based on a multifaceted approach that encompasses augmenting AM software capabilities, publishing AM best practices and design bases, creating new model templates, providing guidance for V&V of codes and specific turbine models leveraging field testing best practice, and addressing weaknesses in the current standards. Many of the future objectives identified in this study could leverage the National Renewable Energy Laboratory's upcoming testing campaigns of three distributed wind turbines. Furthermore, this project provided a basis for V&V guidance that can be referenced in future standards and discussions of measurement requirements, and of a sample test plan that can be used to set up future V&V campaigns.

In Table 16, we summarize the recommended actions to improve the AM code OpenFAST, the most widely used code in the DWT industry. Some of the difficulties associated with OpenFAST were identified through dedicated interviews with several consultants and OEMs. Among those challenges are the lack of user-friendly interfaces for both input and output, especially as far as the aerodynamic data are concerned, and the lack of or less-than-ideal capability of modeling physics important to small wind turbines (e.g., tail and passive-yaw aerodynamics). In addition to these steps, continuous support from the national laboratory and industry consultants is envisioned to keep models up to date and verified as new technology gets developed and/or codes get updated.

In parallel to these recommendations for code improvement, we recommend further activities to promote widespread AM use in Table 17. In particular, based on our analysis of the available AM templates, we recommend developing reference wind turbine models for the DWT industry that are more aligned with modern designs.

These activities are expected to be conducted mostly in parallel or at least synergistically, in which the new developments in the OpenFAST code can take advantage of field measurements, and validation can leverage the new code capabilities introduced. Given the extent of these studies, prioritizing turbine archetypes may help with the management of the process, thereby leveraging lessons in the development process of both AM code and design standards.

An important component of this project was to assess priorities in the development of new editions of standards for small wind turbines. There is industry consensus that the small wind turbine standard needs to apply to turbines with a rotor-swept area greater than 200 m^2. Additionally, there is an urgent need for loads assessment and validation requirements of distributed wind turbines for which we have proposed a new categorization based on both rotor-swept area and archetype (see Table 15). Augmenting the standard with prescriptions on V&V and conformity evaluation is also perceived as a high priority. Additional aspects that require enhancement include the simplified loads methodology, which could be improved to account for fatigue loading in modern turbine configurations, and extended to cover VAWTs, while also revising the appropriateness of the assumed partial safety factors. Further strategies for improvements of the standards are summarized in Table 18. In the same table, we offer an estimate of the time involved in the various activities and recommend responsible parties.

Regardless of the accuracy and completeness of any given AM code and/or template, in the end, there is no substitute for an experienced wind system modeler. This expert will need to critically prepare and meticulously review the inputs, dedicate significant time to the building of a new turbine aeroelastic model, and knowledgeably post-process and interpret the simulation results. We trust the findings and recommendations dispensed in this study will promote the growth of the small wind turbine industry toward a more efficient design process with better outcomes through the use of AM.

Table 16. Top Improvement Priorities to the Aeroelastic Modeling Code OpenFAST (see Table 4 for more details)

Need	Strategy	Expected Time Requirement
Tail aerodynamics	Implement new tail aero-elasto-dynamics and validate the model at NREL’s Flatirons Campus	1 year
Yaw dynamics including Coulomb friction and passive yaw for downwind rotors	Implement a new yaw friction module and validate using a downwind turbine. Gather literature on wind tunnel and field experiments on downwind rotors. Run a validation campaign on one or more downwind turbines to assess the current capabilities of the code to capture yaw rates and yaw stability. Plan code improvements as needed to improve rotor aerodynamics. If needed potentially implement new controlled wind tunnel experiments.	1–3 years
Automated Campbell diagram and linearization capabilities	Create a built-in capability in OpenFAST to run all the simulations needed to perform trim search linearization, export relevant data, and visualization with minimum input from the user.	1 year
Develop and verify VAWT AM	Develop capabilities to model VAWTs including structural dynamics, leveraging existing capabilities in OpenFAST (AeroDyn and OLAF) as well as Sandia’s codes (OWENS and CACTUS).	3 years
Documentation	Provide a comprehensive manual to cover all modules, inputs, outputs, and modeling recommendations. The manual should be a living document (Wiki) with sections growing as needed based on users’ requests for clarification or guidance on specific aspects. This, rather than a forum or GitHub issue website, would simplify the end-user experience.	6 months

Table 17. Additional Activities in Support of Aeroelastic Modeling Widespread Diffusion

Need	Strategy	Expected Time Requirement
DWT reference models	Based on new efforts conducted at NREL with test campaigns of distributed wind turbines, produce AM reference models that are representative of modern turbines.[a]	2 years
AM template load, modal, and performance reports	Starting from available distributed wind turbine AM templates and reference turbines, compile complete load, performance, and modal response reports based on IEC standards; compile web library of template + load report for key components.[a]	1 year
Design basis, AM best practice	Starting from available distributed wind turbine AM templates and associated load reports, critically analyze the most impactful parameters; describe the setup of DLCs, especially for fault situations and best practices for data input and post-processing.	1 year
Guidance on failure modes for various archetypes	Research component failures across SWTs, interviews of OEMs, national and international testing laboratories, and CVAs. Compile a document with lessons learned.	6 months
VAWT AM model	Create a new VAWT AM open-source template first based on existing commercial code (e.g., HAWC2), then expanding to new open-source code.[a]	1 year
SLM development	Leverage NREL's upcoming test campaigns of small wind turbines (Bergey Excel 15, QED PHX-20, Xant M-26) to assess whether SLM equations are fit for larger turbines of various archetypes. Cross-compare AHSE simulations to SLM output and field measurements to assess both ultimate and fatigue limit state load estimates.	2–3 years

[a]Note that this activity may require new capabilities in OpenFAST.

Table 18. Top-Priority Improvement Strategies for Future Standards Development (see Section 8 for more details)

Need	Strategy	Expected Time Requirement
Loads assessment categorization	Starting from Table 15 assess whether SLM and AM can perform as prescribed on a round-robin approach with different turbines (e.g., the ones to be installed at NREL's Flatirons Campus).	1 year
V&V prescriptions	Based on the new field campaigns at NREL's Flatirons Campus, assess whether the indicated minimal testing requirements in Table 15 are adequate to qualify a model as fit for certification. Publish a document on V&V practical procedures for DWT OEMs, consultants, and CVAs to use based on information in this document – Section 5.2.	1 year
Turbulence model & turbine classes	Review IEA Wind Task 27 conclusions and propose a new turbulence intensity for the normal turbulence model (NTM) to better represent DWT installations. By the same token, a single IEC class (II) is recommended. IEC Class S would still be available for turbines designed for different operating environments.	IEC version cycle time
VAWT guidance	Validate and augment SLM for VAWT starting from the Japan Wind Power Association's SLM.	3 years
Duration testing	Propose a tiered certification approach together with a reduction in duration testing length and overall specific requirements, balanced by the introduction of a 3-year in-field surveillance to track operational experience as part of the post-certification surveillance.	1 year
Conformity assessment	Conduct a dedicated study of best practices to yield guidelines and methods to support the conformity assessment process. Assess the potential for simplification of the conformity process when making changes to a certified design when using AM.	1 year
Acoustic noise testing	Evaluate if there are lower-effort alternatives to the full acoustic test.	1 year

References

American Clean Power (ACP). 2021. *The Small Wind Turbine Standard*. ANSI/ACP 101-1-2021. Washington, D.C.:American Clean Power Association.

American Institute of Aeronautics and Astronautics (AIAA). 1998. "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations (AIAA G-077-1998(2002))." American Institute of Aeronautics and Astronautics. doi:10.2514/4.472855.001.

American Society of Mechanical Engineers (ASME). 2009. *Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer*. ASME V 20-2009. New York, NY: The American Society of Mechanical Engineers.

Atlantic Orient Corporation. 1994. *Advanced Wind Turbine Design Studies—Advanced Conceptual Study, Final Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-442-4740. https://www.nrel.gov/docs/legosti/old/4740.pdf.

Baring-Gould, I. 2020. Unpublished conceptual/content notes DWEA/NREL – AWEA standards review meeting, February 28, 2020, Arlington, VA.

Baring-Gould, I., R. Preus, and J. van Dam. 2019. *Unpublished Summary of February 27th Standards Forum*. Golden, CO: National Renewable Energy Laboratory.

Bertagnolio, F., N. Sørensen, J. Johansen, and P. Fuglsang. 2001. *Wind Turbine Airfoil Catalogue*. Roskilde, Denmark: Risø National Laboratory. Risø-R-1280(EN). https://backend.orbit.dtu.dk/ws/portalfiles/portal/7728949/ris_r_1280.pdf.

Bianchi, F., H. de Battista, and R. Mantz. 2010. *Wind Turbine Control Systems*. London: Springer.

Bortolotti, P., E. Branlard, A. Platt, P. Moriarty, C. Sucameli, and C.L. Bottasso. 2020. *Aeroacoustics Noise Model of OpenFAST*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75731. https://doi.org/10.2172/1660130.

Corbus, D., and M. Meadors. 2005. *Small Wind Research Turbine, Final Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-500-38550. https://www.nrel.gov/docs/fy06osti/38550.pdf.

Draxl, C., L.K. Berg, L. Bianco, T.A. Bonin, A. Choukulkar, A. Clifton, J.W. Cline, et al. 2019. *The Verification and Validation Strategy Within the Second Wind Forecast Improvement (WFIP 2)*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-72553. https://www.nrel.gov/docs/fy20osti/72553.pdf.

Evans, S., D. Bradney, and P. Clausen. 2018. "Development and Experimental Verification of a 5 kW Small Wind Turbine Aeroelastic Model." *Journal of Wind Engineering and Industrial Aerodynamics* 181: 104–111. https://doi.org/10.1016/j.jweia.2018.08.011.

Evans, S., S. Dana, P. Clausen, and D. Wood. 2021. "A Simple Method for Modelling Fatigue Spectra of Small Wind Turbine Blades." *Wind Energy* 24(6): 549–557. https://doi.org/10.1002/we.2588.

Forsyth, T. 2020. Unpublished discussion notes from the AWEA SWT-1 Standard Meeting, February 28, 2020, Arlington, VA.

Forsyth, T., and R. Baranowski (eds.) 2018. *International Energy Agency Wind Technology Collaboration Programme Task 27 Small Wind Turbine Technical Report, Draft*. Available at https://iea-wind.org/wp-content/uploads/2021/06/IEA-Wind-TCP-Task-27-Draft-Small-Wind-Turbine-Technical-Report.pdf.

Forsyth, T., J. van Dam, and R. Preus. 2019. Summary of European International Standards Assessment Forum, June 26–28, 2029, Dundalk, Ireland.

Hand, M., D.A. Simms, L.J. Fingersh, D.W. Jager, and J.R. Cotrell. 2001. *Unsteady Aerodynamics Experiment Phase V: Test Configurations and Available Data Campaigns*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-500-29491. https://www.nrel.gov/docs/fy01osti/29491.pdf.

Hand, M., D.A. Simms, L.J. Fingersh, D.W. Jager, J.R. Cotrell, S. Schreck, and S.M. Larwood. 2001. *Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-500-29955. https://www.nrel.gov/docs/fy02osti/29955.pdf.

Hansen, M.H., K. Thomsen, A. Natarajan, and A. Barlas. 2015. *Design Load Basis for Onshore Turbines*. DTU Wind Energy. DTU Wind Energy-E-0074(EN). https://backend.orbit.dtu.dk/ws/portalfiles/portal/106567720/Design_Load_Basis_for_onshore_turbines.pdf.

Hills, R.G., D.C. Maniaci, and J.W. Naughton. 2015. *V&V Framework.* Albuquerque, NM, and Livermore, CA: Sandia National Laboratories. SAND2015-7455. doi:10.2172/1214246.

International Energy Agency Wind Technology Collaboration Programme (IEA Wind). 2020a. *Updating Domestic and International Standards for Distributed Wind Technology, Draft.* Available at https://iea-wind.org/wp-content/uploads/2021/02/IEA-Wind-Task-41-DW-standards-challenges-DRAFT-01202020.pdf.

IEA Wind. 2020b. *Research Priorities, Domestic and International Standards for Distributed Wind Technology, Draft.* Available at https://iea-wind.org/wp-content/uploads/2021/02/IEA-Wind-Task-41-DW-Research-Priority-Catalog-DRAFT-01202020.pdf.

International Electrotechnical Commission (IEC). 2013. *Wind Turbines—Part 2: Small Wind Turbines*. IEC 61400-2:2013.

IEC. 2015. *Wind Turbines—Part 13: Measurement of Mechanical Loads*. IEC 61400-13:2015.

IEC. 2017. *Wind Energy Generation Systems—Part 12-1: Power Performance Measurements of Electricity Producing Wind Turbines*. IEC 61400-12-1:2017

IEC. 2019. *Wind Energy Generation Systems—Part 1: Design Requirements*. IEC 61400-1:2019.

Japan Small Wind Turbines Association (JSWTA). 2013. *Small Wind Turbine Performance and Safety Standard. Ed. 2.* JSWTA 0001.

Jonkman, J., J. van Dam, T. Forsyth, and D. Davis. 2003. *Investigation of the IEC Safety Standard for Small Wind Turbine Design Through Modeling and Testing, Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-500-33004. https://www.nrel.gov/docs/fy03osti/33004.pdf.

Kelley, C., and J. White. 2018. *An Update to the SWiFT V27 Reference Model*. Albuquerque, NM, and Livermore, CA: Sandia National Laboratories. SAND2018-11893. https://www.osti.gov/servlets/purl/1481579.

Kelly, M., I. Baring-Gould, and T. Forsyth. 2021. *Recommendations on Potential Standards Changes for Distributed Wind: Driving Research via IEA Task 41*. DTU Wind Energy. DTU Wind Energy E No. E-0219. https://backend.orbit.dtu.dk/ws/portalfiles/portal/257413831/IEA_Task41_D1.1_Final_Jun42021.pdf.

Maniaci, D.C., and J.W. Naughton. 2019. *V&V Integrated Program Planning for Wind Plant Performance*. Albuquerque, NM, and Livermore, CA: Sandia National Laboratories. SAND2019-6888. https://www.osti.gov/servlets/purl/1762662.

Naughton, B., S. Schreck, and A. Wright. 2018. "Wake: Wake Steering Experiment." Atmosphere to Electrons, U.S. Department of Energy. https://a2e.energy.gov/projects/wake.

Ning, S., G. Hayman, R. Damiani, and J. Jonkman. 2015. *Development and Validation of a New Blade Element Momentum Skewed-Wake Model within AeroDyn, Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-63217. https://www.nrel.gov/docs/fy15osti/63217.pdf.

National Renewable Energy Laboratory (NREL). 2020a. Unpublished notes from NREL/DWEA Small Wind Turbine Standard Meeting, February 13, 2020, Denver, CO.

NREL. 2020b. Unpublished notes from NREL/DWEA Small Wind Turbine Standard Meeting, February 28, 2020, Arlington, VA.

NREL. 2020c. Unpublished notes from DWEA SWT-1 Virtual Meeting. April 9, 2020.

NREL. 2021a. Appendix A - Statement of Work in RFP RFX-2021-10493 - "Aeroelastic Modeling for Distributed Scale Wind Turbines". Golden, CO.

NREL. 2021b. Request for Proposal No. RFX-2021-10493.

NREL. 2021c. Reference OpenSource Controller (ROSCO), Version 2.2.0. Accessed on Oct 2021. https://github.com/NREL/rosco.

Oberkampf, W.L., and C.J. Roy. 2010. *Verification and Validation in Scientific Computing*. Cambridge University Press.

Poore, R. 1998. *NWTC AWT-26 Research and Retrofit Project—Summary of AWT-26/27 Turbine Research and Development*. Golden, CO: National Renewable Energy Laboratory. NREL/SR-500-26926. https://www.nrel.gov/docs/fy00osti/26926.pdf.

Ramsay, R., M. Hoffmann, and G. Gregorek. 1995. Effects of Grit Roughness and Pitch Oscillations on the S809 Airfoil. Golden, CO: National Renewable Energy Laboratory. NREL/TP-442-7817. https://www.osti.gov/servlets/purl/205563-GvbHua/webviewable/.

Resor, B., and B. LeBlanc. 2014. *An Aeroelastic Reference Model for the SWiFT Turbines*. Albuquerque, NM, and Livermore, CA: Sandia National Laboratories. SAND2014-19136. https://www.osti.gov/servlets/purl/1503792.

RRD Engineering, LLC. 2021. “Publicly Available Aeroelastic Models for Distributed Wind Turbines.” DWT_AeroelasticModels.xlsx. Arvada, CO.

Summerville, B. 2020. Unpublished notes from AWEA SWT-1 meeting, February 2020, Denver, CO.

Summerville, B. 2021. Unpublished AWEA SWT-1 background and meeting notes for RRD. NREL.

Summerville, B., J. van Dam, R. Preus, I. Baring-Gould, T. Forsyth, and M. Bergey. 2021. *Justification for Updates to ANSI/ACP Small Wind Turbine Standard*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-79775. https://www.nrel.gov/docs/fy21osti/79775.pdf.

Tangler, J., and D. Somers. 1995. *NREL Airfoil Families for HAWTs*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-442-7109. https://www.nrel.gov/docs/legosti/old/7109.pdf.

Timmer, W., and R. Rooij. 2003. “Summary of the Delft University Wind Turbine Dedicated Airfoils.” *Journal of Solar Energy Engineering* 125: 488–496. https://doi.org/10.1115/1.1626129.

Verelst, D., T. Larsen, and J. van Wingerden. 2016. “Open Access Wind Tunnel Measurements of a Downwind Free Yawing Wind Turbine.” *Journal of Physics: Conference Series* 753(7): 072013. https://doi.org/10.1088/1742-6596/753/7/072013.

Wind Energy Model Evaluation Protocol (weMEP). 2021. “Traceable Model Evaluation for Wind Energy.” Accessed July 7, 2021. https://wemep.readthedocs.io/en/latest/.