Challenges and Possible Solutions in Aeroelastic Modeling for the Distributed Wind Industry

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Abstract. Aeroelastic modeling (AM) is the primary methodology for structural and performance assessment of any wind turbine; it provides an understanding of the impact of design parameters on turbine loading and power response before witnessing it in the field. Despite these advantages, the use of AM in the distributed wind technology (DWT) sector is limited. This article represents a short summary of an in-depth assessment by the authors of the status of AM and its role within the distributed wind technology design standards. The research gathered input and feedback from a large number of U.S. 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. Several goals were achieved including providing strategies for the load assessment categorization of turbines based on rotor swept area and archetype, and guidance for AM verification and validation. 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 technology products.

1. Introduction

The United States is a global leader in installed capacity of distributed wind turbines, yet the industry is microcapitalized and under competitive pressure from foreign manufacturers [1], some without certification. The U.S. Department of Energy (DOE) Wind Energy Technologies Office is supporting efforts to improve the certification process according to national and international design standards for distributed wind turbines – defined here as small wind turbines (SWTs) having peak electrical power of 150 kW or less per [2]. Similar efforts led by research and industry groups around the world [e.g., 3] pursue the common goal of increasing both the efficiency and the market diffusion of distributed wind technology (DWT). Yet, recent international stakeholder meetings [4–6] report that SWT standards and certification are increasingly perceived as obstacles to innovation and market penetration. In particular, as the International Electrotechnical Commission (IEC) 61400-2 design standard for SWTs [7] comes due for revision in 2022, a renewed demand has emerged worldwide for its overhaul to revitalize the SWT market that has seen declines especially in the United States and Europe [8]. Another perceived obstacle to the diffusion of SWTs is the limited use of aeroelastic modeling (AM), especially by the less established original equipment manufacturers (OEMs).

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In this paper, we report on the findings of a study sponsored by the DOE and the National Renewable Energy Laboratory (NREL) that set out to accomplish three main tasks: 1) assess the status of AM in the DWT industry; 2) assess strengths and weaknesses of the current design standards with regard to load modeling and in particular AM; and 3) assess availability and review of public aeroelastic models that could be used as templates for most common turbine archetypes. Of particular interest was the understanding how to best utilize decades of distributed wind turbine modeling and measurement expertise to both improve and simplify the certification for small and midsized wind turbines. The overarching goal of the project was to help strategize, develop, and implement a research method to improve national and international standards.

This paper is organized as follows: in Section 2, we offer a review of the key turbine archetypes present in the current DWT market and a summary of the status of AM and the broader loads modeling within the context of design and certification standards. The summary also draws from an expert elicitation and a review of recent international stakeholder meetings. Section 3 presents some actions taken and recommended future research steps to facilitate the widespread adoption of AM and simplify certification of SWTs. In particular, we introduce a collection of AM templates that can be used as initial reference models to help with verification and validation (V&V) efforts, and further present a breakdown of turbine categories for establishing load assessment and model validation requirements. Section 4 offers concluding remarks.

2. Analysis of Market Status, Certification, and AM

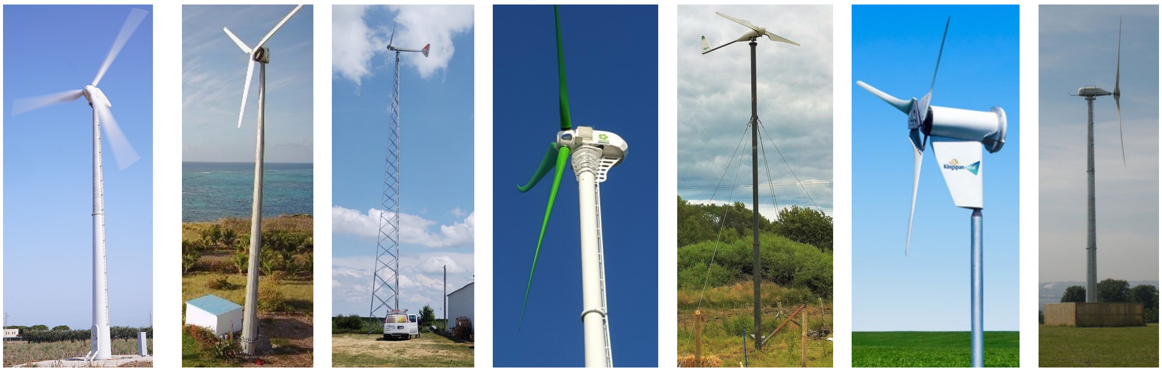
In this Section, we offer salient points obtained from a larger study [9] that was directed at assessing the status of AM in the context of design and certification standards for DWT on the eve of the expected revision to [7] and the issuing of a new U.S. standard [2].

The study reviewed minutes and notes by stakeholder leaders taken during national and international meetings that took place in 2019 and 2020: 1) Standards Forum held on Feb. 27th, 2019 — during the Distributed Wind Energy Association (DWEA) business conference — denoted as DWEA0227; 2) American National Standards Institute (ANSI)/AWEA SWT-1 — now ANSI/American Clean Power (ACP) 101-1 — meetings collectively denoted as ACP2020; 3) European International Standards Assessment Forum held on June 26–28, 2019, in Dundalk, Ireland, denoted as ISA2019; 4) International Energy Agency (IEA) Task 41 meeting held on January 20, 2020, denoted as IEA41 with comments and recommendations in [5, 10] and a comprehensive document currently being edited [11]. Furthermore, an expert elicitation was conducted to collect input from an international group of stakeholders with dedicated interviews and a dedicated 2-day workshop (denoted Distributed Wind Aeroelastic Modeling Workshop) virtually held in October 2021.

That study highlighted perceived weaknesses in the design and certification standards for DWT and listed a number of recommended actions [9], of which we give an overview in this paper. In the following subsections, we start from an analysis of turbine archetypes currently present in the distributed wind market and then offer conclusions from [9] grouped in terms of aspects related to the general requirements for load assessment and certification, role of AM, simplified load methodology (SLM), load measurements, and additional certification activities.

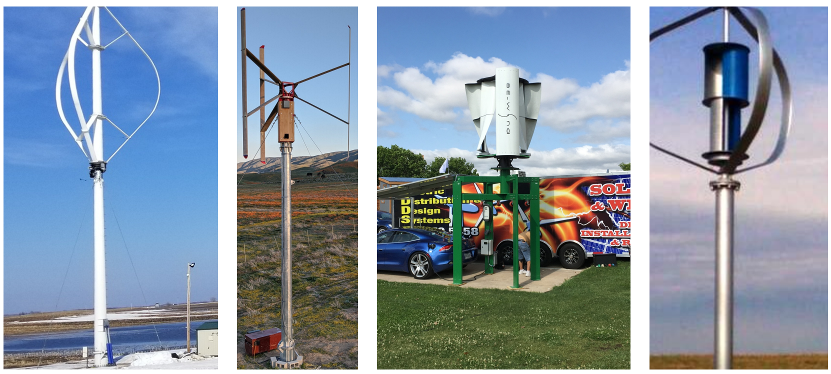
2.1. Model Archetypes

In contrast to the utility-scale market, where the upwind, three-bladed, active-pitch and active-yaw design is the vastly dominant configuration, in the DWT market, many different archetypes are still proposed. The horizontal-axis wind turbine (HAWT) archetypes span passive yaw, stall-control, and up- or downwind rotors with two, three, and even more blades (Fig. 1). New research impetus has even been dedicated to ducted turbines (e.g., Ducted Wind Turbines, Inc.), though they are not very common in today's market. Among the vertical-axis wind turbine (VAWT) archetypes (Fig. 2) are the Darrieus (troposkein, H, and helicoidal rotors), the Savonius, and the hybrid Darrieus-Savonius types.



(a) (b) (c) (d) (e) (f) (g)

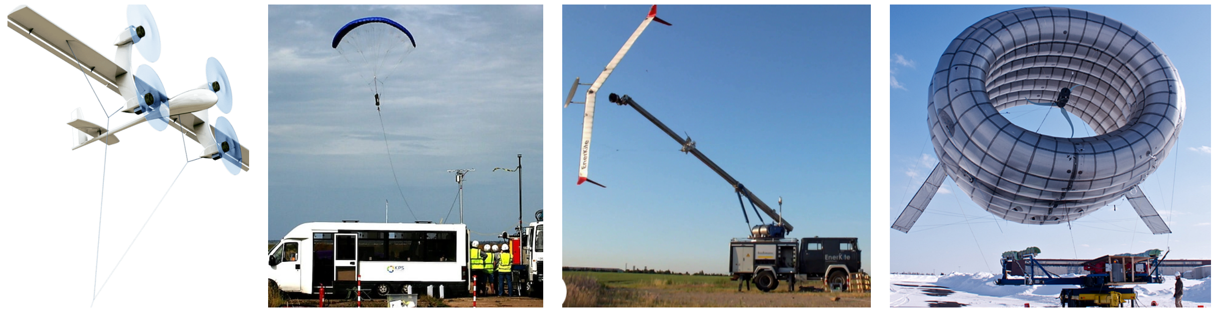
Figure 1: Common HAWT archetypes found in the current DWT market: (a) upwind with active pitch and yaw (photo credit: Tozzi Nord); (b) upwind with stall-control and active yaw (photo credit: QED); (c) upwind with stall-control and tailed passive yaw (photo credit: Bergey Wind Power); (d) downwind with stall-control and passive yaw (photo credit: Xant); (e) upwind with tailed passive yaw and furling (photo credit: Bornay); (f) downwind with pitch or pitch-coning control, and passive yaw (photo credit: SD Wind (formerly Proven)); (g) downwind with stall-control, passive yaw, and teeter (photo credit: Ryse Energy (formerly Gaia)).



(a) (b) (c) (d)

Figure 2: Common VAWT archetypes found in the current DWT market: (a) Darrieus Troposkien (photo credit: Chava Wind); (b) H-Darrieus (photo credit: Xflow Energy); (c) Savonius (photo credit: BE Wind); (d) combined Savonius-Darrieus (photo credit: HiVAWT).

From this quick overview, it is no surprise that providing design and certification guidance in the form of codified standards is a formidable task. Furthermore, the numerical models needed to support the development and steady diffusion of these machines must be versatile and robust. The distributed wind industry is poised to become even more varied and complex as airborne wind energy (AWE) devices, or "kites", are entering this space (Figure 3). Whereas it is expected that AWE will need a dedicated set of standards, it is obvious that they will heavily rely on the SWT standards in the interim.



(a) (b) (c) (d)

Figure 3: AWE archetypes currently being proposed in the distributed wind space: (a) fly-gen (photo credit: Windlift); (b) ground-gen flexible kite (photo credit: Kps); (c) ground-gen rigid kite (photo credit: Enerkite); (d) aerostat (photo credit: Altaeros).

2.2. Load Assessment Requirements

The most critical aspect that surfaced from the expert elicitation study and the review of the industry meetings is that the requirements for load assessment prescribed by the design standard [7] should be adequately modified not to overburden the SWT manufacturers with unduly and expensive activities. The new U.S. standard [2], for example, is defining new SWT subcategories (Micro to Large) based on peak electrical power (Table 1). Following the recommendations in [2], the Micro category is not required to provide any load assessment, whereas the other categories would be expected to use AM with various degrees of validation. Yet this may still fall short of being effectively applicable to the various ranges of archetypes.

Table 1: SWT categories per [2] and categorization proposed by ISA2019.

Category	Peak electrical power [kW]	RSA[a]	Load assessment requirements
Micro	$\leq 1\,\mathrm{kW}$	$3\,\mathrm{m}^2 - 5\,\mathrm{m}^2$	None
Small	$1\,\mathrm{kW} - 30\,\mathrm{kW}$	$5\,\mathrm{m}^2 - 50\,\mathrm{m}^2$	SLM[b] or AM and power/rotor RPM validation
Medium	$30\,\mathrm{kW} - 65\,\mathrm{kW}$	-	AM-only, validation as Small plus validation of yaw behavior and eigenfrequencies
Large	$65\,\mathrm{kW} - 150\,\mathrm{kW}$	$50\,\mathrm{m}^2 - 500\,\mathrm{m}^2$	as Medium plus validation of key component loads

[a] Rotor swept area (ISA2019 proposal).
[b] Simplified load methodology not recommended above 10 kW peak power per [2].

Furthermore, there seems to be consensus to limit the turbine classes in [7] to just Class II and Small, while raising the reference turbulence intensity at $15\,\mathrm{m\,s^{-1}}$ from TI = 18% to TI = 20% [6, 12] and the reference annual energy production wind speed to $6\,\mathrm{m\,s^{-1}}$ from $5\,\mathrm{m\,s^{-1}}$.

2.3. Role of Aeroelastic Modeling and Perceived Obstacles to Its Use

Aeroelastic modeling can be seen as the primary methodology for structural loading and performance assessment of any wind turbine as it allows the evaluation of:

(i) the load and power behavior of the turbine before witnessing it in the field;
(ii) extreme loading events that cannot be captured in the field;
(iii) control parameters that have the highest impact on the design;
(iv) the configuration's most efficient layout.

Whereas AM is routinely employed by the more established manufacturers in the medium and large segments of the DWT industry, there are several perceived obstacles to its widespread use.

First, historically, AM has been well-tuned for three-bladed upwind HAWTs, but less for downwind HAWTs, and progressively less validated for passive yaw, pitch-to-stall, furling, and VAWT machines [13].

Second, model V&V procedures are not well codified in the standards and are perceived as time-consuming and expensive. V&V activities entail both the verification of the software used for the numerical simulations and the validation of the specific turbine model. The degree of validation of an individual model should be adjusted depending on the experience of the code and the modeled configuration.

Third, the lack of publicly available model templates and load reports, especially for certain turbine archetypes, seems to deter many OEMs from adopting AM in their design procedures.

Other concerns that arose from our study deal with the realization that the normal turbulence model and associated turbulence power spectrum (e.g., Kaimal or von Kármán) used by AM codes do not reflect the turbulent environment of DWT sites. This leads to loading and performance that are not representative of actual SWT deployment conditions. Additionally, vertical inflow is perceived as an important factor for DWT turbines.

Furthermore, there is a widespread sense that the current development of AM codes is focusing solely on utility-scale wind turbines and the renewed challenges and idiosyncrasies that giant-scale rotors may bring forth. As an example, recent efforts [14] in the development of automatic control tuning for OpenFAST[1], the most widely used AM code in the DWT industry, have neglected fixed-speed generators that are still being used by several SWTs. Analogously, the tail and passive-yaw aero-servo-elastic dynamics are no longer supported by OpenFAST.

AM could, in principle, help understand the complex aero-servo-elastic response of SWTs, but appropriate guidance in detailed modal analysis is not present in the current standards. Current standards also avoid discussion of rotor nacelle assembly-to-tower vibrational dynamic coupling. This is perceived as a safety gap.

2.4. Simplified Load Methodology and Other Aspects of Certification

For the more typical three-bladed, upwind HAWTs, SLM captures the loads conservatively and up to relatively large sizes ($200\,\mathrm{m}^2$), thereby leading to overdesigned but safe components. New proposals (as for example that gathered by ISA2019 or [2]), however, are leaning toward relegating SLM to the smallest turbines (below $50\,\mathrm{m}^2$ or 10 kW of peak power, see Table 1) and enforcing AM for the Medium and Large categories.

SLM for Small and Micro VAWTs is not available in [7]. An annex of the Japanese SWT standard [15] contains some VAWT SLM guidance, which, at a minimum, should undergo an international validation to inform future national and international standards development.

Consensus exists on the need for the development of renewed SLM fatigue analysis methods that would account for different control archetypes, on-grid vs. off-grid turbines, and include factors such as yaw bearing loads (for passive yaw control), yaw error (for active yaw control),

[1] `https://github.com/OpenFAST/openfast`

and load cases such as power production plus fault, normal shutdown, and parked/idling (low cycle/high fatigue) [13, ISA2019]. This development effort would also require structural test data (e.g., blade fatigue testing results) and field measurements from different archetypes and site conditions, and support from AM campaigns.

SWT certification currently requires the completion of duration and acoustic sound tests. The acoustics test is perceived as the most difficult of all the testing requirements and as having limited use for the consumer. It is expected that future standards editions will decrease the emphasis on acoustic test requirements.

DWEA0227 and ISA2019 highlighted that the duration testing is too lengthy, and as a result ACP2020 [16] proposes to lessen the requirements while implementing a postcertification surveillance program to monitor turbines installed in the field.

Finally, there is a significant need for guidance on conformity assessment. 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. There appears to be a lot of uncertainty on these procedures, and conformity assessment is generally unclear and poorly documented in the standards. A study of current practices would be needed to yield an official guide outlining the conformity assessment process.

An expanded use of validated AM could help lessen the burden of duration and acoustic sound testing, and even simplify the conformity assessment and recertification following a change in the turbine architecture.

2.5. Field Testing and Validation Needs

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

(i) Certification (turbine model validation). Field testing is expensive and time-consuming. Research to determine the minimum number of channels and the minimum capture matrix required to validate a model will help reduce the burden on OEMs. Confidence levels will be higher for more traditional archetypes and lower for innovative and/or unconventional designs. Focused testing can help determine which archetypes require more measurements to confidently validate the models.

(ii) AM code validation and development. As more test data are accumulated, the AM codes are expected to become more accurate and to accommodate more diverse archetypes. 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.

(iii) 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 archetype) to which the SLM equations are applicable.

The first item targets the end-user community, whereas the other two primarily apply to the research community and stakeholders involved in the development of the design codes and design standards. Relevant V&V details pertaining to these areas of research are discussed in [9], which also provides a review of performance and load measurement requirements, testing site requirements, model-to-measurement comparison strategies, and a sample test plan. Here, we emphasize the role of validation with regard to the development of SLM. As mentioned above, the expectation is that only the smallest turbines will use the SLM in the future, whereas most larger turbines will find that approach to loads assessment too conservative and thus resulting in overdesigned components. Any field data collected in the Micro and Small turbine categories, however, will be useful and would allow the following tasks to be performed:

(i) The SLM can be evaluated against AM and load measurements to determine whether there are calculations that are either too conservative or nonconservative. This type of study was successfully carried out in the past and provided great insight into SLM validity and its improvement [17, 18]. Of particular interest would be a study to verify the existence of operating characteristics that are being missed or underemphasized.

(ii) Similarly, the SLM can be evaluated to explore whether a turbine size limit exists where the equations should no longer be used.

(iii) Development and validation of a renewed SLM for VAWTs starting from the active Japanese standard [15]. A new internationally approved SLM would build confidence in its validity for certification.

3. Proposed Measures to Facilitate the Use of AM

Given the results of the analysis described in the previous sections, we offer a number of suggestions to facilitate the use of AM in the DWT space, starting from a collection of model templates and ending with a priority list of research needs.

3.1. Publicly Available Aeroelastic Models

We collected 10 (plus some variants) publicly available aeroelastic models for various turbine archetypes[2]. The complete table of retrieved models is available from NREL upon request. Most of these AM templates make use of the numerical tool OpenFAST (and its variant KiteFAST for AWE). The templates span rotor swept area (RSA) values from $\sim 1.8\,\mathrm{m}^2$ to $\sim 573\,\mathrm{m}^2$ for HAWTs and include two AWEs kites: a fly-gen (crosswind flight with airborne generation) and a ground-gen (figure-eight 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 and can be considered solid templates for new model build-ups; yet no load reports are presently available to help stakeholders cross-verify their own results. The templates that include tail dynamics and furling, however, are no longer supported by the latest version of the aeroelastic tool OpenFAST.

No templates were retrieved for either VAWTs or ducted turbines, which represent a small but not insignificant category of SWTs.

3.2. Proposed Classification for DWT

From section 2, it appears that the most urgent need is to arrive at a substantiated assessment of the load categories for DWT turbines to allow for a rigorous differentiation of requirements for certification depending on the turbine category. The new classification of SWTs in future standards editions should account for both rotor size and archetype. On the one hand, the rotor size is linked to aeroelastic quantities such as eigenfrequencies and eigenmodes, Reynolds number, and dynamic wake induction, but also to financial cost and risk of the machine. On the other hand, the archetype is tied to multibody dynamics aspects and the V&V of these physical characteristics in the AM codes.

A logical plan would entail 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. A similar effort was undertaken in [17] and led to a series of improvements to the first edition

[2] The institutions that kindly made models available are: NREL, University of Newcastle, Technical University of Denmark, University of Florence, Delft University of Technology.

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.

To start this process, we created Table 2 that breaks down SWTs into load assessment and V&V categories. Based on both RSA and archetype, a SWT is assigned a load assessment requirement (SLM vs. AM) and then a ranking (1 through 3), which corresponds to different degrees of model validation requirements or minimum field measurements as described in the Table's legend. Table 2 condenses the various archetypes (see Section 2.1) to six key ones

Table 2: Category breakdown for load assessment and V&V.

Turbine Category	RSA	Load Model	Turbine Archetype: HAWT, control active yaw, Pitch	HAWT, control active yaw, Stall	HAWT, control passive yaw, Pitch	HAWT, control passive yaw, Stall	VAWT	AWE
Micro(XS)	$<5\,\mathrm{m}^2$	None	1	1	1	1	1	1
		SLM	1	1	1	1	1*	
Small(S)	$5\,\mathrm{m}^2$–$100\,\mathrm{m}^2$	SLM	1	1	1	1	1*	
		AM	1	2	2	2	2	3
Medium(M)	$100\,\mathrm{m}^2$–$500\,\mathrm{m}^2$	AM	2	2	3	3	3	3
Large(L)	$>500\,\mathrm{m}^2$	AM	2	3	3	3	3	3

LEGEND	
1	Performance testing only: • power, rotor speed; • environmental conditions: air density, wind speed and direction; • key control parameters such as: yaw angle, furl angle, teeter angle.
2	Performance testing plus tower-base loading
3	Performance testing, tower-base loading, and blade root$^+$ bending moments (flap and edge). • For AWEs: Performance testing, tether/bridle loading, and wing root bending moments. • Measurement of shaft loads, tail boom loads and strut loads as applicable is encouraged.

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

* Any SLM for VAWTs will need to be verified for use.

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

based on the results of this research. The six archetypes represent various levels of uncertainty in the ability of the AM 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 above 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 2 allows some well-verified aeroelastic models and well-validated archetypes to require less validation (regardless of their size). Conversely, aeroelastic models for less validated archetypes have more onerous V&V requirements even if they are small in size.

3.3. AM Recommended Actions
Below is a list of recommended actions that can be carried out by industry and the research community at large, including national laboratories and academic institutions:

- Compile reference models and load reports
- Provide V&V guidance with loads assessment categorization
- Publish a design load basis document
- Support further development of SLM
- Publish guidance on conformity assessment
- Provide support to code development

4. Conclusions and Next Steps
This study highlighted key needs to help aeroelastic modeling become more common and more useful for the design and certification of distributed wind turbines.

We started this study by conducting an analysis of the status of AM and the wider loads assessment and their role within the design and certification standards for the distributed wind industry. We also gathered input and feedback from a large number of national and international stakeholders. AM is a powerful design and optimization tool that can also be used to 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. This study's findings and recommendations 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. This study highlighted the steps required to improve the AM adoption based on a multifaceted approach that encompasses augmenting AM software capabilities, publishing AM best practices and design bases, creating new reference turbine models, providing guidance for V&V of codes and specific turbine models leveraging field testing best practices, and addressing weaknesses in the current standards. A number of actions were taken in this direction.

First, we collected ten publicly available aeroelastic models that could be used by researchers as well as OEMs as starting templates to create new models and to aid in the V&V of new AM code capabilities and less-validated configurations. The templates cover the most common turbine archetypes in the current market and even include two AWE archetypes. Most notably, however, is the absence of a VAWT model and an open-source aeroelastic code to simulate VAWTs — a fundamental obstacle to the certification of distributed wind VAWTs.

Second, we created a matrix tool that can be used to assign minimum load assessment and field measurement requirements to a SWT, based on both RSA and archetype.

Third, we have listed a number of research priorities to both improve the design standards for applicability to different archetypes and the reduction of the certification burden, and augment confidence in the prediction capability of AM codes.

We trust the findings and recommendations dispensed in this study and the forthcoming report publication [9] will promote the growth of the industry toward a more efficient design process with better outcomes through the use of AM.

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