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A WHITE PAPER ON WIND TURBINE BLADE DEFECT AND DAMAGE CATEGORIZATION

Current State of the Industry

1. Introduction

The uniqueness of wind turbine blades leads to significant maintenance challenges. Blades are subjected to demanding and wide-ranging environmental conditions and severe operational fatigue and are challenging to access for inspection and repair. Nonetheless, regular maintenance of blades is prudent to ensure they function properly throughout their intended life. The evolving wind energy industry has not settled on standard blade maintenance practices, nor are such practices mandated by any regulations.

An early step in blade maintenance is understanding blade condition. Inspection, which is the critical examination and checking of blades, is the most common approach.

Inspections produce findings. Findings are observations, such as damage or defects, that exceed design and/or manufacturing expectations, including tolerances. Findings are assessed in order to determine the ability of blades to meet their design objectives, such as ability to resist fatigue and extreme structural loading throughout their full design life, and to produce expected power levels.

Assessing a finding typically includes determining its severity and/or criticality; this process lends itself to categorizing findings of common severity into categories. There is no standard wind turbine blade damage or defect categorization system. Various categorization systems have been developed and are in use by turbine or blade manufacturers, service providers and blade inspection/maintenance companies, drone operators, turbine owners and operators, consultants, and industry groups/consortia.

Categories are assigned by individuals with varying experience, knowledge, and motives. Most categorization of defects and damage, and thus decisions regarding execution and timing of repairs, is based on experience and judgement, as well as practical and commercial considerations such as season, accessibility, impact of downtime, and availability of crews and materials. Commercial agreements (e.g., a turbine warranty) may refer to maintenance actions that are taken or excluded based on damage categories. As responsibility (e.g., costs of repairs and lost production) for maintenance action can be costly, and damage and defect categorization is inherently subjective, damage and defect categories may be disputed by stakeholders in a project.

Blade and turbine manufacturers' quality systems typically define acceptance criteria for defects, and structural repair manuals will typically define repair limits for damage. This information is generally not made available beyond the manufacturer. As such, industry standard guidance is necessary for assessing defects in new blades. The content of this paper is intended to apply to both new blades and operational blades.

This white paper draws from an ongoing EPRI study of current practices in blade maintenance. The objective of the information presented in this paper is to report on the state of the industry with regards to categorizing damage and defects, as determined through analyzing the results of an industry survey.

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2. A Review of Current Practice In Damage and Defect Categorization

In order to understand the current approaches the industry takes to categorizing damage and defects, EPRI distributed a survey to approximately 350 individuals across the spectrum of owners/operators of wind turbines, blade manufacturers, turbine manufacturers, blade repair service providers, consultants, and academics to gage current industry practices related to damage and defect categorization. The survey asked participants to categorize damage and defects and to describe their blade maintenance programs. Responses were received from 112 survey participants. Seventy-three percent (73%) of respondents indicated that they were directly involved in assignment of damage categorization, either as a final decisionmaker or via providing recommendations to decisionmakers. This result suggests that the survey captured a broad section of decisionmakers associated with blade damage and defect categorization and blade maintenance actions. All responses were anonymous.

The survey questions included:

- An initial question about the respondent's role in blade damage categorization and maintenance decision making.
- Specific examples of damage and defects of varying severity, including a photograph, with requests to:
  - Assign a category
  - Select actions (e.g., continue to monitor, repair, or shut down the turbine) based on the severity
  - Estimate the extent of growth required to recategorize to the next category or to change the action chosen in response to the damage or defect
- A freeform question requesting a description of the respondent's blade maintenance program.
- Questions regarding the frequency of inspection, and methods used for blade inspection.

For assessing the various blade damage and defects, categories of 1 through 5 were offered as potential responses. An answer of "Other" was also accepted. Most respondents considered categories 1 and 2 to apply to minor damage or defects, categories 3 and 4 for moderate damage or defects, and category 5 for major damage or defects.

Damage and defect examples in the survey spanned findings of less serious nature, such as coating scratches, to more significant findings such as a split trailing edge. The results from questions related to specific examples of damage are captured in Figure 2-1, and the key take-aways from the survey results are summarized in Table 2 1.

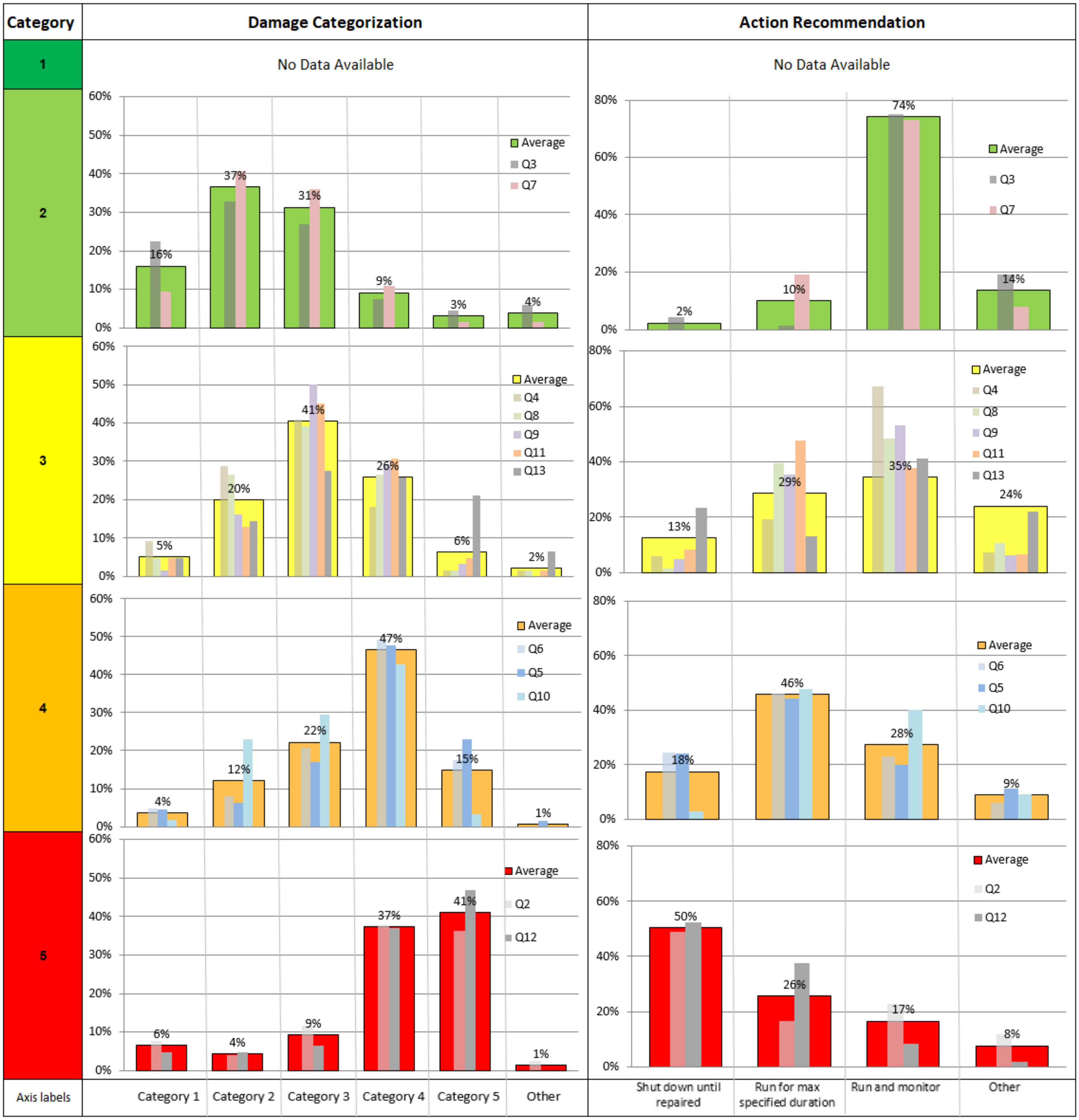


Figure 2-1 Damage categorization and action recommendation distributions. "Q" indicates question.

Table 2-1
Summarized key survey results

Subject	Observations	Key take-aways
Categorization	All but five survey respondents chose to define less severe damage or defects to be categorized with lower numerical values, and more severe damage to be categorized with higher numerical values. Responses related to findings that were manufacturing defects showed poor agreement among participants. Many respondents indicated that manufacturer's acceptance criteria should primarily determine the course of action. Generally, agreement on any one damage category was rare. Most often the votes were split between two damage categories, and sometimes three, as shown in Figure 2 1. This could be due to a true diversity of interpretations of the damage categories or it could be a function of the survey construct, which asked for participants to categorize damage with limited information.	Concrete definitions of categories are needed. In the meantime, categorization results could be considered to have an uncertainty of one category to account for variability in interpretations and judgment.
Response plan	Category 1-3 damage or defects can often be operated with inspections every 6 to 12 months. Category 3 or 4 damage or defect should be repaired or shut down within 6 to 12 months with at least an inspection every 6 months. Category 4 or 5 damage or defect should be repaired or shut down within 1 to 12 months, with monthly monitoring	Only the most severe damage and defects were considered serious enough to stop the turbine until it could be repaired. Moderate and less serious damage can be monitored once or twice a year with operation.
Lightning	Lightning damage also showed particularly poor agreement among participants. Some respondents considered lightning damage always a risk for water ingress, rapid damage propagation, and likely damage to the lightning protection system (LPS), and thus felt that more urgent action was prudent.	Better understanding of impacts of lightning damage is needed.
Recategorization	For lower category damage and defects, growth would need to be 100% or more before reconsidering their action plan, whereas with damage or defects already in categories 4 or 5, any (or a small amount of) growth would be cause for concern and re-evaluation.	In terms of size or extent of damage, the steps between lower categories (such as stepping from 1 to 2) is greater than between higher categories (such as stepping from 4 to 5).
Inspections	Almost all respondents indicated that they conduct some degree of external inspections between once a year and once every 3 years, with more than half doing annual external inspections. Responses regarding internal inspection campaigns were less consistent: roughly a quarter of respondents perform internal inspections annually, and at least half responded that they do not have a regular schedule. In some cases, responses suggested that there needs to be a reason to conduct an internal inspection, rather than conducting internal inspection on a regular schedule. Drone-based external inspection has clearly become typical throughout the industry.	External inspections are standardizing on annual to every 3 years, while internal inspections are not standardized. Method of inspection is not standard, but drone inspections have become ubiquitous.

3. Towards a Standard Damage and Defect Categorization System

The survey results discussed above, as well as the authors' experience and industry interactions, inform development of a standard damage and defect categorization system. Table 3 1 presents a damage and defect categorization system that represents current industry practice and provides a basis for a global industry standard for damage categorization. Table 3 2 presents actions to take in response to damage or defect findings.

Examples of defects and damage typical of each category are summarized in Table 3 3, with photographic examples in Table 3 4. Additional examples with photographs are in Appendix B. Terminology for informing standardized descriptions of damage and defects is provided in Appendix A.

There may be multiple findings on a blade. In some cases where multiple findings are present, lower-category findings may be grouped together to form a higher-category finding. Further, it may be cost efficient to monitor several lower-category findings as a single, higher-category finding.

The standard approach to blade damage and defect categorization presented above does not include prescribed durations to continue operation or inspection frequency for damaged blades. As seen in the survey results, the industry today has a broad spectrum of practices. To the extent that there was agreement, current practice can be referenced for specific durations for specific actions (as summarized in Section 2).

Table 3-1
Categorization system for wind turbine blade damage and defects

Category	Characteristics	
1	**Description**	Minor variances from supply specifications but within acceptable (or industry typical) tolerances; may affect the appearance of the blade or blade feature. Though minor, can be useful to identify as position references, or for blade identification.
	Potential for growth	None expected
	Impact to aerodynamics	None expected
	Impact to life	None expected
2	**Description**	Minor damage or defects that exceed supply specification acceptance criteria. Multiple cosmetic findings and/or a single major cosmetic finding that are damage, defects, or former repairs. Findings exceed tolerances of supply conditions or industry typical manufacturing variability. Repairs of more severe damage or defects can be recategorized to category 2 upon review of repair.
	Potential for growth	Not likely but may accelerate leading edge erosion when located on the leading edge, additionally may leave laminate or bond lines exposed to environmental degradation. Generally 100% growth in size or severity pushes finding into next category.
	Impact to aerodynamics	May have minor impact to aerodynamics depending on details, though beyond what could reasonably be measured
	Impact to life	None expected
3	**Description**	Moderate to minor structural damage or minor manufacturing defects in non-critical areas. Features are moderately out of compliance with supply conditions and/or below minimum typical industry practice. May present as surface indications when in fact there is damage to the underlying structural laminate. Internal inspection may be needed to determine the extent of the finding. May be particularly challenging to assess criticality due to lack of design data such as load margins. Findings may be category 3 when category 4 actions seem too drastic and category 2 is not appropriate, because there is a slight risk of loss of structural capability.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity by 50% or more is likely to push finding into next category.
	Impact to aerodynamics	May have an impact to aerodynamics depending on details
	Impact to life	Life is expected to be reduced without some other measures such as monitoring or repair or engineering evaluation (in the case where there is sufficient margin)
4	**Description**	Significant damage or defects that have notable impact to structural capability and/or aerodynamic performance.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity of 10-50% is likely to push finding into next category.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details
	Impact to life	High confidence the blade will not achieve intended life
5	**Description**	Severe degree of damage or defect such that there is a high risk of imminent failure.
	Potential for growth	Likely to rapidly increase in size or extent.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details
	Impact to life	The blade is expected to fail within a short period of time if operated.

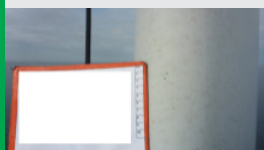
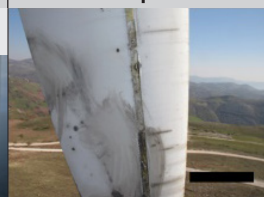
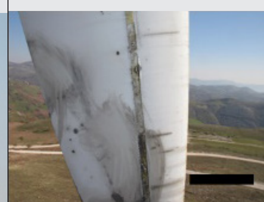
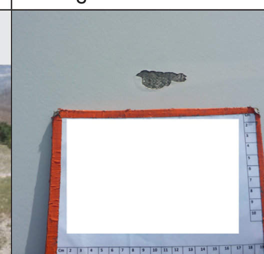
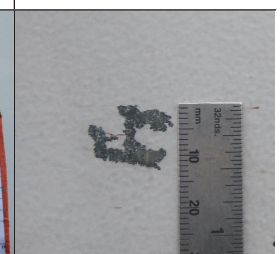
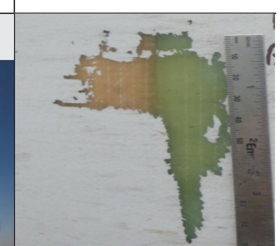
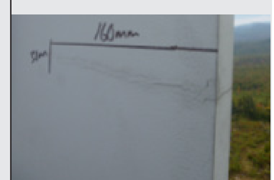
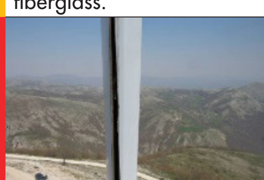
Table 3-2
Actions by category for wind turbine blade damage and defects

Category	Actions	
1	**Repair**	None needed, though some can be remedied with minimal effort in conjunction with other blade maintenance activities.
	Continued operation of turbine	Yes
	Additional monitoring	None needed
2	**Repair**	Evaluate cost/benefit of repairs.
	Continued operation of turbine	Yes
	Additional monitoring	Monitor during routinely scheduled maintenance for damage initiation or progression. Depending on the damage, internal inspection may be warranted to differentiate surface cracks from more severe laminate damage.
3	**Repair**	Determine depending on circumstances, criticality, and O&M approach. If found during manufacturing, should be repaired prior to installation. Investigation and repair or replacement of missing aerodynamic devices should be performed to regain energy capture benefits. Timing of repairs can be linked to other blade-related needs. Leading edge erosion or small external cracks should be repaired to prevent damage progression.
	Continued operation of turbine	Yes
	Additional monitoring	Inspection frequency driven by assessment of risk; may be more frequent than routinely scheduled inspections recommended by the OEM. If no growth in damage over time, an engineering assessment may downgrade finding to category 2.
4	**Repair**	Repair within a limited number of months of initial observation. Repairs may be performed uptower or blade removal and ground repair maybe necessary, depending on the finding. If found during manufacturing, should be repaired prior to installation and a manufacturing quality assessment should be undertaken to find and correct root causes.
	Continued operation of turbine	Engineering evaluation required to deem blade can operate until repair is scheduled. Operation shall stop if repair cannot be implemented within the allowable time period.
	Additional monitoring	More frequent or more comprehensive monitoring than routine inspections are required until repairs are complete.
5	**Repair**	Replace, or repair depending on repair feasibility and cost/benefit relative to replacement.
	Continued operation of turbine	The blade is not safe to operate until the damage or defect is repaired or the blade is replaced.
	Additional monitoring	If repair is implemented, repair should be deemed a Category 3 defect until sufficient operating experience is gained to provide confidence that the repair is sufficient to achieve expected remaining operating life.
	Further steps	A formal root cause analysis should be performed to ensure complete understanding of events or defects and prevent repeated occurrences.

Table 3-3
Examples of damage and defects in each category

Category	Examples	
1	**Cosmetic**	Light dirt, oil, grease, or insects on the blade surface. Missing or unreadable labels or stickers. Marks from small mold positioning devices. Small or thin foreign objects in laminate that do not form wrinkles. Minor variability in thickness of coatings, detectable as translucence. Minor blade surface variability due to mold features.
2	**Cosmetic**	Coating discoloration, scratches, or cracks, profile deviations in repairs, mold marks protruding from the blade surface, rough paint patches. Excessive oil on the internal surfaces of the blade. Thin or flaking coating Early stages of leading edge erosion or other increased surface roughness.
	Aerodynamic	Heavy dirt, oil, grease, or insects on the blade surface. Several missing aerodynamic devices (e.g. vortex generators, trailing edge devices).
	Defects	Minor foreign objects in laminate resulting in small wrinkles. Minor manufacturing deviations that have been evaluated by an engineer and do not impact structural capability due to design margins or it is in an area of low structural criticality.
	Lightning	Pin holes or very small marks on the blade shell where lightning was intercepted (not at the lightning receptor).
3	**Aerodynamic**	Extensive missing aerodynamic devices (e.g., vortex generators, trailing edge devices).
	Structural	Small cracks in shells or along leading or trailing edge bonds, small areas of underinfused laminate, voids in adhesive bonds. Significant root face laminate wrinkles. Spanwise wrinkles in laminate.
	Lightning	Laminate damage where lightning attached to blade surface, not at the intended receptor. Lightning penetrated the shell, however the exterior surface appears structurally adequate.
4	**Structural**	Significant cracks, delamination, buckling of shells Significant lead edge or trailing edge separation, exposing internal structure to water ingress Moderate to large core gaps or missing core material Leading edge erosion through shells, exposing blade internal structure Broken blade bolt
	Defects	Chordwise wrinkles of laminate fibers in highly loaded regions Significant areas of underinfused or improperly cured laminate Large gaps or underbite/overbite at shell bonded joints Significant missing adhesive bond material, cavities, voids, or cracks in adhesive bonds, or significant deviations of the geometry of adhesive bonds beyond allowable limits Large foreign objects in laminates that result in significant wrinkles
	Lightning	Obvious structural damage such as delamination and cracking, with exposed laminate and/or Holes in the shells, leading edge or trailing edge bond separation, broken Damaged LPS components (receptors, downconductor cables, etc.)
5	**Structural**	Buckled shear webs Separation of shear webs from spar caps Numerous broken blade bolts Significant chordwise or spanwise cracks or large delaminations in shells

Table 3-4
Photographic examples of damage and defects in each category

Category	Example 1	Example 2	Example 3	Example 4	Example 5
1	 Pinholes in coating at leading edge.	 Broken vortex generators.	 Scratch in coating.	 Erosion or chipped coating.	 Grease leakage on blade collar.
2	 Small spanwise crack.	 Small quantity of vortex generators damaged or missing.	 LPS receptor coating damage.	 Small area of coating damage.	 Small area of coating damage.
3	 Several scattered areas with coating damage.	 Crack in structure at the leading edge.	 Coating damage.	 Leading edge erosion.	 Coating damage.
4	 Leading edge erosion with large exposed surfaces of fiberglass. Signs of damage to the underlying fiberglass.	 Coating damage with damage to and exposure of the underlying fiberglass.	 Trailing edge open over a small length.		 Chordwise crack.
5	 Trailing edge open over a significant length.	 Long leading edge chordwise crack with spanwise cracking.			

4. Conclusions and Future Work

Wind turbine blade maintenance strategies are informed by multiple inputs, and the success of a maintenance strategy benefits numerous stakeholders. Categorization of damage and defects in wind turbine blades is a challenging task that lacks guidance in the form of an industry standard.

EPRI has surveyed the industry to capture current practices in blade damage and defect categorization. The survey results suggest and inform the content of a standard categorization system and have highlighted gaps in current practice of its application. Those gaps will be addressed in an upcoming EPRI report 3002017731, *Wind Turbine Blade Maintenance – Industry Practices*.

Feedback to this paper and industry discussions are intended to drive toward establishing a formal Recommend Practice, published by DNV GL, to provide standard guidance for damage and defect categorization for wind turbine blades. The content of the Recommended Practice may be included as informative guidance in a future update to standards such as DNVGL-ST-0376 or IEC 61400-5.

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Renewable Generation Program

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