GL Garrad Hassan

TECHNICAL MEMO

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1 INTRODUCTION: RE-EVALUATING TURBINE RELIABILITY

1.1 Turbine Reliability Risk: Toward a More Accurate Assessment of Financial Performance

In its role as leading consulting engineer for wind energy projects worldwide, GL Garrad Hassan has had the opportunity over the years to closely observe evolving trends in wind farm performance. Garrad Hassan uses this vantage point to develop and refine methods of assessing wind turbine reliability, quantifying risk, and projecting future performance.

In 2008, an industry-wide tendency was recognized for pre-construction P50 performance estimates to be higher than actual performance; over-projection of turbine availability was identified as a significant contributor to this error. Garrad Hassan took that opportunity to develop a more nuanced and data-driven method of projecting the performance of individual wind turbine models. This method was presented in a July 2008 position memo [1] which outlined Garrad Hassan America's system of evaluating turbine performance in the United States, elaborating a method to distinguish "commercially proven" turbine technologies. The memo defined and explained maximum expected availability levels and ramp-up rates; it also made a point of distinguishing North American availability from historical European statistics for the same turbine model.

Since issuing that memo, GL Garrad Hassan North America (GH) has applied its criteria and methods to project the long-term performance of the turbines at scores of wind farms. As more data have become available and as the industry has further matured, some refinement and clarification of these methods has become appropriate. This memo seeks to build on the methods set out in the 2008 memo based on the ensuing two years as well as on the experience of applying these criteria to dozens of turbine models, both new designs and variants of established turbines.

In particular, GH has recognized a need to address the experience of manufacturers introducing variants of already proven turbines, and provide more resolution to the evaluation of turbines in the process of commercialization. This memo addresses these cases with the added category of "qualified" turbines as a transitional stage on the way to proven status, giving credit for making measurable strides toward becoming proven without yet meeting all the criteria for full proven status.

This memo will also outline GH's updated methods for projecting turbine availability levels and assessing the design of a turbine model as "commercially proven" or "qualified".

1.2 GH's Application of Availability Assessments

It is common in the wind industry to apply a blanket availability rate to all turbine models based on broad industry averages, despite a clear correlation between turbine model and availability. Rather than using such a blunt tool, GH estimates turbine availability for specific turbine models individually. GH's evaluation of a turbine model is then applied to many phases of GH's work including services for project developers, investors, and owners.

These projected availability levels are a significant parameter in a wind farm's preconstruction energy production assessment and can have a strong influence on project revenues streams. For a given site, availability is one of the loss factors that can best be controlled by a project developer, e.g., through the choice of turbine model and the budgeting for operations.

Availability is also an important variable in a due diligence review of a North American wind farm. The projected availability is a key factor in estimating the size of the revenue stream. Furthermore, the extent to which a turbine design is proven is used to evaluate operations and maintenance (O&M) budgets and may be used to justify the recommendation for elements of the financing structure. For instance, a major maintenance fund may be required by lenders to cover unexpected issues with a new technology, or for unproven designs a serial defect reserve may be called for, in case issues arise after the turbines are out of warranty. A project's spare parts budget must be reviewed with a view of the reliability of the turbine model as well.

1.2.1 Separate Evaluation of North American Fleets

GH frequently receives requests to estimate performance of a turbine model that is being introduced to the North American market, based solely on the track record in its European or Asian home market. GH has found it necessary, however, to evaluate the North American fleet separately.

The requirement that turbine models be independently evaluated on their North American performance, rather than allowing reliance solely on home experience, grew from a notable disparity between the performance of turbines new to North America and that in their original market. This effect has been explored in past GH publications [such as 2-6]. This distinct drop in availability can be attributed to any or all of several factors:

- *Established supply chain:* The development of a service infrastructure and regional supply chain in North America is accomplished over time. For instance, there were a few notable examples of early US installations that were out of service for extended periods while gearboxes were shipped from European suppliers.
- *Skilled technical staffing:* The development of a technical workforce experienced in a new turbine model takes some time. Good turbine availability relies not only on good design, but also on experienced commissioning and maintenance crews, and readily available expertise in trouble-shooting.
- *Design changes:* Changes in turbine design such as those due to grid frequency, voltage, and electrical codes.
- *Different environmental conditions:* Many early turbines were designed for the conditions in northern Europe and had initial difficulties in the North American market due to the higher turbulence, wind speeds, and lightning frequency, as well as the wide range of temperature and air density in some North American regions.
- *Larger wind farms than in Europe:* With larger numbers of turbines operated in one wind farm came certain challenges that did not arise in the smaller European installations. For instance, maintenance strategies had to be modified, and some SCADA systems did not accommodate the larger number of turbines.
- *Larger distances between wind farms:* Some European turbine suppliers initially underestimated the demands placed on service infrastructure by the wide geographic differences of wind farms throughout the United States and Canada.

As the North American wind industry has grown and matured, many of these issues are better understood than they were in early to mid 2000's. That said, GH continues to observe a distinct difference in turbine availability levels between established European turbine models and their new North American installations. When assessing a new entrant to the North American market, GH evaluates the extent to which the supplier has addressed these aspects of this market.

2 PROVEN AND QUALIFIED TURBINE DESIGNS

In estimating a project's availability, GH has historically made an effort to determine whether the turbine design is "proven". A commercially proven turbine design is one that has sufficiently stabilized such that it is possible to base a judgment about the long-term availability of the turbine on the turbine's recent track record.

2.1 Criteria for "Commercially Proven" Design Status

GH considers a turbine model to be commercially proven in North America when:

1. The manufacturer is capable of performing all contractual and commercial obligations in North America;
2. The manufacturer can demonstrate the ability to support warranty, O&M, and supply chain obligations in North America;
3. The version of the turbine that will be supplied to North America carries a valid Design Statement of Compliance (SoC)[1] to IEC 61400-1 standards issued by an accredited certification agency;
4. The turbine model has at least 100 turbine-years of experience in the North American market, operating at 95% fleet turbine availability or greater.

These criteria are essentially the same as the criteria set out in the 2008 memo, with a few refinements; these modifications do not change the status of any existing turbine models, but are intended to clarify the criteria's application.

GH uses the degree to which a turbine model is commercially proven in projecting its availability ramp-up schedule and expected long-term turbine availability, as well as other aspects of a project pro forma budget. Typically, a project using a proven turbine will not only have a higher projected long-term turbine availability and shorter ramp, but may also benefit from reduced need for a serial defect reserve, spare parts budget, etc.

2.2 "Qualified" Turbine Design Status

In performing energy assessments and due diligence for wind farms, GH seeks to understand how the turbine design affects the risks posed by variations in wind turbine availability. For this purpose, GH has used the framework provided by the "proven" criteria described above, and has applied these criteria to dozens of turbine models, including new designs and variants of established turbines. In the course of this work, it has became evident that a finer gradation is required than was afforded by the proven/unproven dichotomy. GH's observations of turbine performance have made it clear that it is important to better characterize certain distinctions; three cases in particular stood out:

A. <u>Variants</u>: Evolutionary variants of turbines already proven in North America. Examples include rotor diameter changes for new wind classes, cold weather packages, or other modifications sufficient to require a new IEC certification but not a fundamental re-design.

B. <u>Imported designs:</u> A turbine proven in its home market but new to North America.

C. <u>New entrants:</u> Turbines that have been performing well in North America for some time but are still without sufficient track record to be designated as proven.

With a limited but already respectable track record these turbines differentiate themselves from entirely new, "unproven" turbines; however, they do not meet the guidelines to be considered "proven" as

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[1] Sometimes called an "A-Design Assessment"

discussed in Section 2.1. To set these cases apart from unproven designs, GH developed a new category of "qualified" designs.

In order for a turbine model to be considered "qualified", it first must meet the following general criteria, similar to proven turbines:

1. The manufacturer is capable of performing all contractual and commercial obligations in North America;
2. The manufacturer can demonstrate the ability to support warranty, O&M, and supply chain obligations in North America;
3. The version of the turbine that will be supplied to North America *is in the process* of obtaining a Design Statement of Compliance (SoC) to IEC 61400-1 standards issued through an accredited certification agency.

Furthermore, the model should demonstrably[2] fall into one of the following three groups of demonstrated experience:

4A. Variants: The *original model* has at least 100 turbine-years of experience in the North American market, operating at 95% fleet turbine availability or greater. That is, the original turbine on which the variant is based must be proven. For more significant modifications[3], GH expects there will be at least one prototype unit in North America with more than 4,000 hours of operation.

4B. Imported designs: The model has at least 100 turbine-years of experience *in its home market*, operating at 95% fleet turbine availability or greater. That is, the turbine model must be proven in its original region. Furthermore, for manufacturers that do not have extensive North American wind experience, GH looks for at least one prototype unit in North America that has operated for more than 4,000 hours.

4C. New entrants: The model has at least 25 turbine-years of experience with 95% demonstrated turbine availability during the past 12 months in North America. In contrast to the other criteria listed above, earlier model years may be excluded in this assessment; in other words, early units do not necessarily have to be averaged into the turbine's "fleet" availability that is evaluated for this purpose. For new entrants in particular, GH looks for signs of demonstrated experience, so a broader review of overall turbine performance, quality, or manufacturing may be suggested at GH's discretion.

3 TURBINE AVAILABILITY PROJECTIONS

After determining whether a turbine design can be considered "commercially proven" or "qualified" in North America, GH reviews all available data on the turbine model, turbine supplier, and project. This information is used in projecting an availability ramp-up schedule and expected long-term turbine availability levels for that turbine model and/or project.

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[2] See Section 4 for substantiation requirements.

[3] For example, GH would not necessarily expect a full pre-commercial prototype for a cold weather package on an established turbine.

This section discusses GH's methods for making availability projections. First, however, it will be necessary to define "availability" more carefully; the next subsection, along with the Appendix, lays the groundwork for a more detailed discussion of turbine availability.

3.1 Definitions of Availability

The term "Availability" as used in the wind industry, is a measure of the potential for a wind turbine or wind farm to generate electrical power. In general, an "available" turbine is one that will generate power, when the wind and other climatic conditions are within the turbine's operating specification. The availability figure is used for many purposes, including energy estimates, revenue projections, turbine design performance evaluation, warranties, and performance bonuses or penalties.

The many uses of this key statistic have given rise to divergent methods of calculation, each suitable for its own purpose. For the purposes of evaluating technology across all turbine models, GH uses a uniform definition of availability that is designed to be compatible with the calculation of production estimates. This definition is a *time-based, "wind-in-limits", technical turbine availability* that takes the form of a *loss factor* (these terms are discussed in the Appendix). It is calculated as follows:

$$\frac{\text{(Total time producing kW)}}{\text{(Total time that the wind is between cut-in and cut-out, and there are no grid-out or BoP issues)}}$$

This definition results in different values than the contractual availability definitions such as those used in warranties, and therefore GH's *"wind-in-limits"* availability projections cannot be directly compared with *contractual* or warranted availabilities. Contractual availabilities may in some cases be 1-2 percentage points higher than GH's "wind-in-limits" technical availability projections; this disparity can arise from the inherent differences in the calculation methods and is not an indication of differing opinions about expected performance. For further discussions of availability calculations and how various definitions serve different purposes and can differ in outcome, refer to the Appendix.

3.2 GH Projections of Long-Term Availability for Proven Turbines

Table 1 shows GH's updated guidelines for projected long-term availabilities.

	Guidelines for Projected Long-Term Availability [1] and Ramp-Up Rates		
	Proven Turbine	**Qualified Turbine**	**Not Proven Turbine**
Usual ramp length [2]	1 year	2 years	3 years
Year 1	Up to 94.5%	Up to 94%	Up to 91%
Year 2	Up to 96.5% (3)	Up to 95%	Up to 92%
Year 3	"	Up to 96% (3)	Up to 93%
Year 4-20	"	"	Up to 94% (3)

1 These numbers use a time-based, "wind-in-limits", technical turbine availability definition, and should not be directly compared to most contractual definitions.

2 The ramp length is the number of years expected to experience a reduced availability level.

3 The final value listed in each column is the long-term average. The "long-term" average turbine availability is defined here as the average value for all the years following the initial ramp-up. For instance, for turbines with a one-year-long ramp-up, the long-term average is the average of years 2 through 20.

Table 1: GH position on turbine availability projection ranges based on status

These guidelines are applied based on the merits of each turbine on a case-by-case basis; they represent typical *maximum* values and GH may assign lower values depending on an individual turbine's design and experience. Sponsors and clients have the opportunity during the technical due diligence process to justify higher levels if they can be substantiated with operational data.

When GH assigns a projected availability to a turbine model, this value represents a default level for that model in the general case, with the assumption that proper and thorough maintenance will be performed. GH's availability projections for a given turbine model are based on a review of the turbine technology and its operational history; they do not consider project-specific factors, which can have a significant impact on availability. In the specific case of a given project, when GH has the opportunity to review in detail the project's O&M capabilities, plans, and budgets, a project-specific adjustment may be made based on demonstrated capabilities to perform maintenance and meet supply chain obligations. This review may include examination of the maintenance budget, plan, and provider; it may also include known site and climatic conditions. If a project has an availability warranty, GH will convert the contractual availability to a technical availability and will take this into consideration when recommending an availability level during the warranty period.

The phrase "long-term average turbine availability" is used in this memo to mean the average value for all the years following the initial ramp-up. For instance, for a turbine with a one-year-long ramp-up, the long-term average listed here is the average of years 2 through 20. In practice, turbine availability will vary over time around that average. Given the small number of modern wind farms with ten or more years of operation, it is difficult to generalize the nature of that variation; however, in general, GH considers it prudent to assume that O&M budgets should be increased in later years to maintain levels of availability.

Note that a subsequent elevation to proven status does not necessarily modify the availability projection for those turbines installed in earlier years. For example, suppose a project consists of 40 units of an unproven turbine whose projected long-term availability is 93%. If that turbine design becomes proven a year after the project's installation, the 40 turbines of that project should still be assumed to perform to the originally projected long-term average of 93%. The industry-wide data that GH has analyzed have demonstrated that early model years tend to retain a somewhat depressed availability in the long-term. This can be attributed to the fact that later "model years"[4] benefit from the lessons of a larger fleet.

3.3 Availability Ramp-Up Periods

Availability levels can be expected to be somewhat lower in the first years after commissioning as turbines undergo a "teething" period. After recent analysis of over 100 North American wind farms, GH has revised its guidelines for the length of the projected ramp-up periods for many wind turbines, as shown in Table 1 above.

Turbines may have a reduced availability in the first few months, due to a short period of testing after the Commercial Operation Date (COD); this will typically further depress the average of the first full year's availability. In defining the first year's availability, GH averages the 12 months after COD, whereas manufacturers and projects may omit the first few months from their first year figure. This difference in definition may account for some disparities between GH and others' projections.

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[4] A "model year" is the set of turbines installed in a given year in a given region. Please refer to the Appendix for a discussion of model years and expected availability.

3.4 Validation of Availability Projections

In the course of conducting analyses on behalf of wind farm developers, lenders, owners and other parties, GL Garrad Hassan has gathered significant information on wind farm availability, including performance statistics and operational records for over 1,000 wind farm years, representing all major turbine manufacturers in hundreds of wind farms across Europe, North America, and Asia. Using this wealth of data, GH has analyzed wind farm availability trends in North America and worldwide, and has presented the results in a number of publications [2-6]. A summary of North American system[5] availability is presented in Figure 1, which shows the mean and median system availability for over 100 wind farms across North America, by year of operation.

GH's analysis makes it clear that the availability of unproven and early model year turbines tends to be lower and have a longer ramp-up. These data and analyses serve as the foundation for the recommendations and guidelines presented in this memo. The wide distribution of availability levels evident in Figure 1's percentile lines suggests that a closer analysis is needed rather than assuming an average level across the wind industry.

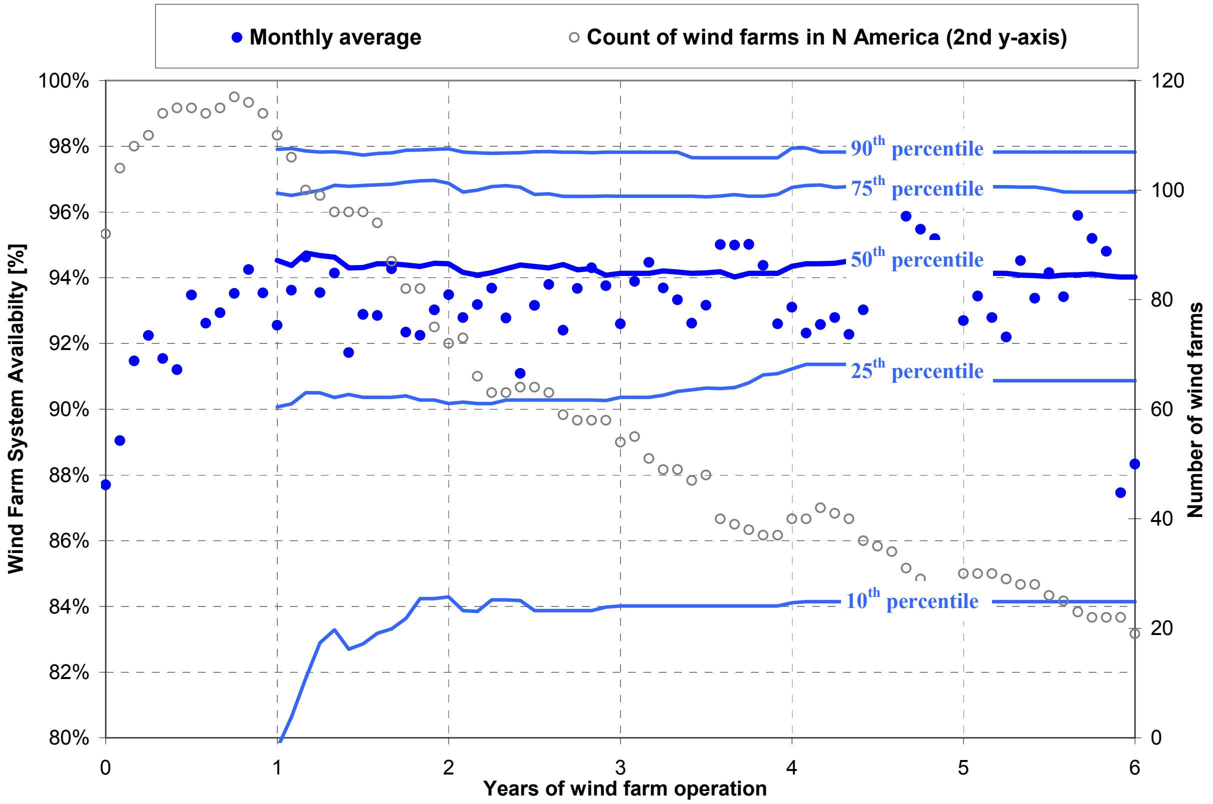

Figure 1: System availability as a function of age, of over 100 wind farms in North America

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[5] The figure shows system availability and is distinct from the *turbine* availability discussed in the rest of this memo; that is, the data shown in this graph includes balance of plant availability, and so is likely to be 1-2 percentage points lower than turbine availability.

The figure clearly illustrates the typical one-year ramp-up in availability. Similarly, a comparison of availabilities of turbines that were installed when the design was still young or just entering the North American market, and those installed once proven, clearly demonstrates the need for higher projections for proven vs. qualified and unproven designs.

As can be seen in Figure 1, actual turbine performance varies noticeably from case to case. GH projections of availability are intended to be median values and in practice some variation around those medians will occur. Availability projections for unproven turbines can be expected to have a wider distribution.

4 SUBSTANTIATION REQUIREMENTS

In deriving availability projections, GH examines historical availability data to the extent possible. GH typically begins this process with at least a full year of raw project operations data for the entire fleet. These data are used to evaluate availability based on the definitions described in Section 3.1 above and in the Appendix.

If a project's sponsor would like to make the case for a higher level of availability, GH welcomes the opportunity to evaluate data substantiating better performance. This section presents guidelines for the submission of project performance data.

4.1 Historical Fleet Availability Data

To be representative of North American performance, a dataset should encompass the entire North American fleet for the given turbine model for a minimum of one year. A review of the full fleet is necessary to ensure that GH is not evaluating only certain better performing projects. GH typically works closely with a turbine supplier to make certain that the full dataset is being reviewed.

The "fleet" can be defined as the set of non-prototype turbines that have been operating for at least one year. The first months following commissioning may be omitted. The data should encompass the most recent twelve months available or more.

The data used to evaluate fleet availability are the raw, time-based data files recorded by the SCADA system, as well as fault, curtailment logs, and service logs. Additionally, GH requires a listing of the state codes that are used by the SCADA system.

5 CONCLUSION & SUMMARY: GH POSITION ON TURBINE RELIABILITY RISK

In pursuing increasingly accurate quantification of the risks associated with wind turbine reliability, GL Garrad Hassan North America (GH) developed a more nuanced and data-driven method of projecting turbine availability. This memo offers GH's revised guidelines for projecting availability levels and ramp-up rates. Also in this memo are revised criteria for "proven" turbines and a newly developed intermediary category for variants and imported designs. GH formed this category for "qualified" turbine designs in order to characterize turbines that do not fit into either the proven or the not proven categories for various reasons.

GH has used this general framework since it was originally introduced in 2008, and GH will continue to apply this system, with the revisions presented here, in all energy assessments and in the financial due diligence process. Sponsors and clients have the opportunity during the technical due diligence process to justify higher levels if they can be substantiated with operational data.

GH welcomes the opportunity to discuss these policies and methods and their implications for project reliability risk assessment.

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7 APPENDIX: DEFINITIONS OF AVAILABILITY

7.1 Introduction: Availability Definitions Vary

The term “Availability” as used in the wind industry, is a measure of the potential for a wind turbine or wind farm to generate electrical power. If the turbine is available and the wind and other conditions are within the turbine specification, then power will be generated. The availability figure is used for many purposes, including energy estimates, revenue projections, turbine design performance evaluation, warranties and performance bonuses or penalties.

The many uses of this key statistic have given rise to divergent methods of calculation, each suitable for its own purpose. An understanding of the various definitions of availability is important since the resulting values differ and cannot necessarily be interchanged or easily compared. For instance, project developers may mistakenly use warranted turbine availability figures in ways that are not consistent with the definition of the value, which can lead to error in revenue projections. The choice of availability definition can have an influence on legal, financial, and technical matters.

This appendix offers a common basis to evaluate various availability calculation methods, and discusses the uses and implications of commonly used availability definitions.

7.2 Types of Availability

The current memo focuses on *time-based, “wind-in-limits”, technical turbine* availability levels, whereas other forms of availability calculations may be more appropriate for other purposes. This section explains how and why the following distinctions must be made whenever one discusses availability of wind projects[1]. Each type of availability definition serves its own function and no one definition is superior in general.

7.2.1 Contractual vs. Technical Availability

The “contractual” availability is a metric negotiated in a Turbine Supply Agreement (TSA) or Operations Service Agreement (OSA) for a given project. The project’s performance goals are measured with this metric and it should be tracked by the project's SCADA system. Contractual availability definitions typically have certain “carve-outs” or allowances that serve an important purpose in the context of that contract but are not necessarily appropriate as a careful measure of turbine performance or for comparison between projects and between turbine models.

In contrast, “technical” turbine availabilities seek to describe the technology’s performance without special allowances and with uniform treatment of system states. Specifically, turbines are expected to generate power when site conditions are within specified operating ranges. This form of availability does not provide carve-outs for maintenance or other project-specific clauses. Technical availability can then be a more accurate measure of technology performance and provide a common basis for comparison across the industry.

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[1] The various definitions of availability and their implications are discussed in more detail in GH’s paper “Characterizing Turbine Availability: Many Uses, Many Definitions” [7]

7.2.2 Turbine vs. System Availability

If the primary interest is in understanding a wind plant's total power production, then a "system availability" is used, and all downtime may counted as unavailable. System availability counts all downtime against availability, regardless of cause. It may also be called "commercial availability".

On the other hand, if the turbine technology itself is being evaluated, as in the current memo on turbine availability, then downtime related to other factors such as the balance of plant may be removed from the calculation. Any downtime due to non-turbine causes such as balance of plant or grid outages are removed from both the numerator and denominator of the availability fraction.

7.2.3 Time-weighted vs. Energy-weighted Availability

Availability may be calculated as a ratio of two time values or as a ratio of energy values. While the former may be simpler computationally, the latter is a better representation of the energy losses, if the energy values can be accurately calculated.

The calculation of availability based on a ratio of times does not capture the added importance of a turbine's availability during high wind periods. It is not uncommon for turbines to have lower availabilities during high-wind periods than during low-wind periods. So for example, if one turbine is able to confine its maintenance and repair time to low-wind hours, it could produce more energy than another with the same total number of down-hours but which suffered faults particularly during windy times. For this reason, a careful review of project operational reliability often considers an "energy-weighted" availability.

The more common time-weighted calculations take a form such as:

$$\text{Time-weighted Availability} = \frac{\text{Time available (in hours)}}{\text{Total time in consideration (in hours)}} \qquad \text{(i)}$$

In contrast, an energy-weighted calculation considers the energy made as a fraction of the amount that would ideally be expected based on actual wind speeds and site conditions:

$$\text{Energy-weighted Availability} = \frac{\text{Energy actually produced (in kWh)}}{\text{Energy expected (in kWh)}} \qquad \text{(ii)}$$

In practice, energy-weighted availability is more difficult to compute because of the added requirements for data and calculation; however, in most cases, GH finds that the energy-weighted availability calculations give results that are statistically equivalent to *wind-in-limits* time-weighted calculations, which are discussed in the next section.

Energy-weighted availability clearly carries an important distinction related to turbine reliability. GH's use of *wind-in-limits* availability calculations for comparison of turbine technologies allows GH to consider this distinction in most cases, without the need to rely on energy-weighted availability.

7.2.4 "Wind-in-Limits" vs. "Full Period" Availability

Availability is often calculated as the ratio of hours deemed available as a fraction of the full period (e.g. the month or the year):

$$\text{Full Period Availability} = \frac{\text{Number of hours available}}{\text{Number of hours in the period}} \qquad \text{(iii)}$$

Alternately, in a "wind-in-limits" form, only the availability during windy times is considered:

$$\text{Wind-in-Limits Availability} = \frac{\text{Number of hours generating kW}}{\text{Number of hours that the wind is between cut-in and cut-out}} \quad \text{(iv)}$$

GH uses its projected availability figures for loss factors in energy estimates. For loss factor purposes, an energy-weighted availability would be the most accurate; however, energy-weighted availabilities are often difficult to calculate from project data, and so it is often more practical to calculate a time-weighted availability. GH has found that the "wind-in-limits" form of availability tends to closely approximate energy-weighted availabilities. For this reason, "wind-in-limits" availabilities are preferable to a "full period" definition for use as a loss factor[2]. This definition allows "available" time to more carefully and meaningfully represent the time actually producing power, when a full energy-weighted calculation is impractical.

Time for which other environmental conditions are out of specification may also be removed from the denominator of a Wind-in-Limits Availability; for instance, times when ambient temperatures are outside of the turbine's operating range may not be included in this calculation either.

7.3 The Form of Availability Definitions

7.3.1 Generic Framework

This section offers a framework for evaluating all types and definitions of availability.

For any definition of availability, one begins by categorizing states as "**Available**" "**Unavailable**" or "**Not to be considered**", and then assigning every unit of time (typically 10 minute periods) so that they are all placed into one of these three bins – call them **A, U,** and **N**.

Then all definitions of availability take this form:

$$\textbf{Availability} = \frac{\mathbf{A}}{\mathbf{A + U}} \quad \text{(v)}$$

For time-based availability calculations, the full study period (e.g. the month or the year) will be accounted for by these three categories, so we can say:

$$\textbf{Period} = \mathbf{A + U + N} \quad \text{(vi)}$$

where "Period" is the full number of hours in the period under consideration; for instance, for a year that is not a leap year,

$$\textbf{Period} = \mathbf{365*24 = 8{,}760}\ \textbf{hours} \quad \text{(vii)}$$

A little algebraic manipulation allows us to write:

$$\textbf{Availability} = \frac{\mathbf{A}}{\textbf{Period} - \mathbf{N}} \quad \text{(viii)}$$

This formula can be used to describe *all* time-based definitions of availability and is a convenient basis for the discussion of the specific availability definitions below.

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[2] See Section 7.5.1 for an explanation of loss factors and why a "wind-in-limits" definition is appropriate in the absence of a full energy-weighted availability calculation.

7.3.2 Assignment and Prioritization of States

All states must be assigned a priority because states are non-exclusive; that is, two or more states may be in effect simultaneously. For instance, suppose that a given turbine is not producing power between 2 pm and 3 pm for several reasons – it is inoperative because of a fault, and the wind is below cut-in, and the turbine cannot be reached for repair due to a snowstorm (this state may be referred to as “suspended” maintenance or repair). In this case, what state should be assigned for this period? From the owner’s point of view, the fault takes precedence over “calm” and “suspended” states, so in this example, the turbine must be listed as faulted.

This precedence ordering of states is part of an availability definition. The difference from one definition to the other lies in the assignment of states to the three bins A, U and N, and in how states are prioritized.

7.4 Definitions of Turbine Availability used by Garrad Hassan

Garrad Hassan formulates availability definitions in order to be compatible for several uses, including as a loss factor in pre-construction energy production estimates, as a comparison across turbine technology, and as an indictor of wind project performance. In the last case, *system* availability is typically used, while in the former cases, the focus is on *turbine* availability. This appendix focuses primarily on GH’s use of *turbine* availability, though much of it applies to system availability.

Table 2 below delineates GH’s turbine availability definition as used in energy assessments, turbine technology reviews, and some other contexts. The definition is given by binning all major types of states and giving them a priority order. The table also compares it with how the states are commonly binned from other points of view. The states are listed in priority order: the first applicable state in the list must be assigned.

As discussed in the body of this memo, this definition of availability can be summarized as follows:

$$\frac{\text{(Total time producing kW)}}{\text{(Total time that the wind is between cut-in and cut-out, and there are no grid-out or BoP issues)}}$$

Prioritized turbine states	**Examples**	**GH Technical “Wind-in-Limits” Availability**	**Example Manufacturer’s Availability**	**Owner’s “Operational” Availability**
		Owner’s Perspective (Energy loss factor)	**Manufacturer’s Perspective**	**Owner’s Perspective**
Resource: Wind out of limits	High or low winds (Based on nacelle anemometer or other available data)	N (2)	--	--
Generating power		A (3)	--	--
Data unavailable		N or U (4)	N	N
Turbine-related stops	Scheduled maintenance Weather-impeded maint. times	U	A	U
	All other repairs/maintenance Turbine faults Lightning (5) Cable untwist (5)	U	U	U
Stops that the turbine is not responsible for	Grid or BoP outage (6) Blade icing Bat curtailment, etc. Ambient temperature out of spec.	N	A	N (possibly A for blade icing)
Operative	Operating at or below design specifications (but not necessarily generating power)	--	A	A

1 All states are assigned one of these three categories: A: available, U: unavailable, or N: not considered. For the period considered, such as a month or a year, Period = A + U + N.

2 GH uses the availability as a loss factor in energy assessment calculations. For this reason, only time between cut-in and cut-out is considered. All other time is removed from the denominator of the general formula, Availability = A/ (Period – N)

3 GH uses only time that the turbine is actually generating power

4 Lack of data creates uncertainty. Periods with lost data may be calculated in any or all of three forms: as N, as U, or as both A and U in the same ratio as appears in the data. These calculations may be used to create a range of uncertainty.

5 GH considers downtime due to lightning and cable unwinding to be unavailable. These may be placed elsewhere by others.

6 Note that this table focuses on *turbine* availability. The owner may also be interested in windfarm availability in which case e.g. BoP outages would be classified as “U”, etc.

Table 2: Comparison of three typical turbine availability definitions, where Availability = A / (8760 – N)

Some of the most significant differences between GH's and manufacturers' availability are:

- *"Wind-in-limits":* GH removes all wind-out-of-limits time from the calculation, i.e. it is put in the "**N**" bin, because these availability values are used as a loss factor[1] in the calculation of energy production. This category is given the highest priority; this is equivalent to saying that GH only considers availability during times when the wind is within limits. Turbine manufacturers and many owners do not remove this time – manufacturers consider it "**A**" and owners may consider it "**U**". Both typically place it lower in the priority list. This characteristic often accounts for a large portion of the deviation of manufacturer's availability figures from GH's values.
- *Grid & BoP:* When comparing turbine technologies, GH removes from consideration periods of gird and Balance of Plant (BoP) outages. That is, GH classifies grid outage time as "**N**", whereas turbine manufacturers appropriately consider it "Available". This is a good example of how the point of view affects the form taken by this calculation.
- *Maintenance:* Scheduled maintenance is usually listed in contracts as "**A**vailable" by manufacturers, and these maintenance periods appear to be growing in length. Owners and GH of course list the time as "**U**navailable".
- *Lightning & Icing:* For the purposes of comparing and evaluating turbine technologies, GH considers lightning-caused outages to be **U**navailable, because some turbines are often able to continue operating during many lightning events.

  GH treats icing outages differently at this time, because most turbines shut down during severe icing. Therefore GH classifies icing outages as "**N**", removing this state from consideration. If anti-icing systems were to become more common and some turbines could significantly reduce icing downtime, icing could be handled similarly to lightning.

  Blade icing not only causes outages; before shutting a turbine down, it may cause a reduction in power output by disrupting the blade's aerodynamics. These two effects of icing are distinct and are not "double-counted" in GH energy calculations. Availability as a metric is not intended to account for changes in performance, which would typically be addressed in a separate metric. Since icing-related downtime is removed from consideration ("**N**"), energy production losses due to icing are not accounted for in GH's turbine availability figures; instead, they would generally be accounted for as part of a separate energy loss factor (Environmental Losses) along with any reduced aerodynamic performance.
- *Force majeure:* Force majeure terms are contractually defined and vary widely. With the exception of lightning, GH generally considers force majeure periods to be in the "**N**" category.
- *Incomplete Data:* The treatment of lost data time varies among definitions and can significantly affect the outcome. Periods with lost data may be calculated in any or all of three forms: as **N**, as **U**, or as both **A** and **U** in the same ratio as appears in the data. Note that using **A** and **U** in the same overall proportions may not be a valid assumption, since data is more likely to be lost during some form of outage. GH typically uses two of these calculations to create a range of uncertainty.

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[1] See Appendix Section 7.5.1.

7.4.1 Relationship to Other Industry Standard Definitions of Availability

The International Electrotechnical Commission (IEC) is currently in the process of drafting a Technical Standard TS 61400-26-1 called "Time-based availability for wind turbines". This document seeks to standardize the reporting of wind turbine states such as those listed in the "examples" column of Table 2 above. In its current draft it does not seek to standardize the availability definitions themselves.

GH's turbine availability definition is largely compatible with the draft TS 61400-26-1; however, a careful characterization of "wind-in-limits" time may require additional information since the TS's "out-of-environmental specification" states may not sufficiently correspond to GH's "wind-out-of-limits" state. For instance, the draft standard does not require the recording of high-wind shutdowns, and the "calm" state is an optional sub-state of out-of-environmental specification. As the TS stands, the "wind-in-limits" periods which constitute GH's denominator may still have to be determined through nacelle anemometer records and other sources, as they typically are now. When the final TS is issued, GH will review the correspondence between GH definitions and the IEC framework.

For a more detailed discussion of GH's availability definition in relation to other industry standard definitions, such as IEEE Standard 762 and NERC's "GADS" wind data reporting system[2], refer to GH's paper on availability definitions [5].

7.5 Definitions of a Few Other Terms

7.5.1 Loss Factors

In estimations of energy production, wind conditions and a turbine power curve are used to calculate a "gross energy output" in GWh/annum. This figure is multiplied by a series of loss factors to account for the many factors that reduce this ideal upper bound; typical loss factors include wake effects, electrical efficiencies, temperature shutdowns, curtailment, BoP availabilities, turbine performance, and turbine availability. For this turbine availability loss factor, GH uses the turbine model's projected availability discussed in this memo.

The availability loss factor, since it is multiplied by the gross energy output, must apply only to the turbine's performance during wind-in-limit times. The turbine's status during calm times is completely irrelevant; for instance, "availability" under cut-in speeds could vary arbitrarily without having any effect on the energy output of the turbine.

The most appropriate availability loss factor would be an energy-weighted availability calculation, which is implicitly "wind-in-limits", since by definition it does not include non-generating times in the numerator or non-windy times in the denominator. An energy-weighted availability can be difficult and sometimes impractical to calculate; however, GH has found that the "wind-in-limits" availability is usually closely related to the energy-weighted availability. For this reason, GH uses a "wind-in-limits" availability definition for the availability loss factor.

In contrast, the use of a "full-period" definition of availability for a loss factor implicitly assumes that performance is the same whether the wind is in and out of limits; this is not typically the case.

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[2] See, for instance, http://www.nerc.com/files/GADS_Wind_Data_Reporting_Workshop_111009.ppt and http://www.nerc.com/page.php?cid=4|43.

7.5.2 Model Year

A “model year” is the set of turbines installed in a given year in a given region. For instance, if commercial installation in North America of the XYZ2.5-100 turbine began in January 2010, the first “model year” includes all those turbines installed here in 2010. GH notes that the life-time average availability of a turbine’s first model year is apt to be somewhat lower than the lifetime average of the same model’s third model year. For this reason, GH often projects a slightly lower long-term availability for the early model years of a turbine design.

The idea that the first “model year” of a given turbine model has a lower *life-time* availability is not to be confused with the “ramp-up”, which refers to the expectation that a turbine will have a lower availability during the *first year* of operation after commissioning.