Recommended key performance indicators for operational management of wind turbines

S Pfaffel[1], S Faulstich[1] and S Sheng[2]

[1] Fraunhofer Institute for Energy Economics and Energy System Technology - IEE, Königstor 59, 34119 Kassel, Germany
[2] National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80401, USA

E-mail: `sebastian.pfaffel@iee.fraunhofer.de`

Abstract. Operational managers of wind turbines usually monitor a big fleet of turbines and thus need highly condensed information to identify underperforming turbines and to prioritize their work. Key performance indicators (KPIs) are a solid and frequently used tool for this purpose. However, the KPIs used in the wind industry are not unified to date, which makes comparison in the industry difficult. Further, comprehensive standards on a set of KPIs for the wind industry are missing. This article identifies and recommends KPIs and provides detailed definitions to make KPIs comparable and to enable benchmarking. The starting point of this work is an industry survey with 28 participants intended to identify commonly used KPIs, collect various possible definitions, and prioritize them. Out of a total of 50 KPIs, we discuss in a next step 33 selected KPIs on performance, maintenance, and reliability in detail and recommend definitions, most of which are based on international standards. As a result, operators can easily use these recommendations to base their system of KPIs. By using this unified set of KPIs, operators can be well-prepared to conduct industrywide comparisons and benchmarks. The survey and this article will also serve as a basis for committee work of the FGW e.V. to develop a corresponding technical guideline.

1. Introduction

After the successful construction of a wind turbine, its operating phase begins. Although some wind turbines (WTs) in Germany are replaced by more modern and, above all, larger types before the standard design lifetime of 20 years [1] is reached [2], the utilization of the remaining useful life and continued operation after 20 years is important for many WTs [3, 4, 2]. Furthermore, a first manufacturer has announced new turbine types having a design life of up to 30 years [5]. This and the fact that operation and maintenance (O&M) accounts for a share between 20% and almost 40% of the levelized cost of energy (LCOE) [6, 7, 8, 9, 10, 11] demonstrates the high importance of sound operational management.

WTs are usually monitored 24/7 from a central operator's control room to react to unexpected technical problems and quickly identify and trigger appropriate measures (e.g., maintenance operations). However, the long-term performance of WTs and the achievement of targets and forecasts in various categories (e.g., technical, financial, safety) must also be monitored for successful operational management. Key performance indicators (KPIs) are metrics to objectively describe the performance of an observed unit (e.g., company, technical system, employee) in a well-defined and traceable way [12, 13]. In order to assess individual results, KPIs must be compared to a target value that could be a forecast, historic result, or comparable unit. As in other industries, KPIs are widely used in the wind industry and are part of contracts, management information, and decision support systems. According to [13, 14], KPIs have to fulfill the SMART (Specific, Measurable, Achievable, Relevant and Time-bound) criteria to provide valuable information. To be specific and measurable, KPIs have to be well defined and unified. Even though guidelines and standards (e.g., International Electrotechnical Commission (IEC) [15, 16] and VGB [17, 18, 19]) on KPIs for the wind industry exist, the KPIs actually used throughout the wind industry, as well as their definitions, are still very heterogeneous and sometimes even contradictory. Books by Tavner [20] or Burton et al. [21] provide valuable information and definitions but are not classified as a guideline or standard.

Publications by Gonzalez et al. [22] or the European Commission [23] evaluate KPIs for the wind industry. Specifically, Gonzalez et al. [22] provide a comprehensive list of valuable KPIs for O&M of WTs. Further research papers [24, 25, 26, 27, 28, 29] make use of KPIs and define single KPIs to their needs, but do not originally intend to provide a set of KPI definitions.

Based on the publications described here as well as standards and guidelines, the objective of this article is to recommend the most important KPIs along with their specific definitions for streamlining day-to-day work of the operational management of WTs and industrywide benchmarking. While recent publications use SMART criteria [22, 13, 14] or even data mining techniques [30] to select a set of KPIs, we decided instead to reach out to the industry and survey experts. For this purpose, we conducted a literature review to gather KPIs that were assumed to be of relevance to O&M of WTs in previous research and international and national standards and guidelines. Main starting point were the publications by Gonzalez et al. [22] and VGB [17, 18, 19], complemented by the expert knowledge of the authors from running the WInD-Pool [31] initiative as well as the gearbox reliability database [32]. KPIs and their definitions were collected, summarized, and categorized to form the basis for a survey among experts involved in O&M of WTs.

The survey (see Section 2) aims to determine the relevance of the individual KPIs and their various definitions, obtain missing KPIs, and prioritize future work. Thus the prioritization is based on the actual use of KPIs in the wind industry and not on a purely theoretical evaluation and literature review as done in previous publications. Next (see Section 3), the most relevant KPIs, their purpose, and application—as well as their definitions—are discussed in detail. While the prioritization of KPIs is based on the survey results, the single recommended KPI definitions are mainly based on a detailed review of literature and standards as well as the experience of the authors. This results in a comprehensive list of unified KPIs including detailed definitions to achieve a common understanding of the most important KPIs and enable industrywide comparisons (see Section 4). The detailed KPI evaluation of this article focuses on performance, maintenance, and reliability metrics. For Health, Safety and the Environment (HSE)- and Finance-KPIs, we evaluated only the results of the survey. The results are expected to serve as a basis for the development of a corresponding guideline by the Fördergesellschaft Windenergie und andere Dezentrale Energien (FGW e.V.) (see Section 5).

2. Survey on KPIs

To focus on KPIs relevant for the day-to-day work performed as part of wind turbine O&M and to prioritize standardization efforts, we conducted a survey to determine the most important KPIs used in the wind industry. The survey was part of the work to add a section regarding the analyses of WT data to the technical guideline part 7 [33] of the FGW e.V., which deals with operation and maintenance of WT. Prepared by the Fraunhofer Institute for Energy Economics and Energy System Technology (Fraunhofer IEE) and coordinated with members of the working group, the request to participate in the survey was circulated by the working group as well as the FGW e.V. to members of a selected target group. The surveyed companies are located in German-speaking areas but are active internationally in many cases.

2.1. Survey design

The survey is based on a list of 34 potentially relevant KPIs gathered during a literature search and complemented by the knowledge of experts within the FGW e.V. working group. In accordance with the different categories of KPIs, the survey is divided into the following five sections:

- Performance KPIs
- Maintenance KPIs
- Reliability KPIs
- HSE KPIs
- Finance KPIs

Following this categorization, the web-based survey also consists of five sections, which are responded to according to the previously indicated order. Depending on the survey participant's expertise and interest, he/she has the option of skipping individual questions, entire sections, or exiting the survey early. Answering questions about a KPI is therefore also considered as an expression of its relevance. Background information about the survey participant is requested but not mandatory. Participants can remain anonymous or provide contact details for follow-up questions. For each KPI, the following questions are asked:

- Is the KPI used in your company?
- Which definition is used?
- Which data serves as a basis?
- How important is the KPI?

The survey comprises a total of 144 questions. Therefore, a decrease in participant motivation to answer later questions has to be considered in the survey design and analyses of the answers. As a result, KPI categories with the greatest expected differences to other industries are queried at the beginning. We expect that finance and HSE KPIs are not wind-specific.

2.2. Survey results

Invitations to participate in the survey were sent out by the FGW e.V. on 4th October 2017, with the last survey completed on 1st November 2017. A total of 30 responses were submitted within 1 month. The answers of 28 participants were considered to be useful, whereas two participants were excluded because of implausible answers. The 28 participants spent about 17 minutes on the survey, on average (median). As expected, none of them answered all of the questions. Figure 1 shows that the primary target group of owners/operators and operational managers accounts for about 50% of all answers. A differentiation of owners/operators and operational managers may not be necessary in many countries, but was made because of the specific situation of the German market. The roles of manufacturers, researchers, grid operators, and consultants were not provided as response options in the original survey design and added by the participants as free text.

The number of participants is within the expected range and does not allow for a detailed statistical evaluation or representative results in a rigorous statistical sampling sense. From our experience, this is still a very decent number of responses for an expert survey in the wind industry, especially if leading manufacturers and operators are participating. Due to the amount of time participants spend on the survey, we assume a high motivation and knowledge of the

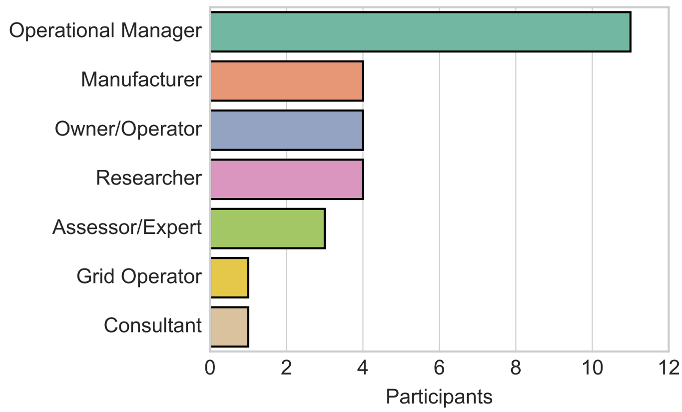

Figure 1. Share of different people and their roles in the wind industry who participated in the FGW e.V. survey on relevant key performance indicators for the operation and maintenance of wind turbines.

participating experts. Thus, conclusions on the importance of a single KPI and prioritization can be drawn. For this purpose, the absolute importance (frequency of use x importance) is determined. Furthermore, the participants pointed out missing KPIs and provided information on possible KPI definitions. Results on the different KPI categories are discussed in the following subsections. Summarizing tables (Tables 1–5) are ordered by the absolute importance. New KPIs are highlighted in grey and KPIs without any answers/importance are highlighted in red.

2.2.1. Performance Performance KPIs show the highest importance of all KPI categories. All 28 participants answered whether they make use of performance KPIs, with 20 indicating that they do; see Table 1. Except for "Remote-Resets," all proposed KPIs are among the top 10, with the highest absolute importance of the whole survey. Furthermore, participants suggested that 10 additional KPIs be considered in a comprehensive KPI systematic. Four of the suggested KPIs are intended to provide more concrete descriptions for the term, "wind conditions." The proposed market value factor is closely linked to financial results.

Table 1. Performance KPIs inquired about in the survey included more precise KPI definitions regarding wind conditions and additional KPIs in general.

KPI	Answers	Use	Importance (1–5)	Abs. Importance
Power curve	20/20	19/20	4.5	85.5
Wind conditions	20/20	16/20	4.5	72
Average wind speed				
Wind speed distribution				
Wind direction distribution				
Average wind speed/site assessment				
Full-load hours	20/20	18/20	3.5	63
Energy consumption	20/20	16/20	3.1	49.6
Capacity factor	20/20	13/20	3.7	48.1
Data availability	20/20	11/20	4.1	45.1
Remote-resets	20/20	5/20	3.2	16
Site quality				
No. of telecommunication interruptions				
Forecast fulfillment				
Operating hours				
Specific yield				
Market value factor				

2.2.2. Maintenance Maintenance KPIs are used by a little more than half (16/28) of the survey participants; see Table 2. While availability metrics are of high importance and part of the top 10 KPIs, further and more detailed KPIs show a significantly lower importance. The survey suggests that respondents consider six additional KPIs, as three of them are expected to increase the level of detail on planned maintenance tasks.

Table 2. Maintenance KPIs inquired about in the survey included more precise KPI definitions regarding planned maintenance tasks and additional KPIs in general.

KPI	Answers	Use	Importance (1–5)	Abs. Importance
Time-based availability	16/16	16/16	4.7	75.2
Production-based availability	16/16	12/16	4.1	49.2
Production ratio				
Yield losses by cause				
Monetary-based availability				
Maintenance tasks	16/16	7/16	4	28
Preventive maintenance tasks	16/16	7/16	3.3	23.1
Number of routine maintenance tasks				
Number of inspections/visual inspections				
Number of repairs				
Reactive maintenance tasks	16/16	7/16	3.3	23.1
Risk priority number (RPN)	16/16	1/16	5	5

2.2.3. Reliability Although only basic reliability KPIs were proposed in the survey, only 10 out of 28 respondents use reliability KPIs at all in their organization; see Table 3. Participants using reliability KPIs have in most cases the role of an owner/operator or manufacturer. No additional KPIs were suggested.

Table 3. Reliability KPIs inquired about in the survey.

KPI	Answers	Use	Importance (1–5)	Abs. Importance
Failure rate	10/10	8/10	3.6	28.8
Mean time between failures (MTBF)	10/10	7/10	3.6	25.2
Mean time to repair / restoration (MTTR)	10/10	7/10	3.3	23.1
Mean down time (MDT)	10/10	6/10	3	18
Mean operating time between failures (MOTBF)	10/10	5/10	3.2	16
Mean operating time to failures (MTTF)	10/10	5/10	2.8	14
Repair rate	10/10	3/10	2.3	6.9

2.2.4. Health, safety, and the environment Only five (most manufacturers) out of 27 respondents make use of HSE KPIs in their organization. Thus, the absolute importance of all KPIs is low, and two KPIs are not used at all; see Table 4. No additional KPIs were suggested. The low importance of HSE KPIs might be caused by the fact that the German wind industry consists mainly of small- and medium-sized companies and that at least data on health and safety related incidents is gathered and analyzed by employer's liability insurance associations, which may provide more accurate information.

Table 4. HSE KPIs inquired about in the survey.

KPI	Answers	Use	Importance (1–5)	Abs. Importance
Total accident rate	5/5	4/5	3.7	14.8
Total lost time occupational illness frequency	5/5	3/5	2.7	8.1
Fatal accident rate	5/5	2/5	4	8
Recordable injury rate	5/5	2/5	3.5	7
Energy demand per employee and year	5/5	0/5	0	0
Pollutant release per employee and year	5/5	0/5	0	0

2.2.5. Finance Nine out of 22 respondents make use of finance KPIs in their organization. Overall, finance KPIs are of medium-to-low importance and one KPI is not considered to be relevant at all. One reason for the low importance of the finance KPIs in the survey can be the subdivision of the operational management of WTs in Germany. The commercial and technical management is usually carried out by different departments or even different companies.

Table 5. Finance KPIs asked in the survey including additional KPIs (highlighted in grey).

KPI	Answers	Use	Importance (1-5)	Abs. Importance
EBITDA	9/9	5/9	4	20
Maintenance costs	9/9	5/9	3.6	18
Operational expenditures (OPEX)	9/9	4/9	4.4	17.6
Levelized cost of energy (LCOE)	9/9	3/9	3.7	11.1
Debt-service coverage ratio (DSCR)	9/9	2/9	5	10
Free cash flow to equity (FCFE)	9/9	2/9	4.5	9
Break-even price of energy (BEPE)	9/9	1/9	4	4
Loan life coverage ratio (LLCR)	9/9	0/9	0	0

3. Recommended KPIs and definitions

A list of 33 KPIs out of a total of 50 KPIs were identified through the survey and selected based on the experience of the authors to be recommended KPIs. These KPIs are subject of a more detailed discussion and effort to provide detailed definitions. See Appendix A, Appendix B and Appendix C for the discussion and definition of the single KPIs. Following the expertise of the authors, the detailed evaluation focuses solely on performance, maintenance, and reliability metrics. We must also mention that some of the KPIs (e.g., on availability) cannot be assigned exclusively to a single category. The chosen assignment should therefore only be regarded as an orientation. For each KPI, its purpose, field of application, possible differing definitions, and required data sources are discussed. A proposed KPI definition is provided, which in case of doubt, takes the point of view of an owner/operator or the operational management. The discussion considers literature as well as information and comments provided by industry experts in the survey. Wherever possible, the definitions are based on accepted standards and guidelines for power plants or other industries of similar nature. Still, the selected definitions reflect the experience of the authors and KPIs had to be set by the authors in some cases.

The temporal resolution of KPIs as well the frequency of calculation should be adjusted to a company's internal reporting period. As a general recommendation, performance and maintenance KPIs should be calculated on a monthly basis and then rolled up to quarterly and yearly values. For reliability, HSE and finance KPIs, a yearly evaluation will suffice.

Performance of a WT can be understood as its ability to meet the expectations placed on it. Thus, performance KPIs (Appendix A) comprise indicators describing operational results like the capacity factor as well as indicators of the underlying conditions (e.g., wind conditions) under which the results were achieved. Furthermore, KPIs designed to identify undesired behavior of the WT can be considered to be performance KPIs as well.

Maintenance KPIs (Appendix B) are mainly intended to monitor the success of maintenance strategies. The selected maintenance strategy has to fit WT specific requirements, as KPIs like the production-based or monetary-based availability show. Although the reliability of the WT technology is always a key factor, historical comparisons or comparisons with other WTs in particular make it possible to evaluate the results.

Reliability KPIs (Appendix C) monitor the ”ability of an item to perform a required function...” [34] by assessing the frequency of failures as well as the duration of the corresponding faults/downtime and required time of repairs. Thus, performance and reliability KPIs are strongly influenced by the WTs reliability. Working with reliability KPIs requires a discussion of some prerequisites.

When assessing the reliability of a WT, different levels of detail can be applied. The term ”item” includes ”systems” as well as ”components” but will be mainly used as a synonym for ”system” in this work. Analyses can be carried out on a WT, system or component level. It is recommended to use a standardized designation system to obtain comparable results. Although the Reference Designation System for Power Plants (RDS-PP) [35] is the recommended system for worldwide application, the North American Electric Reliability Corporation - Generating Availability Data System (NERC-GADS) [36] should be applied in the United States. The level of detail also determines whether the evaluated object is repairable or not. Even though a WT and its systems are always considered to be repairable, subsystems and components have to be replaced in many cases. Different KPIs have to be used for (partially) repairable and non-repairable systems as Figure 2 shows. KPIs for systems that can be repaired to a state as good as new are calculated the same way as for non-repairable system.

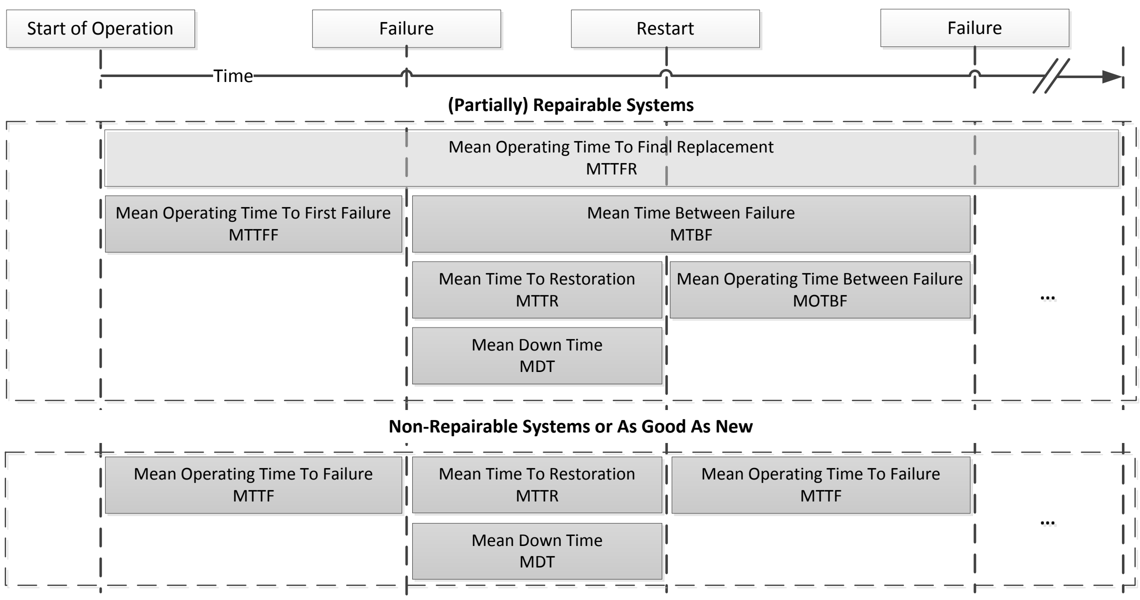

Figure 2. Reliability mean time measures for (partially) repairable and non-repairable systems according to ISO [37, 38] and IEC [39] standards.

This article focuses on mean time metrics as basic reliability KPIs to describe and compare the reliability of WTs. Various definitions are used in the literature. All definitions in this work are based on the International Electrotechnical Vocabulary (IEC 60050-192) [39] as well as on the International Organization for Standardization (ISO) standards 12489 [37] and 14224 [38] which aim at the oil and gas industry. Further publications [40, 41, 42] provide valuable information as well, but also slightly different definitions. The discussed KPIs enable monitoring and benchmarks but are not sufficient for maintenance optimization, which requires detailed reliability distributions. Refer to [43] for further details on the requirements for maintenance optimization.

Time is the commonly used lifetime metric of the discussed reliability KPIs and even part of the KPI names. Its usage to describe the lifetime of systems and components is only a first step though. More sophisticated and system specific metrics are needed. Examples could be the energy yield, revolutions or load cycles. As soon as further lifetime metrics are available, see Guo and Sheng [44] for gearboxes, all reliability KPIs can be calculated using such metrics instead of time.

Work reports on repairs and replacements are the required data sources to calculate reliability KPIs; reports on routine maintenance/service are not necessary. However, they can be supplemented by operational data to obtain information on the total downtime.

4. Conclusions

This article discusses recommended KPIs for the operational management of WTs and therefore takes the operator's perspective. Results of an industry survey are presented to determine the most relevant KPIs. As expected, the limited number of participants does not allow for detailed statistical evaluations and the survey can't be considered to be representative in a rigorous statistical sampling sense. However, from the author's point of view, a basic prioritization of the KPIs is reasonable. As a result, the recommended KPIs in this article are not primarily based on the authors' experience, as in other publications, but on real application in the industry. The recommended definitions for each KPI are based on comments from the survey and on a review of the corresponding literature and standards. Still, it has to be acknowledged that the recommended definitions are always biased by the experience and opinion of the authors. Based on the results (Sections 2 and 3) of this article, the following conclusions can be drawn:

- To date, there are already many KPIs on O&M of WTs available and used by operational managers.
- The set of KPIs used by operational managers as well as the definitions of single KPIs are heterogeneous and do not enable cross company comparisons or benchmarking.
- Performance KPIs are most important for operational managers. Maintenance and reliability KPIs are of importance as well but follow with less relevance.
- HSE and finance KPIs are usually not wind specific and already well defined in the literature. Still, an overview of the related recommended KPIs and their definitions would be beneficial.
- An international technical guideline or standard providing recommendations on a set of KPIs for the operational management of WTs would be beneficial. Such a document should comprise a list of KPIs, their definitions and recommendations for their application.
- The previous paper publication of Gonzalez et al. [22] or the technical guideline published by the VGB [17] already provide a comprehensive list of valuable KPIs. In contrast, the present article follows a more holistic approach and also recommends detailed KPI definitions, which are based on internationally accepted standards wherever possible.
- The survey is based on a list of 34 KPIs, of which 3 KPIs are rejected. 16 further KPIs are recommended by the participants. Out of a total of 50 KPIs, 33 KPIs are discussed in detail.

5. Outlook

The results of the survey and this article will be the starting point for committee work of the FGW e.V. to develop a corresponding technical guideline. However, the corresponding work is not finished with this publication but just getting started. Thus, the list of recommended KPIs is not complete. Further KPIs will be developed within the scientific community or the industry and can become part of the technical guideline at a certain point. KPIs on the fulfillment of power curves or to monitor degradation are just two possible examples.

Further work is also necessary regarding recommended approaches for aggregation and pooling of KPIs as well as regarding the uncertainties of KPIs in general. Aggregated results can strongly differ depending on the selected aggregation approaches. Annex F of the Institute of Electrical and Electronics Engineers (IEEE) Standard 762-2006 [45] is a good example of the importance of a unified approach to make KPIs comparable and shows how this issue can be addressed. The importance of an uncertainty assessment has been shown in [46, 47] for the production-based availability. Further work on uncertainty estimations and especially the uncertainty of additional KPIs is strongly encouraged.

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Appendix A. Recommended performance KPIs

Appendix A.1. Wind conditions

Wind conditions at the site of a WT strongly influence the overall performance. To describe the wind conditions, various KPIs are used. Based on the results of the survey, the most important ones will be discussed below.

$$\bar{V} = \frac{1}{n} \cdot \sum_{i=1}^{n} V_{10\mathrm{min}} \tag{A.1}$$

where

$$\bar{V} = \text{Average wind speed},$$
$$V_{10\text{min}} = \text{Measured wind speed averaged over 10 min}$$

Average wind speed (Equation A.1) is the most commonly used yet least informative KPI to describe wind conditions. It can be calculated as an arithmetic mean based on 5-, 10-, or 15-minute average values of the nacelle-based wind-speed measurement included in the supervisory control and data acquisition system (SCADA) data. Without further information on the range of wind speeds and air density, the informative value on the wind power actually available at the site is low, and comparisons between different years or WTs can be misleading. As an alternative KPI, wind power density (Equation A.2) takes the two above-mentioned issues into account and is more recommended. IEC 61400-12-2 [48] and FGW TR 6 [49] provide basic information regarding the handling of wind speed measurements but KPI definitions are missing. However, the definitions of both KPIs can be considered to be general knowledge and are included in standard literature [21, 50].

$$\bar{P}_{\text{Wind}} = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{1}{2} \rho_{10\text{min}} V_{10\text{min}}^{3} \tag{A.2}$$

where

$$\bar{P}_{\text{Wind}} = \text{Average wind power density},$$
$$\rho_{10\text{min}} = \text{Air density averaged over 10 min},$$
$$V_{10\text{min}} = \text{Measured wind speed averaged over 10 min}$$

To compare wind conditions of a certain year to conditions expected in the site assessment and project planning, the measured results have to be corrected for the long-term variation. During the site assessment, wind speed and/or wind energy indices [51, 27] are used to determine representative wind conditions, as defined in FGW TR 6 [49]. It is recommended to apply the same approach and indices to operational data.

When analyzing and visualizing wind conditions in detail, the wind speed distribution is usually represented by a histogram and in a next step by a Weibull distribution [50, 21]. Even though, both tools can be beneficial for detailed analysis, they do not provide easy-to-grasp information and cannot be counted as KPIs. The same applies for histograms of the wind direction. Average wind directions are not commonly used in the wind industry but can be applied as a first step to identify WT misalignment or problems in the wind measurement system. In any case, it must be ensured that the mean wind direction is calculated vector-based and not as an arithmetic mean [52].

Appendix A.2. Power curve

The power curve of a WT describes the average power output at different wind speeds normalized to standardized conditions, especially regarding air density and turbulence. Different phases in the life cycle of a WT use different power curves. During project development, calculated power curves for new turbine types are a starting point in many cases and usually replaced by measured reference power curves later on. In the O&M phase, power curves are used to compare the actual operational performance of the WT to the intended performance described by the power curve as well as to calculate losses during downtime or derated operation. It is obvious that the power curve does not fit the classical characteristics of a KPI but rather is an indispensable tool for wind turbine O&M, which is necessary for the calculation of further KPIs.

Although the survey shows agreement on the basic definition of a power curve, the procedure for determining it as precisely as possible is complex and many uncertainties have to be considered [53, 47]. Definitions for power curve calculations are provided by the IEC as an international standard and are the recommended definitions. While the IEC 61400-12-1 [15] defines the procedure to calculate a reference power curve using additional measurement equipment like a measuring mast, IEC 61400-12-2 [48] defines the procedure to calculate a power curve based on SCADA data including wind speed measurements by the nacelle anemometer. Further definitions/procedures to calculate power curves for specific applications exist on a national level. Examples are the German technical guidelines TR 2, 5, and 10 [54, 55, 56] of the FGW e.V. and the technical recommendation TR-1 on wind farm power performance of the American Wind Energy Association (AWEA) in the United States, which is still unpublished. The application of different methods for data filtration and power curve modeling can lead to not negligible differences in the results, as Craig et al. [47] showed.

Although the power curve is used to determine various KPIs, the authors are not aware of a generally used KPI to evaluate the power curve itself. It would be beneficial to use such a KPI to compare power curves of different WT or monitor possible changes over time.

Appendix A.3. Full-load hours and capacity factor

Even though full-load hours (Equation A.4) and the capacity factor (Equation A.3) are individual KPIs, they are discussed together because of their very similar statement and definition. The capacity factor compares the actual produced energy to the amount of energy that could have been produced by a WT in perfect wind conditions, thereby enabling continuous operation at rated power without any interruption/downtime. Thus, the capacity factor is a dimensionless value that is usually presented as a percentage value. Full-load hours show the amount of time (hours) that a WT would have needed to operate at rated capacity to produce the actual produced amount of energy during a specific duration, usually a year.

$$CF = \frac{W_{\text{Actual}}}{W_{\text{Nominal}}} \cdot 100\% \tag{A.3}$$

where

$$\begin{aligned} CF &= \text{Capacity factor}, \\ W_{\text{Actual}} &= \text{Generated energy}, \\ W_{\text{Nominal}} &= \text{Nominal possible energy generation} \end{aligned}$$

The available definitions for both KPIs from the survey, the literature [24, 25], and the standards and guidelines show no differences. Recommended sources for the capacity factor are IEC 61400-26-2 Annex C.2 [16] and the IEEE Std 762 3.17 [45] and for the full-load hours the VGB-S-002-05 [18].

$$t_{\text{FL}} = \frac{W_{\text{Actual}}}{P_{\text{Rated}}} \tag{A.4}$$

where

$$\begin{aligned} t_{\text{FL}} &= \text{Full-Load Hours}, \\ W_{\text{Actual}} &= \text{Generated Energy}, \\ P_{\text{Rated}} &= \text{Rated Capacity} \end{aligned}$$

Although full-load hours and the capacity factor depend heavily on site- and year-specific wind conditions as well as the installed turbine type, both KPIs are commonly used to describe

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the performance of WTs and can easily be converted into each other. Typical applications are the comparison between different turbines and turbine types at the same site, different sites having the same turbine type, as well as the comparison to expected values of the site assessment or previous years. Wind indexes can be used to correct long-term variability [51, 49]. There is no doubt that there are better KPIs for all of these different applications, but both KPIs are frequently used in the wind industry, especially because of their universality and simplicity.

Appendix A.4. Data availability

The availability of plausible data (A_{Data}, Equation A.5) from the SCADA system is a prerequisite to determine many of the KPIs discussed in this paper. It is therefore necessary to monitor the availability of the data using a corresponding KPI. This statement is supported by the results of the survey. To date, no known standards or guidelines include a description of data availability. However, there is agreement within the survey/industry on its basic definition. Data availability is the ratio of time having sufficient and plausible information to the total amount of time. Data gaps are of course included in the calculation. Data availability can and should be calculated for different cases. As a first step, the KPI should assess the general availability of data for each time step. Furthermore, the evaluation should drill down to the individual measurements and at least analyze power and wind speed measurements individually.

$$A_{Data} = \left(1 - \frac{t_{\text{NoData}}}{t_{\text{Total}}}\right) \cdot 100\% \tag{A.5}$$

where

$$\begin{aligned} A_{Data} &= \text{Data availability,} \\ t_{\text{NoData}} &= \text{Time of no or bad data,} \\ t_{\text{Total}} &= \text{Total time} \end{aligned}$$

Appendix A.5. Energy consumption factor

WTs always consume energy to supply ancillary systems. Usually those systems are supplied by the electricity generated by the WT itself if the electricity output of the WT remains positive. However, during phases of low wind speeds or downtime, the WT turns from a producer to a consumer of electricity. The described periods are characterized by a negative power output. To date, a standardized definition of a KPI is not available. In order to make the average energy consumption comparable, it can be normalized to the rated power, as with the capacity factor. Because of the rather small values, the result should be presented as a per-mille value and not as a percentage.

$$ECF = \frac{\sum_{i=1}^{n} (\bar{P}_i(P < 0) \cdot t_i(P < 0))}{P_{\text{Rated}} \cdot \Delta t} \cdot 1000 \text{ ‰} \tag{A.6}$$

where

$$\begin{aligned} ECF &= \text{Energy consumption factor,} \\ \bar{P}_i(P < 0) &= \text{Average power of the } ith \text{ period having negative power output,} \\ t_i(P < 0) &= \text{Duration of the } ith \text{ negative power output,} \\ P_{\text{Rated}} &= \text{Rated capacity,} \\ \Delta t &= \text{Observation period in hours} \end{aligned}$$

Appendix A.6. Remote resets

Remote resets occur when the protection system of a WT is activated and the WT is forced to shut down. According to the definitions of DNV GL [57], a manual reset by staff on-site shall be normally performed in such cases. Instead, remote resets can be handled from the remote control center to save money and time as long as further measures like a root cause analysis are taken and the number of remote resets is limited [57]. Remote resets are defined as having a maximum downtime of 1 [31] or 2 hours [7] in the literature. Still, remote resets should be identified by the corresponding signal of the SCADA system.

$$\lambda_R = \frac{c_R}{\Delta t} \tag{A.7}$$

$$MDT_R = \frac{\sum_{i=1}^{c_R} DT_i}{c_R} \tag{A.8}$$

where

$$\begin{aligned} \lambda_R &= \text{Reset rate}, \\ MDT_R &= \text{Mean downtime of remote resets}, \\ c_R &= \text{Count of remote resets}, \\ \Delta t &= \text{Observation period in months or years}, \\ DT_i &= \text{Downtime of the ith reset} \end{aligned}$$

It is important to count the number of remote resets per defined period of time (month, year) to ensure compliance with recommended limitations as well as to detect deviating WTs. The average downtime per reset should be evaluated for the same reason. Very short downtimes can imply an insufficient root cause analysis.

Appendix A.7. Telecommunication interruptions

Reliable and fast network connections are essential in many areas of automated and remotely monitored asset operation [58]. This applies in particular to WTs. WTs are not forced to stop operation in the event of a telecommunications interruption, but can continue to run independently and without monitoring by the control centre. However, the loss of a connection does not only mean a loss of monitoring but also the possibility of human intervention, which is of high relevance in the event of network bottlenecks, for example. With this in mind, the frequency and duration of telecommunication interruptions should be monitored so that measures can be taken if necessary.

$$\lambda_{TI} = \frac{c_{TI}}{\Delta t} \tag{A.9}$$

$$MDT_{TI} = \frac{\sum_{i=1}^{c_{TI}} DT_i}{c_{TI}} \tag{A.10}$$

where

$$\begin{aligned} \lambda_{TI} &= \text{Telecommunication interruption rate}, \\ MDT_{TI} &= \text{Mean downtime of telecommunication interruptions}, \\ c_{TI} &= \text{Count of telecommunication interruptions}, \\ \Delta t &= \text{Observation period in months or years}, \\ DT_i &= \text{Downtime of the ith telecommunication interruption} \end{aligned}$$

Appendix A.8. Operating time

The operating time of a WT can be counted as defined by IEC [16] or VGB [19, 18]. Operating time is defined by the information category "GENERATING" in the IEC standard and as " ... the period in which a plant converts energy" by the VGB. Both definitions have the same meaning. Solely times with a positive power output are counted; standby or idling times are not considered to be operating time. Operating time can be presented either as an absolute value (e.g., for a year or as a percentage value normalized to the total time).

$$t_O = \sum_{i=1}^{n} t_i(P > 0) \tag{A.11}$$

where

$$\begin{aligned} t_O &= \text{Operating time}, \\ t_i(P > 0) &= \text{Time of positive power output for the } ith \text{ period} \end{aligned}$$

Appendix A.9. Site quality

The site quality is a KPI specific to Germany and required by the Renewable Energies Act [59] for all WT participating in land-based wind tenders. To enable competition among different regions, remunerations are adjusted to specific wind conditions. Remunerations are lower at sites with high wind speeds and higher at low wind speed sites. Turbine type and hub-height-specific reference yields — as defined in [55] — are calculated based on a generic reference site (100-m hub height). The wind conditions at the site are described by a Rayleigh distribution using a reference wind speed ($v_{ref} = 6.45\ m/s$) and a reference wind gradient described by the Hellmann exponent ($\alpha = 0.25$) to define a 100% scenario. The energy yield predicted during project planning and the potential energy yield during the operational phase of a WT are compared to the reference yield to determine the site quality. WT specific remunerations are adjusted accordingly. The potential energy yield is used instead of the actual energy yield so that technical or operational losses do not affect the level of remuneration. When calculating the potential energy yield, unavailability of up to 2% are considered to be normal. Further losses caused by technical reasons or compensated losses due to grid curtailment are added to the actual energy yield to calculate the potential energy yield. Detailed calculation specifications are defined in FGW TR 10 [56].

$$SG_{y,WTi} = \frac{SE_{y,WTi}}{R} \cdot 100 \tag{A.12}$$

where

$$\begin{aligned} SG_{y,WTi} &= \text{Site quality per WT and year}, \\ SE_{y,WTi} &= \text{Potential energy yield according to FGW TR10 per WT and year}, \\ R &= \text{Turbine type and hub-height-specific reference yield according to FGW TR 5} \end{aligned}$$

The operator is legally obliged to determine this KPI. In addition, this KPI can be used to compare operational results to expected values from the planning phase.

Appendix A.10. Market value factor

The power generation of WTs depends on the fluctuating wind conditions at the respective sites and does not necessarily meet the electricity demand which also varies. In many countries, wind power is sold on the spot market, in which the price is determined by supply and demand. The market value factor (MVF, Equation A.13) compares the average electricity price achieved by an asset (WT) to the average electricity price over a certain period of time. SCADA data and electricity prices are needed to calculate the market value factor. In Germany, hourly prices of the day-ahead auctions of the EPEX Spot SE market are used [60, 61, 62].

$$MVF = \frac{\sum_{h=1}^{n}(EPEX\_MCP_h \cdot W_h)}{\frac{\sum_{h=1}^{n} EPEX\_MCP_h}{n} \cdot \sum_{h=1}^{n} W_h} \tag{A.13}$$

where

$$\begin{aligned} MVF &= \text{Market value factor}, \\ EPEX\_MCP_h &= \text{Hourly day-ahead price at EPEX spot}, \\ W_h &= \text{Hourly energy yield of the considered asset} \end{aligned}$$

Market value factors are not only important during project planning but can also be of relevance during O&M to update revenue expectations and to determine the value of individual assets for direct marketing contracts. Additionally, the KPI might be of interest to prioritize maintenance measures. Prioritizing the maintenance of WTs showing high market value factors could lead to higher overall financial revenues. The monetary-based availability (see Section Appendix B.3), which is designed to take differing electricity prices into account, follows a similar approach.

Appendix B. Recommended maintenance KPIs

Appendix B.1. Time-based availability

The commonly accepted definition of time-based availability (A_t, Equation B.1) is the ratio (percentage value) of available time to total (available and unavailable) time. However, a wide variety of approaches are used to define available and unavailable times and to exclude times from consideration. The survey names standards, maintenance contracts, manufacturer definitions, and internal definitions as well as definitions included in software tools as sources in the wind industry. Further sources are to be expected. Standardized definitions are provided by the IEC 61400-25-1 [63], which includes definitions from different views. To achieve international comparability, the recommended definition for O&M follows the System Operational Availability (B.2.3) of the IEC standard where all downtime except for low wind is considered as not available. Guidelines like the VGB-S-002-05 [18] or the FGW TR 10 [56] include differing definitions. Because of the characteristics of wind energy, broad definitions from DIN EN 1534 [64] or VDI 3423 [65] cannot be applied directly.

$$A_t = \left(1 - \frac{t_{\text{Unavailable}}}{t_{\text{Available}} + t_{\text{Unavailable}}}\right) \cdot 100\% \tag{B.1}$$

where

$$\begin{aligned} A_t &= \text{Time-based availability}, \\ t_{\text{Available}} &= \text{Time of full and partial performance and low wind}, \\ t_{\text{Unavailable}} &= \text{Time of other cases except for data gaps} \end{aligned}$$

Appendix B.2. Production-based availability and Production Ratio

Production-based availability (A_W, Equation B.2) is the ratio of the actual energy yield of a WT to its potential energy yield. Considering the energy losses during downtimes instead of the downtime duration as well as in some cases losses caused by derated operation makes production-based availability a more holistic KPI compared to the time-based availability. Although this basic definition is common sense and information on the actual energy yield is simple to obtain, various approaches to calculate the potential energy yield are existing. The main differences lie in the consideration of different types of downtime, of generation losses during operation, and in methods for determining the potential power of a wind turbine. Answers of the survey show internal definitions, software-specific definitions, and the standard definitions published within the IEC 61400-26-2 [16] to be the most commonly applied. Like for time-based availability, the "System Operational Availability" (B.2.2) of IEC 61400-26-2 is the recommended definition for WTs operators/owners. In this definition, all differences between potential and actual production are assumed to be losses, and data gaps are excluded from the calculation; see Equation (B.2). VGB-S-002-05 [18] provides an alternative definition, which is less detailed and includes no calculation guidelines. When calculating the production-based availability, the determination of the potential power is a special challenge where plausible wind speed measurements and power curves or reference WTs are required to obtain reasonable results. A comparison of the different methods of the IEC 61400-26-2 [16] to determine the potential production was published by Wilkinson et al. [46]. A detailed categorization of the operating modes also enables an evaluation of yield or availability losses by their causes.

$$A_W = \left(1 - \frac{W_{\text{Potential}} - W_{\text{Actual}}}{W_{\text{Potential}}}\right) \cdot 100\% \tag{B.2}$$

where

$$\begin{aligned} A_W &= \text{Production-based availability,} \\ W_{\text{Actual}} &= \text{Actual energy yield,} \\ W_{\text{Potential}} &= \text{Potential energy yield, data gaps are excluded} \end{aligned}$$

An additional KPI is the production ratio as defined in IEC 61400-26-2 Annex C.3 [16]. It is calculated the same way as the production-based availability but only considers periods of normal operation (full performance). The production ratio is supposed to detect underperformance, which can be caused by icing, degradation, pitch angle deviations, and so on. Depending on the specific conditions, production ratios of more than 100% can occur temporarily, which can be a result of changing turbulences or inaccuracies in wind speed measurement.

Appendix B.3. Monetary-based availability

Monetary-based availability (A_M, Equation B.3) takes the availability assessment of WTs to a new level. First mentioned in this context by Hirsch et al. [66] in 2016, monetary-based availability is not yet used in the wind industry but has potential to be the upcoming most important KPI to assess the overall performance of WTs. While the time-based availability solely considers downtime, the production-based availability focuses on lost energy yield. In fact, the decisive factor is not lost energy but the loss of revenue. Thus, the monetary-based availability compares the achieved gross operating profit (GOP) (numerator) to the potential GOP (denominator). The GOP is calculated using electricity spot market prices to determine revenues. It is assumed that the potential GOP includes only periods of sufficient electricity prices above the marginal costs to operate the WT and the WT would be ideally shut down to avoid losses.

$$A_M = \frac{\overbrace{\sum_{i=1}^{j} \overbrace{\bar{P}_i \cdot t_i \cdot (p_i - c_i)}^{\text{Contribution margin}}}^{\text{GOP}}}{\underbrace{\sum_{\substack{i=1\\p_i>c_i}}^{j} \bar{P}_i \cdot t_i \cdot (p_i - c_i) + \underbrace{\sum_{\substack{i=1\\p_i>c_i\\state_{s,i}\in S}}^{j} (\bar{P}_{PC}(\bar{v}_i) - \bar{P}_i) \cdot t_i \cdot (p_i - c_i)}_{\text{Loss term: Losses due to certain states } (S)}}_{\text{Maximum possible GOP}}} \cdot 100\,\% \tag{B.3}$$

where

A_M = Monetary-based availability for considered period in %,
GOP = Gross operating profit for considered period (e.g. year, month, etc.),
i = i^{th} timestamp (averaging period usually 10 minutes) from j,
j = Number of timestamps within considered period,
$\bar{P}_i$ = Mean power for timestamp i,
t_i = Period duration in hours,
p_i = Electricity market price for timestamp i,
c_i = Marginal costs for timestamp i (user-specific),
$\bar{P}_{PC}$ = Mean power from reference power curve at wind speed $\bar{v}_i$,
$\bar{v}_i$ = Mean wind speed for timestamp i in m/s,
$state_{s,i}$ = WT state s for timestamp i,
S = WT-states considered in the loss term (user-specific)

Shifting O&M strategies toward an optimized monetary-based availability will become more important when more WTs have to rely on market prices instead of guaranteed remuneration. This can lead to situations where maintenance is carried out in medium or high winds, but at low or negative electricity prices, while avoiding low wind times and high electricity prices. Of course some work requires low wind speeds and safety issues and rules must be prioritized. The presented definition is borrowed from an upcoming publication by Lutz et al. [67], which will also look at the application and potential of this KPI in detail.

Appendix B.4. Maintenance tasks

Although availability KPIs measure the result of a maintenance strategy, the corresponding effort needs to be monitored as well. Basic statistics on the different maintenance tasks are a high-level approach to monitor and compare the maintenance effort for various assets. In this context, maintenance tasks are defined as all maintenance-related on-site work on a WT by service staff. All activities during a visit at the turbine are counted as one single maintenance task. If there are different possibilities for categorization, the dominant category will be selected. Corrective maintenance dominates preventive maintenance and repair dominates routine maintenance and inspection is this context. The counted maintenance tasks shall be normalized to a defined period of time—ideally 1 year. In addition, the average downtime and costs shall be gathered to allow for further insights. The KPIs described in this section are not to be confused with reliability characteristics (Appendix C). Reliability characteristics show a higher level of detail (system or component) and are based only on a part (preventive and corrective repair/replacement) of all maintenance tasks.

$$\lambda_{MT,CategoryY} = \frac{c_{MT,CategoryY}}{\Delta t} \tag{B.4}$$

$$MDT_{MT,CategoryY} = \frac{\sum_{i=1}^{c_{MT,CategoryY}} DT_{MT,CategoryY,i}}{c_{MT,CategoryY}} \tag{B.5}$$

$$MMC_{MT,CategoryY} = \frac{\sum_{i=1}^{c_{MT,CategoryY}} C_{MT,CategoryY,i}}{c_{MT,CategoryY}} \tag{B.6}$$

where

$\lambda_{MT,CategoryY}$ = Frequency of maintenance tasks per maintenance category,
$MDT_{MT,CategoryY}$ = Mean downtime per maintenance category,
$MMC_{MT,CategoryY}$ = Mean maintenance costs per maintenance category,
$DT_{MT,CategoryY,i}$ = Downtime of the ith maintenance tasks,
$C_{MT,CategoryY,i}$ = Cost of the ith maintenance task,
$c_{MT,CategoryY}$ = Count of maintenance tasks per maintenance category,
Δt = Observation period in years

Additional insights are possible if maintenance tasks and the corresponding analyses are categorized using maintenance types and activities as depicted in Figure B1. According to BS EN 13306 [34] and BS EN ISO 14224 [38], the first breakdown divides maintenance tasks into preventive and corrective maintenance. The standard [34] defines corrective maintenance to be "... carried out after fault recognition..., " whereas preventive maintenance is "... intended to reduce the probability of failure or the degradation of the functioning of an item." Especially preventive maintenance tasks could be subdivided into further general and abstract maintenance types (predetermined, condition-based and predictive maintenance). Instead, as requested in the survey, we propose to categorize the maintenance tasks in a more practical way according to the associated activities. The most relevant and thus recommended activities are inspection, routine maintenance, and repair. Because of different legal requirements on inspections (e.g., elevator inspections), it is necessary to distinguish between inspections and routine maintenance. Definitions are provided by the BS EN 13306 [34] and BS EN ISO 14224 [38], which also include further categories. The category names in both standards differ slightly, thus Figure B1 covers both naming schemata.

Appendix C. Recommended reliability KPIs

Appendix C.1. Mean operating time to failure and mean operating time to first failure

The mean operating time to failure (MTTF) and mean operating time to first failure (MTTFF) as defined by the International Electrotechnical Vocabulary (IEV) [39] describe the average failure free operating time of a system as being after the start of operation or its replacement. Although MTTF is a KPI for non-repairable systems or systems repaired to a state as good as new, MTTFF considers the operational time to the first failure of a repairable system only. While every failure of a non-repairable system is always the first failure, the semantic differentiation

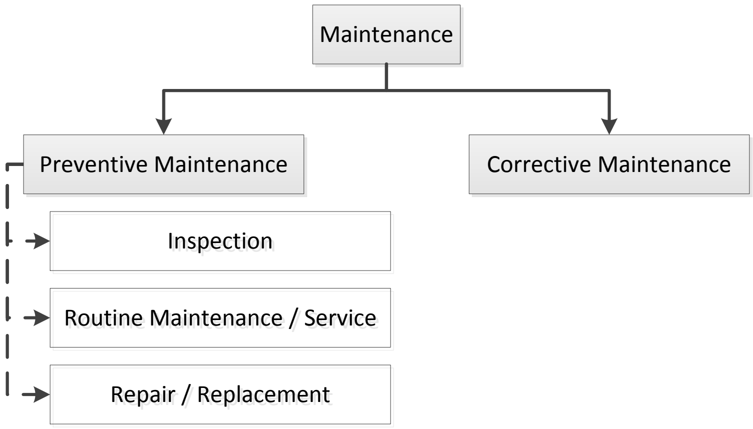

Figure B1. Structure to categorize maintenance tasks by the maintenance type and activity according to BS EN 13306 [34] and BS EN ISO 14224 [38].

of both KPIs is supposed to avoid confusion. Further failures of repairable systems will be considered in the mean time between failure (MTBF) (see Section Appendix C.2).

$$MTTF_{ItemY} = \frac{\sum_{i=1}^{c_{R,ItemY}} \Delta t_{operational,ItemY,i}}{c_{R,ItemY}} \tag{C.1}$$

$$MTTFF_{ItemY} = \frac{\sum_{i=1}^{c_{FR,ItemY}} \Delta t_{operational,FR,ItemY,i}}{c_{FR,ItemY}} \tag{C.2}$$

$$MTTFR_{ItemY} = \frac{\sum_{i=1}^{c_{R,ItemY}} \Delta t_{operational,ItemY,i}}{c_{R,ItemY}} \tag{C.3}$$

where

$MTTF_{ItemY}$ = Mean operating time to failure per non-repairable item,
$MTTFF_{ItemY}$ = Mean operating time to first failure per (partially) repairable item,
$MTTFR_{ItemY}$ = Mean operating time to final replacement per (partially) repairable item,
$\Delta t_{operational,ItemY,i}$ = Operational time to ith failure in years,
$\Delta t_{operational,FR,ItemY,i}$ = Operational time to ith first repair in years,
$c_{R,ItemY}$ = Count of replacements per item,
$c_{FR,ItemY}$ = Count of first repairs per item

Some systems are neither fish nor fowl and thus called partially repairable systems (PRSs). Although many failures are repairable, PRSs have either some components that can not be repaired and need to be replaced or some failure modes that require a replacement of the whole system [68]. A detailed acquisition of the components and failure modes in the maintenance data would allow a clear distinction to be made between repairable and non-repairable cases. In practice, however, this level of detail is usually not given. Thus, it seems reasonable to use a metric to describe the average time until a PRS needs to be replaced. Because a corresponding metric could not be found in either the standards or the literature, it is defined here as mean operating time to final replacement (MTTFR).

Appendix C.2. Mean time between failure and mean operating time between failure
MTBF and mean operating time between failure (MOTBF) as defined by the IEV [39] both describe the mean time between two subsequent failures of repairable systems. While MTBF considers the whole time between two failures (failure occurrence to failure occurrence) and is thus equal to the mean time between downing events (MTBDE) as defined by MIL-HDBK-338B [40], MOTBF considers the time between restart and the next failure and is a synonym to the mean up time (MUT). Being synonyms of other terms, MTBDE and MUT are not displayed in Figure 2. MOTBF was only introduced because there are different definitions in the literature for the use of MTBF. Because downtime is usually only a fraction of the total time, the differences between MTBF and MOTBF are usually marginal in the real application. However, the more frequent and longer failures become, the more important it becomes to differentiate between the two KPIs.

$$MTBF_{ItemY} = \frac{\sum_{i=1}^{c_{F,ItemY}} \Delta t_{total,ItemY,i}}{c_{F,ItemY}} \tag{C.4}$$

$$MOTBF_{ItemY} = MUT_{ItemY} = \frac{\sum_{i=1}^{c_{F,ItemY}} \Delta t_{operational,ItemY,i}}{c_{F,ItemY}} \tag{C.5}$$

where

$$\begin{aligned} MTBF_{ItemY} &= \text{Mean time between failure per item,} \\ MOTBF_{ItemY} &= \text{Mean operating time between failure per item,} \\ MUT_{ItemY} &= \text{Mean up time per item,} \\ \Delta t_{total,ItemY,i} &= \text{Time to } ith \text{ failure in years,} \\ \Delta t_{operational,ItemY,i} &= \text{Operational time to } ith \text{ failure in years,} \\ c_{F,ItemY} &= \text{Count of failures per item} \end{aligned}$$

Appendix C.3. Mean time to restoration and mean downtime
Mean downtime (MDT) is the expected or average downtime after a system fails and stops operation and before it restarts. The definition provided by the IEV [39] is consistent with definitions in the literature [38, 37, 34]. Downtime is defined as the total time between the stop and restart of operation of a considered unit while the unit is in a down state [34]. This period of time includes all subcategories—for example, waiting time, administrative delays, transportation time, fault detection, and repair time. Whenever possible, failures and the related downtime should be assigned to the causative system or component to gain detailed results for further use.

$$MTTR_{ItemY} = MDT_{ItemY} = \frac{\sum_{i=1}^{c_{F,ItemY}} DT_{F,ItemY,i}}{c_{F,ItemY}} \tag{C.6}$$

where

$$\begin{aligned} MTTR_{ItemY} &= \text{Mean time to restoration per item,} \\ MDT_{ItemY} &= \text{Mean downtime per item,} \\ DT_{F,ItemY,i} &= \text{Downtime due to the } ith \text{ failure,} \\ c_{F,ItemY} &= \text{Count of failures per item} \end{aligned}$$

MTTR is defined to be the mean time to restoration by the recent version of the IEV (IEC 60050-192) [39] but was formally called mean time to recovery according to the outdated IEC 60050-191 [69], or mean time to repair [20] in the literature. Although MTTR (as defined in the

IEV) and MDT are synonyms, other definitions exclude certain times (e.g., for fault detection or logistics). We recommend adhering to the definition of IEV and using other KPIs, such as mean fault detection time (MFDT), mean overall repair time (MRT) or mean active repair time (MART), if required. Figure C1 from the ISO/TR 12489 [37] standard provides a valuable depiction of interrelationships and includes categories for even deeper assessments. MTTR is broken down into its subcategories. Depending on the research question, more detailed KPI can be calculated.

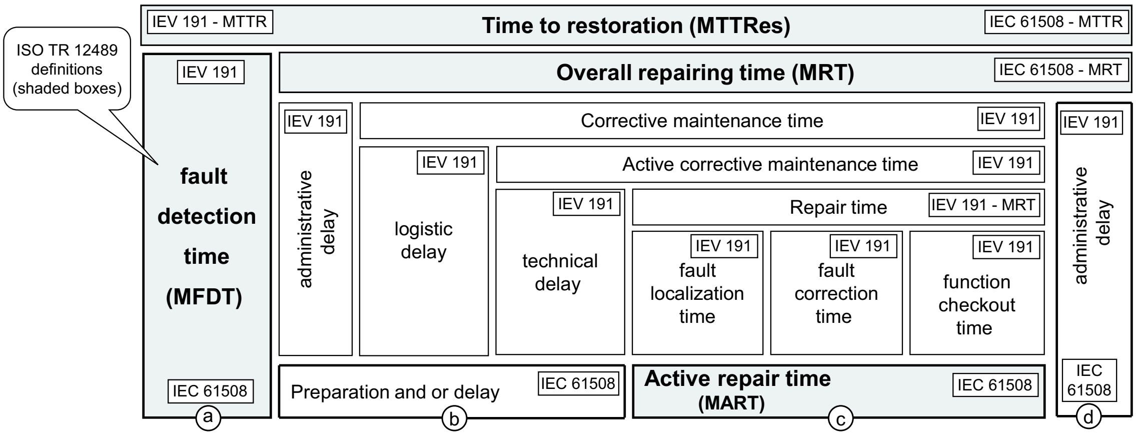

Figure C1. Taxonomies of MTTR subcategories from ISO/TR 12489 [37].

Appendix C.4. Failure rate and repair rate

The failure rate (λ) as defined by the IEV [39] describes the "...probability per unit of time that the item fails..." [38] during a certain period of time. Being a frequency (failures per time), the failure rate can be provided in different resolutions (year, day, hour...). As for MTTF and MTTFF, it has to be differentiated between non-repairable and (partially) repairable systems; see Section Appendix C.1. Accordingly, for repairable systems, it has to be differentiated between a failure rate for first failures, intermediate failures and final replacements. For non-repairable systems, the failure rate is also called hazard rate in the literature [40]. For a constant failure rate, the relationship between the failure rate and other KPIs is described by Equations C.7 - C.10.

$$\lambda_{ItemY} = \frac{1}{MTTF_{ItemY}} \tag{C.7}$$

$$\lambda_{ItemY,FF} = \frac{1}{MTTFF_{ItemY}} \tag{C.8}$$

$$\lambda_{ItemY,IF} = \frac{1}{MOTBF_{ItemY}} \tag{C.9}$$

$$\lambda_{ItemY,FR} = \frac{1}{MTTFR_{ItemY}} \tag{C.10}$$

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where

$$\lambda_{ItemY} = \text{Failure rate per non-repairable item,}$$
$$\lambda_{ItemY,FF} = \text{Failure rate for first failures per (partially) repairable item,}$$
$$\lambda_{ItemY,IF} = \text{Failure rate for intermediate failures per (partially) repairable item,}$$
$$\lambda_{ItemY,FR} = \text{Failure rate for final replacements per partially repairable item,}$$
$$MTTF_{ItemY} = \text{Mean operating time to failure per non-repairable item,}$$
$$MTTFF_{ItemY} = \text{Mean operating time to first failure per (partially) repairable item,}$$
$$MOTBF_{ItemY} = \text{Mean operating time between failure per (partially) repairable item,}$$
$$MTTFR_{ItemY} = \text{Mean operating time to final replacement per partially repairable item}$$

The repair or restoration rate (μ), as defined by the IEV [39], describes the "...probability per unit of time that the restoration of a failed item..." [38] is finished during a certain period of time and is thus the counterpart to the failure rate. For a constant repair rate, the relationship to the MTTR is defined by Equation C.11.

$$\mu_{ItemY} = \frac{1}{MTTR_{ItemY}} \tag{C.11}$$

where

$$\mu_{ItemY} = \text{Repair rate per item,}$$
$$MTTR_{ItemY} = \text{Mean time to restoration per item}$$