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Key Performance Indicators for Wind Farm Operation and Maintenance

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Abstract

Key performance indicators (KPI) are tools for measuring the progress of a business towards its goals. Although wind energy is now a mature technology, there is a lack of well-defined best practices to asses the performance of a wind farm (WF) during the operation and maintenance (O&M) phase; processes and tools of asset management, such as KPIs, are not yet well-established. This paper presents a review of the major existing indicators used in the O&M of wind farms (WFs), as such information is not available in the literature so far. The different stakeholders involved in the O&M phase are identified and analysed together with their interests, grouped into five categories. A suggestion is made for the properties that KPIs should exhibit. For each category, major indicators that are currently in use are reviewed, discussed and verified against the properties defined. Finally, we propose a list of suitable KPIs that will allow stakeholders to have a better knowledge of an operating asset and make informed decisions. It is concluded that more detailed studies of specific KPIs and the issues of their implementation are probably needed.

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1. Introduction

Wind energy has become a mature and cost-competitive source of electricity in Europe [1]. Although new offshore wind projects still show remarkable growth rates [2], changes in regulations amplify the interest in optimising the performance of existing installations. Consequently, in the last years much effort is put into improving operation and maintenance (O&M).

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A key perfomance indicator (KPI) is “a metric, measuring how well an organisation or an individual performs an operational, tactical or strategic activity that is critical for the current and future success of the organisation“ [3]. Using key performance indicators (KPIs) allows stakeholders to measure the progress towards a stated goal. Many industries use KPIs, like the nuclear industry [4], the financial sector [5] and health care [6]. During the O&M phase of a wind farm (WF), KPIs can influence the decision-making process by providing the stakeholders with valuable information assessing the status of the operational asset. Indeed they reflect changes in the O&M strategy.
Although many indicators have been defined, there is still no consensus within the wind industry and no agreement on the calculation or even the definition of KPIs during the O&M phase of a WF yet. The literature on this topic is limited; A study from 2011 only investigated four KPIs for the wind industry initiative [7]. The existing European standards for maintenance [8,9] provide a guideline for terminology and 71 maintenance indicators. We present a complimentary study, focused on the wind industry, by filtering the existing ones. Additionally, this review covers operational and financial indicators.
The Advanced Wind Energy System Operation and Maintenance Expertise (AWESOME) project organized a joint industry workshop (JIW), gathering both industrial and academic partners. The present authors addressed the need for KPIs for the O&M phase of a WF that was stated by the partners during the JIW. This paper presents a condensed and updated version of the results of the report [10] and intends to shed light on the definition of KPI properties, classification of KPIs and assessment of their value to wind farm O&M activities.
This paper is organized as follows. Section 2 describes the methodology of the workshop and of the paper. In Section 3, the different stakeholders are identified and analysed together with their interests resulting in five different categories; major indicators are reviewed and discussed. A proposed list of KPIs is given in Section 4; their properties and suitability are discussed. The study is concluded in Section 5 with further research suggestions.

2. Methodology

Based on the goal of defining KPIs for the O&M phase of a WF we conducted the analysis of the KPIs in five main steps. We used the well-established brainstorming technique [11] that is also applied in other fields [12], since it was suitable for the format of the JIW. First, we addressed the definition of the term KPI. In the context of the O&M phase of a WF, KPIs have to support informed decisions and reduce uncertainty by managing risks. Defining KPIs helps the stakeholders to address different concepts of the WF project by using the same metrics, leading to a common understanding of the important aspects and the success of a WF project. KPIs should answer the question: Which information should be monitored by the different stakeholders during the O&M phase of a WF?
Having defined the purpose of the KPIs, we identified the different stakeholders involved in the O&M phase of a wind power project. Once the stakeholders were identified, we discussed, collected and assembled their needs. Some of them are overlapping, so the main requirements were grouped into five categories. This has been addressed in Section 3.1. Next, we investigated the main properties that KPIs should fulfil, leading to a set of recommended properties that is presented in Section 3.2. For each defined category we conducted a review of the state-of-art, followed by a discussion, in Section 3.3. Our study initiated from the BS EN 15341:2007 [8] standards which offer maintenance related KPIs. These standards deal with all industrial and supporting facilities, introducing 71 KPIs, while they focus only on the maintenance. Finally, we present a comprehensive set of KPIs for the O&M industry that fulfil all the properties we previously defined.

3. Results

3.1. Stakeholders and their requirements

Various stakeholders are involved in the O&M phase of a wind power project. Their strategic decisions rely on the information they have about the current status of the operating asset, referring to different aspects, i.e. regulatory, economical, technical and safety aspects. The different stakeholders are identified and presented here, together with their main needs for information.
Wind Farm Operator
The WF operators’ main interest is to maximise the revenue of the WF and hence the energy production throughout

the lifetime of the project. The operator needs information about the energy production, the efficiency of the WF, the production losses and might also request information about future expectations of energy production and remaining lifetime, as well as the current value of the asset, profits, costs and debt.

The Investor

Investors and banks can partially or completely own the WF. They are mainly interested in the economic and financial aspects of the wind power project development, including information about production, efficiency, future expectations, costs, debt, profits and current value of the asset.

The Maintenance Service Provider

Maintenance services are commonly outsourced to a maintenance service provider (MSP), who is often the original equipment manufacturer (OEM). The most important aspect of a standard O&M contract is the wind turbine availability warranty. This warranty states a certain percentage of time that the WFs operation shall not be affected by maintenance actions from the MSP. Otherwise, the MSP shall pay the WF operator compensations. The main interest of the MSP lies in reducing the time and cost of the maintenance operations through a good understanding of the health status together with the failure history and the component cost. From a safety and efficiency perspective of the maintenance tasks, the MSP also seeks information about health, safety and environmental (HSE) issues, like safety indicators and environmental restrictions.

The Insurance Provider

Insurance companies provide services to cover the costs of various incidents that might occur during the operational phase of the WF. This can include [13] damage to the WTs and associated equipment due to storms, thefts, malicious actions, or fires, costs of spare parts, loss of revenue, damage to third party property or environmental damage. Consequently, the insurance provider is mainly interested in the health status, failure history and the HSE aspects.

Utility and Grid Operator

According to the European grid codes, all the energy produced from wind has to be bought by an electrical companies, i.e a utility. This stakeholder is usually interested in the energy production of the WF, the future expectations of production and the electricity price. In addition to the utility, the integration of energy produced from wind into the grid is a challenge for the Grid Operator [14–16] . This stakeholder is interested in performance, stoppages and energy production, power quality and other quantities that can affect grid stability.

Government, Public and End Users

Here we identify and group together stakeholders that are not technically involved in a WF's operation. First, the governments regulate the activities of the wind industry through regulatory bodies. Non-compliance with these laws and regulations can result in penalties and subsequent withdrawal of operating license. The public expects protection of the environment and minimum interference of the plant with adjacent living communities. Finally, the end users expect competitive prices of energy in comparison to other sources. Consequently, public opinion and political decisions may affect the profitability of a wind power project, since their support of wind energy can have an economic impact on the project, e.g. in terms of subsidies. In summary, this group of stakeholders is mainly interested in the efficiency of the WF, the electricity price and the environmental impact of the project.

An obvious conclusion that can be derived from the above listing of the most important stakeholders, is that their needs are frequently overlapping. This characteristic, along with the fact that it will facilitate our study of the most important KPIs, guided us when categorizing the stakeholders' requirements. The five chosen categories, as well as the corresponding requirements, are shown in Table 1.

3.2. Definition of the properties

One of the main requests that the industry representatives expressed during the discussion at the JIW was the need to identify the properties of the indicators. In this regard, safety indicators have already been developed for the Offshore wind industry [17], which have guided us to define the necessary properties.

As the most important property, KPIs need to be **relevant**, i.e. they have to carry information valuable to stakeholders. Since they have to allow the stakeholder to take informed decisions, the indicators have to be such that they can trigger changes. Another property is that KPIs must be **specific**, meaning that the observed value needs to be well defined, so that it is clear what exactly is being observed and how. In order to have an easily observable value, indicators should be **measurable**, either in a qualitative or in a quantitative way. The measurement can be a numerical value,

Table 1. Categorisation of the stakeholder requirements

Performance	Reliability	Maintenance	Finances	Safety
Efficiency	Failure history	Component cost	Component cost	Environmental issues
Future expectations	Fatigue	Failure history	Current asset value	Health & Safety environment
Production	Health status	Logistics	Debts & Profits	Safety indicators
Production losses	Loads	Maintenance hours	Electricity price	
	Remaining lifetime	Maintenance restrictions	Risks and insurance	
			Subsidies	
			Unnecessary cost	

like hours of operation, or a categorical statement, like "WF is running ok". Stakeholders should be able to use KPIs to compare different assets without much effort; therefore, **comparability** is another necessary property for the KPIs. In this way, WFs with different layout, size and location can be compared to each other, by only looking at the KPIs. To track the wind power project development over time, it is necessary for the KPIs to be **traceable on different timescales**. For some indicators it might be sensible to provide hourly data, whereas for others a yearly summary is more beneficial to the stakeholder. To leave no room for individual interpretations, a standard should be implemented, giving exact definition of all terms and indicators used. With the **standard**, different stakeholders can use the same indicators without worrying about the scope of interpretation. Standardised KPIs enable the comparison of different assets through benchmarking, comparing the performance of a WF to the best performances recorded in the industry [18]. Defining properties for the individual indicators is not enough, since there will be a set of them. This set needs to be able to give a complete picture of the whole WF, both in onshore and offshore cases, with the fewest possible KPIs. Therefore, we are looking for a **minimal set** of KPIs, which are clear and easy to understand. The indicators do not necessarily need to be disjoint, so two or more of them are allowed to present overlapping observations. Sets of KPIs that are disjoint however, should be preferred over non-disjoint sets. For disjoint KPIs, changes in one KPI cannot imply changes in any other KPIs. This means that changes in the observed WF only influence one specific KPI, which makes interpretation of the KPIs easier for the stakeholders. To sum up, effective KPIs need to be **relevant, specific, measurable, comparable, traceable in time, standardised and form a minimal complete set**.

3.3. Review of the existing KPIs and their properties

For each category defined in 3.1, we performed an extensive review of the indicators used in the industry and the ones covered in the literature. The identified metrics are reported here and then assessed with respect to the necessary properties defined in 3.2.

3.3.1. Performance

One of the most important operator's interests is the performance of the asset. The word performance is very broad and can embrace many aspects of the WF operation, from annual energy production (AEP) to generated revenue. We would like to read here WF performance as its efficiency. Indicators should then answer the following question: *is the WF producing as much energy as it could?* The most commonly used indicators are presented subsequently.

Wind / Energy Index [19–22]

First developed in Denmark in 1979, the concept was later copied by other northern countries. It is based on the production of a number of reference WTs over a wide geographic area. It establishes a statistically "normal" period of yearly wind energy content, expressed as 100%, so that the operator can distinguish between WT under-performance and wind strengths below expected levels; it allows for comparison of the production of a WF with the available wind resource. Although it fulfils many of the properties stated in 3.2, it does not provide the operator with sufficient information so that informed decisions can be solely based on the index.

Capacity Factor [23,24]

Defined as the energy generated during a period of time divided by the WF rated power multiplied by the number of hours in the same period. Since the denominator is a constant, it does not represent the theoretical energy production according to real on-site wind conditions. Although it is a valuable indicator during feasibility and wind project development stages, we believe it is not an effective indicator for evaluating WF operational efficiency.

P_{50} deviation [25]

During the process of wind resource assessment, the P_{50} energy yield gives the level of AEP that is expected to be exceeded with a probability of 50%. Many operators currently look at the deviation of the actual AEP from the calculated P_{50}, especially when looking into deviations of planned budget. From our experience, the P_{50} is subject to important uncertainty. Furthermore, there is no standard procedure to obtain this figure.

Time-based availability [26]

Defined as the accumulated time that the WT is operational divided by the total period of time. This indicator is specific, since the observed value is clearly defined and is the time that a WT is operational; measurable and easy to understand, it is relatively easy to distinguish periods of power production from periods of inactivity; strategies to reduce the downtime result in an increase of this metric. Despite existing technical specifications for its calculation, no international standard exists. Furthermore, it does not provide information about WF efficiency or power losses due to unavailability. The existing standard [8] defines four technical indicators, namely T1 T6, T7 and T15 which relate the total operating time with downtimes due to maintenance activities. TBA comprises the information included in these three technical indicators but it does not consider that the operating time of the wind turbine is influenced by the wind conditions.

Energy-based availability [27,28]

Defined as the ratio between the real energy production and the actual energy available. In our opinion, it illustrates the "real" efficiency of a WT or WF since it reveals the percentage captured from the available energy. It is a more objective indicator for comparison between different assets, but difficult to implement. Although it is very easy to measure the produced energy over a certain period of time, it is quite difficult to precisely define the actual available energy for the same period. Therefore it is very challenging to define a standard procedure. Current approaches rely on theoretical production calculation from an operational power curve based on SCADA data.

3.3.2. Reliability

Reliability is defined as the "ability of an item to perform a required function under given conditions for a given time interval" [9]. Applied to a WT, its reliability can be defined as its ability to perform properly, without failures, during specified site wind conditions for the whole lifetime (defined to be at least 20 years) or in a specific time window. WT reliability is compromised by component failures, leading to downtime. For that reason, the industry currently uses different metrics to assess WT reliability [29] by answering questions like: *How often does a WT fail?* and *Which WT downtimes are associated with which failure?* [9]. The indicators are summarised below.

Mean Time between Failures (MTBF) & Failure rate [9,30]

The MTBF expresses the total operational hours divided by the number of failures for a specific component or for the whole WT. The term MTBF is frequently used to describe reliability, as well as its reciprocal value, the failure rate. Both indicators satisfy the majority of the identified properties for KPIs. However, an effective comparison between WTs or WFs will not be possible until a standard WT taxonomy is defined. Even though some recent approaches have been published, like RDS-PP [31] and ReliaWind [32], there is still no agreement on a unique and standard designation. This issue has been discussed in detail by Reder et al. [33]. MTBF is defined in the standard [8] as the technical indicator T17.

Mean Time to Repair (MTTR) & Repair rate [9,30]

The MTTR is the average time to return a WT to its functional state [9]. This can imply either a repair or a full replacement of the faulty component, leading to the term of restoration, as defined in [8]. This indicator can be assessed by dividing the total time of restoration by the number of failures. Given the definition in the maintenance standards [9] this term should rather be referred to as mean time to restoration. Nevertheless, we stick here to the designation as mean time to repair due its widespread used in the industry. The reciprocal of the MTTR is the repair rate. As well as the previous indicators, they meet all the desired properties and their definition is specific and standardized within the industry. But again, comparison is limited due to the lack of a standard WT taxonomy and the inconsistency of intervention specific failure definitions. MTTR is defined in the standard [8] as the technical indicator T21.

Mean Time to Failure (MTTF) [30]

The MTTF is similar to MTBF but it is used to describe reliability of non-repairable systems. Non-repairable refers to systems that are replaced after a failure because there is no possible maintenance action that can make them work properly. Hence, over the lifetime of a non-repairable system, this fails once and the MTTF measures the average time until this unique failure occurs.

Availability [34]

The time-based availability (3.3.1) is the amount of time that a system or component is available for use divided by the total amount of time in the period of operation. From the previous metrics, it can be defined as the ratio between the MTTF and the sum of MTTF and MTTR. In our opinion, availability is most closely related to energy production. Thus, the previous metrics seem to be more adequate to assess WT reliability.

The identified indicators satisfy most of the necessary properties for KPIs. Nonetheless, we believe that it is difficult to make them comparable due to the lack of a standard WT taxonomy and due to potentially different component behaviour in different WTs, especially with regard to differences in turbine size and technology [33]. Moreover, data collection on wind turbine failures is not standardised and there is an important lack of failure data, contributing to a high level of uncertainty related to the indicators. We would also like to mention the importance of initiatives for standardisation of data and reliability analyses like [35] and [36].

3.3.3. Maintenance

Maintenance activities are crucial to keep a system in good condition. In general, these activities can be divided into corrective and preventive actions, including both time-based and opportunity-based maintenance. While preventive maintenance intends to avoid failure, corrective actions are implemented once a component has already failed. Maintenance indicators assess the quality of the maintenance, in terms of time consumed for different interventions and related costs. The reported indicators are presented in the following.

Response time [37–41]

Defined as the time between failure occurrence and maintenance intervention, it informs about the efficiency in maintenance planning. Since it is often difficult to detect the failure starting time, it can be redefined as the time between failure detection and intervention. This new indicator is then specific and measurable. However, since the sensors and alarm systems vary between different WT types [42], this indicator is not comparable.

Number of interventions [37–41]

An intervention is the fieldwork conducted to keep a WT in good condition; it implies a displacement of the maintenance crew. Monitoring the number of interventions, both scheduled and unplanned, can show the results after an optimisation of the O&M strategies. In case of higher WT reliability, less interventions should be needed; this would result in lower O&M costs, especially in offshore cases where the number of interventions is related to the necessary vessel transfers. Nevertheless, there is no agreement on the definition of intervention; during a maintenance work one intervention could be accounted for the entire WF or per WT intervened. Even though this indicator could easily fulfil most of the necessary properties with a consensual definition, the comparability between assets remains difficult. This is not only due to possible differences in terms of size of the WFs, but also to the duration of the interventions, and their related costs. Comparability could be improved by normalising the number of interventions by the number of turbines in a WF, but their duration should be definitely included. Further research would be needed on this issue.

Corrective maintenance (%) [37–41]

Defined as the ratio of the purely corrective interventions over the total number of interventions, this indicator meets all the properties and defining a standard is possible. Since corrective interventions are generally more costly than preventive actions, it also allows the assessment of the success of new O&M strategies. Indeed, some operators are experiencing a decrease of this percentage after the introduction of condition-based strategies. The existing standard [8] includes two organizational indicators (O16, O18) which describe the corrective maintenance activities and the immediate corrective maintenance activities, respectively. Our indicator does not distinguish between immediate and non-immediate activities. These two indicators are expressed in man hours instead of number of interventions.

Schedule compliance (%) [37–41]

It is defined as the ratio between the scheduled maintenance tasks completed on time and the total number of tasks. This indicator fulfils most of the properties and a standard can be easily defined. Furthermore, it can be used to assess the efficiency of maintenance execution or accuracy in maintenance planning. The organizational indicator O22 in [8] also describes this.

Overtime jobs (%) [37–41]

Defined as the ratio between the overtime working hours and the planned working hours (working hours per worker and per size of the workforce), this metric can be measured on different time-scales. It is comparable and a standard can be defined. It informs about effectiveness of maintenance planning, worker health or ideal work force size. The organizational indicator O21 in [8] describes this in terms of internal man hours. We do not distinguish between internal and external man hours.

Total Downtime [37–41]

Since downtime is affecting the WT availability, we presented this in the Sections 3.3.1 and 3.3.2.

Equipment reliability [37–41]

We also do not show the equipment reliability here, since it was already presented in section 3.3.2.

Backlog [37–41]

It can be defined as the list of maintenance work that still needs to be completed. Hence, its size might sound like a very intuitive way to measure the effectiveness of maintenance execution. However, there is no specific definition for this effectiveness and it cannot therefore be measured. Indeed, it is possible to sum the time for the expected scheduled interventions but it might not correspond to the exact time that will be finally needed. Furthermore, a big backlog can be due to very different reasons, among them poor planning, poor execution or too small workforce.

Labour costs versus total maintenance costs (TMC) (%) [37–41]

The labour costs, expressed as a percentage of the total maintenance costs (TMC), inform about the effectiveness of maintenance execution; most operators agree on the importance of having qualified maintenance staff to ensure an ideal percentage of labour costs. It fulfils most of the properties defined and can be easily standardized. The standard [8] defines two economic indicators (E8 and E9) describing the total internal and external personnel cost, respectively. Again, we do not make a distinction between internal and external personnel cost.

Cost of spare parts versus total maintenance costs (TMC) (%) [37–41]

The cost of spare parts, expressed as a percentage of the TMC, is directly related to the number of failures followed by replacements. Moreover, historical values might help in the budget planning. This indicator provides information about the proportion of cost of spare part cost of the TMC. Other factors to the TMS include equipment hire, consumables and labour costs. Moreover the indicator fulfils many of the desired properties for KPIs. However, its specificity and standardisation depends on the costs included in the definition.

Total annual maintenance cost versus annual maintenance budget (%) [37–41]

Setting the TMC in relation to the annual maintenance budget (AMB) can give insight into the quality of maintenance planning and is therefore relevant to stakeholders. Defining the indicator as three categories ($TMC<AMB \equiv green$, $TMC \approx AMB \equiv yellow$, $TMC>AMB \equiv red$) is specific and measurable. It can further be compared between WFs, is traceable in time and can be defined in a standard. The stakeholders can use this indicator to know, whether they are spending as much as anticipated or more on the maintenance of their asset. Using three different colours is intuitive and very demonstrative.

The standard [8] includes many more indicators concerned with the cost of maintenance and materials, e.g. T16, E11. However, the indicators presented here are a comprehensive overview of the most important aspects of the maintenance phase of a WF.

3.3.4. Finance

The financial status of the wind power project is a general concern throughout its entire lifetime. Financial KPIs are fundamental tools for making an asset status summary or for comparing different investment options. Consequently, they can be used as a feedback mechanism for management decisions evaluation. Some might be more useful during the feasibility phase, as they can influence the decision of undertaking the project [43,44]. As the investment is already made in the O&M phase, the main interest is to know about the financial status of the operating asset; any decision-making process seeks to maximise the return on the investment. The most widely used indicators are summarised in the following.

Operational Expenditures (OPEX) [43]

The OPEX include the cost of operating the site, planned O&M and unscheduled maintenance. These costs can be grouped into two different categories: the O&M costs, which represent approximately 60% of the OPEX and tend to increase as the WF reaches the end of its lifetime [45]; the other category covers other operating costs like rent, taxes and insurance. In order to be comparable, this metric should be normalised by WF installed capacity.

Earnings Before Interest, Taxes, Depreciation, and Amortisation (EBITDA) margin [46,47]
The EBITDA margin is a financial metric used to assess profitability by comparing revenues with earnings. It is defined as the percentage of the revenue remaining after covering the OPEX. This indicator meets all the desired properties and is used to track changes due to new O&M strategies. Its drawback is the omission of the capital expenditures (CAPEX). Even if a negative margin undoubtedly indicates profitability problems, a positive margin does not necessarily indicate that the WF generates cash. Indeed, this metric cannot track changes in working capital, CAPEX, taxes, and interest rate. In our opinion, CAPEX should be included when evaluating the profitability of a WT or WF project. Hence, the EBITDA margin could be considered as a good KPI allowing the comparison between different WFs profitability, but it should be presented in conjunction with another KPI which includes the CAPEX.
Loan Life Coverage Ratio (LLCR) [46,48]
Defined as the ratio between Net Present Value (NPV) of the cash and the amount of debt, it informs about loan repayments. Financial modelling of LLCR is now a standard metric calculated in a project finance model and has been standardised. Apart from other properties that this metric clearly fulfils, it has a special relevance since it provides the WF Operator with information about the ability to repay the debt over the whole lifetime of the asset.
Debt-Service Coverage Ratio (DSCR) [46,49]
The DSCR is the ratio between the available cash for debt payment and the sum of interest, principal and lease. It is an accepted financial KPI in industry for the measurement of an entity's ability to balance debt payments with produced cash. The main difference with the LLCR is that it measures the ability to pay the debt in a specific year. Similar to the LLCR it meets all the desired properties for KPIs.
Free Cash Flow to Equity (FCFE) [46,50]
The FCFE is a measure of how much cash can be paid to the equity shareholders of a company after all expenses, reinvestment and debt repayment. FCFE takes into account the net income, the depreciation of amortisation, the change in working capital and the net borrowing. A standard definition can be found in [46,50]. Although it provides the investor with relevant financial information, this indicator cannot be used for benchmarking since it is not comparable between assets.
Levelised Cost of Energy (LCOE) [7,51]
The LCOE is probably the most popular financial KPI in the wind industry and particularly useful for investors seeking to compare different generation sources. It allows to compare different WFs in terms of financial status. The LCOE takes into account the CAPEX, the installed capacity, the capital recovery factor, the discount rate, the WF lifetime, the OPEX and the annualised energy production. A complete definition can be found in [7,51]. A standard methodology was proposed, discussed and approved in [7]. This KPI is now a standard and specific indicator and includes both CAPEX and OPEX. However, the suggested methodology was criticized, since the normalisation for benchmarking is done in terms of installed capacity (MW); indeed, the LCOE could be better described in terms of $€/m^2$ of rotor swept area since it would be directly related to the WT energy production. Unfortunately this would require a much more complex model and further data uncertainties. In any case, this KPI remains as a very effective indicator to evaluate the financial performance of an operating asset. As an example, many recent studies are mostly focused on improving the LCOE [51].
Other indicators
Some other more complex indicators might be found as the wind speed dependent cash flow, semi-elasticity (function of averaged weighted payment duration and interest rate) and relative convexity (ratio between convexity of cash flow and semi-elasticity) [52]. The break-even price of energy (BEPE) for renewable energy projects, defined in [53], tries to overcome the omission of the legal framework in the LCOE by taking into account parameters such as inflation and tax rate. Given that the renewable energy sector is highly influenced by local conditioning factors, the suggested metric seems to be an interesting alternative to the LCOE.

3.3.5. Safety

In the RAMS literature [54], KPIs for the system performance are often distinguished from indicators monitoring the safety of a system (safety indicators). KPIs are more focused on system performance and output in terms of financial gain. Safety indicators on the other hand help to monitor the safety of both the system and the workers. We want to refer to an analysis by Scottish Power [55] concerned with major hazard risks, as an example for system safety indicators. For the worker health and safety, we want to refer to a publication on safety indicators for offshore WFs

[17]. Safety indicators enable the operator to track changes in the worker health and safety for different maintenance strategies, legal regulations and specific procedures.

4. Discussion

The review of the indicators showed some of the shortcomings of the potential KPIs in terms of fulfilling all properties. For the KPIs describing **performance**, the energy-based availability allows to have a better tracking of variations in the WF energy efficiency. However, theoretical production cannot be measured accurately and neither indicator is standardized. Although time-based availability does not inform about power losses, it can be helpful for illustrating downtime reduction. All of the indicators concerned with **reliability** fulfil all properties except for being standardised, due to the lack of a common WT taxonomy. Since there is a common understanding in RAMS literature, defining a standard seems feasible and much effort is currently devoted to nomenclature standardisation. In any case, the suggested KPIs allow to track the progress towards increased WT reliability. Also the KPIs for the **maintenance** category lack the definition of a standard. This should be a common goal of the wind energy industry and academia for the future. All discussed **financial** KPIs fulfil the necessary properties and can be used as they are, allowing to reveal variations in the financial status of the asset. An overview over the proposed indicators and their properties can be found in Table 2.

Table 2. Proposed list of indicators and their properties, as listed in section 3.2. The property of a minimal set of indicators is not included in the table. A checkmark indicates that the indicator fulfils the properties, a crossmark that the indicator does not fulfil a property and the asterisk indicates indicators that are not yet fulfilling the property in question but can be modified to do so.

	Relevant	Specific	Measurable	Comparable	Traceable in time	Standard
Performance						
Time-based availability (%)	✓	✓	✓	✓	✓	✗
Energy-based availability (%)	✓	✓	-	✓	✓	✗
Reliability						
MTBF & Failure rate (%)	✓	✓	✓	✓	✓	✓*
MTTR & Repair rate (%)	✓	✓	✓	✓	✓	✓*
MTTF	✓	✓	✓	✓	✓	✓*
Maintenance						
Interventions per WT	✓	✓	✓	✓*	✓	✓*
Corrective maintenance (%)	✓	✓	✓	✓	✓	✓*
Schedule compliance (%)	✓	✓	✓	✓	✓	✓*
Overtime jobs (%)	✓	✓	✓	✓	✓	✓*
Labour costs vs. TMC (%)	✓	✓	✓	✓	✓	✓*
TMC vs. AMB (%)	✓	✓	✓	✓	✓	✓*
Finance						
OPEX	✓	✓	✓	✓	✓	✓
EBIDTA margin	✓	✓	✓	✓	✓	✓
LLCR	✓	✓	✓	✓	✓	✓
DSCR (historical & expected)	✓	✓	✓	✓	✓	✓
LCOE	✓	✓	✓	✓	✓	✓

5. Conclusions and further work

In this paper the topic of key performance indicators for the wind industry has been discussed. After defining properties and a thorough review of existing indicators, we propose a list of possible key performance indicators that fulfil these properties or can be modified to do so. The work was based on discussions with representatives from industry. However further numerical validation with real WF data is highly recommended to make a quantitative evaluation among different KPIs both for onshore and offshore cases.

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