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Effect of curtailment scenarios on the loads and lifetime of offshore wind turbine generator support structures

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Abstract. Curtailment is a known phenomenon for wind turbine operators of both onshore and offshore wind turbine generators (WTG). Curtailment refers to the situation in which the power output of all WTG's within a windfarm is forced below the expected power output at the occurring environmental conditions. A direct consequence of curtailment is the loss of power production. In the present contribution further consequences of curtailment of an offshore wind farm (OWF) are studied from the perspective of the support structure, in specific the foundation. In relation to curtailment a couple of potentially critical operational conditions impacting the fatigue consumption of the support structure can be identified. Besides the standstill during operational windspeed conditions, in specific damaging for the +7MW generation WTG's, curtailment introduces repeated transitions between operational conditions. Since transitions between operational conditions of a WTG are known to be a cause of high fatigue loads in the structural components of the WTG, their increased occurrence due to curtailment might also have an impact on the fatigue consumption of the support structure. With the growing interest of the industry to quantify and potentially optimize the structural lifetime consumption in view of potential lifetime extension of OWF assets, any potential fatigue damaging operational condition is to be investigated. The present work focusses on the investigation of the impact these transitional load cycles may have on the structural lifetime of the WTG foundation. To assess the impact on lifetime, the assessment of the damage equivalent loads (DEL) derived from structural health monitoring (SHM) data are used as a data-driven alternative for model-based load simulations. In the present work such data-driven lifetime assessment studies the impact of curtailment regimes with different frequency of stop and start cycles on the structural lifetime. The study is performed based on 1 year of SHM data collected from two OWF's. The assessment demonstrates that the impact of additional transitional load cycles on the structural fatigue life consumption is to be considered when defining a long-term curtailment strategy for an OWF.

1. Introduction and motivation

Curtailment is a known phenomenon for wind turbine operators of both onshore and offshore wind turbine generators (WTG). In the present contribution curtailment of an offshore wind farm (OWF) refers to the situation in which the power output of all its wind turbine generators (WTG) is forced below the expected power output at the occurring environmental conditions. The OWF is curtailed by the Balance Responsible Party (BRP). There may be various reasons for which the BRP forces an OWF in curtailment, by example to balance the demand and production of energy (grid congestion) or commercial reasons. With a growing variability in supply and demand curtailment of OWF's is expected to rise in the foreseeable future. Besides the loss of power production - which is the (desired) direct consequence of curtailment - the imposed curtailment regime introduces more standstill periods and transitions between operational conditions of the WTG which will influence the entire structure. Since load cycles due to transitions between operational conditions of a WTG are known to be a potential cause of high fatigue loads in the WTG's structural components, their increased occurrence due to curtailment might also have a detrimental impact on the fatigue life consumption of the support structure. In the present contribution these consequences of curtailment of an offshore wind farm (OWF) are studied from the perspective of the impact on the lifetime of the WTG's support structure.

A curtailment assessment from this perspective ties in with the growing interest from the industry in the quantification of consumed and remaining useful lifetime in view of potential lifetime extension of the offshore wind support structures, which are typically designed for 20 – 30 year service lifetime. To support decision making towards lifetime extension, it is important to investigate any potential fatigue damaging operational condition. An earlier investigation towards the influence of OWF curtailment indicated a reduction of damage equivalent loads (DEL) at tower bottom and thus beneficial effect on lifetime consumption of a Vestas V-52 (850kW) support structure [1].

The evolution to larger, +7MW, WTG's resulted in new insights in the structure's dynamic behavior influencing the fatigue design. For these larger WTG's the introduction of curtailment regimes leads to a couple of potentially critical operational conditions in relation to fatigue life consumption of the support structures. Besides the additional periods of standstill during operational windspeed conditions, which is a known critical fatigue design load case in the design of support structures of large WTG's [2], curtailment introduces repeated transitional load cycles (event load cycles due to WTG stop and start cycles). The increased number of events introduced due to more frequent transitions between the operational regimes, and more standstill, might result in exceeding the provisions taken in design for the event loads, and standstill period. The present work focusses on the investigation of the impact the amount of events may have on the WTG foundation its structural lifetime. This impact of additional event load cycles has to the authors' knowledge not yet been investigated in this context.

The industry's current recommended practices in relation to lifetime assessments (DNVGL-ST-0262, 2016) require to base this assessment on a combination of practical assessments (i.e. offshore inspections) and analytical assessments (i.e. updated fatigue assessments for updated environmental conditions and using an updated design model for the load simulations). This updated model-driven simulations have been subject of research and industrial applications [3][4]. While the use of monitoring data is also recommended in current guidelines, the actual use-cases of data-driven fatigue assessments with load monitoring data are mainly found in a research context [5][15]. The present work aims to investigate the potential of using load monitoring data in data-driven fatigue assessments methodology to evaluate the impact of curtailment scenarios on structural lifetime.

To assess the impact on lifetime, the evaluation of fatigue damage (D) or damage equivalent loads (DEL) derived from structural health monitoring (SHM) data may be used as an alternative for model-based load simulations. The use of D is particularly in favor when changing corrosion models. For purpose of this work DEL is the most suitable parameter to assess the impact on lifetime. The DEL is a commonly known fatigue load parameter used in design of foundations, other structural components and subject of ongoing research for farm wide predictions as disclosed in [5][10]. The present work particularly investigates the role of curtailment regimes with different frequency of stop and start cycles on the consumed lifetime. The study is performed based on 1 year of SHM data collected from four WTG's on two OWF's.

The motivation of this work lies in (i) the growing interest of the industry towards the use of monitoring data for structural assessments of the assets in operation, (ii) the importance to understand the long-term impact curtailment scenarios may have in view of the interest in lifetime extension and (iii) the opportunity to provide data-driven support in asset management decisions towards sustainable curtailment strategies supporting the flexible use of wind energy assets.

2. Available data

For this work, data collected over a period of 1 year on four WTG's across two OWF's in the Belgian North Sea has been utilized. The available data consists out of 10-minute environmental and operational condition parameters available through the SCADA system and load monitoring data collected through an SHM system. In view of using data for fatigue predictions over time, it has been demonstrated in earlier research that data collected over a consecutive period of 1 year is recommended in view of including seasonal variations [6]. A recommendation which has been confirmed in various other research on this topic, e.g. [10][13][15].

All four foundations, type monopile with transition piece, are equipped with 6 strain gauges, with a sensor for temperature compensation, equally positioned every 60 degrees along the circumference. The sensors are placed close to the transition piece – tower interface at a distance of 500mm from the nearby primary steel weld to avoid monitoring stress concentrations due to this weld. From the 6 strain measurements the stresses and bending moments are calculated. In accordance with IEC61400-13, the loads measurements are processed in a fore-aft (FA) – side-side (SS) reference determined by the WTG's yaw angle. The load monitoring signals are processed in 10-minute intervals such the SHM and SCADA databases are complementary for further analysis. The derived SHM data is stored in a 10-minute subset database as explained in various earlier publications [7-10][15].

The derived load monitoring metric of interest for further fatigue analysis in the present work is the 10-minute damage equivalent load (DEL). This metric can be derived from the FA and SS stress timeseries. By cycle counting the 10-minute stress signals and evaluation of the cycle counts (stress ranges and corresponding number of cycles) over the Basquin's law for a chosen SN curve with single slope (m = 5) and number of equivalent cycles (N_{eq} = 1e7), the 10-minute DEL can be calculated. The 10-minute DEL is stored in the SHM database as damage equivalent moment (DEM) [7].

3. Methodology

Three domains are to be addressed in the description of the methodology. (i) The annotation of data to allow a binning approach per operational conditions which can be used to simulate curtailment scenarios is explained in 3.1. (ii) The defined operational scenarios to study the impact of various curtailment strategies is described in 3.2. (iii) The methodology to derive a lifetime metric by performing an assessment of the loads (DEM) is explained in 3.3.

3.1. Database annotations

In view of performing a lifetime assessment, a technique to allow for extrapolations over time based on the available monitoring data is found in a binning approach. The 10-minute timeseries database with SCADA and SHM parameters is supplemented with annotation labels to allow binning the data (e.g. based on windspeed). The binned data allows to perform an assessment of the loads per bin and assign a probability of occurrence of each bin. There is various research ongoing towards the most suitable binning approaches in view of lifetime predictions based on limited data. [6][12]

For the purpose of this impact assessment the use of a binning approach based on operational conditions only, a so called 1-dimensional (1D) -binning, is found most suitable. The operational conditions used for binning are limited to: operational, standstill and events. This 1D-binning approach allows to assign probabilities to each of the bins in normal and curtailed operating regimes when defining the curtailment scenarios (see 3.2).

With the available data for both OWF's the decision was made to annotate the data for this initial impact assessment based on 10-minute mean SCADA metrics and SHM load monitoring data. The boundaries of the operational condition bins for the two OWF's are based on 10-minute mean metrics (e.g. RPM, power, pitch, windspeed and damage equivalent moment). Each timestamp of the considered data is evaluated against the boundary conditions of a bin, and assigned to the appropriate bin. To assure the binning was in accordance with the expected behaviour a visual inspection of randomly sampled data was performed. The quantity of data that passed through the classification (due to missing metrics used for classification) and did not get assigned to a bin is neglectable, approximately 0.6%. Inspecting this data confirmed it did not contain a disproportional amount of one of the three operational bins and it can safely be disregarded for further assessments.

More advanced annotation methods based on a detailed analysis of 1-second SCADA are under development by Daems et al. [14]. The applied annotations with the simplified binning approach have been found to be plausible in relation to the initial results from said advanced annotations. The initial integration of the advanced annotation insights in the present work is limited to making use of the probability of curtailment in the assessed curtailment scenarios.

For the purpose of the present work, the applied simplified annotations have been found sufficient to demonstrate the impact of the frequency of events on lifetime. When assessing the entire operational spectrum in future works the advanced curtailment annotation methods will be of added value to perform a refinement (with i.e. de-rated operational conditions during curtailment, further refinement of operational cases in normal or curtailed conditions or including the influence of longer standstill).

Another future refinement of the binning may be to bin the data in each bin according to windspeed, resulting in a 2D-binning. To not overload the work, the 2D-binning has not been assessed in detail.

3.2. Operational scenarios with curtailment regimes

The priority objective of this work is to study the impact of the number of events initiated by curtailments on the support structure's lifetime. In view of this, four operational scenarios with variable curtailment regimes are defined. To allow a realistic assessment with focus on the impact of increased amount of events due to curtailment, the operational scenarios are to be comparable to the real world situation within each OWF, but differ in amount of events due to differences in curtailment regimes. The amount of events has been determined based the power set-point time. The power set-point time is the period which the BRP needs to respect when curtailing an OWF. In consultation with one of the involved OWF operators three set-point times have been defined for the analysis: 30 minutes, 10 minutes and 5 minutes.

The two OWF's have been operated differently. This difference has been reflected in the probabilities assigned to the investigated operational scenarios in each of the OWF's.

Similarly, the two WTG's in each OWF have not been operated identically. The operational scenario per OWF is an intermediate scenario applicable to both WTG's to meet the general operational condition on the OWF but not an asset specific scenario.

By assigning a probability of occurrence to each operational condition (see 3.1) in normal and curtailed regime, the following scenarios are defined for investigation:

- An approximated as-operated scenario: aligned with the initial insights in curtailment windows resulting from the advanced annotation methodology [14].
- Curtailment regime with 30-minute set-point time
- Curtailment regime with 15-minute set-point time
- Curtailment regime with 5-minute set-point time

With wind energy being a flexible energy asset, the real world case is expected to be a combination of various curtailment regimes. As matter of example, an assessment of the lifetime impact when combining the above scenarios has been performed. This combination scenario could be a basis for a long-term curtailment strategy, with the flexibility for short-term variations in curtailment regimes.

Given the approximation of the real world situation, the probabilities of operating conditions under the different scenarios may not be mentioned for reasons of confidentiality.

For a future integral study on the impact of curtailment on structural lifetime, more parameters amongst these scenarios could be varied. Examples of possible extensions to the variations in scenarios could be the period of curtailment, the time in standstill during curtailment, possible stable de-rated operational levels during curtailment and 2D-bin refinements by e.g. new probabilities of occurrences of windspeed.

3.3. Load and lifetime assessment

The load monitoring signals from 6 strain gauges are processed on a 10-minute basis into damage equivalent moments (DEM) in fore-aft and side-side direction according the heading of the turbine. The two turbines in each OWF are very similar in terms of loads. With the objective to investigate the impact of curtailment scenarios with variable number of events on loads and lifetime, the DEM in FA direction is the most suitable metric. This is illustrated in Figure 1 in which a curtailment window at OWF1 is visualized. The DEM's in FA (dots) at the initiation and termination of the curtailment window (see red circles) are clearly exceeding the FA DEM's in operational conditions while the SS DEM's (crosses) do not show similar behaviour. To illustrate the origin of the high FA DEM, the timeseries of the bending moments from which these DEMs are derived are shown in Figure 2. The large load cycles in FA direction (orange) both during a WTG stop and start event are the main contributors to the high DEMs in FA direction. The windspeeds shown in Figure 2 illustrate it concerns events within the operational windspeeds and not nearby cut-in or cut-out conditions. In the further description of the load assessments and results, we refer to the DEM in FA direction as DEM.

In future extensions of the analysis, in which also the detrimental effect of standstill of larger WTG's on the support structure's fatigue life consumption will be investigated or when a comparison to the as-designed DEM is required, the DEM in SS direction will need to be considered as well for a more refined directional assessment similar to earlier data-driven lifetime case studies [12].

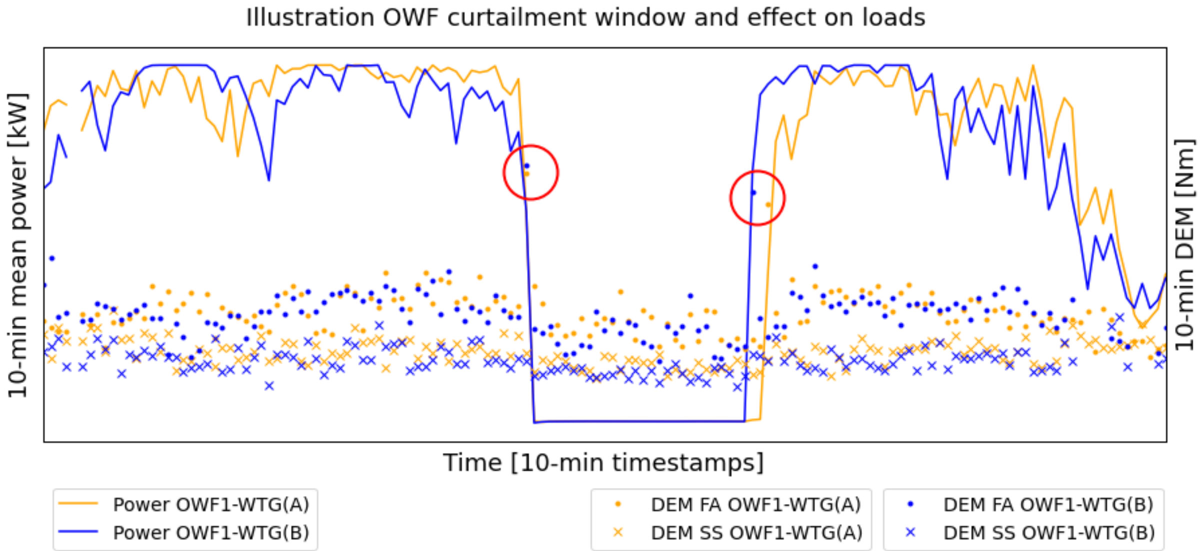

Figure 1: Illustration of OWF1 curtailment windows and effect on DEM FA and DEM SS

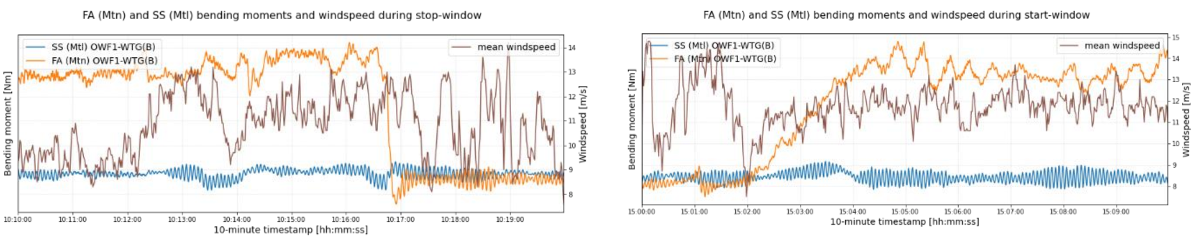

Figure 2: FA and SS bending moment time signal at WTG stop (left) and start (right)

The chosen binning approach allows to assess the DEM's per operational condition as described in Section 3.1. A representative value of the DEM per bin in normal and curtailed conditions needs to be chosen. The statistical distribution of the 10-minute DEM's per bin is verified to define a representative

DEM for each bin. A detailed statistical analysis of the distributions within each bin is expected to be an extension of the present study when 2D-binning is being applied, an aspect which was not assessed in detail (ref. section 3.1). A commonly applied representative value per bin in a research context is the mean value [15]. For the purpose of the present work, an engineering judgement based on the quantile values per bin was performed. A sensitivity study to assess the impact of selecting different percentiles (varying between P25 and P90) as representative DEM per bin showed similar – yet amplified - trends as the outcome with a uniform P50-approach. To not overload this impact assessment, the uniform use of P50 as representative DEM per bin was chosen for this work.

Combination of the representative DEM's with the probability of occurrences of the bins per scenario using (1), results in a total DEM for that respective scenario. The factor m in (1) represents the Wöhler coefficient for which the DEM has been derived (in this assessment m=5).

$$DEM_{tot,scen} = \sqrt[m]{\sum_{bin,0}^{Number\ of\ bins} probability\ of\ occurance_{\ bin,i} \cdot DEM_{rep,bin,i}^{m}} \quad (1)$$

From the total DEM per scenario the impact on lifetime of the operational conditions of that respective scenario can be determined by comparison to a reference DEM. The impact on lifetime is based on the ratio of both DEM's (2). In lifetime assessments based on DEM, the reference DEM is typically the as-designed DEM. Given our focus on events and FA DEM only, the comparison with design is not the most relevant for the purpose of this work. Instead of using the as-designed DEM as reference, the fictive operational scenario with a curtailment regime and 30-minute set-point time is used as reference. This scenario is chosen as reference since it may be the consensus between interests of BRP's, grid operators and wind farm operators when developing a curtailment strategy and allows to evaluate the approximated as-operated scenario of the OWF's.

$$Lifetime\ Factor\ (LF) = \left(\frac{DEM_{reference}}{DEM_{total,scenario}}\right)^{m} = \left(\frac{DEM_{total,scenario\ 30-\min set\ point\ time}}{DEM_{total,scenario}}\right)^{m} \quad (2)$$

In case the reference DEM is higher than the total DEM in a scenario, the fatigue consumption according the operational conditions in the scenario is less than expected in the reference case. In the above a Lifetime Factor (LF) greater than 1 indicates a potential extension to the reference lifetime. The LF can be used to quantify the lifetime prediction based on the lifetime related to the reference DEM according (3).

$$LF \cdot Reference\ lifetime = data\ driven\ lifetime\ prediction \quad (3)$$

For publication of the results indicating the positive or negative impact on lifetime under each curtailment regime, the LF is converted to a Lifetime Impact Factor (LIF) according (4).

$$LIF = LF - 1 \quad (4)$$

A LIF of zero corresponds with no impact on lifetime compared to the reference scenario. A negative LIF indicates the evaluated scenario has a lower lifetime compared to the reference scenario. A positive LIF greater than zero indicates a lifetime reserve compared to the reference scenario.

4. Results and discussion

While the exact operating conditions may not be mentioned for reasons of confidentiality, we can share that the probabilities of events in curtailment regimes included in the calculations are as follows:

- Curtailment with 30-minute set-point time: 0.33 %
- Curtailment with 15-minute set-point time: 0.67 %
- Curtailment with 5-minute set-point time: 2%

As explained in 3.3, the results in this publication are based on the load assessment with the 50th percentile (P50) DEM in each of the bins in normal and curtailed conditions as representative DEM used in (1).

Below the resulting Lifetime Impact Factors for various scenarios relative to the reference scenario are visualized. Figure 3 is the bar chart with LIF per turbine for the various scenarios. The resulting lifetime impact of the investigated scenarios allows to discuss a couple of observations:

1. The difference between current operational conditions (red) at OWF1 and OWF2. The LIF at OWF1 is greater than the LIF at OWF2. This indicates that the current operational conditions at OWF1 are more favourable compared to the reference curtailment regime opposed to the operational conditions of OWF2. This observation matches with the insight that OWF2 has been more frequently subjected to curtailment regimes during the assessed period. OWF2 has an operational regime closer to the reference scenario, thus subjected to more event load cycles, compared to OWF1.
2. The more frequently curtailment of OWF2 can also be observed from the lower effect of the more flexible evaluated curtailment regimes with 15- and 5-minute set-point times (yellow and blue) opposed to the impact on the lifetime in OWF1.
3. The difference between WTG(A) and WTG(B) of OWF1 in the approximated as-operated scenario (red) is minor, which is corresponding with the very similar operational conditions of both turbines. The minor difference can be explained by the fact that WTG(B) has been subjected to a slightly larger portion of events.
4. Similar, but more significantly the difference between WTG(A) and WTG(B) of OWF2 in the approximated as-operated scenario (red) can be explained. WTG(A) in OWF2 has been subjected to approximately 18% more events relative to the number of events at WTG(B). This is visualised in Figure 4 in which the LIF is shown in function of the number of events per evaluated scenario.
5. The impact of curtailment regimes with shorter set point times, allowing a more frequent possibility to stop and start the WTG, has a detrimental impact on the lifetime. The impact for a 15-minute set-point time (yellow) varies from a 20% to 30% reduction of lifetime, while the impact of a 5-minute set-point time (blue) ranges between 50% and 75% reduction of lifetime.
6. The evaluation of the combination scenario (grey) indicates that by combining the different regimes the detrimental effect of flexible curtailment regimes on lifetime consumption can be mitigated while still allowing flexible curtailment for a certain period of time.

At first sight the results indicate the detrimental effect of flexible curtailment regimes on the support structures' fatigue lifetime. Prior to drawing conclusions, it is however important to mention that it is not the intention of this work to advocate against the flexible curtailment of OWF assets, since this flexibility is one of the great advantages of wind energy.

The first objective of this work is to highlight the importance to take the long-term detrimental effect from transitional load cycles, due to frequent curtailment instructions, on the consumed fatigue life of a WTG support structure into consideration. Based on the rather theoretical curtailment regimes we believe this awareness is created.

The second objective is to provide data-driven support in asset management decisions towards curtailment strategies supporting the flexible use of wind energy assets. In view of this, we made an interpretation of the research findings towards an industry context. The real world operational scenario will be likely a combination of various curtailment regimes. The resulting lifetime impact factor plots below include this combination scenario (grey). The combination scenario is an arbitrary combination of the evaluated scenarios. In the example below we assessed the lifetime impact of a combination scenario based on a curtailment strategy in which the BRP's and grid operators can influence the operation of the turbines within following boundary conditions:

- For at least 40% of the time as per the current operational conditions
- Up to 20% of the time as per a curtailment regime with min. 30-minute set-point time
- Up to 25% of the time as per a curtailment regime with min. 15-minute set-point time
- Up to 15% of the time as per a curtailment regime with min. 5-minute set-point time

The resulting LIF > 0 in the combination scenario indicates the feasibility to operate an OWF with a very flexible curtailment regime, without critical long-term detrimental effect on lifetime. With the above combination of scenarios the LIF at OWF2-WTG(A) indicates a minor detrimental impact on lifetime. As mentioned before, this matches with the insights in the operational condition of this asset.

In the present case study the comparison is made against a reference scenario, in integral lifetime assessments this reference would be the design which would allow to identify a critical condition in relation to the as-designed structural capacity.

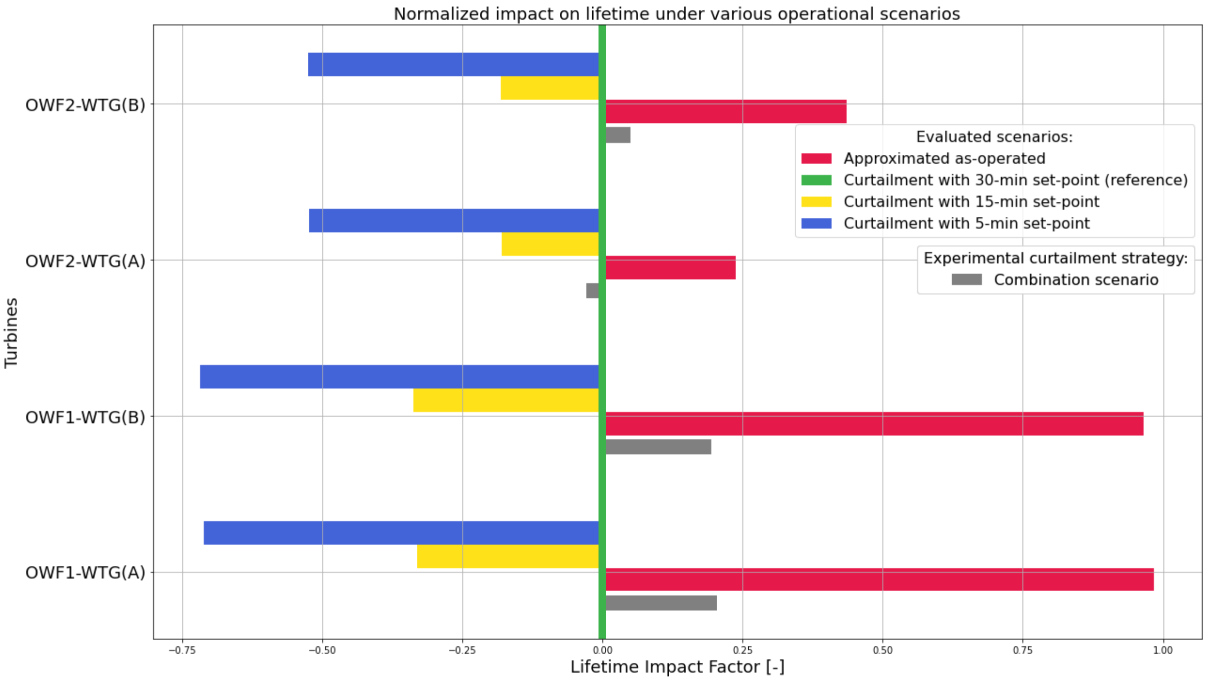

Figure 3: Data-driven lifetime impact assessment for various operational scenarios

Figure 4 shows the LIF in function of the amount of events in each scenario.

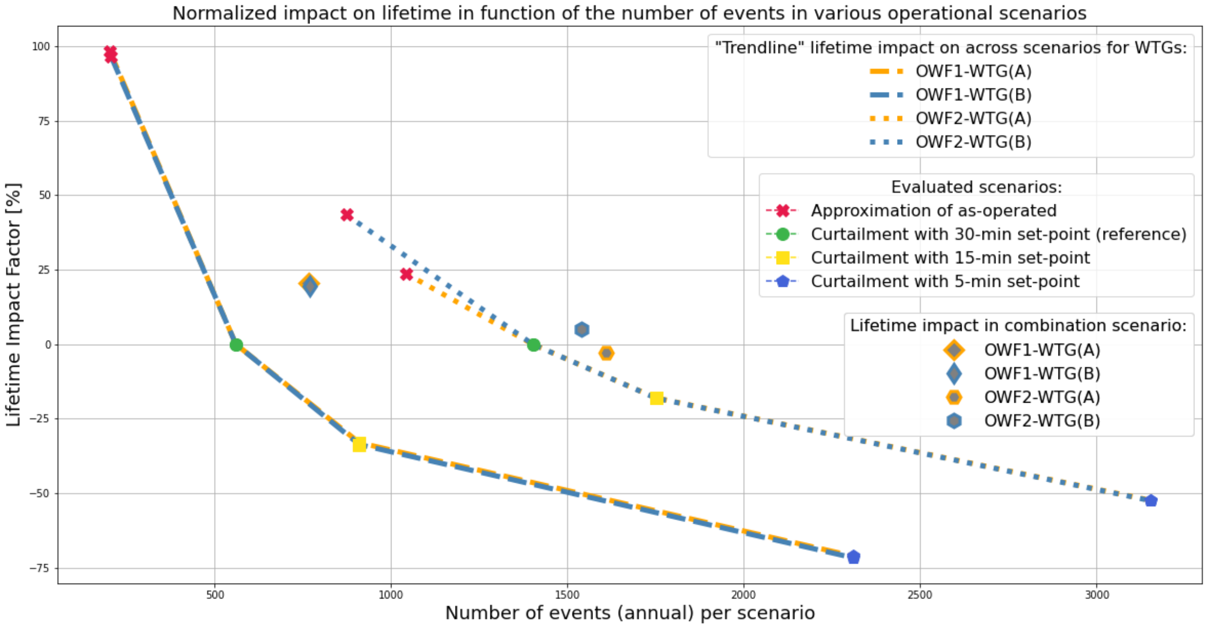

Figure 4: Data-driven lifetime impact assessment in function of number of events in the investigated operational scenarios

5. Conclusion

One of the advantages of having wind energy assets in the grid is their flexibility. In today's energy management, the use of curtailment is an essential tool to balance production and demand on short-term. The long-term impact on the support structure's lifetime from the consequences curtailment has on structural load cases has been discussed and studied in this work.

While there is the general awareness on the criticality of standstill of larger WTG's, the present work focussed on the impact on the foundation's fatigue life when additional event load cycles are introduced by curtailment regimes. We demonstrated that the impact of additional event cycles under various curtailment regimes on the fatigue life of the WTG's support structure cannot be neglected and can be quantified with data-driven lifetime assessment methods using real-world load measurements. To safeguard the flexible use of wind energy assets on short-term and continuous reliable energy asset on the long-term with the ambition of lifetime extension a long-term curtailment strategy may thus be advised.

The structural integrity may not be the priority concern when discussing short-term curtailment regimes. However in view of the general interest to explore lifetime extension of OWF's, we cannot lose sight on the detrimental long-term effects of curtailment to the structural lifetime. To address this, there might be the need for a discussion between the BRP, the grid and turbine operators for a long-term, but still flexible, curtailment strategy. A strategy which may potentially be defined similarly to the arbitrary combination scenario presented in this work. With designs becoming less conservative, such alignment might be needed at an early stage of the operational phase of the OWF or during the design phase if feasible.

Within an OWF this type of assessments may also highlight critical assets, like the OWF2-WTG(A) in the above example.

In the broader picture, these curtailment strategies may be synchronized between different OWF's to ensure a balanced curtailment, taking into account the structural reserves as one of the parameters.

6. Outlook

The limitations mentioned in this work lead to the future works.

Following this initial impact analysis, the ambition is to perform an integral assessment addressing both detrimental consequences curtailment regimes have on the support structure's fatigue lifetime: increased standstill time and additional transitional load cycles.

Besides broadening the view to the entire load spectrum, refinements to the currently applied methodology are to be investigated. Examples of such refinements are the further implementation of advanced annotations [14] to serve in the binning approach, more refined curtailment regime definitions with e.g. a de-rated power production regime instead of going to standstill, extending to a 2D-binning approach by including the windspeed as binning parameter.

In addition to the current deterministic approach, a probabilistic assessment by means of statistical methodologies to perform analysis with resampled datasets, e.g. by means of bootstrapping may be of interest to quantify the uncertainty [13].

The present analysis has been performed on a WTG support structure which is instrumented with a load monitoring setup. Future work will be to assess the influence of curtailment on loads and lifetime farm wide by implementation of the research towards farm wide DEL predictions [10].

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