



D4.7





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EXECUTIVE SUMMARY

The present document constitutes Deliverable D4.7 “Acceptability requirements and usability guidelines of the WILLOW WF tools” in the framework of the Project titled “Wholistic And Integrated Digital Tools for Extended Lifetime and Profitability of Offshore Wind Farms” (Project Acronym: WILLOW; Grant Agreement No 1011122184.).

This deliverable will present the identification of all the relevant needs and functional requirements from potential users of the WILLOW tools.

This is the first version of the Acceptability requirements and usability guidelines to define the baseline of our tools for our potential users. Following related deliverables D4.8 and D4.9 in M20 and M36 respectively will update this first version once WILLOW developments are in a more mature state and after getting valuable feedback from NORTHER (our offshore wind farm operator) and our industrial experts in the WILLOW Advisory Board.

Focus is put on describing the role of the various stakeholders in order to identify variables that may be modified to provide grid balancing services taking into account structural health. Once these variables have been identified, control approaches are suggested, followed by their respective requirements from the wind farm operator and stakeholders' perspective.



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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
KER	Key Exploitable Result
LCoE	Levelized Cost of Energy
OPEX	Operational Expenditures
O&M	Operation and Maintenance
RUL	Remaining Useful Lifetime
SHM	Structural Health Monitoring
EOC	Environmental and Operating Condition
WT	Wind Turbine
WF	Wind Farm
WFO	Wind Farm Operator
TSO	Transmission System Operator
BRP	Balance Responsible Party
OEM	Original Equipment Manufacturer
PPA	Power Purchase Agreement



1 INTRODUCTION

The aim of this report is to identify all the relevant needs and functional requirements from potential users of the WILLOW tools. Although each work package and task feature its own products, we defined by tools here the smart curtailment tool targeted with wind farm operators as end users. Hence the focus is set on the activities of WP4, which are implicitly fed by data coming from sensors and models developed at wind turbine level within WP2 and farm wide data-driven models developed within WP3 to enhance their performance.

Smart curtailment may be divided into two objectives: (1) suggesting measures to adapt how curtailment is imposed and actuated to reduce structural damage, and (2) evaluating and informing about the impact of these measures on the remaining useful lifetime (RUL).

All Tasks T4.1-5 in WP4 contribute to one of the two objectives, as shown in Figure 1. In addition, Task T4.7 aims at enhancing usability and acceptability by the end user, through this deliverable and its two forthcoming updates throughout the project.

This report is organised as follows: Section 2 gives first a description of stakeholders and context in sufficient detail to enable providing a first overview of activities to be carried out in WP4. A brief presentation of tasks in WP4 is then given and linked to potential stakeholders. Section 3 presents first an overview of activities and products is then presented with focus on feasibility with respect to stakeholders. Requirements for the development of the various products and their implementation by stakeholders are finally listed.



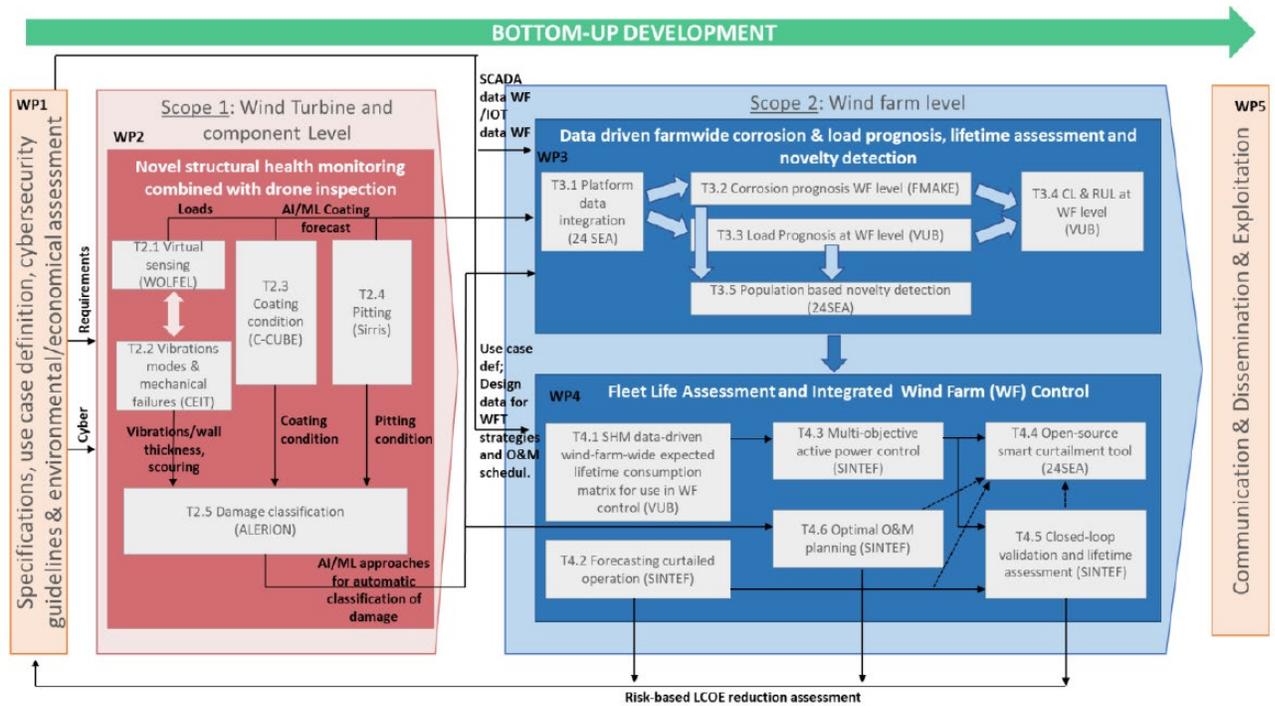


Figure 1. WILLOW preliminary system scheme

2 BACKGROUND AND STAKEHOLDERS

2.1 Description of stakeholder role and state of practice

A general introduction to wind farm curtailment and current industry approach is given in D1.1 "Use Case Definition". A more detailed revision is provided in this section. Smart curtailment solutions will exploit degrees of freedom in the underlying processes. To identify these degrees of freedom, it is important to understand the role of the different parties involved. This description is simplified on purpose for general understanding by a broader audience, avoiding electrical engineering and energy market jargon as much as possible. More information may be found in references^{1,2,3}.

2.1.1 Transmission System Operator

The Transmission System Operator (TSO) is in charge of the electrical grid, transporting electricity over long distances. There is typically one TSO per country, and it is the final responsible to deliver stable and clean power to consumers. To this end, the TSO needs support from electricity producers. This is realised through the so-called ancillary services, and through trading processes in energy markets. These may here be divided into two categories: (1) balancing active power between production and consumption and (2) providing reactive power and voltage support.

Category (2) refers to ancillary services achieved — in the case of wind farms — by controlling the grid-side converter of each wind turbine. It is mostly independent on curtailment and will therefore not be the focus in WILLOW.

Processes in Category (1) takes different forms and names depending on their operating timescale and their preventive or corrective nature and will be presented in the following sections.

A thorough review of wind farm participation in ancillary services is given in references⁴.

2.1.2 Balance Responsible Party, energy markets, preventive curtailment and Power Purchase Agreement

The Balance Responsible Party (BRP) is an intermediary between the Wind Farm Operator (WFO) and the TSO. It is typically a large energy company owning a large portfolio of assets of complementary natures (wind and solar, hydro, fossil...). Its role is to help the TSO balancing electricity production and consumption, by trading in energy markets.

Energy markets relate to preventive processes in Category (1) above, where the electricity price acts as an intermediary variable to balance *predicted* production and consumption: high prices correspond to a large demand and incite BRPs to increase production, while low prices correspond to overproduction and incite BRPs to decrease production and save resources (e.g., water in hydropower reservoirs and fossil fuel) for periods with higher electricity price. There are different markets corresponding to different timescales:



- **Day-ahead market** where BRPs bid in energy pools, telling —and committing to— how much they can produce at which price for each hour of the next day. Summing over all BRPs and combined with an estimation of consumption by the TSO, this determines the electricity price and the corresponding share of power that has to be delivered by each BRP for each hour of the next day.
- **Intra-day market** where BRPs trade power on a short-term basis. Typically, the trade occurs 5 to 30 minutes (lead time) before the actual power delivery, that may be from 15 min to 1h long. Trades occur between BRPs as a mean to match their respective bids in the day-ahead market, and between BRPs and the TSO to compensate for errors in estimating consumption.

Wind farm curtailment may then occur for one of the following reasons:

- Once a bid or trade has been made, the BRP must deliver the promised power or will suffer from economical loss through over- or underproduction fees imposed by the TSO, or —to a lesser extent— through disadvantageous trading with other producers in the intra-day market. In this context, any unplanned shortfall or surplus from an asset should be compensated by other assets. In the case of surplus, BRPs may curtail wind farms to decrease production and match the trade.
- The BRP may curtail wind farms following a trade with the TSO in the intra-day market to balance the grid in the case of a positive imbalance in the total production due to an overestimation of the consumption in the day-ahead market.

These events will be referred to as *short-term preventive curtailment*.

Approaching real time, new markets are introduced:

- **Reserve market** where BRPs trade *power reserves* on the same time frame as the day-ahead and intra-day markets. A power reserve is unused production capacity that constitutes the available resource for real-time (very short term) preventive balancing in the balancing market (described below), as well as for corrective balancing through ancillary services (described in 2.1.3).
- **Balancing market** where BRPs having offered short-response power reserve compensate for real-time (minute resolution) imbalances. In case the power reserve is provided by a wind farm, tracking a real-time power demand can be used by BRPs/WFOs to participate in the balancing market. This will be referred to as *real-time preventive curtailment*.

In some cases, the BRP and WFO are the same entity, meaning that it both owns and operates the wind farm. This reduces grid-side feasibility requirements to an internal organisation problem. This is however not the case for the case study considered in WILLOW, where the BRP and WFO are different entities linked through a Power Purchase Agreement (PPA). The PPA is a bilateral



contract setting among others the terms of curtailment services: maximum amplitude of curtailment events, minimum time between two events, maximum annual number of events... It is flexible in the sense that it is negotiated between the two parties, but is generally a long-term contract (10 to 15 years).

2.1.3 Ancillary services and corrective curtailment

Corrective processes in Category (1) in 2.1.1 actively regulate the grid frequency *after* a system imbalance. They are meant to compensate for imbalances that have not been resolved through preventive processes in day-ahead, intra-day and balancing energy markets described in 2.1.2, and are in essence ancillary services to the TSO. They use power reserves from the reserve market described in 2.1.2: If necessary to stabilise frequency, the TSO will ask BRPs that have offered power reserves to use this reserve. Wind farm curtailment appears then as a low-threshold way of providing negative reserves in the case of a production surplus, leading to what will be called *corrective curtailment*.

These ancillary services may be divided according to timescale:

- Primary frequency reserve (Fast Frequency Reserve) occurs immediately after an imbalance, triggered by an abnormally low or high system frequency. For wind farms, this refers to grid forming / synthetic inertia services occurring on a faster timescale than curtailment.
- Secondary frequency reserve (Frequency Containment Reserve) occurs at the minute timescale. They are the corrective equivalent to balancing market trades, so the corresponding *real-time corrective curtailment* resembles real-time preventive curtailment in 2.1.2 from the perspective of the WFO.
- Tertiary frequency reserve (Frequency Restoration Reserve, Reserve Replacement). Tertiary reserves are of the same timescale as intra-day trades, so the corresponding *short-term corrective curtailment* resembles short-term preventive curtailment in 2.1.2 from the perspective of the WFO.

Although preventive and corrective curtailment may look similar from the perspective of the WFO, they are different from the perspective of the BRP and TSO: the former relates to flexible trades, the latter to a long-term ancillary service agreement.

Although power reserves solve imbalances on a global level, there might still be local congestion in the grid due to limited transmission capacity motivating the TSO to directly curtail wind farms without going through power reserves set by the BRP. These rare events will be referred to as *grid-based curtailment*.

The various processes described in the last sections are illustrated in Figure 2. Note that *load* takes here an electrical meaning linked to power consumption, not to be confused with structural loads.



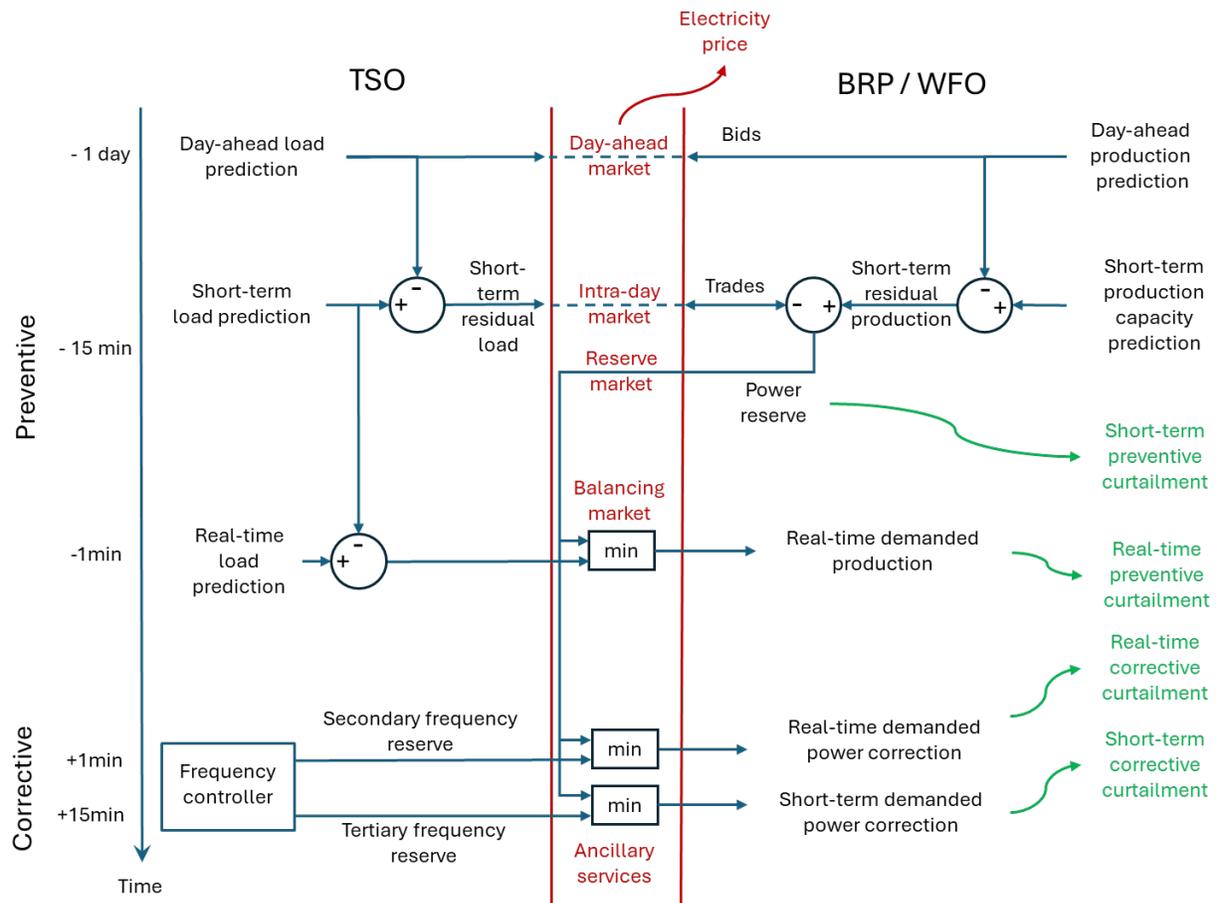


Figure 2: Link between energy markets, ancillary services and curtailment

2.1.4 Wind Turbine Original Equipment Manufacturer, power transmission architecture and plant integration agreement

The responsibility of the wind turbine Original Equipment Manufacturer (OEM) occurs first and foremost at the turbine level, guaranteeing the reliability of each wind turbine based on well-established design standards approved by certification bodies. This responsibility covers all components in the wind turbine, including the power converters and transformers delivering medium-voltage power output to the export cable. As electricity is transmitted to the collection grid through cables and switchgear connecting turbine strings, and down to the power substation exporting high-voltage power to the transmission grid, the power transmission responsibility which started at the OEM is passed to the WFO and then to the TSO.

Consequently, since wind farm curtailment sets the desired total power output from the substation, to be spread over turbine strings gathering power from individual turbines, the actuation of downregulation following curtailment events appears as a shared responsibility between the TSO, the WFO and the OEM. Who of the WFO and OEM should decide how the individual turbines

should be downregulated to achieve the desired total power is an open question. In practice, downregulation is a feature of plant control services included in the total plant design and management package offered by OEMs to WFOs. The power plant controller is, however, a different product than the turbines themselves and the underlying plant integration agreement can be negotiated without violating turbine design certifications.

2.1.5 Other stakeholders

Political authorities (state or EU) are also a stakeholder influencing PPAs. Despite its role to stabilise grid and market, curtailment may be seen as a loss of green energy which should be reduced by various measures. In the case of Belgium, for instance, the share of curtailment services in WFOs' economics depends on the share of governmental subsidies. The corresponding degree of freedom lying in deciding which wind farm should participate in curtailment is out of WILLOW's scope.

PPAs may also be signed directly between the WFO and large energy consumers (e.g., technology companies operating large datacentres). If connected through the public grid, the contract will involve the TSO and possibly a BRP. This is however not the standard case and will not be considered in WILLOW.

2.2 Link between stakeholders and tasks in WP4

To put this in context, we will remind the description of the first five tasks within WP4 in more detail.

- Task 4.1: SHM data-driven windfarm-wide expected lifetime consumption matrix

This task will use the results from WP3 —itself using results from WP2— to provide information about current degradation state and damage rate for use in wind farm control. The provided data may be environmental conditions such as mean wind speed and direction, turbulence intensity, salinity and temperature, wave conditions, etc., but also the effect of controls themselves (power setpoint, stop/start events). This model will be in turn called during wind farm simulations to inform the WF controller for use in smart WF curtailment algorithms in task 4.3. Extension to lifetime assessments considering the effects of control will be made in task 4.5.

- Task 4.2: Forecasting the share of curtailed operation

This task will characterise future scenarios of wind farm curtailment. Curtailment may be grid-initiated for power reserve provision (main reason of wind farm curtailment today), to rectify local or system-wide demand mismatch. Although not practiced by farm operators today, self-imposed curtailment for added flexibility in low electricity price events may also become actual. Both will be analysed as function of their location and the evolution of the electrical grid and energy markets around the North Sea. The outcome of this task will be plausible scenarios with various combinations of energy demand, energy production and energy storage in the grid on the one hand, and OPEX costs versus production income on the other hand, leading to a probability distribution of degrees of curtailment across the wind farm's lifetime.

- Task 4.3: Multi-objective active power control



This task will devise and validate multi-objective active power control algorithms jointly satisfying grid requirements, such as tracking a power reference or maintaining a power reserve and maintaining power quality, and prevention of asset degradation in curtailed operation. To this end, farm-wide degradation models and power fluctuation models are needed. Degradation models will be provided by task 4.1. Simplified proxies will be devised and used in the WF controller's damage mitigation objective in early stages of the project to enable parallel development. Modelling power fluctuations for use in wind farm control will build on previous projects giving a physics-based basis. The focus here will be more on data-driven calibration against in-situ wind and power measurements, as well as validation against high-fidelity farm simulations. This will result in a hybrid physics-based and data-driven model. The outcome of this task will be a set of curtailment strategies ready to be implemented in the smart curtailment tool in T4.4 for use by the farm operator. Validation and further improvements will be made in T4.5.

- Task 4.4: Open-source smart curtailment tool

This task will develop a user-friendly open-source software for use by wind farm operators to decide on curtailment strategy as function of remaining useful lifetime and damage rate. The tools should use 24SEA's monitoring data as a starting point and should be able to integrate the developed methodologies in WP3 informing about the degradation state of the farm within its automated data pipelines. The tool will be developed as an open-source package with a service-oriented software design and data integration and sharing features, targeting a proof of concept rather than industrial deployment. The user interface will be minimal, focusing on interaction with other operational processes within NORTHER. Tasks 4.1 & 4.3 provide a sufficient basis for this task, while results from tasks 4.2 and 4.5 will enrich/update it.

- Task 4.5: Closed-loop validation and lifetime assessments

This task will incorporate the effects of wind farm control into lifetime assessments. It will consist in iteratively updating the methods used in WP3, by means of wind farm simulations capable of performing "what-if" analyses. It will consist in: (i) developing an efficient modelling platform for dynamic farm-level aero-hydro servo elastic simulations embedding the methods from task 4.3 with focus on structural load modelling, building on results from previous projects; (ii) validation against 1-year measurement data; and (iii) using these dynamic simulations in long-term analysis to calculate remaining useful lifetime/damage equivalent loads considering uncertain changes in operational (share of curtailed operation from task 4.2) and environmental (climate change) conditions. This task may be seen as the end task of the project, continuously de-risking and updating the tool in task 4.4.

From these five tasks, we have foreseen five KERs as the exploitable outcomes as is shown in Table 1. The key potential stakeholder of most of these KERs is the Offshore Wind Farm Operator (WFO) but other users such as Wind turbine OEMs, or Balance Responsible Parties (BRPs) — linking to Transmission System Operators (TSOs)— can be benefit with the use of these WILLOW tools.

Table 1 KERs from WP4 tasks and potential stakeholders



Key Exploitable Result (KER)	Task	Potential Stakeholders
SHM data-driven windfarm-wide expected lifetime consumption matrix for use in wind farm control	T4.1	WFOs OEMs BRPs
Curtailed operation forecast scenarios, to assess offshore wind ancillary power reserve service provision versus power maximisation	T4.2	TSOs BRPs WFOs
Multi-objective active power control algorithms complying grid requirements and preventing assets degradation in curtailed operation	T4.3	WFOs
Open-source smart curtailment tool	T4.4	WFOs OEMs
Closed-loop probabilistic decision-making tool for wind farm control based on calculated remaining useful lifetime / damage equivalent loads	T4.5	WFOs OEMs BRPs



3 ACCEPTABILITY REQUIREMENTS AND USABILITY GUIDELINES

This section describes the activities that will be carried out in WILLOW to devise smart curtailment solutions, and feasibility concerns for stakeholders defined in 2.1.

In order to organise the smart curtailment solutions, a distinction should be made regarding whether the cost associated with structural health awareness is quantified (i.e., monetised) and included in the wind farm control objectives or not. If it is included, the control strategy seeks for a trade-off between power production and damage mitigation, in other terms reducing damage justifies discrepancies between demanded and delivered power and hence a loss in revenues. This approach is deemed not yet actual for WFOs as the cost (or possible revenues from lifetime extension) associated with damage is highly uncertain. If damage costs are not included, power production prevails in any case and damage mitigation only acts as a secondary objective constrained by the primary, power production objective. WILLOW will explore control solutions belonging to the latter category, but constraints from the power production objective (i.e., curtailment) are kept as a variable through negotiations of the PPA with the BRP. This means that the influence of terms of contracts regarding curtailment (as listed in 2.1.2) on remaining useful lifetime will be studied, but control algorithms will be designed assuming fixed PPA terms and will fulfil these terms as a primary objective. Damage mitigation will then make use of remaining degrees of freedom, which will depend on the PPA and the plant integration contract with the OEM.

As a result, solutions may be divided into devising guidelines for curtailment parameters in the PPA terms on the one hand and control strategies on the other hand.

3.1 Curtailment parameters

This section scans the various parameters defining wind farm curtailment that should be discussed when establishing a PPA between the WFO and BRP. This will have a direct impact on the WFO's economics, whose quantification will be part of the LCOE assessment in D1.6 "Risk-based LCOE reduction assessment". However, such a quantification will not be certain enough to enable suggesting optimal guidelines, and negotiating PPAs is outside the scope of WILLOW. Instead, the analysis of curtailment details will be used to suggest plausible scenarios to be used as input for control design and RUL assessments.

Degrees of freedom in the PPA directly depend on terms and constraints defined in energy markets and grid codes. Nuances will lie in whether curtailment is preventive or corrective. A non-exhaustive list of questions that should be asked is presented in the following:

- How much should the amplitude and frequency of occurrence of curtailment be reduced as a trade-off with structural damage? Direct comparisons between the cost of curtailment linked to structural damage and loss of revenues in balancing markets and ancillary services would be ideal. However, as mentioned above, uncertainties on damage-induced



costs are too large for this purpose. Instead, it is possible to do qualitative assessments comparing the difference in damage on the one hand and on loss of revenues on the other hand: if changing a parameter leads to a large decrease in damage but a marginal revenue loss, negotiating changes in the PPA becomes actual.

Examples of variables that may be discussed are:

- Total annual number of curtailment events and prioritisation for events providing high revenues as function of Environmental and Operating Condition (EOC)—e.g., when electricity prices are high
 - Amplitude and duration of curtailment events, as function of EOC
 - Time between curtailment commands in a curtailment event (an event consists in a sequence of commands)
 - Relative changes between consecutive commands in an event
- Should the wind farm provide a real-time power tracking functionality to participate in the balancing market and offer secondary frequency reserve ancillary services?
 - There is an allowed activation time margin for the use of power reserves in the balancing market or in ancillary services. Can this be used as a no-cost degree of freedom to: (1) progressively curtail wind farms with a smooth downregulation command, and (2) choose the appropriate moment to curtail wind farms as function of wind conditions?

3.2 Description of control approaches and feasibility assessment

At this point, it is assumed that parameters defining curtailment events have been set. The way the wind farm should be downregulated as a response to curtailment commands relates to *control*. This section describes control approaches that have been considered in WILLOW for health-aware wind farm downregulation, ranked according to their feasibility with respect to the wind turbine OEM.

These approaches seek to improve current downregulation practice, where all turbines are equally downregulated without consideration for local EOCs of the individual turbines. This means that if, for instance, a reduction of power of 50% from installed capacity is sought, all turbines will be downregulated by 50% of their capacity regardless of local available power in the wind, structural health or fault.

3.2.1 Damage-aware selective curtailment

A first approach that would be relatively easy to implement consists in selecting which turbines should participate in curtailment, or rather which turbines should be excluded for structural health reasons. This selection would in a first stage be manually made by the WFO: the smart curtailment tool would provide information about accumulated, instantaneous and predicted—with and without selective curtailment—loss of RUL for each turbine, enabling relative comparisons on which the WFO would base its decision. More advanced schemes would involve optimisation algorithms suggesting an optimal selection based on the information above.



In practice, the WFO would define a *cluster* of turbines to be excluded from curtailment. These clusters would likely correspond to geographical areas with unfavourable wind conditions and wake effects. Changes in this cluster selection would be regular but not frequent, making feasible the adjustment of the plant integration contract with the OEM.

A barrier to feasibility lies in changes required in the power plant controller developed by the OEM. Power plant control groups turbines in *strings*, i.e., connected via the same cable in the collection grid. Excluding one string from curtailment is therefore easier in terms of implementation. However, differences in RUL between turbines would typically be independent on electrical connection and there is no reason to believe strings and clusters would coincide.

Another practical barrier, again stemming from power plant control being grid-oriented, lies in the provision of other ancillary services (Category (2) in 2.1.1). The converters of the turbines that are excluded from curtailment should still be able to provide reactive power (or voltage support), as the total reactive power to be delivered should be spread over all turbines to avoid inducing excessively large current in the converters.

3.2.2 Hierarchical active power dispatch

A second approach is to control the dispatch of power commands (or setpoints) sent to the individual turbines to achieve the desired curtailed power output. Unlike selective curtailment, this control solution allows for tracking a power reference and hence participating in the balancing market and providing secondary frequency reserve ancillary service, and is therefore a prospect for additional revenues by the WFO through the BRP/PPA. To this end, it encompasses local variations in wind conditions at each turbine from turbulence and wakes. It may also play with the activation time allowance for power reserves.

Multiple control strategies have been suggested in the literature (see ⁴ for a review, ⁵ for the starting point in WILLOW from past projects). In most of these, it is assumed that the WFO has full control over the power plant controller. As introduced in Section 2.1.4, this might not be the case and major changes in the plant integration contract with the OEM maybe required.

Unlike selective curtailment, this control strategy sends continuous commands to the turbines as function of power demand and damage info. It should therefore be embedded in the power plant controller and cannot be achieved through sporadic adjustments of the plant integration contract. Instead, the contract terms should allow for the WFO to send power setpoints to the turbines with possible additional constraints ensuring safe turbine operation. This is deemed a medium feasibility solution, lower than selective curtailment but with a significantly higher potential.



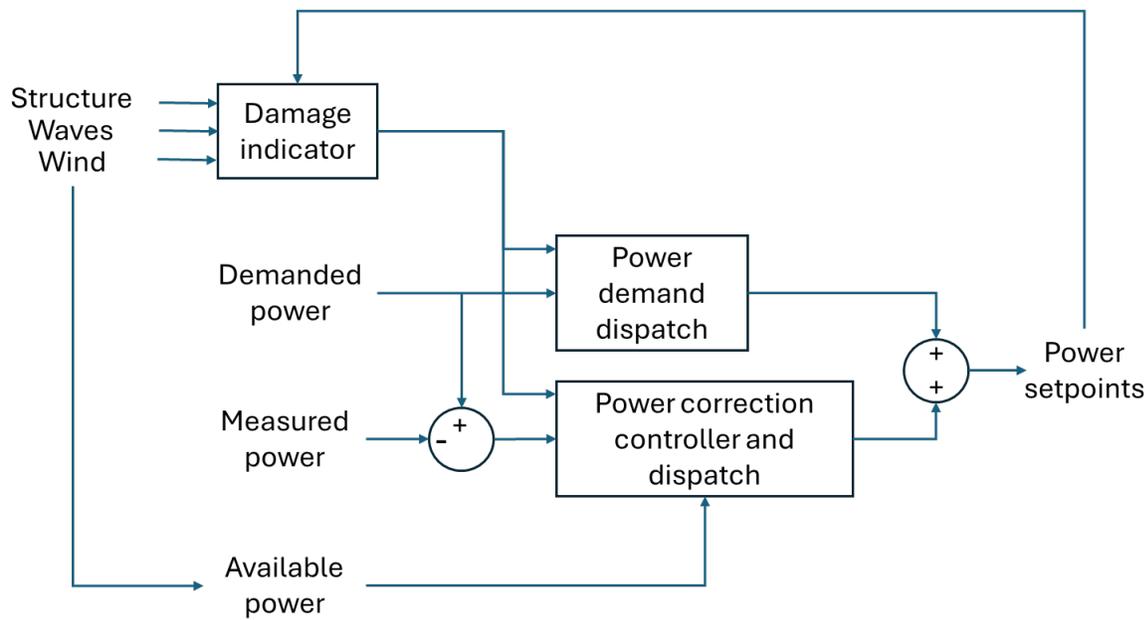


Figure 3: Concept of hierarchical active power dispatch

3.2.3 Load-mitigating turbine downregulation

3.2.1 and 3.2.2 exploit the degree of freedom lying in the repartition of curtailment over turbines. A more engaged control approach consists in exploiting the degree of freedom lying in how the power setpoint is actually handled by the turbine to deliver the desired power output. This is turbine-level control, playing with blade pitch angle and generator torque. This has been the topic of a many studies in the literature^{6,7}, because the load mitigation potential is large. The concept is illustrated in Figure 4 and described in the following: there are multiple operating points yielding a desired power (lower than available in the wind), corresponding to multiple thrust force values. The selection of operating point in current industrial wind turbine controllers is based on safest short-term operation rather than long-term damage mitigation. Choosing the operating point such that thrust force variations are as small as possible would mitigate damage. In the figure, typical current practice for downregulating a turbine by 50% starting from optimal operation is shown by the continuous purple arrows. This yields a thrust reduction of about 55%. In theory, a 90 degrees turn in the curves shown by the dashed arrows would yield the same decrease in power, but with no thrust variation. In practice, this is subject to limits in allowable rotor speeds and should be weighted against damage on other turbine components, but a significant reduction in load variations and hence fatigue is still achievable within feasible turbine operation limits.

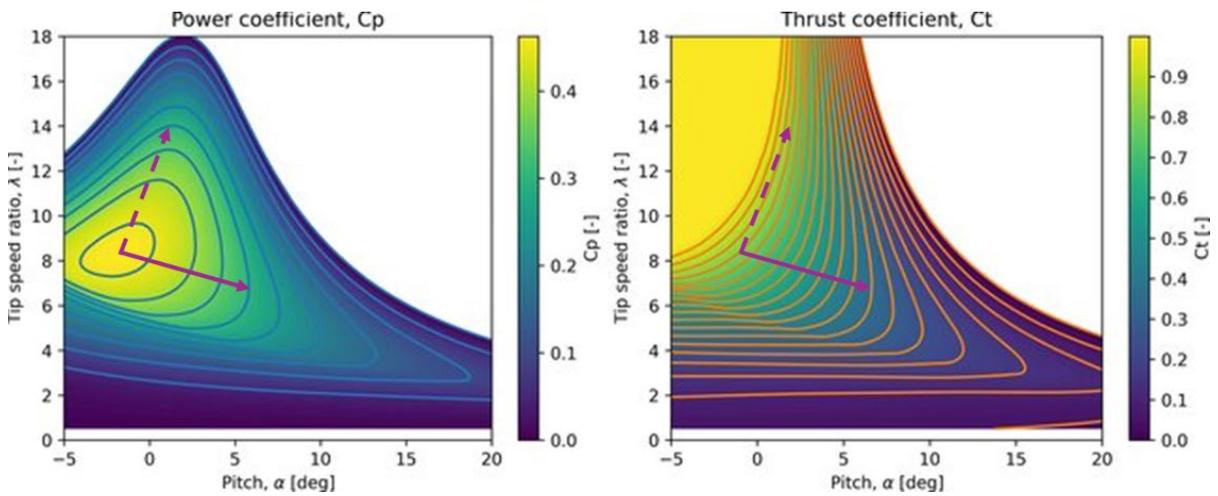


Figure 4: Concept of load-mitigating turbine downregulation. Source ⁸ (license CC BY 4.0).

However, despite its promises, this approach faces a major barrier in turbine certification, as it implies modifying the turbine controller and therefore the turbine design. Modifying the turbine controller may be considered by OEMs, when necessary, as for instance adapting to floating substructures to avoid negative damping in rigid-body motions. This is nevertheless deemed a low feasibility solution, still included in WILLOW for its potential. The benefit of load-mitigating turbine downregulation will be quantified, providing knowledge-based guidelines for OEMs.

3.3 Feasibility assessment and guidelines for stakeholders

This section sums up the required input/additional flexibility that would be required from wind turbine OEMs and BRPs to enable the realisation of various control strategies described in 3.2. It also suggests hypothetical acceptability requirements that would need to be fulfilled for this additional flexibility to be eligible for negotiation in contracts and implemented in practice.

3.3.1 Grid side

The grid side relates to the BRP through the PPA, and further up to the TSO. Terms of the PPA will define scenarios used as input to control design. To this end, economical assessments from the BRP defining the space of possibilities would be needed.

Damage-aware selective curtailment	<p>Estimation of a trade-off between loss in revenues induced by limiting curtailment and damage-induced costs, setting the shape of curtailment events</p> <p>Use of freedom in power reserve activation time to shape curtailment commands</p>
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Hierarchical active power dispatch	Trade-off estimation as above Participation in balancing markets and secondary frequency reserve Use of freedom in power reserve activation time to decide when to actuate curtailment as function of wind conditions
Load-mitigating turbine downregulation	N/A

The main underlying acceptability requirement from the BRP is a neat economical profit through trades in energy markets and provision of ancillary services. Proving this requirement implies a deeper look in the BRP's asset portfolio, economics, and operation practices, which is subject to confidentiality issues. However, energy market data is mostly open, enabling qualitative estimates.

Acceptability requirements from the TSO include the satisfaction of grid codes regarding power quality, implying checks in the hierarchical active power dispatch and modified wind turbine controllers.

3.3.2 Wind farm side

The wind farm side relates to the wind turbine OEM in charge of power plant control and turbine control.

Damage-aware selective curtailment	Change in power plant control architecture grouping turbines in clusters rather than strings, and separating reactive and active power Regular adjustments in plant integration contract defining clusters to be excluded
Hierarchical active power dispatch	Change in power plant control architecture and plant integration contract enabling the real-time control of power setpoints for each turbine from the WFO
Load-mitigating turbine downregulation	Change in turbine controller enabling the selection of downregulation operating points minimising thrust variations



Acceptability requirements for modifications in the power plant controller would include analyses ensuring that power setpoint commands from external sources (i.e., the WFO) would not damage the turbine. Of particular concern is the triggering of structural natural frequencies in the wind turbine, which may occur (1) if the rate of change in power setpoint is too sharp (ringing) or (2) if fluctuations in power setpoints occurs at the same frequency as natural frequencies (resonance). Following a curtailment event, current power plant controllers already downregulate turbines in an abrupt manner, so (1) should not be an issue for the OEM — this is rather a concern on the WFO side: the setpoint rate of change should perhaps be decreased upfront to minimise damage. (2) should be solved by low-pass filtering, ensuring no frequency content in the structural natural frequency range (typically larger than 0.2 Hz). Floating foundations, however, feature lower natural frequencies that would need a more careful analysis.

Modifying the wind turbine controller is much more involved and implies a thorough check of structural integrity following turbine design standards, with all load cases therein, using validated state-of-the-art aero-hydro servo elastic codes. Third parties may perform these analyses on a reference wind turbine. This is a necessary proof of concept, but not sufficient. Thorough analysis and testing for each wind turbine model featuring this new controller will have to be performed in more detail by the OEM itself (design specifications being confidential) and approved by certification bodies.



4 CONCLUSIONS

This deliverable presents usability guidelines and acceptability requirements with respect to stakeholders involved in wind farm curtailment. A simplified but detailed enough description of the role of each stakeholder and their interactions through the electrical grid, energy markets and plant integration contracts is given. This describes the origin of wind farm curtailment and enables identifying possible degrees of freedom to exploit for structural damage mitigation. Activities to be performed in WILLOW are divided into guidelines characterising the shape of curtailment through the Power Purchase Agreement, and the actuation of curtailment through downregulation by the power plant and wind turbine controllers. Regarding the latter category, three families of control approaches ranked according to their feasibility have been suggested. For each of them, requirements from the Balance Responsible Party, Transmission System Operator and wind turbine OEM have been identified. These requirements go both ways: on the one hand additional flexibility and input are needed by the Wind Farm Operator from other parties, and on the other hand proof of concepts and feasibility checks have to be provided by the WFO to enable implementation by other parties.



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