Paving The Way For Wind Farm Control In Industry

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Executive summary

Wind energy has achieved a remarkable reduction of electricity production costs in the last decade, expressed by a significant decrease of levelised costs of energy (LCoE). This is nowadays a competitive energy source compared to other energy resources such as coal, oil and neutral gas and an increasing portion of renewable energy in the grids of the industrialised countries are supported by a strong contribution of wind energy. The technical maturity of wind turbines has also improved, and recently entered the 10MW limit for rated power per unit with continuing work ongoing to get this further established by high-tech companies. The interests and ambitions of the industry is to further drive down the cost of energy and this has shifted the focus towards looking at intelligent control algorithms, optimised operation modes and software solutions that would make this possible.

Wind farm control as supervisory control units of a whole wind farm (or wind power plant) which are optimising the overall performance on the individual turbine level has the potential to bring energy costs further down. Previous testing and the research work within this FarmConners project have demonstrated this (i.e. see work package 1), and it’s becoming more evident as more wind farms are entering the energy stock markets opening up new possibilities of trading. Wind farm control is the key technology that will allow for this to happen with short term and flexible energy supply according to the market demand. (as FarmConners work package 3 points out).

The technical challenge of wind farm control is the handling of the high complex physics of the turbulent flow field within a wind farm whilst maintaining the safety level of the wind turbines and grid quality. A large wind farm consists typically out of 80 and more individual wind turbines which are shadowing each other in a more or less unfavourable way. Achieving optimal flow conditions for all turbines is a non-trivial, multi-variable optimisation problem. Turbulence and wake effects are natural phenomenon still under research and existing numerical simulation approaches easily reaches todays computational capacity limits.

The difficulty of quantifying the physical effects of complex flow conditions and their impact on the individual turbines is also a reason for the lack of standardised requirements for wind farm control in the todays regulatory landscape.

This deliverable looks at the status of certification and standardisation in the field of wind farm control. First, a review of most common farm control strategies is performed. There are many concepts in the development right now and no concept has been clearly established yet. The most common strategies are the so-called curtailment and the wake steering strategy. Previous research work shows that these control strategies potentially increase the loading and the operational costs of individual turbines within the wind farm (as a result of an increased overall annual energy production). Here new standards should consider the advanced operation modes and provide certification methodologies which assuring the compliance with design limits and grid codes.

A second aspect is the review of the present (European) electricity market mechanisms and their impact on the operational profiles of wind farms in a liberalised energy market. Curtailment and down times of wind farms due to stock market pricings has been increased over the last years and forecasts indicate that this

trend will further continue until 2030 and 2050. Increased start and stop procedures as well as down times will change the operational profile and are an issue for certification too.

Other aspects identified and discussed, looks at what hinders the introduction of wind farm control strategies. Among this, is the electricity grid requirement e.g. to support the grid during short-terms voltage dips. During such grid failures the local wind turbine controller should avoid a shut-down and maintain energy production in an island mode. The decision for this support mode must to be made within milliseconds. This could cause hierarchy conflicts of the different control levels within a wind farm.

Looking into more detail to the existing turbulence and wake models established in the current standards and guidelines, it becomes clear that for the near future, certification of wind farm control effects will still apply simplified models and conservative clustering approaches in order to capture the complex site specific flow conditions. This is underlined by the fact that present load simulation tools do not cover correctly the 3-D flow effects on rotor blades which occur e.g. when applying WFC wake steering strategies.

However, in the final section, it is concluded that certification of wind farm control strategies is generally possible by applying existing standards and three practical certification approaches are introduced. One approach is dealing with long term measurements which will be verified by the certification body after several years. If no exceedance of design loads has been identified, a certificate for the full lifetime of the wind farm will be issued. This approach is already drafted for the 2020 update of the service specification DNVGL-SE-0190 “Project certification of wind power plants”. The second approach is a general risk-based certification which is applicable to every novel technology. Furthermore, standards from other industries with similar technical issues are referenced as well. Here the standards, e.g. from maritime and Oil & Gas industry, provide valuable input that is transferable to wind farm control certification procedures. Finally, temporary trails in defined regional areas could support certification and acceptance of novel control strategies. Energy suppliers would receive temporary allowance to test novel control applications in a defined work frame under realistic environmental conditions. The experiences and results of this sand-box approach are then to be shared with the industry and authorities. The review made in this study concludes that there is a further need for full scale testing of advanced wind farm control applications in line with the development of simulation codes which are capable to predict entire operational wind farm behaviour on an industry level. More testing and better tools will also allow the development of new codes and standards which are supporting the shift of advanced wind farm control applications towards higher technology readiness levels.

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List of abbreviations

Table 2 List of abbreviations used in this report

Abbreviation	Description
ACER	Agency for the Cooperation of Energy Regulators
AEP	Annual Energy Production
BEM	Blade Element Momentum theory
BOA	Bid-Offer Acceptances
BSC	The Balancing and Settlement Codes
CapEx	Capital Expenditure
DA	Design Assessment certification module
DCUSA	Distribution Connection and Use of System Agreement
DEL	Damage Equivalent Load
DK1	Denmark-West Network
DLC	Design Load Cases
DSO	Distribution system operator
DWM	Dynamic Wake Meandering
ENTSO-E	European Network of Transmission System Operators
EPEX	European Power Exchange
ETM	Extreme Turbulence Model
EU	European Union
FCR	Fixed Charge Rate
FMECA	Failure Mode Effects and Criticality Analysis
FRT	Fault Ride Through
GB	Great Britain
GCC	Grid Code Compliance
IPC	Individual Pitch Control of rotor blades

Abbreviation	Description
LCC	Life Cycle Costing
LCoE	Levelised Cost of Energy
NETP	Nordic Energy Technology Perspectives
NRA	National Regulatory Authority
NTM	Normal Turbulence Model
OEM	Original Equipment Manufacturer (here: wind turbine manufacturer)
Ofgem	Office of Gas and Electricity Markets
O&M	Operation and Maintenance
PA	Power Available
PC	Project Certificate (certification level for wind farms)
PCC	Point of Common Coupling
REC	Retail Energy Code
RES	Renewable Energy Sources
RNA	Rotor-nacelle assembly (entire machinery on top of the tower)
RNO	Relevant Network Operator
RWF	Reference wind farm
SCADA	Supervisory Control and Data Acquisition
SSDA	Site-Specific Design Assessment
TC	Type Certificate (certification level for wind turbines)
TRL	Technology Readiness Level
TSO	Transmission system operator
VRE	Variable Renewable Energy producer
WFC	Wind Farm Control
WPP	Wind Power Plant
WT	Wind Turbine

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1 Introduction

The term "Wind Farm Control" (WFC) used in this study comprises the supervisory control unit which is allowed to adjust operational parameters of the individual turbines within a wind farm or wind power plant. The purpose of this super-ordinated control is to improve the overall performance of the wind farm as a unit (or power plant) and to reduce the total Levelised Costs of Energy (LCoE) over the operational lifetime. Wind farm control is applicable to both to large on- and offshore wind farms.

Beneficial reduction of LCoE by intelligent wind farm control algorithms can be achieved in different ways, e.g. directly by an increase of the energy yield, or indirectly by a reduction of loading, component fatigue and maintenance costs as described in detail in section 3. Further, LCoE reduction is achieved by tailored power production following the energy stock market prices as described in section 4. Figure 1 provides an overview of the parameters influencing the LCoE interpretation considered in this paper, where CapEx is Capital Expenditure, FCR is Fixed Charge Rate, OpEx is Operational Expenditure, and AEPNet is Annual Energy Production.

$$\text{LCoE} = \frac{\text{CapEx} \times \text{FCR} + \text{OpEx}}{\text{AEPnet}}$$

Figure 1 Definition of Levelised costs of Energy

Farm control techniques typically affect the AEPnet and the OpEx. Further key drivers are the reliability of the turbines which have an impact on CapEx, OpEx and AEPnet, availability which is directly linked to energy output, and operational and maintenance costs (O&M), related again to availability and OpEx. It is the challenge of farm control algorithms to find an optimum among these interconnected cost drivers. This is further elaborated in section 4 Wind farm control economics.

A common farm control strategy which enables overall energy output increase combined with simultaneous load reduction is the axial induction control, see section 3.2.1. In short words this strategy reduces the energy capture of the wind turbines which are facing the undisturbed inflow, typically the first row of turbines positioned towards the main wind direction. As a result, more wind speed remains for the downstream wind turbines which compensate (or even overcompensate) the energy loss of the first row. The other important benefit is the reduction of the downstream wind turbine loads as a result of the reduced wake behind the first turbine row. This leads to a significant reduction of fatigue loads and an increase of component lifetime of downstream wind turbines.

Another recently developed strategy is using the wind turbine yaw system to redirect the wake behind the rotor plane. By demanding an active misalignment angle between rotor axis and wind direction the wake is routed aside the next downstream turbine which again experiences less loading, see details on wake steering strategy in section 3.2.2.

On one hand the described wind farm control strategies have a potential for improvement of the overall wind farm performance. On the other hand, the load spectrum experienced by the individual turbines will be changed in comparison to the original load assumptions made during design and certification. In the ideal case the novel farm control strategies achieve a reduction of load levels of all components within the wind farm.

Wind farm control applications are basically software packages which can be implemented with just little hardware modifications. Thus, at a first glance it appears easy to implement wind farm control into existing wind farms. However, there is a risk that some turbines could experience critical loads and structural relevant effects occur caused by farm control activities. Also, the interaction with the safety system and possible hierarchy conflicts between individual turbine and supervisory control have to be checked and clarified. These risks have been analysed in a failure mode, effects and criticality analysis (FMECA) and are presented in section 5.3. Here standards and guidelines can support to mitigate those risks with conformity checks against previously defined design limits, e.g. in the wind turbine's type certificate.

Taking into account the technology readiness level (TRL) rating scale, wind farm control technology could be located currently at TRL 6 ("Technology demonstrated in relevant environment") as shown in Figure 2. This rating scale has been established by the EU Horizon2020 project [1] and is applicable to cross industry novel technology developments.

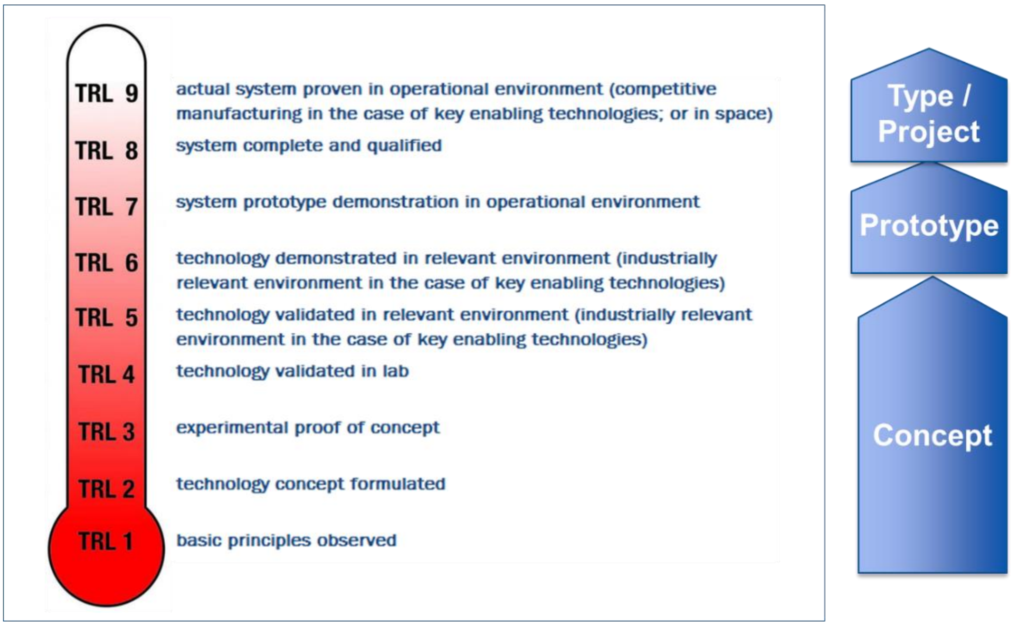


Figure 2 Technology Readiness Levels according to European Commission [1]

Figure 2 also demonstrates certification levels associated with technology readiness levels. In order to lift wind farm control toward higher technology readiness levels respective certification activities can accelerate the industrialisation of wind farm control strategies. An overview on the certification landscape for wind farm control is given in the following section.

2 Regulatory landscape

Certification is generally focusing on safeguarding personal safety and the structural integrity of a product within a predefined lifetime. By checking the conformity against proofed and established standards a defined safety level for operating of the product (here: the wind turbine) are maintained and possible risks during the whole life cycle of the product can be mitigated.

The supervisory farm control strategies will have a characteristic influence on the loading profile of each individual turbine within the controlled wind farm. In order to maintain a defined safety level, it shall be assured that the additional load effects caused by farm control strategies do not exceed defined component design limits. Further, functionality of the safety system of the individual wind turbine has to be maintained. Such design limits are typically defined by a type certificate (for the Rotor-Nacelle Assembly RNA) or by a project certificate (for site specific support structures or a wind farm). Both certification levels are state-of-the art for commercial wind farm installation worldwide. Certification can be applied in all life cycle stages and on different levels of verification levels as shown in Figure 3, and a comprehensive compendium of standards and engineering service documents relevant for wind farm project certification is presented in Table 3.

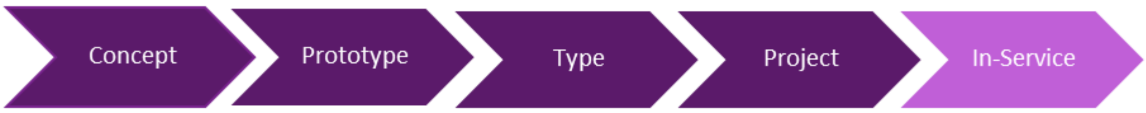


Figure 3 Typical certification phases

2.1 Certification schemes

Today, the most relevant documents for the certification of wind farms are IECRE standards OD-501 Ed. 2.0, 2018-05-24 for type testing [2], and OD-502 Ed. 1.0 2018-10-11 for project certification [3], as well as DNVGL service document SE-109 Ed. December 2015 for the project certification of wind power plants[1] [4]. Both IECRE standards make a provision to include wind farm certification, but with no clear guidance about how this should be performed. Figure 4 shows how wind farm control is just an optional module within the full project certification picture that IECRE OD-502 provides.

[1] There is a 2020 edition update expected from DNV GL RC including wind farm control certification aspects.

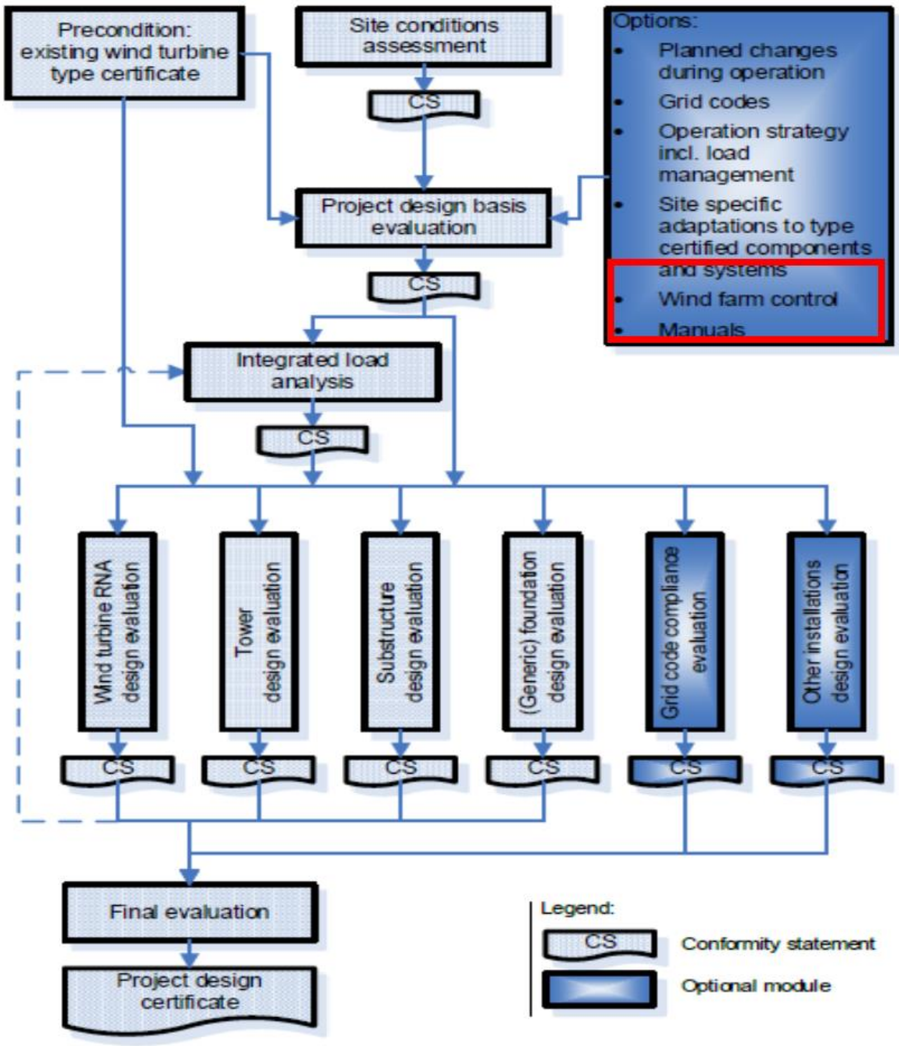


Figure 4 Modular structure of project certification as per IECRE OD-502 [3]

Within DNVGL-ST-190 [4] update to be published 2020 the wind farm control is considered by performing a “Site-Specific Design Assessment (SSDA)”. In this case, the wind farm is considered as a power plant and during design it is optimised as a whole and run by a supervisory wind farm controller. The site-specific design assessment includes as a minimum analysis and review of:

- Wind conditions at the site
- Wind farm influence (site description/layout) / wake analysis (highest loaded wind turbine)
- Site complexity analysis
- Site-specific extreme loads
- Site-specific fatigue loads

The following flow chart shows a possible scenario how these additional assessment modules could be integrated into a DNV GL certification scheme.

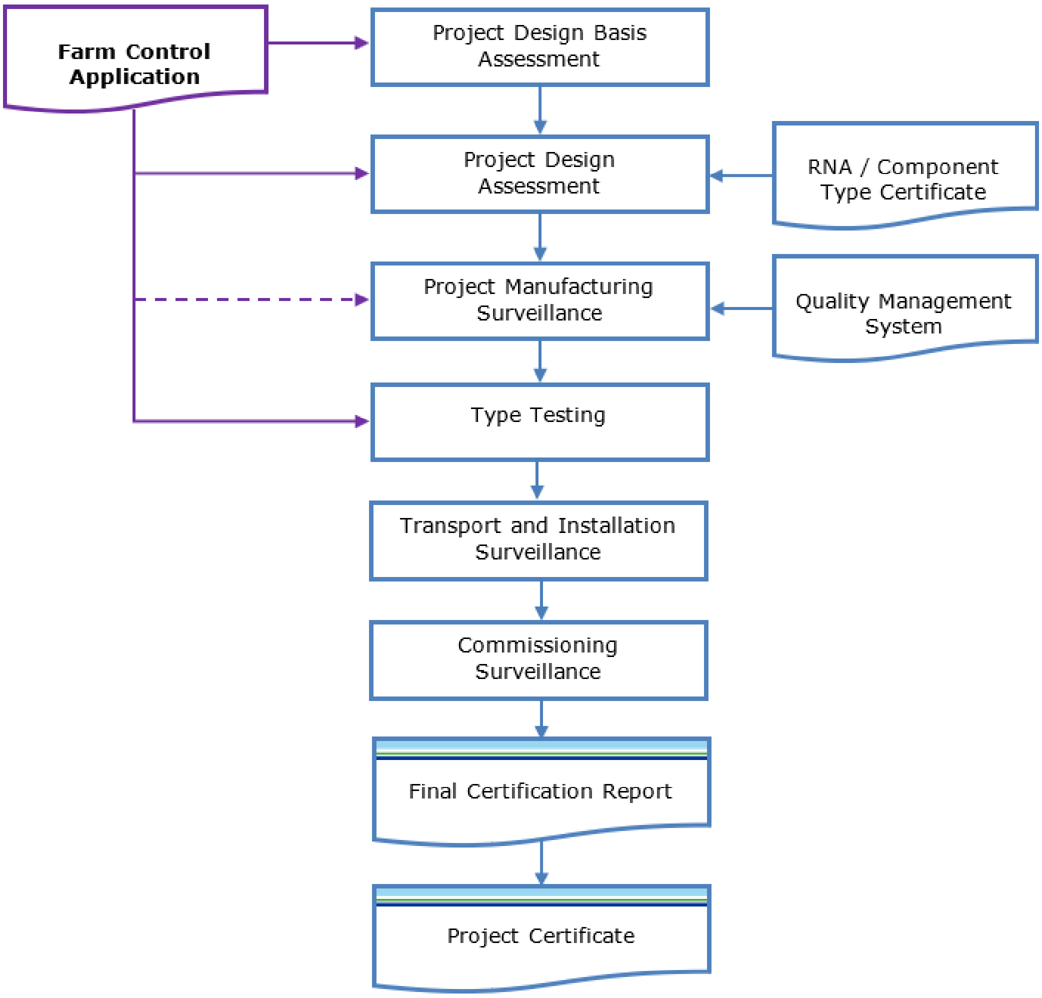


Figure 5 Modular structure of project certification as per DNV GL service specification

2.2 Standards and guidelines

As the existing standards in practice do not cover the wind farm control case explicitly, an individual approach will be needed, based on general requirements of standard wind turbine control systems, as far as applicable. The intended approach is to consider the wind farm as a power plant with a complex integrated control system both on plant and individual turbine level. As such the general requirements for the turbine should accordingly be applied.

Three alternative approaches for the certification of turbines operating under a farm control strategy are presented in this report. The first approach proposed long term measurement and the identification of on-site loading in controlled wind farm, see section 6.1. The second approach introduces the established risk assessment procedures and Failure Mode Effects and Criticality Analysis (FMECA) which are in general applicable for every novel technology development. The risk-based approach for wind farm control operation is laid out in section 6.2. Finally, a test and trail approach to gain more experience and confidence into novel technologies is presented, see section 6.3. Table 3 provides an overview on existing standards with relevance for wind farm control certification.

Table 3 Wind engineering standards and service documents

Group	ID	Revision	Description
IEC 61400 series	IEC 61400-1 [5]	Ed.3.0, 2005-08	Wind energy generation systems Part 1: Design requirements
	IEC 61400-1 AMD1	Ed. 3.0, 2010-10	Wind turbines – Part 1: Design requirements, Amendment 1
	IEC 61400-1 COR1	Ed. 3.1, 2014-04	Wind turbines – Part 1: Design requirements, Corrigendum 1
	IEC 61400-1	Ed. 4.0, 2019-02	Wind turbines – Part 1: Design requirements,
	IEC 61400-13	2015	Wind turbines - Part 13: Measurement of mechanical loads
	IEC 61400-3-1	2019	Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines
IECRE system	IECRE OD-501	Ed. 2.0, 2018-05-24	IEC System for Certification to standards relating to Equipment for use in Renewable Energy applications (IECRE System), Type and Component Certification Scheme
	IECRE OD-502 [3]	Ed. 1.0, 2018-10-11	IEC System for Certification to Standards relating to Equipment for use in Renewable Energy applications (IECRE System), Project Certification Scheme
	IECRE OD-501-4	Ed. 1.0 2017-04-06	IEC System for Certification to Standards relating to Equipment for use in Renewable Energy applications (IECRE System), Conformity Assessment and Certification of Loads by RECB’s
DNV GL service documents	DNVGL-SE-0073	Edition January 2018	Project certification of wind farms according to IEC 61400-22
	DNVGL-ST-0438 [6]	Edition April 2016	Control and protection systems for wind turbines

Group	ID	Revision	Description
	DNVGL-SE-0190 [4]	Edition December 2015	Project certification of wind power plants
	DNVGL-ST-0262	Edition March 2016	Lifetime extension of wind turbines
	DNVGL-ST-0126	Edition April 2016	Support structures for wind turbines
	DNVGL-ST-0054	Edition June 2017	Transport and installation of wind power plants
	DNVGL-ST-0437	Edition November 2016	Loads and site conditions for wind turbines
	DNVGL-SE-0441	Edition June 2016	Type and component certification of wind turbines
	DNVGL-SE-0074	Edition December 2014	Type and component certification of wind turbines according to IEC 61400-22
	DNVGL-RP-A203 [7]	Edition June 2017	Recommended Practice – Technology qualification
Other	EN 50308	2004	corrected 2005 Wind turbines – Protective measures – Requirements for design, operation and maintenance
	FGW TG 8	2019	Certification of the electrical characteristics of power generating units and systems in low-, medium-, high- and extra-high voltage grids
	ISO 12100	2010	Safety of machinery – General principles for design – Risk assessment and risk reduction
	ISO 13849-1	2015	Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design
	ISO 13849-2	2015	Safety of machinery – Safety-related parts of control systems – Part 2: Validation
	IEC 62061	2005	Safety of machinery – Functional safety of safety-related electrical, electronic and programmable electronic control systems
	IEC 60812	2018	Failure modes and effects analysis (FMEA and FMECA), Edition 3

2.3 Grid code requirements

Further requirement set up by grid codes. One example is the ability of a wind turbine to stay connected to the electrical grid in case of grid faults while still delivering electrical power for stabilisation purposes – fault ride through (FRT). This feature is controlled on wind turbine level only whereas WPP control does not become active. The reason is that a grid fault like a short circuit in the network close to the wind farm requires a dynamic reaction in time ranges of a few milliseconds only (related to the electrical current sine waves with a period of 20 ms). To notice this fault by the WPP control unit and to distribute it to the individual wind turbines would require too much time.

Certification of grid code compliance (GCC) is done for Germany applying FGW TG 8 where the WPP control unit therein is named 'EZA-Regler' [8], and for other parts of the world applying DNVGL-SE-0124 [9]. Design requirement are stated in IEC 61400-27-2 [10], while testing is to be performed according to oncoming IEC-61400-21-2 [11].

Further technical requirement for the connection of power plants are given by the European Network Code "Requirements for Generators (RfG)" [12]. As an example, a further detailing of these requirements for Germany, which applies also to the whole EU, is given in the following standards:

- VDE-AR-N 4110 [13] for the connection of wind farms to medium voltage grids
- VDE-AR-N 4120 [14] for the connection of wind farms to high voltage grids
- VDE-AR-N 4130 [15] for the connection of wind farms to maximum voltage grids

3 Wind farm control functionalities

The implementation of new control functionalities to the whole wind farm has a clear objective: the reduction of the levelised cost of energy. This is expected to be achieved by going beyond the greedy-control concept, in which each turbine maximises the energy capture ignoring its impact on downstream turbines. Instead, the key idea is to consider the whole wind farm as a single power plant so that it is the total energy output of the wind farm what is maximised.

This section begins with an overview of the existing wind farm architecture in terms of control levels (classic approach). This information helps to understand the interfaces and hierarchies of existing wind farm control architectures. Then a detailed description of most promising wind farm control strategies (WFC) is provided, followed by proposals how to integrate these WFC concepts into existing wind power plants (WPP).

3.1 State-of-the-art of classic wind power plant control

A state-of-the-art wind farm usually applies two control levels. The first one addresses each wind turbine separately ensuring a safe and optimised operation of the individual wind turbine under given wind conditions – this controller in the following is referred to as 'WT controller'. The second control level, referred to as the wind power plant (WPP) control unit, addresses superordinate tasks including grid code compliance and has a centralised position among the individual wind turbines and the connection of the WPP to the electrical network. This connection is referred to as 'Point of Common Coupling (PCC)'. For the case that all wind turbine of the WPP are supplied from the same original equipment manufacturer (OEM) the arrangement is sketched in **Error! Reference source not found.**. Data on actual active power P and reactive power Q of the individual wind turbines, measured data on wind speed and direction are sent from the wind turbines to the WPP control unit. Information on electricity supplied to the grid is measured at the PCC and thus available to the WPP control unit.

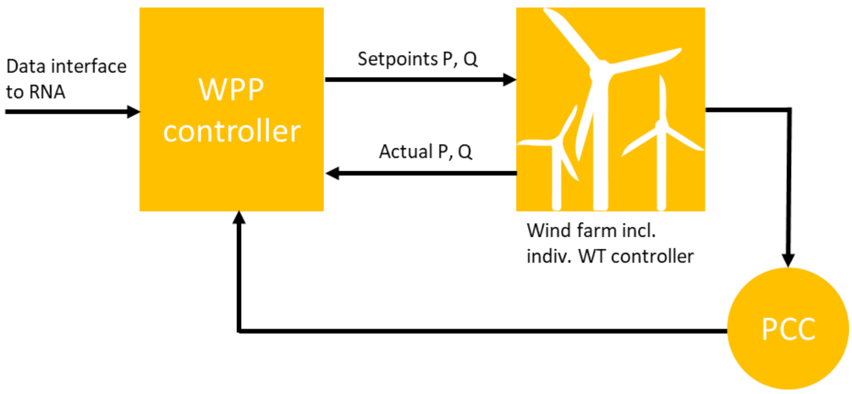


Figure 6 Standard arrangement of the WPP control unit in a wind farm without WFC

At the PCC the wind farm grid ends, and the electrical energy is passed through into the net of the grid operator. The grid operator in case of adverse electrical conditions in the grid may deliver a data signal to the WPP control unit. This data signal requires the WPP to react according to certain requirements defined in national grid codes, as exist e.g. for Spain and Germany, see section 6 in CL-Windcon D4.7 [16]. The aim is to stabilise the electrical grid as described in section 2.3.

Main functions of the WPP control unit in this context are:

- Receive set points for the whole WPP from the grid operator regarding:
  - Output throttling (reducing active power P to a specified value in specified time)
  - Reactive power Q, power factor or voltage control set points
- Calculation of how to distribute the required demands of the grid operator within the plant:
  - Allocating the overall plant active power reduction requirement to single wind turbines
  - Allocating the reactive power set points to the individual wind turbines

The WPP control unit will distribute electrical setpoints to the wind turbines, but it will not interfere with the independent, optimised control of the individual wind turbine. If the WPP control unit is activated e.g. due to a grid disturbance, it will usually distribute any set points required by the rotor-nacelle assembly (RNA) equally to all wind turbines to react properly to the fault.

A larger wind farm can consist of several subunits with wind turbines supplied from different OEM's ('mixed wind farms'). This adds additional complexity to the arrangement, see **Error! Reference source not found.**. Each subunit requires a separate WPP subunit controller. It communicates with a superordinate WPP control unit which builds the link between the WPP subunit controller and the data interface to the RNA. Thus, this kind of wind farm consists of three control levels [17].

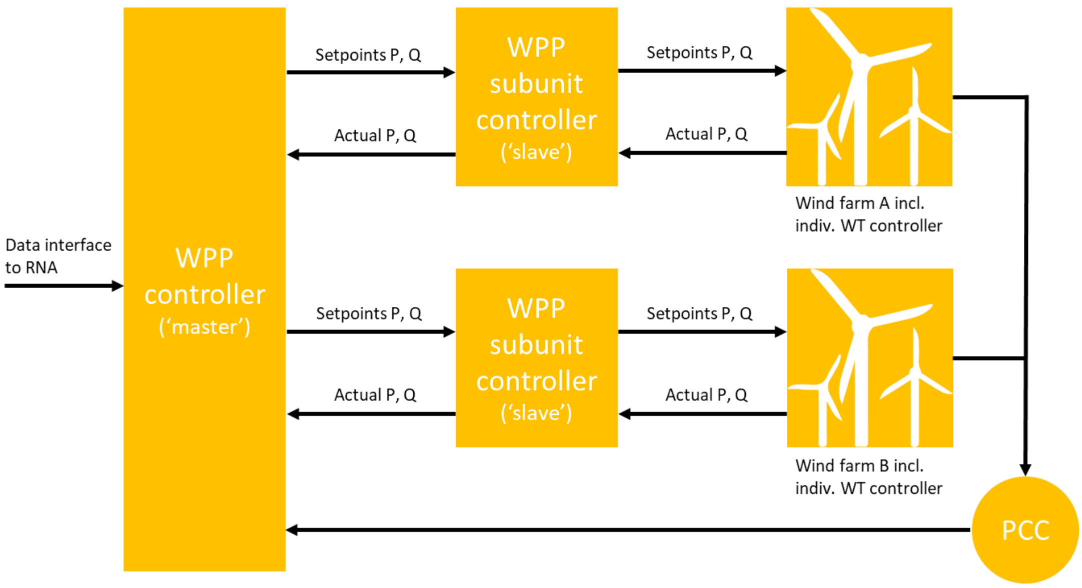


Figure 7 Arrangement of WPP sub-unit and common controllers in mixed wind farms

3.2 Concepts of novel wind farm control strategies

Although wind farm control consists in its broadest sense in the coordinated operation of the different wind turbines within a wind farm to serve a common goal, one of the most extended uses of this concept is to refer to wind farm flow control, which aims to reduce the negative impact of wake interaction effects in the overall performance and costs of a wind farm.

For such purpose, there exist different control technologies that can be used, as described in the following subsections, and which can be applied either individually or in a combined way, and through different actuation methods. Their primary objectives include increasing wind farm power production, reducing turbine loads and providing grid services in an optimised way. It should be noted that some of these technologies are still at a conceptual and feasibility analysis stage, while others have been tested experimentally in wind tunnel and field testing. Different tutorials and reviews on this matter are also available in the literature, see [18], [19], [20].

3.2.1 Axial induction control

It consists in the modification of the energy harvest of either upstream or downstream turbines so that the effect of wake interaction can be mitigated.

- Derating upstream turbines, which is the most popular in the literature, applied either through blade pitch or generator torque control actuation. Although different results at wind tunnel tests and field tests call static induction control into question regarding wind farm power increase ([21], [22], [23]), this control technology has shown an interesting performance in structural load reduction for both the upstream derated turbine and the downstream turbines [24]. Therefore, its main applications are currently intended for optimised life management in operation and grid services provision ([25], [26], [27], [28], [29]).

- Uprating downstream turbines, with the aim of increasing the power capture in the farm.

Both axial induction approaches grant the capability to provide grid services in an optimised way.

3.2.2 Wake steering

It consists in redirecting the wake from the upstream turbine so as to avoid or modify its impingement in the downstream turbine, therefore reducing the wake interactions within the wind farm. It can be applied to either increase the power production or to avoid undesired structural loading in downstream turbines (i.e. partial wake events).

This technology can be implemented through different control actuation such as:

- Yaw misalignment, the most widely used for wake steering, where the rotor varies the direction of the wake horizontally by introducing in the upstream turbine a yaw angle of the rotor plane with respect to the main inflow wind direction. As a quite promising technology, it has attracted significant attention, having been tested in real wind farms ([30], [31], [32], [33], [34], [35]).

- <u>Tilt misalignment</u>, where the redirection of the wake is performed vertically by the use of a varying tilt angle ([36], [37], [38], [39]). However, this approach is still in conceptual status because of the need of a complete redesign of RNA.

- <u>IPC moment induced</u>, where either a yaw or tilt moment is induced by Individual Pitch Control (IPC) to achieve a horizontal or vertical wake redirection downstream, respectively [37].

3.2.3 Wake mixing

In this category, there can be found control technologies aimed at favouring the wake mixing phenomenon, by which the wake interacts with the adjacent free-streamflow –of higher velocity- and recovers some of the energy previously transferred to the upstream turbine. This allows the downstream turbines to experience a higher velocity inflow. For such purpose, work has been performed on the dynamic induction control concept [40], mainly focused on sinusoidal signals ([41], [42], [43], [44]). Equally, it can be found the helix approach [45], also referred as dynamic individual pitch control (DIPC), where the IPC actuation is used to manipulate the wake smoothly, varying its direction over time.

Additionally, there exist other wake mixing technologies where the yaw angle of the upstream turbine is varied dynamically to induce higher wake meandering ([46], [47]).

3.2.4 Wind turbine repositioning

Finally, a concept has also been suggested for floating wind farms to reposition the downstream turbines depending on the wake interaction occurrences [48].

3.3 Integration of wind farm control into existing wind power plants

As sketched in section 3.1 a state-of-the-art wind power plant (WPP) without additional wind farm control (WFC) already contains mainly two, in mixed wind farms even three, control levels. For the respective standard WPP control unit a number of requirements from standards and further constraints from the design of the wind farm have to be applied. Adding features of WFC as described in section 3.2 furthermore increase the complexity of the system and raises questions regarding the certification of the grid code compliances (GCC) of the wind farm, but also regarding the certification of the wind farm including the individual wind turbine.

So far in research large focus was put on the simulation of wake effects in wind farms and on the investigation of WFC functionalities, e.g. wake steering, wake mitigation and induction control, their design, modelling and testing. Little information has been published on how these functionalities can be implemented into the wind turbine and the standard WPP control unit or how these functionalities are to be certified. In this context some ideas on the integration of WFC were sketched in EU-research project CL-Windcon [16], see Figure 8 for a proposed control scheme. Until now, no design standards for certification exist containing explicit requirements for WFC. Thus, in the present report the complexity of the problem can be shown. Anyway, section 6 will show ways how a wind farm applying WFC nowadays can already be certified.

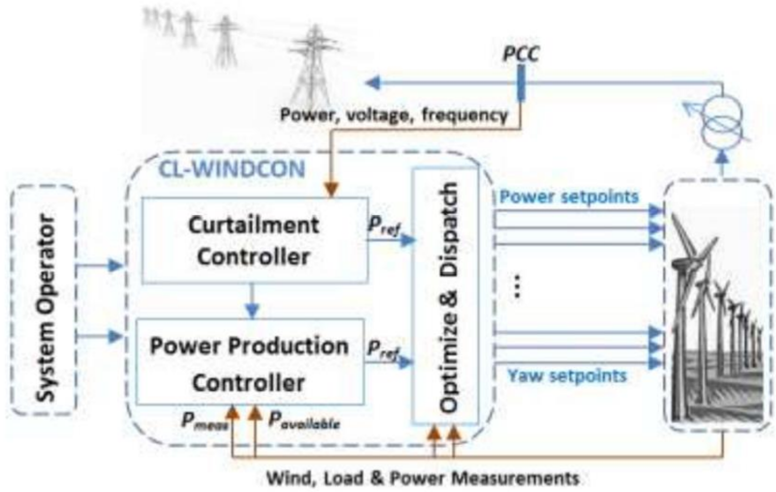


Figure 8 Proposed control scheme for WFC as proposed in CL-Windcon EU project

3.3.1 Hierarchy of design requirements

Wind farm control (WFC) changes the design philosophy of a wind farm substantially from optimisation of the individual wind turbines towards the optimisation of the wind farm as a power plant (WPP) over its whole lifetime. The main aspects of WFC are listed in the yellow box of Figure 9. The proper trade-off between several design goals is to be found, e.g. as the mechanical load level of the individual wind turbine has to be balanced against a maximised energy yield. At the same time operational costs have to be reduced as much as possible while it appears desirable to extend the features of the wind farm to market ancillary services as described in section 4.3. To achieve these design goals a careful design of the WFC is required.

The optimisation and efficient operation of a wind farm applying WFC features basically is not a matter of certification. Certification mainly addresses aspects of safety, structural and electrical integrity of the wind farm. Considering the individual wind turbine its control functions realise the general operation of the wind turbine under normal and extreme conditions. At the same time its protection functions – owning the highest priority in the control design – monitor the behaviour of the wind turbine also in unusual and fault conditions and are designed such that they shall always be able to guide the wind turbine into a safe state. From certification's perspective the hierarchy of design requirements is sketched in Figure 9. For the design and certification of WFC this hierarchy has to be observed.

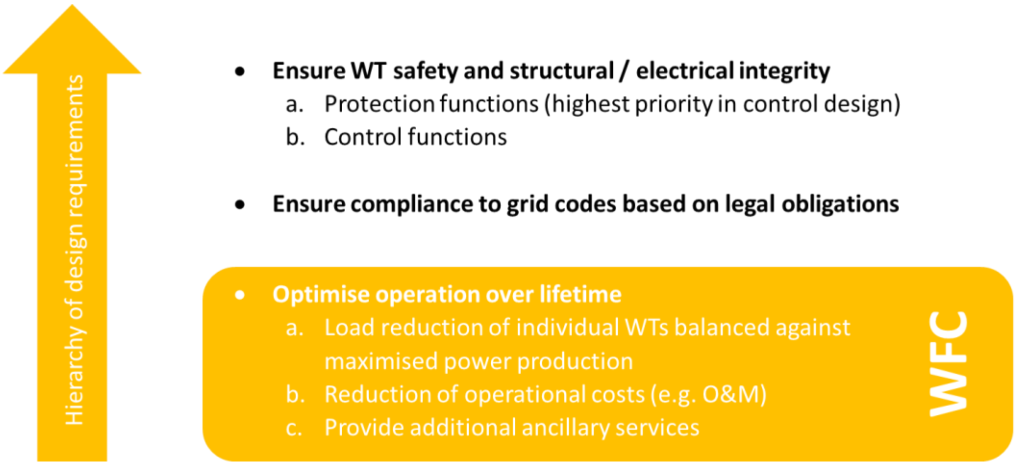


Figure 9 Hierarchy of design requirements applying WFC from certification's perspective

3.3.2 Implementation of wind farm control into the WPP control unit

As described in TotalControl, a wind farm applying WFC control is faced with external conditions and events during operation [17]. Examples are given in Figure 10: In purple colour events related to the electrical network and electricity market as well as to operation and maintenance of the wind farm are listed. In blue colour meteorological phenomena, flow conditions in the wind farm as well as events related to the operation of the wind turbine are found. By their nature they are acting according to different characteristic time scales as indicated at the left-hand side of Figure 10. The arrows on the right-hand side show that a hierarchy of different control levels, WFC – WPP control unit - wind turbine controller, are acting at different time scales and control time steps.

The WFC tasks as addressed in section 3.2 features control time steps of 1-20min. The quasi-static open-loop WFC intends to optimise active and reactive power set points and yaw angles of the individual wind turbines to adapt to slowly changing environmental conditions and market elements (e.g. wake steering). It also aims at reducing mechanical loads and O&M costs by axial induction control and wake steering and can provide tertiary ancillary services as described in section 4.3.

A fast closed-loop WFC can have control time steps smaller than 1 min and intend to react to environmental events like turbulent gusts to reduce mechanical loads. It can provide the basis for primary and secondary ancillary services. It may use further sensor inputs, i.e. wind speed and direction measured at individual wind turbines or by Lidar. And it may apply model-predictive control or other control methodologies to influence dynamic wake behaviour and wind turbine loads.

The typical wind turbine controller uses control time steps smaller than 1 s. It aims at further load reduction, turbulence or market-based derating and primary ancillary services. For these tasks, additional sensors like Lidars may be used e.g. for Lidar assisted control or a backward-looking Lidar for closed-loop wake steering. Besides the basic control also grid stabilisation, such as fault ride through (FRT) abilities, of the individual wind turbine independent of WFC are provided.

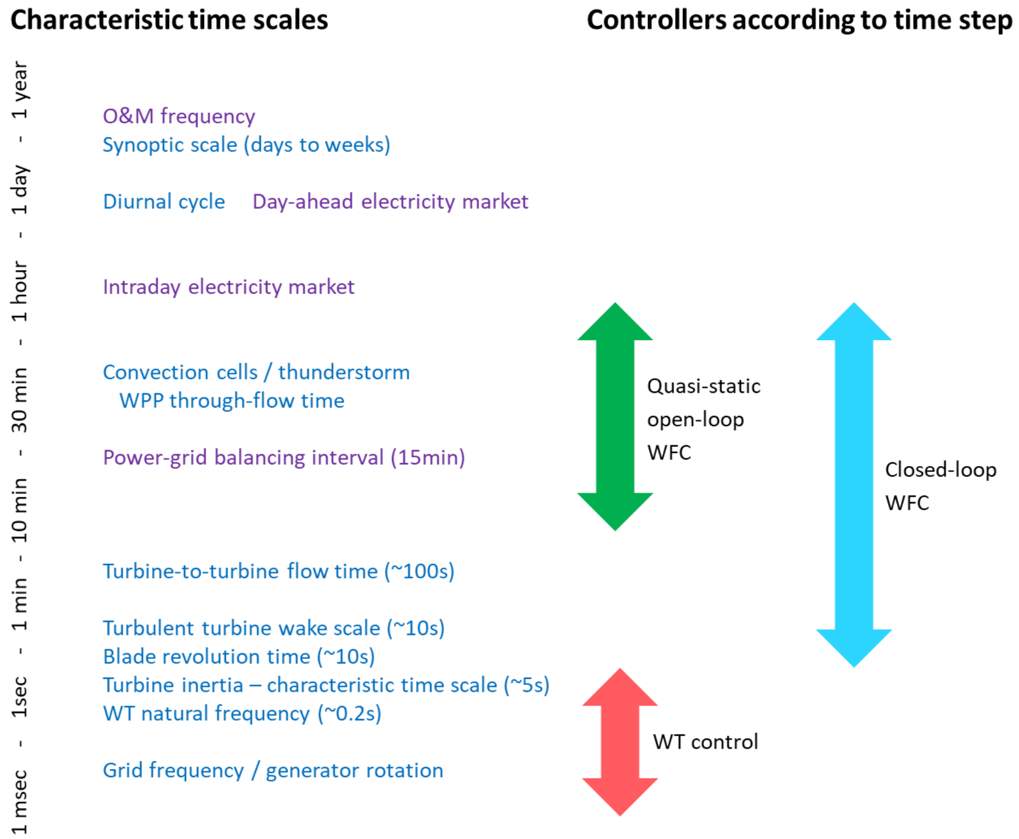


Figure 10 Characteristic time scales for control tasks (based on Total Control [17])

4 Wind farm control economics

4.1 Electricity market structures

The more wind energy becomes independent of local subsidiaries, combined with continuous decrease of electricity production costs, the more the energy market conditions will influence the operation of wind farms and wind power plants. The trend of operating a wind farm as power plant which is directly coupled to energy prices on the stock market is advancing. In the following an overview on the European electricity market and its trading mechanisms is given.

4.1.1 Current market structures

European electricity markets operate on several different levels and they vary in geographical scope, ranging from local offers on the retail market to multinational wholesale markets. The wholesale market is where electricity is traded (bought and sold) before being delivered to end consumers (individuals, households or businesses) in retail markets via the distribution grid. The main objective of wholesale markets is to achieve the balance of electricity supply and demand on all time scales, ranging from long-term contracts to real-time system operation. The wholesale market structure will be elaborated in this section and a description of the electricity market in the EU is presented in Figure 11.

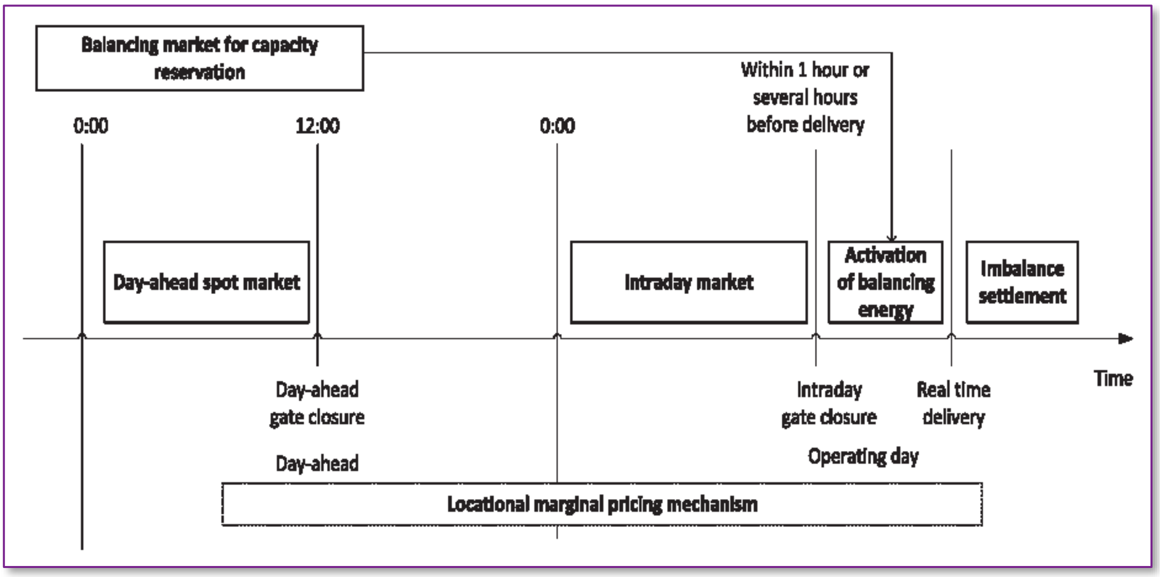


Figure 11. Electricity market in the EU [56]

The participants in the wholesale market are generators (energy suppliers), electricity retailers and large industrial consumers. In a liberalised market, different entities are responsible for generating electricity, as well as for operating the transmission system (Transmission System Operators, TSO) and the distribution system (Distribution System Operators, DSO). The system operators are required to provide third-party access to their networks. Most market-clearing transactions are forward-looking, meaning that they involve the delivery of electricity at some point in the future. The transactions are based on the type of contract or market, which involve different periods of time. The framework for transactions as presented in [57] can be summarised as follows:

- Long-term contracts: up to 20 years or more. Long-term energy contracts were heavily involved in many decisions of the European Commission to support the opening of the electricity markets. Contracts were seen to foreclose the market, therefore the Commission formulated strict criteria for new long-term contracts [58]. Accordingly, the majority of market participants is reluctant to engage in long-term contracts today.
- Forward and future markets (mid-term contracts): weeks to years in advance. Although varied, mid-term contracting is an established procedure in many European countries. The time span is usually limited to contracts up to four years ahead, where in several countries they are significantly shorter. Additionally, most power is contracted year ahead with significantly reduced shares for longer duration.
- Day-ahead spot market: the following day. Generation and transmission scheduling in Europe is primarily taking place in the price-coupled integrated European day-ahead market. Each day before 12 o'clock, the market actors in the whole of Europe make their bids to the market operators for electricity supply and demand. The spot price is settled at the cross of the supply and demand curves in the day-ahead spot market.
- Intra-day market: delivery within a specified time period (for instance, an hour or a quarter). The intraday markets facilitate trading from 36 hours before and up to one hour before delivery (real time). They aim to enable market participants to trade internally and thereby adjust their positions in the market as the production and consumption forecasts become more accurate. All market participants can place orders of buying or selling in this anonymous trading which is facilitated by a regional power exchange.
- Balancing markets: real-time balancing of supply and demand. In the balancing market, the TSOs buy up- or down-regulation to ensure continuous balance of supply and demand in their respective balancing areas. Market participants can send bids (generation/demand) to the market until about an hour (*e.g.* 45 min in the Nordic market) before delivery. The bids must at maximum have an activation time of 15 minutes. The largest driver for imbalance in Europe is the uncertainty of the future variable renewable power production. Further details regarding provision of ancillary services is given in section 4.3.

Prices on the markets are highly affected by supply and demand: on the wholesale market, the limit for prices in Europe is +/- €3000/MWh. These limits were met due to generation scarcity or oversupply or. Additionally, the renewables on the grid, which can offer low(er) prices due to the lack of 'fuel cost', increasingly determine the price levels for the other generators.

Wholesale markets are integrated on a transnational regional level, as in the case of the central west European region (known as 'European market coupling'), which enables optimal use of interconnection capacities between grids, due to implicit scheduling of the interconnectors, see Figure 12. In case of sufficient interconnection capacity, prices across the market are bound to converge. When the demand for cross-border trading exceeds the interconnection capacity ('congestion'), electricity cannot flow from a lower to a higher-price area, accordingly even the integrated regions may experience different prices. At EU level, the Agency for the Cooperation of Energy Regulators (ACER) defines the guidelines for transnational electricity networks and markets, the so-called network codes. These are then further developed by European Network of Transmission System Operators (ENTSO-E).

Nordic Region	Price coupling since 1999 (Eastern Denmark 2000)
Belgium, France, Netherlands (TLC)	Price coupling since 2006
Nordic region-Germany (operated by EMCC)	Volume coupling since November 2009
Central West Europe (CWE)	Price coupling since November 2010
CWE-Nordic region (+ Estonia) Flow calculated by EMCC Prices calculated by PXs	**Interim solution NWE:** Interim Tight Volume Coupling (ITVC) since November 2010
Nordic region– SwePol/ Nordic region-Lithuania/ Nordic region-Latvia	Price coupling since Dec. 2010 / June 2012/ June 2013
North West Europe (NWE) - One price calculation for entire area	Price coupling since February 2014 = target model
NWE+SWE = MRC (multi regional coupling) One price calculation	Price coupling since May 2014
MRC + Italian borders	Price coupling since February 2015
4M – **not yet coupled to MRC**	Price coupling since November 2014

Figure 12 - European Market Coupling by 2015: Geography and Timeline [59]

To ensure grid stability, capacity remuneration mechanisms are introduced increasingly across Europe. It involves payments to electricity generators to keep generation capacity (power plants) in reserve, in order to enable provision of generation capacity in case of demand peaks. It is still under discussion whether capacity markets are necessary or an energy-only market with time-variant pricing can provide sufficient incentives for the provision of spare capacity. It should also be noted that an EU-wide capacity mechanism is not feasible with limited interconnection capacities where only limited amounts of electricity can flow across borders.

4.1.2 Market operation in future energy scenarios

There have been many future energy scenario projections by researchers and different agencies such as WindEurope, European Network of Transmission System Operators (ENTSO-E and ENTSO-G) [60], IEA etc. This section mainly concerns with market operation for European countries (mainly near North Sea) with massive projections of offshore wind developments in near future.

As a relevant example we have the Nordic Energy Technology Perspectives (NETP) delivered as part of the Energy Technology Perspectives 2016 [61]. These developed European-wide scenarios using 2014 as base year [62]. The features of the NETP are as follows:

- Electricity consumption: Projection of a stagnant demand development in total until 2050.

- Fuel and emission prices: Assumptions include stagnation of coal price after 2015, and an increase of CO2 prices after 2020, slight decrease of oil and natural gas prices until 2020 and substantial increase after that. Fossil fuel prices stagnate while emission prices increase beyond 2030.
- Regions: Countries are split into different market areas as shown in Figure 13 below.

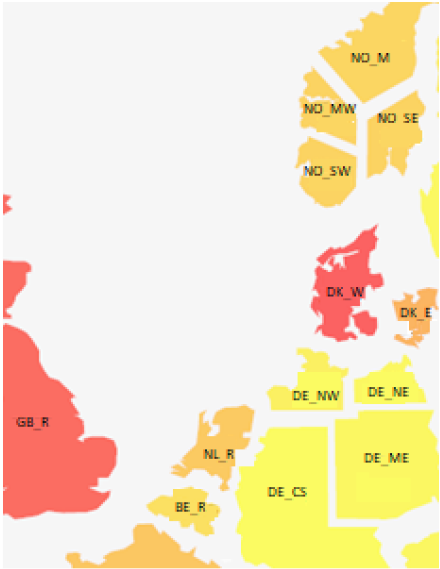


Figure 13: Regional split of the countries [59]

- Transmission grid: It was assumed that the Viking Link (DK-UK) and the COBRA line (DK-NL) are built. The assumed development also considers that the current congestion problems that affect DE north to DE south are drastically reduced. The scenario does not include any offshore grid developments.
- Installed generation capacity: The expected installed capacity by 2020 is shown in Figure 14. Further development of generation capacities is optimised based on different assumptions on commissioning and decommissioning of units.

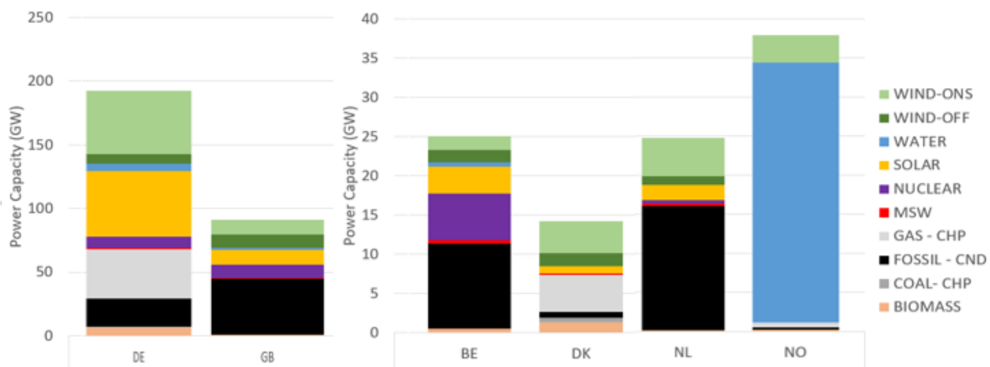


Figure 14: Installed capacities for different countries in 2020 [62], [63]

These NETP scenarios are further updated and modified with more details of renewable energy sources based on investment optimisation in Balmorel [63], [64]. The modified scenarios are further used for analysing the market operation in the North Sea countries based on current market operation practices.

Details of the modelling and results can be found in [65], [66]. Two different scenarios – namely – project-based and offshore grid scenario are modelled for 2020, 2030 and 2050. Meteorological and grid load profiles of 2012 were used for the analysis.

The installed capacities for different scenarios are shown in Figure 15. The penetration of variable renewable energy (VRE) towards 2050 is remarkable regardless of the scenario, at the expense of decreasing the use of fossil fuels.

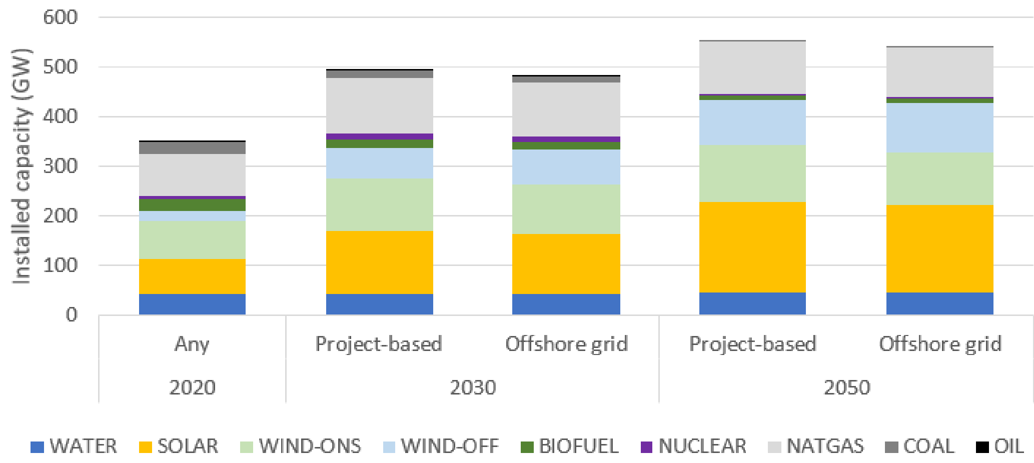


Figure 15: Electricity generation per year, fuel, and scenario in the countries in focus (TWh) [65]

Relevant results for market model analysis of future scenarios are as follows:

- Electricity spot prices: The probability distribution function of electricity prices in the network Denmark-West (DK1) is shown in Figure 16. It can be observed that 1) average prices increase from 2020 to 2030 and decrease from 2030 to 2050, 2) the volatility of prices increases towards 2050, and 3) the prices in these regions are lower in the offshore grid scenario than in the project-based.

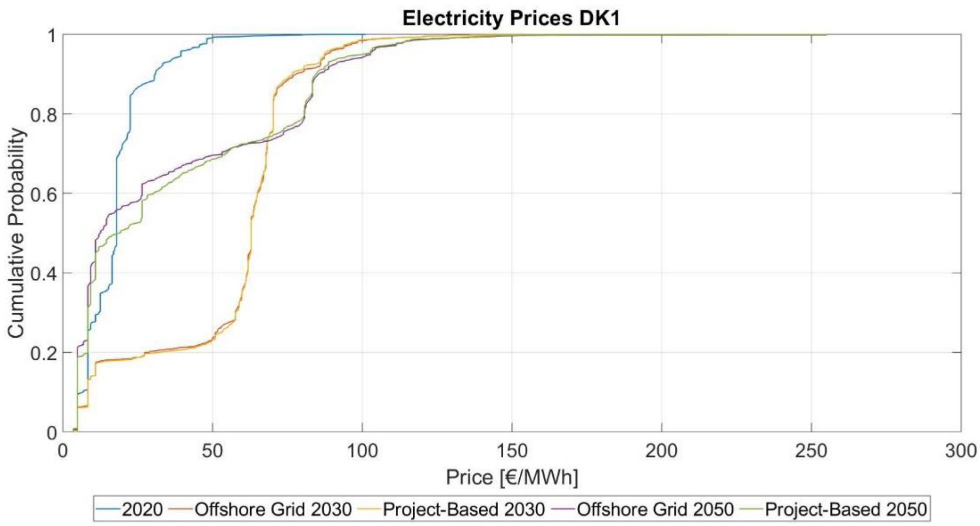
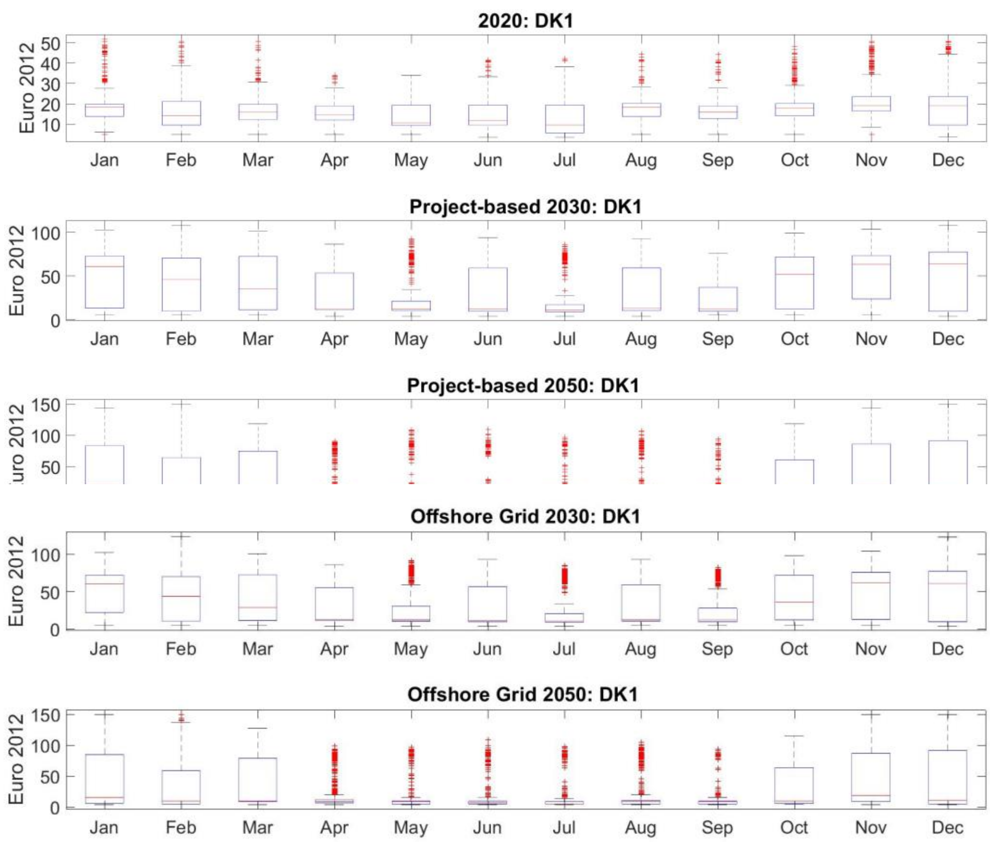


Figure 16: Probability distribution function of the hourly electricity price in DK1 for each scenario [65]

In order to assess the seasonal variation of the electricity prices, box and whisker plots for the above scenarios are shown in Figure 17. It can be observed that during spring and summer months (April to September), the prices present lower mean values than the autumn and winter months (October to March). Electricity is cheaper in spring and summer months because the demand for electricity is lower in these months compared to the colder months of winter and autumn. This variation fits to the characteristic annual wind resource distribution and corresponding electricity production of wind farms.

Figure 17: Box & whisker diagram of electricity price (Euro2012/MWh) in DK1 for each scenario [66]



- Wind Power Curtailment: In the day-ahead sport market, the optimisation algorithm is allowed to curtail generation from wind power. Since wind technologies present low operational cost the model tries through the optimisation algorithm to cover as much as possible of the electricity demand with wind energy. Even if the demand for electricity is lower than the available wind energy in a particular region, the model will export the surplus to the neighbouring regions, if possible, in the specific time step. Wind generation will be curtailed if the available wind power cannot be used domestically or be exported. This curtailment mode leads to a different wind turbine loading profiles compared to an operation mode which is only driven by available wind resource. Hence, this changed loading profile might be relevant for certification review.

The box and whisker diagram of the monthly wind power curtailed in DK1 for each scenario is depicted in Figure 18. As shown, there is no seasonal pattern in wind power curtailment in 2030 and 2050.

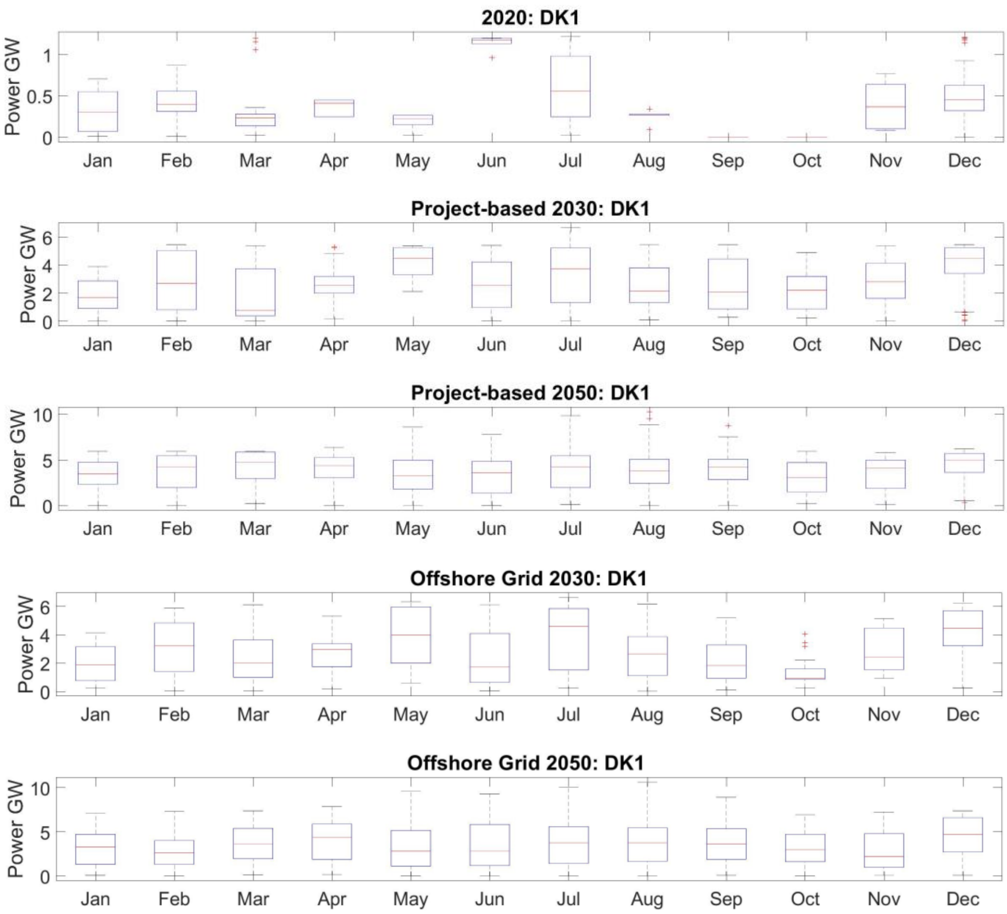


Figure 18: Box and whisker diagram of curtailed wind power (GW) in DK1 for each scenario [66]

The total amount of curtailed wind energy in each control area, scenario and year is presented in the table below. As expected, since the wind generation expands towards 2050, the curtailed wind energy is increasing as well.

Day Ahead Curtailment (GWh)

Control & Synchronous Areas	2020	Offshore Grid 2030	Offshore Grid 2050	Project-based 2030	Project-based 2050
BELGIUM	0	752	3659	1020	4749
GERMANY	9605	6534	43941	3808	18750
NETHERLANDS	3	93	663	1278	14513
NORWAY	2	2033	9049	426	5118
SWEDEN	6	7	106	8	124
DK1	106	1691	6344	1866	6147
DK2	14	65	565	79	1060

This increasing portion of reduced power operation of wind farms is probably a typical operation mode in the near future for wind farms operating in a cross border and liberalised market. Beside load reduction caused by curtailment strategies it is possible that wind turbine loading could increase due to the lack of aerodynamic damping. Therefore, such curtailment scenarios should be implemented into the wind turbine standards, e.g. by introducing generic curtailment profiles.

- Generator/energy supplier revenue in the electricity market: The difference between the scenarios is rather small for all the years. One can observe an increase in specific energy revenue in 2030 with respect to 2020 and a decrease in 2050 compared to 2030. This trend is analogous to the electricity price trend. The loss of market value of various variable renewable energy producers (VRE) with its penetration can be seen in the graph; the specific energy revenue by 2050 is around 50% lower than in 2030 for VRE.

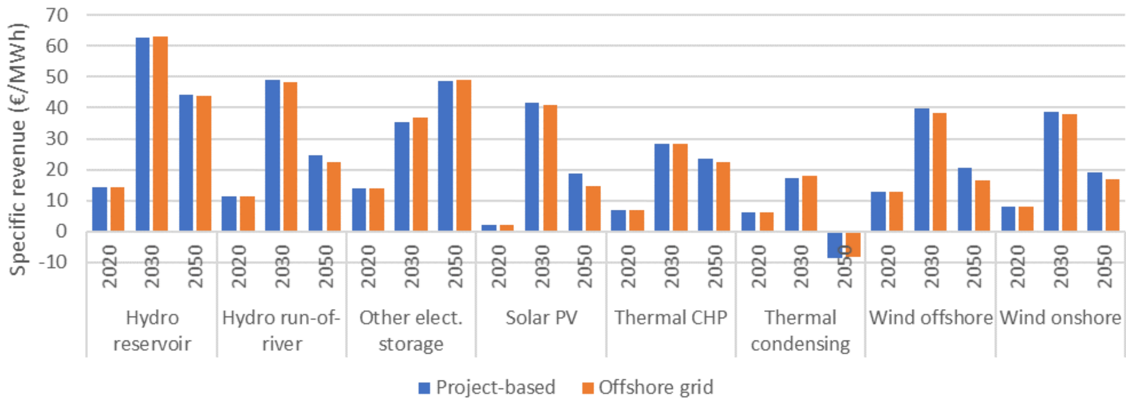


Figure 19: Technology specific Day-Ahead market revenue in considered countries' scenarios [65]

- Balancing Cost: Cumulative probability distribution curves of the prices derived from the intra-hour balancing market are presented for the control area DK1 in Figure 15 for upregulation and downregulation, respectively. The average prices of all control areas increase from 2020 to 2030 and decrease from 2030 to 2050. This development is related to the CO2 price assumptions and the penetration of VRE in the energy system. The fact that the use of fossil fuels is still considerable in 2030 and at the same time, the CO2 price experiences a big increase (from 6 EUR/tCO2 to 76.7 EUR/tCO2) increases the prices.

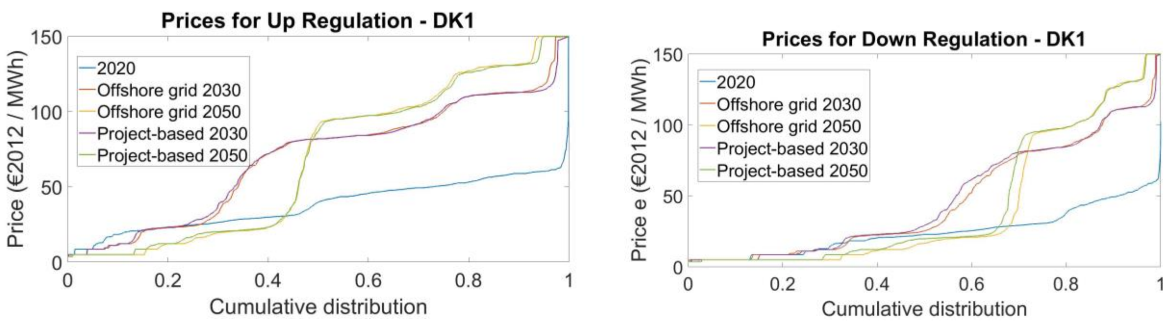


Figure 20: Electricity price cumulative probability curves for up & down regulation in region DK1 [66]

Detailed analysis from day-ahead market model simulations can be found in [65] and balancing model analysis can be found in [66]. It should be noted that the integration of sector coupling in these calculations has been limited.

4.2 Economic potential of wind farm control

In the literature, there barely exist public references dealing with the economic impact of wind farm control, what seems to be one of the factors impeding the industrial adoption of this new technology. Performance improvements of wind farm control are usually demonstrated for specific test cases, which do not provide enough insight to perform complete economic calculations.

A partial approach dealing with cost estimations can be found at the on-going project TotalControl. This project has submitted the deliverable D2.1 (Cost model for fatigue degradation and O&M) [67] which focuses in the quantification of the influence of wind farm control on fatigue degradation of mechanical and electrical components and on the O&M cost. This deliverable presents a review of existing literature searching the most significant aspects of costs, fatigue and their relationship. Of course, these references do not deal specifically with wind farm control operation, but they can serve as a summary of information to be used on the elaboration of cost models for the wind farm control economics evaluation. The references compiled in the deliverable are: [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79].

A feasibility analysis of wind farm control implementation has been performed from the economic point of view within CL-Windcon[2] project. The analysis is based on the active wake steering control as it is considered the most promising control technology in terms of power maximisation. This study has been presented in deliverable D4.6 (Cost-benefits analysis) [80] and compares the application of this control technique in a reference wind farm (RWF) against the operation without control. The selected reference wind farm is an offshore site called NORCOWE, which was developed in a Norwegian project called NORCOWE [81] by industry and science partners. It is a fictitious, yet realistic RWF used across different research projects. The RWF is located around 80 km west of the German island Sylt, and near by the met mast FINO 3 is installed (NORCOWE, 2019). The RWF comprises 80 turbines of the type INNWIND.EU 10 MW reference wind turbine [82].

The study takes into account the final outputs from CL-Windcon project, and in particular for the economic analysis it uses the results of deliverable D4.5 (O&M Cost Modelling) [83]. This deliverable presents a study of the effect of the wake steering control on three KPIs, i.e. OPEX, Energy Production and Availability, on the NORCOWE RWF comparing them with the no control case. To perform this it makes a thorough analysis of the Operation and Maintenance (O&M) costs using an in-house model, which is also adapted to a wind farm control scenario by considering wake effects and a failure rate distribution within the wind farm to account for varying loads dependent on the turbine position in the wind farm. The outputs of this model show that the active wake steering control slightly improved the availability of the wind farm by a value which is almost negligible and increased the OPEX and the energy production. By calculating the revenue

[2] http://www.clwindcon.eu/
https://cordis.europa.eu/project/rcn/205917/en

due to power production gains with the averaged EPEX electricity spot price, it can be concluded that the wake steering control is economically viable.

A Life Cycle Costing (LCC) analysis over the lifetime of the RWF (25 years of useful life and 1 additional year for dismantling) has been performed in [83] and [80] to compare the use of the wake steering control against a baseline scenario with no wind farm control applied. The results in Table 4 show that the use of wind farm control increases the O&M operations implying additional € 3.59 million cost (for 25 years), with extra incomes for the AEP rounding € 30.47 million. Therefore, the gaining during the whole lifetime rounds € 26.88 million, which represents the 1.10% of the whole project costs (in present value).

Table 4 Main economic lifetime comparison Farm-wake-steering-control / Individual-control

Concept	Absolute (EUR)	Relative (%)
Increase in LCC (Present Value)	€ -3,592,100	-0.15%
Increase in Net Energy sales (Present Value)	€ 30,479,236	0.79%
Net differences	€ 26,887,136	1.10%

The final economic results are summarised in Table 5. They consider an average price of the electricity of 50 €/ MWh throughout the 25+1 years. They show how the use of a wind farm yaw wake steering control reduces slightly the LCOE from 31.55 €/MWh to 31.35 €/MWh, representing an improvement of 0.63 %. Both cases consider a weighted average cost of capital of 5.19% and an inflation rate of 1.5%

Table 5 Main project economic results Farm-wake-steering-control vs Individual-control

SCENARIOS/Concepts	Units	Yaw control	Individual
Total Present Value Costs	€	2,451,886,907	2,448,294,807
Total Energy Produced (Non discounted)	MWh	114,448,000	113,556,000
Total Energy Produced (Present Value)	MWh	78,212,726	77,603,141
Total incomes sales of energy (50€/MWh)	€	3,910,636,301	3,880,157,065
Average Cost (Present Value) per MW	€/MW	3,064,859	3,060,369
Total Net Energy Production (NPV)	MWh/MW	97,766	97,004
LCOE	€/MWh	31.35	31.55

Some comments on the results: First, the obtained figures are wind farm dependent, as costs and power production gains depend on the layout, wind turbine model, and the electricity market framework for LCoE computation, among others. Second, one of the conclusions from this analysis is the major importance that a good estimation of the effects that wind farm control has on the LCC is required to evaluate its viability. A key issue is to get good adjustments of the failure rates considering the impact of the control to obtain a detailed picture of turbine reliability and its influences. Physical models of individual components could provide an in-depth understanding of root causes for different failure types. Thus, better knowledge for quantifying the impact of controller technologies on turbine reliability could be attained.

A novel approach was proposed in the study to determine failure rates based on Damage Equivalent Loads (DEL) calculation, which covers a hardly explored field. Consequently, the simulation tool for DEL computation plays a relevant role in the results. It needs to represent the effect of wakes, e.g. including partial wake events, to the required extent to fully demonstrate the benefits provided by wind farm control. In other words, it is hard to show improvements in performance if the problem (the wake effect) was not properly represented and detected in the baseline case. The calculation performed in CL-Windcon represents a conservative value considering the fidelity of the used simulation tool.

4.3 Ancillary services from wind power

In section 4.1.2 the importance of balancing markets for the wind energy producers has been already addressed. In the context of European power systems, ancillary service is defined as 'a service necessary for the operation of a transmission or distribution system' [49]. Each electricity transmission system operator (TSO) has within its remit to 'manage electricity flows on the system, taking into account exchanges with other interconnected systems, and to that end, be responsible for ensuring a secure, reliable and efficient electricity system and, in that context, ensure the availability of all necessary ancillary services'. This includes the collection of all the transmission system related charges including access charges, balancing charges for ancillary services such as purchasing of services (balancing costs, energy for losses).

It is therefore European TSOs that define the (ancillary) services they need for the safe and secure operation of their power transmission systems. And they need to do so under the supervision and guidance of the correspondent National Regulatory Authority (NRA). A great amount of work in this space is delivered cooperatively thought the European Network of Transmission System Operators of Electricity (ENTSO-E) and the Agency for Cooperation of Energy Regulators (ACER). However, it is ultimately each individual TSO that is responsible for the definition and procurement of the services in agreement with the relevant NRA. The European Commission has legislated in these matters in recent years, e.g. guideline on electricity balancing [50] and network code on requirements for grid connection of generators [12], and interpretation of these laws as well as additional support materials are regularly updated into the correspondent ENTSO-E web pages [51], [52].

In GB for instance, it is the Office of Gas and Electricity Markets (Ofgem), and NationalgridESO in its role as transmission system operator in GB, that define the ancillary services required for the safe and efficient operation of the system, as well as the market mechanisms required for those to be procured and delivered. Information on different aspects of the system operability framework is regularly published by the TSO with further details on the current situation and strategic plans for the future of ancillary services [53]. **Error! Reference source not found.** below presents the denomination of some of the most common ancillary services in GB transmission, as well as orientative, average values for the revenues associated with them.

Table 6 Indicative values of revenue streams associated with ancillary service provision in GB [54]

Ancillary service	Revenue indicative value
Enhanced frequency response (EFR)	60-105 k£/MW/year
Firm Frequency response (FFR)	50-145 k£/MW/year
Fast Reserve (FR)	50-70 k£/MW/year
Short term operative reserve (STOR)	20-35 k£/MW/year
Capacity Market (CM)	22.5 k£/MW/year[8]
Triad avoidance (TA)	Region dependant - 30 k£/MW/year S. Scotland
Capturing Split Energy (CSE)	Site dependant.
Managing Imbalance risk (MIR)	7-30.6 k£/MW/year
Wholesale price arbitrage (WPA)	20 k£/MW/year
Black start (BS)	Undisclosed

Historically speaking, most of these ancillary services have been provided by the big, centralised thermal power plants directly connected into the transmission system. This was the paradigm throughout the whole of the 20th century. Since the liberalisation of the electricity market in Europe, there have been numerous mechanisms by which TSOs have procured them from generators capable of operating above and beyond the conditions set in their connection agreements. This has brought understanding of those services by the wider power industry, as well as an increase in the number of operators participating in those mechanisms and associated markets. However, the contribution from renewable sources of electricity (RES) into these mechanisms for the provision of ancillary services to transmission system operators has been almost non-existent during the last two decades.

Installed wind power capacity in Europe has increased significantly during the last two decades from around 10 GW at the turn of the millennium, up to approximately 220 GW expected by the end of 2020. The increase in the presence of other renewable energy sources of electricity (RES), such as photovoltaic solar power, has also been remarkable. This has made the total share of electricity produced by renewable sources in the European electricity generation mix just shy of 30% at the end of the decade (**Error! Reference source not found.** below shows the latest official statistics of the electricity production in the European Union segregated by power source). This is bringing the decarbonisation and decentralisation of electricity generation and, in this situation, the ancillary service provision paradigm described is changing to make room for wind power. Real change has just started though.

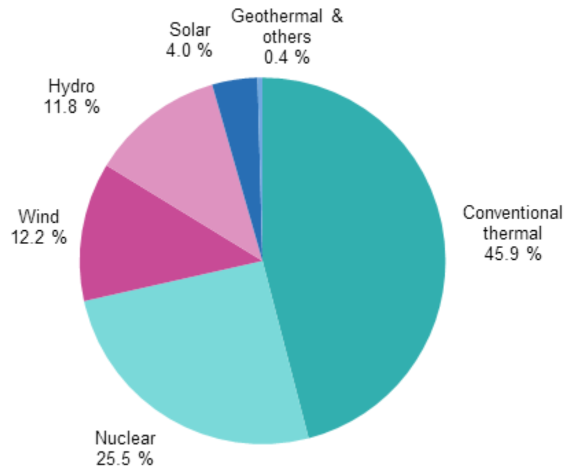


Figure 21 EU-28 electricity production by source 2018 (EUROSTAT)

Two recent developments are worth noting as evidence of a significant change in the way TSOs procure ancillary services, and that are designed to increase the participation of wind power in these markets, i.e. available power, and auction trials. The former tries to give some steps necessary to increase the visibility on active power generation headroom from wind power plants in system operation control rooms, and therefore, allow them to participate in balancing mechanisms (BM). The latter, is an on-going trial for a live market structuring the provision of frequency support services, open to wind power operators, and running on a weekly basis, as an intermediate step towards a participation of wind power in day-ahead markets. A high-level description of both innovations is presented below, and further details can be found in [55].

Power Available (PA) is a live data feed available to TSO control room engineers which tells them what the potential maximum power output of a wind generator is at a given time and in given conditions – and they can compare this to the generator's current operating output (the difference is often referred to as its 'headroom'). Then, control systems can then accurately calculate the response and reserve capability held on each generator, enabling them to compete with other generation technologies to provide real time response and reserve services. PA signal is defined in the Grid Code Glossary and Definitions but in summary is the real-time (1 s resolution or better) potential MW output (1 MW resolution or better) that a Power Park Module could generate allowing for current weather conditions and available Power Park Units. It is a new requirement from electricity system operation control room to balance the system using generation from intermittent generators such as wind power and other RES.

An example of the power available (PA) real time signal role in the participation of wind power in the provision of frequency response services is shown in **Error! Reference source not found.**. When wind farms [and other generating units] are instructed into 'frequency sensitive mode' operation, the Power Park Module[3] must change output in relation to system frequency, reflecting the frequency response capability curves as tested and included in the Mandatory Services Agreement. If the National frequency is higher

[3] It may well be one of the functions implemented in future wind farm control (WFC) systems.

than 50Hz the Power Park Module will deload. The reverse is true: if the National frequency is lower than 50Hz the unit will increase output if it was not at full output (PA) before the National frequency fell below 50Hz. At all times the PA MW value should remain what the Power Park Module would be generating if it was at full output, not following a Bid-Offer Acceptances (BOA) instruction[4] or providing frequency response.

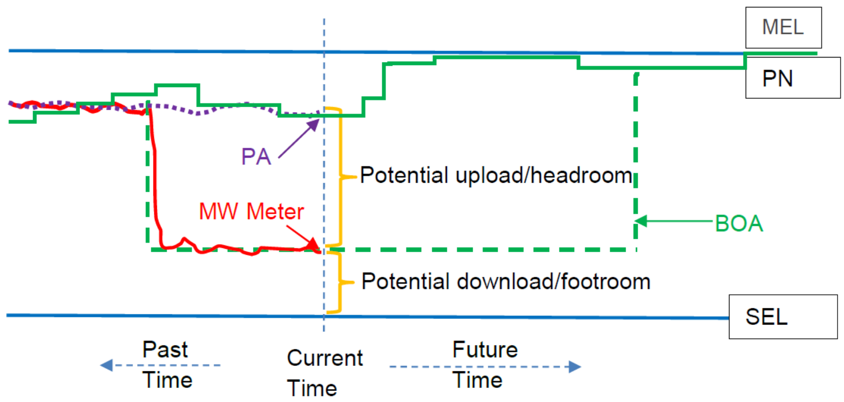


Figure 22 PA signal and WPP module frequency support during BM window(NationalgridESO)

On the other hand, weekly auction trials are being held in GB opening up a new opportunity for parties such as wind power to access the frequency response market. The alignment of procurement activities of certain frequency products closer to real-time would also allow all parties to assess which revenue streams offer them greatest value, thereby being able to determine where and when to offer their Megawatts. There is a system benefit from, and a desire from many stakeholders for, even closer to real-time procurement, such as day-ahead. Whilst this is ultimately the direction of travel, at least in GB but possibly in most European countries, we must test and learn from this first fundamental shift in order to inform further changes. Given the weekly nature of the auction trial, there will be one day-head opportunity per week which may better suit providers with particularly variable demand or generation.

[4] Physical note (PN) or generating instruction previously provided by the ESO control room.

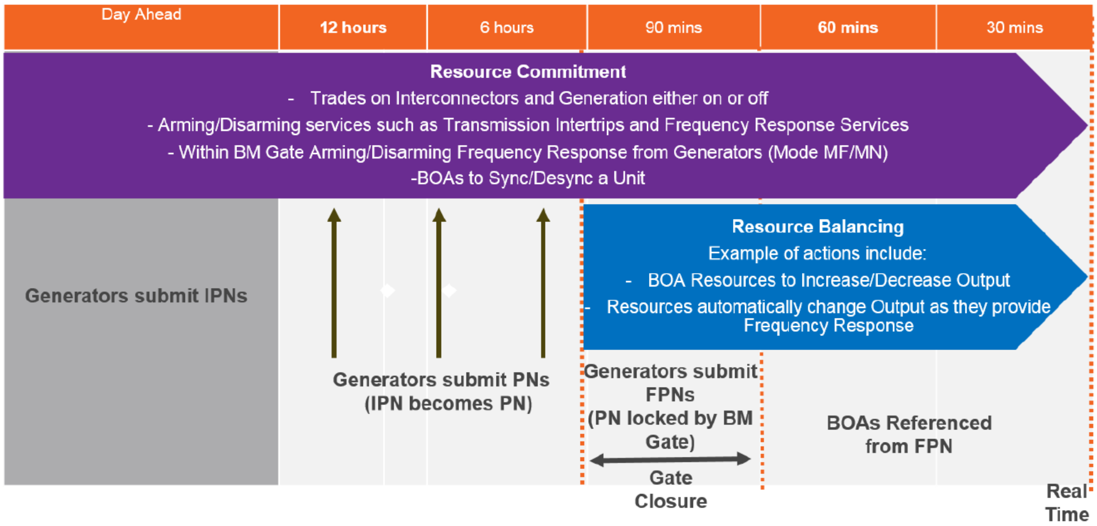


Figure 23 Resource commitment and balancing from day-ahead to real-time [53]

Both developments described above, i.e. the power available and ‘close to balancing mechanism’ auctions, are very relevant developments and worth a mention in the context of this report as wind farm control specifics will necessarily have to be considered and be part of any future industrial implementation of these solutions.

5 Issues hindering wind farm commercialisation

In this section current obstacles for the introduction of farm control strategies into the wind farms and wind power plants are collected. First, the complex physics of turbulence and wake in a wind farm are addressed. As described in section 3.2 wind farm control strategies aim to control the complex flow conditions. The problem to predict reliably the complex turbulence and wake effects on the individual wind turbine leads to certification issues still to solve. Furthermore, requirements from the grid operators differ significantly across European borders and could cause restrictions for wind farm control applications.

5.1 Challenges to grasp turbulence and wake effects

The goal to increase energy yield cannot be seen as an isolated, independent task but has to be accompanied by the guarantee that the structural integrity of the wind turbines constituting the wind farm is preserved. This is accomplished by optimising the distribution of the mechanical loads among the different wind turbines.

5.1.1 Standard certification approach

From a certification point of view, the assessment of the structural integrity of a wind turbine for site-specific conditions is described by the given standards of section 2.2, e.g. the IEC61400-1 Edition 4 [84]. The IEC standard offers two possibilities to assess the structural integrity of a wind turbine within a wind farm: by reference to wind data, Sec. 11.9, and by load calculations with reference to site-specific conditions, Sec. 11.10.

In the first case, it is basically verified that the wind conditions at the site are covered by the environmental characteristics considered for the design of the wind turbine. The wind conditions to be compared include both the ambient characteristics (without wake effects) as well as the wind conditions in the presence of wake.

The mostly used model considered for the wake analysis in the industry is based on the Frandsen turbulence model [85]. This model is based on the assumption that the standard deviation of wind speed fluctuations is the key driver for fatigue loading under both ambient conditions and under wake conditions. In the realisation of the model prescribed in the standard, the complexity involved in the wake physics and its interaction with a downstream wind turbine, is empirically reduced to an increase of the turbulence intensity, in a similar way to earlier models [86] [87].

In the realisation of the IEC wake model, a constant amplitude of the wake equal to 21.6 degrees is assumed, independently of the distance to the upwind turbine. The added turbulence intensity is assumed to be only dependent on the hub-to-hub distance. In addition, no wake deficit, i.e. wind speed reduction, is supposed to be considered for the load analysis. Within this picture, a downstream wind turbine is assumed to be under wake if half of the rotor lies within the wake generated by the upstream wind turbine. Simple variations of this model include have been made, among others, by [88], [89], [90] and [85].

These simplified approaches allow to identify the turbine with the highest wake induced effective turbulence intensity (and fatigue loading). The identified most severe location is then subjected to a detailed load simulation. Thus, IEC standard still follows the philosophy of the verification of the single turbine exemplary for the whole wind farm. For large offshore wind farms it is common practice to separate clusters, based on local environmental conditions and perform load analysis for representative turbines for each cluster. **Error! Reference source not found.** shows an example from IEC standard for the determination of the most severe location in a wind farm.

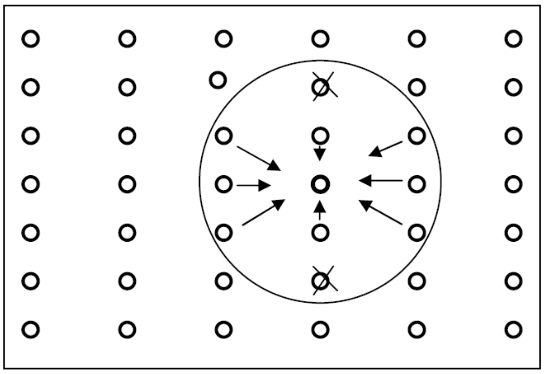


Figure 24: Configuration inside a wind farm with more than 2 rows, Annex E [84]

The loads obtained are finally compared with the design loads to determine the suitability of the wind turbine for the specific site. The description presented so far has the big advantage that it is extremely easy to implement and be used in simulations. Therefore, this approach is today common practice in industry and certification.

This approach, however, would not be suitable for the identification of critical turbine locations using variable farm control strategies. Here the full loading picture of the wind farm is needed. Therefore, the simplifications and neglection of intrinsic issues of wake effects receive recently more and more attention.

5.1.2 Wake description: from Frandsen to Dynamic Wake Meandering model

As mentioned in the previous section, the most common methodology for the prediction of fatigue loads in wake operation is the approach where the influence of the wake is taken into account by introducing an increased, effective turbulence. This is designed to give estimates of the lifetime fatigue load of a wind turbine, what seems reasonable since fatigue loads scale approximately linearly with wind speed fluctuations.

Frandsen model presents, though, some significant limitations which are relevant for dynamic wake conditions introduced by wind farm control activities. The most important one is the reduction of the complexity involving the wake physics to a simple turbulence intensity scaling. In particular, no explicit way to estimate partial wake effects is provided. A more realistic estimation of the ultimate and fatigue loading level within a wind farm requires a detailed description of the physical characteristics of the wake formation, evolution and interaction with the downstream wind turbines.

In the IEC61400-1 Edition 4 [84] an alternative approach to Frandsen is introduced; the Dynamic Wake Meandering model (DWM). This model represents a compromise between model fidelity and computational time. The DWM model is a low fidelity wake model continuously developed at Risø DTU since 2003 [91], [92], [93]. The idea behind the model is to capture the key features of the wake with regard to wind turbine loads and power production, while maintaining sufficient computational speed for design calculations. The most important assumption of the DWM model is the split in turbulence scales, so that the main characteristics of the wake are clearly identified and separately described. The DWM model is based on the combination of three corner stones:

- Quasi-steady wake deficit: The wind speed reduction observed in the wake is calculated based on the two-dimensional axisymmetric thin shear layer approximation of the steady Reynolds averaged Navier-Stokes equations. Turbulence closure is obtained by using an eddy viscosity formulation that is assumed to be constant in radial direction, and thus dependent only on the downstream position in the wake. The current description that can be found in IEC Annex E.2.2 represents an extension of the work done in [94].
- Stochastic meandering: The wake meandering part is based on the fundamental presumption that the transport of wakes in the atmospheric boundary layer can be modelled by considering the wakes to act as passive tracers driven by the large-scale turbulence structures. The meandering process is modelled as random displacements of the wake deficit by large scale turbulent fluctuations perpendicular to the flow direction.
- Rotor added turbulence: is included to incorporate the effect of added turbulence due to tip, root, and bound vortices as well as shear layer generated turbulence in the wake.

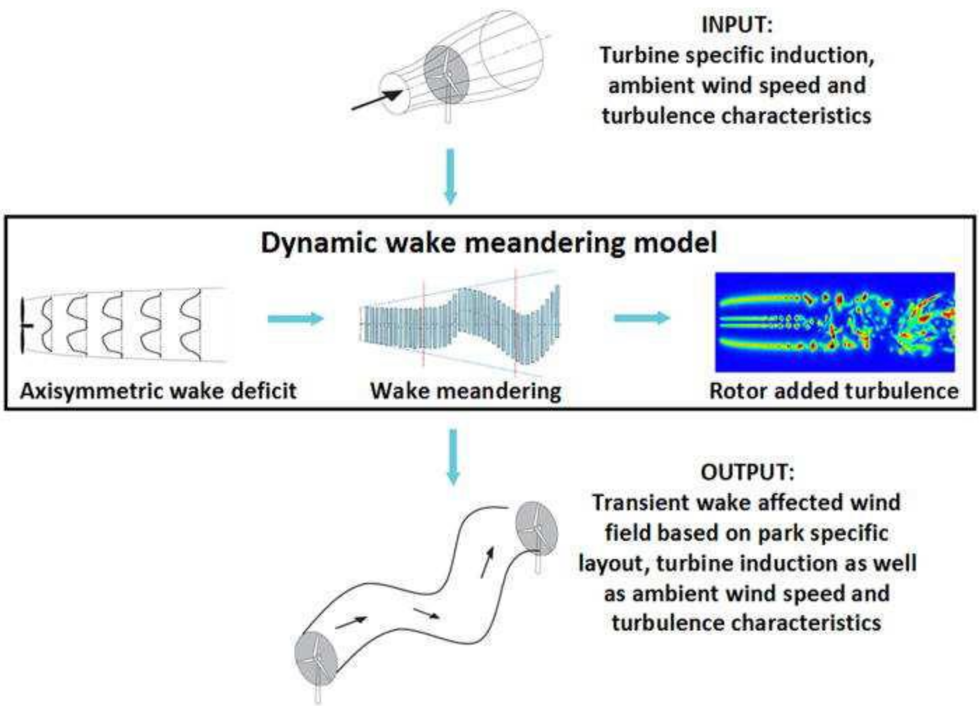


Figure 25: Dynamic wake meandering model based on velocity deficit according to Ainslie's model

5.1.3 Limitations of the Dynamic Wake Meandering model

In spite of the detailed description of the aforementioned methods, its application to specific projects is not always trivial but faces important challenges. These become even more relevant when trying to incorporate future aspects like advanced wind farm controlling.

The list below represents a succinct summary of some of the most important issues that are usually encountered.

<u>Calculation of wake effects at all turbine positions:</u>

Although this does not pose a problem in Frandsen's approach, it becomes a non-trivial task if a more realistic wake model like DWM is used. Different solutions include for instance:

- <u>Surrogate model:</u> High-fidelity models can be used to extract information about specific characteristics of the wake, e.g. meandering [95], which can then be stored for future used in a lookup table.
- <u>Two-model approach:</u> A simple but fast model, e.g. Frandsen, is used to quickly scan over all positions. A first group of wind turbines are identified as the most loaded ones. Afterwards, a DWM calculation is carried out for this subset of wind turbines only. In this case, the limitations of the model used for the first estimation of the turbulence intensities, must be taken into account so that important positions are not excluded.

<u>Load calculation at all turbine positions:</u>

A detailed load calculation at each position may become extremely challenging. Defining a powerful strategy to quickly calculate the loads expected in a wind farm plays a key role in the wind farm design, and in particular in the development of wind farm controllers. The following ideas are currently being discussed:

- <u>Surrogate model:</u> Despite the robustness of this approach, creating and using a table with so many dimensions accounting not only for different environmental conditions but also the details of the wake evolution requires a computational effort which easily becomes unacceptably high. To reduce this complexity, variations of this idea using simulations only for a subset of the range of environmental and operational conditions can be found in the literature, e.g. [96].
- <u>Deterministic-stochastic decoupling:</u> An alternative method applied to fatigue load calculation [97] involves combining the deterministic effects of wake profiles, shear, yaw misalignment, upflow, etc. with the stochastic effects of rotationally sampled turbulence coupled with structural dynamics. The effects are calculated separately from models fitted to appropriate sets of runs, and then combined. The number of simulations needed is much smaller than for a usual database.
- <u>Two-method approach:</u> As in the case of the wake effects, this procedure requires a simpler method to quick establish the candidate positions and then perform the detailed load calculation only for these wind turbines. The difficult task consists of finding a fast method but reliable enough to guarantee that all key positions have been selected.

<u>Effects of wind farm controller:</u>

The aforementioned issues assume a static approach to the problem, namely, given that each position it is possible to derive how long, and under which conditions each wind turbine will operate. Based on this, the whole task is "reduced" to identifying the most severely loaded turbines. This method is characteristic of current open-loop control scenarios, where a pre-tuned surrogate model is used to generate the optimal operation conditions of all turbines inside a farm and then assumes that the model remains accurate throughout the wind farm operation lifetime.

This picture, though, will change once future wind farm controller concepts are considered. On the one hand, new ingredients, such as induction control and wake steering, will need to be taken into account and consistently implemented in the load case definition. This means that for design purposes, it should be stated which turbines are going to be affected by the new controller features and how long. On the second hand, deviations between the assumed environmental conditions during the design process and the actual time-dependent situation at the wind farm may have an impact on the load assumptions at each position. Consequently, a more dynamic approach may become necessary. This is the situation arising in the so-called closed-loop framework, where the aforementioned pre-tuned surrogate model cannot be considered as fixed but is calibrated constantly in order to provide reliable setpoints [98].

5.1.4 Modelling and simulation tools

There are several situations involving wake physics, for which there is no sufficient consensus about the applicability of the current methods. Some examples are:

- Description of near wake, especially at inter-turbine distances, between 2 D and 3 D
- Wake behaviour in the presence of complex terrain
- Non-axial inflow conditions due to wind shear, wind veer, slopes and yaw error. Especially relevant are the wake effects induced by large yaw error configuration, as required for wake steering control strategies.
- Deep array. The recovery of the wake deficits deep inside a wind farm is reduced due to the presence of other wind turbines wakes. Sufficiently deep into the wind farm, kinetic energy is mainly transferred into the wake vertically.
- Impact of atmospheric stability. This will affect three aspects of wake physics: the turbulence intensity, the turbulent length scale and the atmospheric boundary layer shear.
- Although there are presently empirical attempts to describe these effects, a more conclusive validation of the models describing them is still lacking.

With the new control strategies, amendments to the existing standards and guidelines are expected, which reflect the more complex control algorithms, additional sensors, and optimisation procedures.

Different existing software packages can be used nowadays to perform wake simulations following DWM:

- HAWC2, developed by Risø DTU, incorporates the three elements of the "standard" DWM [99]
- Bladed is developed by Garrad Hassan & Partners Ltd. Version 4.9 [100] allows to perform DWM simulations taking into account the wake deficit and the meandering. The rotor added turbulence, as prescribed in Annex E.2.4 [84], has not been implemented yet.
- FAST.Farm is a tool developed by NREL [101]. It makes use of FAST to model the aero-hydro-servo-elastics of distinct turbines in the wind farm and relies on some of the DWM modelling principles

but trying to solve some of its limitations. It includes the controls capability of FLORIS, and functions more like SOWFA. To our understanding, as in the case of Bladed, the current version of the tool has not incorporated the rotor added turbulence.

- LongSim is a wind farm simulation code developed by DNV GL GH designed to simulate the dynamic behaviour of turbines and their wakes within a realistic wind field [102]. The DWM implementation assumes a Gaussian-shaped profile for the wake deficit and the Quarton-Ainslie model [103] for the added turbulence. The meandering is considered following [Ainslie suggestion].
- In addition to these known packages, manufacturers have developed also their own implementations.

Although some of the mentioned simulation tools include already enhanced capabilities to model dynamic wake and meandering effects, it is still a challenge to perform full wind farm simulations including wind farm control activities. The generation of realistic of wind inflow data for such a simulation task itself is a challenge with respect to data size. The aerodynamics of the state-of-the-art simulation tools are modelled according to the Blade-Element-Momentum method (BEM) for calculating aero-forces at defined rotor blade sections. However, this method is basically valid for straight inflow, parallel to blade cross section. This condition is not given when the wind turbine is operating at high yaw angles, e.g. during wake steering. Here an extension of the aerodynamic models is needed which is taken high yaw angles into account.

Hence, a development of new approaches and the validation of enhanced tools by full scale benchmark projects is required to enable reliable predictions of wind farm control effects on turbine level. This is for instance subject of Farmconners workpackage 1 [104].

5.2 Challenges matching grid requirements

From the certification point of view the compliance of the wind power plant (WPP) with applicable grid codes is of higher importance than an optimised wind farm control (WFC). If grid codes require the wind farm to behave in a certain manner to support the stability of the electrical network, this is a legal obligation. Noncompliance may have a large impact on the public power supply and can lead to high penalties.

5.2.1 Coordination of WPP control and WFC

When implementing WFC into a new control design concept it is important to ensure the necessary hierarchy in the control requirements. According to Figure 26 the compliance with grid code requirements is to be prioritised to any wind farm optimisation. According to CL-Windcon [16] two grid conform possibilities for the arrangement of the existing WPP control unit with the new WFC are described as 'parallel' and 'integrated' approaches. A summary of the key features of both options is presented below.

Parallel approach:

WPP control unit and WFC are implemented in a parallel approach as schematically shown in Figure 26. During normal operation the WPP control unit activates WFC. This means WFC exclusively controls additional setpoints and optimising strategies on the wind turbines. In case the grid operator submits any requests for a setpoint, or a grid fault is detected, then the WFC is deactivated and WPP controller takes over. Thus, a clear hierarchy is ensured.

This approach for WFC implementation might be easiest to develop based on existing controller designs for WPP control on the market. Due to its modular structure it offers ways both to implement it into new control design concept for the next generation of wind farms with WFC and to implement it into existing wind farms for a retrofit including WFC.

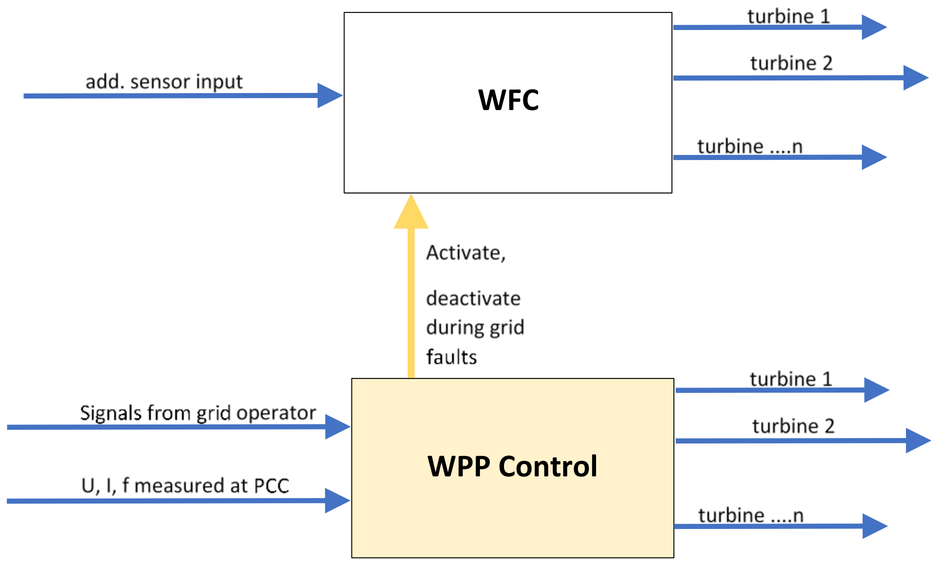


Figure 26 Parallel approach for co-ordination between WPP control and WFC

<u>Integrated approach:</u>

An integrated approach of WPP control unit and WFC will join both controllers more closely and is expected to lead to a more optimised system and a clearer hierarchy (Figure 27). Any setpoint requirements from the grid operator, information on the electric variables at the PCC or on any grid faults as well as additional sensor inputs are available to WFC and WPP control unit where required. Ancillary services or requirements from grid codes can be dealt with.

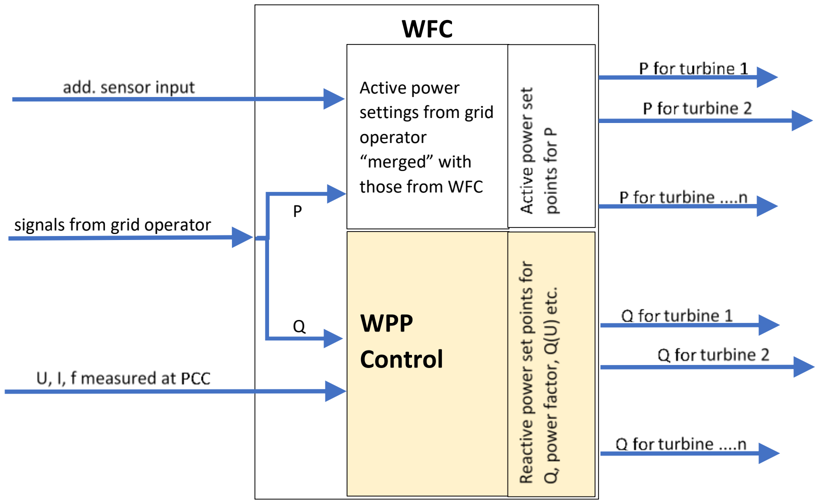


Figure 27 Integrated approach for co-ordination between WPP control and WFC

The output signals for active power P, reactive power Q as well as pitch and yaw angle setpoints are further on processed in the individual wind turbines, see Figure 28. Further output signals to turbines besides active power P and reactive power Q like pitch and yaw angle setpoints have been omitted in the figure for better oversight. Here, it is important that the control and protection system supervises the operation of the wind turbine. A fault in the WPP control unit or WFC may never endanger the structural and electrical integrity of the individual wind turbine. It is important to mention that fault ride through (FRT) behaviour of the wind turbine as one requirement from grid codes has to be controlled in the individual wind turbine. The communication between the wind turbines is too slow to deal with this fault within the required time range of only a few ms (related to the electrical current sine wave with 20 ms period). It has to be ensured that WFC does not restrict the wind turbine to comply with FRT requirements.

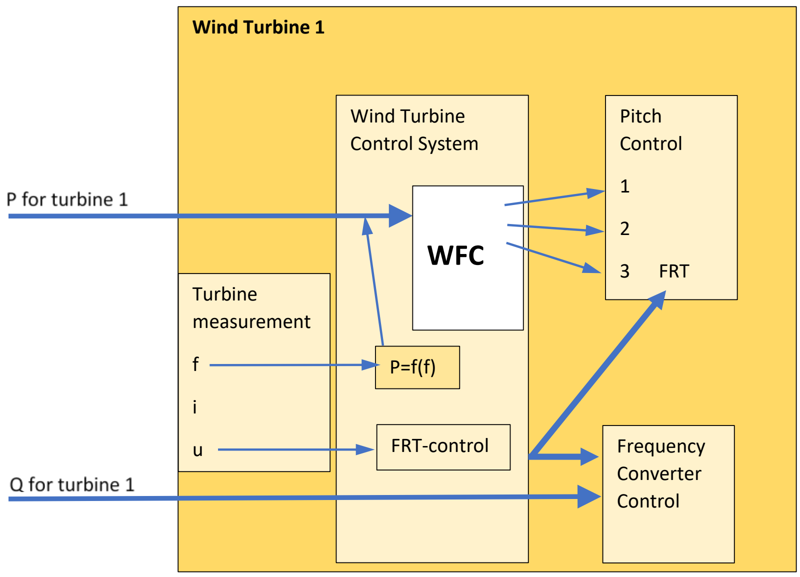


Figure 28 Additional co-ordination of WPP control and WFC on wind turbine level

5.2.2 Potential conflicts between WPP control unit and wind farm control

The individual wind turbine is basically controlled by adapting the control variables pitch angle, yaw angle, rotor speed and generator torque. Possible control targets additional to normal operation stemming from grid codes and WFC including ancillary services apply the same control variables. For example, the requirement of a reduced setpoint for active power is addressed by the wind turbine controller adapting pitch angle and generator torque appropriately. Fulfilling control targets from normal wind turbine operation, grid codes or ancillary services may be in conflict with each other. Clear control targets and priorities have to be defined for the different controller ensuring a safe operation. It has to be ensured that dynamic transitions between operational modes function well. The following list based on CL-Windcon [72] presents examples of possible conflicts:

- WFC may influence the dynamic behaviour of the wind turbine during active power control. This includes the functionalities a-d listed below, mainly in the wind turbine, but also on WPP level. It has to be ensured that these cases are properly considered in control design.
    - Control strategies for re-connection after faults
    - Ramp-up after zero voltage situations (switch-off)
    - Ramp rate control
    - Frequency response
- WFC by pitch and yaw modification may bring the wind turbine into unusual operation conditions. Yaw steering can for example require the wind turbine to yaw out of the wind up to +-30°. If e.g. in such condition a short-circuit occurs in the electrical grid close to the wind farm, the grid code might request the wind turbine to stay connected to the grid for stabilisation purposes. This case is called fault ride through (FRT). Concerns are existing regarding the mechanical and electrical loads during such voltage dip, when operating the turbine under high yaw misalignments. It is questioned if the necessary behaviour of the wind turbine regarding speed, torque and electric characteristics can be kept when running through a voltage dip. The grid code might require the wind turbine type to be tested for this case. State-of-the-art FRT testing does not include such large yaw misalignment angles.
- Fault case 'grid frequency above 50Hz': The grid operator might require reducing the active power. At the same time WFC could desire to increase the electrical power leading to a conflict.
- Fault case 'line congestion (overloading)': The grid operator might require the WF to reduce active power output to specific set points. Dynamics and accuracy are well-defined. It is to be ensured that wind farms operating with WFC are still able to comply with these requirements which also require testing during type and project certification.
- Due to mutual dependencies of active and reactive power, requirements on one magnitude by the grid operator and on the other magnitude by an ancillary service might lead to a conflict.

5.3 Risks for wind turbine components

Within CL-Windcon project a Failure Mode Effects and Criticality Analysis (FMECA) of potential risks of different wind farm control techniques have been analysed to extract conflicts and possible gaps with actual standards. The control strategies as described in section 3.2 were analysed:

- Axial induction control
- Wake steering control (Yaw control)
- Wake mitigation technique (periodical pitch control)
- Combination of axial induction control and yaw control

From this analysis the following conclusions have been extracted:

- The 'Axial induction control' does not conflict with current standards. Although de-rating the wind turbine by pitch control method in order to give more energy yield to downstream wind turbines may influence control function parameters like the rotor speed, power regulation etc. of the de-rated wind turbine, the standard design procedure, following IEC 61400-1 [84] requires only to prove the none-de-rated conditions of wind turbines, as they are considered to cause the higher loads. Therefore, the protection functions do not get influenced by axial induction control.
- In the case of the 'Wake steering control', the wind farm control has to access to the wind turbine yaw control, and this is a novelty. The actual wind turbine controller, in normal condition, is a closed loop feedback control and it normally does not have any interfaces for receiving external commands. So, the related changes in wind turbine's control software need to be done carefully. It must be ensured, that the wind turbine never moves out of the allowable yaw angle range. The risk here is to overlook any important matter, when revising wind turbine's control software. For the downstream wind turbines the FMECA found a potential risk for increased fatigue damage and risk of increased ultimate loads due to prolonged non-aligned operation.
- The 'Wake mitigation techniques' implemented by changing the pitch angle periodically may lead the pitch angle to reach the maximum permissible angle in the control system or causes abnormal vibration on the structure. This has to be assessed by simulating these special load cases. Wind farm control will submit values for the "Wake mitigation pitch offset", which would be maximum amplitude and cycle time. Wind turbine controller needs to be adapted to perform the additional changing pitch angle movements according to the values from the wind farm control. For the cyclic pitching wind turbines there is a risk of increased fatigue damage on the pitch system.
- No additional risk by combining the features 'axial induction control' and 'yaw control' has been found. The risks are comparable to the application of each feature separately.

One benefit is that the integration of wind farm control into the existing certification scheme can be often realised in a simple way by just prioritising the existing control and protection function. An example is the prioritisation of the individual wind turbine control over wind farm control for certain limiting parameters of the turbine like active power under grid fault conditions or switching off the new controls in certain wind farm operational states like "start-up" or "shut down". A precondition for this is that there is enough time to switch off from wind farm control mode to normal operation mode.

But also unplanned situations must be considered: especially fast control action is necessary to preserve the safety of the turbine for grid stabilisation in fault cases with no time to bring the turbine to normal operation first. Therefore, it must be proven, that all external or internal demands can be fulfilled safely even under wind farm control operation.

For the "control system" compliance it is important to guarantee that wind farm control will only be active during the normal operation and not during the safe mode operation which is the status of the turbine if certain safety limits are exceeded. All major functionalities to switch off wind farm control or to prioritise turbine safety functions over wind farm control demands need to be proven before the wind farm starts operation. It must also be proven that the wind farm control modes do not lead to excessive vibration during operation and all control actions are still safe under communication failures.

In conclusion, a few critical control actions may need further attention and possible amendments of standards. It is recommended to extend the existing standards and develop criteria and requirements for at least the following certification tasks:

- Requirements for the wind turbine safety system (highest priority) in combination with farm control access to turbine manoeuvres such as blade pitch, yaw and torque
- Requirements to the redundancy of the farm controller and definition of possible “fall back” situations
- Load case amendments for the wake steering control approach and wake mitigation technique
- Definition of load cases covering possible failure modes related to farm control algorithms
- Specification of admissible maximum start and stop procedures
- Definition of increased idle operation and consideration of low aerodynamic damping situations
- Definition of enhanced testing procedure during type testing
- Extension of commissioning procedure including farm control functionalities
- Specific check procedures during periodic monitoring (in-service) including farm control functionalities

6 Proposed solutions

In general, any new method or tool being used for the calculation and the certification of loads for a wind farm can be approved by a priori validation of each single component. This could be either done by an approval of the procedures and codes on a theoretical / analytical basis, or by a thorough validation campaign by measurements or a combination of both. In fact, this would not be an “alternative” approach, but rather the traditional approach for load simulation methods or tools as outlined in section 6.1.

But since the simulation of site-specific wind farm loads including wind farm control strategies is rather complex, as a first step a “Technology qualification” might be carried out, according to DNVGL-RP-A203 [7]. The approach by applying the technology qualification is described more in detail in section 6.2 of this report.

6.1 Temporary/conditional project certification

The calculation (and subsequently the certification) of loads for a wind farm is a processing intensive work. Usually, the wind farm is clustered and only individual representative wind turbines are calculated. The ambient turbulence as well as the wind farm effects must be considered in the load simulations.

6.1.1 Load calculation process including wind farm control strategies

More complex is the simulation in case wind farm control strategies are included in the simulation, see section 5.1 of this report. The purpose of wind farm control strategies is to optimise power output and/or to reduce loads. As described above, this is done e.g. by de-rating or wake steering by applying additional yaw offset up to 40deg. The increased complexity of the wind farm behaviour is followed by an increase of complexity in the wind farm simulation. Figure 29 illustrates this.

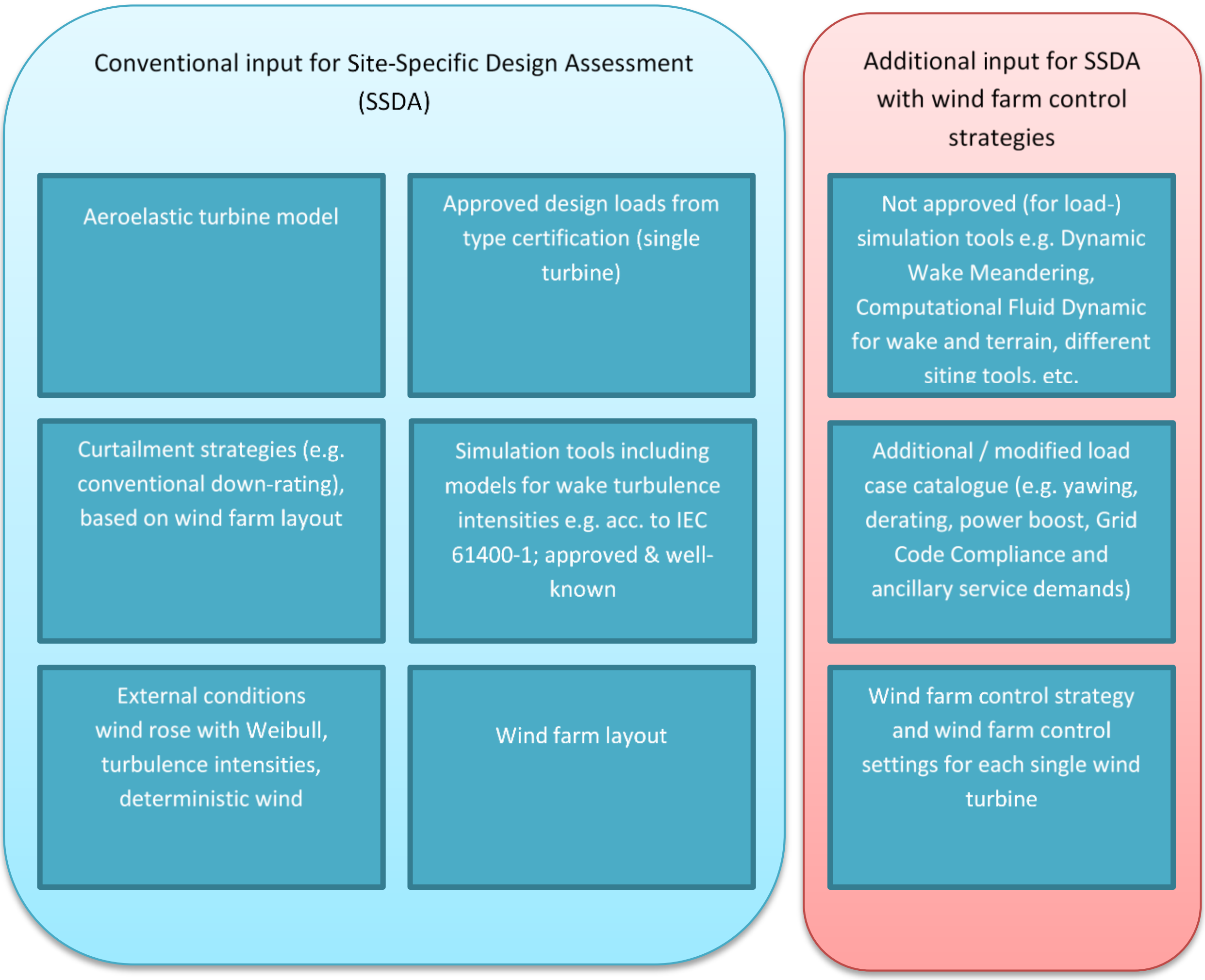


Figure 29 Conventional Site-Specific Design Assessment (left) and additional input for wind farm control strategies (right)

In the blue left-hand side box of this figure (SSDA stands for Site-Specific Design Assessment) the required input for wind farm load simulations without wind farm control strategies is listed. In the red right hand-side box the additional input is listed for wind farm load simulations including wind farm control strategies.

As shown in Figure 29, the additional aspects of wind farm control effects are:

- new tools that describes external conditions, e.g. wind speeds and turbulence intensities within steered wakes and with or without terrain influence
- modified load case catalogue. Additional or modified load cases are necessary to cover effects from the changed control strategy of the wind turbines. For example, wake steering by applying additional yaw offset leads to changed operational conditions for the yawed turbine, while the downwind wind turbines are affected by changed wake conditions. This needs to be mirrored in new or modified load cases.
- applied wind farm control strategies as input for the wind turbine and wind farm control system, including any required parameter settings for any single turbine.

6.1.2 Certification of site-specific wind farm loads including wind farm control strategies

Significant uncertainties exist due to not sufficiently validated new models for the determination of external conditions and simulation of loads applying wind farm control strategies (upper red right hand-side box in Figure 29. For example, the Blade-Element-Momentum method (BEM) [106], frequently applied for aeroelastic load simulations, may have problems in simulating correct loads for high yaw misalignments. Further on, the correct modelling to steered wakes as external condition to downwind turbines has not yet proven to be exactly enough.

Based on the information available, it seems difficult for the near future to have those new or modified models sufficiently validated, meeting certification requirements for commercial applications. Such uncertainties might be decreased during thorough validation e.g. within research projects, where all new or modified models for determination of external conditions and load simulations are tested separately against measured data and then combined to the entire process.

An alternative approach is presently developed at DNV GL. Instead of a a-priori-validation of those models and tools, a validation could be carried out during operation of the (commercial) wind power plant under investigation. During the Site-Specific Design Assessment (the desktop work based on documents) the new or modified models for determination of external conditions and simulation of load simulations are only assessed on a plausibility basis, but not finally approved. The issued SSDA includes conditions, that the validity of the new modules shall be approved by measurements during the first years of operation of the realised wind farm. This is based on a measurement plan to monitor first years of wind farm operation and yearly reports on the wind farm control performance and data acquisition. If these measurements (external conditions, loads, SCADA data, etc.) show that all new models and tools have determined correct calculations, an unconditioned SSDA can be issued. In case the new models have underpredicted the loads, the realistic loads must then be calculated based on the measured values. Load mitigation procedures must be applied to the plant, e.g. by curtailment to meet the initially planned lifetime.

This new certification approach is described step-by-step:

- Within the SSDA, the load simulations including the tools and methods of the wind farm control strategies are assessed by plausibility checks only; external conditions are optionally assessed.
- Issue of the SSDA covering the advanced wind farm control strategies and conditions for operation. The conditions for the SSDA may include:
    - The performance of the wind farm control is monitored during the first years of operation based on a measurement plan. The measurements cover at least the external conditions, wind turbine loads, SCADA data, etc.
    - A yearly evaluation report on the wind farm control performance and data acquisition for the measurement verification is issued.
    - This is followed by a load validation based on the measured data.
- A revised SSDA is issued. Depending on the results of the load validation, this SSDA confirms the intended wind farm configuration and / or requires load mitigation strategies.

By carrying out a number of such projects with the same or very similar methods and tools, a step-by-step validation of the new models may be obtained, leading to the full approval of the new models. This means, that the validation measurements to prove wind farm control strategies would not be required after a while. For the formal description of this approach see DNVGL-SE-0190 [4] the latest edition of which is still to be issued and expected to include wind farm control aspects. It is pointed out here, that research project as CL-Windcon or the present FarmConners project contribute significantly to the edition and / or update of standards and guidelines for the design and certification of wind turbines and wind farms.

6.1.3 Practical recommendations to Design Assessment

The state-of-the-art Design Assessment (DA) of single wind turbines does not consider wind farm effects, except for some optional load cases. Presently, Design Assessments consider stand-alone turbines only. Wind farms on the other hand are covered by Site-Specific Design Assessments (SSDA), as described above.

However, it is recommended to include any wind farms effects (including wind farm control strategies), already into the Design Assessment, as far as possible. These wind farm effects might be the application of any specific wind turbine controller features (including the possibly to be updated control system) on grid code requirements and ancillary services, as well as applied simulation tools and methods. The specific set of external conditions and wind farm control strategy parameters might be chosen to cover a typical but generic wind farm. The project specific external conditions wind farm control strategy parameters will then be covered later in the Site-Specific Design Assessments (SSDA). The benefit of this early inclusion of wind farms effects is, that any occurring problems in the interaction of wind turbine control and wind farm control or by the complexity of the load simulations including wind farm control strategies is addressed at an early stage.

6.2 Risk based certification

Risk based approaches are generally applicable where novel technologies or technical issues with only little field experience are not covered by existing standards and guidelines. DNV GL has developed several standards and recommended practices based on experiences in different industries (maritime, Oil&Gas, energy) to capture such technical challenges.

In the IEC standard it is specified that a failure mode and effect analysis (FMEA) or equivalent fault analysis shall be carried out to determine control system fault events relevant for the wind turbine loading. This may include fault-tree analysis or similar methods to identify any common cause failures. The set of events addressed in the fault analysis shall include at least:

- excessive rotor speed
- excessive vibrations
- excessive power production
- actuator faults, e.g. pitch and yaw actuation faults

Within DNVGL-ST-438[5] [6] a risk-based four step approach is proposed for certification, but more advanced risk-based design methods may be followed. The four steps are:

[5] Several wind engineering standards and service documents are mentioned throughout this section. See Table 3 in section 2 for further detail.

- Identification of the protection functions.
- Determination of the required performance level (PLr).
- Design of the protection functions.
- Documentation the protection functions.

These steps, applied for wind farm control, could be presented as follows:

- Identification of the protection functions, supported by a failure consideration of all possible failures in the wind turbine that require a protection function. This shall be performed on system level and include the wind farm control and/or monitoring features used to reduce the loads on the wind turbine and increase power. In this consideration, all possible failures of the wind farm control systems shall be specified. For each failure, the following information is needed:
    - Designation and description of the possible failure
    - Affected component(s).
    - Possible cause(s).
    - Type of detection.
    - Effect(s) of the fault.
    - Measure(s) for limiting negative consequences.
    - Reference to the design load case in the documentation of the load calculation, if applicable.

  The technique chosen for this consideration can e.g. be failure mode and effect analysis (FMEA according to IEC 60812 fault tree analysis). The failure consideration shall be used for the definition of load cases of the groups DLC 2.x and DLC 7.x as for every control system failure. The failure consideration shall also be used for the evaluation of redundancies in the protection system and the evaluation of measures against possible dormant faults.

- Determination of the required performance level (PLr). Each protection function identified shall undergo a determination of its PLr using the consequence level "risk to investment" method as per ISO 13849-1. This method analyses the design before a protection function has been added. Table 7 and Figure 30 below provide a quick view on the method.

Table 7 Risk parameters with respect to ISO 13849-1

Severity of impact	S1	Normally repairable turbine damage / repair costs* < 1/3 of investment sum
	S2	Major or unrepairable turbine damage / repair costs* ≥ 1/3 of investment sum
Probability of hazardous failure**	F1	Seldom-to-less-often i.e. < 10-3 p.a.
	F2	Frequent-to-continuous i.e. ≥ 10-3 p.a.
		(Letter P is not used in this application.)

* Total costs comprise material and labor costs as well as potential expenses on required equipage like trucks, cranes, and offshore installation vessels. They do not compromise loss of earnings caused by stand still.

** The evaluation of the probability of hazardous failure may also comprise the environmental conditions, e.g. wind speed, direction, turbulence, others.

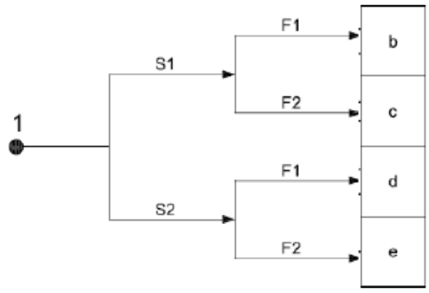


Figure 30 Risk graph for determining protection functions PLr as per ISO 13849-1

- Design of the protection functions. Protection functions are designed minimising the probability of the identified failures or their consequences sufficiently by meeting the required performance level that was determined with respect to ISO 13849-1 and IEC 62061.
- The documentation of protection functions may follow consisting of the following:
    - A table listing all wind farm control relevant protection functions including each required performance level (PLr)
    - A safety-related block diagram including possible subsystems for each protection function
    - Circuit diagrams showing the wiring of all safety related parts of the overall control system (SRP/OCS) performing the protection functions
    - A table for every protection function/subsystem which lists up the performing SRP/OCS including the parameters the calculation is based on
    - A table which lists the protection function/subsystem with evaluation results
    - Documentation of software

6.2.1. Technology Qualification

Technology qualification is a method for the assessment and certification of novel technologies, as shown within the INNWIND.EU project, in that case for a superconducting generator [107]. The method is technology agnostic and may be used for wind farm control systems too and is described in the recommended practice DNVGL-RP-A203 [7].

In the Certification Basis document, the technology is described, the functional description of the technology is given, and all relevant interfaces are defined. The purpose of creating a Certification Basis document is to define the expectations of the technology. It generally considers the following:

- general system description
- system functions
- standards and industry practices, or parts of them intended to be used for qualification
- boundary conditions including interfacing system requirements, environment and environmental loads and functional loads
- relevant areas of expertise considered necessary to understand the technology
- already existing evidence claimed to support the qualification, such as demonstration and testing.

The Technology Assessment is performed and includes the following steps:

- Division of the technology into manageable elements.
- Assessment of the technology elements with respect to the novelties.
- Identification of the main challenges and uncertainties related to the new technology aspects.

Next step is the failure mode identification and risk ranking. The objective of this step is to identify all relevant failure modes of concern for the elements defined as new technology in the technology assessment (TA) carried out and judge the associated risks. Prior to the identification of failure modes, various classes of probability and consequence severity are qualitatively defined. Based on these definitions a risk matrix is produced showing fully acceptable combinations ("low risk") and unacceptable combinations ("high risk") as well as intermediate combinations ("medium risk") of probability and consequence classes. All relevant failure modes are assigned a probability class and consequence class based on documented reliability or expert judgement. The classes are shown in the following tables:

Table 8 Probability classes

No.	**Name**	**Description**	**Indicative Annual Failure Rate (up to)**	**Reference**
1	Very Low	Negligible event frequency	1.0E-04	Accidental (event not failure)
2	Low	Event unlikely to occur	1.0E-03	Strength / ULS
3	Medium	Event rarely expected to occur	1.0E-02	Fatigue / FLS
4	High	One or several events expected to occur during the lifetime	1.0E-01	Operation low frequency
5	Very high	One or several events expected to occur each year	1.0E+00	Operation high frequency

Table 9 Consequence classes

Class	**Description of consequences (impact on) - Device Level**				
	Safety	**Environment**	**Operation**	**Assets**	**Euro**
1	Negligible injury, effect on health	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	1k

Class	Description of consequences (impact on) - Device Level				
2	Minor injuries, health effects	Minor pollution / slight effect on environment	Partial loss of performance (retrieval not required outside maintenance interval)	Repairable within maintenance interval	10k
3	Moderate injuries and/or health effects	Limited levels of pollution, manageable / moderate effect on environment	Loss of performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	100k
4	Significant injuries	Moderate pollution, with some clean-up costs / Serious effect on environment	Total loss of production up to 1 month	Significant but repairable outside maintenance interval	1m
5	A fatality	Major pollution event, with significant clean-up costs / disastrous effects on the environment	Total loss of production greater than 1 month	Loss of device, major repair needed by removal of device and exchange of major components	10m

Table 10 Risk Matrix

	Consequence				
Probability	**1**	**2**	**3**	**4**	**5**
5	Low	Med	High	High	High
4	Low	Med	Med	High	High
3	Low	Low	Med	Med	High
2	Low	Low	Low	Med	Med
1	Low	Low	Low	Low	Med

The objective of this step is to select qualification methods that adequately address the identified failure modes of concern with respect to reduction of uncertainties and documentation of sufficient margins to failure. These are activities considered necessary in addition to the normal certification activities performed for the component.

The qualification methods, in most cases, include technical analyses, testing or combinations of the two where the purpose of the testing is to reduce uncertainty in the analysis model or calibrate it. They may also involve collection of available reliability data and review of procedures intended to reduce probability or consequence of failure. The list of Qualification Methods does not include proposed improvements to the concept and further design details to be defined, though these are mentioned in the Failure Mode Identification worksheet. It is expected, however, that these will also be considered in the subsequent phases of the project.

For the “High” and “Medium” risks qualification or mitigation actions need to be defined. Usually for medium risk cases standards from other technologies may be adapted while for high risk cases both analysis and testing need to be performed.

6.2.2. Alternative approaches

Alternative approaches may be applied, based on the experience of other industries. One option is to use codes form the maritime industry as defined in the DNVGL rules [108], where requirements for control, monitoring and safety systems are stipulated, mainly considering vessels maneuverability in regard to propulsion and steering. Therein control, monitoring and safety systems are classified into three different system categories as shown in accordance with the possible consequence a failure

Table 11 System categories as defined in [108]

Service	Effects upon failure	System functionality
Non-important	Failure of which will not lead to dangerous situations for human safety, safety of the vessel and/or threat to the environment	Monitoring function for informational / administrative tasks
Important	Failure could eventually lead to dangerous situations for human safety, safety of the vessel and/or threat to the environment	Alarm and monitoring functions. Control functions which are necessary to maintain the ship in its normal operational and habitable conditions
Essential services and safety functions	Failure could immediately lead to dangerous situations for human safety, safety of the vessel and/or threat to the environment	Control functions for maintaining the vessel’s propulsion and steering. Safety functions

The classification of control, monitoring and safety systems is performed according to the following principles:

- type approval (components approval)
- certification of control, monitoring and safety systems (plan approval, manufacturing survey)
- on-board inspection (visual inspection and functional testing).

In all stages relevant design requirements for the system configuration, the response to failures, the system design, the requirements to the software quality and development, component design and installation and user interface need to be considered.

6.2.3. Additional remarks

The main focus of risk assessment for certification is on system structural safety and HSE. Nevertheless, the energy capture, the risk of reduced production should be considered considering the full lifetime of the windfarm. As a consequence, risk should be considered as short-term risk e.g. for the structural integrity but also long-term risk to the structure and power production. This implies that an analysis for short term or long-term effects should be performed.

A failure or error in wind farm control may result to short term / immediate failures e.g. through extreme loads or deflections beyond the design limits. But errors may result in long term effects e.g. fatigue or crack propagation which need consideration since they may result in a catastrophic failure at a later stage. In addition, a suboptimal power production due to farm control system malfunction need to be recognised. Important services need to be monitored and two work streams should be considered as shown in Figure 31.

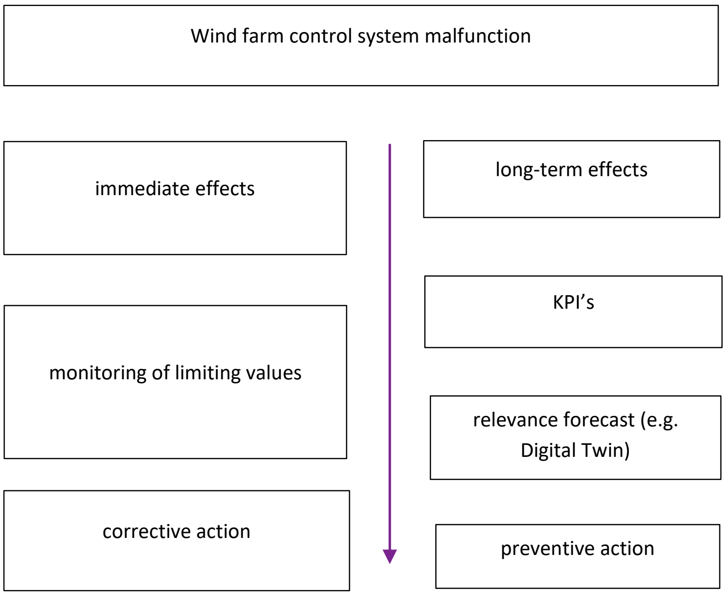


Figure 31 Short and long term effect monitoring workstreams (DNV GL)

Since the parameters involved in a farm control system are multiple and the monitoring may be complex, a robustness check should be performed during design. Within this robustness check a systematic variation of governing parameters of the wind farm control should be performed and the effect on the system analysed to identify critical situations and the response of the wind farm understood as per IEC 62443. Based on the robustness of the system preventive and corrective actions may need to be determined.

6.3 Regulatory 'sand-box' approaches

Regulatory sand-boxes are mechanisms by which a particular regulatory agent provides companies with an exemption from the obligation to comply with existing regulation in the context of a particular project, usually associated with real world trials of new products or services. In the financial services community for instance, a regulatory sandbox is understood as 'safe space' in which businesses can test innovative products, services, business models and delivery mechanisms without immediately incurring all the normal regulatory consequences of engaging in the activity in question [109].

In the space of energy markets as well, a regulatory sandbox allows a small, temporary trial for new products, services, and business models in a real-world environment where some rules have been temporarily removed. Each trial will run for a set period with a limited number of customers. The trial is also expected to have explicit learning objectives to test the viability of the model. At the end of the trial, all rules will apply as normal once again. The innovator will report what it has learnt, and the regulator will consider the results during future policy development [110].

The sandbox service currently available in the UK for instance, can support innovators in delivering trials, or entering the market with a new product or service. Each trial will run for a set period of time with a limited number of customers. The trial is also expected to have explicit learning objectives to test the viability of the model. At the end of the trial, all rules will apply as normal once again. The innovator will report what it has learnt, and the regulator will consider the results during future policy development.

<u>Trials:</u>

- An innovator may want to trial (or pilot or demonstrate) a new proposition in a live operating environment but are concerned about how the rules apply to them.
- The sandbox could provide bespoke guidance on what the rules would mean in their specific trial circumstances. Or, it could provide comfort about our approach to enforcement for the purposes of a trial.

<u>Market entry:</u>

- An innovator may have developed a product or service and are near market ready, but investors and customers are not clear that what they are being offered is permitted. The sandbox will not endorse a specific product or business but can confirm whether a type of activity is permissible.
- Alternatively, an innovator has identified a specific rule that is blocking their proposition and wants to explore what flexibility might be available (by way of derogation) for temporary or enduring relief.

The sandbox is for innovators who already (or intend to) operate in a regulated energy market. This does not mean that only licensees (generally speaking, holders of generation, distribution and supply licences) can benefit, but in most cases an innovator wanting to run a live trial either has to be a licensee, work with a licensee or be a party to industry codes that allow them to participate in the system.

In the UK for instance, one of the main changes is the range of tools that have recently made available to serve regulatory sandbox related trials. The Balancing and Settlement Codes (BSC) and the Distribution Connection and Use of System Agreement (DCUSA) both have recently set up sandbox capabilities [111],

[112]. The forthcoming Retail Energy Code (REC) is expected to hard-wire sandbox flexibility, and the Code Administrators have adopted an innovation principle as part of their collective Code of Practice (CACoP). Innovators are free to apply to Ofgem's Innovation Link for sandbox support. This is an open-access service, available at any time, and that keeps a one-stop-shop principle where the regulator offers a single point of entry for innovators guaranteeing coordinate support from the code bodies. The experience during the first three years of operation has allowed innovators to make use of the mechanism to fast-track pilot projects on peer to peer local energy trading platforms, and obtain feedback on open consultations for the co-location of wind and electricity storage assets at a point where the implications of this co-location on running RES incentives was not clear.

This type of initiative could have in accelerating the commercialisation of new wind farm control products and services. However, bearing in mind recent power system events however, like the frequency event in August 2019 that involved the automatic disconnection of a significant amount of wind power (see Figure 32 below), and the subsequent forced disconnection of millions of customers, these trials are likely to require 'small scale' demonstration projects first. In some cases, certain exemptions from the connection agreement conditions that are agreed with the system operator, and allowed by the regulator, may be one of the tools required by the industry to try new WFC products and services in a safe and efficient environment before bringing them formally into the marketplace.

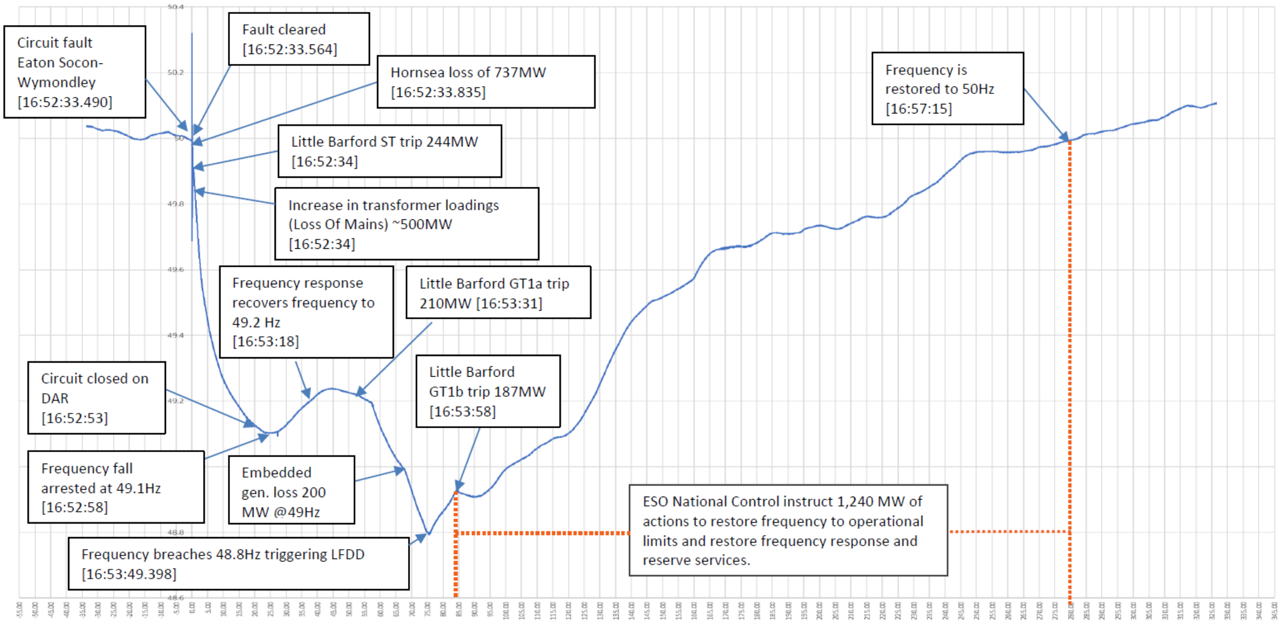


Figure 32 Annotated frequency trace of the partial black-out event in August 2019 (NationalgridESO)

It is reasonable to expect an increase in the number of test and validation projects and trials at a smaller scale, and possibly onshore. This will allow the industry trying new wind farm control solutions and services in the controlled environment that operational assets can provide and controlling the risk that first adopters incur when planning and delivering these first trials.

7 Conclusion

The installed wind power capacity in Europe has increased significantly over the past two decades and the total share of electricity produced by renewable sources in the European electricity generation mix is just shy of 30%. The push towards net zero decarbonisation targets has led to the gradual phasing out of traditional coal power plants and the restructure of the electricity markets in the industry moving towards a more decentralised system of electricity generation. The paradigm thus has shifted making way for increased the participation of wind power in the electricity generation mix.

With increased participation of wind within the electricity grid and markets comes its challenges on how wind farms can be appropriately controlled to optimise its operation over a lifetime whilst ensuring the compliance to grid codes, the safety and structural integrity of the wind turbines and the connection of the wind farm to the electrical network. This requires existing and new wind farm control concepts (WFC) in theory and practice to be implemented which covers aspects of the network control, of the electrical infrastructure and the control of wind farm flow dynamics around the wind turbines.

The current state-of-the-art with the wind power plant (WPP) control is not adequate to take on these challenges and is built with the conventional functionalities that receive setpoints from the whole wind power plant (WPP) from the 'Relevant Network Operator' (RNO) and would distribute when required equally to all the wind turbines. Such approach with the WPP controller does not interfere with the independent, optimised control of the individual wind turbine (wind turbine), and as such blades pitch and yaw control the which is required for advanced wind farm control techniques such as wake steering can't be implemented.

The task for the industry is to help advance the development of wind farm controllers that are fit for purpose in existing and new markets and progress existing and new control concepts of wind farm control into commercialisation. There are certain key areas which this position paper discusses and looks at which would pave the way for wind farm control to progress towards commercialisation in the industry.

One of the key aspects is the current regulatory landscape around the certification and standards. For the certification of wind farms, either the IECRE [3] scheme or the DNVGL scheme [4] applies. In both there is a provision to include wind farm certification, but no clear guidance about how this should be performed. Certification and standards also do not cover novel control strategies for wind farm control, and if these are to be applied in future, it will have a characteristic influence on the loads of each individual turbine within the controlled wind farm. The design limits also for loads are typically defined by a type certificate (for the Rotor-Nacelle Assembly RNA) or by a project certificate (for site specific support structures or a wind farm project certification) and new methods to assess this for wind farm control need to be established.

From a standards point of view with wind farms, the IEC 3rd edition offers two possibilities to assess the structural integrity of a wind turbine within a wind farm either by reference to wind data; which verifies the wind conditions at the site are covered by the environmental characteristics considered for the design of the wind turbine or by load calculations with reference to site-specific conditions. For the load calculations, the Frandsen methods widely used in this approach are not detailed enough to cover the complexity in the wake physics as this is empirically reduced to an increase in turbulence intensity. This presents some significant limitations as there is no explicit way to estimate partial wake effects. The Dynamic Wake Meandering (DWM) approach in IEC 4th edition provides an alternative method as this captures the key features of the wake with regards to wind turbine loads and power production, while maintaining sufficient computational speed for design calculations.

In spite of the aforementioned methods specified in the standards, its application to specific projects faces challenges such as how to calculate wake effects at all positions and the effect of the wind farm controller with pre-determined methods that don't account for closed loop control scenarios that deviate away from the assumed environmental conditions during the design process. The detailed load calculation at each position may also become extremely challenging and powerful strategy to quickly calculate the loads expected in a wind farm is required in the wind farm design.

Another other aspect which this position paper looks at is on the improvements to wind turbine and wind farm control functionalities in terms of the concepts of their control strategies and the challenges in integrating and implementing wind farm control into existing platforms.

For control strategies, there exist different control technologies that can be used within the objectives of optimising wind farm power production, reducing turbine loads and providing grid services. Axial induction control is the most popular in literature but comes with it challenges as wind tunnel tests and field tests call static induction control into question regarding wind farm power increase. Hence, its main applications are therefore currently intended for optimised life management in operation and grid services provision. Wake steering is another concept with yaw misalignment one of the promising techniques that has attracted significant attention, having been tested in real wind farms.

To integrate and implement these wind farm control strategies into existing platforms, a challenge arises in that research available in this area mainly focuses on the simulation of wake effects in wind farms and does not cover how these can be integrated in practice. The design philosophy also changes from the conventional norm and new designs need be built around the understanding of the hierarchical importance of the protection functions and grid codes in the design requirements. Potential conflicts between the wind turbine and WFC needs to be resolved whilst fulfilling the normal operation of the wind turbine, as the WFC may influence the behaviour of the wind turbine during active power and fault ride through (FRT) situations. The time scales of different approaches also need to be considered with regards to how they react to events related to the electrical network and events relating to the meteorological phenomena, flow conditions as this vary over different time scales (mins/days/years).

The final aspect this paper addresses is the ability for wind farms to participate within the electricity markets. Access to the electricity markets will depend on the robust WFC that can coordinate the control actions within the windfarm to adhere to the market participation rules while abiding under the grid codes and the normal operation of the wind farm.

Getting towards solutions that allow for wind farm control, would require change to the existing regulatory structures to accommodate its application and proving its compliance with projects in existing and new wind farms in the industry This position paper proposes three solutions that may help bridge the gap in the aforementioned aspects in paving a pathway towards commercialisation.

1. **Temporary and conditional certificates:** To help with the issue around certification and standards, temporary and conditional certificates are proposed. This approach is presently developed by DNV GL (DNVGL-SE-0190) and modifies the conventional Site-Specific-Design-Assessment (SSDA) to include additional inputs with wind farm control strategies. The step-by-step approach assesses windfarm control by plausibility checks and issues the SSDA under specific conditions that involve monitoring based on measurement plans, yearly evaluation reports and load validation based on measured data. Provided the results are acceptable afterwards, a revised SSDA is issued. This offers a step-by-step approach that helps gets the approval of new models of wind farm control in projects.

2. **Risk based Certification:** To help assess safety concerns, risk assessment for wind farm control can be carried out with certificates issued out. DNVGL-ST-438 [6] proposes a four-step approach that identifies the protection functions, determines the required performance level and designs document the protection functions. Other alternate approaches suggested that could be adopted are technology qualification is a method for the assessment and certification of novel technologies, as shown within the INNWIND.EU [107] project and other methods used from other industries such as the maritime industry as defined in the DNV GL rules [108].

3. **Regulatory sand-box approaches:** To help ease regulatory barriers, sand-box approaches which provide companies with an exemption from the obligation to comply with existing regulations can be used. This provides a 'safe space' which allows a small, temporary trial for new products, services, and business models in a real-world environment without the hassle immediately incurring all the normal regulatory consequences. For instance, the UK recently made available regulatory sandbox related trials in the Balancing and Settlement Codes (BSC) and the Distribution Connection and Use of System Agreement (DCUSA). This type of initiative could help foster the implementation of new wind farm control applications in electricity markets.

Achieving the commercialisation of wind farm control would require a joint effort within research institutions, academia and industry. This paper has detailed aspects which we deem are concerns that if tackled and responded to, will help pave a path towards commercialisation. However, we recognise the journey towards commercialisation covers other aspects such as the hardware and software infrastructure and would be required and - will require - an effort from industry to retrofit this into new and existing systems. There's also the need the fast track innovative and new solutions that will be in the lower TRL levels move then them further up through testing and validation and into commercialisation.

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