Dynamic repositioning in floating wind farms

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1 Summary

The potential for harvesting Norwegian offshore wind power resources is undoubtably tremendous, however, currently limited by the cost of energy especially at deep waters. A general challenge for wind power production is the so-called wake effect, in which up-wind turbines shadow downstream neighbours. When moving into the domain of floating offshore wind power, the fact that turbines are not fixed to the seafloor may open new opportunities. Specifically, the ability of moving downstream turbines out of detrimental wakes may allow for higher energy output than for fixed turbines with the same spacing.

Simulation studies described in the literature suggest that horizontal repositioning of floating wind turbines as the wind direction changes could be an attractive option to increase the power output. In the present study, simple simulations using readily available tools confirm this. Further, the potential gain of vertically displacing individual turbines has been investigated in current simulations, complementary to other studies in the literature only considering horizontal repositioning.

The current study has been organized in three main activities. First, an initial study with simple simulations and engineering type wake models has been performed. In this, the possible energy gains of horizontal and vertical repositioning of downstream turbines has been evaluated. Through this, rough estimates were found regarding order of magnitude of movement required to achieve significant energy gains, both through simplified two-turbine configurations and more realistic wind park scenarios.

Second, a concept evaluation was done to identify main challenges and options relevant for implementation of the dynamic repositioning. Different floating wind turbine concepts were considered regarding horizontal and vertical movability, control mechanisms to enable displacement, mooring/anchoring requirements, cabling etc. The evaluation also included an assessment of existing simulation models for wind field description and energy production, including turbine interactions, and dynamic properties such as turbulence intensity and its impact on structural loading/fatigue. When introducing the additional degree of freedom of varying turbine position, there is a clear need to deploy simulation tools that can accurately capture the wind field dynamics and at the same time be sufficiently fast for frequent wind field updates.

The third activity has been on defining a full research project to bring the concept closer to industrial realization. This includes description of state of the art, project contents and organization. In the proposed project, the focus is on modelling of the wind field and turbine dynamics, development of optimization tools and methods for assessment of cost/benefit, and establishing software tools for case studies and concept evaluation.

It is believed that there is a great potential of the proposed concept of dynamic repositioning the floating wind turbines relative to each other, but there is clearly a need to bring this a step further through in-depth studies, development of new methods and qualification of technical and economic implications.

2 Table of contents

3 Introduction

3.1 Offshore wind power potential

According to a recent publication [3], the Norwegian offshore wind annual average energy production potential (AEP) can reach more than 12 000 Terra Watt hours per year. This makes the Norwegian offshore wind AEP hundred times larger than the currently available hydro energy. According to the same study, Norway has the world's second largest AEP behind Australia and is ahead of countries like Argentina, Brazil, Chile, and China.

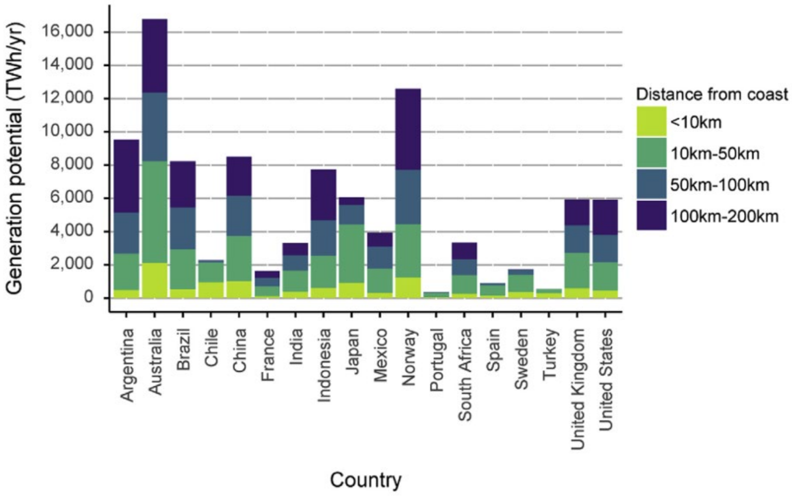

Figure 1 Average annual energy potential (AEP) for selected countries per 2018 [3]

Offshore wind farms are increasing in popularity for many reasons. The most important reasons are high wind energy potential and less acoustic and visual disturbance. However, offshore wind farms are deployed in challenging conditions which require higher installation and maintenance costs. Consequently, offshore wind farms need to be well designed and controlled.

Research in the field has to a large extent been focused on prediction tools for wind farm design. The general design framework roughly addresses site selection based on annual wind rose and turbines layout for a maximum power production. In that respect, a study performed by [4] has shown that in some cases irregular layouts can perform better than gridded layouts due to the large variations of the wind conditions. More recent research [5] compared different wake models with lidar measurement for yaw control purposes. The control is mainly on the turbines' plane of rotation relative to the wind direction (yaw angles), and the blades' pitch angles which in turn affect the power production of not only the controlled turbines but also other turbines downstream due to changes in the wake characteristics. An earlier work [6] has indirectly considered the effect of turbine height changes through the impact of waves on power production and implemented a prediction tool that couples wind and waves dynamics.

The optimum placement of an individual turbine in a park will, principally, change with the wind conditions. Thus, to operate the wind farm closer to its global optimum requires moving the wind turbines in relation to each other. To do so in practice, critical areas of research are necessary to find out how floating wind turbines can be modified to enable and characterize the control of turbines horizontally and vertically, an option not available for bottom fixed turbines and therefore not deployed yet.

3.2 About the current study

Offshore wind energy has great potential and can contribute with renewable power with less area conflicts and higher energy production per turbine compared to most onshore wind projects. However, harvesting available wind energy at deep waters – a particular concern in Norway – implies utilizing floating structures. To date, the cost of floating wind power cannot compete with that of bottom-fixed installations at shallow waters and therefore technology development is necessary to develop cost-effective wind power at water depths that are not currently exploited.

Clustering wind turbines in close proximity (forming wind farms) offers benefits in terms of reduced cost of grid connection, installation and area use. From an operational perspective, however, such clustering creates aerodynamic interactions between individual turbines, diminishing the overall energy efficiency of the wind farm as a whole. Downstream turbines experience so-called wakes generated by viscous interaction along the blades of upstream turbines, causing decelerated incoming air flow. This wake effect may result in significant annual wind farm production losses, even when turbines are spaced relatively far apart.

The idea of repositioning floating turbines relative to each other has been conceptually described in literature, including preliminary studies on potential gains of such a strategy. However, there is an apparent need to clarify a number of issues before the concept can be termed qualified for field application. Some of these issues have been studied and discussed with relevant competence groups, and results in terms of a suggested future research project are presented in the following. This includes assessment of areas of improvement to reach the desired positioning dynamics. Furthermore, the study covers the required competences, engineering services, industrial actors, and academic collaborations to develop a complete project.

Through initial investigations performed at NORCE, the concept of dynamic repositioning the floating wind turbines during production has shown promising results. This way, turbines can be moved out of wakes as wind direction changes, offering higher energy production compared to the conventional solution of installing turbines at fixed positions. Similar results are presented by other research groups studying the concept of relocating turbines [1] [2] . However, existing studies have only to a limited extent addressed issues such as technical solutions for moving the floating structures, implications regarding load on floaters and turbines, understanding of the wind field when reconfiguring the placement of turbines, optimization strategies including a complicated set of constraints, etc. Further, published studies include only horizontal displacement of the turbines. In the current and ongoing investigations lead by NORCE the possibility of vertical displacement is also included.

The target of the current project has been to perform the necessary pre studies to position the research community and industry to prepare a complete research project proposal. The pre-project is aimed towards acquiring more details on existing technologies and determine the size and extent of a main project. Specifically, the sub goals are:

- Evaluating the potential for dynamic positioning of floating turbines
- Assessing the energy production gain using state-of-the-art wind farm simulation models
- Investigating methodology for validating/testing the concept
- Establishing a strong consortium for a main project

The finalized pre-study will in the next stage be used as a base for the further work on a project application sent to the Research Council of Norway through their research program ENERGIX and/or relevant EU calls.

In addition to the VRI funding, the authors acknowledge the significant internal NORCE funding that has been allocated to the present studies. In addition, input from industrial partners and contributors from the University of Stavanger and University of Bergen are greatly appreciated.

4 Initial Study

This section illustrates the potential energy gain when dynamically positioning floating wind turbines. We have performed the study using simplified wake models that are implemented in the open source package [7]; Jensen [8] and a Gaussian wake model [5]. These models have the advantage of being computationally fast but at the cost of prediction accuracy. Nevertheless, simplified models can quickly estimate the power generation of an entire wind park given wind speeds, and in some cases wind directions. This study exploits the computational efficiency of these models to assess the power gain potential by moving wind turbines on the horizontal and vertical planes. However, we do not consider variable wind direction, wind turbine maintenance costs, turbulence effects, or any other phenomena that would influence the power gain/loss estimations.

4.1 Turbine properties

We use the generic wind turbine NREL 5MW [9] with properties illustrated in Figure 2. The NREL 5 MW turbine has a hub height of 90 m and blade length of 63 m (turbine diameter 126 m). The power production of the wind turbine is approximated by $P = \frac{1}{2}\ A.\rho.C_p\,.u_w^3$, where A is the rotor swept area, ρ the air density, C_p the coefficient of power, and u_w the wind speed at the rotor height. Each of $A, \rho, and\ \ C_p$ are considered as given, while u_w is only known at the wind turbines that are not exposed to wake. The wind speed for turbines in the wake must be estimated by a wake model.

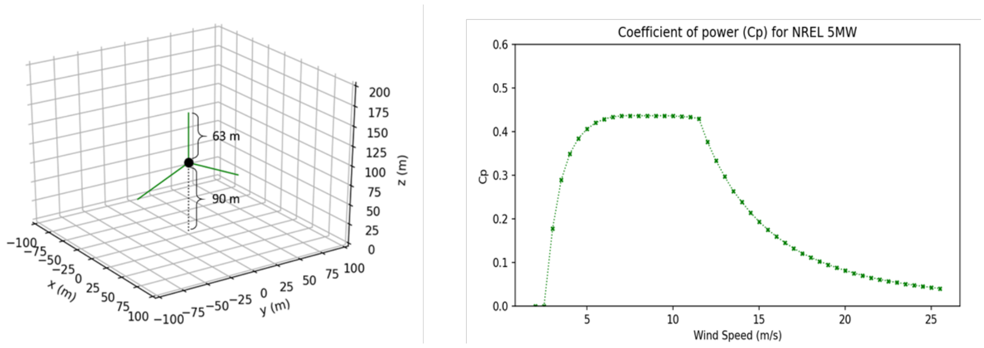

Figure 2 Properties of the NREL 5 MW wind turbine

4.2 Impact of turbine displacement along *X Y*

For simplicity, we define a scenario with two wind turbines and place the downstream turbine at the positions (red crosses) shown in Figure 3. For each location we apply two different wake models; a gaussian model and a traditional model called Jensen. The Gaussian model is generally considered as more accurate and came as an improvement to the traditional Jensen model. As the figure illustrates, the main difference between the two models is on the estimation of the wind velocity deficit. For the interested reader, a comparison study can be found here [5].

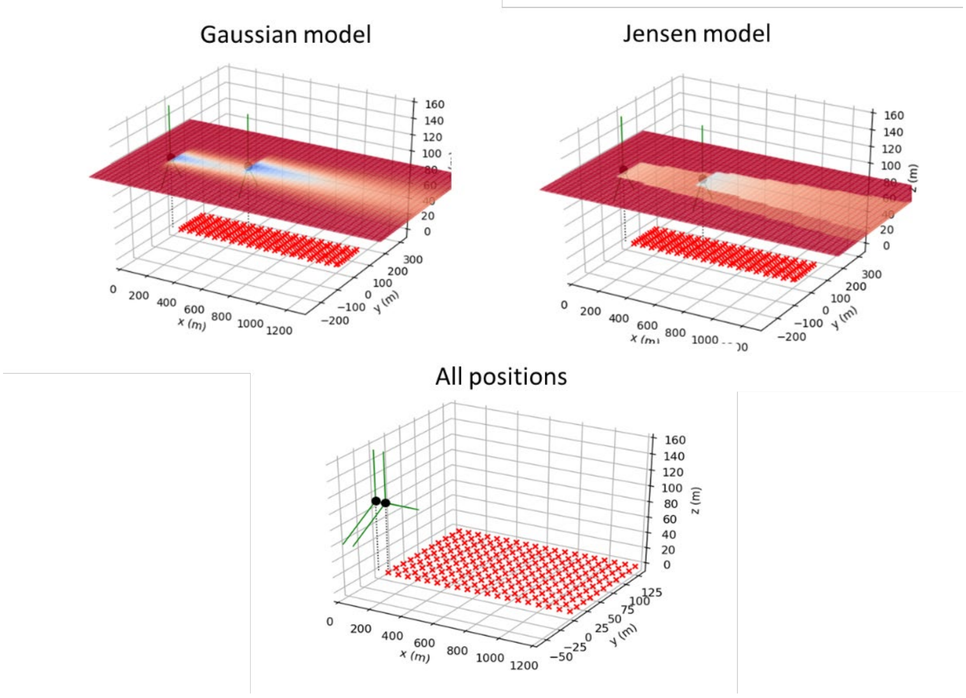

Figure 3 Two turbines scenarios

Furthermore, and for the sake of illustration, we apply a constant wind speed of 12 m/s facing the turbine at the front. The results are shown as a colormap in Figure 4, and a cross section plot of power generation in Figure 5. The first thing to notice is that the wake models provide different results but agree qualitatively on the effect of displacement along *y* axis. From the colormap we can notice that moving the downstream turbine by ½ a diameter will on most cases increase the power production by a factor of 3.

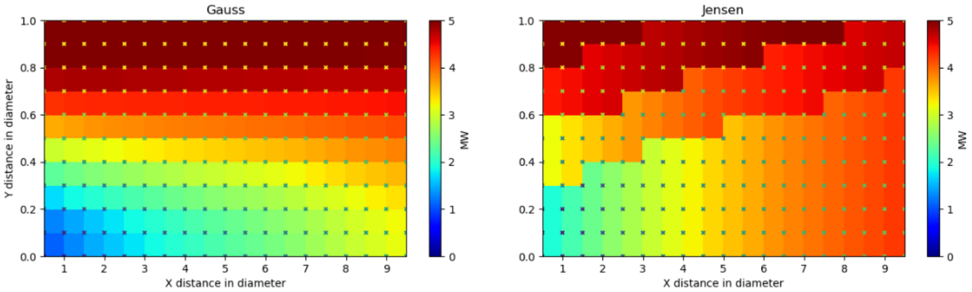

Figure 4 Colour map of power generation of the downstream Turbine on the horizontal plane

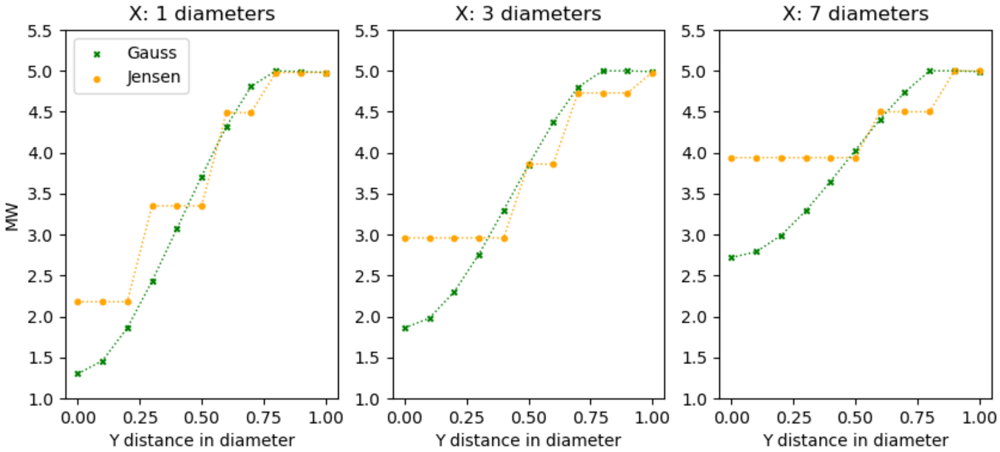

Figure 5 Horizontal cross section Power plot of the downstream Turbine

4.3 Impact of turbine displacement along *Y Z*

We run a similar scenario as the one with the horizonal plane but this time we include a vertical movement by lowering the wind turbine at the front and elevating the wind turbine at the back as shown in Figure 6 and Figure 7. The delta height on the plot is equivalent to the height difference between the two turbines. We can notice that the height impact on power production starts becoming visible when the difference of height is more than ca. 15 m. This limitation is probably due to the grid size used in the simulation. Note that fine tuning the simulation grid is not within the scope of this study and would require additional effort to get a more in depth understanding of the Floris simulator. However, this limitation emphasises the need of having a flexible and easy to use simulator for studying various wind park configuration scenarios with various levels of details.

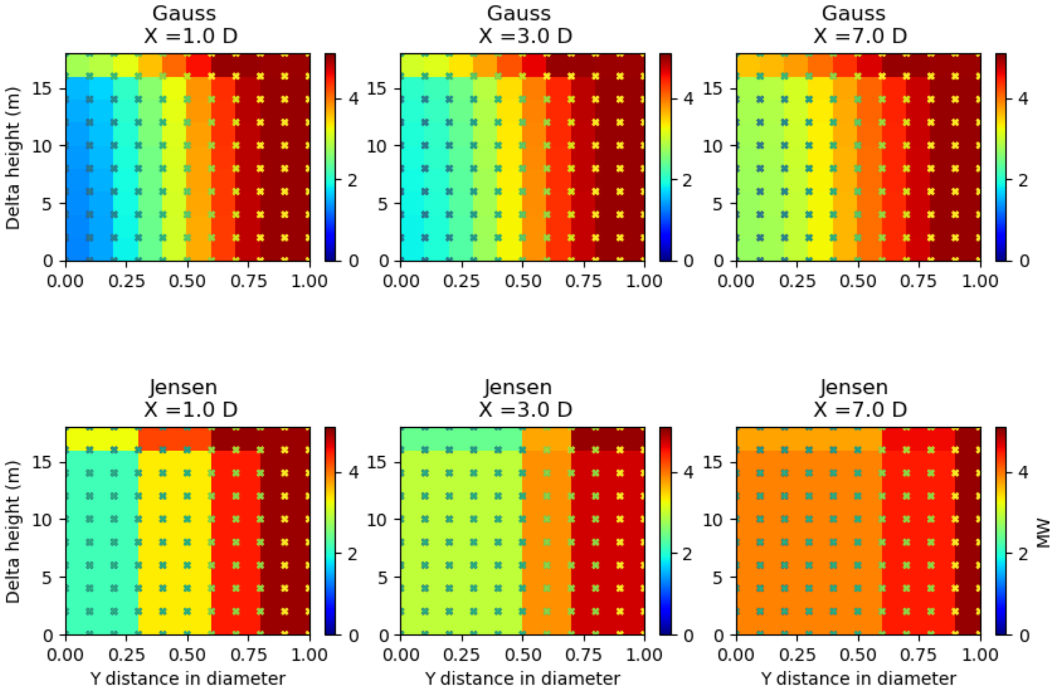

Figure 6 Colour map of power generation for the vertical displacement

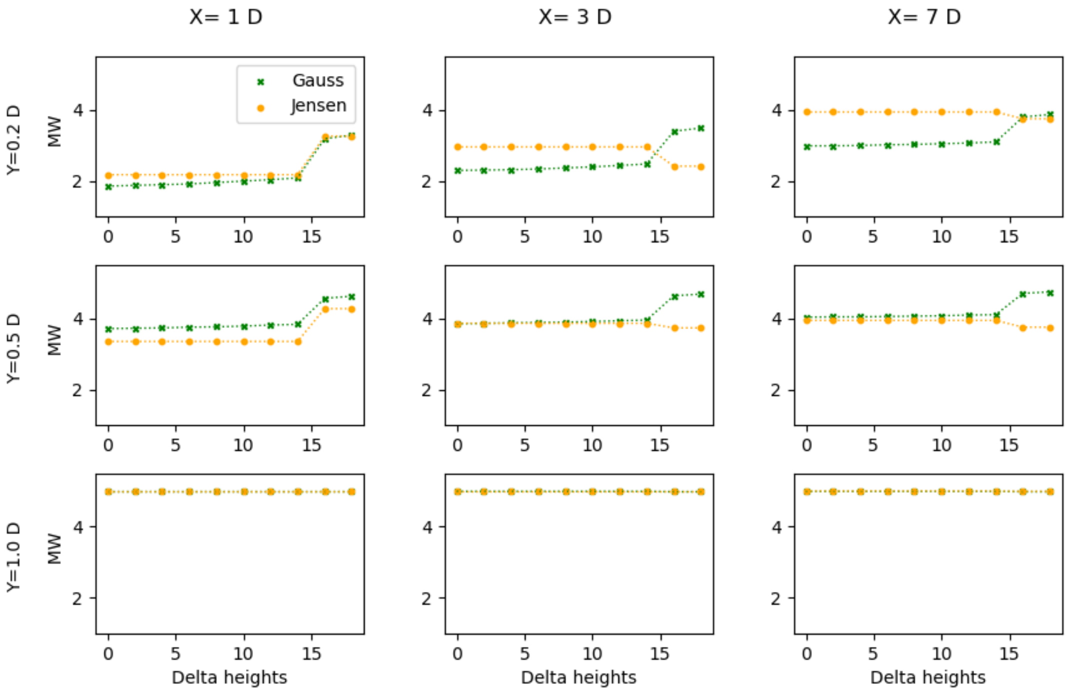

Figure 7 Cross sections for vertical displacement

4.4 Simulation on 5 x 5 wind park scenarios

Finally, we run three simulation cases using only the Gaussian wake model. We started with a worst-case turbine layout in which the turbines upstream perfectly shadow those downstream. In the second simulation we systematically move every other row one turbine diameter along the *y* axis. Finally, we reduce the heights of every other row by 10 meters and elevate the remaining turbines by 10 meters. We assume a fixed wind direction with variable speed for a characteristic wind sample. Using a wake model, we estimate the wind speed reduction (the wake effect), which in turn is used to calculate the power generation for the entire wind park. Figure 9 shows a comparison between the three scenarios. Notice that the power production is more than doubled with 1 *D* displacement along the *y* axis and further improved with up to 10 % with a vertical displacement (see Figure 10).

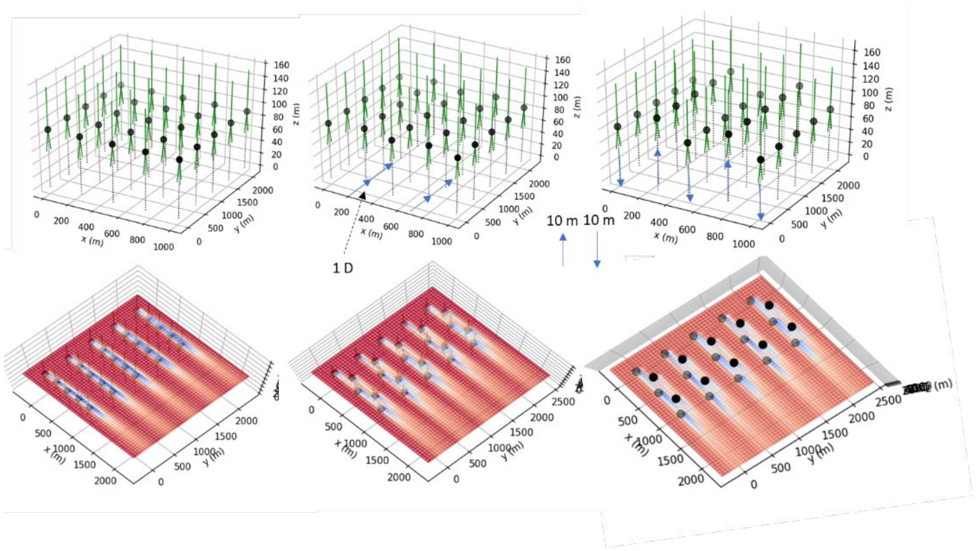

Figure 8 5x5 different simulation layouts

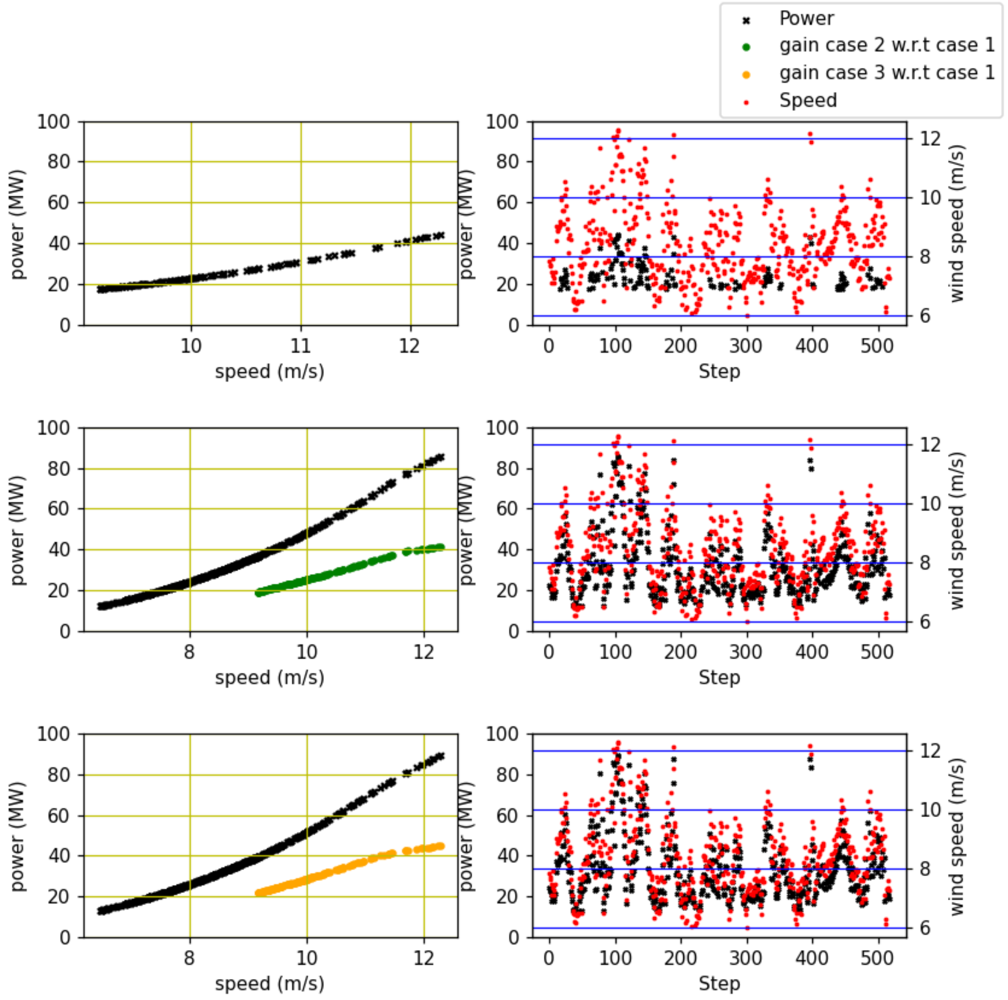

Figure 9 Power generation for 3 scenarios

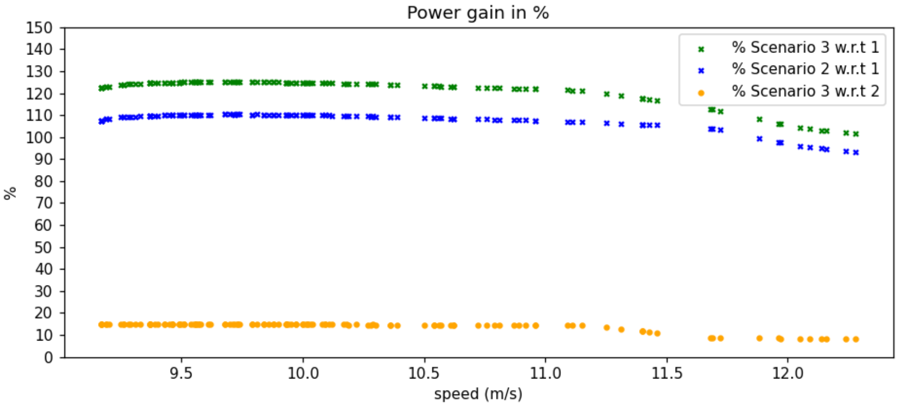

Figure 10 Improvement in % from scenario 1 to 3

5 Concept Evaluation

The current study is about introducing additional control opportunities for a wind farm by enabling displacement of individual turbines. The investigations have been focused on what kind of developments that need to be done to achieve the expected energy gains when assuming that turbine displacement is possible. Coarse and initial studies have indicated overall energy gains well beyond 10 %, but this needs to be verified through further research.

In the present pre-study, the following topics have been addressed, paving the way for the contents of a full research project described in more detail in section 6.

5.1 Evaluation of automatic positioning of floating turbines

There are several conceivable ways of achieving movement of the floating turbine structures. However, some fundamental aspects should be obtained. The method should be robust, energy efficient and allow for sufficient spatial accuracy. However, all these concerns need to be part of a cost/benefit analysis.

In the following, initial considerations and assessments are presented regarding possibilities and limitations of different strategies and methods. As a minimum requirement, any method for repositioning the turbines should at least yield higher energy output than the potential penalty of moving the turbines – when assessing accumulated energy output over a certain period. In addition, one needs to make sure that additional structural loading causing e.g. maintenance and fatigue issues is considered in terms of overall system performance.

For *vertical* motion, the most apparent method would be to use ballast tanks and water pumps to vary the buoyancy of the floating structure. This is well-proven technology, but the available lifting/lowering range and required dimensioning (tanks, pumps etc.) should be clarified for given floaters. As an initial approach we can estimate the energy requirements of 10 m vertical displacement by considering the pumping energy of different floating structures – see TABLE 1. Not surprisingly, the energy cost of vertically moving the slim spar buoy is much less than for structures of bigger water plane area. Therefore, the effectiveness of vertical displacement of spar-based turbines is apparent. However, the energy gained by vertically moving wind turbines out of the wake may imply that the approach could be relevant also for the other floating structures. For instance, if a 6 MW turbine is de-rated by 10 % due to wake effects, the penalty is 600 kWh per hour. Spending pumping power may therefore at least be worthwhile when wind directions are relatively stable for, say, more than a day.

Design considerations regarding ballast dimensioning and their safe operating limits for the entire structure (e.g. consequences of changing the centre of gravity) have not been included in these preliminary calculations. Depending on available space and weight limitations, the ballast pump should be selected depending on the properties of the floating structure. A small pump may well be suitable as we do not expect rapid movements to be required. For instance, a pump of 70 m^3/h capacity will spend about 4 hours to move the spar (OC3) downwards by 10 m. Such a small pump could be relatively easily fitted even on the spar platform.

Cost and reliability of ballast pumping systems are considered not particularly challenging, especially when allowing for relatively low pumping rates, i.e. low vertical movement speed.

In principle, jack-ups may also be using for vertical motion. However, these machines utilize the pinion and rack system and therefore involve large contact stresses which in turn limits their applicability as they are typically not designed to last many runs.

Table 1 Energy cost of vertical motion by ballasting for different floaters[1]

	@ SWL	Water plane area (m^2)	Volume of water (m^3) (10 m vertical movement)	Energy consumption[2] (kWh)
OC3 (spar)	D6.5 m circle	33.2	332	90.5
OC5 (semi-sub)	3 x D12 m circles	339.3	3393	924.6
MIT/NREL (TLP)	D18 m circle	254.5	2545	693.5

Horizontal motion can be achieved by adjusting the mooring lines' lengths through winching to achieve pulling force in the desired direction. This approach may be utilized on individual turbines or groups of turbines, e.g. every second row, thus allowing for (partly) synchronized motion if beneficial. Mooring line lengths, number of lines required (vs. fixed positioning) are among the points that should be investigated. The standard configuration would be to have three mooring lines for each floater, but it could be relevant to look at using more lines to increase the flexibility in positioning at a range of wind directions [2], showing that the effect of "yawing" is strongly depending on mooring line orientation vs. wind direction).

To implement mooring line winching to horizontally move the floaters, towing winches should be available on the floating structure. Winches could in principle be placed on separate floaters within the wind farm, allowing for "winch hubs" with several winches between the wind turbine floaters. However, this probably introduces both complexity and cost that points towards placing winches on the turbine platform. Even so, the question could be worthwhile investigating.

Placing winches on spar buoys could be challenging due to limited space. This should be studied in greater detail. For instance, rope or chain capstan systems (with vertical axis) systems with loose storage in the bottom of the spar could be an alternative to save size and weight.

Simple considerations regarding power requirements to move the floating structure suggest that the winching power is much less than the power rating of the turbine when assuming the turbines should be moved at relatively low speeds. This means that even minor power output improvements achieved by horizontally moving the turbine are paid back very quickly. Winches are generally reliable and not expensive equipment and are considered a significant cost driver in this context.

Another way of horizontal motion control could be through adjusting the yaw angle to be slightly different from the dominant wind direction, thus achieving sideways thrust on the turbine structure. The technique could be combined with pitching of turbine blades to manipulate the so-called axial induction. The feasibility of such a "Yaw and Induction-based Turbine Repositioning" has been discussed by [2], but mainly conceptually. Considerations regarding control opportunities have not yet been investigated. For instance, when using the yaw and pitch control to dynamically position

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[1] Courtesy of Prof. Yihan Xing, UiS

[2] Assuming 60 % pump efficiency, 60 m head

the floating wind turbine the ability to control the turbine’s loads may be diminished. If this is the case beyond the displacement phase, severe fatigue loads may be introduced. These are some of the complex questions that need to be studied in detail.

The means of motion control can be applied independently of each other, or in combination to achieve the best overall effect. The approach could be to develop control systems that are primarily passive or active – the optimal solution has not yet been identified.

Compared to fixed-position turbines, the mooring line length needs to be extended for turbines with ability to move horizontally. This means some additional cost, but probably a relatively modest contribution. In-depth studies need to be performed to assess the proper mooring line configuration in terms of line length and weight to ensure sufficient movability and appropriate stiffness for stability and control purposes.

Figure 11 gives a brief overview of the main control mechanisms for different floater designs. It should be noted that this only gives coarse suggestions and should not be used to exclude other options at this stage.

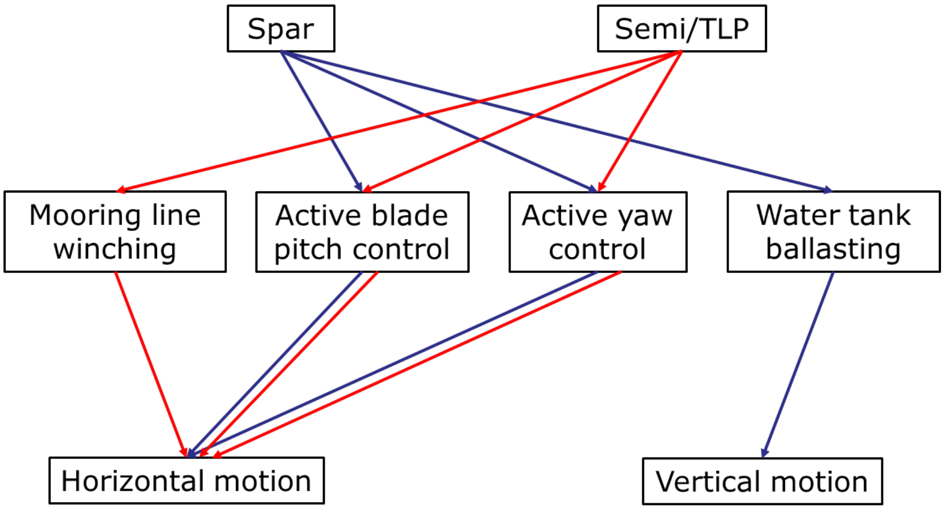

Figure 11 Main control mechanisms illustrated schematically for different floater designs

The challenge of cabling clearly becomes more pronounced in a configuration of floating structures that are to be connected through the grid from a range of possible positions. However, it is believed that as improved-performance flexible cables are being developed for floating turbines, suitable cables will be available for the application at hand here.

Regardless of which concepts are brought further, close collaboration with industrial partners working on floating structures, mooring systems etc. is essential to investigating the potential of dynamic repositioning.

5.2 Evaluation of potential of existing simulation models

Wind field simulation is a large scientific area, including a variety of models to calculate wake losses inside the wind farm – with different levels of accuracy. Models range from simplified engineering type to sophisticated high-fidelity solvers of the complete wind field. Without the option of reconfiguring the placement of the turbines during the production phase, the conventional approach is to use wind field simulations in the planning phase, thus establishing the optimal placement of turbines given the wind conditions of the location (represented e.g. by an annual wind rose). All turbines are assumed to be facing the wind direction, and wake effects typically only include downstream air speed reduction.

For the present concept of dynamic reconfiguration of the wind park layout, including wind field effects caused by moving turbines and manipulating yaw and pitch angles for sideways thrust, simulation models should be sufficiently capable of capturing the complexity of the wind field. On the other hand, detailing generally comes at higher computational cost, suggesting that near real-time recalculation of the wind field may not be performed with conventional solvers. It is essential to employ simulation tools with sufficient accuracy and great flexibility, allowing for fast updates that can serve as input for the problem of finding a (near) optimum global turbine placement configuration.

Available tools for wind field simulation have served as a basis for pre-qualifying the concept of dynamic turbine repositioning. Simplified turbine layouts and wind fields have been used to give indications of the value of being able to move turbines out of the wake of upwind neighbours, but an important step in qualifying the concept is to perform in-depth studies that capture more of the complexity and dynamics of turbine layout, wakes, change in wind directions etc. In this way, we can assess the value of the concept with more confidence. Further, optimization studies to find applicable strategies for realistic wind farm conditions heavily rely on capturing sufficient wind field detailing to achieve maximum overall wind farm performance (e.g. power output vs. structural wear). A key task is therefore the development of fast solvers for wind field dynamics as turbine placement changes during operation.

5.3 Discussion of concept validation

When qualifying the dynamic wind farm concept, it is crucial to validate simulation results against lab test results and – in the next phase – field tests. However, the complexity of the question at hand and the challenges of constructing relevant experimental setups for such a problem suggest that experimental validation should be done after concept and numerical studies. An experimental validation, even at reduced length scales, is also believed to be costly and does not come with certainty of reliable results. Therefore, in the first stage of developing the concept, numerical case studies, using models benchmarked against state-of-the-art ones, should be the main approach for validation. A description of an experimental test campaign could be one of the outputs of a full project.

6 Development of research project

The overall concept of achieving improved efficiency and reduced energy cost through dynamic repositioning floating wind turbines seems very promising, but clearly requires significant additional research prior to industrial deployment. The first step suggested in the present study is to develop a full research project, in which research topics and work packages are described, and potential partners are specified. In a longer-term perspective, such a research project is considered essential on the way to full industrial deployment – as illustrated in Figure 12.

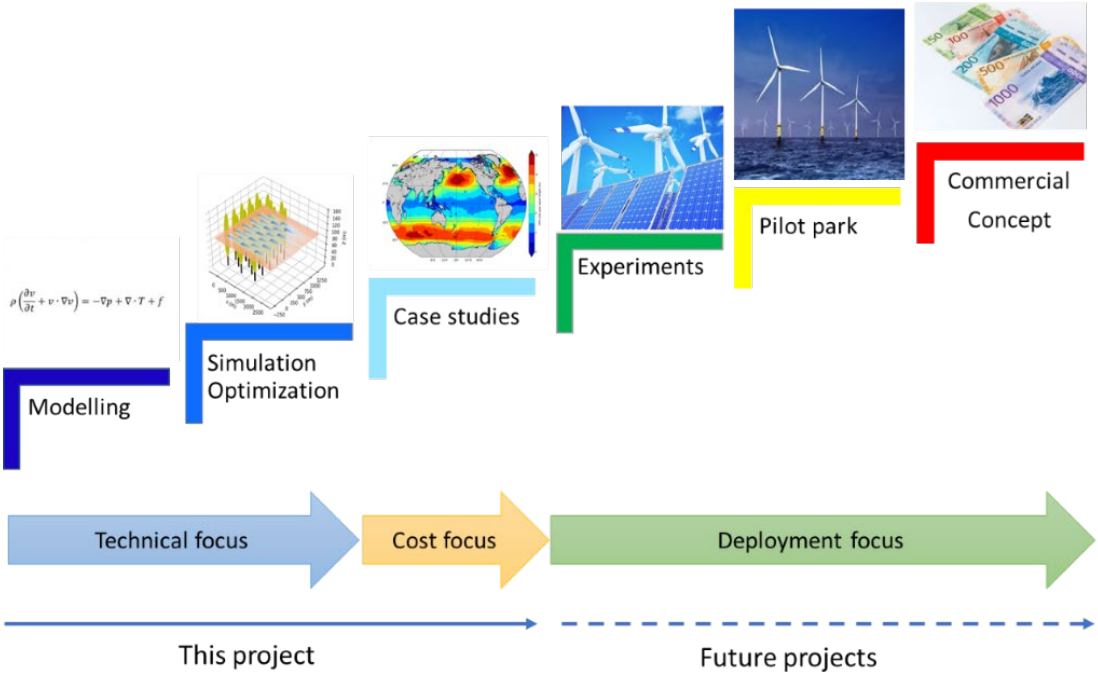

Figure 12 Project vision

6.1 State of the art and research questions

Existing floating wind turbines and wind turbines under development can be dynamically re-positioned. The main question is "How would dynamic position control work?".

To increase the power output, it is important that energy-efficient methods are used in the dynamic positioning (DP) of the floating wind turbines (FWTs). The proposal will study three energy-efficient methods in detail, (i) adjusting the skew angle of the rotor by utilizing the yaw actuator to move the FWT horizontally, (ii) adjusting the ballast by utilizing water pumps to move the FWT vertically and (iii) adjusting mooring line length by utilizing winches to move the FWT both horizontally and vertically. The methods can be applied independently, or a combination of the methods can be also applied. Combining the methods allows for customization to the different types of FWTs, different FWT sizes, wind sites and water depths. It is expected that the use of DP will result in increased dynamic loading for the FWTs. These are due to increased load imbalances on the rotor and changes in FWT global dynamics due to DP. The increase in dynamic loads due to DP should be quantified. Controlling the increase in dynamic loads is crucial to ensure the reliability of the machinery components and to limit extreme responses. In particular, the use of individual blade pitch control and active generator control to limit this increase in dynamic loads will be focused on.

Different relevant floating structures should be investigated with regards to implementation. First, the practical implications of applying the DP methods will be studied. Second, a fully coupled FWT model will be developed using general purpose state-of-the-art dynamic multibody tools. The entire FWT will be modelled in multibody simulation tools. The models are of high-fidelity and consist of flexible multibodies, complex bearing models and gear teeth models. The models will include more detailed models of the major components of the FWT, such as the pitch actuators, the drivetrain and the generator. UiS researchers have extensive experience in the use of these models in various applications [10] [11] [12]. Detailed fully coupled FWT models allow for the possibility of detailed description of dynamic loads which can then be used in first principle reliability and extreme value assessments. UiS researchers have been actively involved in previous detailed reliability studies of various types of wind turbine machinery components, including those on floating wind turbines. Examples of these can be found in [13] [14] [15] [16]. Additionally, load scenarios experienced by a single FWT in a wind farm applying DP will be established. This is to provide a modelling and analysis framework to use a single FWT model that can be integrated into a larger model of an entire wind farm. Finally, the load-effects caused by the DP methods with focus on the effects on reliability and extreme loads will be studied. UiS researchers have previously established first principle reliability methods for various machinery components in the wind turbines. Based on the detailed modelling, a simplified model suitable for use in a software implementation (see below) will be developed.

Furthermore, previous research has shown that the wind conditions offshore are often dominated by non-neutral conditions particularly around rated wind speed. This has a significant effect on the loads and response of floating wind turbines in the free-wind and in a wake situation [17]. In unstable atmospheric conditions (i.e., when the air temperature is cooler than the sea temperature) simulations and observations have shown that the spar type wind turbine has enhanced yaw motions and fatigue [18]. It is therefore important to define a wider range of non-neutral wind conditions particularly when using the yaw actuator to adjust the skew angle of the rotor.

From a wind field simulation perspective, the standard approach is to consider wind turbines to be at fixed positions and their turbines always facing the wind direction. In addition, the wake simulations only include down-wind air speed reduction caused by the wake behind turbines. Recently, more attention has been given to the operational performance of wind parks. As an example, [19] study the potential for improved performance by redirection of the wake. Large scale effects like the so-called blockage effect [20], i.e. up-wind speed reduction of the wind due to presence of turbines, will reduce the power output and needs to be accounted for in the design and operation of wind parks. Predictions of power production on scales of minutes are of importance to grid operators and the variations at these scales may be significant, see e.g. [21]. Such applications require advanced flow simulations ideally running faster than real time. Computationally fast codes may be obtained by simulating the Navier-Stokes equations by time-averaged approaches, such as Reynolds Averaged Navier-Stokes Solver (RANS) models, see e.g. [22]. However, to capture a more accurate load and energy production per turbine requires the representation of all relevant phenomena from the turbulence and shear profile in the incident flow through the detailed flow over the rotor blades, more accurate methods are needed.

In this project, we plan to employ lattice-Boltzmann (LB) methods [23] for solving the LES Navier-Stokes and energy equations [24] [25]. This is an alternative to finite difference, finite volume or finite element methods. One appealing feature of the LB algorithm is that it renders the strain field of the fluid directly accessible at no extra computational cost. This renders it an excellent choice for LES where the strain field is typically necessary in the calculations. Complex boundaries are also easily implemented. Due to some of its inherent features, the LB method is an excellent choice for parallelization when running simulations on parallel platforms such as graphics processing units (GPUs) or a cluster of CPUs. The LB algorithm is a general-purpose algorithm for fluid flow simulations, which means that it can be used for a diverse range of different fluid dynamical problems with minimal modifications. In its standard form, the LB method is an explicit finite difference scheme for solving the Boltzmann equation. And, as for the continuum Boltzmann equation, it can be shown to take the form of the continuum fluid dynamical equations in the long-wavelength limit.

For High-Reynolds-number and turbulent flow scenarios, so-called regularized LB methods have typically been used, due to its significantly enhanced numerical stability at moderate computational costs [26]. Newer approaches to LB simulation of LES [27] using the cumulant lattice Boltzmann methods [28] is also a good alternative to the traditional LB methods. [27] reports simulating turbine behaviour in wind fields with Reynold's numbers up to 107. Other LB-model approaches for turbulent flow include Large Eddy Simulations (LES) and Reynolds Averaged Navier-Stokes (RANS) modelling [24].

Our approach to simplify the simulations is to develop an efficient theory for describing the interaction between wind and turbines. In the most computational demanding system description, one will treat the interaction between air and turbines as a moving boundary problem. This means that one needs to track the surface positions and have a high enough spatial resolution of the boundary to get an accurate description of the geometry. To alleviate these computational demands, actuator line models have been developed, to account for the movement of the turbine blades using special tailored bulk forces introducing lift and drag as functions of the relative movement between blades and air. Here we will simplify this further by taking advantage of the local stress field calculations in the LB solver. This will allow us to treat the wind turbines as stress generators for the fluid fields.

To take full advantage of the flexibility offered by floating turbines at offshore wind farms, it is essential to operate them in an optimal way. Each turbine can, within certain limits, be moved both horizontally and vertically. Both the yaw and the pitch angles can be set according to the wind direction and strength. Adjustments to the position and the said angles have implications on the wake field behind the turbine, and thereby also on the wind harvest at other turbines. Finding all turbine positions, along with the yaw and pitch angles, that jointly maximize the energy production of the entire wind farm, is an extremely complicated task.

The optimization problem will be approached through two conceptually different methodologies, namely 1) Ensemble-based stochastic optimization, and 2) Optimization models built upon simplified wake models.

In the first optimization methodology, the wind field simulation model will be used to find the optimum wind turbine placement in the presence of uncertainty in wind forecasts, wake model, turbine wear model, and electricity production per turbine. We will solve the optimization problem using ensemble-based optimization (EnOpt). EnOpt is highly competitive (pragmatic and performing) approach for data assimilation [29] and control [30]. They are proven for geoscientific applications, having originated in the domain of atmospheric and oceanographic forecasting [31]. Forecasts are always uncertain due to data sparsity and imprecision. Furthermore, uncertainty grows in time due to model error and chaos. The lower importance of time-distant conditions (due to larger uncertainty) should be reflected in the cost function. This is inherent in the uncertainty quantification provided by the ensemble approach. Including uncertainty quantification in optimization problems makes the approach “robust”. The uncertainty will reside in the weather (wind) conditions, wind field and in the wind farm, turbines power generation, turbines wear, jointly will be subject to optimization, at certain time interval (hours, days, weeks, months). EnOpt method has been widely applied in petroleum research to find the optimal well positions and well controls [32] [33]. The performance of this method depends on multiple factors that should be investigated when applying to turbine positioning. For example, the dimensionality of the control parameters depends on the number of time intervals when the turbines should be repositioned, and how many turbines should be moved at a certain time.

The second optimization methodology will be focused on models in which a simplified understanding of wake effects is incorporated. That is, analytical wake models [19] [8] become an inherent part of the optimization model, and determine the wake effects as functions of exogeneous parameters (wind direction and speed), and endogenous variables representing the operation of the turbines. The strength of such an approach, is its ability to capture how the optimization objective (maximize energy production) depends on decision variables (e.g. turbine locations and blade angles). Its weaker side, namely that decisions must be supported by possibly inaccurate wake estimates, can be compensated by use of the wind simulator: Through adjustments of the parameters with which the wake models are equipped, it will be possible to make the simplified wake models coherent with the more advanced simulation tool, such that their wake predictions to a large extent coincide.

The work on this methodology will build on past experience and recent advancement in the field. Noteworthy contributions to the scientific literature on optimized wind farm layout, such as [33]. Associated solution methods adapted for the models will be developed. This will include both exact methods for non-linear integer programming, and fast, possibly inexact, metaheuristics.

6.2 Project structure and contents

A research project should include studies of possibilities and constraints regarding dynamic repositioning of floating wind turbines based on mechanical loads on structures and power requirements enabling movement. The displacement constraints will be integrated with wind field simulation and stochastic optimization to perform a reference study on electricity generation and wear for floating offshore wind parks, under certain wind conditions (past and forecasts).

To improve the effectiveness of offshore wind farms by dynamic repositioning of wind turbines in all directions, the project will explore the wind farm control optimization problem. The goal of the optimization is to maximize electricity production and minimize turbines’ wear, given present (requiring measurements) and forecasted (WRF) wind conditions, and of course mechanical constraints on the movements of the turbines. For layout optimization it is necessary to use a wind field model which is computationally fast, and sufficiently accurate with respect to wake effects (electricity production) and turbulence (wear). Finally, the inherent uncertainties of measurements, forecasts, power generation and wear models, suggest stochastic-based optimization which again requires computationally fast wind field model to be practical at all.

The project will target three interrelated objectives. Objective 1 is to answer how dynamic positioning can be mechanically achieved with existing and potentially emerging floating turbines. Objective 2 is to determine how the displacement affects the energy gain and wear. Objective 3 is to find the optimum displacement plan given various constraints on the speed of repositioning, effects on energy gain and wear, and uncertainty in wind predictions. The results of the research will be implemented as a software and applied to perform a reference case study using simulations, past and forecasted wind data for selected offshore sites.

The structuring of the objectives is suggested reflected on the work package (WP) structure of the project. In addition to the three targeted objectives implying specific WPs, a dedicated WP will couple results from WPs 1 to 3 through a software prototype implementation. This will enable case studies, possibly served over a web interface. The structure is illustrated in Figure 13.

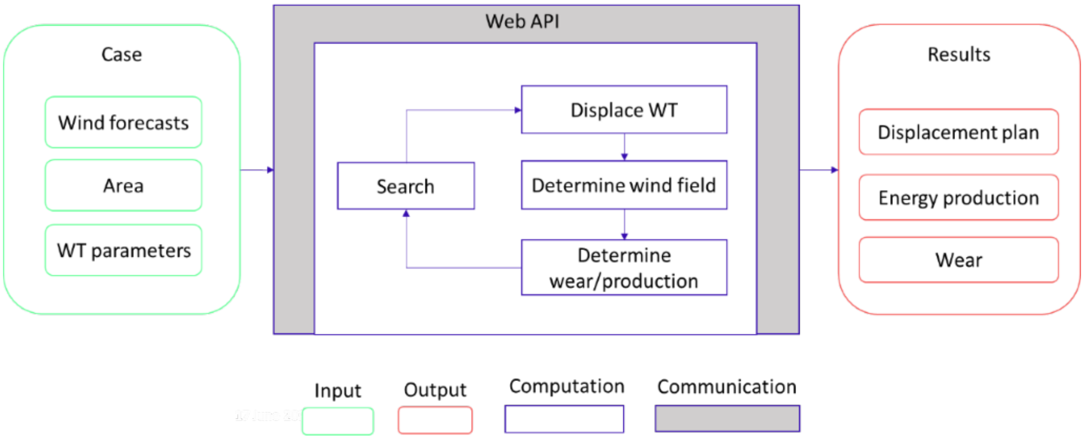

Figure 13 Scope of the prototype software implementation

6.3 Work packages and responsible partners

The preliminary structure and contents of a research project has been established, however, industrial inputs are still required and it is expected that revisions will be made prior to finalization. Based on the research objectives presented in section 6.2, the following preliminary work package structure has been proposed:

WP1 *Displacement characterization* will be focusing on how dynamic position control may work, both in terms of displacement methods and resulting loads on structures. A PhD project will be dedicated to the WP, which will be managed by the University of Stavanger.

WP2 *Fast wind farm simulation* will aim at obtaining fast wind field simulation, accurately capturing the wake effects and turbulence intensity, also when turbines are in movement. NORCE will manage this WP.

WP3 *Position optimization* will essentially target the question of optimal positioning of wind turbines, given constraints and wind field dynamics established in WP1/2, enabling maximizing of power production and minimizing of wear. The University of Bergen will manage the WP, and a dedicated PhD project will be part of the work.

WP4 *Prototype implementation* will integrate WP1/2/3 into a prototype dynamic wind farm software service, enabling case studies and qualification of the concept prior to the next stage of lab and field scale testing. NORCE will manage the WP.

In addition to the technical WPs listed above, dedicated WPs on project management and dissemination/communication will be developed as well.

The Federal University of Rio de Janeiro (UFRJ) has been included as international partner. The goal is to include other national and international partners during development of a full proposal. It is especially essential to involve relevant industrial partners.

A video conference workshop was held 7 December 2020 in which development of the concept into a full project was discussed. The following organisations were present:

- Aker Offshore Wind
- Seasystems
- PwC
- Cognite
- Core Marine
- Norwegian Offshore Wind Cluster
- University of Bergen
- University of Stavanger
- NORCE

7 Discussion and next steps

The present study has been on the concept of dynamically repositioning the floating wind turbines in a park relative to each other, showing that the potential of this approach is large and that the concept should be investigated further. Both vertical and horizontal motion can be achieved, but the type of floating structure will determine applicability, range, speed of motion, energy cost, structural loading and influence on other types of turbine control. In any case, the minimum requirement is that the gained power output outweighs the penalty of moving the floaters.

Initial simulation studies, as well as literature, suggest that the increased power output even by moderate movement of turbines out of the wake zones is substantial. However, more precise understanding and description of wind turbine interaction are major challenges and additional work should be done to accurately capture the wind field. This again needs to be done sufficiently fast to recalculate the total wind field as wind farm layout constantly changes with moving turbines.

Using wind forecasts and simulation tools to capture the wind field within the park allows for optimization of the placement of all turbines. The optimization study should include (changes in) power output, structural wear (e.g. due to turbulence), investment and maintenance cost and other parameters necessary to calculate the overall energy cost. It is believed that stochastic optimization methods are key to capturing the complexity of forecasts, wind field inside the park and structural loading.

The main method for validating the concept at the present stage is believed to be through further research and development focusing on studies and simulation. Experimental validation, especially of the interaction between repositioned turbines, is a very complex task which should probably performed at a later stage when more in-depth knowledge is acquired on the potential of the concept.

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