

FLOATING WIND JOINT INDUSTRY PROGRAMME

Large Static Pitch Angles

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LARGE STATIC PITCH ANGLES (LSPA)

Introduction

Static pitch angle refers to the tilt angle of the floating substructure. It plays a key role in the overall efficiency of a wind farm array and is therefore a highly discussed topic in floating wind, due to concerns about its potential impact on Annual Energy Production (AEP) losses and drive on design loads. This was confirmed in previous studies performed as part of Stage 2 Phase 4 of the Floating Wind Joint Industry Programme (Floating Wind JIP) that concluded that allowing larger static pitch angles (LSPA) of floating offshore wind turbine generators (WTGs) from an early concept design stage can reduce the levelised cost of electricity (LCoE) by enabling more compact floater designs, with associated reductions in cost. It was noted that increasing static pitch angles needs to be balanced with the resulting power production loss, along with the increased loads and motions during power production which could be experienced under high rotor thrust forces.

However, the effects of reducing the size of a floater are complex and Design Load Case (DLC) specific, depending on the dominant source of loading (e.g. wind, wave, coupling structural modes). Such changes can bring additional challenges including tower loads, blade clashing, and high rotor nacelle assembly (RNA) accelerations and can be heavily influenced by the WTG controller. It is also important to understand the subsequent impact of a particular concept at a farm level, allowing for a clear trade off on loads and power performance at a turbine level versus farm level where increased tilt can influence wake spreading and wake incidence on downstream turbines.

Quantifying the impact of a chosen mean static pitch angle in terms of AEP, loads and impact on floating foundation design is becoming ever more important, especially in a challenging market that requires certainty and confidence to progress. Therefore, having a set of tools and methodologies to quickly navigate this trade-off space easily at early project stages will help improve confidence in a chosen design, and ultimately inform better engagement with the relevant stakeholders as a project progresses.

Project objectives

1. Understand the effects of static pitch angles and determine the conditions under which a trade-off between power generation and floater mass may justify greater static pitch angles.
2. Evaluate the different test case scenarios and floater technologies to determine how flexible the static pitch (loads on the RNA, power generation loss) can be, and how this affects the floating substructure design (mass, dimension, etc.), as well as the LCoE.
3. Assess the potential trade-off between power production and floating platform design (mass, dimensions, technology) when allowing higher static floating platform tilt as well as investigating the impact of deflection on wind farm-level wake effects and their influence on LCoE.

Methodology

Literature Review and Problem Definition

A literature review was conducted to assess the most viable floating technology to take forward for detailed loads assessment in later stages of this project. This included the definition and impact assessment of moving to LSPA against a broad set of criteria related to a floating wind energy system and LCoE.

Through a combination of stakeholder engagement and numeric modelling tools for floating dynamic analysis (Orcaflex) and wind farm energy production analysis (internal proprietary FLORIS tool), this study sought to understand the benefits and challenges of moving to LSPA designs above the current limits defined by the WTG original equipment manufacturers. Noting that stakeholder feedback from WTG OEMs and floating foundation designers during this project put this in the range of 5 to 7 degrees.

Evaluation Criteria

The following set of evaluation criteria was defined for each mean static pitch operating point:

- Interface Load (ultimate limit state (ULS) and fatigue limit state (FLS)) impact: Understanding the impact of the WTG tower–floating foundation interface load as a function of increasing mean static pitch angle;
- AEP impact: Understanding the impact of the AEP generated from a single WTG as a function of increasing mean static pitch angle;
- Floating foundation mass savings: Understanding the impact of potential floating foundation mass savings as a function of increasing mean static pitch angle.

Technology Assessment

A detailed numerical analysis on four different LSPA models was created based on the Floating Wind JIP reference semi-submersible model defined in previous work packages¹. The models were created using an internal scaling approach. This approach focused on characterising a set of potential designs through the modification of the column height, distance and radius (for a given WTG tower and rotor combination). An euclidean norm optimisation function was then defined to choose an applicable design at the following operating points:

- LSPA3: The baseline (previously defined) Orcaflex model of the semi-submersible, operating at a mean static pitch of 3 degrees, coupled with the IEA 15MW reference turbine;
- LSPA6: A scaled model of the semi-submersible, operating at a mean static pitch of 6 degrees, coupled with the IEA 15MW reference turbine;
- LSPA9: A scaled model of the semi-submersible, operating at a mean static pitch of 9 degrees, coupled with the IEA 15MW reference turbine;
- LSPA12: A scaled model of the semi-submersible, operating at a mean static pitch of 12 degrees, coupled with the IEA 15MW reference turbine.

¹ Floating Wind Joint Industry Programme Phase 4 summary report - [Link](#)

The models were then used to perform the following assessments:

- Behaviour of system mass (i.e. floating foundation mass and WTG tower) as a function of increasing mean static pitch angle;
- Behaviour of interface loads (i.e. WTG – floating foundation interface) as a function of changing mean static pitch angle, alongside any notable design changes required to accommodate higher load levels;
- Turbine performance, defined in terms of AEP as a function of changing mean static pitch angle.
- Farm level assessment of expected yield for each of the four static pitch angle models defined was undertaken using the aforementioned FLORIS tool.
- An LCoE assessment of the trade-offs of the WTG-floating foundation system against the impact on AEP at a wind farm level.
- Stakeholder engagement to understand expected impacts and considerations of a given mean static pitch angle.

Key Assumptions

The following key assumptions were made for developing this study:

- The IEA 15MW WTG model was used to conduct this analysis.
- The detailed models were derived in Orcaflex using a 15 MW reference semi-submersible platform defined in previous work packages. Loads were assessed at the global level and no detailed load levels were calculated on specific structural components of the semi-submersible. Also, assessment of interface risk was kept strictly to the interface loads at the foundation – WTG tower connection;
- Full-model performance was assessed only at a particular set of ‘moderate’ metocean conditions.² Only four models were evaluated; therefore, any ‘optimum’ point derived from this work should be viewed in the context of site conditions associated with a particular site, the specific dynamics of the sub-structure chosen for that project, and the behaviour of the WTG, chosen alongside the real WTG controller.

² Floating Wind Joint Industry Programme Phase 4 summary report - [Link](#)

Key findings

1 From the mean static pitch angles of 3, 6, 9 and 12 degrees, the optimal mean static pitch angle was found to be in the range of 3– 6 degrees (in-line with current limits considered for commercial and demonstration projects).

A set of representative Design Load Cases were evaluated using the previously stated moderate environmental conditions for each model against the initial criteria identified. The key conclusions from these assessments were:

- **Interface loads increase as a function of mean static pitch angle, causing potential risk of re-design of WTG components:** ULS and FLS WTG – floating foundation interface loads both increased as a function of the increase in the mean static tilt of the system. This results in the need to re-design specific components to handle the increase in ULS loads (i.e. WTG tower);
- **Potential foundation mass savings as a function of mean static pitch angle:** There is potential for mass savings on the foundation as a function of the mean static tilt of the system. However, the net mass saving at high angles (i.e. above a mean static pitch of 9 degrees) was marginal because of the need to strengthen the WTG tower to handle the increase in ULS interface loads observed;
- **AEP reduction as a function of mean static pitch angle:** There is a significant reduction in expected AEP as a function of increasing the mean static tilt of the system. This effect, at a turbine-level, dominates any potential benefit at a farm level, meaning this will significantly influence the applicability of larger angles.

Illustrate trends for these conclusions are represented in Figure 1 below:

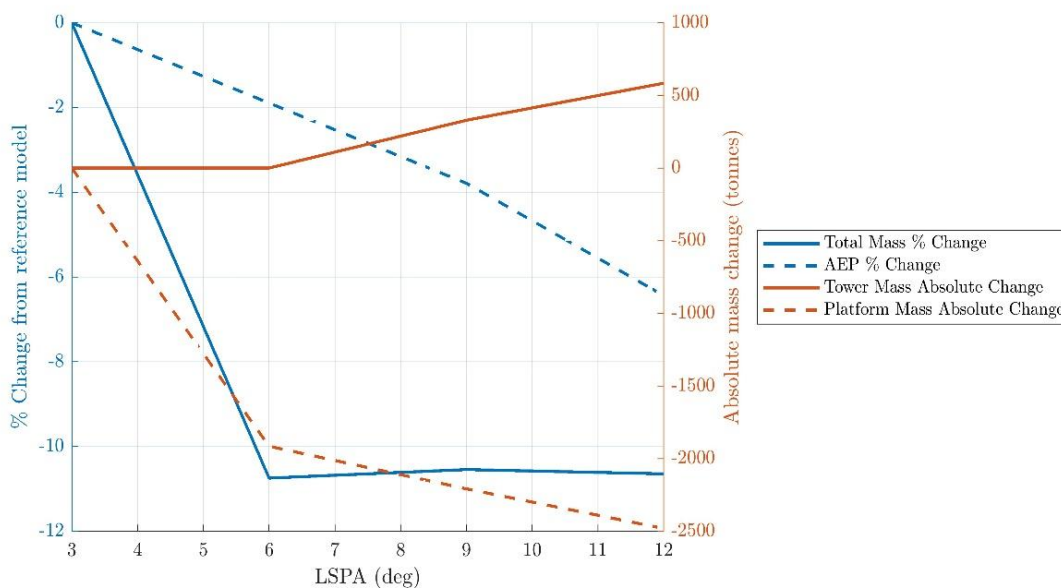


Figure 1 - Trends on foundation mass, tower mass and AEP as a function of increasing mean static pitch angle.

The conclusion of this assessment is that mass savings above a mean static pitch of 9 degrees would be limited due to the need to re-design and strengthen the turbine tower to handle an increase in ULS

loads. Additionally, alongside a significant drop in expected AEP at high mean static pitch angles, there are no expected material benefits of considering angles above the operational limits currently defined as industry standard - typically between 5 and 7 degrees. A more detailed analysis on a project basis to fully understand the given trade-offs within that industry standard range is, however, recommended to better understand the expected system behaviour.

2

The core loss of power from a single turbine dominates the loss in AEP - for a given mean static pitch angle-, outweighing any benefits at farm level from floating wind yield effects.

An analysis on floating yield effects (yaw oscillation, streamwise displacement and turbine tilt) was conducted to assess the net improvements in AEP as a function of moving to LSPA. This assessment was performed at a farm level, as opposed to a single WTG – floating foundation. All floating effects were investigated both individually, and in combination, on a hypothetical five by five and ten by ten grid layout at 4 rotor diameter (4D) and 10D spacings, respectively. The outputs of this analysis were compared against the conclusions drawn from the single WTG – floating foundation assessment. These were used to inform whether there are any additional drivers missed that offer substantial improvements at larger mean static pitch angles.

The key conclusions of this analysis were:

1. When considering each floating effect in isolation, positive impacts on farm level yield were observed for the following effects:
 - a. **Yaw oscillation:** The impact of oscillating yaw wake spreading was shown to be positive regardless of configuration but is greatest at lower spacings (i.e. 4D) when downstream turbines see a larger wake deficit;
 - b. **Platform Tilt:** The tilt function vertically deflects the turbines wake to a degree which is dependent on the turbines tilt angle. This was not observed to have any material impact on AEP until above a mean static pitch angle of 9 degrees. The primary driver for this is that - up until 9 degrees - the vertical wake deflection is not significant enough that it positively impacts the incoming wind velocity on multiple downstream rows.
2. Any positive impact observed at farm level, regardless of the mean static pitch angle considered, is low in comparison to the AEP loss of the single WTG – floating foundation system. This is shown in Figure 2, where the AEP loss from the assessment of a single WTG - floating foundation is comparable to the loss observed at farm level.

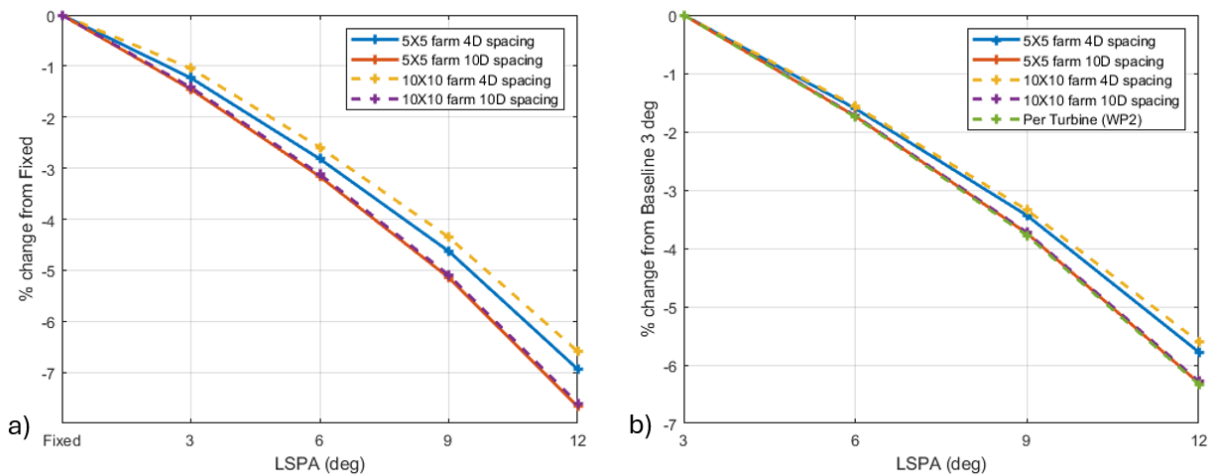


Figure 2: a) Total variation of AEP with LSPA as a percentage change with respect to the fixed case. Presented for each farm layout. b) Total variation of AEP with LSPA as a percentage change with respect to the baseline floating case (at a mean static pitch of 3 degrees), for each farm layout. The per-turbine AEP results from WP2 are also plotted (i.e. the summation of single turbine performance exclusive of wake effects).

3

For a given WTG – floating foundation combination, the AEP is significantly affected by both mean static pitch angle of the coupled system and pre-rotor tilt of the WTG

It was well established through Orcaflex modelling that, for a single WTG – floating foundation system, the AEP reduces as a function of increasing mean static pitch angle. This AEP reduction is driven primarily by the reduction in effective rotor wind speed, which itself is dominated by two effects: the platform tilt and the pre-tilt applied to the WTG rotor to prevent blade - tower clashing.

At small mean static pitch angles, the platform tilt is low and any impact on effective wind speed will be dominated by the pre-tilt applied on the rotor (which is captured in existing fixed power curves). However, at high mean static pitch angles, this effect becomes more nonlinear and the cumulative effect of platform tilt, plus pre-tilt, has a more material effect on the effective wind speed and hence power output of the WTG system. This conclusion is important for two reasons:

- When conducting analysis at farm level (i.e. using a tool such as FLORIS for yield calculations) consideration of performance at higher mean static pitch angles must include an explicit characterisation of the pre-rotor tilt. This could either be from the modelled power curve directly or from a fixed-floating representation that accounts for the impact of pre-rotor tilt;
- In conventional fixed turbine wake loss assessments, the wake direction aspects of pre-tilt are generally disregarded (i.e. small), although the effects of pre-tilt are included within the prescribed power curves and calibrated within the wake models. This warrants further review to ensure the various contributors to tilt are captured and included in a consistent manner at high mean static pitch angles.

4

For large mean static pitch angles the dominating effect on LCoE is the variation in AEP, opposed to design changes to the turbine or platform

The LCoE impact was assessed as a function of mean static tilt at turbine and farm level from previous analysis undertaken within the project, namely; AEP changes at farm level, platform mass savings as a function of increasing mean static pitch angle and tower re-design (i.e. mass increase to account for increased ULS loads) impact as a function of increasing mean static pitch angle. The conclusions were as follows:

- At smaller mean static pitch angles, the loss in AEP is compensated by reductions in mass and thus, relatively little change is observed in overall LCoE;
- Above a mean static pitch of 6 degrees, the LCOE begins to rise rapidly driven by an increase in AEP loss per degree, alongside diminishing reductions in foundation mass and tower mass increases due to load and not the stiffness of a driven tower.

5

Environmental factors are observed to have a second order impact on the performance of the coupled system at different mean static pitch angles.

The results from the core work packages were determined using the 'moderate'¹ conditions used in previous analysis. This means that the trends identified depend on: the site mean wind speed (and associated Weibull distribution), a single turbulence intensity distribution per wind speed bin, a single wave profile per wind speed bin, and a single turbine model.

To broaden understanding of the applicability of the conclusions a sensitivity study was conducted to explore the impact of changing the following:

1. Mean site wind speed: through variation of mean wind speed and associated Weibull parameters;
2. Wind variation: through variation of wind speed and turbulence intensity;
3. Wave variation: through variation of wave height and wave period at specific wind speed bins.

The core conclusions from the sensitivity analysis were as follows:

- At high mean wind speed, sites with higher wave loading and lower extreme winds could benefit from larger mean static pitch angles. These factors could be considered when fine tuning the inclination targets;
- Lower mean wind speed sites, with highly wind driven loading, will be less favourable for large mean static pitch angles.

These conclusions should be considered alongside RNA mass, turbine thrust, peak thrust wind speed and AEP stability (with respect to inclination) when considering initial mean static pitch angle target and limits.

Industry needs/innovations

1

When assessing the potential power loss at both turbine and farm level, turbine specific power performance should be assessed as a function of tilt angle and pre-rotor tilt.

The impact of AEP loss coupled with increasing interface loads as a function of increasing mean static pitch angle has been clearly identified as key driver which may limit the adoption of large mean static pitch angle designs. However, AEP, at a given mean static pitch, will also be influenced by the pre-rotor tilt and WTG controller dynamics, both of which are specific to a particular manufacturer and model. This creates dependence on early engagement with turbine manufacturers to properly ascertain the expected impact on AEP for a chosen platform operating point.

Therefore, to help improve early-stage project assessments, the following actions are recommended:

1. Definition of an AEP versus platform tilt loss viability curve at the early project stages: explicit consideration of the expected AEP loss as a function of tilt angle from the turbine manufacturer at an early stage will help provide confidence and understanding of the wider trade-offs required to optimise the WTG – floating foundation system;
2. Exploring the impact of including pre-rotor tilt in wake calculations: assessing the potential impact of including this effect at farm level should be undertaken when a mean static pitch angle of 6 degrees or more is being considered for a given project.

2

The trade-offs of having lighter floating foundations and maintaining mean static pitch through active trim systems should be better considered.

Currently, there is not an industry-agreed set of methods to fully understand and quantify the benefits and drawbacks of an active ballast system in the context of AEP design optimisation for a floating wind project. Better defining and understanding the approach to characterise an active ballast system will allow for a more informed view on the potential net savings of lighter floating foundations at a given target mean static pitch angle. This could include considering non-steady state performance by fully evaluating the following parameters:

1. System accuracy and activation strategy;
2. Transient response to changing environment;
3. System response time and any increase to downtime (i.e. pre-ballasting);
4. Ballast system downtime;
5. Power consumption.

3

The target and optimal inclination should be considered at a system level (i.e. for a given WTG – floating foundation) and on a site-by-site basis.

Whilst the conclusions of this study suggest that there is no net benefit beyond existing mean static pitch limits, it should be noted that this is in the context of just one WTG – floating foundation combination. In practice, an optimised design will be a function of a thorough assessment of both the chosen WTG and floating foundation, and should be conducted holistically and at a system-level to ensure the appropriate understanding of trade-offs across all components. This would be relevant for the higher end of the industry standard range defined (i.e. a mean static pitch of up to 7 degrees of platform tilt given the trend on observed LCoE / AEP), and could still be viable based on the following second-order observations within the study:

1. Load performance of key turbine RNA sensors suggested there is no step change in structural loading on the RNA (i.e. blade/nacelle) when moving to mean static pitch angles beyond 6 degrees. However, this observation may be site-dependent and hence should be considered on a project basis;
2. Similarly, accelerations of the nacelle and platform do not have a significant step change as a function of mean static pitch, suggesting that there is no major increase in risk of new failure modes compared to the baseline;
3. Between a mean static pitch of 6 and 9 degrees there is still potential for significant mass savings on the floating foundation.

ABOUT THE FLOATING WIND JIP

The Floating Wind Joint Industry Programme (Floating Wind JIP) is a collaborative research and development (R&D) initiative between the Carbon Trust and 17 leading international offshore wind developers: bp, EDF Renouvelables, EnBW, Equinor, Kyuden Mirai Energy, Ørsted, Ocean Winds, Parkwind, RWE Renewables, ScottishPower Renewables, Shell, Skyborn Renewables, SSE Renewables, TEPCO, Tohoku Electric Power Company, Total Energies and Vattenfall.



The primary objective of the Floating Wind JIP is to overcome technical challenges and advance opportunities for commercial scale floating wind. Since its formation in 2016, the programme scope has evolved from feasibility studies to specific challenges focusing on:

1. Large scale deployment
2. De-risking technology challenges
3. Identifying innovative solutions
4. Cost reduction

Stage 3 of the Floating Wind JIP commenced in 2022 and projects are expected to run until early 2027. With several commercial scale floating offshore wind farm projects in design phase and having the ambition to be commissioned by 2030, the industry needs to address several challenges. The 17 Floating Wind JIP partners agreed on six research areas where further understanding and advancement is required to reach full commercialisation of floating offshore wind projects.

Electrical systems	Mooring systems	Logistics	Windfarm optimisation	Foundations	Asset Integrity and monitoring

This Larger Static Pitch Angles (LSPA) project addresses the ambitions of the Windfarm Optimisation research area:



Windfarm optimisation

1	Assess technology developments such as ballast, sizing and cost to support with both floater and tower developments.
2	Understand floating specific windfarm layout and turbine specific developments to maximise yield.
3	Define floating specific controllers and modifications required in context to floating specific turbines.



The Stage 2 summary reports can be found here: [Phase I](#), [Phase II](#), [Phase III](#), [Phase IV](#) and [Phase V](#).

ABOUT THE CARBON TRUST

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