Response to Anonymous Referee #1

This paper reflects a great part of the complexity in modelling AWE systems, from the ABL over the wing to the flight dynamics and control modelling. It also explores different energy extraction methods advocated in the AWE community. They model the flow in an AWE wind farm with a simplified, pressure driven ASL and an actuator sector representation for the wing forces. The aerodynamic forces are calculated by a steady-state lifting-line, the dynamic motion by a point-mass model and the trajectory & operation is governed by model predictive control. Despite the complexity at hand, the authors have submitted a well-structured and exhaustive description of the methodology supported by high quality visualizations. The appendices and open provision of datasets also necessitates special mention.

We would like to thank the reviewer for the time and effort spent in reviewing this article. The reviewer comments have contributed to improve the quality of the paper. Below, we discuss the specific comments of the reviewer and indicate how they are addressed in the final manuscript.

Nevertheless, there are some areas the authors should improve on. At times certain modelling choices and their implications on the quantities of interest need more elaboration and verification. Not including unsteady aerodynamics in the wing modelling for instance could change the dynamic behavior. The grid resolution is extremely coarse with respect to the wing span and chord, so it is questionable if the unsteadiness on a chord-scale is captured at all by the current setup. This should be discussed in the paper. Furthermore, the aerodynamic behavior is only shown in terms of integrated quantities, yet the spanwise load distributions should be provided to demonstrate the correct and anticipated behavior of the wing. Finally, the value of the publication would greatly benefit from a more thorough analysis of the results. Despite the high modelling fidelity the authors are missing the opportunity to extract some high order statistics of the flow and loads and limit themselves to high-level descriptions and presenting average flow quantities. They are missing an opportunity here to highlight how AWE park flows differentiate themselves from conventional wind farm flows; if they are different at all. This could be enhanced by analyzing the induction factors of the AWES inside the farm and a discussion around how the trajectories could be optimized to avoid upstream wakes etc.

Thank you for these comments. We have identified two main points of criticism that we would like to shortly address here:

- **Fidelity level of the framework.** To our knowledge, this study is the first attempt to integrate LES and OCP in a single framework in the context of airborne wind energy in order to investigate the complex fully-coupled interaction between AWESs and ABL. As correctly observed by the reviewer, the framework is based on simplified models of the different modules: pressure-driven BL as LES flow model, steady-state lifting line as AWES representation in the LES, point-mass model for AWES dynamics and control, and pre-computed reference flight path for the farm supervision. In particular, the reviewer highlights the omission of unsteady aerodynamics, which are not considered in the model. We further agree that the coarse LES grid resolution does not allow us to investigate the related phenomena, such as flow separation, dynamic stall, or aero-elastic deformation of the wing. Nevertheless, Appendix A shows that the chosen LES grid resolution captures quite satisfyingly the mean wake velocity deficit, such that it allows us to investigate the occurrence of wake effects and address their adverse impact on AWE farm performance.Nonetheless, the highlighted limitations need to be addressed in the future. Hence, we have re-written the conclusions in Section 5 of the manuscript (see page 38) in order to emphasize on the current limitations of the framework and formulate precise suggestions to overcome those limitations.

- **Depth of the analysis.** With this study, we want to demonstrate the capability of the framework and highlight the significant impact of wake effects for large-scale AWE parks. The reviewer however suggested interesting additions, and in particular the investigation of AWES loads. Unfortunately, the limited availability of loads data generated during the farm simulations makes it difficult to provide a complete investigation of wing loads in turbulent wind conditions without performing new simulations. In addition, a thorough analysis of loads would benefit from using higher grid resolutions in order to estimate more accurately the local wind conditions at the wing sections. Therefore we will consider the reviewer's suggestion as valuable recommendation for future work. Nevertheless, load and aerodynamics data of wing sections are available for the high-resolution single-AWES simulations presented in Appendix A2. Therefore we have extended the appendix in order to include the discussion of local aerodynamics and loads.

In addition, the reviewer formulated 40 comments in the manuscript: The major comments are discussed hereafter while technical corrections are directly addressed in the revised manuscript.

Overall the paper is of great relevance to the wind energy community and is of very high quality. Unfortunately the discussion is not matching the level of detail and attention given to the methodology, thus not allowing to derive any general conclusions applicable to other AWE parks.

We thank the reviewer for the encouraging words and hope that the proposed revision of the manuscript increases its quality.

Specific comments

- P1-L16: "*For an operation period of 60 minutes at a below-rated reference wind speed of 10 ms−1, the lift-mode AWE park generates about 84.4 MW of power, corresponding to 82.5% of the power yield expected when AWE systems operate ideally and interaction with the ABL is negligible. For the drag-mode AWE parks, the moderate and dense layouts generate about 86.0 MW and 72.9 MW of power, respectively, corresponding to 89.2% and 75.6% of the ideal power yield.*"

  To allow the comparison with existing wind farm configurations, it would be interesting to quote the power density of the AWEs and their estimated induction factors. Maybe also their size (around 60m, diameter of 200m and circle centre).

  In the abstract, we concentrate our statements on the power performance of the different farm configurations, in particular the farm power density at rated wind speed, the power yield of each configuration in operating (below-rated) conditions and the farm efficiency relative to ideal conditions (10 m/s mean wind speed, no wake interaction). We have however added a statement containing the dimensions of the systems:

  "*In this study, we consider ground-based power generation pumping-mode AWE systems (lift-mode AWES) and on-board power generation AWE systems (drag-mode AWES). The aircraft have wingspans of approximately 60 m and fly large loops of approximately 200 m diameter centred at 200 m altitude. For the lift-mode AWES, we additionally investigate* *different reel-out strategies to reduce the interaction between the tethered wing and its own wake*".

- P2-L52: "*Arising from the seminal work of Loyd (1980), a majority of designs are based on the introduced lift- and drag-modes of operation. Both operation modes rely on the high aerodynamic forces generated by the crosswind flight of a tethered aircraft, and while for the lift-mode technology power generation is ground based, the drag-mode technology generates power directly on board.*"

  A sentence detailing how the power is generated for each system might be helpful for non-AWE specialists.

  Following addition was made: "*Arising from the seminal work of Loyd (1980), a majority of designs are based on the introduced lift- and drag-modes of operation, which rely on the high aerodynamic forces generated by the crosswind flight of a tethered aircraft. For the lift-mode technology, power is generated on-ground by a generator driven by the rotation of the tether winch, which is induced as the tether is reeled out. For the drag-mode technology, power is directly generated on-board by small turbines mounted onto the airframe.*"

- P3-L89: "*In this methodology [TH:LES], large-scale, energy-containing flow structures, which play a predominant role in the energy extraction process of the AWES park, are directly resolved with sufficient spatio-temporal resolution whereas the influence of smaller-scale, dissipative motion on the ABL flow is modelled using a subgrid-scale model.*

  By stressing the importance of LES for AWES park simulations, it seems as if this is particular to AWES parks. Is this the intended meaning here and if so how is different to conventional wind farms with HAWTs? If we talk about energy containing scales, which ones are the relevant ones that need LES resolution? This is a very general statement which might mean very different things depending on the reader's background.

  We agree with the reviewer that the statement might be misleading and propose following rectification: "*In LES methodology, large- and medium-scale flow structures are directly resolved with sufficient spatio-temporal resolution whereas the influence of smaller-scale, dissipative motion is modelled. The large, energy-containing structures, such as wind speed variations over regions spanning several hundreds of meters, play a predominant role in the energy extraction process of conventional and airborne wind energy systems alike. In LES computations, the transfer of kinetic energy across (a large part of) the inertial sub-range is further resolved, while the viscous dissipation of energy at the smallest scales is modelled using a subgrid-scale model.*

- P5-L92: "*In the current study, we neglect Coriolis and thermal effects, such that we only need to consider the turbulent surface layer of the ABL.*".

  Simplifying the ABL in this particular study is very sensible due to the complexity of the problem at hand, however it would be interesting if the authors could elaborate why a full ABL model might be especially important to AWE concepts. After all the AWEs sample a larger part of the ABL than HAWTs, at least in comparison with the current turbines available. Isn't this another motivation for using LES, ie possibility that you can study these effects in the future as well?

The investigation of more complex boundary layer models, including thermal effects and wind weer, is indeed intended in the future but is outside the scope of the current study. We have updated the conclusion section with following comments: "*First, we can improve the modelling of the atmospheric boundary layer. The description of the ABL flow can be enhanced by including Coriolis forces and thermal effects into the LES framework (Allaerts and Meyers, 2015). The inclusion of these effects modify significantly the structure of the flow, in particular capturing the inversion layer separating the turbulent boundary layer from the free atmosphere above. The height of the inversion layer, the strength of wind veer in the boundary layer, or the occurrence of low-level jets, will affect the flight path characteristics of AWE systems, such as optimal heights and tether length. These effects will further impact the controllability and power performance of the systems and hence require further investigations.*".

- P6-L128–146: "*Therefore, we opt for an actuator sector method that can both capture the local variations of aerodynamic quantities along the wingspans of individual AWE systems and accurately operate across a larger range of temporal scales.*
  The time step of the LES is denoted by Δt and its value is set to $\Delta t = 0.25\,\mathrm{s}$ throughout the simulations for the chosen grid resolution of the ABL, with cell size $\Delta x = 10\,\mathrm{m}$ in the axial direction. The dynamics of the AWE systems are however much faster and require a smaller time step δt. A stable simulation of the system dynamics is achieved for $\delta t = 10\,\mathrm{ms}$. Hence, for the duration of an entire LES time step, ie. between the instants t^n and $t^{n+1} = t^n + \Delta t$, the kinematics of the AWE system (see Sect. 2.2.3) are solved for each $t^l = t^n + l\delta t \in [t^n, t^{n+1}]$ while assuming a frozen flow field $\tilde{\vec{v}}^n \equiv \tilde{\vec{v}}(t = t^n)$.
  At every sub-step t^l, we compute the local aerodynamic forces per unit segment length $\vec{f}_q^l(s_k)$ from the procedure outlined in Sect. 2.2.2. Subsequently, the local aerodynamic forces of each segment are smoothed out over the LES grid cells in the vicinity of the wing using a Gaussian convolution filter $G(\vec{x}) = (6/(\pi\Delta^2))^{3/2} \exp\left(-6||\vec{x}||^2/\Delta^2\right)$, where the width of filter kernel is set to $\Delta = 2\Delta_x$ (Troldbord et al., 2010). The instantaneous, spatially filtered forces, integrated over the complete normalised wingspan $s \in [-1/2, +1/2]$, read

$$\widehat{\vec{f}}^{\,l}(\vec{x}) = \int_{-1/2}^{+1/2} G(\vec{x} - \vec{q}(s))\vec{f}_q^l(s)\mathrm{d}s. \tag{1}$$

  When flying crosswind manoeuvres at high speed, the AWE system may fly through several LES cells within one simulation time step Δt. For conventional wind turbines, blade tips sweeping several mesh cells in one time step result in a discontinuous flow solution in the near wake (Storey et al., 2015). Hence, the contributions of the spatially distributed forces $\widehat{\vec{f}}^{\,l}$ are subsequently weighted in time using an exponential filter (Vitsas and Meyers, 2016)

$$\overline{\vec{f}}^{\,l} = (1-\gamma)\overline{\vec{f}}^{\,l-1} + \gamma\widehat{\vec{f}}^{\,l}. \tag{2}$$

  The filter parameter γ is defined as $\gamma = \delta t/(\tau_f + \delta t)$ with the filter constant $\tau_f = 2\Delta t_{\mathrm{LES}}$. Accordingly, the complete force distribution $\overline{\vec{f}}$ accurately captures the fast and local dynamics of each individual AWE system and when added to the momentum equation, Eq. (1.b), emulates their collective effects onto the boundary layer flow.".

The reviewer formulated a series of comments on that section that are addressed here individually before we present a new formulation of the entire section further below:

- Have studied the influence of having a non-uniform resolution on how the body-forces are applied in the domain? It probably is coupled to the time-filtering but the resolution of the sector is different if it is at the top/bottom or on the sides of the circle.

  We haven't investigated non-uniformity of the grid because the pseudo-spectral discretization does not allow non-uniform grid resolutions in the horizontal directions. However, we do use a uniform filter kernel width in all three directions. We have added a specific mention in appendix A1 on page 41: "*The filter width of the Gaussian filter is uniform in all three spatial directions and is set for all actuator methods to $\Delta_f = 2\Delta_x$ following the recommendations in Troldborg et. al, (2010)*".

- Even after reading Sect 2.2.3 it is still slightly unclear to me. At each substep the velocities are sampled from the underlying LES domain, but where are the forces applied. I assume the forces from t^{n-1} are applied over the region in which the velocities are sampled? This is generally a bit of an issue with the actuator sector method, as it is hard to extract the angle-of-attack accurately, as the self-induction is hard to remove.

  The sub-step forces between t^n and t^{n+1} are all computed using the frozen flow field at t^n. The first sub-steps indeed experience self-induction from the sector forces computed between t^{n-1} and t^n, as opposed to the later sub-steps further away from the previous sector. The section was re-formulated as shown below and on page 6-7 in the revised manuscript.

  With respect to the local aerodynamic quantities, they can vary substantially depending on the actuator method used. In appendix A1, we have therefore updated figure A2 on page 41 and added the following statement: "*Figure A2 shows time series of the angle-of-attack, measured at the wing tip sections, and of the specific aerodynamics forces added onto the flow. The ALM simulations exhibit large fluctuations of the added forces due to the varying flow conditions experienced by the wing. Within one LES time step, the local flow conditions monitored by individual wing section varies greatly due to the very localized effects of the ALM forces. The ASM simulations, on the other hand, weight the individual force contributions at discrete AWES time steps, hence resulting in smoother force distribution, while introducing a slight time delay, but also smoother variations of angle of attack in time given the low velocity gradients encountered due to the wider smearing of the forces onto the LES domain.*

- Any particular reason for this factor [scaling parameter of Gaussian filter] ?

  The Gaussian convolution filter stems from Pope (2010) [p. 563] and its scaling parameter is set such that the second moments of Gaussian and box filter match. Following mention was added on page 6: "*The variance $\sigma^2 = \Delta_f^2/12$ of the Gaussian distribution, where the width of filter kernel is set to $\Delta_f = 2\Delta_x$ (Troldbord et. al, 2010), is chosen to be similar to the second moment of the box filter.*"

- If we consider the span of the wing, ie around 60 m, than the ratio span to filter width is 3. That is extremely coarse. The wing is more of a elongated blob in the CFD domain. Could you comment on how this can influence the flight dynamics and aerodynamics? The grid study in the Appendix is little unclear with regard to the influence of the kernel width.

Given the grid resolution, the description of the wing as an elongated blob is accurate for the AWE farm simulations and was addressed in the updated version of Appendix A3. With respect to the filter width, we added the following mention on page 43: "*In this grid analysis, the ratio of filter width to grid size is kept constant, hence $\Delta_f/\Delta_x = 2$. The simulation with the fine grid, which captures explicitly the individual tip vortices during the reel-out phase of lift-mode AWE systems, is considered the reference simulation.*"

With respect to the wing aerodynamics, we have added figure A5 on page 45 with the following statement: "*Figure A5 shows time series of the aerodynamic wing forces integrated over its wingspan acting on the drag-mode AWE system for the three grid resolutions. The decrease in grid resolution comes with a simultaneous increase of the simulation time step, hence drastically reducing the computational expense of the simulations. This comes however at the cost that the larger spatial filtering and temporal smoothing result in a much wider sector, representing the wing more as blunt body in the LES domain. The widespread of the added forces in turn reduces the accuracy of the local aerodynamic quantities of each wing section compared to the reference simulation. Nevertheless, the integrated forces overestimate the reference by less than 2% such that lower grid resolution can still sufficiently capture the resulting aerodynamic forces in order to accurately compute the AWES dynamics.*

- Here the reference to the Appendix would be good. The dynamics of the sector will be a filtered version of reality so the dynamics are probably different and only "accurate" depending on the quantities of interest. If the goal would be to optimize the aerodynamic control of the AWE I would doubt the resolution used here is sufficient and it would be good to comment somewhere on this.

The section was re-formulated including an early reference to appendix A on page 6: "*While the methodology is outlined hereafter, Appendix A addresses the choice of LES settings and tuning parameters.*"

Additionally, on-line control by means of NMPC is used to track the pre-computed optimized reference flight path and ensure that the AWESs remain airborne despite turbulent perturbations. We have added a mention on page 16 for clarification: "*In the LES-generated virtual wind environment, the operation conditions of the AWE systems differ substantially from the model assumptions in Eq. (27). The complex dynamics make the motion of the AWE system highly sensitive to fluctuations. Therefore a control algorithm is required to lead the system onto its pre-computed optimized reference trajectory. Accordingly we apply non-linear model predictive control (NMPC) (Gros et. al, 2013)*".

- It would be helpful to refer to the Appendix already at the start of this section or early on, as otherwise some of the choices made within this section are not fully accounted for. Also comment on the influence of distributing the forces on the wing aerodynamics. Smearing the forces leads to the formation of viscous cores that influence the actuator line and thus also the actuator sector angles-of-attack. Most likely the loading towards the tips of the sector are very elevated.

In addition to the discussions of actuator parameters in appendix A1 and grid resolution in appendix A3, we have added a discussion on spanwise angle-of-attacks and loads distributions for the high-resolution simulations of AWESs in appendix A2 on page 42 supporting the additional figure A4 on page 44: "*Figure A4 shows the spanwise distribution of angle of attack and wing loading for the three different systems. During power generation, the angle of attack is kept below the critical angle of attack. For the lift-mode AWE systems, the wing tips stall briefly during the turn manoeuvre initiating the reel-in phase. This effect is reduced when using the induction-based limitation of the reel-out speed and lasts less than 1 s without modifying significantly the total aerodynamic force acting on the wing. The force distribution along the wingspan is not elliptically distributed, as opposed to the assumptions of the point-mass model: The starboard side of the wing, the wing half flying at the outer side of the flight path, experiences a stronger wing loading than the port side due to the wing angular velocity, in particular during upward flight. For the drag-mode AWE system, the additional loading of the on-board turbines modifies only slightly the spanwise load distribution of the wing, in particular during the downward path of the loop.*"

The section was reformulated to clarify certain comments of the reviewer:

"*Therefore, we opt for an actuator sector method (ASM) that can both capture the local variations of aerodynamic quantities along the wingspans of individual AWE systems and accurately operate across a larger range of temporal scales. Similar to the actuator line method (ALM), the ASM projects the force distribution along the system wingspan onto the simulation grid of the LES, with an additional temporal smoothing that allows one to consider larger time horizon than just one instantaneous position of the AWE system. The resulting projected force distribution hence depends on the main parameters of the LES, ie. the grid resolution of the flow domain, parametrized by the cell size* $\Delta_x, \Delta_y, \Delta_z$*, and the simulation time step denoted by* Δt*, the time step of the AWE system dynamics denoted by* δt*, and a set of tuning parameters. While the methodology is outlined hereafter, Appendix A addresses the choice of LES settings and tuning parameters.*

For the current AWE farm simulations presented later on, the cell size is $\Delta_x = 10\,\mathrm{m}$ *in the axial direction and the LES time step is set to* $\Delta t = 0.250\,\mathrm{s}$*. In order to achieve a stable simulation of AWE system dynamics, which are much faster and require a smaller time step, its value is set to* $\delta t = 0.010\,\mathrm{s}$*. Accordingly, the kinematics of the AWE system (see Sect. 2.2.3) are evaluated 25 times per LES time step. The LES flow field is however only updated after each time step* Δt*, hence AWE systems operate, for the duration of an entire LES time step, in a frozen flow field* $\tilde{\vec{v}}^n \equiv \tilde{\vec{v}}(t = t^n)$ *evaluated at the beginning of the time step.*

From the perspective of the AWE system, the time horizon between the instants t^n *and* $t^{n+1} = t^n + \Delta t$ *provides a static snapshot of the flow field and is further discretized into a collection of 25 sub-steps* $t^l = t^n + l\delta t \in [t^n, t^{n+1}]$*. At every sub-step* t^l*, the local aerodynamic forces (per unit segment length)* $\vec{f}_q^{\,l}(s_k)$ *are computed along the aircraft wingspan given its instantaneous position* q^l *in the frozen flow field. The procedure to compute* $\vec{f}_q^{\,l}(s_k)$ *is outlined in detail in Sect. 2.2.2. Subsequently, the local aerodynamic forces of each segment are smoothed out over the LES grid cells in the vicinity of the wing using a Gaussian convolution filter*
$G(\vec{x}) = \left(6/(\pi\Delta_f^2)\right)^{3/2} \exp\left(-6||\vec{x}||^2/\Delta_f^2\right)$*, where the width of filter kernel is set to* $\Delta_f = 2\Delta_x$ *(Troldbord et al., 2010). The instantaneous, spatially filtered forces, integrated over the complete normalised wingspan* $s \in [-1/2, +1/2]$*, read*

$$\widetilde{\vec{f}}^{\,l}(\vec{x}) = \int_{-1/2}^{+1/2} G(\vec{x} - \vec{q}(s))\vec{f}_q^{\,l}(s)\mathrm{d}s. \tag{3}$$

When flying crosswind manoeuvres at high speed, the AWE system may fly through several

LES cells within one simulation time step Δt. For conventional wind turbines, blade tips sweeping several mesh cells in one time step result in a discontinuous flow solution in the near wake (Storey et al., 2015). In order to avoid this discontinuity, the individual contributions of the spatially distributed forces $\overset{\frown}{\vec{f}}{}^{l}$ can subsequently be weighted in time using an exponential filter (Vitsas and Meyers, 2016) given a certain time horizon, hence sweeping over a sector of the LES domain. The time-averaged force distribution is given by

$$\overline{\vec{f}}{}^{l} = (1-\gamma)\overline{\vec{f}}{}^{l-1} + \gamma\overset{\frown}{\vec{f}}{}^{l}. \tag{4}$$

The filter parameter γ is defined as $\gamma = \delta t/(\tau_f + \delta t)$ with the filter constant $\tau_f = 2\Delta t_{\mathrm{LES}}$. The force distribution $\overline{\vec{f}}$ is then added to the momentum equation, Eq. (1.b). The size of the sector, ie. the amount of sub-steps sampled, depends on the stage of the Runge-Kutta time integration scheme. At the first stage, only the force distribution evaluated at t^n is added to the previous sector. At the second and third stage, the force distributions between t^n and $t^n + \Delta t/2$ are further considered. While for the fourth and last stage, the new sector consists of the entire range of sub-steps between t^n and t^{n+1}. Ultimately, the added force distribution accurately captures the fast and local dynamics of each individual AWE system and emulates their collective effects onto the boundary layer flow.".

- P7-L173: The complexity of the fully-coupled system is quite impressive. Maybe in the discussions this could also be addressed. What challenges would be expected once moving towards a more complete aeroelastic description?

  We have updated the concluding remarks in Section 5 on page 38 with detailed suggestions on how to increase the complexity of the framework: "*The fully-coupled computational framework integrates numerous building blocks into a single simulation platform with a high level of complexity. The overall fidelity of the simulations can however be improved in the future by increasing the complexity of individual components of the framework and addressing the following known limitations: ...*" With respect to aero-elasticity, please refer to the following comment.

- P11-L259: "*The instantaneous, local section force per unit segment length $f^l_q(qk)$ at the time instant t^l contains the sum of local lift forces, drag forces and eventual on-board turbine forces.*".

  Unsteady aerodynamics is not considered here at all. Please comment on this. The sector will not fully capture the unsteady behaviour at a chord scale due to the force smearing. The lifting-line you are employing is also only considering steady-state aero.

  In the framework, we don't consider unsteady aerodynamic effects such as dynamic stall or aero-elastic deformation of the wing. The aerodynamic coefficients of local wing sections are taken from steady-state 2D airfoil analysis, while the local angles of attack are computed from the LES flow velocities, and hence depend heavily on the grid resolution. With respect to steady-state aerodynamics, we have added following statement on page 18: "*The discussed properties of the elliptical wing and the aerodynamic coefficients given in Eq. (37) are valid for steady-state, level flight, nevertheless they will be used as surrogate model for the wing of the AWE system. Unsteady aerodynamic effects, which are not considered here but might play a significant role for AWE systems, need to be addressed* *in the future.*"

We have added following statement on the dependence of aerodynamic properties to the grid resolution in the conclusion on page 39: "*The current predictions formulated in this study can be refined by increasing the resolution of the LES flow domain. With a higher grid resolution, the representation of the individual AWE systems can be enhanced, limiting their forcing effects to the direct vicinity of the wing instead of large sectors. The estimation of the aerodynamic quantities along the wingspan of the aircraft would also benefit from higher resolutions as a larger range of turbulent motions is resolved, hence increasing the modelling accuracy of the wing behaviour.*"

In order to include unsteady aerodynamics, one requires a much stronger knowledge of the aircraft aerodynamics, such as the pitch-rate dependency of aerodynamic coefficients, and perform fluid-structure interaction in order to quantify the deformation of the aircraft under aerodynamic loading. These analyses are outside the scope of this study and should be addressed in the future. Therefore, a specific mention was added to the concluding remarks on page 39: "*The modelling of the tethered aircraft can further be improved by incorporating unsteady aerodynamics. Fast pitching manoeuvres of the wing and sharp turns of the aircraft can have considerable effects on the local aerodynamic characteristics of the wing sections and hence have a significant influence upon the resulting aerodynamic forces of the system. Additionally, the aero-elastic response of the aircraft to the unsteady loading should be considered in order to prevent fatigue of the structure.*"

- P12-L281: "*with the tether diameter* d_T *and the drag coefficient of a cylinder* $C_{\mathrm{cyl}} = 1.0$ *at high Reynolds numbers.*".

  This is for steady aerodynamics, however you are modelling unsteady behaviour. Please comment.

  The tether is modelled as rigid rod and its drag is added to the system dynamics, while its effect on the LES flow field is neglected. Incorporating tether dynamics, in particular tether sag (Trevisi et al., 2020), would benefit the completeness of the framework and should be considered in the future. A specific mention was added to the concluding remarks on page 39: "*Although the rigid-rod assumption performs well for the high-tension power generation phases (Malz et al., 2019), this model lacks to capture the tether dynamics. The incorporation of tether sag (Trevisi et al., 2020) would benefit the completeness of the modelling effort.*".

- P12-L305: "*The controller does not have knowledge of the unsteady, three-dimensional wind field from the LES and hence assumes that the wind field is given by a one-dimensional, height-dependent profile* v_w.*"

  How would this be estimated in a reality? With a lidar? and how accurate would this have to be?.

  We have added following statement on page 13: "*In practice, the value of the wind speed can be derived from the measured airspeed using on-board instrumentation.*

- P13-L321: "*The values of axial induction factors reported in AWE literature (Leuthold et al., 2017; Haas and Meyers, 2017; Kheiri et al., 2018) are lower than the known Betz limit a =*

1/3 of conventional wind turbines (Jenkins et al., 2001), suggesting that axial induction is less significant for airborne wind energy systems although it cannot be fully neglected.".

The induction of Kite depends on different parameters than a HAWT as shown by Gaunaa, 2020. Maybe this model could be used instead.

In the current study, axial induction of AWESs is not modelled when generating reference flight paths given that the LES flow field already contains the effects of axial induction, as mentioned on page 13: "*In the current approach, the LES-based wind velocity sampled by the wind speed estimator already contains the effects of axial induction. Hence, optimal trajectories are later generated for reference wind speeds U_{ref}, computed by the wind speed estimator, and equivalent to the actuator-based wind speed U_{D} instead of the inflow wind speed U_∞.*"

The literature on induction of AWES is mentioned in the introduction on page 2: "*For individual systems, recent investigations of flow induction and wake effects were performed, mainly considering axisymmetric AWES configurations in uniform inflows using either analyses based on momentum theory (Leuthold et al., 2017; De Lellis et al., 2018), vortex theory (Leuthold et al., 2019; Gaunaa et al., 2020) or the entrainment hypothesis (Kaufman-Martin et al., 2021), or high-fidelity CFD simulations (Haas and Meyers, 2017; Kheiri et al., 2018).*

- P14-L344: "*In this study we generate a set of reference power-optimal flight trajectories by using optimal control techniques.*".

  Please motivate your particular choice of control strategy to which these reference trajectories are also linked.

  Optimal control techniques, and the awebox toolbox in particular, allow us to first, generated reference trajectories, and second, track them with NMPC in the perturbed flow. We have added following statement on page 14: "*In this study we generate a set of reference flight trajectories by using optimal control techniques. Optimal control techniques allow us to optimize the flight of the AWE system for different objectives while respecting a large number of constraints during operation. First, we can generate power-optimal reference trajectories optimized for various flow conditions, as shown hereafter. Second, optimal control also allow us to perform path tracking of the reference trajectories in the turbulent LES flow field, as shown in Sect. 2.4.*"

- P15-L379: "*... where $C_{\mathrm{L,opt}} = 1.142$. The lower bound ensures that the tether tension remains positive at all time while the upper bound limits local stall along the wing.*".

  From the reading the paper sequentially it is not obvious where this figure comes from.

  Thank you for pointing this out, we added the correct references to section 3.1 and Figure 5 on page 15: "*... where $C_{\mathrm{L,opt}} = 1.142$. The lower bound ensures that the tether tension remains positive at all time while the upper bound limits local stall along the wing. The value of the upper bound $C_{\mathrm{L,opt}}$ stems from Figure 5 and its choice is further discussed in Sect. 3.1.*"

- P15-L384: "*Further, we constrain the operation range of the control variables u.*".

  Please add a reference justifying your choices. Cl dot seems pretty low, it should be possible to get a faster pitch change.

  The bounds were set using an heuristic approach in order to avoid aggressive manoeuvres of the aircraft, in particular given the limitations of the point-mass model, that does not consider rotational dynamics. Allowing faster control actions would result in unrealistic values of the approximated angular velocity. On page 16, we have therefore added following mention: "*Further, we constrain the operation range of the control variables $\mathbf{u}$ in order to avoid aggressive pitch and yaw manoeuvres which are not suited to large-scale aircraft. The bounds on $\mathbf{u}$ are derived using a heuristic approach in order to avoid unrealistic values of the approximated angular velocity.*"

- P15-L391: "*Figure 3 shows the different trajectories computed for the range of wind speeds. At the end of the sampling period T_s, the controller verifies whether the reference wind speed from Eq. (31) has changed, and if so, chooses the closest value in the range [5.0,12.0] and commands the AWE system to track the new trajectory defined by the reference states x_r.*"

  It would be interesting to see the approx. radii of the trajectories and the centre of rotation. A range would be fine as well, this would facilitate the comparison with HAWTs.

  A parametrization of the trajectories is given in the introduction of Sect. 4 on page 29 to facilitate the comparison: "*To ease the comparison, the trajectories of the AWE systems are parametrized as circular flight path centred around a virtual trajectory center. For the lift-mode system, the diameter of the trajectory is approximately 240 m and its center is located 645 m downstream of the ground station at an altitude of 220 m. Equivalently, for the drag-mode system, the diameter of the trajectory is approximately 200 m and its center is located 610 m downstream of the ground station at an altitude of 190 m.*"

  The variations of the states and other quantities with changing wind speeds are presented in Appendix B, enabling a detailed comparison of flight altitude or loop diameter. We have added a mention of the appendix in Sect. 2.3.2: "*Figure 3 shows the different trajectories computed for the range of wind speeds. At the end of the sampling period T_s, the controller verifies whether the reference wind speed from Eq. (31) has changed, and if so, chooses the closest value in the range [5.0,12.0] and commands the AWE system to track the new trajectory defined by the reference states x_r. The wind speed dependency of the trajectories is presented in Appendix B.*".

- P17-Fig3: What is happening here? A nice visualization of the trajectories but the x axis can be misleading.

  The depicted loop shows the flight path of the retraction phases of the tether, inherent to the working principle of ground-based pumping mode AWESs (lift-mode). A specific mention of the retraction phase is added on page 15: "*The power-generation phase consists of four loops and is followed by the retraction phase to wind the tether back up on the winch*"

The retraction phase consists of transition out of power generation, tether reel-in phase, and transition into power generation. The specific shape of the retraction phase of the optimized trajectories is described in details on page 24: "*The retraction phase consists of a steep upward flight at maximal tether length to transition out of the last power generation loop, followed by the reel-in phase of the tether at high altitude and is completed by a dive manoeuvre to transition into to the new power-generation phase.*"

The caption of the figure was updated to clarify the streamwise positioning of the flight paths: "*The maximal streamwise extent of each trajectory does not exceed 1000 m, but for the sake of visualization the positions of successive ground stations were shifted by 1000 m.*"

- P19-L448: "*Therefore, a wing with elliptical planform is chosen here for simplicity. Furthermore, elliptical wings exhibit a low induced drag and a constant downwash along the wingspan, and also provide an analytical formulation of the aerodynamic lift and drag coefficients of the wing (Anderson, 2010)*

$$C_\mathrm{L} = a\left(\alpha_\mathrm{g} - \alpha_{\mathrm{L}=0}\right), \text{ and } C_\mathrm{D} = C_{\mathrm{d},0} + \frac{C_\mathrm{L}^2}{\pi AR}, \tag{5}$$

where α_g is the geometric angle of attack of the wing. In addition, $\alpha_{\mathrm{L}=0}$ and $C_{\mathrm{d},0}$ respectively represent the zero-lift angle of attack and profile drag coefficient of the airfoil. The lift slope a of the finite wing is given by $a = a_0/\left(1 - a_0/(\pi AR)\right)$ with $a_0 = 2\pi$ the airfoil lift slope from inviscid flow theory."

and thus also abrupt stall over the entire wing span ...

We added a mention of the unfavourable stall characteristics of elliptical wings and mentioned the limitations of steady-state aerodynamics: "*Therefore, a wing with elliptical planform is chosen here for simplicity. Elliptical wings exhibit advantageous aerodynamic properties given that their planforms generate low induced drag. Nevertheless, their stall characteristics are unfavourable: Elliptical wings generate a constant downwash along the wingspan. Therefore, in the absence of geometric twist and for a uniform airfoil distribution, the induced angle of attack is constant along the wingspan. As a consequence, the effective angle of attack of each wing section is equal, which might cause the entire wing to stall simultaneously. Elliptical wings provide an analytical formulation of the aerodynamic lift and drag coefficients of the wing (Anderson, 2010)*

$$C_\mathrm{L} = a\left(\alpha_\mathrm{g} - \alpha_{\mathrm{L}=0}\right), \text{ and } C_\mathrm{D} = C_{\mathrm{d},0} + \frac{C_\mathrm{L}^2}{\pi AR}, \tag{6}$$

where α_g is the geometric angle of attack of the wing. In addition, $\alpha_{\mathrm{L}=0}$ and $C_{\mathrm{d},0}$ respectively represent the zero-lift angle of attack and profile drag coefficient of the airfoil. The lift slope a of the finite wing is given by $a = a_0/\left(1 - a_0/(\pi AR)\right)$ with $a_0 = 2\pi$ the airfoil lift slope from inviscid flow theory. The discussed properties of the elliptical wing and the aerodynamic coefficients given in Eq. (37) are valid for steady-state, level flight, nevertheless they will be used as surrogate model for the wing of the AWE system: This model is used to approximate the wing orientation in the lifting-line model introduced in Sect. 2.2.2 and to derive the state bounds of C_L in the AWES model of the controller in Sect. 2.3 and Sect. 2.4. Unsteady aerodynamic effects, which are not considered here but might play a significant role for AWE systems, need to be addressed in the future."

- P19-L457: "*At high angles of attack past the critical angle of attack, the airfoil is subject to stall, characterized by a drop of the lift coefficient and a sharp increase of the drag coefficient.*

  As this is a panel code it's validity approaching stall should be treated carefully. Even when operating at 8 degrees a gust can easily lead to a variation of above 2degrees around this set point, bringing the wing close to stall. Please add a comment.

  The validity range of the polar curve is indeed limited to shortly after stall, we have therefore added a related mention on page 21. The fluctuations of local AoA due to turbulence and angular velocity was however considered when generating the reference flight paths, so we have also added a comment highlighting this aspect, and we also refer to appendix A2 where the wingspan distribution of aerodynamic properties of the optimized trajectories are discussed on page 44, as mentioned in an earlier comment.

  "*The lift and drag predictions of XFOIL are only valid just beyond α_c (XFOIL, 2021). In addition, the distribution of angles of attack in the lifting-line model can vary substantially along the wingspan, due to the spatial fluctuations of the LES-based wind velocity and the speed difference between the two tips of the aircraft. Therefore, the operation of AWE system is to be optimized such that not only the adverse effects of stall are avoided but also ensure an accurate prediction of the aerodynamic behaviour of local wing sections of the lifting line. To do so, we restrict the values of the states variable C_L, and equivalently the values of the model-equivalent angle of attack $\tilde{\alpha}$, to a range well below stall, as explained hereafter.*"

  "*The linear approximation of the wing lift coefficient given in Eq. (37) is only valid for the range of angles of attack up to $\alpha_\mathrm{g,max} \approx 10.6\,\mathrm{deg}$, well below the critical angle of attack of the wing $\alpha_\mathrm{c,W} \approx 20.6\,\mathrm{deg}$, as shown in Fig. 5(a). Therefore, the upper bound of C_L is set to a value $C_\mathrm{L,opt} \in [0.0, C_\mathrm{L}(\alpha_\mathrm{g,max}) \equiv C_\mathrm{L,max}]$ that maximizes the glide ratio G of the tethered wing system: The glide ratio $G = C_\mathrm{L} / \left(C_\mathrm{D} + C_\mathrm{D,T}\right)$ is defined as the ratio of aerodynamic lift forces to the combined contribution of wing and tether to the overall drag forces (Diehl, 2013). The contribution of the tether is given as $C_\mathrm{D,T} = C_\mathrm{cyl}\left(l_\mathrm{max} d_\mathrm{T}\right) AR/(4b^2)$ with the drag coefficient of a cylinder at high Reynolds number $C_\mathrm{cyl} = 1.0$. For the targeted wingspan of 60m and an expected tether diameter of 3.5×10^{-3} m, the maximal glide ratio $G \approx 16.5$ is achieved at a geometric angle of attack of $\alpha_g \approx 8.1$, and results in $C_\mathrm{L,opt} = 1.142$, as shown in Fig. 5(b). Consequently, the upper bound of the wing lift coefficient is $C_\mathrm{L,opt} = 1.142$ in the POCP (33) and $C_\mathrm{L,max} = 1.37$ in the NMPC (36). A discussion of the angle of attack and load distributions of the trajectories optimized with (33) and using this approach is presented in appendix A2.*"

- P21-L492: "*While the value of the induction factor a is a priori unknown, we opt for the conservative guess $a = 0.25$, such that the maximal reel-out speed of the tether becomes wind speed-dependent.*

  Why not use as more sophisticated method here for estimating a? Especially when simulating a full power curve, this might become important.

  At the time of setting up the concept of the study, most of the work performed on AWES induction and available in literature was addressing axisymmetric configurations in uniform inflow conditions, as specified in the literature review on page 2: "*For individual systems,* *recent investigations of flow induction and wake effects were performed, mainly considering axisymmetric AWES configurations in uniform inflows using either analyses based on momentum theory (Leuthold et al., 2017; De Lellis et al., 2018), vortex theory (Leuthold et al., 2019; Gaunaa et al., 2020) or the entrainment hypothesis (Kaufman-Martin et al., 2021), or high-fidelity CFD simulations (Haas and Meyers, 2017; Kheiri et al., 2018).*".

To the best of our knowledge, no off-the-shelf engineering model for induction of AWESs was developed and verified for large-scale systems relying on lift- and drag-modes for operation in sheared inflow conditions. Therefore, we opted for this simplified approach and chose the value $a = 0.25$ based on an empirical choice. A comment was added to the manuscript: "*While the value of the induction factor a is a priori unknown, we opt for the conservative guess $a = 0.25$ based on an empirical choice.*"

- P22-L502: At the danger of having missed it, how are the flights initialized? Is the AWE put on track with the precomputed initial conditions?

  Indeed, at time $t = 0$ in the LES, the states of each individual system are initialized with the values from the pre-computed references. The following mention was added: "*At the initial simulation time, the states of the AWE systems in the parks are initialized to the states values of the pre-computed reference trajectories for $U_\mathrm{D} = 10.0\,\mathrm{m/s}$.*"

- P23-Fig7: Why is there this loop, here and also above? What is happening?

  Similar to the explanations provided for the earlier comment on Fig. 3, the depicted loop shows the flight path of the retraction phases.

- P23-L505: "*The drag-mode AWE system operates at a constant tether length $l \approx 650m$ and follows an near-circular flight path of diameter $D \approx 200m$ at a mean elevation of about 17 degrees.*

  At what height is the circle centred?

  The height of the trajectory center is approximately 200 m. A parametrization of the trajectories is provided later in the introduction paragraph of Sect. 4 on page 31: "*To ease the comparison, the trajectories of the AWE systems are parametrized as circular flight path centred around a virtual trajectory center. For the lift-mode system, the diameter of the trajectory is approximately 240 m and its center is located 645 m downstream of the ground station at an altitude of 220 m. Equivalently, for the drag-mode system, the diameter of the trajectory is approximately 200 m and its center is located 610 m downstream of the ground station at an altitude of 190 m.*"

- P25-Fig9: hard to see what is going on.

  We have reformulated the two paragraphs supporting Fig. 8 and Fig. 9 with additional clarifications on page 26:

  "*In particular, the figure shows the effect of the reel-out strategy on the generation of tip vortices: With the first reel-out strategy, the individual tips vortices of each loop cannot be precisely identified, suggesting that the induced tip vortices are advected downstream by* *the background flow at a speed similar to the reel-out speed of the tether. Consequently, the wing interacts with its own wake during the reel-out phase. With the second strategy, the induction-based limitations of the reel-out speed reduces the interaction between the tip vortices at each loop, resulting in more distinct structures. The interaction can however not be completely prevented, such that the individual structure eventually merge later downstream.*”

“*The effects of the reel-out strategy on wing–wake interaction can also be observed on the local flow conditions measured by the wing. Figure 9 shows the instantaneous streamwise wind speed component $\tilde{v}_x$ monitored at seven equidistant locations along the wingspan. For comparison, not that without interaction between the AWE system and the wind environment, wing sections would experience wind speeds in the range 9.7–10.9 m/s. For the first reel-out strategy (see Fig. 9(a)), we observe large fluctuations of the instantaneous wind speed: Sharp drops of the streamwise velocity components are measured during the lower part of the four power-generation loops. These drops are particularly important for the entire starboard side (sections c000 to s030) suggesting that a large portion of the wing suddenly encounters a region of low wind speed that we can identify as the wake. Furthermore, the intensity of the velocity drop increases after every loop as the system reels out further downstream, indicating that the individual wakes of each loop are combined into a single wake. With the second reel-out strategy (see Fig. 9(b)), the patterns are less distinct and the magnitude of the fluctuations less significant, hence indicating that the interaction between wing and wake is limited. We still observe that the outer starboard part of the wing (sections s020 and s030) experiences sharp fluctuations suggesting that the starboard wing tip flies through some wake region. However, these fluctuations are very local and temporary, while for the first reel-out strategy most of the wing is interacting with the wake.* ”

- P25-L545: “*We still observe that the outer section of the wing, referred as p020 and p030, experiences very sharp fluctuations at the end of reel-out phase, suggesting that the outer wing tip flies through some wake region.*

  Was the number of aero sections in the lifting-line mentioned somewhere earlier?

  The number of wing section is specified in Sect. 2.2.2 : “*In this study, each AWES wing is discretized using 61 actuator segments.*”

- P25-L548: “*Given the limited interaction between the wing and the wake when using the second reel-out strategy, ie. with an induction-based upper limit of the reel-out speed, we will perform the lift-mode AWES farm simulation with the second design of lift-mode AWE system.*

  In this context it is important to mention that the behaviour might be different at greater grid resolution/smaller Gaussian kernel size. As mentioned earlier the force smearing also leads to vorticity smearing, which will reduce the velocity gradient when flying through the tip vortices.

  As rightly noted by the reviewer, the effectiveness of the reel-out speed limitation also depends on the grid resolution. We have therefore added a special mention in the updated Appendix A3 on page 46: “*While for the coarser resolution it cannot be assured* *that lift-mode AWE systems, even with the induction-based reel-out speed limitation, won't interact with their own wakes, this effect will be weakened given that the force smearing also reduces the strength of the tip vortices*".

- P26-L564: "*During the upward flight, the on-board turbines switch to propeller-mode in order to overcome gravity and keep a constant flight speed and tether tension, and hence consume some power.*

  What is the propeller efficiency ?

  The electrical efficiency of the turbines is not considered here, however the rotor efficiency is 0.8 as presented in Sect. 2.3.2: "*Here, $\eta_r = 0.8$ is the rotor efficiency and characterizes the ability of the on-board turbines to extract power from the surrounding flow, ie. the axial induction associated to the actuator disk assumption. In line with (Echeverri et al., 2020), where η_r is defined as "rotor efficiency from thrust power to shaft power", Eq. (35) [$P_D(t) = \eta_r F_G(t)||va(t)||$] defines the mechanical power that drag-mode AWE systems can extract from the wind.*"

- P30-Fig13: Could you comment on the non-symmetric nature over the farm centre-line? Is this due to the averaging time not being sufficient or is it the wake rotation or non-axi-symmetric trajectories? Nice plots!

  We have added a comment on the asymmetry observed in Fig. 13 on page 34, derived from the discussion of Fig. 15: "*At the start-up of the operation, each system experiences similar conditions from the unperturbed ABL flow. As systems begin to harvest power and induce their own wakes, upstream wakes travel downstream and start to impact the operation of downstream rows until the complete park operates in fully waked conditions at the end of the spin-up phase at $t = 900\,\mathrm{s}$. The variations of the tracked value for the front row AWE system (AWES 003) are due to the inherent unsteadiness of the ABL flow. We observe how these large-scale wind fluctuations experienced at the front row propagate with some delay through the downstream rows of the park. However, the large decreases of tracked speed for the downstream systems are due to the effects of upstream wakes. As discussed above, drag-mode AWE systems experience much stronger wakes and hence track lower wind speeds than lift-mode AWE systems. In particular, a larger decrease is observed from the front row to the second row.*

  Note that the amplitude of the large-scale variations of the ABL vary from one column to another. Consequently, the different columns of the parks do not operate similarly and impose a different forcing on the ABL flow field. This effect can explain the asymmetry observed in the time-averaged quantities shown in Fig. 13. In particular, the averaging period of one hour may not be sufficient to entirely smooth out these temporal and spatial variations across the entire AWE farms."

- P30-L620: The analysis could be improved here. Having performed LES simulations I would expect seeing some higher-order statistics here. Spectra inside the farm and also of the loads on the kites. Having said that, I am generally missing some presentation of the kite loads in this paper. Using the LL should enable some interesting insights into the spanwise load distribution of the AWES as they move through this complex flow. Their presentation and analysis is also important to demonstrate that the the AWE is operating as expected and in a physically correct manner.

We thank the reviewer for pointing out these limitations. As already mentioned earlier in the introduction to this answer, we cannot provide a thorough analysis of the AWES loads in the turbulent flow field due to the limited availability of generated loads data. Nevertheless we have added an analysis of the loads of single AWESs in Appendix A2 on page 43 supporting the newly added Fig. A4, in which we can observe the correct system behaviour using high-resolution LES simulations, as mentioned in earlier comments.

- P32-Fig15: These curves seem extremely non-smooth. Is this due to the large time step?

  We have clarified the content of Fig. 15 on page 33: "*Figure 15 shows the reference wind speed of the trajectories tracked by the AWE systems as directed by the supervision level of the controller. Each reference trajectory is tracked for the duration of respectively one cycle for lift-mode systems (≈ 65 s) and five cycles for drag-mode systems (≈ 50 s) before it is updated by the controller based on the averaged velocity sampled by wind speed estimator over that time period. In particular, we show the tracking behaviour of the five rows of AWE systems of the central column of the three park configurations.*"

- P39-L751: "*Figure A2 shows the specific aerodynamics forces added onto the flow by a single drag-mode AWE system for different actuator methods. The system operates at a reference trajectory UD = Uref and the flow domain is discretized with the fine grid.*"

  How did the kernel width change here? Was the ratio 2*dx kept or was the width constant, ie 20 m?

  We have added following clarification in appendix A3 on page 44: "*Next, we perform the simulation of the single drag-mode AWES and assess the time-averaged flow quantities using the three grid resolutions specified in Table A1. In this grid analysis, the ratio of filter width to grid size is kept constant, hence $\Delta_f/\Delta_x = 2$. The simulation with the fine grid, which captures explicitly the individual tip vortices during the reel-out phase of lift-mode AWE systems, is considered the reference simulation.*

Response to Anonymous Referee #2

General comments

- The article presents the combination of large-eddy simulation with a control theory model for ground-gen and fly-gen fixed wing airborne wind energy systems. There is a complex interaction between the different components of the model. Each component in the model is explained to a certain level in a dedicated section.
- The level of fidelity of the wind model is high, except for the relatively low grid resolution, while the model of the airborne wind energy system is very simplified.
- The control strategy uses the model with several constraints, among others to avoid flying in the own wake. It results in the generation of optimal trajectories.
- After explaining the model, results are presented for 3 different farm configurations. Wake effects are shown to be of importance. The fly-gen systems cause significantly stronger wakes than the ground-gen systems. In all farms, the flight path stays close to the optimal trajectories.
- The article is technically of a high level, uses a scientific method and is definitely relevant for the wind energy science community. The amount of information and the forward references make the article a challenge to read, but this is unavoidable given the amount of work that is presented.
- The open data will be an added value for the community.

We would like to thank the reviewer for the time and effort spent in reviewing this article. The reviewer comments have contributed to improve the quality of the paper. Below, we discuss the specific comments of the reviewer and indicate how they are addressed in the final manuscript.

Specific comments

- Line 155: The authors state that fewer states and control variables result in a less computationally intensive model. However, is this reduction relevant compared to the computational cost of the LES calculations? Some information about the time spent in each component of the model would be an interesting addition.

  The computational cost of one NMPC evaluation is indeed in most cases much smaller than the computational cost of one LES time step. However, given that AWES dynamics are faster than ABL flow dynamics, the control actions of each AWES are evaluated several times per LES time step. Consequently, the total execution time of the LES time step may depend on the execution time of individual NMPC evaluations.
  For drag-mode AWESs, the execution time of NMPC evaluations is almost negligible, accounting on average for less than 5% of the execution time of an LES time step. For lift-mode AWESs, the execution time of NMPC evaluations can vary substantially. While about 95% of the evaluations are performed in less than $1.0\,\mathrm{s}$, similar to drag-mode AWESs, the remaining 5% of the evaluations require about 15–$30.0\,\mathrm{s}$. This performance drop is generally observed when AWESs operate in heavily-constrained regions of the variable space or transition between considerably different reference flight paths.
  Additionally, synchronization of the NMPC evaluations of all AWESs at the end of each LES

time steps are necessary in the implementation, further reducing the computational performance of the framework. Also, given that NMPC evaluations are performed by one unique processor, the scalability of the framework is limited. Last, the performance of NMPC evaluations depends on additional parameters, such as the length of the prediction horizon or the number of model variables. The employed point-mass model consists of only 11 states and 3 control variables, whereas the rigid-body model (Malz et al., 2019) consists of 23 states and 4 control variables. Given the important number of NMPC evaluations (54000 evaluations per AWES) and the aforementioned performance bottleneck of the current implementation, the model choice may further limit the computational performance of the framework.

The reviewer underlines a significant point – the computational performance of the LES framework – which is often discussed in LES studies. A paragraph containing the presented arguments and computational cost of the simulation was added in Sect. 3 on page 29: "*The simulations are performed on the high performance computing infrastructure of the Flemish Supercomputer Center (VSC). The computational cost of one LES time step typically largely exceeds the computational cost of one NMPC evaluation. Hence the required computational resources depend heavily on the grid resolution, which also limit the simulation horizon. However, given that AWES dynamics are faster than ABL flow dynamics, the control actions of each AWES are evaluated several times per LES time step. In total, 54000 evaluations per AWES are performed during the simulation horizon of 4500 s. Consequently, the total execution time of the LES time step may depend on the execution time of individual NMPC evaluations. The performance of NMPC evaluations depends on several parameters, such as the length of the prediction horizon or the number of model variables. For drag-mode AWESs on the one hand, the execution time of NMPC evaluations is almost negligible, accounting on average for less than 5% of the execution time of an LES time step. For lift-mode AWESs on the other hand, the execution time of NMPC evaluations can vary substantially. While about 95% of the evaluations are performed in less than* $1.0\,\mathrm{s}$*, similar to drag-mode AWESs, the remaining 5% of the evaluations require about* 15–$30.0\,\mathrm{s}$*. This performance drop is generally observed when AWESs operate in heavily-constrained regions of the variable space or transition between considerably different reference flight paths. As a result, the drag-mode AWE park simulations require about 1200 node-hours (or 52 node-days) while the lift-mode AWE park simulation requires about 1600 node-hours (or 67 node-days) on the Tier-2 hardware of VSC.*"

- Line 209: The authors obtain the model-equivalent angle of attack from the aerodynamic state, which is then used to define the orientation of the airborne wind energy system and as such influences the calculation of the aerodynamic forces. The authors had to do something to complete the limited information provided by the 3DOF model, and there is no obvious other way of doing this, but it remains a questionable approach in my opinion.

  We agree with the observation of the reviewer. The limitations of this assumption are known to us and are highlighted in the manuscript on P7-L159. We originally opted for the point-mass model for its simplicity, scalability and versatility in order to demonstrate the capability of the fully-coupled LES-OCP framework. The model limitations can be resolved by using a rigid-body model such as the reference model defined by Malz et al. (2019). In this model, the body-fixed orientation frame (ie. the 9 components of the basis vectors) and the angular velocity of the aircraft are explicit states of the AWES and are incorporated in the system dynamics. We identified this model update as a major improvement to the framework and already mentioned it in the conclusion on P38-L729. In order to better highlight this point, we have improved the list of recommendations in the concluding remarks in Sect. 5 on page 40.

Technical corrections

- Line 30: axissymmetric => axisymmetric
- Line 36: can not => cannot
- Line 98: N_s probably refers to the number of segments of the wing, but this is not mentioned explicitly.
- Line 260: eventual => if applicable
- Line 357: The “min” and “s.t.” are aligned too much to the left.
- Line 405: The “min” and “s.t.” are aligned too much to the left.
- Line 655: stremwise => streamwise
- Line 757: magnitude aerodynamic => magnitude of the aerodynamic
- Caption figure A4: Is there a precursor simulation in this case? Isn’t it a turbulence free, sheared inflow according to line 786?

Thank you for these specific corrections, they have been incorporated in the revised manuscript.