Response to Anonymous Referee #1

Authors' responses to reviewer comments after major revision appear in purple text.

We would like to express our sincere gratitude to the referee for their valuable time and effort in reviewing our paper, as well as for their insightful suggestions.

Authors' responses to reviewer comments appear in blue text. Line numbers referenced in the authors' responses refer to the revised document. Figures with Arabic numerals (e.g., Figure 5) correspond to the revised manuscript; figures with Roman numerals (e.g., Figure vi) only appear in response to the reviewer's comments.

1. Little bit of background is required in the abstract;

Thank you for your comment regarding the background information in the abstract. In the updated abstract, we have provided more details about airborne wind energy systems and particularly balloon wind turbines, as below:

In the realm of novel technologies for generating electricity from renewable resources, an emerging category of wind energy converters called Airborne Wind Energy Systems (AWESs) has gained prominence. These pioneering systems employ tethered wings or aircraft that operate at higher atmospheric layers, enabling them to harness wind speeds surpassing conventional wind turbines' capabilities. The balloon wind turbine is one type of AWESs that utilizes the buoyancy effect to elevate the turbine to altitudes typically ranging from 400 to 1000 meters. In this paper, the wake characteristics and aerodynamics of a balloon wind turbine were numerically investigated for different wind scenarios. Large eddy simulation, along with the actuator disk model, was employed to predict the wake behavior of the turbine. To improve the accuracy of the simulation results, a structured grid was generated and refined by using an algorithm to resolve about 80% of the local turbulent kinetic energy in the wake. Results contributed to designing an optimized layout of wind farms and stability analysis of such systems. The capabilities of the hybrid ADM-LES model when using the mesh generation algorithm were evaluated against the experimental data on a smaller wind turbine. The assessment revealed a good agreement between numerical and experimental results. While a weakened rotor wake was observed at the distance of 22.5 diameters downstream of the balloon turbine, the balloon wake disappeared at about 0.6 of that distance in all the wind scenarios. Vortices generated by the rotor and balloon started to merge at the tilt angle of 10°, which intensified the turbulence intensity at 10 diameters downstream of the turbine for the wind speeds of 7 m s^{-1} and 10 m s^{-1}. By increasing the tilt angle, the lift force on the wings experienced a sharper increase with respect to that of the whole balloon, which signified a controlling system requirement for balancing such an extra lift force.

2. The introduction is complete and extensive, but lacks some structure. In particular, two questions remain unanswered: 1) what are the advantages and disadvantages of balloon turbines with respect to other AWE systems?; 2) what is the common layout that is expected for wind farms using this technology and how does it justify a high-fidelity study of the wake of these machines?;

We provide more information about the merits and demerits of balloon wind turbines, the preferred wind farm layout for them, and the reasons for conducting a high-fidelity study of their wake in Line (35) of the manuscript as follows:

Line (35): Among these, the balloon wind turbine, also known as the buoyant airborne turbine (Altaeros, 2022), has relatively simpler take-off and landing maneuvers due to the buoyancy effect, which makes it suitable for deployment in various locations and temporary power generation where rapid setup is required. Moreover, these machines have minimal visual impact and can operate at higher altitudes, 400-1000 m, where wind speeds tend to be stronger and more consistent, which allows them to harness more energy compared to other AWE systems operating at lower altitudes. However, these turbines may have limitations in terms of scalability for large-scale energy generation projects. Also, employing these turbines requires adherence to aviation regulations and safety standards. And, Servicing and repairing components at high altitudes or remote locations may involve additional logistical complexities, and costs which can be complex. To mitigate these limitations, balloon wind turbines can be installed closely together within a rectangular layout. The proximity of turbines allows for satisfying higher power output requirements, efficient use of the available airspace, and enables easier maintenance and control of the turbines. In wind farms for these turbines, the wake of one turbine can affect the performance and efficiency of neighboring turbines. A high-fidelity study allows for a detailed analysis of wake interactions, including the velocity deficits, turbulence, and impact on power generation, which can help optimize the layout and spacing of the turbines.

3. The sections 2, 3.1 and 3.2 are very general and probably redundant for a technical publication like this. Please reduce them, reporting only the details specific to this work;

The governing equations of LES and sub-grid stress model for turbulence modeling were removed from section 2. General descriptions of Momentum and Bladed element theories were eliminated from sections 3.1 and 3.2. Moreover, primary equations in these theories, i.e., equations 1, 2, 13, 14, and 15, and their descriptions were eliminated from the previous manuscript. Nevertheless, the secondary equations resulting from the substitution of various variables in these equations were retained to convey the fundamental principles of the BEM theory.

4. Section 3.3: the use of XFoil in the preliminary design phase is acceptable (please refer to the approach, not the airfoilTools database). However, its use for final design and simulation is questionable, especially for airfoils like the S809 with pronounced stall characteristics. At least a validation of the adopted polars with the experiments available in the literature is needed. It would also useful to specify here what conditions are gonna be simulated and how the turbine is controlled;

To choose the wind turbine in the first step, we attempted to select a rotor with available experimental data, such as NREL Phase VI. However, the dimensions of the experimentally studied rotor would not allow us to locate them inside the balloon. Therefore, we decided to customize NREL Phase VI's geometry in agreement with the balloon geometry's dimension. In this respect, the turbine's blade was divided into eight sections, and NREL Phase VI's airfoil (S809) was employed to generate the blade profile at each section. The Q-blade software was then utilized to calculate the optimized pitch angle and chord length at each section by importing the inflow details and operating conditions. To optimize the pitch angle by the program, the AOA was computed for each section using the tip speed ratio and the following equation:

$$\alpha = \tan^{-1}\left(\frac{2}{3}\frac{1}{\lambda_r}\right)$$

Optimize for lift/drag sets the twist at the specified. λ_r at which the blade section operates to an AoA that yields the highest glide ratio. The chord distribution was optimized according to BETZ (Gasch and Twele, 2010):

$$c(r) = \frac{16\pi r}{BC_L} sin^2(\frac{1}{3} tan^{-1}\left(\frac{R}{r\lambda_r}\right))$$

The description of the optimization method in Qblade was added to Line (175) of the manuscript.

In our specific case, the pitch angle and chord length of the airfoils used in the blade's profile were customized specifically for their application in balloon turbines. Unfortunately, since there is no existing literature that experimentally studies the aerodynamics of this particular blade design, we were unable to validate the adopted polar against such results.

The QBlade software is a widely recognized and validated tool within the wind energy community. QBlade utilizes a blade element momentum (BEM) method and incorporates a range of empirical and theoretical models to calculate the aerodynamic performance of wind turbine blades.

By using QBlade, we were able to generate polar data for the customized airfoil profiles under the specific operating conditions of our balloon turbine design. While direct experimental validation against literature data was not feasible due to the unique nature of our blade design, the use of QBlade allowed us to capture the key characteristics of the airfoils.

5. First part of Section 4 should be moved to Section 3, in order to complete the overview of the selected test case. To what real life operating conditions do the selected tilt angles correspond?;

Thank you for your valuable suggestion. We have moved the first part of Section 4 to Section 3 to provide a complete overview of the selected test case.

The wind speeds at 400 m above the ground was estimated by using averaged meteorological data and the power law formula. The corresponding data for wind direction at the desired altitude was unavailable, and we chose the common tilt angles for the conventional wind turbine near the ground.

6. Line 234: what criterion was used for the computation of the timestep?;

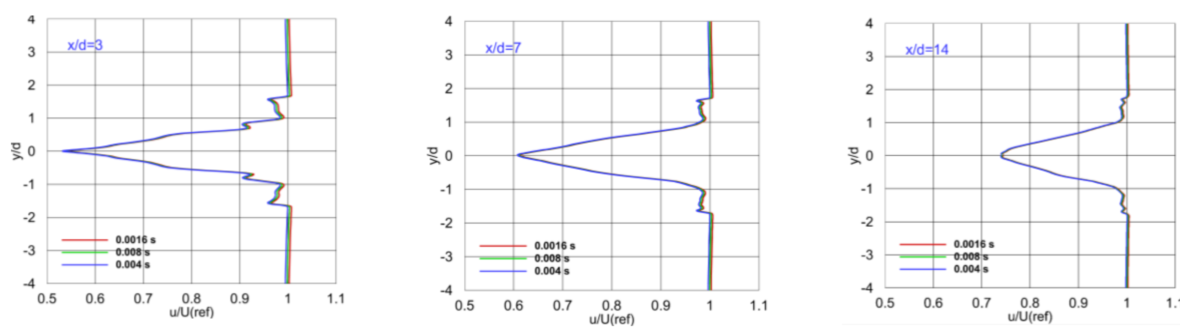
The criterion used for the computation of the time step was added to Line (215) of the manuscript as follows:

Line (215): The size of the time step was selected after sensitivity studies to assess the impact of the time step size on the convergence. To avoid excessive computational costs, the maximum time step required for the simulations to converge was selected, which was approximately close to the time required for a rotor rotation of 2.5 degrees ($\Delta t =$ 0.0016 s). LES calculations were run sufficiently to reach stable statistics of the flow.

In response to your query regarding the criterion employed for determining the time step, we wish to provide a comprehensive view of our approach. Initially, we considered multiple methods for selecting the time step size, including an evaluation of the independence of results from the time step and an assessment against the minimum flow time scale in critical regions. However, after careful deliberation and consideration of our computational resources, we opted to primarily rely on the convergence criterion. This decision was driven by the merits of the convergence criterion, which had a robust track record and was meticulously established through sensitivity studies to ensure both the stability and accuracy of our simulations. Nonetheless, we present the results of our additional methods here to underscore the robustness and reliability of our approach.

1. Independence of the results from the selected time step:

To address this, we duplicated a similar simulation setup as detailed in Section 4 of our paper, with U_{ref} set to 7 and θ_{tilt} at 0°. We conducted simulations employing smaller time steps (specifically, 0.0004 s and 0.008 s) compared to the time step used in the original simulations. It is important to note that when using larger time steps, we encountered numerical instability that failed to meet the convergence criterion. Figure i illustrates the vertical profiles of the time-averaged normalized x-velocity at various positions downstream of the wind turbine, spanning the range of -4 < y/d < 4 at z = 0.



(a) (b) (c)

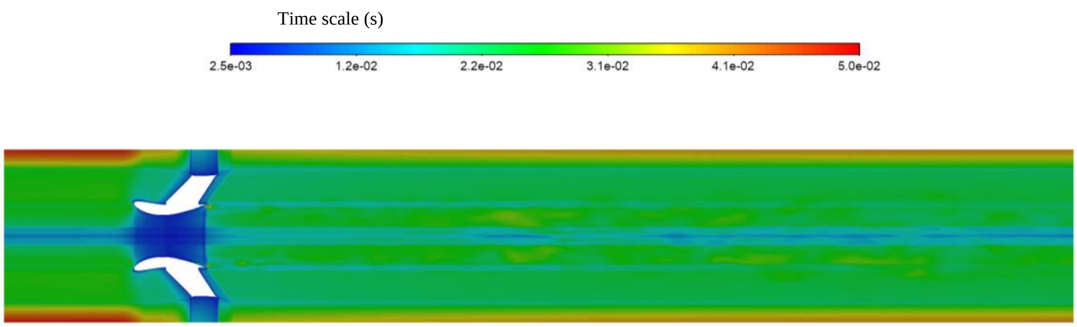
Figure i. Comparison of vertical profiles of the time-averaged normalized x-velocity for different time steps for U_{ref} =7 m s^{-1} and -4<y/d<4, and z=0 with θ_{tilt}= 0° at (a) x/d= 3 (b) x/d= 7 (c) x/d= 14.

According to figure i, the difference in the time-averaged normalized x-velocity at x/d = 3 for simulations using Δt = 0.0016 s and Δt = 0.004 s is found to be below 1 percent. Moreover, this difference further diminishes in downstream locations. The negligible variation observed between the original time step and the smaller time steps demonstrates that the chosen Δt is sufficiently small to accurately capture the intricate details of the flow. This includes the representation of small-scale turbulent features and the unsteady behaviour of the wake, which are directly linked to the precise prediction of velocity deficits in the wake region.

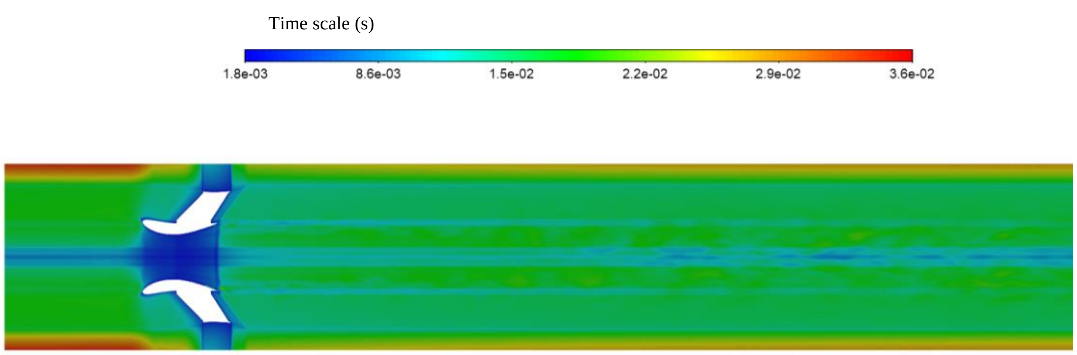
2. Time scale method:

The selected time step was then assessed to ensure it remained lower than or close to the smallest time scale governing the flow dynamics within our critical areas of interest —specifically, in the wake zone and the vicinity of the balloon. In this refined approach, we considered cells within these regions with the largest edge length (Δx) and local average velocity (V). We aimed to ensure that our time step (Δt) was sufficiently small to provide the necessary temporal resolution to accurately capture the flow's behaviour as it traversed these cells (Δt ≤ Δx / V). In this regard, LES calculations were run sufficiently to reach stable statistics of the flow. The time scale was then computed using Eq. (1). Time scale contours in the iso-clipped symmetry plan of the balloon (z=0 and -9<y<9) for $U_{ref} = 7, 10$ m s^{-1} and $\theta_{tilt} = 0^{\circ}$ are shown in figure ii.

$$Time\ scale = \frac{cell\ volume^{\frac{1}{3}}}{|V|} \tag{1}$$



(a)



(b)

Figure ii. Time scale contours in the iso-clipped symmetry plan of the balloon (z=0 and -9<y<9) for $\theta_{tilt} = 0^{\circ}$ (a) $U_{ref} = 7$ m s^{-1} and (b) $U_{ref} = 10$ m s^{-1}

As depicted in figure ii, the minimum time scale within the wake region and surrounding the balloon remains within the range of 0.0025 seconds for $U_{ref} = 7$ m s^{-1} and 0.0018 seconds for $U_{ref} = 10$ m s^{-1}, which falls comfortably below the time step determined through sensitivity studies for convergence (0.0016 seconds). Further examination of the time scale and independence of the results from the selected time step under varying conditions, specifically for $\theta_{tilt} = 5^{\circ}$and 10° at both inlet reference velocities, serves to confirm that the chosen time step aligns with both aforementioned criteria.

7. In the majority of the results there is a typo: "separation" instead of "separation"

Thank you for pointing out the typo, and we have now corrected "seperation" to "separation" throughout the relevant sections of the paper.