Exploring future production scenarios for the Italian offshore wind power
by
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Comments to Reviewer #2:
(the text of the reviewer is in italic)

We appreciate the feedback regarding our manuscript. In the following we address the reviewer's suggestions for improvement, and point out the changes compared to the original manuscript. Parts that have been rewritten or added due to comments by the referees have been highlighted in red in the revised version of the manuscript.

> *1. The algorithm chosen to determine the optimal layout is ineffective because of two reasons: it ignores the wind rose (i.e., the joint frequency distribution of wind speed and wind direction) and it ignores common practices/requirements in the marine environment.*
>
> *a. Starting with the first issue (no wind rose): the proposed genetic algorithm maximizes the minimum inter-turbine spacing, thus it ignores which wind direction(s) is (are) prevailing or which wind speed occurs more often in which direction. By ignoring this information, the identified layout will not guarantee the highest Annual Energy Production (AEP), actually, it will not even guarantee a high AEP. Optimizing over the entire wind rose would be ideal, but possibly beyond the scope of the study. An alternative would be to maximize the spacing along the prevailing wind direction only. This would require the calculation of the prevailing wind direction at each of the 55 wind farms, thus not a terribly long task, and then the modification of the fitness function to maximize the average distance along that direction, rather than that along all the possible directions.*

We agree that ideally each wind farm should be further optimised based on site measured data, energy production, actual installed capacity (which may change based on the Developer's plans), actual wind turbine, LCOE to account for cables optimisation for example, and last but not least geophysical surveys or MASE comments. Each of these inputs could significantly change any layout, either irregular or regular. Although we welcome the Reviewer's comments for next steps of the work, we have a different aim for this initial study. Namely, we are not considering the single developments but instead a global approach where we consider the overall system developments in the TERNA areas rather than a single wind farm. We wanted to make a more realistic assessment by including wake losses as they will be relevant for projects with tight spacing between turbines. Rather than performing the optimization as usual with the AEP as fitness function, we decided to maximize the minimun distance between turbines, i.e. a geometric approach that does not require continuous assessments of wake losses for the various wind directions.

To further address the comment of the Reviewer, we have performed the same procedure on the existing Swedish wind farm Lillgrund, where 48 Siemens wind turbines with diameter 93 m are installed. The array efficiency is available from SCADA data reported by Sebastiani et al. (Wind Energy, 2021). Knowing the bounding polygon, the number of turbines and the turbine power curve, the geometrical optimization was performed and the result is shown in figure 1. The identified layout has similar wake losses as the real Lillgrund farm, namely our estimate is realistic, which is what we wanted from the beginning of the project. We don't want to propose a new methodology to design wind farms (as we also would prefer to maximize the AEP in a single farm project), but rather estimate realistic wake losses for a global feasibility assessment of the planned Italian offshore installation. We have now included the Lillgrund farm analysis in the revised version of the manuscript as a validation case.

We have also run an independent test case for one of the planned wind farms featuring more than 35 wind turbines over a large area. The AEP optimised approach has produced a layout on 3 parallel rows with cross-wind distances in the order of 8 rotor diameters. This optimisation is not factoring electrical losses or cables costs. The genetic algorithm optimisation has been run for the same wind farm over the same area, leading to an irregular layout as expected. The wake losses have been estimated with the WindPro software and the Park2 wake model, based on the long-term wind speed and direction data obtained from the EMD WRF Europe+ dataset with a 25 years time-series. The wind farm area shows a prevailing wind direction, and the wake loss has been weighted by the frequency of the sectors. The wind farm wake loss difference between the AEP optimised layout and the genetic algorithm layout is only 0.6%, confirming in our opinion the quality of the genetic

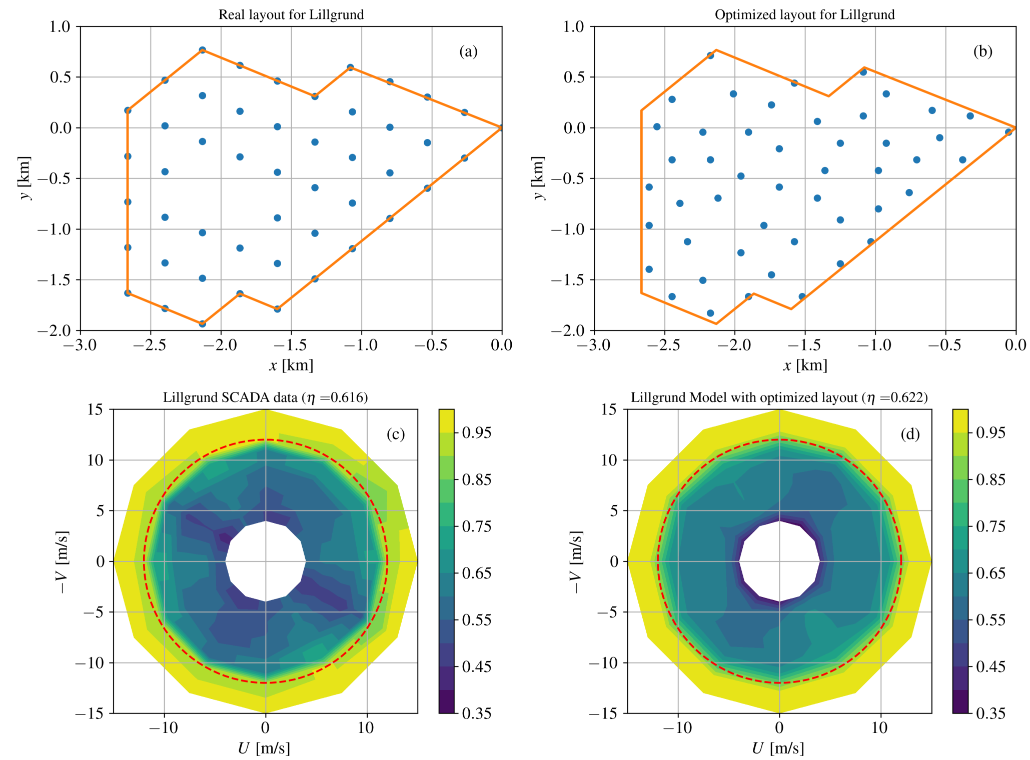

Figure 1: Validation of the optimization method on the Lillgrund wind farm. (*top row*) layout of the farm, (*bottom row*) array efficiency for different wind velocities and directions (the red dashed line indicates the rated speed of the installed Siemens wind turbine, 12 m/s). (*left*) real farm with SCADA data analized in Sebastiani et al. (Wind Energy, 2021) (*right*) optimized layout with the minimum distance fitness function. The title of the bottom row reports the average array efficiency of the farm for velocity below rated speed.

algorithm approach for this phase.

> *b. The second issue is that the resulting optimal layout is very irregular, meaning that it will look like a Swiss cheese with apparently randomly-placed wind turbines in the project area (e.g., figure 9b). While this is possibly OK over private onshore land with no vehicular traffic or no public access, in the marine environment offshore an irregular layout will likely encounter huge opposition from entities like the Guardia Costiera or the Marina Militare or even just fishing boats, because the ocean/sea is a public space. Navigating at night through such layouts will be a recipe for disaster and in fact in recent years the tendency for offshore layouts has been towards regular rows and columns that are aligned with the perpendicular and parallel directions with respect to the coastline, to facilitate fast deployment of emergency rescue boats and avoid collisions between boats and turbines even in bad weather and rough sea conditions. The genetic algorithm should be modified to accept only layouts with straight rows and columns.*

The layouts we are identifying will not be most likely used since their purpose was just to help us estimate wake losses. Nevertheless, in terms of navigation issues, each approved area will not be available to commercial navigation: hence, it is independent on the selection of a regular or irregular layout. It might be a challenge in terms of permitting, but this has not been factored yet and we refer to a possible future study.

> *2. The calculation of the actual AEP of each wind farm must take the wind rose into account. But the authors assumed, incorrectly, an even distribution of the wind directions, thus they averaged the array efficiency over all wind directions. Instead, they should have calculated the actual production at each hour of the 31 years for whatever the wind direction and wind speed were at that hour (with the power curve, which is a function of wind speed at hub height, and then the Jensen model, which is a function of the wind direction at hub height), and then sum them all up for each year. Averaging over all directions, regardless of how often each wind direction may occur (from the wind rose), is*

unacceptable. In fact, rather than identifying an optimal layout with the proposed genetic algorithm (which is not optimal at all) and then calculating the wake losses with Jensen (which is wrong if the wind rose is ultimately ignored), I recommend using a typical percent of wake losses (like 10%, although the average of the study is closer to 7.6% [(158-146)/158 7.6%], which seems too low to me) would be faster and possibly more accurate that going through all that work, plus it is already the approach chosen for transmission and generic other losses (15%).

As visible in the case of the Lillgrund layout, the array efficiency is mostly velocity-dependent rather than direction-dependent and this is particularly true to our identified layouts that do not follow a precise alignment and smear out wake losses. Since our suggested layouts are tentative, the accuracy gain obtained by performing a two-dimensional interpolation (wind speed + wind direction to get array efficiency) against our simple velocity-based interpolation would not be worth (the Reviewer is reminded that we are forced to perform this interpolation for every time step in every Monte Carlo simulation, since we are interested to the farms correlation in time). We agree that a typical percentage wake loss for all wind farms, as suggested by the Reviewer, would in fact be less representative compared to the proposed methodology for the portfolio of the wind farms, given the different shapes of the development areas.

As stated above, also the test case run with the WindPro software has not shown significant deviations either.

3. The equation proposed to give a total score (Eq. 2), which is ultimately a probability of success used in the Montecarlo simulations later, is odd because it uses the squares of the individual scores. Since the individual scores, varying between 1 and 3, are higher for lower challenges (from Table 1), the equation effectively gives a lot more weight to lower challenges, which is counter-intuitive. In the proposed equation, a great challenge would receive a low weight (the square of 1 is 1), whereas a small challenge would receive a high weight (the square of 3 is 9), thus the approach implicitly favors wind farms with low challenges, which may be desirable, but it does not give enough weight to great challenges, which may actually be a game stopper. For example, wind *farm A has 2 high challenges, 1 medium, and 1 low challenge, thus a score of 15; wind farm B has only medium challenges, thus a score of 12. The equation would favor A over B, which seems unrealistic. Either the equation should be changed to better reflect reality and give more weight to high challenges, or the use of squares should be justified.*

The formula (2) is defined with four parameters. We can consider following the example of the Reviewer. By considering that farm A and B have 2 parameters that have low challenge and 1 parameter with high challenge and they differ only in the last parameter where farm A has high challenge and farm B has medium challenge, we get that the score of farm A is 61.8%=$100(\sqrt{9+9+1+1}-2)/4$, while farm B has score 70%. We don't expect that the formula (2) is right and we are aware of its pitfalls. For instance, a farm where all parameters have challenges will have a score 0% (so it is impossible to be activated in the Monte Carlo simulation), while a farm presenting only low challenges will have a score of 100% (so it will certainly be activated). Both extremes show that the formula has pitfalls.

Regarding the sum of squares, we have used the principle used in uncertainty analysis where various uncertainties are summed as squared terms (regardless of their sign) as every scoring assessment is performed independently from each other. This is also a standard procedure according to the maximum likelihood principle (Kalnay, Atmospheric Modeling, Data Assimilation and Predictability, 2002). Although we agree in principle with the Reviewer comment, that the total Score formula could reflect different approaches, we are not addressing critical issues which could stop the development altogether. In fact we assume that all challenges can be to some extent resolved: this optimism leads to be higher weight to the low challenge project. We have added in the text to reflect that the score is one of the possible descriptions.

4. I do not understand how the concept of L (Eq. 3) is used and why. It is not an optimal spacing because it assumes a uniform layout, which is not optimal in the real world (given the wind rose) and not even in the study ("[L] does not aim to be the optimal configuration"). At first I thought it was a purely theoretical value, one that may or may not even be feasible once the actual shape of the area is accounted for. But figure 11b shows an actual *efficiency for a layout made with L, thus I got confused. Why is L used and how do you obtain a layout with it, since "the irregular shape of the polygon makes the layout identification challenging"?*

The Reviewer is right about the theoretical meaning of the parameter L. Given a bounding convex polygon, we expect that the best wind farm should be the one with equal spacing between the turbines, i.e. the distance L. Therefore, for a given area and number of turbines, we can always compute L even if we cannot identify the associated layout. L is indeed a theoretical parameter of little interest in itself. However, consider the case when we perform no optimization at all, but knowing the bounding area and amount of turbines, we get a distance $L/D = 10$. By using figure 11b, we can estimate that the layout should have an array efficiency of about 90% at 8 m/s. Of course, the final layout might have better or worse performance but the estimate is undeniably rapid and quite reliable based on 55 optimizations. We have added a clarifying sentence in the revised version of the manuscript. There we explain that the ordinate of the figure is just the efficiency obtained from the genetic algorithm optimization. the abscissa of the blue points is the minimum inter-turbine distance obtained from the genetic method, while the orange points differ in the abscissa since that is the L parameter.

5. While the Montecarlo approach seems reasonable to me, there is no validation whatsoever of its results. How can we trust that the results obtained with it are close at all to the success/failure chance of an offshore farm in Italy? I realize that there is only one offshore wind farm in Italy today (if I am not mistaken), thus perhaps not enough data to validate the method, but there are many offshore wind farms in Northern Europe. I am not requesting a thorough validation here, but at a minimum a literature review on the topic and a qualitative comparison are needed, otherwise this is all for nothing because it will be considered as a purely numerical exercise with no practical use.

The design of the Lillgrund wind farm can be considered as a validation about a plausible farm layout and its resulting wake losses. The available wind is also obtained from the ERA5 dataset and from the CERRA database and it was validated extensively in the literature. The only aspect that we cannot validate is whether an offshore wind farm will be constructed or not.

We are not aware about the existence of a database of farms (offshore or onshore) that have been build or not. One of the co-authors (Medici) has more than 20 years of experience in the wind-energy field and therefore his opinion and educated guess is considered to be more than a purely numerical exercise. The bottom-line is that the Monte Carlo simulations highlight some of the possible scenario for the future Italian offshore installations, pointing out about feasibilities and expectations of the current plans.

6. L. 15: Also maintenance issue are important factors in offshore wind costs.

Correct, we have now added this in the revised paper.

7. L. 24: I found a value of 4.6 GW, not 3.8 GW, on 4Coffshore.

The Decree includes 3.8 GW, amended in main text of the revised manuscript.

8. L. 27: What exactly are these "ambitious targets"? Please specify how many GW for offshore wind.

We have added further details in the main text of the revised manuscript.

9. L. 30 (related to comment 8): Of these 84 GW, how many are offshore wind?

All 84 GW are offshore wind request of connection.

10. L. 56: Assuming that "between" should be replaced with "among", how exactly were these 55 projects selected among all those submitted? How many were submitted (I think 64)?

The projects were selected to provide a good sample of the developments, especially for the Sardinia, Sicily and Sud TERNA areas.

11. L. 57: Why and how are these 35 clusters/geographical areas selected? I think that individual projects that have an overlapping area are grouped together in a cluster, but it is not clear. Maybe provide a list of the 35 and 55?

Both very near and overlapping projects had similar wind characteristics with a wind correlation very close to 1. We have therefore considered them to be all exposed to the same wind for simplicity.

> *12. L. 59: Give the URL of the MASE website where the data were collected from.*

https://va.mite.gov.it/it-IT/Ricerca/Via. We have included this in the revised manuscript.

> *13. L. 63 (related to comment 11): Define "proximity": how close do two wind farms have to be in order to be clustered together?*

Wind farms with a distance from each other of less than 8 km have a correlation coefficient higher than 98% (see figure 5 of the manuscript). Therefore it was assumed that they were exposed to the same wind to avoid the download of time series that nominally should be very similar.

> *14. L. 64: How do you calculate the centroid? Show equation.*

The centroid was calculated as the arithmetic mean of the latitude and longitudes of the bounding polygon. We do not desire to report this in the main text as we consider this information marginal within the entire project.

> *15. L. 83 and 87: Is it 31 or 37 years of data?*

The used wind speed time series is 31 years of data. It is the entire CERRA dataset instead which has 37 years of available wind speed data as described in the manuscript.

> *16. L. 82 (related to 11): Again, how are the 35 areas identified in the CERRA domain? Are they grid cells? The sentence does not make much sense, what does it mean "to obtain a comprehensive time history of the site representative of the cluster climate"? Which site? Which cluster? Rephrase.*

Given the centroid (latitude-longitude), the velocity time series at the nearest grid points were downloaded from the CERRA database and linearly interpolated to the centroid location.

17. L. 90: Here you state that you did not use ERA5, but then on L. 98 it looks like you did.

At the beginning we used both datasets to asses the wind speed values, and we did a correlation analysis between the datasets. It resulted in an good correlation hence we decided to proceed with CERRA which has an higher spatial resolution, as described in the manuscript.

18. Fig. 2: This figure does not add much to the discussion because it has almost exactly the same pattern as Fig. 1, consider removing it or purng it in an Appendix.

We disagree. Figure 2 is qualitatively similar to Fig. 1 but it shows the 90^{th} percentile, namely an information about the 10% most intense winds, providing a better information about the mean itself.

19. L. 96: Spell out ECMWF the first time. Add details about the years and resolution etc. of the EMD WRF dataset.

Good suggestion. We have now spelled the European Centre for Medium-Range Weather Forecasts in the paper. The EMD WRF dataset is still not described due to its limited importance in our work.

20. L. 113: Almost a major issue: why use the power law, which is a rather poor approximation, when you have the model levels surrounding hub height and you could easily interpolate to hub height?

When we initiated the project, we intended to use ERA5 data first that has only wind data at 10 m and 100 m near the surface (the other pressure levels are too high to be used). The CERRA dataset, on the other hand, allows to access data at 150 m but we did not do that (unfortunately), requiring to download the data once again for the CERRA dataset over all the farm locations at 150 m. We agree that it would be better to have that information, but we feel that the error in the extrapolation might be comparable to the error of the CERRA database (especially considering that the majority of the surface wind measurements are performed at height lower than 100 m).

21. Fig. 3: Please use more resolution for the low bathymetry (0-500 m)! For example, 0-10, 10-30, 30-50, 50-100, 100-250, 250-500, 500-1000, ¿1000 m. At a minimum, add the intervals from Table 1. We do not need resolution for the high depths above 1000 m.

Good suggestion. The figure is now updated in the revised version of the mansucript.

22. Fig. 4: Rephrase the caption as follows: "The cut-in and cut-out wind speeds are marked with red dashes."

Done.

23. Fig. 5: What power is this? The average? Median?

Figure 5 shows the power correlation coefficient, so neither the mean power or median power.

24. L. 145: Remove "Some", just say "Results of ..."

Done.

25. L. 147: Are you sure it is an "optimal: time lag, perhaps you mean "worst"?

We confirm optimal in the sense that it maximises the correlation coefficient.

26. L. 143-156: Why talk about the time-lag analysis at all if you did not even use it ("30 years ... a sufficiently representative climatology")? I do not understand what it means: is a positive value indicating that the first farm affects the second but not vice versa? What is the interpretation of the non-symmetric distribution? Consider removing this piece entirely.

If the correlation between one farm and another one is positive and peaks after some amount of time (a skewed distribution), it means that a period of high wind in the first farm is expected to have an influence in the second farm with highest probability at the peak time lag. Initially we aimed to develop a statistical approach reconstructing time series with the same statistical content and correlation between the various point. However, having collected 31 years of data, we considered this historical series sufficient to perform the analysis. However, the correlation analysis remains interesting and worth, quantifying how different wind farms could combine or have phase differences in the power production.

> *27. Fig. 7: How did you use the Weibull distribution here exactly? What were the values of the shape and form coefficients?*

We don't use that. However, given the power curve of the turbine, $P(U)$, and the frequency distribution of the wind, $f(U)$, it is possible to compute the average power as

$$P_{mean} = \int_0^\infty P(U) f(U) dU \,. \tag{1}$$

Knowing the wind distribution, the average power can be computed. Alternatively (and this is the method we have chosen) we can compute the average power from the instantaneous time series of the power retrieved from the historical wind, without the need to compute the probability density function of the wind.

> *28. Table 1: It seems to me that a large farm is more challenging and more complex to site, finance, build, and operate than a small wind farm. Why is the "Capacity" score opposite instead?*

The assumption is that a scale factor can make a development cheaper. It is acknowledged that other descriptions could equally be introduced and this is only one of the possible views.

> *29. L. 234: In English "former" and "latter" are used when there are two terms to discuss. Here, there is only the fitness function, thus replace "the latter" with "the fitness function"*

Done

30. L. 238: What is "crossover"?

31. L. 240: What is "mutation"?

32. L. 241: What is "elitism"?

We have now added a reference about these terms to a reference book in genetic algorithms. In Genetic Algorithms crossover, mutation, and elitism are core evolutionary operators that collectively drive optimization. Crossover (or recombination) combines genetic material from two parent solutions to produce offspring, enabling the exploitation of high-quality traits. Mutation introduces small, random alterations to individual genes (such as bit flips or Gaussian noise) preserving population diversity and facilitating exploration of new solutions to avoid local optima. Elitism ensures the best-performing individuals from each generation are preserved unchanged into the next, maintaining high-fitness solutions and accelerating convergence. Together, these mechanisms balance exploration (via mutation) and exploitation (via crossover), while elitism safeguards progress, mirroring natural selection to efficiently navigate complex search spaces.

33. Fig. 10: This figure should have "all considered farms" from L. 252, thus 55 (or 35 clusters), but I count 49 dots.

We confirm that there are 55 points in the plot.

34. L. 261: Why would a spacing of 8-10 diameters be indicative of a strongly unidirectional wind regime? Most offshore wind farms have a spacing of ¿8Dx8D.

Spacings tend to be smaller across prevailing wind directions in order to save on cables costs, since some wind directions might have a nearly zero frequency therefore high wake losses in these directions are not of concern.

35. L. 265: As mentioned in 2, it is not OK to average over all directions.

We have addressed this concern in our reply to 2.

36. L. 266: What about Fig 11b? It is not discussed at all. There I count 40 dots, not 35, not 55 ...

Correct. There were 40 points. Now we have updated the figure with all the 55 projects. Thank you for the careful review.

> *37. L. 287: Cannot use a capacity factor of 100%! Never ever!!!! You do not need to calculate the number of TWh if the CF was 100%, it would be misleading (plus the value would be 403 TWh, not 406). From the ratio of 158/403, the CF is about 39%, which is really good.*

Good point, we have rephrased the manuscript: considering that by looking at the global numbers, all the 55 wind farms feature almost 3,100 turbines for a global installed capacity of approximately 46 GW. By applying the power curve to the historical time series, the production of the portfolio is estimated to be 158 TWh/year, a number which decreases to 146 TWh/year when an average wake loss of 7.6% is accounted for across the portfolio. The net production is then reduced to 124 TWh/year when other losses are included to the assumed metering point. This corresponds to a capacity factor of 30.8% across the portfolio.

> *38. L. 292: This sentence is unclear. I think it means this: "the license to build should be granted to at least a third ...". Also at L. 330.*

Yes, correct. We have modified the text in the revised manuscript.

The comments from the referee have certainly helped us to improve our manuscript and we hope that the comments have been taken into consideration satisfactorily.