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Trading Off Sound Pressure Level and Average Power Production for Wind Farm Layout Optimization

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Abstract

This research explores the trade-offs between a wind farm's average power production and noise impact on nearby observers. Two specific wind farm designs were studied and optimized using the FLORIS wake model and an acoustic model based on semi-empirical turbine noise calculations. It was found in the two wind farms that the average power production could be increased, up to 8.01% in one and 3.63% in the other, ignoring sound level considerations. Including a noise restriction in the optimization had a minimal impact on the optimal average power production within about a five-decibel range. Past this range, sound limitations decreased the wind farm's power production significantly. By analyzing average power production and sound pressure level together, we can take advantage of the multi-modality of the optimization to find solutions where noise impact can be improved with an insignificant effect on power production.

Keywords: turbine acoustics, wake model, wake propagation, wind farm optimization, wind turbine

1. Introduction

Wind is a valuable source of energy as it is renewable, available in many parts of the world, and has the ability to produce twenty times more power than the world currently consumes [1]. As turbines are grouped together in wind farms to harness large amounts of wind energy in a limited area, each turbine extracts energy from the wind and causes a reduction in wind momentum. This reduction, called a wake, propagates downstream and can cause a significant impact in the wind energy conversion of nearby and downwind turbines. Due to this impact, efforts are made to position turbines in such a way that minimizes the wake interference [2–4].

One way to determine the position of turbines within a wind farm is through optimization. Wind farm layout optimization can be used to control different aspects of a wind farm, such as fatigue loading of turbines [5–7], and can be applied to minimizing wake interference using reduced-order wake models. Reduced-order wake models, which reduce the complex wake behavior to mathematical relationships, are an effective way to gain an understanding of a wind farm's wake distribution with a minimal computational cost. Because the behavior of a turbine wake is complex, many reduced-order wake models have been created in an attempt to classify different characteristics of wake creation and propagation [8–10]. Wind farm layout optimization using different wake models has been conducted by many researchers using wake models and optimization techniques to successfully increase turbine power production [10–16].

Wind turbine noise generation is another important consideration for wind farm layout optimization as this noise can cause disturbances to residential areas located in the vicinity of wind farms. While the sound

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¹Abbreviations used in this paper:

BPM: Brooks, Pope, and Marcolini (referring to the acoustic model)

FLORIS: FLOW Redirection and Induction in Steady-state

NACA: National Advisory Committee for Aeronautics

NSGA: Non-dominated Sorting Genetic Algorithm

SNOPT: Sparse Nonlinear OPTimizer

SPL: sound pressure level

coming from wind turbines poses no physical or psychological harm to humans, it can be an annoyance to individuals living nearby wind farms [17]. This annoyance has the potential to limit the areas available to build wind farms to remote locations away from populated regions. Ideally, a wind farm layout should constrain the turbine noise disturbance below a specified limit while maximizing power output. This noise limit varies throughout the world ranging from about 35 to 60 decibels, about the loudness of a refrigerator to the loudness of a normal conversation [18–20]. The main source of the turbine noise is the turbulence-induced noise from the wind flowing over the blades [21] and is the type of noise we explored in our research.

While wind farm layout optimization using both a wake and an acoustic model has not been studied extensively, previous research efforts performed by Kwong et al. and Sorkhabi et al. produced a simple analysis of turbine optimization using the Jensen wake model and the ISO-9613-2 standard that predicted only the propagation of the turbine noise [22, 23]. The optimization used a grid-based approach and implemented the gradient-free NSGA-II algorithm to demonstrate the trade-offs between noise level constraint and maximum power production of the wind farm. We conducted a similar study presented in this paper with some differences in optimization technique and wake and acoustic modeling. We used gradient-based optimization and allowed the turbines to move freely within the bounds designated by the wind farm. This type of optimization is effective in allowing gradients of the functions to direct the optimizer to an optimal solution rather than sampling the entire design space with large computational costs and relying on “survival of the fittest” to find the solution.

To calculate wake velocities, we used a newer, more accurate model in place of the Jensen model to provide better velocity calculations in the wakes of the turbines. Although the Jensen model is simple and easy to use while providing reasonable results [8], using a wake model that better predicts the complexity of turbine wakes would more accurately predict velocity deficits of an actual wind farm. We also used an acoustic model that could calculate sound based on factors like a turbine’s geometry, rotation rate, and distance away from an observer allowing us to tune the acoustic model to the turbines used on the wind farms more closely. This is an improvement to the ISO-9613-2 standard as our model would predict how sound was both created and propagated from the turbine.

In a previous version of this study, we used only a single wind direction, which allowed turbines to be positioned unrealistically close to nearby residences [24]. However, as wind can come from any direction and must be considered in a complete wind farm layout optimization, this work expands on our previous work by using the frequency of wind in all directions. We have also expanded this work to consider the impact of varying noise level constraints, similar to previous research [22, 23], that would allow us to observe the trade-off between constraining the noise level of the wind farm and maximizing its power output. For this work, we consider two wind farms as case studies and explore the impact on average power production from varying the sound pressure level (SPL) constraint. We first describe the characteristics of the two analyzed wind farms, then overview the wake and acoustic models used in the wind farm layout optimization, and finally we discuss the results of the optimizations.

2. Methods

In order to conduct our study, we identified the initial wind farm layouts for our optimization and determined the frequency of wind directions we would use. We also defined the turbine wake and acoustic models in a way that could be used for a gradient-based optimization. This meant that the models needed to be smooth (continuous gradients), have no flat areas in the function values, and provide values both quickly and accurately. The following sections describe in more depth the wind farms we chose for our optimization, the wake and acoustic models we used, and the techniques we implemented for our gradient-based optimization.

2.1. Wind Farm Locations

In an effort to make the research applicable to a real-world situation, we used the general layout of two actual wind farms as models for our optimization. These wind farms were selected due to problems they have had with noise disturbance in the past [25, 26]. The purpose of our research is not to suggest redesign of existing wind farms, as this would be would be unrealistic environmentally and financially. Rather it is to explore the potential benefits of including acoustic impacts during the initial layout process instead of correcting the problems later on with costly alterations of blades or significant rotation speed reductions.

The first wind farm was based on the Lissett Airfield Wind Farm in East Yorkshire, England, which was constructed on a former Royal Air Force airfield and is now run by Infinis Energy PLC [27]. It was found that high wind speeds in certain directions caused an increase in turbine noise, so efforts were made to reduce the noise by slowing the turbine rotation [25]. While slowing the turbines down decreases the turbine noise, it also decreases power production. Repositioning turbines to more optimal locations could decrease the noise disturbance from the turbines without sacrificing power production. The specifications of this wind farm include twelve Nordex N90-2.5MW turbines with 90-meter rotor diameters creating two rows of turbines [28]. The actual wind farm boundary follows the curves of the property line of the former airfield, but we simplified the wind farm boundaries to a rectangular area to allow for linear constraints. To act as points of sound measurements, we chose seven villages and residences located near the wind farm. The wind farm layout used in our optimization can be seen in Fig. 1. Due to a lack of weather information of the actual wind farm, the wind direction frequencies used in the optimization were based on weather data at Humberside Airport located about 48 kilometers south of the wind farm [29]. The wind direction frequencies can be seen in the wind rose in Fig. 2.

Figure 1: An approximation of the layout of the Lissett Airfield Wind Farm used as a reference in our first case study. Each of the seven observer locations used for the sound measurements are indicated as well as the rectangular boundary used in the optimization.

Figure 2: A wind rose indicating the averaged annual wind direction frequency at Humberside Airport located about 48 kilometers from the Lissett Airfield Wind Farm. This data was used for the optimization in our first case study.

The second wind farm was based on the Rosiere Wind Farm run by Madison Gas and Electric in Kewaunee

County, Wisconsin. This location was an interesting case study as individuals who lease the land to the company still live within the bounds of the wind farm. They even plant crops right up to the base of the turbines in some cases [30]. Since noise control would be important to individuals living so close to the turbines, we explored positioning and changing the rotational speed of each turbine to reduce noise while keeping the turbines within the limits of their respective leased property. The specifications of this wind farm include seventeen Vestas V47-660kW turbines with 47-meter (154-foot) rotor diameters spread out into two geographic regions separated about two kilometers from each other [30]. Simplifications were also made on the wind farm’s boundaries by straightening the slightly curved property lines. Twelve residential locations were used as the sound measurement references and can be seen in Fig. 3, located within the turbine boundaries in many cases. The wind direction frequencies were based on the company’s weather database [31] shown in the wind rose in Fig. 4.

Figure 3: An approximation of the layout of the Rosiere Wind Farm used as a reference in our second study. Each of the twelve observer locations used for the sound measurements are indicated.

Although the wind speed varies during the operation of a wind farm, we fixed the wind speed to the rated wind speed of the respective turbines: 14 m s^{-1} for the Lissett Airfield Wind Farm and 15 m s^{-1} for the Rosiere Wind Farm. These wind velocities were chosen in order to produce rated power of the turbines not affected by the wake. To discover at what point the average power production would approach zero for decreasing noise levels, we allowed the rotation rates to range from zero to the maximum rotation speed of the respective turbines: 16.1 RPM for the Lissett Airfield Wind Farm and 28.5 RPM for the Rosiere Wind Farm. All of these values were based on published information for the Nordex and Vestas turbines used on the wind farms [28, 32]. Although the Vestas turbines used in the Rosiere Wind Farm operate at a fixed rotation speed, to provide the ability to lower the SPL limit similar to the Lissett Airfield Wind Farm, we allowed the turbines to vary in rotation rate giving us similar trends in average power production and SPL between the two wind farms.

Figure 4: A wind rose indicating the average annual wind direction frequency at the Rosiere Wind Farm.

2.2. Wake and Acoustic Models

To predict the wake velocity deficits in the wind farm, we used the FLOW Redirection and Induction in Steady-state (FLORIS) model [10]. Although derived from the simple Jensen model, the FLORIS model more accurately predicts wake velocity deficits by splitting the wake into different zones called the near wake, the far wake, and the mixing zone and accounting for decay and offset of the wake propagation [10, 33], which is illustrated in Fig. 5. It also predicts wake redirection through turbine yaw angle adjustments. The power for a given turbine (P_i) is based on the equation:

$$P_i = \frac{1}{2} \rho A_i C_P(a_i, \gamma_i) U_i^3 \quad (1)$$

where ρ is the density of the air, A_i is the swept area of a given turbine's blades, C_P is the power coefficient of a given turbine based on its axial induction factor (a_i) and its yaw position (γ_i), and U_i is the effective wind velocity at a given turbine's rotor. For turbines that are waked by upstream turbines, the effective wind velocity is found using:

$$U_i = U_{u(i)} \left[1 - 2 \sqrt{\sum_{j=1}^N \left[a_j \sum_{q=1}^3 c_{j,q}(X_i) \min \left(\frac{A_{j,i,q}^{OL}}{A_i}, 1 \right) \right]} \right] \quad (2)$$

where $U_{u(i)}$ is the effective wind velocity of the turbine that overlaps a given turbine the most, $c(x_i)$ is a wake decay coefficient as a function of the downstream position (X_i) of a given turbine in the wind reference frame, A^{OL} is the overlap area of the wake of an upstream turbine on a given turbine, and sums are taken over N turbines creating the overlapping wakes and the three wake regions as defined by the FLORIS model. Further work was conducted to refine the FLORIS model by making the wake velocity distribution smooth and providing gradients that would allow a gradient-based optimization to perform more effectively [34]. Efforts were made to adjust the power capacity of the turbines with respect to the turbines' speed as much as possible to the actual turbines using calculated power curves to reflect reasonable average power production values in our optimization.

The acoustic model used in this research was based on the equations developed by Brooks, Pope, and Marcolini, referred to as the BPM equations [35]. These equations produce a semi-empirical acoustic model based on experimentation conducted using NACA 0012 airfoil data. The sources of sound in this study included turbulence from the blade along the trailing edges and at the tips as well as the vortex shedding of

Figure 5: A diagram of the FLORIS model taken from the work of Gebraad et al. showing the three wake regions with respective diameters (D_w), the wind velocity in front of a turbine (U_i), and the influence turbine yaw has on the propagation of the wake downstream [10].

the boundary layer and trailing edge bluntness. Each of these sources produce a sound pressure level (SPL) measured in decibels (dB), and the SPL from each noise source is added together using:

$$SPL_{total} = 10 \log \left(\sum_{i=1}^N 10^{SPL_i/10} \right) \quad (3)$$

for N noise sources to produce a total SPL coming from the turbine blades. The noise level perceived from the turbine depends on the orientation and distance an observer is from the trailing edge of a turbine blade. To account for these factors, the distance between the turbine blade and an observer as well as high- and low-frequency directivity functions are used:

$$\begin{aligned} \overline{D}_h(\Theta_e, \Phi_e) &\approx \frac{2 \sin^2(\Theta_e/2) \sin^2 \Phi_e}{(1 + M \cos \Theta_e)[1 + (M - M_c) \cos \Theta_e]^2} \\ \overline{D}_l(\Theta_e, \Phi_e) &\approx \frac{\sin^2 \Theta_e \sin^2 \Phi_e}{(1 + M \cos \Theta_e)^4} \end{aligned} \quad (4)$$

based on the angular position from the blade to an observer in the chord reference (Θ_e) and span reference (Φ_e) as well as the Mach number of the wind over the blades (M) and the convective Mach number ($M_c = 0.8M$). The angular orientation calculations were based on work conducted by Vargas [36] and produced louder noise above or below a blade and quieter noise upstream or downstream of the trailing edge.

This acoustic model was further studied by other researchers, such as Moriarty and Migliore who performed validation studies of the acoustic equations with different configurations of blades and wind speeds [37]. Since the turbines used at the two wind farms do not have NACA 0012 blade cross-sections [28, 32], we calibrated our acoustic model using published noise data [30, 38] with a correction factor of 0.86 for the Rosiere Wind Farm and 0.82 for the Lissett Airfield Wind Farm. As the original model contained sharp discontinuities in the gradients moving to the sides and above the turbine, we used quadratic fitting to provide a smooth transition through these discontinuous regions. This allowed the model to be used more effectively in a gradient-based optimization. Because we had no information on the actual geometry of the turbine blades, we used the blade geometry of the theoretical NREL 5MW turbine [39] that we dynamically scaled to bring the diameter of the turbine to the size of the turbines in the wind farms. Fig. 6 shows an example of the SPL distribution of a three-bladed, 90-meter diameter turbine rotating at 16.1 RPM in 13.5 m s^{-1} wind illustrating how the noise is loudest in front of and behind the turbine and much quieter to the sides.

Initial power and noise levels were calculated using our wake and acoustic models based on the original positions of each of the turbines and the observer locations using the calibrations described above, which can be seen in Table 1. As shown, the Lissett Airfield Wind Farm with fewer turbines has a greater average

Figure 6: An example of the SPL distribution calculated by the BPM equations for a three-bladed, 90-meter diameter turbine rotating at 16.1 RPM in 13.5 m s^{-1} wind moving in the direction indicated. The SPL measurement, in decibels (dB), is calculated for an observer at a given position in the lateral and downwind position, in meters, of the turbine at ground level.

power production than the Rosiere Wind Farm due to the higher power production of the Nordex turbines. The SPL is typically greater at the Rosiere Wind Farm due to the close proximity of the turbines to the observers within the boundaries of the wind farm.

2.3. Optimization

In gradient-based optimization, gradients are used to direct the minimization of an objective function, a method we used in our study while enforcing the bounds of the wind farm and a specified SPL limit. Using the FLORIS and BPM models as functions in the objective, the optimization was performed using Sparse Nonlinear OPTimizer (SNOPT), a sequential quadratic programming optimizer used for solving large, nonlinear problems [40]. For the optimization to be effective, the evaluated functions need to be smooth and free of flat areas and discontinuities to prevent the optimization from failing in these areas. The optimization in our research was defined by:

$$\begin{aligned}
 & \text{maximize} && P(x, y, \Omega) \\
 & \text{with respect to} && x_i, y_i, \Omega_{iw}, \quad i = 0, 1, \dots, m \\
 & && w = 0, 1, \dots, f \\
 & \text{subject to} && d_{i,j} \geq 2D_{turbine}, \quad i, j = 0, 1, \dots, m \\
 & && B_{x,low} \leq x_i \leq B_{x,high}, \quad i = 0, 1, \dots, m \\
 & && B_{y,low} \leq y_i \leq B_{y,high}, \quad i = 0, 1, \dots, m \\
 & && 0 \leq \Omega_{iw} \leq \Omega_{max}, \quad i = 0, 1, \dots, m \\
 & && w = 0, 1, \dots, f \\
 & && SPL_k \leq SPL_{limit}, \quad k = 0, 1, \dots, n
 \end{aligned} \tag{5}$$

where $P(x, y, \Omega)$ is the average power production of the wind farm based on the x and y locations of each of the m turbines in the wind farm and the rotation rate, Ω , for each turbine in each of the f wind directions. The distance between turbines i and j ($d_{i,j}$) was set to be at least two times the turbine diameter ($D_{turbine}$). The turbines were constrained between the lower and upper x and y boundaries of the wind farm limits

Table 1: Initial Layout Measurements

Lissett Airfield Wind Farm	
Average Power Production: 27.27 MW	
Maximum Sound Pressure Levels	
Observer 1: 43.05 dB	Observer 5: 40.78 dB
Observer 2: 42.98 dB	Observer 6: 44.56 dB
Observer 3: 42.82 dB	Observer 7: 43.07 dB
Observer 4: 43.36 dB	
Rosiere Wind Farm	
Average Power Production: 10.78 MW	
Maximum Sound Pressure Levels	
Observer 1: 44.66 dB	Observer 7: 51.92 dB
Observer 2: 46.37 dB	Observer 8: 49.44 dB
Observer 3: 51.74 dB	Observer 9: 50.81 dB
Observer 4: 51.87 dB	Observer 10: 50.17 dB
Observer 5: 46.05 dB	Observer 11: 51.99 dB
Observer 6: 45.62 dB	Observer 12: 50.65 dB

($B_{x,low}$, $B_{x,high}$, $B_{y,low}$, and $B_{y,high}$). The rotation rate of the turbines in this conceptual study was also constrained between zero and a given maximum rotation rate, Ω_{max} . The SPL at each of the n observers was constrained to a given SPL limit. Because different wind directions would produce a different SPL for a given observer, the limit was enforced for all wind directions to ensure that an observer was never subjected to a higher SPL than specified. We allowed the feasibility tolerance to be within a tenth of a decibel, as such a small difference in SPL would not be audibly detectable by an observer [19].

3. Results

The optimization was run many times for each wind farm to gain results for varying SPL limits. When the SPL limit was sufficiently high, the optimization proceeded as if there was no SPL limit and produced results similar to other wind farm layout optimization studies by moving turbines out of wake regions and maintaining an optimal rotation speed. Once the SPL constraint was lowered to make it active in the optimization, the turbines moved further from the observer locations. At some point, simply repositioning the turbines could not quiet the wind farm enough and rotation rates were slowed. The following sections present more detailed results from the Lissett Airfield Wind Farm and the Rosiere Wind Farm case studies.

3.1. Optimization of the Lissett Airfield Wind Farm

The optimization of the Lissett Airfield Wind Farm was conducted by starting each of the twelve turbines in their original locations with a rotation rate of 16.1 RPM. The SPL limit was varied in the range of 20 to 80 dB and did not have an effect on the results of the optimization until it dropped below 45 dB.

When the SPL limit was kept above 45 dB, the optimal average power production attained was just under 29.5 MW (a 8.01% increase from the original layout) by moving turbines away from each other towards the bounds of the wind farm, as seen in Fig. 7. This type of behavior was expected as when turbines are far from each other, the wake interference is minimized and turbines can receive more wind energy. In each of these configurations, rotation rates were kept at about 16 RPM with a few exceptions where a slower rotation rate would maximize the turbine's power capacity with slower moving winds.

Figure 7: The optimized layout of the Lissett Airfield Wind Farm with no active sound pressure level limit. In this case, the turbines were free to move apart from each other to minimize wake interference.

As the SPL limit was reduced below 45 dB, the turbines began to be repositioned further away from the observers and closer to each other, as seen in Fig. 8 where the SPL limit was set at 35 dB. Because turbines were closer together, more significant wake interference between the turbines was experienced and reduced the maximum power the turbines could attain. Rotation rates were also decreased as the SPL limit was decreased further, spinning slower than 10 RPM at SPL limits below 33 dB. Although a rotation rate as low as zero was acceptable for this conceptual layout optimization, it would not be recommended for an actual wind farm. At extremely low SPL limits, turbines had to significantly curtail power production.

Figure 8: An example of the optimized layout of the Lissett Airfield Wind Farm with a 35 dB limit enforced. The contour map shows the sound pressure levels in the wind direction indicated that caused the highest sound pressure levels to the observers although the optimization considered all wind directions in the turbines' positions.

Comparing the various SPL limits with the optimal average power production values obtained, a Pareto front was formed and can be seen in Fig. 9. The dashed lines in the chart indicate the average power production and the highest SPL from the original turbine layout as a point of reference. As seen in this specific curve, an SPL limit above 39 dB allowed the optimizer to increase the average power production from the original layout but dropping below 39 dB began to significantly impact the wind farm's ability to produce power. This represents a decrease of about 5.17 dB for the same average power production as the original layout simply by repositioning and adjusting the rotation rate of the turbines.

Figure 9: A Pareto front of the Lissett Airfield Wind Farm comparing the wind farm’s average power production in megawatts (MW) to the sound pressure level limit in decibels (dB). The dashed lines indicate the average power production and the sound pressure level of the original layout.

3.2. Optimization of the Rosiere Wind Farm

We conducted the optimization of the Rosiere Wind Farm in the same way as the Lissett Airfield Wind Farm by starting the turbines in their original locations with a rotation rate of 28.5 RPM. The optimization was performed using an SPL range from 30 to 60 dB and we found similar results to the previous case study.

While the trend in average power production decrease was the same as the Lissett Airfield Wind Farm, the different turbines used in this wind farm resulted in lower average power production values. When the SPL limit was effectively not active above 50 dB, the optimal average power production was about 11.2 MW (a 3.63% increase from the original layout) with the configuration seen in Fig. 10. Again, as expected, the turbines were positioned away from each other as much as possible while keeping them within their respective leased property boundaries. The rotation rate for each of the turbines also stayed near 28 RPM.

As the SPL limit was decreased, the optimization began to reposition the turbines away from the observers and decrease the rotation rates to minimize the noise, similar to the previous case study. Fig. 11 shows an example of the optimized layout with an SPL limit of 42 dB moving the turbines towards the boundaries of the wind farm. This resembles the behavior of the Lissett Airfield Wind Farm when no SPL limit was active simply due to the fact that observers are inside the wind farm instead of just outside. As the turbines are so close to the observer locations, moving them to the boundaries of the wind farm allowed the noise level to be reduced.

For this wind farm, using an SPL limit above 47 dB (4.84 dB lower than the original layout) still allowed the optimizer to increase the wind farm’s average power production from the original layout, but below this the power production began to be significantly impacted (see Fig. 12).

3.3. Discussion of Results

As shown in the two case studies, we were able to increase power production and reduce the noise disturbance in reference to the original layout of the wind farms for a given range of SPLs. These results were possible because this optimization problem was very multi-modal, meaning that many local optimum existed in the design space. As the wakes behind turbines cause a very complex velocity field that turbines could be placed in, there are several turbine locations and a wide range of rotation rates that would result in an increased power production. We took advantage of this principle to include a noise level constraint in the optimization rather than a sequential technique of optimizing average power production and SPL separately. Because there were many optimal locations of turbines, the optimizer could search for a solution that had no impact on the average power production but that would reduce the noise.

However, the presence of many local optimum presented challenges as we compared each of the optimized average power production values at the different sound pressure levels. Because many solutions existed that

Figure 10: The optimized layout of the Rosiere Wind Farm with no active sound pressure level limit. The turbines were moved apart from each other to minimize wake interference.

satisfied the optimization problem, we found instances where a result at a lower SPL limit produced a greater average power production value than a result at a higher SPL limit. As this was expected due to the inherent multi-modality of the optimization, we made efforts to re-run these instances using the results of similar SPL limits to create Pareto fronts that followed the same trend. Since our purpose in this research was to compare the trade-offs between average power production and SPL of a wind farm optimization, this method of finding consistency in the decreasing trend of average power production values at continuously lower SPL limits allowed us to better understand the relationship between the two parameters.

We were also able to gain confidence in the values we obtained from the optimization by comparing them with real-world data. In both studies, we found that average power production could be increased in the decibel range of the upper 40's to the lower 50's. This agreed with the general trend of SPL limits imposed on various wind farms around the world [18–20] and gives validity to the assumptions we made in the wind farms we analyzed.

Figure 11: An example of the optimized layout of the Rosiere Wind Farm with a 42 dB limit enforced. The contour map shows the sound pressure levels in the wind direction indicated that caused the highest sound pressure levels to the observers although the optimization considered all wind directions in the turbines' position.

Figure 12: A Pareto front of the Rosiere Wind Farm comparing the wind farm's average power production in megawatts (MW) to the sound pressure level limit in decibels (dB). The dashed lines indicate the average power production and the sound pressure level of the original layout.

4. Conclusions

In designing the layout of a wind farm, one of the main goals is to maximize the turbines' potential to convert energy from the wind. As the wake regions behind turbines can cause decreases in power production due to the decreased wind energy, efforts are made to position turbines in a way that minimizes power loss. Another placement consideration is the noise coming from the turbine blades. This noise can cause disturbances to nearby residential areas, and wind farms attempt to quiet the turbines typically through means that decrease the wind farm's power production efficiency, such as reducing the rotation rate of the turbines.

For this research, we considered both wake interactions and turbine noise in our optimization to maximize the wind farm's average power production while holding the SPL constraint at a specified levels. By using more accurate wake and acoustic models, we obtained a more realistic view of how turbine wakes and sound propagate from a wind farm. We also implemented an approach that allowed the optimizer to position the turbines anywhere inside the boundaries of the wind farm. Implementing these techniques with the two specific wind farms that we studied, we observed that the wind farm's average power production could be increased by up to 8.01% in the Lissett Airfield Wind Farm and 3.63% in the Rosiere Wind Farm by adjusting the placement of the turbines with respect to each other. As a noise restriction is active, this power output begins to diminish slightly over a range of about 5.0 dB, after which the average power production sharply decreases for quieter noise limitations. The significant decrease in SPL, with essentially no decrease in average power production, illustrates the benefit of introducing reasonable noise constraints during wind farm layout optimization. This advantageous result is possible because many local optimum exist when maximizing average power production, all with very similar performance. We can take advantage of the fact that multiple solutions exist for maximum power production, and introduce noise constraints that allow SPL to be reduced significantly with negligible impact on average power production. If considered separately, the solution obtained for the maximum average power production would dictate the noise level of the wind farm and likely require additional acoustic shielding or curtailing of performance.

As this research has shown, an overly restrictive SPL limit can significantly impact the wind farm's ability to maximize its average power production and negatively affect the wind farm's cost efficiency. In order to avoid these negative outcomes, proper planning in the initial layout process is needed to determine where the turbines are located with respect to residential areas nearby as well as the wake propagation effects from other turbines to allow a wind farm to quietly maximize its power production. As seen in this study, a range of SPL limits exists where a slightly quieter wind farm has a small impact on its average power production due to the optimizer taking advantage of the complex, multi-modal wind velocity profile in a wind farm. However, as the SPL limit becomes quieter than this range of SPL limits, a more significant impact on average power production occurs.

In this research, we used reduced-order wake and acoustic models to allow the optimizer to find reasonably accurate solutions within a relatively short amount of time. As this work has shown the benefit of considering wake and acoustic effects simultaneously to maximize wind farm power production while maintaining a wind farm below a given noise level, future research could use higher-fidelity modeling to more accurately assess the results of the optimized wind farm layouts. Future work could also explore the use of wake and acoustic modeling with vertical-axis wind turbines (VAWTs). Because VAWTs have the potential of increasing power production through closely spaced turbine pairs [41–43], aero-acoustic wind farm layout optimization of VAWTs could be accomplished by implementing the BPM equations with orientation adjustments and a recently developed VAWT wake model [44].

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