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Wind farm layout optimization in noise constrained areas

Andrew Brunskill GL Garrad Hassan 151 Slater Street, Ottawa K1P 5H3 Canada andrew.brunskill@gl-garradhassan.com

Summary

Wind turbine noise is a key factor when designing a wind farm layout in a noise constrained area. GL Garrad Hassan has developed a methodology by which a turbine layout can be optimized for energy yield while simultaneously ensuring that modeled sound levels at all nearby receptors are compliant with local regulations. This involves the application of sound propagation modeling to the field of wind farm design.

The two overarching goals of layout design are minimising risk and maximising return on investment. Proper consideration of turbine noise during the layout design stage is crucial to achieving both these goals. For given costs, maximizing return on investment is often synonymous with maximizing the energy yield of a wind farm. Therefore, the turbine layout is designed to produce maximum energy yield while maintaining compliance with noise limits. Environmental regulators generally require that wind turbine sound pressure levels at all receptors in the vicinity of a wind farm do not exceed prescribed limits, which vary by jurisdiction. Penalties for exceeding these limits can be severe, including curtailed operation or even removal of turbines. Accurate noise modeling is necessary to minimize this risk.

In the approach developed by GL GH, environmental noise propagation is modeled using the ISO 9613 methodology. WindFarmer software is used as a tool to enable the modeling of noise and the consideration of the many other factors relevant to wind farm design including topography, wind speed variations, ground cover, and wake effects. Noise model inputs such as atmospheric attenuation and ground factor should be chosen to be accurately representative of the site and, in case they vary significantly on a seasonal basis, should be conservative in terms of noise propagation to meet regulatory limits.

A case study including a wind farm layout design in Ontario, Canada is presented in this paper to demonstrate that if noise is not evaluated when optimizing the layout of a wind farm, then it is easy to produce a layout which is not compliant with noise regulations. The effect of noise constraints on a wind farm layout will be highly site specific, and more significant if the more noise constrained part of the site also has a relatively good

wind resource. Noise reduced turbine variants should be considered on a site specific basis using wind farm design software.

1. Introduction

When developing a wind farm, industry uses wind farm design software to determine the specifications for and layouts of the various elements of a project, such as the turbines, the collector system, the substation, and access roads.

Perhaps the most important element to be designed is the turbine layout. The simultaneous goals of layout design are minimising risk and maximising return on investment. Maximizing return on investment means reducing the cost of each kWh of electricity generated, and is therefore linked to the capability of maximizing the wind farm's energy yield, while designing a configuration which reduces construction and operation costs to the highest degree possible. Important considerations when designing for optimal energy yield include site topography, ground cover, and turbine wake effects.

There are also constraints which must be met when designing the turbine layout. Human related and biophysical setbacks must be respected. The costs of the collector system and roads should be minimized. Environmental effects such as acoustical and visual impacts must also be considered. Regulators generally require that wind turbine sound pressure levels at all receptors in the vicinity of a wind farm do not exceed prescribed limits, which vary by jurisdiction. Penalties for exceeding these limits can be severe, including curtailed operation or even removal of turbines. Accurate noise modeling is necessary to minimize this risk.

Wind farm design quickly becomes a complex problem requiring the consideration of many inter-related criteria and constraints. Wind farm design software is an essential tool because it facilitates simultaneous consideration of all relevant factors.

This paper focuses specifically on the methodology developed by GL GH to consider wind farm acoustical impact in conjunction with all other constraints, while concurrently optimizing the turbine layout for energy production. WindFarmer software is used to model noise propagation from the wind farm while creating a turbine layout which meets regulatory requirements and is cost effective, buildable, and optimized for energy.

Significant noise sources at a wind farm generally include the turbines and the substation, all of which can be considered by WindFarmer. Acoustical impacts from existing and future neighbouring wind farms should also be evaluated. In some cases, other industrial noise sources should be modeled as well, for example, the electrical infrastructure associated with other types of power plants.

Wind farm sound level limits at receptors are often set relative to reference wind induced background sound levels. As an example, the wind turbine sound level limits for receptors in rural areas in Ontario, Canada, are shown in Figure 1 [1]. In this case, the sound level limit is expressed in terms of the hourly A-weighted equivalent sound

pressure level Leq. The reference wind induced sound level is expressed in terms of the hourly ninetieth percentile sound pressure level L90.

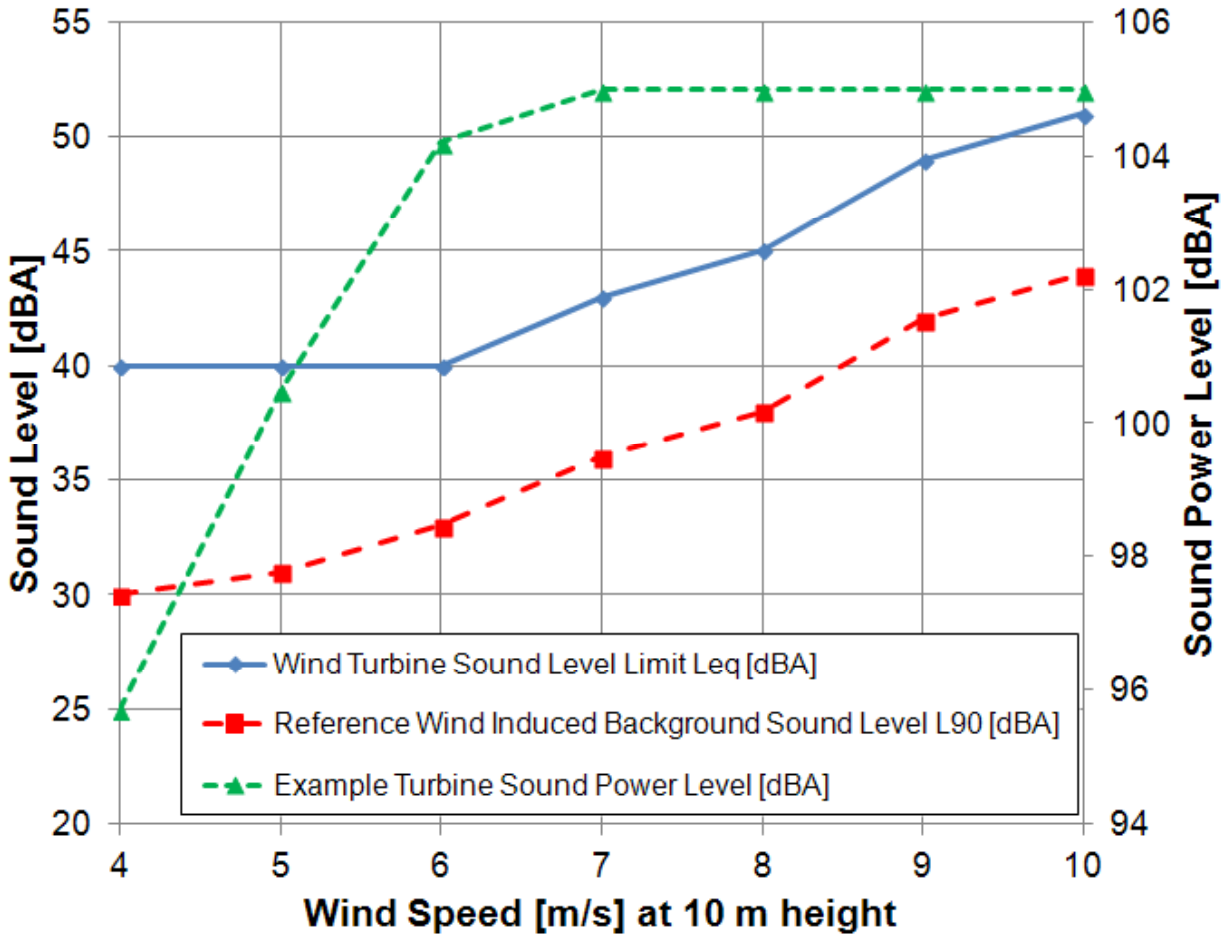

Figure 1 – Example summary of sound level limits for wind turbines

Also shown is an example of how a turbine's apparent broadband sound power level can vary with 10 m wind speed. Noise regulators, such as Ontario's Ministry of the Environment, commonly require "worst case" wind shear assumptions to be considered which are more conservative than those described in IEC 61400-11 Ed. 2 [4]. Therefore, wind turbine noise modeling is often only carried out using the highest turbine sound power level (105 dBA in the example shown in Figure 1). Predicted sound pressure levels at nearby receptors are then compared to the lowest noise limit (40 dBA in the example). Effectively, in many jurisdictions (such as Ontario), when determining the regulatory compliance of a wind farm layout, the only relevant sound pressure level limit is the lowest limit, and the only relevant turbine sound power level is the highest level. In Ontario, site specific background sound levels are generally not considered when carrying out a noise impact assessment.

Noise modeling to ensure regulatory compliance is an essential part of wind farm design in many areas. There are several reasons why a certain region may be more noise-constrained than another, including:

- A lower effective sound pressure level limit in the project's jurisdiction;
- The presence of many dwellings or other points of reception close to the project;
- The presence of one or more existing neighbouring wind farms in the vicinity of the project.

In Ontario and many other jurisdictions, acoustic sound measurements for wind farms in operation are undertaken as per Ontario's Compliance Protocol for Wind Turbine Noise - Guideline for Acoustic Assessment and Measurement [2]. If a project is deemed non-compliant during operation, mitigation measures would be applied to the wind farm in order for it to meet its regulatory and permit obligations.

Designing a compliant layout in such a region requires expertise in noise modeling as well as knowledge of the relevant regulations, in addition to an understanding of the many factors previously discussed. Therefore, wind farm design software with strong noise modeling capabilities is an essential tool for wind farm designers.

2. Case Study

For the design and optimisation of a wind farm layout, GL GH use the software package WindFarmer. This software is developed in-house and sold commercially, and offers the possibility to input the sound power levels for all sources and calculate the sound level at any point in the workspace area. Noise propagation is typically modeled using the ISO9613-2 standard [5], where ground attenuation is modeled with the *General* or *Alternative* method, according to the specific site characteristics. Details on how the ISO9613-2 is implemented in WindFarmer are available in its theory manual [3].

A case study is presented herein to better illustrate how wind farm design software can be used to optimize the layout of a wind farm in a noise constrained area.

The purpose of the current analysis is to define the turbine layout. As discussed in Section 1, there are many factors which will affect the placement of the turbines. Here, for simplicity, only two factors are considered. The turbine layout will be optimized for energy production while ensuring that the layout is compliant with local noise regulations.

2.1 Project Description The hypothetical ProjectX wind farm is based in Ontario, Canada, as seen in Figure 2. The project is to consist of twelve turbines of type Turbine Type X. Project components will be installed on privately-owned agricultural lots which have been leased by the project developer.

Figure 2 – Ontario, Canada, the jurisdiction of the case study.

The terrain can be described as simple with gently sloping hills. The Project Area is dotted with residential farm houses and related buildings. The development pattern is typical of most rural areas in Southern Ontario with dwellings built near the roadways.

A constraints analysis has been completed to establish proper setbacks from various natural features such as water bodies, wetlands and woodlands, as well as built features. The land area available for turbine placement has been defined and loaded into WindFarmer as a Shapefile. A thorough investigation of the region has resulted in the identification of 203 points of reception (“receptors” or “dwellings”) at which wind turbine noise limits apply. As described in Section 1, in Ontario, the wind turbine noise limit at a point of reception is effectively 40 dBA. Receptor height ranges from 1.5 m to 7.5 m. The locations of all receptors can be seen in Figure 3.

There are two existing wind farms in the area. ProjectA is located to the south and west, and consists of fifteen Turbine Type A turbines. ProjectB is located to the north and consists of seven turbines. The impacts of these neighbouring projects on energy production and receptor sound levels must be considered as part of the ProjectX layout optimization process. The neigbouring wind farms can be seen in Figure 3. Also shown

is a map of the existing wind turbine noise, which is entirely the result of contributions from ProjectA and ProjectB.

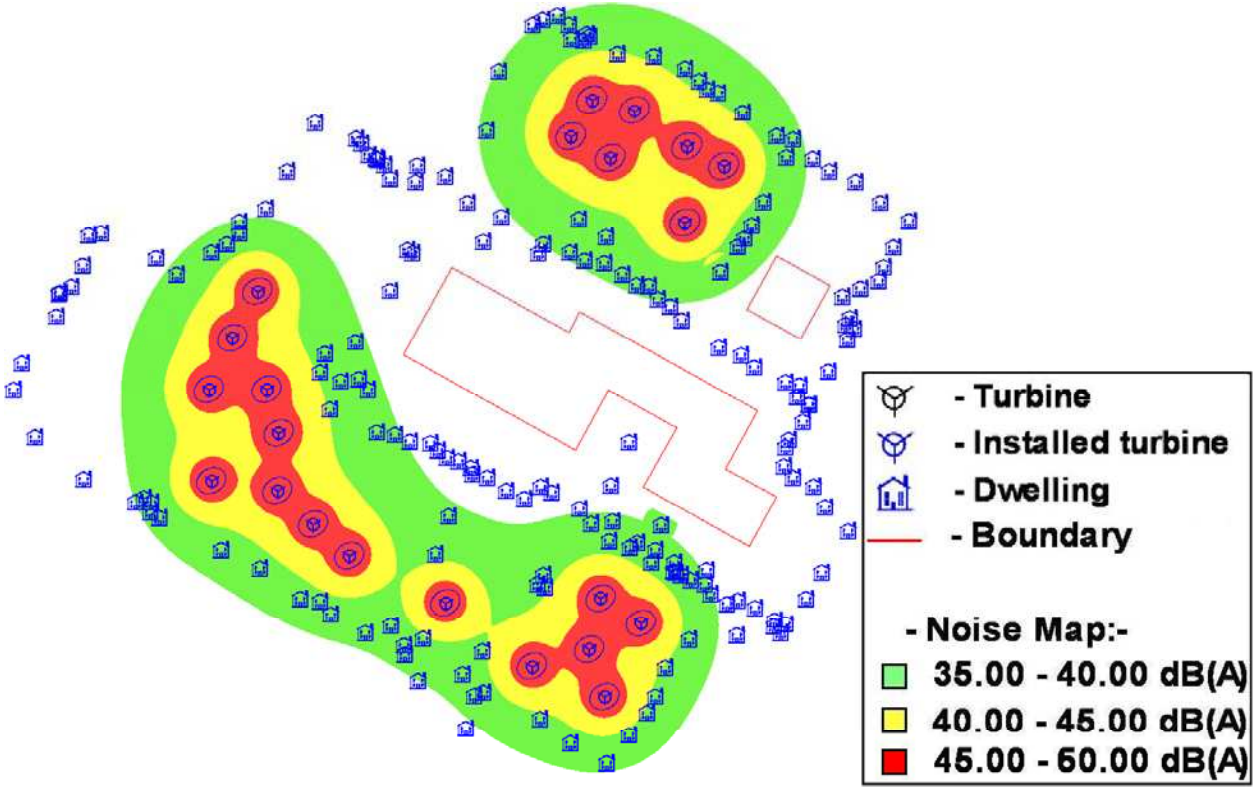

Figure 3 – ProjectX available area (red boundaries), locations of noise receptors (blue house icons), and existing wind farms ProjectA (turbine icons, south) and ProjectB (turbine icons, north)

This area can be considered to be noise constrained due to the large number of dwellings in the area as well as the presence of the two neighbouring wind farms. Therefore noise considerations are expected to have a significant influence on the turbine layout.

2.2 Noise Model Description For this case study, the ISO9613-2 General noise model is used to be compliant with the Ontario regulations. All turbines are modeled as point sources at hub height. Turbine octave band sound power levels are defined as described in Section 3.3. Sound level attenuation is calculated by octave band.

A global value of 0.7 has been assumed for the ground factor other than at a small number of receptors, where a ground factor of 0 has been applied to illustrate the significance of receiver ground factor.

Atmospheric attenuation coefficients have been evaluated considering the local characteristics and using the formulas defined in ISO 9613-1 [6]. Since there are large

variations during the seasons, the most conservative situation, in terms of noise propagation, has been considered for the layout design and optimisation.

The meteorological correction factor and all additional attenuations, such as attenuation due to foliage, have been set to 0 dBA.

2.3 Noise Source Description The octave and broadband sound power levels of Turbine Types A, B, and X have been provided by the manufacturers and are based on measurements made in accordance with IEC 61400-11 Edition 2 [4]. As described in Section 1, turbine noise modeling in many jurisdictions must be carried out using the maximum turbine sound power level. Table 1 shows the sound power levels of each turbine type. Noise regulations often dictate that a penalty must be applied to tonal noise sources. However, these turbines are not considered tonal as per the definition in [4].

Table 1- Turbine sound power levels

	Octave Band Sound Power Level [dBA]								Broadband [dBA]
Frequency [Hz]	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	
Turbine Type X	86.0	91.6	97.5	98.3	99.9	97.2	93.5	77.9	105.0
Turbine Type X noise reduced variant	85.1	89.8	95.3	94.8	95.9	94.8	90.7	78.0	102.0
Turbine Type A	86.9	93.3	97.0	99.3	98.6	95.5	87.6	80.4	104.4
Turbine Type B	87.6	96.1	99.8	98.6	93.7	89.2	84.3	78.3	104.0

Also shown are sound power levels for a noise-reduced variant of Turbine Type X. This variant produces significantly less noise than the standard turbine. However, for a given wind speed, it also produces less power than the standard version.

Other noise sources, such as substation transformers, are not considered in this case study.

2.4 Turbine Layout Optimization This analysis is carried out using WindFarmer which uses an advanced optimization algorithm which is adapted to the particular challenges associated with wind farm design. The algorithm used avoids local minima and delivers a maximum of ProjectX energy yield, while also being compliant with the given constraints.

The site boundary defines the physical area available for turbine placement. Every ProjectX turbine must be within the site boundary. In this case, as a result of the constraints analysis, it has been determined that there are two unconnected areas in which turbines can be placed, as seen in Figure 3. The larger boundary area is

approximately 5 km long and 1.5 km wide. There are no exclusions zones beyond the constraints mapping described above in this specific test case.

The minimum space allowable between any two turbines is defined by an elliptical exclusion zone around each turbine. At this site, the wind rose is fairly omnidirectional, with a tendency for stronger winds towards the southwest and west. Therefore, an elliptical exclusion zone with a long axis separation of 5 rotor diameters, a short axis separation of 4 rotor diameters, and a long axis bearing of 240 degrees has been applied. This turbine exclusion zone can be seen in Figures 5 to 7.

Layout design often requires that other aspects are considered, for example visual impact or set-back distances. In this case no further constraints to those mentioned above have been considered.

In the case described herein, the wind speed variation across the site is predicted by WindFarmer's built-in simple flow model. One particularly important factor in determining the wind farm layout and energy production is the turbine wake effect. A wind turbine removes energy from the wind, resulting in lower wind speeds in the downwind region. This negatively affects the energy output of a downwind turbine. Therefore, turbine wake effects should be minimized. This is generally accomplished by increasing the spacing between turbines, or with a proper selection of the turbine locations.

Layout optimization of ProjectX has been carried out for three scenarios. The first scenario uses the standard version of Turbine Type X with the noise limits as described previously. (In Scenario 1, one noise-reduced turbine is specified, by necessity, as discussed in Section 3). The second scenario uses the noise reduced variant of Turbine Type X with the same noise limits. The third scenario was carried out for comparison purposes only and uses the standard version of Turbine Type X with no sound level limits at nearby receptors. Additional combinations of standard and noise reduced turbines are also possible although this has not been investigated here. Scenarios 1, 2 and 3 are summarized in Table 2.

2.5 Results Figure 4 shows the mean wind speed variation across the ProjectX available area. The variation in wind resource is a key driver of the turbine layout.

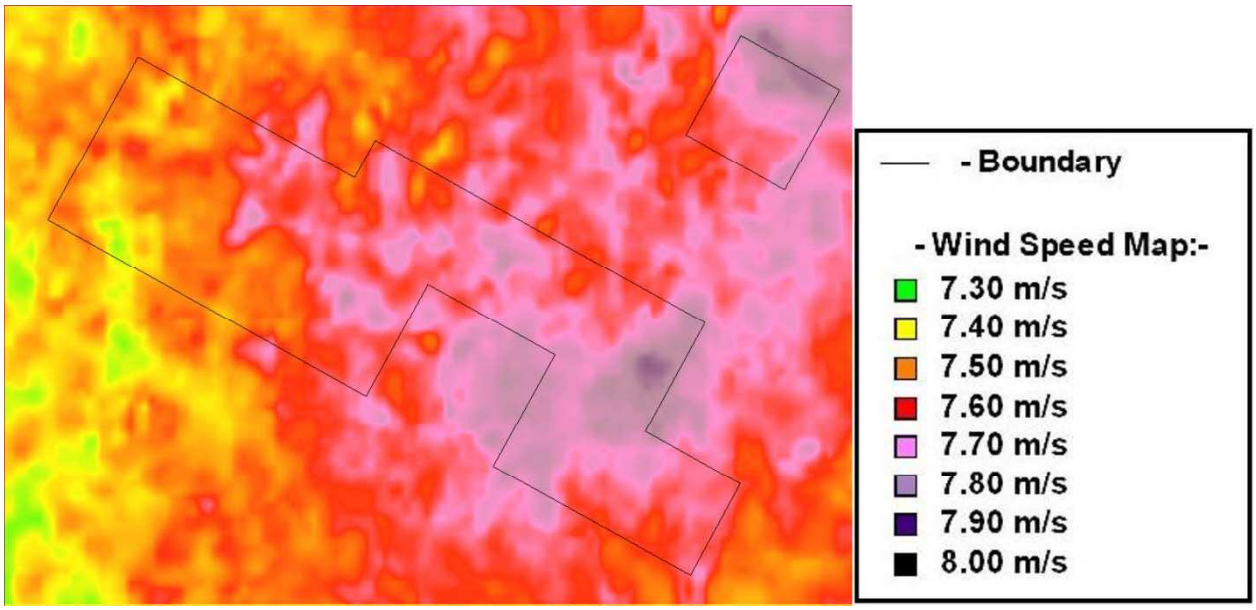

Figure 4 – Variation of mean wind speed across the ProjectX available area

Figure 5 shows the optimized layout of ProjectX for Scenario 1, which uses the standard version of Turbine Type X and complies with the sound level limit all receptors.

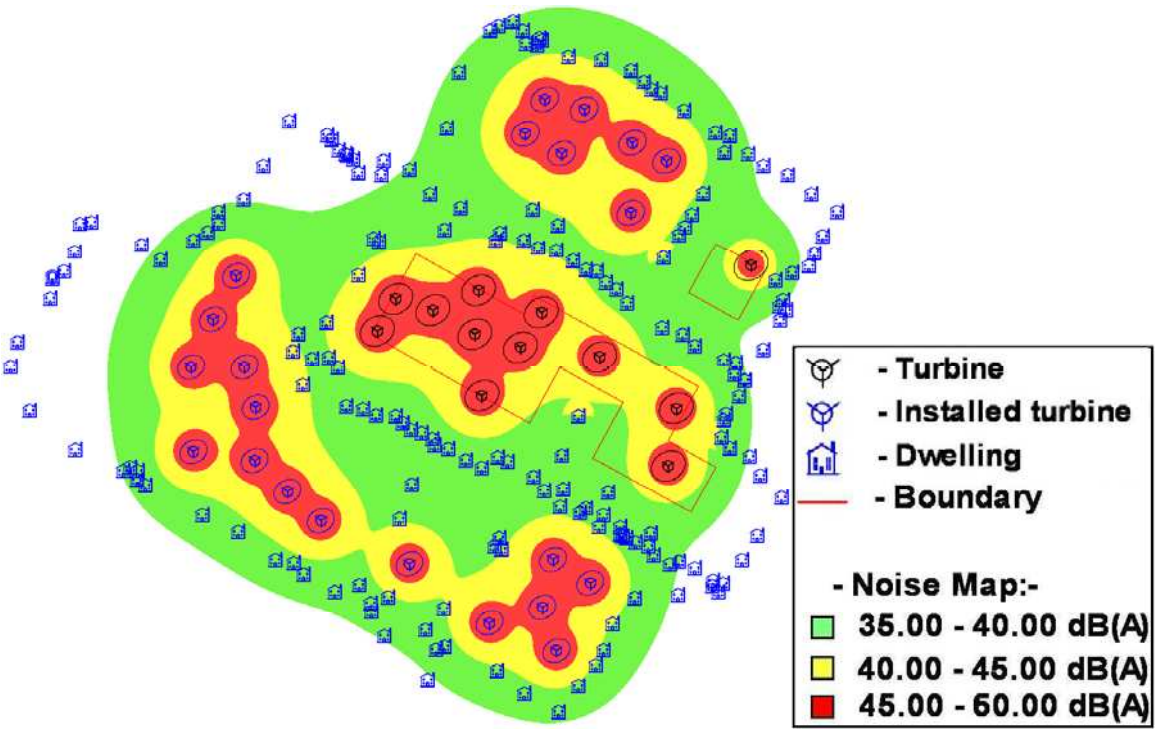

Figure 5 – Optimized ProjectX turbine layout for Scenario 1

Figure 6 shows the optimized layout of ProjectX for Scenario 2, which uses the noise reduced version of Turbine Type X.

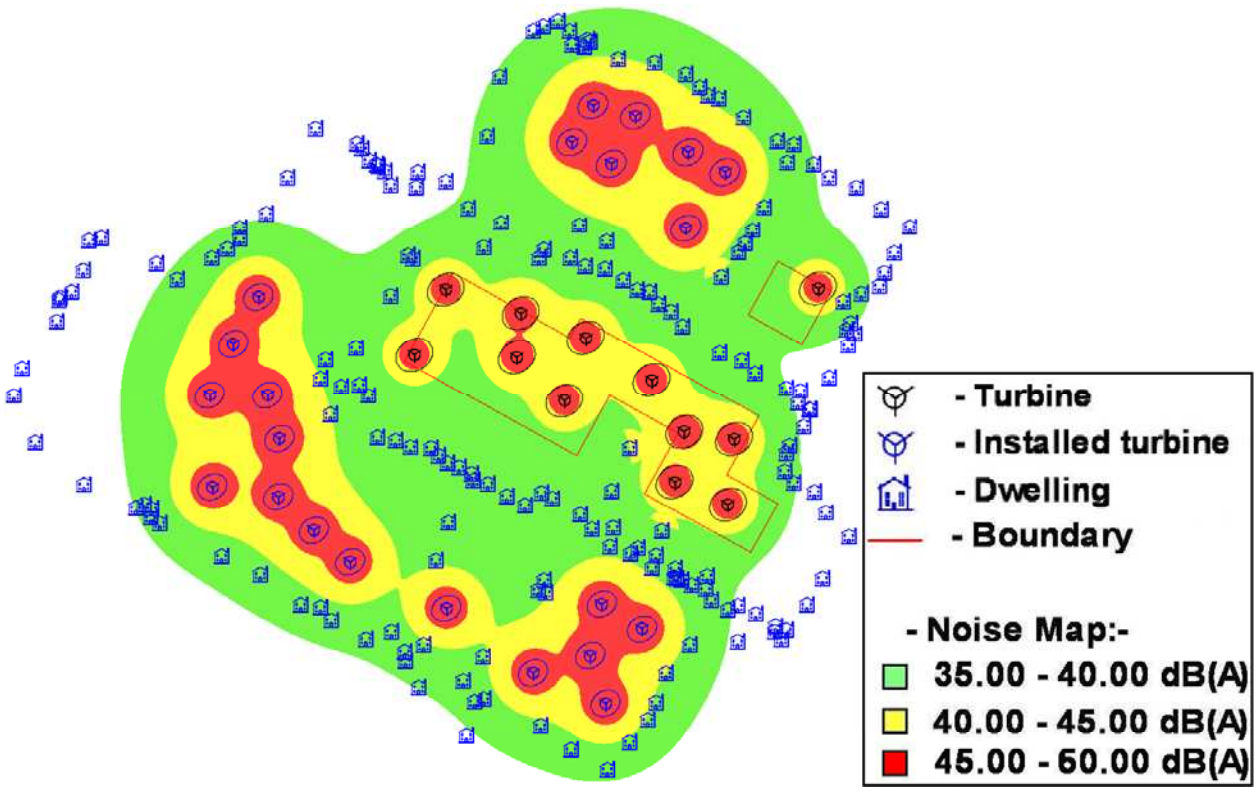

Figure 6 – Optimized ProjectX turbine layout for Scenario 2

Figure 7 shows the optimized layout of ProjectX for Scenario 3, which uses the standard version of Turbine Type X but does not comply with the sound level limit at all receptors.

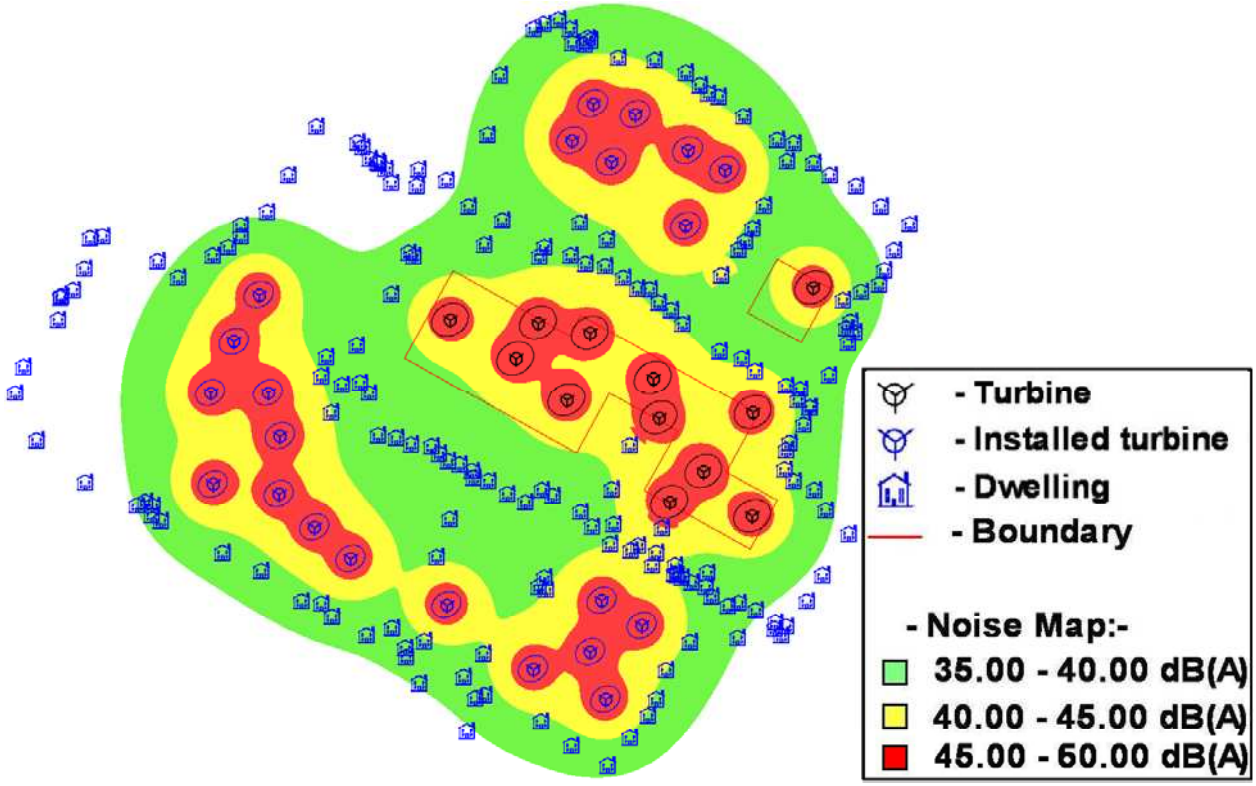

Figure 7 – Optimized ProjectX turbine layout for Scenario 3

Table 2 shows the estimated net annual energy yield of ProjectX for the three optimized layouts. The energy yield values are given as a percentage of the optimized energy yield when noise is not considered.

Scenario	Turbine Type	Layout noise compliant?	Energy yield [% of Scenario 3]
1	11 Turbine Type X 1 Turbine Type X noise-reduced variant	Yes	98.1
2	12 Turbine Type X noise-reduced variant	Yes	88.6
3	Turbine Type X	No	100.0

3. Discussion and Conclusions

The key factors driving the wind farm layout in this case study are the wind resource, turbine wake effects, and noise constraints. As seen in Figure 4, the eastern part of the available area experiences greater mean wind speeds compared to the western portion of the site. When considering the wind resource alone, the layout optimiser would tend to produce layouts with more turbines in the east. This can be seen in Figure 7, which shows the optimization of Scenario 3. Five turbines have been placed in the southeast. However, since noise was not considered during the Scenario 3 optimization, the sound pressure level produced by the wind turbines is predicted to be above the limit of 40 dBA at ten receptors, with a maximum predicted level of 45.5 dBA. This layout is not compliant and would likely not be approved by the local regulatory agencies.

As seen in Figures 3 and 5, the eastern part of the available area is noise constrained to a greater degree due to several nearby dwellings and a relatively high concentration of ProjectA turbines to the south. As a result, although the wind resource is better in this region, when noise limits are considered during optimization, only two turbines of type X can be located in the eastern part of the site. In Scenario 1, Figure 5, more turbines are forced to be in the less windy but less noise constrained western part of the site. This results in greater wake losses because the inter-turbine spacing is lower.

At a small number of receptors, a receiver ground factor of 0 has been applied to illustrate the importance of this optimization input. For example, as seen in Figure 6, the receiver region ground factor is defined as 0 for the receptor in the middle of ProjectX. As a result, the area near this receptor is significantly more noise constrained, and the turbines are placed further away.

The small available area to the north has a relatively good wind resource but is severely noise constrained due to the close vicinity of ProjectB as well as several dwellings. The addition of a single standard Type X Turbine anywhere in this area results in sound levels at nearby receptors which exceed the limit. Therefore, in order to make use of this area, only a single noise reduced turbine can be placed here. This has been done for Scenarios 1 and 2. In reality, due to the additional balance of plant costs associated with placing a single turbine in a relatively isolated location, it may be more cost-effective to leave this area empty. Further analysis would be required to arrive at an informed decision.

When the noise reduced variant of Turbine Type X is considered for all ProjectX turbines, the optimizer places four turbines in the eastern part of the site, as seen in Scenario 2, Figure 6. Compared to Scenario 1, Figure 5, noise is not as significant of a constraint. The lower sound power level of this turbine type allows for a greater number of turbines to be placed in the east, and will result in the exposure of these turbines to a better wind resource. Wake losses will also be lower due to the greater inter-turbine spacing.

As seen in Table 2, the wind farm is estimated to produce approximately 2% less energy as a result of the noise constraints at this site. This is a significant amount of

energy in the context of total investment. When the noise reduced turbine variant is used at all locations, the reduction in estimated energy yield is over 11%. In this case, the benefit of having less stringent noise constraints associated with a quieter turbine does not offset the decrease in energy output resulting from the less productive noise-reduced power curve.

A reasonable next step in this analysis would be to investigate combinations of standard and noise reduced turbines. For example, there may be a layout consisting of nine standard turbines and three noise reduced turbines which produces more energy than Scenario 1. Combinations of standard and noise reduced turbines are common in actual wind farms. In some cases, multiple noise-reduced options are available, each with a different maximum broadband sound power level. This allows further refinement of the layout.

The two existing neighbouring wind farms, ProjectA and Project B, have a significant effect on the ProjectX turbine layout, the wind farm's energy production, and sound levels at nearby receptors. Similarly, ProjectX will have a negative effect on the energy output of ProjectA and ProjectB. However, since ProjectX is being developed later than the other two projects, it will not affect their compliance with noise regulations. In order to receive regulatory approval in Ontario, and many other jurisdictions, the developers of ProjectX must include existing wind farms when carrying out a noise impact assessment. The responsibility lies with later developers to ensure sound level compliance.

As seen in Scenario 3, Figure 7, if noise is not considered, then the optimizer can easily produce a layout which is not compliant with noise regulations. Therefore noise should always be carefully considered during layout optimization. In general, the effect of noise constraints on the optimized layout will be highly site-specific, and more significant if the noise constrained part of the site also has a relatively good wind resource.

Noise propagation models are continuing to be developed. As improved models become available, they should be incorporated into the wind farm design process to facilitate the placement of turbines in compliant locations. It is in the best interest of the wind energy industry to use accurate models with low levels of uncertainty.

References

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