Panther Grove Wind Project

Ice Shed and Blade Throw Risk Assessment

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Table of Contents

I. Executive Summary

The proposed 400 MW Panther Grove wind project is located in Woodford County, IL and is under development by Tri Global Energy. During the project design phase, it is common to perform environmental studies to understand any possible impacts that the project may have on the surrounding community. The purpose of this document is to present a study of the risks imposed by ice shed and blade throw from wind turbines to homes, properties, and roads in the vicinity of the wind farm.

Persimia performed a detailed and extensive analysis of the risk imposed by ice shed and blade throw for the Panther Grove Wind Project. This analysis involved an assessment of icing frequency based on local climate characteristics, physics-based simulation of ice fragment trajectories, and probabilistic analysis of the risk imposed by ice fragments to homes, properties, and vehicular traffic on roads. Likewise, a blade throw analysis was performed by first performing a literature review to determine the frequency of blade throw occurrences. Simulation of blade fragment trajectories was then performed and combined with failure rate data to produce a blade throw risk assessment for homes, properties, and vehicular traffic. A summary of the findings of this study is presented below, with detailed explanations provided in subsequent sections.

Summary of Ice Fragment Impact Risk

The overall finding of this study is that the setback distances used by Tri Global in siting wind turbines provides sufficient clearance to homes, roads, and property lines such that **the risk from ice shed is extremely low.** Ice throw mitigation measures will be implemented at Panther Grove in which turbines will be shut down when icing or thawing meteorological conditions are detected. This will greatly reduce the likelihood that ice throw occurs. Ice pieces will instead be shed directly beneath the turbine, posing no risk to the surrounding area. Professional wind turbine operations staff are trained to be familiar with safe icing and thawing procedures that involve curtailment and safe deicing processes. It is also important to note that **experimental data has shown that ice pieces shed from wind turbines are fairly small in size**, weighing on average only 1.3 lbs [3].

Additionally, a worst-case analysis was performed to simulate the risks from ice throw if turbines continued normal operations during ice shed events. This analysis, described later in this report, calculated risks for each turbine to the nearest receptor in the current layout proposed by Tri Global. Persimia's simulation models show that, even in the worst-case event that turbines are not shut down during thawing conditions, the probability that ice pieces impact surrounding homes, personnel, or vehicular traffic **is extremely low**. A summary of the nominal and worst-case risks calculated by Persimia's model for each receptor type is provided as follows:

- **Unsigned habitable residences:** The nominal and worst-case risks imposed by ice throw is extremely low. The **nominal risk to unsigned residences is zero** since turbines will be shut down during icing and thawing events. In a worst-case scenario where turbines are not shut down, the median risk is calculated to be **less than 1 fragment impact in 1 million years.**

- **Unsigned parcels:** The nominal and worst-case risks imposed by ice throw to personnel on unsigned parcels is extremely low. The **nominal risk to personnel on unsigned parcels is zero** since turbines will be shut down during icing and thawing events. In a worst-case scenario where turbines are not shut down, the median risk is calculated to be **less than 1 fragment impact in 330,000 years.**

- **Public Roads:** The nominal and worst-case risks imposed by ice throw to vehicles on public roads is extremely low. The **nominal risk to vehicles on public roads is zero** since turbines will be shut down during icing and thawing events. In a worst-case scenario where turbines are not shut down, the median risk is calculated to be **less than 1 fragment impact on a vehicle in 180,000 years.**

The ice pieces that are shed from turbines during thawing conditions tend to be fairly limited in size. Reference [3] describes an experimental study in which 530 ice fragments shed from turbines operating in a cold climate were collected and analyzed. The average ice fragment recovered in this study had a weight of 1.3 lbs. This experimental data indicates that ice fragments released from a turbine during an ice fall or ice throw event would be fairly small.

Summary of Blade Fragment Impact Risk

The overall finding of this study is that the setback distances used by Tri Global in siting wind turbines provides sufficient clearance to homes, roads, and property lines such that **the risk from blade throw is extremely low.** Blade fragment throw events from operating wind turbines are exceptionally rare occurrences, as modern wind turbine blades are designed specifically to avoid such failures. Furthermore, protection systems are in place to detect vibration, blade imbalances, and overspeed conditions which act to further reduce the risk of blade throw. **Because blade failure on modern turbines is so rare, there is no experimental dataset documenting the frequency of blade throw.** Some archival literature exists that suggests that the probability that a blade fragment is thrown from a turbine each year is between 10^{-3} and 10^{-4}, although this data is for turbines that are now several decades old. These older turbines were not as reliable as modern turbines, and thus the 10^{-3} or 10^{-4} failure probabilities are probably much higher than is realistic for the state-of-the-art turbines to be installed at Panther Grove. However, to maintain a conservative analysis, an assumed failure rate of 10^{-3} blade throw events per turbine per year was used for this analysis.

Randomized simulation trials were performed to model how far blade fragments may fly from a turbine if released during operation. These studies indicate that the risk to unsigned habitable residences as well as personnel on unsigned parcels due to blade throw **is less than 1 fragment impact in 1 million years.** Likewise, the risk to vehicular traffic on public roads is assessed to be **less than one fragment impact in 1 million years.** These risks are comparable to those due to other highly unlikely events such as the probability of a person being killed by a lightning strike in a given year [1]. Additional details regarding blade throw risk and the simulation process employed in this analysis can be found in subsequent sections of this report.

Management Practices to Safely Shed Ice

Wind energy facilities are actively managed 24 hours per day, 7 days per week, 365 days per year. Operating turbines are monitored remotely at all times for malfunctions, error codes, or abnormalities in performance. Trained operations and maintenance personnel are also on-site to physically observe operation, immediately address site emergencies, and ensure turbines are operating safely.

Turbines operating in many parts of the world are subject to icing conditions, or environmental conditions that can cause ice to build up on turbine components at some points in the year. As temperatures warm in these areas, "icing conditions" become "thawing conditions," or environmental conditions that can cause ice to begin to thaw and release from turbine components. Ice is not typically shed from turbine components during icing conditions, but the risk of turbines shedding ice increases when thawing conditions are present.

Wind farm operators use several methods to detect icing and thawing conditions so that proper management actions may be taken to ensure safety. First, it is possible for operators to recognize icing conditions from a few data sources. Sensors exist in turbine blades that detect when blades become imbalanced or create vibration due to ice accumulation. If ice is detected on turbine blades and it is causing an imbalance or vibration that could damage turbine components, control systems on the turbines will automatically shut the turbine down until ice is safely shed. If ice accumulation does not cause an imbalance, operators can still detect icing using meteorological data from on-site permanent meteorological towers, on-site anemometers, and other relevant sources. If ice accumulation is occurring and is anticipated to cause imbalance or unusual vibrations, operators can manually shut down the turbines to avoid this circumstance. Furthermore, since turbine components can be damaged by operating with the additional loads and stress caused by ice build-up, it is considered a best operational practice to shut down a turbine any time ice is accumulating on the equipment. Ensuring that turbines are not operating under these unusual loads will help preserve blade bearings, main bearings, and gearboxes over a typical wind farm's lifetime.

Even more importantly, operators are able to recognize thawing conditions from the data sources described above. If on-site permanent meteorological towers, on-site anemometers, and other relevant sources suggest that thawing conditions are present and ripe for ice shed to occur, operators will manually shut down turbines until the ice is safely shed. Similarly, if any ice shed is observed by operators in the field, turbines will be manually shut down until ice is safely shed. Operators may "shudder" turbine blades or use other operations techniques to help encourage ice to safely shed while turbines are not spinning. Turbines will not resume operations until all ice has been shed, or until thawing conditions are no longer present and turbines are back in balance.

These operations management protocols ensure that ice is not shed from turbines while they are spinning, thus significantly limiting the distance ice fragments may travel during periods of shedding. Because ice is shed while turbines are not rotating (ice fall), the resulting ice pieces tend to land directly beneath or very near the turbine tower (with downwind travel on the order of tens of meters due to the effects of wind as they fall). Ice shed from stationary turbines therefore poses essentially no risk to the surrounding area.

II. Assessment of Ice and Blade Throw Frequency

Ice Throw Frequency

When evaluating ice fall and ice throw risk for a specific wind project, it is important to account for the frequency of icing events. Local climate characteristics play a large role in determining the frequency of ice fall or ice throw for a given wind site. Generally, the International Energy Agency (IEA) classifies wind sites into five IEA Icing Classes, with IEA Icing Class 5 being at highest risk for ice accumulation and IEA Icing Class 1 being at lowest risk [1]. The Icing Class determination for a given site is based on the expected number of icing days per year. An Icing Class 1 site can expect meteorological icing to occur 0-0.5% of the year, whereas a site with a Class 5 rating can expect meteorological icing to occur greater than 10% of the year. Table 1.1 shows the correlation between the meteorological icing frequency, instrumental icing frequency, and IEA icing classification rating.

VTT Research of Finland has compiled a Wind Power Icing Atlas (http://virtual.vtt.fi/virtual/wiceatla/) which provides an Icing Class rating for most international locations [2]. This data is derived from long-term meteorological measurements obtained from thousands of weather stations across the world over several decades. Figure 1.1 presents the icing classification rating for the North-Central Illinois region. The area of the proposed Panther Grove wind project is outlined in red. The VTT map classifies the Panther Grove project area in Woodford County as Class 1, which corresponds to the lowest icing risk.

As additional verification, meteorological data evaluated by Tri Global also indicates that the site is Class 1. This assessment was made based on instrumental icing frequency measured over several years. This provides further confidence that the Class 1 (low risk) assessment for the Panther Grove project location is accurate.

Table 1.1. IEA Icing Class and Predicted Number of Ice Pieces Per Year [1].

IEA Icing Class	Meteorological Icing (% of year, days)	Instrumental Icing (% of year)	Production Losses (% of year)	Yearly Number of Ice Pieces Per Wind Turbine
5	> 10% (> 36 d)	> 20	> 20	> 8000
4	5-10% (18-36 d)	10 – 30	10 - 25	4000
3	3-5% (11-18 d)	6 – 15	3 – 12	2000
2	0.5-3 (2-10 d)	1 - 9	0.5 – 5	1000
1	0-0.05 (0-1 d)	0 – 1.5	0 - 0.5	200

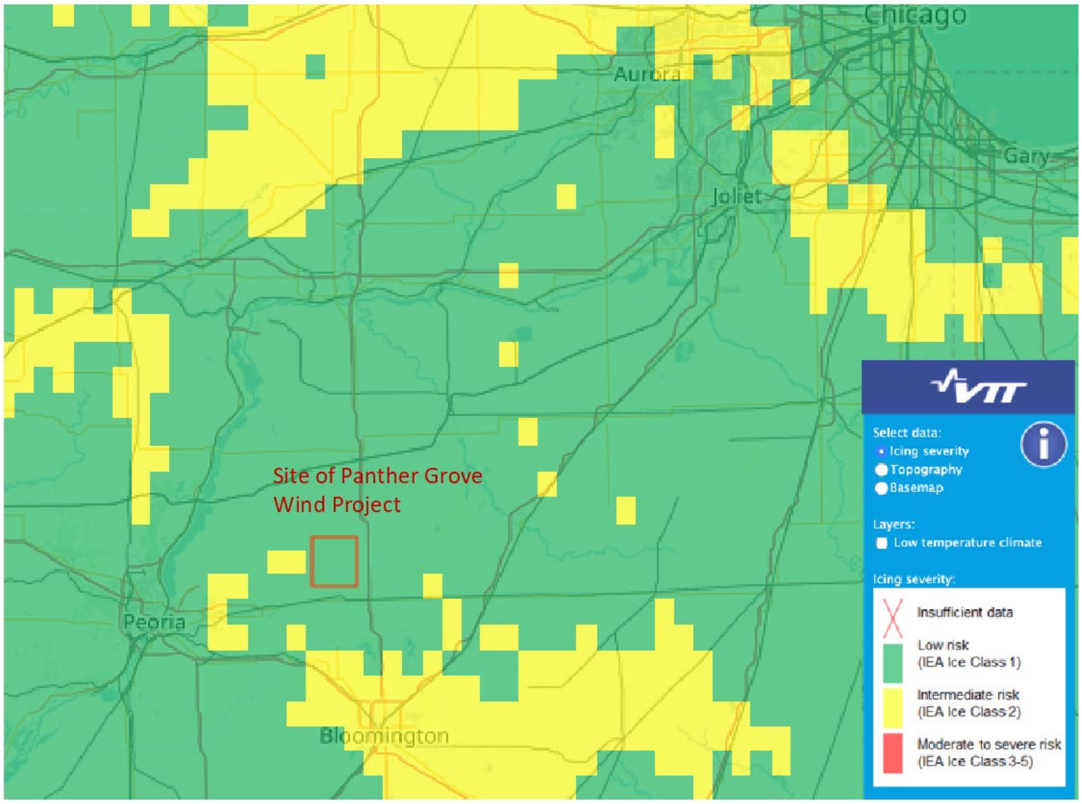

Figure 1.1. Icing Class Map for Central Illinois [2].

The Icing Class 1 rating leads to an estimate of the number of ice pieces that are shed from a single turbine each year. The IEA guidelines in Reference [1] provide estimates of the number of icing events for each Icing Class, shown in Table 1.1. Note that in Table 1.1, 200 ice pieces per turbine per year are predicted to be shed for a Class 1 site. However, these values were obtained through measurement data in which no distinction was made between ice fall and ice throw. Some of these 200 ice pieces are shed from the tower, and thus occur as ice fall events. The degree to which the remaining ice pieces are shed through ice throw versus ice fall depends on the operational procedures used at the wind site to shut down or slow the rotor when icing is detected. As mentioned above, the wind turbines at Panther Grove will be curtailed when icing or thawing events are detected per proper operating procedure, and thus all shed ice pieces are expected to land directly beneath or very near the turbine.

A final note is in order regarding the expected size of ice fragments. Reference [3] describes an experimental study in which 530 ice fragments shed from turbines operating in a cold climate were collected and analyzed. The masses of each ice fragment were recorded, with results showing that the average ice fragment mass was 0.6 kg (1.3 lbs). The vast majority of ice fragments had a mass less than 1 kg (2.2 lbs). While the largest ice fragment had a mass of almost 5 kg (11 lbs), this fragment was found only 20 m (65 ft) from the turbine base and thus was likely caused by an ice fall rather than ice throw event. Given this experimental data, it would be expected that ice fragments released from a turbine during an ice fall or ice throw event would have a mass less than 1-1.5 kg (2.2-3.3 lbs).

Blade Throw Frequency

When assessing the likely number of blade fragment releases per year, it must be recognized that wind turbine blade throw events are extremely rare occurrences. Because blade throws are a result of failure of the turbine blade, turbine manufacturers naturally strive to improve blade designs and fabrication processes in order to reduce the likelihood of blade throw. Furthermore, onboard vibration monitoring systems and rotor overspeed protection systems are standard equipment on most modern turbines and may trigger warnings to an operator or automatically shut down the turbine if an impending blade or rotor failure is detected. Blade throw events are so rare with modern turbines that no comprehensive experimental dataset of blade throw distances currently exists (unlike ice throw, for which several experimental datasets exist including Reference [3]). Furthermore, blade throw risk for modern turbines is so rare that it is not usually considered as a primary factor in permitting and siting activities for modern wind farm developments.

There is agreement in prior literature that blade failure is rare, but there are some discrepancies in predicted blade throw frequencies. References [8-11] all provide estimates of blade throw frequency. Reference [11], prepared for the UK Health and Safety Executive, states that reported manufacturer and limited experimental data shows that blade failure probability is between 10^{-3} and 10^{-4} per turbine per year. This is equivalent to a per-turbine failure rate of one per 1,000 years, and one per 10,000 years, respectively. However, it is important to note that these failure probabilities are for older turbines, manufactured in the 1990s and early 2000s. Modern wind turbines are much more reliable and thus these failure probabilities are likely much higher than what will be observed at Panther Grove. Nevertheless, to maintain conservative predictions, the risk analysis performed here uses a blade throw frequency of 1 blade throw per turbine per 1,000 years (or N_{ip} = 0.001 blade fragments per year per turbine). This is consistent with all of the predictions from References [8-11] and represents a highly conservative estimate as it is the highest value reported in the literature.

III. Ice Shed and Blade Fragment Throw Simulation Methodology

Simulation Methodology Overview

Persimia's ice and blade throw simulation program models the trajectories of ice and blade fragments that may potentially be released from wind turbines. The simulation predicts the probability that an ice or blade fragment will impact a receptor site. The kernel of the analysis is a six degree-of-freedom atmospheric flight dynamic simulation that computes the trajectory of a fragment from the point of release on the wind turbine to impact with the ground. The sophisticated simulation model includes the effects of gravity, atmospheric wind velocity, aerodynamics, altitude, air temperature, fragment mass, fragment size, and fragment inertia. Given the location of wind turbines and receptor sites, thousands of simulations are rapidly performed in Persimia's cloud computing environment in which the initial release conditions of the fragments are automatically randomized. The ground impact locations for these simulations are recorded and used to quantify impact risk to surrounding structures. Results from Persimia's ice shed and blade fragment simulation models have been used in wind turbine setback studies and permitting processes across the US. Detailed descriptions of the simulation methodology can be found in References [4] and [5].

Computing Trajectories of Ice and Blade Fragments

The trajectory simulation of an ice or blade fragment released from a wind turbine predicts position, orientation, velocity, and angular velocity of the fragment from the instant in time when the fragment breaks free from the blade until impact. During this time period the fragment is in atmospheric free flight. As shown in Figure 3.1 (left, depicting release of an ice or blade fragment), at the instant of release the fragment has a specific position, orientation, velocity, and angular velocity, which are used as initial conditions for the trajectory simulation. The numerical simulation consists of a rigid body six degree-of-freedom model typically utilized in flight dynamic modeling of air vehicles and projectiles. The degrees of freedom include three position components of the mass center as well as four quaternion orientation parameters of the body. Quaternions are employed in place of Euler angles to avoid singularity problems in the kinematic differential equations since the fragment can take on an arbitrary orientation during flight.

The resulting thirteen differential equations of motion describing the flight dynamics of the system, including the translation kinematics, rotation kinematics, translation dynamics, and rotation dynamics, are given by Equations (1) through (4). In these equations, (x, y, z) denotes the mass center position, (q_0, q_1, q_2, q_3) are the quaternion orientation parameters, (u, v, w) are the body frame components of velocity, and (p, q, r) are the body frame components of angular velocity.

$$\begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{Bmatrix} = \left[T_{IB} \right] \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \qquad (1)$$

$$\begin{Bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{Bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{bmatrix} \begin{Bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix} = \begin{Bmatrix} X/m \\ Y/m \\ Z/m \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix} = [I]^{-1} \left(\begin{Bmatrix} L \\ M \\ N \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} [I] \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} \right) \tag{4}$$

Notice that *X, Y, Z* are the body frame components of the total applied forces while *L, M, N* represent the body frame applied moments about the mass center. The mass of the fragment is denoted as *m*. The matrix $[T_{IB}]$ is the body to inertial frame rotation transformation matrix and $[I]$ is the mass moment of inertia matrix of the body evaluated at the mass center with respect to body frame coordinates. Note that the forces and moments in (3) and (4) contain a contribution from aerodynamics. These aerodynamic forces can be computed using a variety of possible aerodynamic models, including bluff body, flat plate, and airfoil models. The specific model used in simulation of blade and ice fragments is discussed below. Note that in computation of the aerodynamic forces and moments, the wind velocities are used to calculate the fragment aerodynamic velocity and angle of attack.

Given initial conditions for the ice fragment at the instant of release from the wind turbine, the flight dynamic model described above is numerically integrated forward in time until the fragment impacts the ground. This process generates a single fragment trajectory from the release point on the wind turbine to ground impact. The flight dynamic simulation model is essentially the kernel that drives the overall risk analysis process. The simulation software has been optimized to run rapidly, allowing thousands of different trajectories to be simulated in an automated fashion. Note that the difference between an ice fall and ice throw simulation is that, in an ice fall simulation, the turbine rotor speed at release is assumed to be zero, while for ice or blade throw, the turbine rotor speed at release is assumed to be non-zero.

The difference between modeling an ice and blade fragment arises in the aerodynamic models used in the flight dynamic simulation. Ice fragments can be irregularly-shaped but are assumed to have some planar aspect to their geometry such that they generate both drag and potentially lift forces as well. Thus, a flat plate aerodynamic model is used in simulation of ice fragments. Blade fragments are assumed to be airfoil-shaped, and thus an airfoil aerodynamic model is used in simulation of blade fragments.

Monte Carlo Simulation

The trajectory of an ice or blade fragment is a complex function of many parameters, including but not limited to atmospheric wind velocity and direction, rotor radius, tower height, rotor rotational speed, fragment mass and inertia, and location of release along the blade. Since a fragment can be released at an arbitrary point in time during operation, statistical methods must be used to determine the probability that a released mass fragment will impact a given area around a wind turbine installation. To this end, Monte Carlo simulation is employed to generate ground impact patterns of released ice fragments (see Figure 3.1, center and right) [4]. At different points in the blade revolution, the blade attains different states, yielding different release conditions. For Monte Carlo simulation, numerous parameters are randomized including: the blade rotation angle, rotor speed, atmospheric wind velocity magnitude and direction, release position on the rotor blade, and fragment mass and inertia characteristics. Each of these parameters possesses a statistical distribution for typical wind energy system installations. These different release conditions lead to different individual trajectories and associated ground impact points. In Monte Carlo simulation, all key parameters that can vary at release are considered random variables with known statistical properties. For each random variable, a set of samples is created such that the samples exhibit the proper statistical distribution. For each sample, a free flight trajectory is computed and the associated ground impact point is recorded using local terrain data.

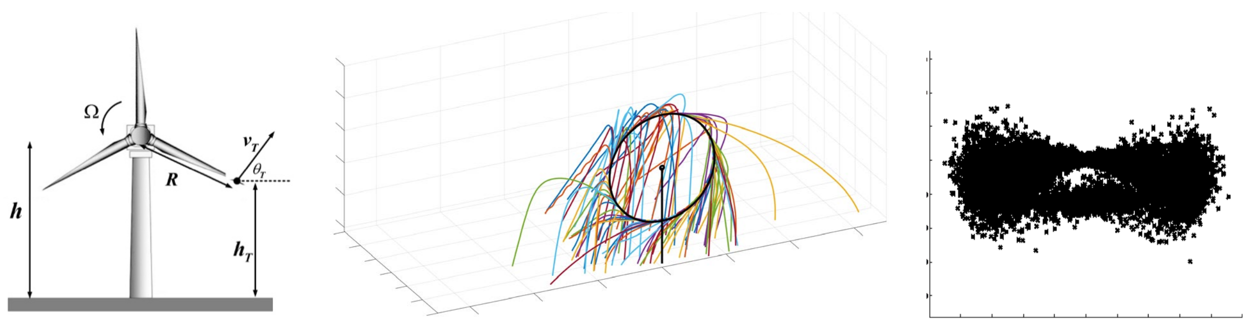

Figure 3.1. Ice Throw Release Diagram (left), Ice Fragment Trajectories (center), Example Monte Carlo Impact Point Distribution (right).

Monte Carlo Distributions and Model Validation

The turbine make and model to be installed at Panther Grove has not been selected yet; however, Tri Global has narrowed down the possible options to several candidate models. In order to perform a worst-case analysis, the turbine model with the maximum tip height was selected for this analysis. This is the General Electric (GE) 5.5/158 turbine with a hub height of 352 ft, rotor radius of 259 ft, and tip height of 612 ft. Key specifications for this turbine are listed in Table 3.1.

Table 3.1. GE 5.5/158 Turbine Specifications.

Parameter	GE 5.5/158
Hub Height	352 ft
Rotor Diameter	518 ft
Number of Blades	3
Maximum Rotor Speed (estimated)	11.4 RPM

To capture the important random elements of the throw process, numerous variables were randomized for each ice or blade fragment release in the Monte Carlo simulation according to specific distributions as follows:

- **Radial Release Location:** For ice fragments, the radial release location was considered as a uniform random variable between 0 and 259 ft. For blade fragments, the fragment size was first generated as a uniform random variable between 20% and 100% of the blade length. Given this random fragment size, the radial position of the fragment center of mass was computed to be between 129.5 ft and 233.1 ft (corresponding to fragment sizes between 100% and 20%, respectively).
- **Rotation Angle of Blade:** The rotation angle of the blade at fragment release was considered as a uniform random variable between 0 and 360 deg.
- **Wind Speed:** The wind speed distribution was created to match the measured wind speed distribution for the Panther Grove wind project site provided by Tri Global.
- **Wind Direction:** The wind direction for each fragment release was created to match the measured wind direction distribution for the Panther Grove wind project site provided by Tri Global.
- **Fragment Mass:** For ice fragments, the fragment mass distribution was assumed to be a truncated Gaussian with mean of 0.6 kg and standard deviation of 0.55 kg, truncated at zero. This distribution is matched to measured ice fragment mass data documented in Reference [3]. For blade fragments, the fragment mass was computed based on the randomized fragment size (between 20% and 100%) and the assumed weight of the blade (20,000 kg). For instance, a 50% blade fragment has a mass of 10,000 kg.
- **Fragment Area-to-Mass Ratio:** For ice fragments, the fragment area-to-mass ratio was assumed to be a Weibull-distributed random variable with mean of 0.088 m^2/kg and standard deviation of 0.045 m^2/kg, based on the data provided in Reference [1]. This value was not calculated for blade fragments.
- **Rotor Speed:** Rotor speed is computed based on the wind speed using a linear interpolation process. It is assumed that the minimum rotor speed of 4.7 RPM occurs at the cut-in wind speed for the GE 5.5/158 turbine (which is 3 m/s) and the maximum speed occurs at wind speeds in the range of 13 m/s to 22 m/s (cut-out wind speed). In between these intervals, linear interpolation is used to obtain a smooth function relating wind speed to rotor speed.
- **Fragment Area:** For ice fragments, the fragment frontal area is computed as the area-to-mass ratio multiplied by the mass for each sample. For blade fragments, the fragment area is computed as the length of the fragment multiplied by the average blade chord, which is assumed to be 3.0 m.
- **Fragment Chord:** For ice fragments, the fragment chord is computed as the square root of the fragment area, under the assumption that the fragment is approximately square in shape. For blade fragments, the fragment chord is assumed to be equal to the average blade chord of 3.0 m.
- **Fragment Moments of Inertia:** For ice fragments, the fragment moment of inertia is computed from the mass and chord values for each simulation, assuming a square flat plate geometry for each fragment with a depth-to-length ratio of 0.1. For blade fragments, the fragment moment of inertia is computed from the mass, length, and chord values for each simulation, assuming a thin rod geometry for each fragment.
- **Mass Center Location:** The fragment mass center is assumed to be at the geometric center of the fragment.

- **Aerodynamic Center Location:** For ice fragments, the fragment aerodynamic center is assumed to be a Gaussian-distributed random variable with a mean value at the center of each fragment, and a standard deviation of 5% of the chord for each sample. Note that this disturbance of the aerodynamic center off of the geometric mean is added so that the aerodynamic center and the mass center are not collocated for the simulation runs. For blade fragments, the aerodynamic center location is assumed to lie span-wise at the mass center location, and chord-wise at the quarter-chord location (which is a common assumption for airfoil-shaped bodies).

The Persimia ice throw model uses a flat-plate aerodynamic model that involves aerodynamic lift and drag coefficients. Because ice fragments are typically irregularly-shaped, these coefficients must be tuned such that simulated data matches available experimental data. **The Persimia ice throw model has been tuned and validated against the experimental ice throw data in Reference [3]**, which documents the geometric and inertial composition of over 500 ice fragments shed from wind turbines, as well as their resulting throw distances. A detailed report documenting this validation study is available on the Persimia website at the link below: https://persimia.com/pdfs/Persimia_Ice_Throw_Validation_Report.pdf.

Ice and Blade Fragment Impact Probability Density Function

The outcome of the Monte Carlo simulations described above is a set of ground impact points across the local terrain. These impact points are useful for examining the distribution of throw distances but cannot be used directly to estimate the expected risk of ice or blade throw impacts to a given receptor area. To this end, a probability density function (PDF) is estimated using a kernel density approximation to describe the probability that an ice or blade fragment impacts a particular location. Kernel density estimation is a technique to estimate the unknown probability distribution of a random variable based on a sample of points [6]. Kernel functions, in this case a Gaussian function, are associated with each point. To obtain the overall probability density function, the kernel density functions associated with each point are summed as follows:

$$\hat{P}(x, y) = \frac{1}{2\pi n h} \sum_{i=1}^{n} e^{-\frac{1}{2}\left((x-x_i)^2+(y-y_i)^2\right)/h^2} \tag{5}$$

where n is the number of Monte Carlo sample points, h is the kernel bandwidth, and (x_i, y_i) are the impact locations of the Monte Carlo samples. The resulting kernel density approximation $\hat{P}$ is a smoothed probability density function that enables accurate probability computation to be performed with fewer ground impact data points. The transformation between impact points and the smooth PDF estimate is illustrated in Figure 3.2, which shows 5,000 example ice throw impacts and the resulting function $\hat{P}(x, y)$ estimated from these impact points using Equation (5).

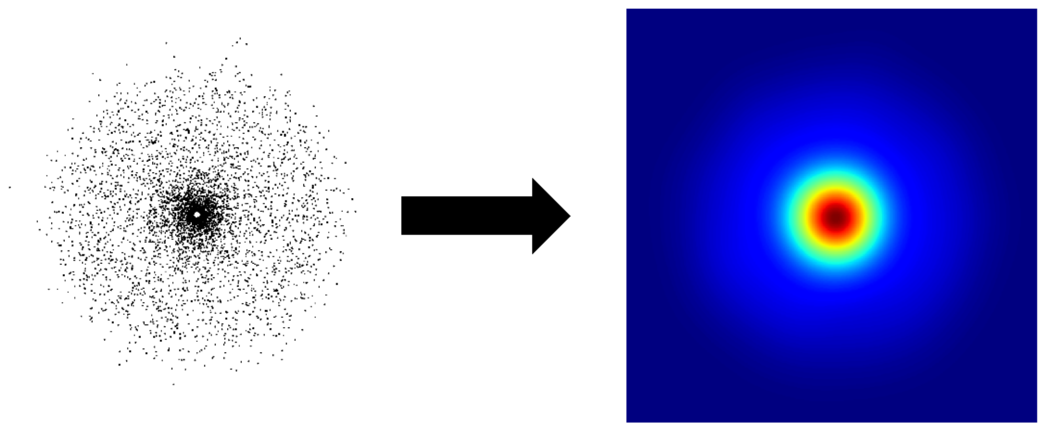

Figure 3.2. Monte Carlo Impact Points (left) and Associated Probability Density Function (right) Estimated Through Kernel Density Estimation.

The probability density function $\hat{P}$ must be integrated inside a certain area to obtain the probability of an impact occurring. Given a receptor location *R* with an area *A*, the PDF can be integrated inside *A* to obtain the probability that a fragment lands inside receptor *R* given that it is thrown from the turbine:

$$Prob(R) = \int_A \hat{P}(x, y)dxdy \quad (6)$$

Note that the area of the receptor plays a large role in the magnitude of the resulting probability. A receptor with zero area (*A* = 0) has, as shown in Eq. (6), zero probability of being impacted by a fragment, which is intuitive. Likewise, a receptor with an area covering the entire area of the wind farm and the surrounding region will have an impact probability of 1, since the fragment is certain to land somewhere in the specified area if it is thrown from a turbine. Thus, the receptor area and location is critical in determining the final receptor impact probabilities once the PDF approximation has been computed.

Expected Number of Ice and Blade Fragment Impacts

The probability estimation techniques described above quantify the probability that an ice or blade fragment will impact within a specified receptor, given that an ice or blade fragment is thrown from the turbine. However, this value does not provide the likely number of impacts to be expected at a receptor per year, as this would also depend on the frequency with which ice or blade fragments are released. The approach taken in this analysis is to compute the estimated number of ice or blade fragment impacts inside a receptor over the course of one year. This is an expected value computation using the above probability value and the estimated number of ice or blade fragments shed from a turbine each year. The expected number of ice or blade fragments that impact inside a receptor *R* each year due to ice or blade throw is given by the following expected value calculation:

$$EV(R) = Prob(R) \times N_{ip} \quad (7)$$

where N_{ip} is the expected number of ice or blade fragments thrown from the turbine each year and *Prob*(*R*) is the probability that any individual fragment will impact inside receptor *R* if it is thrown from the turbine. The specific values of N_{ip} used in this study are N_{ip} = 200 ice pieces per year per turbine, and $N_{ip} = 10^{-3}$ blade fragments per year per turbine. The justifications for selecting these values are discussed extensively in Section II of this report.

IV. Ice Shed Risk Assessment Results

A Monte Carlo simulation of 5,000 ice throw trajectories was performed using the modeling techniques described in Section III. The impact point distribution (assuming flat terrain near the turbine) is shown in Figure 4.1, and a histogram of the throw distances is shown in Figure 4.2. Note all of the simulated impact distances land within 1,500 ft of the turbine base, with the majority landing directly underneath or near the rotor. Note the similarity between the shape of the impact histogram in Figure 4.2 and the measured histogram of ice throw distances in the experimental study in Reference [3] (although the distances in this case are larger since the tip height is higher). This positive comparison against experimental data provides further confidence in the simulated ice throw results.

The results in Figures 4.1 and 4.2 illustrate potential throw distances but do not provide an assessment of actual risk. This is because they do not account for ice throw frequency or the areas of specific receptor types. When accounting for these factors, the risk levels for each receptor type are computed to be:

- The risk imposed by ice throw to unsigned habitable residences is assessed to be **less than 1 fragment impact in 1 million years**. This is a worst-case risk assuming turbines will not be shut down during icing or thawing events.
- The risk imposed by ice throw to personnel on unsigned parcels is assessed to be **less than 1 fragment impact in 330,000 years**. This is a **worst-case risk** assuming turbines will not be shut down during icing or thawing events.

Additional details regarding how these calculation were performed are provided in the next section.

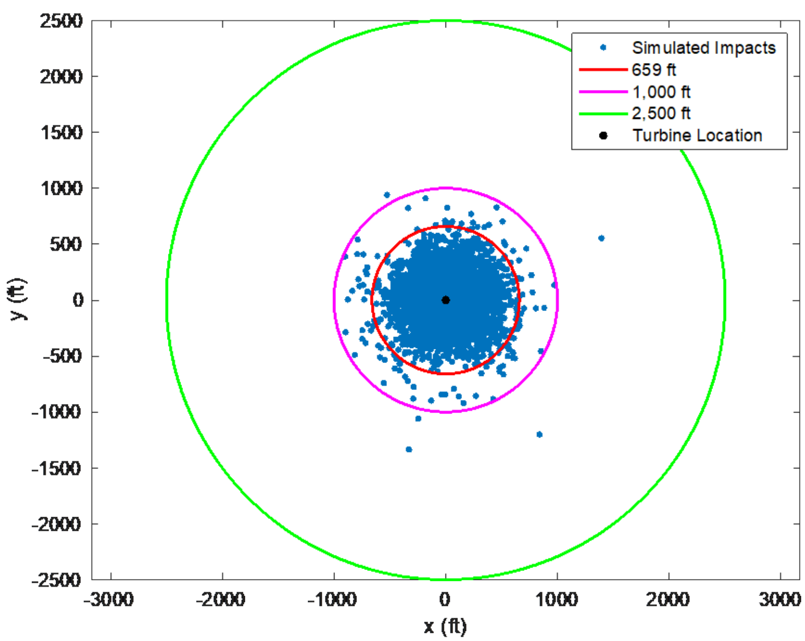

Figure 4.1. Monte Carlo Ice Fragment Impact Distribution and Associated Setback Distances.

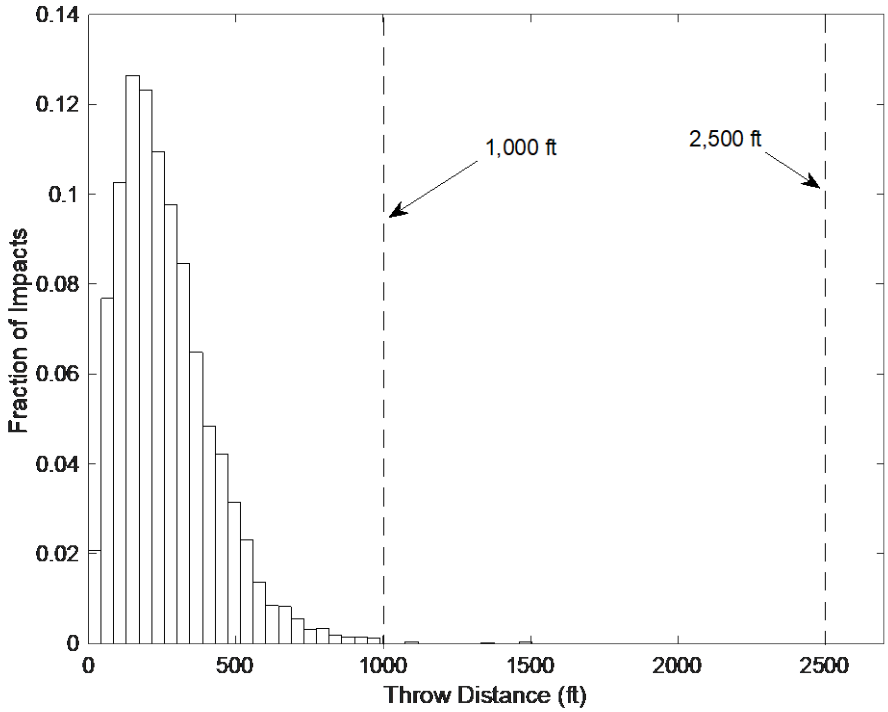

Figure 4.2. Monte Carlo Ice Fragment Impact Distance Histogram.

Ice Throw Risk Assessment to Residences and Unsigned Parcels

While the results in Figures 4.1 and 4.2 are valuable in providing an assessment of physically possible throw distances, they do not provide a realistic assessment of risk to surrounding structures and infrastructure since they do not account for the area of receptors or the number of likely ice pieces shed per year. The expected value methodology detailed in Section III is applied using the Monte Carlo impact data to arrive at an estimate of the number of fragments per year that can be expected at receptors located at the proposed setbacks. For this study, N_{ip} = 200 ice fragments per year per turbine is used based on the values documented in [1]. This represents a worst-case scenario in which turbines are not curtailed during icing or thawing events as dictated by proper operational procedures. As a result of this worst-case assumption of 200 ice fragments per year, **the subsequent risk values are highly conservative and likely overestimate the risk from ice throw substantially**.

In the calculations below, a receptor area of 2,500 sq ft is assumed when analyzing risk to residences. This represents the area of a typical house and is derived from the median US home size given in [7]. When computing the risk to unsigned parcels, a receptor area of approximately 10 sq ft is assumed. This represents the exposed area of a typical person, as risk to personnel near properties on the boundary of the wind farm are of primary interest in this analysis. Furthermore, it is assumed that there is 1% chance that a person is actually present at the receptor location (closest point on the property line to the turbine) at the time that the ice fragment lands. Thus, the expected value computed in Eq. (7) is multiplied by a 1% occupancy probability to determine the overall probability that a person on an unsigned parcel is struck by an ice fragment.

For each of the 86 turbine locations proposed by Tri Global, the distance to the nearest receptor of each type (unsigned habitable residence and unsigned parcels) was identified. Receptors were placed at these locations and risk for each receptor was computed using the throw distances shown in Figures 4.1-4.2, the assumed ice throw frequency of 200 ice pieces per year, and the assumed receptor areas. A summary of the computed risk results for each receptor type is provided below:

- **The risk imposed by ice throw to unsigned habitable residences is assessed to be extremely low.** The median worst-case risk is calculated to be less than 1 fragment in 1 million years. This is a **worst-case risk** assuming turbines will not be shut down during icing or thawing events.
- **The risk imposed by ice throw to personnel on unsigned parcels is assessed to be extremely low.** The median worst-case risk is calculated to be less than 1 fragment in 330,000 years. This is a **worst-case risk** assuming turbines will not be shut down during icing or thawing events.

As evident in the results described above, the risk due to ice throw for all of the receptor types is objectively extremely small. It should be emphasized again that, because of the operational measures that will be implemented at Panther Grove to shut down turbines during icing and thawing conditions (so that ice is shed directly beneath the turbine), the risk values specified above represent a worst-case scenario and almost certainly over-estimate the actual risk from ice shed. Given the low worst-case probability values and the prescribed operational procedures to be implemented at Panther Grove to mitigate the effects of ice shed, **the risk imposed by ice shed to residences and personnel in the vicinity of the Panther Grove project is assessed to be minimal.**

Ice Throw Risk Assessment to Vehicular Traffic on Public Roads

To assess ice throw impact risk to roads in the vicinity of Panther Grove, a related methodology to that used to assess risk to home sites and unsigned parcels is used. Rather than assessing the risk to roads themselves, however, this analysis assesses the risk to cars traveling on a public road near wind turbines at Panther Grove. This is because any injury risk from fragments would be due to their potential impact with a vehicle, rather than a result of them landing harmlessly on a road. Thus, the goal of this analysis is to assess risk to cars traveling on a public road in the vicinity of a wind turbine.

To assess risk to vehicles on a roadway, the risk analysis methodology described in Section III is modified. This is because, when assessing risk to home sites or properties, the receptor locations are stationary. In the case of vehicles on a roadway, the vehicles themselves may be in any location on the road when an ice fragment is shed from the turbine. Thus, the risk of impact must consider not only the landing location of an ice fragment, but whether a vehicle happens to be at the impact location on the roadway at the time the fragment lands. Thus, to perform this analysis, the methodology from Section III is modified as follows. Ice throw simulations are performed for a single turbine using the Monte Carlo process described in Section III to include the local wind data for Panther Grove and specific turbine parameters for the GE 5.5/158. For each ice throw simulation, a vehicular geometry is randomly generated along a 1-mile stretch of road at the minimum road setback distance from each turbine. For each ice throw, a random vehicle location is generated along the road, and an 86 sq ft (8 sq m) rectangle is defined at the center of the random location, representing the area of a notional vehicle on the road. The impact point for this particular simulation is computed, and then assessed as to whether it lands inside the random vehicle location or not. If it lands inside the rectangular area representing the vehicle, it represents a fragment impact on a vehicle on the roadway. This process is depicted in Figure 4.3 (note that this figure is not to scale, as the 8 sq m vehicle boundaries are smaller relative to the length of the road). The use of one vehicle per mile of roadway is considered reasonable for the rural roads in the vicinity of the wind project.

For each turbine, the distance to the nearest public road was provided by Tri Global. For each of these distances, a Monte Carlo simulation consisting of 40 million simulated ice throws was performed using the methodology described above, where for each ice throw simulation a new random vehicle geometry was generated. Assuming 200 expected ice pieces per year, this represents approximately 200,000 years of ice throw data for each individual turbine. Figure 4.4 shows 5,000 of the simulated impact points as well as a portion of the notional 1-mile stretch of roadway for the nearest distance between a public road and a turbine (659 ft). While some fragments do impact near or beyond the road, they make up only a small fraction (2.4%) of the 5,000 impacts in the figure.

The results of this simulation show that **the risk of an ice fragment impacting a vehicle on a public roadway are extremely small**. The median risk is observed to be **less than 1 impact on a vehicle in 180,000 years**. Furthermore, this is an overly conservative estimate of the risk as it assumes that the turbines are not shut down during icing and thawing conditions. In summary, the risks imposed to vehicles on public roads using the setback distances currently proposed for the Panther Grove facility are objectively extremely small. This low risk to vehicular traffic is a result of the limited range of ice throw distances (with 97.6% of fragments landing inside the 659 ft setback) and the rural nature of the roads in the vicinity of Panther Grove which leads to low traffic density.

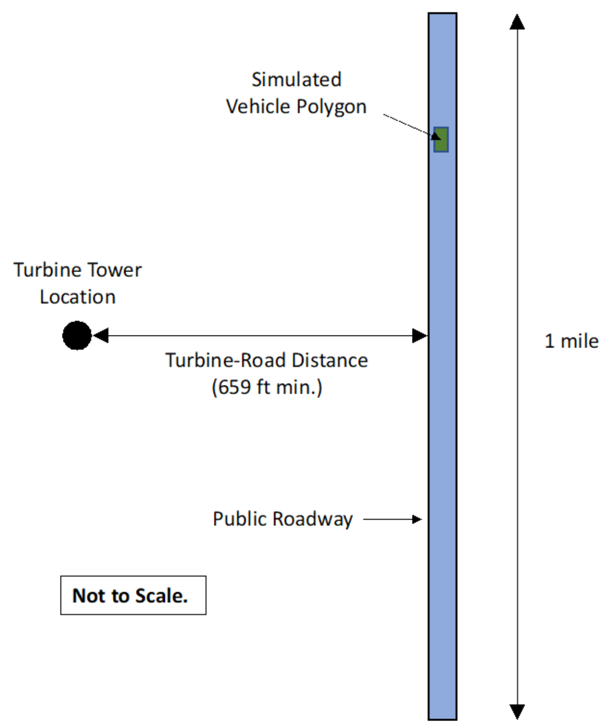

Figure 4.3. Road Analysis Geometry (figure not to scale).

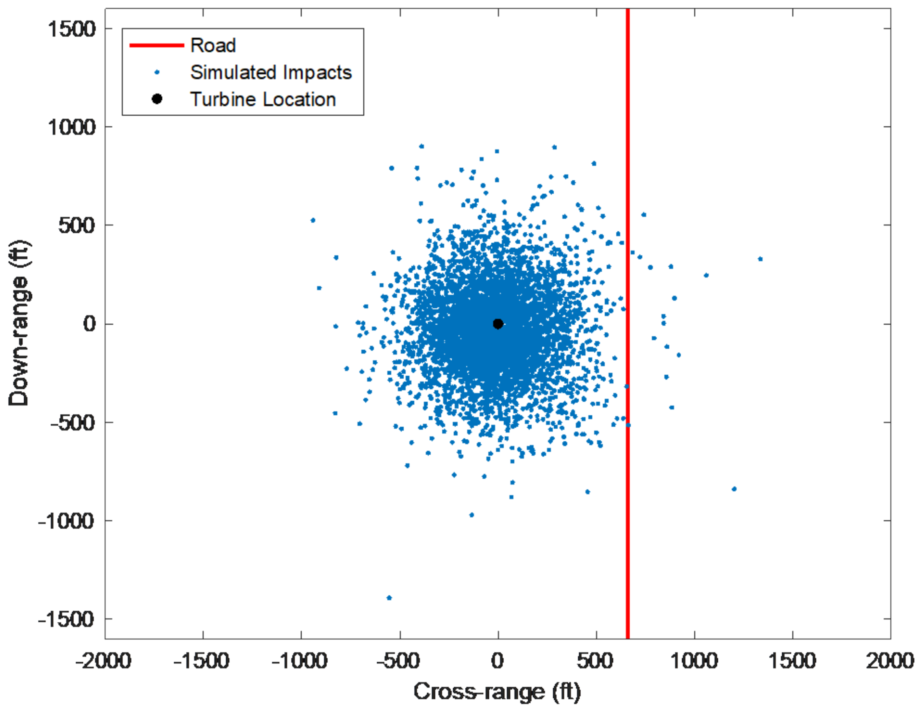

Figure 4.4. 5,000 Simulated Impacts from GE 5.5/158 Ice Throw and Road Segment at 659 ft Setback.

V. Blade Throw Risk Assessment Results

A Monte Carlo simulation of 5,000 blade fragment trajectories was performed using the modeling techniques described in Section III. The impact point distribution (assuming flat terrain near the turbine) is shown in Figure 5.1, and a histogram of the throw distances is shown in Figure 5.2. Note that no simulated impact distance exceeds 1,550 ft.

The results in Figures 5.1 and 5.2 illustrate potential throw distances but do not provide an assessment of actual risk. Assessment of actual risk from blade throw must account for blade throw frequency and the dimensional areas of specific receptor types. A complete risk assessment including these factors is summarized here, with a more detailed discussion provided below:

- The risk imposed by blade throw to unsigned habitable residences is calculated to be **less than 1 fragment impact in 1 million years**.
- The risk imposed by blade throw to personnel on unsigned parcels is **calculated to be less than 1 fragment impact in 1 million years.**

The next section describes how these risk levels were derived from the impact data.

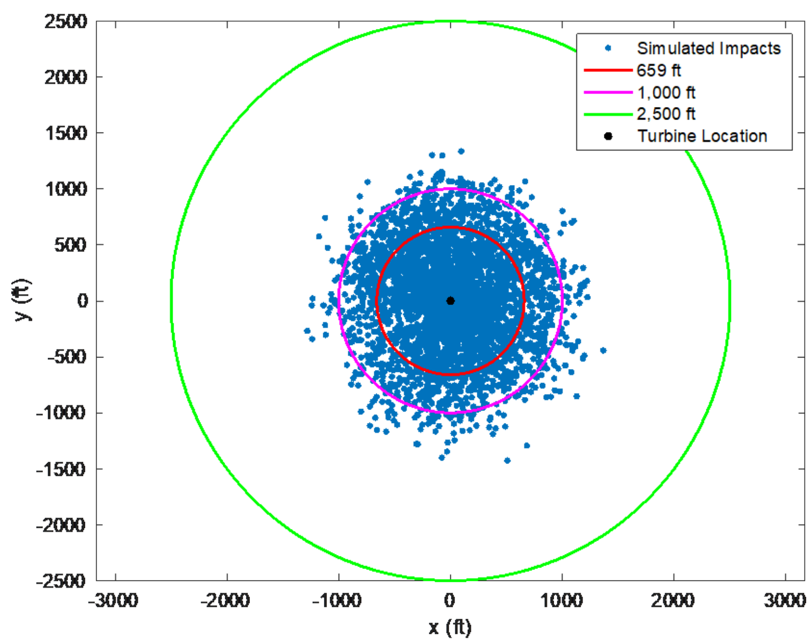

Figure 5.1. Monte Carlo Blade Fragment Impact Distribution and Associated Setback Distances.

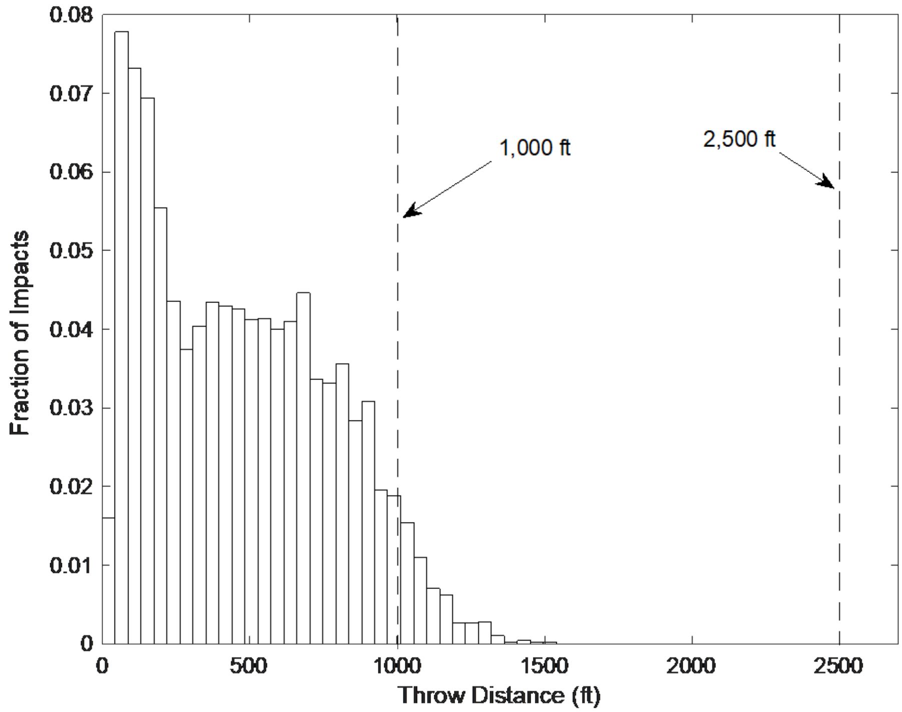

Figure 5.2. Monte Carlo Blade Fragment Impact Distance Histogram.

Blade Throw Risk Assessment to Residences and Unsigned Parcels

While the results in Figures 5.1 and 5.2 are valuable in providing an assessment of physically possible throw distances, they do not provide a realistic assessment of risk to surrounding structures and infrastructure since they do not account for the area of receptors or the frequency of blade failure. The expected value methodology detailed in Section III is applied using the Monte Carlo impact data to arrive at an estimate of the number of blade fragments per year that can be expected at receptors located at the proposed setbacks. For this study, the probability of blade failure is 10^{-3} per turbine per year. This is a conservative estimate and is based on the highest failure rate estimates documented in literature as discussed in Section II.

As in Section IV, a receptor area of 2,500 sq ft is assumed when analyzing risk to signed and unsigned habitable residences, and a receptor area of 10 sq ft is assumed when analyzing risk to unsigned parcels. For each of the 86 turbine locations proposed by Tri Global, receptors were placed at the distance to the nearest receptor of each type (unsigned habitable residence and unsigned parcels). The 1% occupancy probability was applied for the risk calculation for unsigned parcels. Risk of blade fragment impact for each receptor was computed using the throw distances in Figures 5.1-5.2, the assumed failure probability of 10^{-3} per year, and the assumed receptor areas. A summary of these results for each receptor type is provided below:

- **The risk imposed by blade throw to unsigned habitable residences is exceptionally low.** The median risk is calculated to be less than 1 fragment impact in 1 million years.
- **The risk imposed by blade throw to personnel on unsigned parcels is exceptionally low.** The median risk is calculated to be less than 1 fragment impact in 1 million years.

The results above illustrate the exceptionally low risk imposed by blade throw to receptors of all types. The genesis of this low risk is the fact that blade failures are so rare. The low blade failure rates exhibited by modern turbines makes it unlikely that any blade throw events will occur over the lifetime of a wind farm. In fact, for modern turbines blade throw is so rare that it is not usually considered as a primary factor in permitting and siting activities for modern wind farm developments. When this low failure rate is mathematically combined with the limited travel distance of the fragments and the relatively small receptor areas (compared to the total area surrounding the turbine in which the fragments can land), **the resulting total risk imposed by blade failure is computed to be exceptionally small.**

Blade Throw Risk Assessment to Vehicular Traffic on Public Roads

To assess blade throw impact risk to roads in the vicinity of Panther Grove, the same methodology was used as in assessing ice throw risk. In this case, the blade throw simulation data was used to assess risk to vehicles on public roads near each of the 86 turbine locations, using nearest public road distances provided by Tri Global. For each turbine, 1,000 random blade throws were simulated representing 1 million years' worth of operation (using the failure probability of 10^{-3} per turbine per year). **No vehicular impacts were observed in any of the simulations performed. Therefore, it is assessed that the risk imposed by blade throw to vehicles traveling on public roads in the vicinity of Panther Grove is less than 1 blade fragment impact on a vehicle in 1 million years.**

As in the risk calculation for the other receptor types, the risk to vehicles on public roads is minimal largely because of the rare occurrence of blade failure. Furthermore, even in the extremely rare event that a blade failure does occur and a fragment is thrown from the turbine, the chances of it striking a vehicle on a public road are very small since the fragments travel only a limited distance (over 2/3 of them land inside the nearest distance to a road), and because the area of vehicles on a rural public road is so small compared to the total area in which the fragment may potentially land. As a result, the risks imposed by blade fragments to vehicles on public roads are exceptionally low and of the same order as the risk of a person dying in a lightning strike each year [1].

About Persimia

Persimia, LLC is an environmental consulting firm based in Atlanta, Georgia, focused on the development of physics-based modeling and simulation tools for wind project environmental assessment and optimization. Persimia was founded by two highly experienced and internationally recognized Georgia Tech professors with extensive expertise in aerodynamic modeling, multi-physics simulation, and probabilistic analysis. Persimia has developed unique modeling and simulation software for wind project environmental impact analysis, with particular specialization in modeling potential risks from ice shed and blade throw. These engineering tools have been used in a variety of wind project siting studies worldwide, making Persimia the industry leader in assessment of wind project ice shed risk. Persimia has also developed advanced optimal control and curtailment strategies for mitigating wildlife impacts at wind installations using data-driven methods and optimization algorithms.

Dr. Jonathan Rogers served as the primary analyst for this project. Dr. Rogers is the CEO of Persimia and is also the Lockheed Martin Associate Professor in the School of Aerospace Engineering at Georgia Tech. Dr. Rogers is a leading aerospace researcher with extensive expertise in modeling and simulation of air vehicles, control design and optimization, and ballistics analysis. He has performed research for NASA, the US Air Force, US Naval Air Systems Command, and other aerospace organizations. Dr. Rogers is a leading expert in modeling and simulation of blade and ice throw fragments from wind turbines and has testified as an expert on this topic in numerous wind project siting and permitting processes throughout the United States.

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