Appendix 18

Blade Throw Assessment

THUNDERBOLT ENERGY HUB – STAGE 1

Blade Throw Assessment

Umwelt (Australia) Pty Ltd

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1 INTRODUCTION

Umwelt (Australia) Pty Ltd ("Umwelt") on behalf of Neoen Australia Pty Ltd ("Neoen" or "the Proponent") has commissioned DNV to assess the potential blade throw risks in the vicinity of the proposed Thunderbolt Energy Hub – Stage 1 ("the Project") in the Kentucky Area of New South Wales (NSW). The results of this work are reported here.

The typical risks of blade throw incidents are discussed in this technical note, based on a review of the available literature and guidelines, and the potential risks at dwellings, roads, and neighbouring properties in the vicinity of the Project site boundaries ("the Project Area") are evaluated.

2 BACKGROUND AND OVERVIEW

2.1 What is blade throw?

Blade throw describes an incident in which a structural failure occurring in the blade of a wind turbine generator (WTG) during operation results in parts of the blade detaching and being thrown into the surrounding area. Such incidents may involve the detachment of the entire blade or a large portion of the blade (if the failure occurs at or near the base of the blade where it attaches to the hub of the WTG rotor) or a relatively smaller blade fragment, such as a blade tip section or a piece of the outer shell of the blade [1, 2, 3, 4]. It is also possible for a structural failure to occur without causing parts of the blade to detach, in which case there is no danger within the surrounding area, or for a blade or blade fragment to detach and fall close to the WTG while the rotor is not in motion.

Reasons for WTG blade failure may include physical damage to the blade caused by external factors such as erosion or lightning, extreme wind conditions that cause the loads on the WTG to exceed the loads it has been designed to withstand, material or manufacturing defects, and material fatigue [1, 2, 3]. If left untreated, erosion to the blade surface caused by rain or fine particulates in the air can eventually progress into the blade or allow water to seep between the material layers, weakening the blade structure. Similarly, damage caused by an excessive lightning strike may affect the structural strength of the blade. The mechanical stresses experienced by a WTG blade during normal operation and under extreme weather conditions can, over time, lead to weak points or cracks in the material structure, while flaws in the design or materials used may make the blades more susceptible to failure.

2.2 Mitigating factors for blade throw risks

Modern WTGs and components supplied by major manufacturers are generally designed and certified in accordance with recognised international standards to ensure structural integrity and safe operation over the lifetime of the WTG. International Standard IEC 61400-1 [5] establishes the minimum requirements for the design of WTGs and related components with the objective of avoiding structural failure and the consequential risk of personal injury or damage to property. Other international standards that apply to the design and certification of WTG blades include IEC 61400-23 [6], which specifies the requirements for testing the structural integrity of blades, and IEC 61400-24 [7], which describes the requirements for lightning protection systems installed on WTGs.

Besides meeting the required design and manufacturing standards, modern WTGs incorporate sophisticated control systems that are designed to shut the WTG down during high wind speed conditions and in response to a range of faults or abnormalities detected during operation. These control systems include redundant monitoring and protection systems that are intended to prevent situations where the WTG rotor could accelerate to speeds higher than its rated speed (described as overspeed conditions) and to therefore be subjected to excessive or unbalanced loads [1, 2, 8]. Other conditions that may indicate a structural blade failure and which will cause a WTG to automatically shut down include abnormal vibration, rotor imbalance, or reduced power output [3]. Furthermore, due to the lightning protection systems used in modern WTGs, damage caused by lightning strikes is usually limited to the blade surface where it can be seen and repaired during preventative maintenance operations [2, 3]. High-quality operational monitoring and maintenance programs at wind farms help to increase the likelihood that WTG faults or minor damage are prevented or are detected and rectified at an early stage, thus reducing the risk of serious or dangerous problems developing. DNV understands that the Proponent maintains a 24-hour Operations and Control Centre that will allow the Project to be monitored remotely and may assist in detecting potential faults or damage early and quickly.

On account of these safeguards, blade throw incidents are relatively rare events for modern WTGs. However, due to the potential consequences arising from a blade throw incident, there is still a need to recognise and evaluate the associated risks. An understanding of the likelihood, dynamics, and risk associated with blade throw has been developed within the wind industry through a combination of investigation into historical blade throw incidents and theoretical research.

2.3 Regulatory requirements and guidelines for assessing blade throw risks

The Secretary's Environmental Assessment Requirements (SEARs) for the Project [9] specifies that the Environmental Impact Statement (EIS) for the Project must *"assess blade throw risks"*.

However, neither the SEARs or the NSW Wind Energy Guideline for State significant wind energy development (NSW Wind Energy Guideline) [10] provide any guidance on the methodology that should be used to assess blade throw risks, or the blade throw risks that would be considered acceptable. DNV is not aware of any additional regulatory requirements or guidelines related to the assessment of blade throw risks in any other Australian jurisdiction.

In the absence of any relevant guidance in the SEARs or NSW Wind Energy Guideline, DNV has adopted the guidance provided in the 2014 edition of the Dutch Wind Turbine Risk Zoning Handbook ("the Dutch Handbook") [1], which forms the basis of the 2020 Dutch Wind Turbine Risk Zoning Guide [11]. The Dutch Handbook is distinctive in that it presents both a methodology for performing a detailed site-specific analysis of blade throw risks and a methodology for conducting a conservative high-level risk assessment which can be used as a screening assessment to evaluate the potential risks for a wind farm and hence determine whether a more detailed assessment is needed. These methodologies have been developed based on conservative assumptions and thorough, well-documented research into the probability of a blade throw incident occurring, the distances that a blade or blade fragment may be thrown, and the risks of impact to people in the area around a WTG. The results of the research presented in the Dutch Handbook are broadly consistent with other literature and with observations made from historical blade throw incidents. DNV also understands that the methodologies given in the Dutch Handbook have been used to inform blade throw risk assessments in other jurisdictions in Europe outside of the Netherlands. Based on these factors, DNV considers that the Dutch Handbook provides an appropriate basis for the blade throw assessment presented in this document.

For the purposes of this assessment, DNV has also applied a classification of blade throw risks published by the United States Renewable Energy Laboratory (NREL) [12]. The NREL classification categorises the risks associated with a blade throw incident in terms of the probability of occurrence and potential consequences to people, and provides a consistent way of describing each probability and risk. Further details about the NREL classification are presented in 3.3.2.

2.4 Outline of this document

This document begins with a review of existing studies that have considered the risks of blade throw for wind farm developments, based on the likelihood of a blade throw incident occurring, the distance that a blade or blade fragment may be thrown, and the potential for a thrown blade to cause injury or death to people in the surrounding area. The purpose of this review is to establish typical blade throw risks in the vicinity of a WTG, and to consider these risks in relation to the Project.

A high-level, site-specific risk assessment for the Project is then presented, based on the methodology outlined in the 2014 Dutch Handbook [1]. As discussed in Section 2.3, this methodology has been developed in a conservative manner based on statistical analyses of historical blade throw incidents, mathematical modelling of the maximum potential blade throw distances for generic WTG models, and calculation of the corresponding risks at varying distances from the WTG. The methodology is considered applicable to a wide range of modern WTGs and can therefore be used to make an initial assessment of the potential risks for a proposed wind farm development in situations where the approximate WTG dimensions are known but a specific WTG model has not yet been chosen. Based on the results of the high-level assessment, the need for a more detailed site-specific assessment considering the specific WTG parameters and expected wind conditions can then be determined. The use of a site-specific risk-analysis approach to evaluate the likely risks of blade throw, rather than generic setback distances, is consistent with the recommendations and approaches presented in the relevant literature [8, 4, 13, 3].

2.5 Project configuration considered in this assessment

A conceptual WTG layout consisting of 32 WTGs with a rotor diameter of 190 m and tip height of 260 m (defined as the WTG hub height plus half the rotor diameter) has been considered in this assessment. These dimensions represent the maximum tip height and rotor diameter under consideration for the Project. Additionally, DNV understands that the Proponent is considering a two-part WTG blade design for the Project, in which the blade is manufactured and transported in two sections and assembled on site. The locations of dwellings, other sensitive locations, and roads in the vicinity of the Project Area have been provided by the Proponent.

3 POTENTIAL RISKS OF BLADE THROW INCIDENTS

The risk posed to people, property, or infrastructure by a potential blade throw incident is determined by three factors [14]:

1. the probability that a blade or blade fragment will detach and be thrown from a WTG, and the circumstances under which this happens
2. the probability that the blade or blade fragment will land at a given location
3. the probability that a blade or blade fragment landing at a given location will cause injury or death to a person, or damage to property or infrastructure.

The likelihood of a blade throw incident occurring, the maximum distance that a blade or blade fragment may be thrown, and the risk of death posed to people in the vicinity of a wind farm (being the most serious consequence of a potential blade throw incident) is discussed further in the following sections.

3.1 Probability of a blade throw incident occurring

Detailed, publicly available information about actual blade throw incidents is limited. There is currently no comprehensive database of blade throw incidents that includes accurate measurements of the throw distance and fragment size, details of the WTG model and the environmental and operating conditions involved, or information about the consequences of the incident [1, 2, 3, 13]. In response to these limitations, most studies reported in the literature have adopted a conservative interpretation of the available historical data and have supplemented this with theoretical modelling where appropriate.

To aid in the development of the risk assessment methodology presented in the Dutch Handbook, two detailed reviews of historical records were conducted with the aim of quantifying blade throw incident rates. In the initial analysis undertaken for the 2005 edition of the Dutch Handbook, two categories of blade throw incidents were considered: detachment and throw of an entire blade or large portion of a blade, and detachment and throw of a small blade fragment [2]. Although the definition of a blade fragment was not specified for the purposes of the review, a later section of the 2005 Dutch Handbook considered the relative risks associated with a blade fragment 3 m long and 1 m wide being thrown from a WTG with a rotor diameter of 68 m. This equates to a fragment size of approximately 10% of the WTG blade by length. The corresponding risks were subsequently found to be insignificant compared to the risks of blade throw incidents involving large portions of the blade [2], as will be discussed further in Section 3.3.1. Consequently, blade throw scenarios involving small blade fragments were not explicitly considered in the updated analysis described in the 2014 edition of the Dutch Handbook [1]. The estimated blade throw frequencies derived from the data are summarised in Table 1.

The results presented in Table 1 suggest that a blade throw scenario involving the detachment of a small blade fragment is less likely than the detachment and throw of a whole blade. The composite fibre materials and manufacturing methods used for WTG blades mean that it is relatively unlikely for fragments of the blade to detach under normal operating conditions [3]. According to the 2005 Dutch Handbook, many of the blade throw incidents classified as a detachment and throw of a blade fragment actually involved the detachment of a mobile blade tip mechanism used to control the WTG speed [2]. Such mechanisms are not commonly used on modern WTGs, which would further reduce the expected frequency of blade throw events involving small blade fragments.

Table 1 also shows that the number of all blade throw incidents that are expected to occur under overspeed conditions (in which the failure of multiple safety mechanisms allows the WTG rotor speed to increase to approximately twice the rated speed) is much lower than the number of incidents occurring under normal operating conditions. Although blade failure and blade throw may be more likely to occur if a WTG is operating under overspeed conditions, compared to normal operating conditions, the probability of those conditions actually being experienced is very low [1, 2, 8]. For the purposes of the analysis undertaken for the Dutch Handbook, the researchers made the conservative assumption that the overall probability of a blade throw incident occurring under overspeed conditions would be equal to the probability of any overspeed event, based on expected likelihood of complete failure of the WTG overspeed protection systems.

Based on the estimated blade throw frequencies determined for the Dutch Handbook, the researchers proposed conservative values for the probability of a blade throw incident occurring that could then be used in blade throw risk analyses [1, 2]. These probabilities, which take into account the limitations of the historical data and the subsequent uncertainty in the estimated blade throw frequencies, are also presented in Table 1.

Table 1 Probability of a blade throw incident occurring

Blade throw scenario	Estimated frequency of occurrence (incidents per WTG per year)		Probability recommended for use in blade throw risk analyses, considering uncertainty in estimated frequencies [1]
	Based on data recorded from 1984 to 2000 [1, 2]	Based on data recorded from 2001 to 2010 [1]	
Detachment and throw of entire blade or large portion of blade			
All operating conditions [1]	6.3×10^{-4}	6.3×10^{-4}	8.4×10^{-4} incidents per WTG per year (1 incident per year per 1,190 WTGs)
Normal operating conditions (rated rotor speed) [2]	3.1×10^{-4}	6.2×10^{-4}	8.4×10^{-4} incidents per WTG per year (1 incident per year per 1,190 WTGs)
Mechanical braking conditions (1.5 times the rated rotor speed) [2]	3.1×10^{-4}	Included with normal operating conditions	Not applicable to modern WTGs
Overspeed conditions (2 times the rated rotor speed) [3]	Less than 5.0×10^{-6}	Less than 5.0×10^{-6}	5.0×10^{-6} incidents per WTG per year (1 incident per year per 200,000 WTGs)
Detachment and throw of blade tip or other small blade fragment			
All operating conditions [1]	1.2×10^{-4}	Not explicitly considered	2.6×10^{-4} incidents per WTG per year [2] (1 incident per year per 3,846 WTGs)
Overspeed conditions (2 times the rated rotor speed) [3]	Less than 5.0×10^{-6}	Not explicitly considered	5.0×10^{-6} incidents per WTG per year [2] (1 incident per year per 200,000 WTGs)

1. Derived directly from the number of recorded blade throw incidents. For the detachment and throw of an entire blade under all operating conditions, the actual rate of blade throw incidents observed in the data recorded from 2001 to 2010 was slightly less than 6.3×10^{-4}. However, for the sake of conservatism, the researchers conducting the review chose to retain the blade throw frequency derived in the previous analysis [1].
2. Assumed, based on probability of a blade throw incident under all operating conditions and expected proportion of incidents occurring for WTGs operating under normal conditions, under mechanical braking, and under overspeed conditions.
3. Assumed, based on expected likelihood of complete failure of the WTG overspeed protection systems.

The 2014 Dutch Handbook notes that the probabilities presented in Table 1 are likely to be conservative in comparison to the actual probability of a blade throw incident occurring for a modern WTG [1]. The underlying data sets used to derive the probability of a blade throw incident contain information for WTGs that may not have been certified to modern standards and are therefore unlikely to have had the sophisticated control and safety systems of a modern WTG. This is supported by statistical analysis presented in the 2014 Dutch Handbook, which shows a downward trend in the frequency of recorded blade throw incidents over time, with the five-year average probability for the detachment and throw of an entire blade decreasing from approximately 3.5 x 10^{-4} incidents per WTG per year (1 incident per year per 2,857 WTGs) in 2001-2005 to less than 2.5 x 10^{-4} incidents per WTG per year (1 incident per year per 4,000 WTGs) in 2006-2010 [1].

DNV is not aware of any studies that have specifically considered the probability of a blade throw incident occurring for WTGs with a two-part blade and, given that such blades are a relatively new technology, it is unlikely that the data used to derive the probabilities presented in Table 1 includes blade throw incidents for these WTGs. However, since two-part blade designs are expected to be subject to the same standards as other modern WTGs, a blade throw probability of 8.4 x 10^{-4} incidents per WTG per year (1 incident per year per 1,190 WTGs) is also expected to be conservative for WTGs with two-part blades.

3.1.1 Comparison of blade throw probabilities to Australian incidents

According to the Australian Energy Market Operator (AEMO), there are currently 3,238 WTGs installed and operating in Australia, 759 of which are located in NSW [15]. For this number of WTGs, based on the conservative blade throw probability of 8.4 x 10^{-4} incidents per WTG per year (1 incident per year per 1,190 WTGs) presented in Table 1 for an entire blade or large portion of blade, up to approximately three blade throw incidents on average across Australia or less than one blade throw incident on average in NSW could be expected to occur in a year. If the conservative probability of a blade fragment being thrown is also considered (being 2.6 x 10^{-4} incidents per WTG per year or 1 incident per year per 3,846 WTGs, as shown in Table 1), up to approximately one additional blade throw incident on average could be expected to occur in Australia in a year. Therefore, the total number of blade throw incidents that may be expected to occur in Australia is up to approximately four incidents on average in a year.

DNV maintains a database of WTG incidents that have occurred in Australia from 2005 onwards, based on details recorded in public databases, reports made in industry journals and other media, and information received from participants in the wind industry. Assuming that all of the WTGs currently operating in Australia were installed between 2005 and 2020 at a constant number of WTGs per year (which is expected to give a reasonable representation of the increase in the number of WTGs over time), the average number of WTGs in Australia during this period is approximately 1,600. Based on the conservative blade throw probabilities of 8.4 x 10^{-4} incidents per WTG per year (1 incident per year per 1,190 WTGs) for an entire blade and 2.6 x 10^{-4} incidents per WTG per year (1 incident per year per 3,846 WTGs) for a blade fragment, it is expected that up to 28 blade throw incidents could have occurred in Australia in the 16 year period from 2005 to 2020. For confidentiality reasons, the actual number of blade throw incidents recorded in DNV's incident database cannot be disclosed. However, to DNV's knowledge, the number of blade throw incidents recorded in Australia since 2005 is notably less than the value predicted according to the conservative probability presented in Table 1 and is therefore within the expected probabilities of a blade throw incident occurring.

3.1.2 Implications for the Project

As discussed above, the probabilities presented in Table 1 are expected to represent conservative estimates of the probability of blade throw incidents for modern WTGs such as those proposed for the Project. Therefore, it is reasonable to assume that the probability of a blade throw incident occurring within the Project Area will be less than the conservative estimates shown in Table 1 of

- 8.4 x 10^{-4} incidents per WTG per year (1 incident per year per 1,190 WTGs) for an entire blade
- 2.6 x 10^{-4} incidents per WTG per year (1 incident per year per 3,846 WTGs) for a blade fragment

and could be closer to 2.5 x 10^{-4} incidents per WTG per year (1 incident per year per 4,000 WTGs) as evaluated in the 2014 Dutch Handbook for the five-year period from 2005 to 2010. To state this another way, for the proposed 32 WTGs, it is expected that on average one blade throw incident could occur approximately every 31 to 125 years on average.

Nevertheless, for the high-level blade throw risk assessment presented in Section 4, the methodology recommended in the Dutch Handbook based on the more conservative blade throw probability of 8.4 x 10^{-4} incidents per WTG per year (1 incident per year per 1,190 WTGs) has been used.

3.2 Maximum theoretical blade throw distance

A number of theoretical studies have been undertaken to assess the likely distribution of WTG blade fragments in the event of a blade throw incident, or the probability that if a blade or section of blade is thrown it will land at a specific location. These have been performed using mathematical modelling to simulate the motion of thrown blades or blade fragments of various sizes for a range of WTG parameters, operating behaviours, wind speeds, and other conditions.

The results of several such studies are summarised in Table 2, for the case of WTGs operating under normal conditions (referring to operation at the rated rotor speed), and Table 3, for the case of WTGs operating under overspeed conditions of 2 to 2.5 times the rated rotor speed. Although the results of these studies are not directly comparable due to the different modelling parameters and assumptions used in each investigation, it is possible to draw some general conclusions.

Table 2 shows that, for WTGs operating under normal conditions with a tip speed of approximately 70-80 m/s, the maximum theoretical throw distances predicted in the literature for an entire blade or large portion of a blade range from 140 m to 260 m for rotor diameters ranging from 47 m to 294 m. At higher tip speeds of around 100 m/s, which is approximately equal to the upper limit of the range of normal tip speeds for most modern WTGs, the predicted maximum theoretical throw distances for an entire blade or large portion of blade range from 200 m to 300 m. As would be expected, smaller blade fragments are predicted to travel further than an entire blade, with maximum throw distances ranging from 450 m to 861 m under normal operating conditions for blade fragments of up to 20% of the entire blade by either length or weight (corresponding to fragment lengths of up to approximately 30 m) and 510 m to 1,000 m for higher tip speeds.

In practice, higher WTG tip speeds are typically associated with higher incoming wind speeds. However, in the theoretical studies considered in this assessment, the WTG tip speeds were varied independently of the assumed wind speed. Where the incoming wind speed was considered in the modelling, this was used to simulate the aerodynamic behaviour of the blade or blade fragment after detachment rather than to determine the WTG tip speed and initial release velocity. While the theoretical studies suggest that smaller blade fragments may travel further under high wind speed conditions, as a result of being carried by the wind, this effect appears to be largely dependent on the WTG operating conditions and behaviour at the time of the blade throw incident [8, 4]. The throw distances presented in Table 2 represent the maximum predicted distances over the range of incoming wind speeds considered in each study.

The predicted throw distances shown in Table 2 increase slightly as the size of the WTG increases, but are not directly proportional to the WTG dimensions. In other words, a doubling of the WTG rotor diameter or tip height does not correspond to a doubling of the predicted throw distance for either an entire blade or a blade fragment. The results of the theoretical studies therefore suggest that the WTG dimensions do not significantly influence the maximum blade throw distance under normal operating conditions [8, 4].

Instead, the results presented in Table 2 indicate that, for similar WTG dimensions, the blade throw distance is primarily dependent on the tip speed. A higher tip speed means that the blade or blade fragment will be travelling at a higher velocity when it detaches, and therefore will have the potential to be thrown a greater distance from the WTG. The same observation was made by Rogers *et al.* [8] and Sarlak and Sørensen [4], who both concluded that the blade tip speed plays the most important role in determining the maximum potential throw distance for any WTG.

Table 2 Theoretical maximum blade throw distances for WTGs operating under normal conditions (rated rotor speed)

Study reference	Blade fragment sizes considered	Modelled WTG parameters			Maximum throw distance (m)	
		Diameter (m)	Tip height (m)	Tip speed (m/s)	Entire blade	Blade fragment
Rogers *et al.* [8]	Entire blade, 20% of entire blade by weight	47	73.5	70.0	210 [1]	520 [1]
		70	115.0	80.5	260 [1]	750 [1]
		90	125.0	76.1	240 [1]	550 [1]
Cotton [13]	Entire blade, 10% of entire blade by weight	90	110.0	65.0	185 [2]	861 [2]
2014 Dutch Handbook [1]	Entire blade or large portion of blade only, small blade fragments not considered	141	190.5	96.7	214	-
		156	198.0	107.0	245	-
Sarlak & Sørensen [4]	Entire blade, 20% of entire blade by length	100	150.0	70.0 [3]	140 [1]	450 [1]
		147	220.5	70.0 [3]	180 [1]	500 [1]
		208	312.0	70.0 [3]	200 [1]	580 [1]
		294	441.0	70.0 [3]	210 [1]	610 [1]
		100	150.0	100.0 [4]	200 [1]	510 [1]
		147	220.5	100.0 [4]	220 [1]	860 [1]
		208	312.0	100.0 [4]	250 [1]	930 [1]
		294	441.0	100.0 [4]	300 [1]	1000 [1]

1. Value has been approximated from graphed results presented in the original source.
2. 99th percentile (1-in-100) result, assuming medium air drag. Throw distances of 203 m and 1395 m were predicted for an entire blade and a blade fragment respectively assuming very low air drag, but it is unclear whether these conditions would be experienced in reality.
3. Representing normal operating conditions.
4. Representing high tip speed conditions.

The maximum theoretical throw distances presented in Table 3 for WTGs operating under overspeed conditions, where the rotor speed is 2 to 2.5 times the rated speed, support the observation that the throw distance is primarily dependent on the tip speed. For the same WTG dimensions, the predicted maximum throw distance for an entire blade under overspeed conditions is typically around 2.5 to 3 times the distance predicted for normal operating conditions. Although the predicted maximum throw distances for entire blades and blade fragments under overspeed conditions are more sensitive to the WTG dimensions than the distances for normal operating conditions, the influence of the diameter and tip height on the throw distance appears to decrease as the WTG size increases [4].

Table 3 Theoretical maximum blade throw distances for WTGs operating under overspeed conditions (2 to 2.5 times the rated rotor speed)

Study reference	Blade fragment sizes considered	Modelled WTG parameters			Maximum throw distance (m)	
		Diameter (m)	Tip height (m)	Tip speed (m/s)	Entire blade	Blade fragment
Cotton [13]	Entire blade, 10% of entire blade by weight	90	110.0	216.8	183 [1]	886 [1]
2014 Dutch Handbook [1]	Entire blade or large portion of blade only, small blade fragments not considered	141	190.5	193.4	602	-
		156	198.0	214.0	716	-
Sarlak & Sørensen [4]	Entire blade, 20% of entire blade by length	100	150.0	150.0	390 [2]	780 [2]
		147	220.5	150.0	450 [2]	1450 [2]
		208	312.0	150.0	480 [2]	1800 [2]
		294	441.0	150.0	500 [2]	2000 [2]

1. 99th percentile (1-in-100) result, assuming medium air drag and a 1-in-50 year extreme wind speed. Throw distances of 198 m and 1462 m were predicted for an entire blade and a blade fragment respectively assuming very low air drag, but it is unclear whether these conditions would be experienced in reality.
2. Value has been approximated from graphed results presented in the original source.

The maximum throw distances presented in Table 2 and Table 3 represent low probability events in themselves and, to determine the overall likelihood of a blade or fragment being thrown that distance, this probability must be combined with the likelihood of a blade throw incident occurring. In the case of the results presented by Cotton [13], for example, the maximum blade throw distances shown in Table 2 and Table 3 correspond to a 1-in-100 or 99th percentile throw distance (likelihood of 1 x 10^{-2}). When this is combined with the likelihood of a blade throw incident occurring under normal operating conditions (conservatively estimated as 8.4 x 10^{-4} incidents per WTG per year for an entire blade and 2.6 x 10^{-4} incidents per WTG per year for a blade fragment, as discussed in Section 3.1), the overall risk of blades or blade fragments being thrown to these maximum distances is very low (likelihood of 8.4 x 10^{-6} incidents per WTG per year or 1 incident per year per 119,000 WTGs for an entire blade, or 2.6 x 10^{-6} incidents per WTG per year or 1 incident per year per 384,600 WTGs for a blade fragment). The risk of blades or blade fragments being thrown to the maximum distances predicted for WTGs operating under overspeed conditions is even lower, due to the low likelihood of an overspeed event occurring and causing a blade or blade fragment to detach (conservatively estimated for each case as 5.0 x 10^{-6} incidents per WTG per year, as discussed in Section 3.1), with an overall likelihood of blades or blade fragments being thrown to the maximum distances being in the order of 1.0 x 10^{-7} incidents per WTG per year or 1 incident per year per 10 million WTGs.

3.2.1 Comparison of blade throw distances to recorded incidents

As noted in Section 3.1, information about the distances that blades or blade fragments have travelled in actual blade throw incidents is very limited. Based on incident data recorded from 1984 to 2000, researchers for the 2005 Dutch Handbook were able to confirm blade throw distances of up to 150 m for an entire blade (for a WTG with a rotor diameter of approximately 50 m) and up to 500 m for a blade tip or small fragment [2]. The authors of that review also noted that throw distances of up to 600 m for entire blades had been reported in some publications, but were unable to verify those reports. Similarly, a 2006 review of 37 reported instances of blade throw where a distance was recorded found that most incidents resulted in fragments being thrown to within 600 m of the WTG location [13]. Only one incident identified in that review exceeded a throw distance of 600 m, with a blade fragment reaching an estimated distance of "almost 1,000 m" [13], although the size of the fragment and other circumstances of the incident were not specified. Despite the limitations of the data, these recorded distances are broadly consistent with the range of predicted blade throw distances under normal operating conditions given in Table 2.

3.2.2 Implications for the Project

The WTG parameters under consideration for the Project are summarised in Table 4.

Table 4 WTG parameters proposed for the Project

WTG	Diameter (m)	Tip height (m)	Tip speed under normal operating conditions (m/s)
Theoretical WTG representing maximum WTG dimensions	190 [1]	260	-

1. A two-part blade with a maximum individual section length of 60 m is currently under consideration.

These parameters are closest to those modelled by Sarlak and Sørensen [4] for a theoretical WTG with a rotor diameter of 208 m and tip height of 312 m, as shown in Table 2. Therefore, the maximum potential throw distances for the proposed WTGs are expected to be in the order of 200 m for an entire blade and 580 m for a blade fragment under normal operating conditions at the nominal rated rotor speed, and 250 m for an entire blade and 930 m for a blade fragment at the maximum rated rotor speed. In the unlikely event of overspeed conditions, the throw distances for WTGs of this size could potentially reach 480 m for an entire blade or 1,800 m for a blade fragment. If the two-part blade under consideration for the Project were to detach at the join between the sections, it is expected that this would correspond to a thrown blade portion that is larger than the 20% by length blade fragment considered by Sarlak and Sørensen. Since the maximum theoretical throw distance decreases as the size of the thrown portion of blade increases, the throw distances modelled by Sarlak and Sørensen are expected to encompass the range of potential throw distances for the two-part blade under consideration for the Project.

However, it is important to note that these potential blade throw distances are theoretical maximum values based on assumed scenarios for the WTG behaviour and wind conditions at the time of the blade throw incident, and do not consider the probability of those scenarios actually occurring [4]. The probability of a blade or blade fragment being thrown from a WTG at the Project under normal operating conditions and reaching the theoretical maximum throw distance presented here is expected to be very low, and likely in the order of 10^{-5} incidents per WTG per year (1 incident per year per 100,000 WTGs). For the case of blade throw under overspeed conditions, the probability of a blade or blade fragment being thrown and reaching the theoretical maximum throw distance is likely to be in the order of 10^{-7} incidents per WTG per year (1 incident per year per 10 million WTGs). To state this another way, for the proposed 32 WTGs, it is expected that a blade or blade fragment would be thrown to the maximum theoretical distance for normal operating conditions once every 3,100 years, and to the maximum theoretical distance for overspeed conditions once every 310,000 years. Considering that the typical operating life of a wind farm is 25 to 30 years, the likelihood of a blade or blade fragment detaching and being thrown to the maximum theoretical distance during the operating life of the Project can be considered remote for normal operating conditions and extremely remote for overspeed conditions.

3.3 Probability of a blade throw incident causing injury or death

Most investigations into the risks associated with a potential blade throw incident have focussed on the risk of harm being caused to people by a blade or blade fragment thrown from a WTG, either through direct impact or impact with another object. These risks represent the most serious potential consequences of a blade throw incident and also may be the subject of public policy or regulations, although DNV is not aware of any such policies or regulations in Australia. The likelihood of a blade throw incident resulting in injury or death to a person in the vicinity of a wind farm through direct impact is determined by the probability of the blade throw incident occurring, combined with the probability of a blade fragment actually hitting a person who is in the surrounding area.

A common way of expressing the risk of injury or death from a blade throw incident occurring at a wind farm is in terms of the *location-specific risk* (also called the location-specific individual risk, or LSIR) [1, 2, 3]. The location-specific risk is defined as the probability that a person remaining at a fixed location in the vicinity of the wind farm continuously for a year will be hit and killed by a blade or blade fragment thrown from a WTG. This measure is useful for visualising and comparing the blade throw risks in the area around a wind farm, but does not consider the likelihood that a person will in fact be present in that area when a blade throw incident occurs. Although the work presented in this document is not intended to assess the probability of a blade throw incident causing damage to property, the location-specific risk may also be considered as a measure of the likelihood that a blade or blade fragment will impact a building or other fixed infrastructure in the area around a wind farm.

For situations where a person may be moving through the area in the vicinity of a wind farm, such as on a road or rail network, two further measures of blade throw risk can be considered [1]:

- The *individual risk* (also called the individual risk per annum, or IRPA) is defined as the annual probability that a typical person passing by the wind farm will be hit and killed by a blade or blade fragment. At any given location, the individual risk is given by the combination of the fraction of time in a year the person spends at that location, the probability of being hit by a blade or blade fragment at that location, and the probability of the impact causing death. To determine the overall individual risk of death from a blade throw incident, the individual risks at each location must be summed over all locations in the vicinity of the wind farm.
- The *societal risk* is defined as the annual risk to the entire population expressed as the total number of deaths that would be caused by a blade throw incident per year.

While the location-specific blade throw risk in the area around a wind farm can be estimated based on the WTG characteristics alone, the individual risk and societal risk must be assessed on a site-specific basis using information about the amount of time that people are likely to spend in the vicinity of the wind farm.

3.3.1 Location-specific blade throw risks

To understand how the location-specific blade throw risk varies with the WTG parameters, researchers for the Dutch Handbook modelled the risk of being hit and killed by an entire blade thrown from WTGs of various sizes and how that risk changed with increasing distance from the WTG [1, 2]. These calculations were based on the conservative blade throw probabilities and maximum blade throw distances derived in the Dutch Handbook as discussed in Sections 3.1 and 3.2. The size of the blade and the area it could potentially impact upon landing was also considered, and it was assumed that every impact would be fatal for a person at that location. The location-specific risk for a blade throw incident was then combined with the risks of death caused by a WTG tower collapsing or a rotor or nacelle falling from the tower, which were determined in a similar way, to obtain the overall location-specific risk at each point in the vicinity of the WTG.

Based on the results of the modelling, two observations were made [1, 2]:

- The risk became less than 10^{-5} per year (1-in-100,000) at a distance of half the rotor diameter for all WTG parameters and conditions considered.
- The risk became less than 10^{-6} per year (1-in-1 million) at a distance of either the WTG tip height or the maximum theoretical throw distance for an entire blade under normal operating conditions for that WTG, depending on the WTG parameters and conditions in which blade throw was assumed to have occurred.

Given the conservative assumptions and generic WTG parameters considered in the modelling, the researchers concluded that the location-specific risk for any WTG similar to those considered would be 10^{-5} per year (1-in-100,000) at a distance equal to half the rotor diameter, and 10^{-6} per year (1-in-1 million) at a distance equal to either the WTG tip height or the maximum theoretical throw distance for an entire blade under normal operating conditions, whichever is greater. As defined in Section 3.3, these risks describe the probability that a person who remains at a fixed location at the specified distance from the WTG for a whole year will be hit and killed by a blade thrown from the WTG. These results are summarised in Table 5 for the two largest WTG models considered in the 2014 Dutch Handbook.

Table 5 Results of location-specific risk modelling for two generic WTG models [1]

Modelled WTG parameters			Maximum theoretical throw distance for an entire blade under normal operating conditions (m)	Distance from WTG where the location-specific risk drops below the given value (m)	
Diameter (m)	Tip height (m)	Hub height (m)		10^{-5} per year (1-in-100,000)	10^{-6} per year (1-in-1 million)
141	190.5	100	214	71	214
156	198.0	120	245	78	245

In the 2005 Dutch Handbook, researchers also investigated how the location-specific risk would vary with the distance from the WTG for a blade fragment with a length of 3 m and a width of 1 m being thrown from a WTG with a rotor diameter of 68 m and tip height of 131 m [2]. The results of the analysis showed that the risk of being hit and killed by a blade fragment at a particular location is approximately 100 to 1,000 times less than the risk of being hit and killed by an entire blade at the same distance from the WTG. This is partly due to the lower probability that a blade throw incident will involve a small blade fragment, as discussed in Section 3.1, but also due to the size of the thrown section of blade. Although a blade fragment can potentially be thrown a long way, its smaller size means that it will impact a smaller area and so there is a reduced chance of the fragment hitting and killing a person at any given location compared to an entire blade. Additionally, given the larger potential throw distances for a blade fragment, the area around the WTG in which a blade fragment could land is larger than the area for an entire blade and so there is a reduced chance of any specific location being impacted. At distances greater than the maximum throw distance for the blade fragment under normal operating conditions (approximately 650 m for the WTG parameters considered in the 2005 Dutch Handbook), the results showed that the location-specific risk of being hit and killed is in the order of 10^{-12} per year (1-in-1 trillion). Therefore, the location-specific risks associated with a blade fragment being thrown from a WTG are insignificant compared to the risks posed by an entire blade and can be assumed to be encompassed in the risk levels described above.

3.3.2 Comparison of blade throw risks to other common activities

The typical fatality risks for several common activities are presented in Table 6, along with the risks of being hit and killed by a WTG blade or blade fragment as given in the 2014 Dutch Handbook. Even considering the conservative assumptions made in the calculations performed for the Dutch Handbook, and the hypothetical scenario of a person who spends the entire year in close proximity to a WTG, the risk of death due to a blade throw incident is less than the annual risk of death on Australian roads or for people working in agriculture. For the purpose of comparison, DNV has also converted the location-specific blade throw risks for a person remaining in the specified location continuously for a whole year into the risk for a person spending the equivalent of one working day (8 hours) per year at that location. This duration is considered to represent a more realistic estimate of the amount of time that a person may spend in the vicinity of a WTG. When this hypothetical scenario of a person being in close proximity to a WTG for 8 hours per year is taken into account, the risk of death due to a blade throw incident is lower than the risk of being killed by a lightning strike. The risk of death due to a blade throw incident can therefore be considered very small, particularly when compared to the likelihood of accidents occurring during everyday activities.

Table 6 Typical risks of common activities compared to blade throw risks

Risk	Annual probability	
Death to people working in agriculture in Australia, per agricultural worker (2001-2011 data) **[16]**	1.5×10^{-4} (1-in-6,667)	
Death on Australian roads, per head of population (2019 data) [17]		
- Nationally	4.5×10^{-5} (1-in-22,222)	
- Inner regional areas	7.8×10^{-5} (1-in-12,821)	
- Outer regional areas	1.35×10^{-4} (1-in-7,407)	
Death due to lightning strike, per head of population (1980-1989 data) [18]	10^{-7} (1-in-10 million)	
Death from impact by a WTG blade or blade fragment, for an unprotected person remaining at a fixed location at the specified distance for the specified time [1]	*continuously for a year*	*continuously for one working day per year (8 hours)*
- distance equal to half the rotor diameter	10^{-5} (1-in-100,000)	10^{-8} (1-in-100 million)
- distance equal to the WTG tip height or maximum blade throw distance for an entire blade under normal operating conditions, whichever is greater	10^{-6} (1-in-1 million)	10^{-9} (1-in-1 billion)

To provide further context, the NREL [12] has published a classification of blade throw risks in terms of the annual probability associated with the risk and the potential consequences. The NREL risk classification for consequences to people is shown in Table 7. Based on this classification, the risk of death for a person who spends a whole year in the vicinity of a WTG at a fixed location at either of the distances specified in Table 6 can be described as an "extremely remote" probability and "low" overall risk. For the potentially more realistic scenario of a person who spends the equivalent of 8 hours per year at a fixed location at the specified distances from a WTG, the risk of death due to a blade throw incident becomes "improbable" and a "routine" overall risk. For the purposes of their own assessments, the NREL considers any risks which are classified as "low" or "routine" to be acceptable.

Table 7 NREL classification of blade throw risks [12]

Consequence to people	Probability of risk occurring					
	"Frequent"	"Reasonably probable"	"Occasional"	"Remote"	"Extremely remote"	"Improbable"
	More than 1 per year	Less than 1 per year to 0.1 per year (1-in-10)	Less than 0.1 per year (1-in-10) to 0.01 per year (1-in-100)	Less than 0.01 per year (1-in-100) to 10^{-4} per year (1-in-10,000)	Less than 10^{-4} per year (1-in-10,000) to 10^{-6} per year (1-in-1 million)	Less than 10^{-6} per year (1-in-1 million)
Death or permanent total disability	"High" risk	"High" risk	"High" risk	"Moderate" risk	"Low" risk	"Routine" risk
Partial disability	"High" risk	"High" risk	"Moderate" risk	"Low" risk	"Low" risk	"Routine" risk
Injury	"Moderate" risk	"Moderate" risk	"Low" risk	"Low" risk	"Routine" risk	"Routine" risk
Minor injury	"Routine" risk	"Routine" risk	"Routine" risk	"Routine" risk	"Routine" risk	"Routine" risk

3.3.3 Implications for the Project

Based on the location-specific risk modelling presented in the 2014 Dutch Handbook, the risk of a person who remains at a fixed location in the vicinity of the Project Area continuously for a whole year being hit and killed by a blade or blade fragment thrown from a proposed WTG is expected to be 10^{-5} per year (1-in-100,000) or less at a distance of 95 m (being half the maximum proposed rotor diameter, based on the WTG dimensions given in Table 4). For the hypothetical case of a person who spends the equivalent of one working day (8 hours) per year at a fixed location at a distance of 95 m from the WTG, the risk of being hit and killed by a blade or blade fragment is expected to be 10^{-8} (1-in-100 million).

As stated in the Dutch Handbook, the location-specific blade throw risk drops below 10^{-6} per year (1-in-1 million) at a distance equal to either the WTG tip height or the maximum theoretical throw distance for an entire blade under normal operating conditions, whichever is greater. For the proposed WTGs, the maximum proposed tip height of 260 m is greater than the maximum potential throw distance for an entire blade established in the literature for similar sized WTGs at the maximum rated rotor speed, as discussed in Section 3.2.2, and also greater than the maximum throw distance under normal operating conditions for all WTG models considered in the Dutch Handbook (245 m, as shown in Table 5). Therefore, the risk of being hit and killed by a blade or blade fragment is expected to be 10^{-6} per year (1-in-1 million) or less for a person who remains at a fixed location at a distance of 260 m from the proposed WTGs continuously for a whole year, and 10^{-9} per year (1-in-1 billion) for the hypothetical case of a person who spends the equivalent of 8 hours per year at that location.

A high-level assessment of the site-specific risks of blade throw for the Project (including the location-specific, individual, and societal risks), based on the maximum WTG dimensions proposed for the Project and the conservative risk assumptions used in the Dutch Handbook, is presented in Section 4.

4 SITE-SPECIFIC BLADE THROW RISK ASSESSMENT

4.1 Methodology for evaluating site-specific blade throw risks

The Dutch Handbook provides a practical methodology for evaluating the site-specific blade throw risks for a wind farm, based on the results of the location-specific risk modelling described in Section 3.3.1. Because the methodology draws on conclusions derived from conservative assumptions and modelling of generic WTGs, it is suitable for conducting an initial risk assessment in situations where a specific WTG model has not yet been chosen [1]. Although the Dutch Handbook proposes some limits to the applicability of these conclusions, the results of the risk modelling suggest that they are valid for a wide range of modern WTGs regardless of the WTG parameters. DNV therefore considers that this methodology is appropriate for use in a high-level site-specific assessment of the blade throw risks for the Project, as presented here. DNV is not aware of any similar methodologies or guidelines for blade throw assessments that have been published in Australia.

The first step in performing a site-specific risk assessment based on this methodology is to determine the location-specific risks in the area surrounding the proposed WTGs, in accordance with the guidance given in the Dutch Handbook, whereby:

- the distance from the WTGs at which the location-specific risk is 10^{-5} per year or 1-in-100,000 (also called the 10^{-5} risk contour) is equal to half the rotor diameter
- the distance from the WTGs at which the location-specific risk is 10^{-6} per year or 1-in-1 million (also called the 10^{-6} risk contour) is equal to either the WTG tip height or the maximum throw distance for an entire blade under normal operating conditions, whichever is greater.

Once these distances have been established, the risks associated with specific locations, infrastructure, or activities in the vicinity of the wind farm can be evaluated and compared to the levels of risk that are considered acceptable in the relevant jurisdiction. Where information is available about the amount of time that people who are passing through the area are likely to spend in the vicinity of the wind farm, such as travellers on a road or rail network, the corresponding individual risk and societal risk can also be estimated based on the definitions given in Section 3.3.

Although the assessment presented here is aimed at evaluating the blade throw risks for the Project, it is noted that the methodology and risk levels given in the Dutch Handbook include the risks associated with a WTG tower collapsing or a rotor or nacelle falling from the tower.

4.2 Recommended blade throw risk limits

The Dutch Handbook also presents specific limits for the acceptable levels of blade throw risk at various types of infrastructure [1], as summarised in Table 8. The corresponding NREL risk classification for each blade throw risk limit identified in the Dutch Handbook, based on the definitions given in Table 7, is also shown in Table 8. In the Netherlands, these limits are imposed by national legislation (in the case of dwellings and other buildings and facilities) or are specified in policies applied by the relevant authority (in the case of roads).

DNV is not aware of any published guidance on the blade throw risk that would be considered acceptable in NSW, or any other Australian jurisdiction. In the absence of such guidance, the blade throw risks estimated for the Project have been compared to the risk limits given in Table 8 and the existing risks to people in the vicinity of the Project Area.

Table 8 Blade throw risk limits presented in the Dutch Handbook [1]

Type of building or infrastructure	Relevant measure of risk	Risk limit and corresponding NREL risk classification [12]
Dwellings and other sensitive buildings and facilities (schools, childcare facilities, hospitals)	Location-specific risk	10^{-6} per year (1-in-1 million) "Extremely remote" probability and "low" risk
Other buildings and facilities where large numbers of people may be present for most of the day	Location-specific risk	10^{-6} per year (1-in-1 million) "Extremely remote" probability and "low" risk
Buildings and facilities which are occupied by fewer people or for shorter periods of the day	Location-specific risk	10^{-5} per year (1-in-1 million) "Extremely remote" probability and "low" risk
National roads under the jurisdiction of the Dutch Ministry for Infrastructure and Water Management [1]	Individual risk	10^{-6} per person per year (1-in-1 million) "Extremely remote" probability and "low" risk
	Societal risk	2×10^{-3} persons per year (one death every 500 years) [2]

1. In the Netherlands, requirements for other types of roads (whether provincial, municipal, local, or private) are the responsibility of the local authority and there is no general guidance on the levels of blade throw risk that would be considered acceptable. However, the Dutch Handbook notes that the relevant authority may choose to apply the risk limits set by the Ministry for Infrastructure and Water Management for national roads [1].
2. The NREL risk classifications are only applicable for risks expressed as a likelihood or frequency per year, as in the case of a location-specific or individual risk.

4.3 Assessment of blade throw risks for the Project

DNV has conducted a high-level assessment of the site-specific risks for the Project, based on the methodology and risk levels presented in the Dutch Handbook.

Figure 1 shows the locations of nearby dwellings and other sensitive locations, roads, and neighbouring properties in relation to the Project Area and proposed WTG locations. Figure 1 also shows regions around the proposed WTG locations at distances equal to:

- 95 m, corresponding to half the rotor diameter and hence the distance at which the location-specific risk is 10^{-5} per year (1-in-100,000) based on the guidance in the Dutch Handbook
- 260 m, corresponding to the WTG tip height (which is greater than the expected maximum throw distance for an entire blade under normal operating conditions at the maximum rated rotor speed, as discussed in Section 3.3.3) and hence the distance at which the location-specific risk is 10^{-6} per year (1-in-1 million) based on the guidance in the Dutch Handbook
- 1,800 m, corresponding to the expected maximum theoretical blade throw distance for the proposed WTGs, as discussed in Section 3.2.2. The location-specific risk at this distance is expected to be in the order of 10^{-12} per year (1-in-1 trillion).

Distances between the proposed WTG locations and existing dwellings or other sensitive locations within 1,800 m of the proposed WTGs are given in Table 9.

Table 9 Dwellings and other sensitive locations within 1,800 m of the proposed WTG locations

Building ID [1]	Easting [2] [m]	Northing [2] [m]	Nearest WTG ID	Distance to nearest WTG [m]
17	*334195*	*6599732*	*T28*	*1,690*
270	*334904*	*6598857*	*T24*	*1,473*
277	*332736*	*6595809*	*T26*	*1,524*
302 [3]	*338378*	*6595428*	*T7*	*210*
310 [3]	*3337967*	*6595810*	*T26*	*1,312*

1. Host landholder and associated landholder dwellings are indicated by *underlined italic text*.
2. Coordinate system: MGA zone 56, GDA94.
3. Dwelling identified by the Proponent as vacant.

4.3.1 Blade throw risks at dwellings and other sensitive locations

Figure 1 and Table 9 show that there is one dwelling within 260 m of the proposed WTG locations. This dwelling (dwelling 302) is a host landholder dwelling and has been identified by the Proponent as currently vacant. However DNV notes that the location-specific risk at this dwelling may be greater than 10^{-6} per year (1-in-1 million) and therefore above the acceptable risk limit identified in the Dutch Handbook and shown in Table 8.

Should dwelling 302 remain uninhabited for the life of the Project, this dwelling would no longer be considered a sensitive location for the purpose of this assessment and the risk limit identified in the Dutch Handbook would not apply. However, if there is potential for the dwelling to be inhabited during the operating life of the Project, the conservative blade throw assessment presented here suggests that the location-specific risk of blade throw at this dwelling for the proposed WTG layout and dimensions may be unacceptably high. In the event that dwelling 302 has the potential to be inhabited during the life of the Project, DNV understands that detailed site-specific blade throw modelling that takes into account the wind regime at the Project Area and the intended WTG model (as described in the Dutch Handbook) will be undertaken during the detailed design phase to confirm the expected blade throw risks at this dwelling and hence determine if refinement of the layout or mitigation of the risk is required.

All other dwellings and sensitive locations are more than 1,300 m from the nearest proposed WTG location, which is 1,050 m beyond the expected maximum throw distance for an entire blade under normal operating conditions at the maximum rotor speed and 370 m beyond the expected maximum throw distance for a blade fragment under the same conditions (being 250 m and 930 m respectively, as discussed in Section 3.2.2). At a distance of 1,300 m from a proposed WTG, the risk of an unprotected person who remains at a fixed location continuously for a whole year being hit and killed by a blade or blade fragment thrown from the Project is expected to be significantly less than 10^{-6} per year (1-in-1 million), and is likely to be closer to 10^{-12} per year (1-in-1 trillion), which would be described as an "improbable" probability and "routine" risk using the NREL risk classification shown in Table 7. The location-specific blade throw risk decreases as the distance from the WTGs increases, becoming approximately 10^{-12} per year (1-in-1 trillion) at the maximum theoretical blade throw distance of 1,800 m and negligible at all locations beyond 1,800 m from the WTGs. Therefore, the location-specific risk at all dwellings and other sensitive locations in the vicinity of the Project Area that are understood to be inhabited is expected to be well below the acceptable risk limit of 10^{-6} per year (1-in-1 million) identified in the Dutch Handbook and shown in Table 8.

4.3.2 Blade throw risks at nearby properties

Figure 1 shows that there are some proposed WTG locations within half the rotor diameter, or 95 m, of the Project Area boundary and therefore within 95 m of neighbouring properties. As discussed in Section 3.3.3, the probability of a person who remains at a fixed location at a distance of 95 m from the proposed WTGs for a whole year being hit and killed by a blade or blade fragment thrown from the Project is expected to be 10^{-5} per year (1-in-100,000) or less. However, this probability does not consider the likelihood that a person will be present at a neighbouring property in a location where they are at risk of being hit by a blade or blade fragment at the time a blade throw incident occurs. For the potentially more realistic case of a person who spends the equivalent of one working day (8 hours) per year at a fixed location at a distance of 95 m from a WTG, the risk of being hit and killed by a blade or blade fragment is expected to be 10^{-8} (1-in-100 million). Therefore, the likely risk of blade throw for people on neighbouring properties is expected to be well below the annual risk of death for people working in agriculture in Australia, as discussed in Section 3.3.2, and would be described as an "extremely remote" to "improbable" probability and "low" to "routine" risk using the NREL risk classification shown in Table 7.

4.3.3 Blade throw risks on roads and nearby properties

Figure 1 shows that there are no roads located within half the rotor diameter, or 95 m, of the proposed WTG locations, which suggests that the probability of a person who remains at any fixed location on a neighbouring road for a whole year being hit and killed by a blade or blade fragment thrown from the Project is less than 10^{-5} per year (1-in-100,000). This is lower than the annual risk of death on Australian roads, as discussed in Section 3.3.2, and would be described as an "extremely remote" probability and "low" risk using the NREL risk classification shown in Table 7. Additionally, this probability does not consider the likelihood that a person will be present on the road in a location where they are at risk of being hit by a blade or blade fragment at the time a blade throw incident occurs.

To provide a better understanding of the likely risks for road users in the vicinity of the Project Area, DNV has estimated the individual risk for the section of Green Valley Road passing within 1,800 m of proposed WTG locations as shown in Figure 1. Although Green Valley Road is an unsealed single-lane road, it was chosen for this review as it is the only road classified as a "standard road" with WTGs proposed within 260 m of the road corridor. The only other "standard road" located within 1,800 m of the proposed WTG locations is the New England Highway, for which the nearest WTG location is over 1,000 m away (WTG T11). Table 10 shows that the number of WTGs in close proximity to the road corridor, considering the assessment distances described in Section 4.3, is greater for Green Valley Road than the New England Highway. Therefore, despite the low traffic volumes expected on Green Valley Road, DNV considers that the blade throw risks for this section of road will represent the worst-case risk scenario for all road users in the vicinity of the Project Area.

Table 10 Number of WTGs within specified distances of Green Valley Road and the New England Highway

Distance	Number of WTGs within specified distance of road corridor	
	Green Valley Road	New England Highway
95 m (half the rotor diameter)	None	None
260 m (WTG tip height)	Two (T26, T27)	None
1,800 m (maximum theoretical blade throw distance)	Three (T26, T27, T28)	Four (T1, T10, T11, T21)

The individual risk of blade throw for people travelling on Green Valley Road was evaluated according to the steps outlined in Figure 2, based on the following assumptions:

- The location-specific risk at all points in the region between 95 m and 260 m from the WTGs is assumed to be 10^{-5} per year (1-in-100,000). As shown in Table 11, this is equal to the maximum value for the location-specific risk throughout that region. Similarly, the location-specific risk at all points in the region between 260 m and 1,800 m from the WTGs is assumed to be 10^{-6} per year (1-in-1 million). These are conservative assumptions, as the actual value of the location-specific risk in these regions will decrease as the distance from the WTGs increases, as indicated in Table 11.
- The average vehicle speed along that section of road is assumed to be 40 km per hour, based on the apparent road conditions. A lower vehicle speed is a conservative assumption, as it increases the amount of time that each person will spend on the road in the vicinity of the WTGs.
- On average, each person is assumed to make two trips per day (or 730 trips per year) along that section of road. A larger number of trips is a conservative assumption, as it increases the amount of time that each person will spend on the road in the vicinity of the WTGs in a year.
- Every impact from a blade or blade fragment is assumed to be fatal. This is a conservative assumption, as the actual probability of an impact being fatal will depend on a number of factors, including the size of the blade fragment, its speed at the time of impact, and the extent to which the person is protected by their vehicle [3]. Since the location-specific risks shown in Table 11 also assume that every impact is fatal, this assumption allows those values to be used directly in the calculation of the individual risk as outlined in Figure 2.

Table 11 Location-specific risk assumptions used to estimate the individual and societal blade throw risks for people travelling on Green Valley Road

Distance from WTGs	Location-specific blade throw risk in this region (decreases as distance from WTGs increases)	Assumption used to estimate risk to road users
Less than 95 m	Greater than 10^{-5} per year (1-in-100,000)	Not applicable – no roads located within this distance
95 m to 260 m	Varies from 10^{-5} per year (1-in-100,000) at 95 m to 10^{-6} per year (1-in-1 million) at 260 m	10^{-5} per year (1-in-100,000) throughout entire region
260 m to 1,800 m	Varies from 10^{-6} per year (1-in-1 million) at 260 m to approximately 10^{-12} per year (1-in-1 trillion) at 1,800 m	10^{-6} per year (1-in-1 million) throughout entire region

According to this analysis, the individual risk along Green Valley Road for death caused by a blade throw incident is 2.85 x 10^{-8} per person per year (1-in-35 million). This is approximately 35 times less than the limit identified as acceptable in the Dutch Handbook and shown in Table 8 (10^{-6} per person per year or 1-in-1 million), even with conservative assumptions made for the road usage and location-specific risk in each region as outlined above, and would be described as an "extremely remote" probability and "routine" risk using the NREL risk classification shown in Table 7.

Information about traffic volumes on Green Valley Road is not publicly available. However, traffic volumes on the nearby New England Highway (a sealed two-lane road that forms the main inland route between Sydney and Brisbane) have been estimated at approximately 13,000 vehicles per day [19]. Taking this as the maximum possible upper limit for traffic volumes on Green Valley Road, and assuming an average of two people travelling in each vehicle, DNV has evaluated the potential societal risk of death caused by a blade throw incident according to the steps outlined in Figure 2. For a traffic volume of 13,000 vehicles per day, the societal risk on Green Valley Road is 3.71 x 10^{-4} deaths per year, or one death every 2,700 years, which is approximately 5 times less than the limit identified as acceptable in the Dutch Handbook and shown in Table 8 (2 x 10^{-3} deaths per year, or one death every 500 years). For a potentially more realistic traffic volume of 2,000 vehicles per day, estimated based on the apparent road conditions and equal to twice the maximum traffic volume for a road to be defined as a "low volume road" [20], the societal risk on Green Valley Road is 5.71 x 10^{-5} deaths per year or one death every 17,500 years. This is approximately 35 times less than the limit identified as acceptable in the Dutch Handbook. Considering the apparent road conditions for Green Valley Road, the actual traffic volume, and therefore the actual societal risk, is expected to be much lower than estimated here. The societal risk of blade throw for other roads in the vicinity of the Project Area is expected to be lower again, due to the greater distances from the proposed WTG locations.

4.3.4 Summary of blade throw risks for the Project

The blade throw risks evaluated for the Project as described in Sections 4.3.1 and 4.3.3 are summarised and compared to the risk limits identified in the Dutch Handbook and existing risks in Table 12. The corresponding NREL risk classifications for these risks, as defined in Table 7, are also shown in Table 12. As discussed in Section 3.3.2, the NREL considers "low" and "routine" levels of risk to be acceptable.

Given the conservative methodology and assumptions used throughout this high-level risk assessment, it is expected that the blade throw risks presented here are also highly conservative. In most cases, these risks are already very low, and well below the risk limits considered acceptable in other jurisdictions and existing risks.

However, for one host landholder dwelling, which has been identified by the Proponent as currently vacant, the high-level risk assessment presented here suggests that the location-specific risk may be above the risk limit considered acceptable in other jurisdictions. Should the dwelling remain uninhabited, the risk limit considered in this assessment will not be applicable to that dwelling. If the dwelling has the potential to be inhabited during the life of the Project, detailed site-specific blade throw modelling can be undertaken during the detailed design phase to confirm the expected blade throw risks and determine if refinements to the Project design or operation are required to mitigate those risks.

Table 12 Summary of blade throw risks evaluated for the Project and comparison to relevant risk limits and existing or comparable risks

Risk category	Blade throw risk evaluated for the Project and corresponding NREL risk classification [12]	Blade throw risk limit presented in the Dutch Handbook [1]	Existing risk or comparable risk
At dwellings and other sensitive locations such as schools and childcare facilities			
Location-specific risk (for an unprotected person remaining at that location for a whole year)	Significantly less than 10^{-6} per year (1-in-1 million) for all dwellings and other sensitive locations that are understood to be inhabited [1] "Improbable" probability and "routine" risk	10^{-6} per year (1-in-1 million)	-
At neighbouring properties			
Location-specific risk (for an unprotected person remaining at a fixed location for a whole year)	Less than 10^{-6} per year (1-in-1 million) "Extremely remote" probability and "low" risk	-	Risk of death for people working in agriculture in Australia: 1.5×10^{-4} per year (1-in-6,667)
For road users on Green Valley Road (representing the worst-case scenario for all road users in the vicinity of the Project Area)			
Individual risk (for a typical person travelling on that section of road)	2.85×10^{-8} per person per year (1-in-35 million) "Improbable" probability and "routine" risk	10^{-6} per person per year (1-in-1 million)	Risk of death on all Australian roads per head of population: 4.5×10^{-5} per year (1-in-22,222)
Societal risk (total number of people at risk)	5.71×10^{-5} persons per year (one death every 17,500 years), assuming a conservative traffic volume of 2,000 vehicles per day [2]	2×10^{-3} persons per year (one death every 500 years)	-

1. The location-specific risk at one host landholder dwelling that has been identified by the Proponent as currently vacant (dwelling 302) may be greater than 10^{-6} per year (1-in-1 million), and therefore above the blade throw risk limit presented in the Dutch Handbook.
2. The NREL risk classifications are only applicable for risks expressed as a likelihood or frequency per year, as in the case of a location-specific or individual risk.

5 CONCLUSIONS

WTG blade throw incidents are relatively rare events. Compliance with international standards, implementation of high-quality maintenance programs, and continual improvements in WTG design and materials mean that blade failure is relatively rare for modern WTGs and does not typically result in the detachment of blades or blade fragments. The likelihood of a blade throw incident causing injury to a person in the vicinity of a wind farm depends on the probability of a WTG blade failing, the probability of the blade or part of the blade detaching as a result of that failure, and the probability of a person being struck by the thrown object, all of which are very low.

Based on a conservative assessment methodology and assumptions, DNV has evaluated the risks of death caused by a blade throw incident at dwellings, roads, and neighbouring properties in the vicinity of the Project Area. The results show that, in most cases, the potential risks are at least 35 times less than the blade throw risks considered acceptable in other jurisdictions, and considerably lower than existing risks.

For one host landholder dwelling (dwelling 302), which has been identified by the Proponent as currently vacant, the high-level assessment presented here suggests that the blade throw risk may be above the limit considered acceptable in other jurisdictions. Should the dwelling remain uninhabited throughout the operating life of the Project, the risk limit will not be applicable to that dwelling. If the dwelling has the potential to be inhabited during the life of the Project, detailed site-specific blade throw modelling can be undertaken during the detailed design phase to confirm the expected blade throw risks and determine if refinements to the Project design or operation are required to mitigate those risks.

At all other dwellings, and on neighbouring properties and roads in the vicinity of the Project Area, the risk of injury or property damage associated with blade throw for the proposed WTG layout and parameters is considered very low.

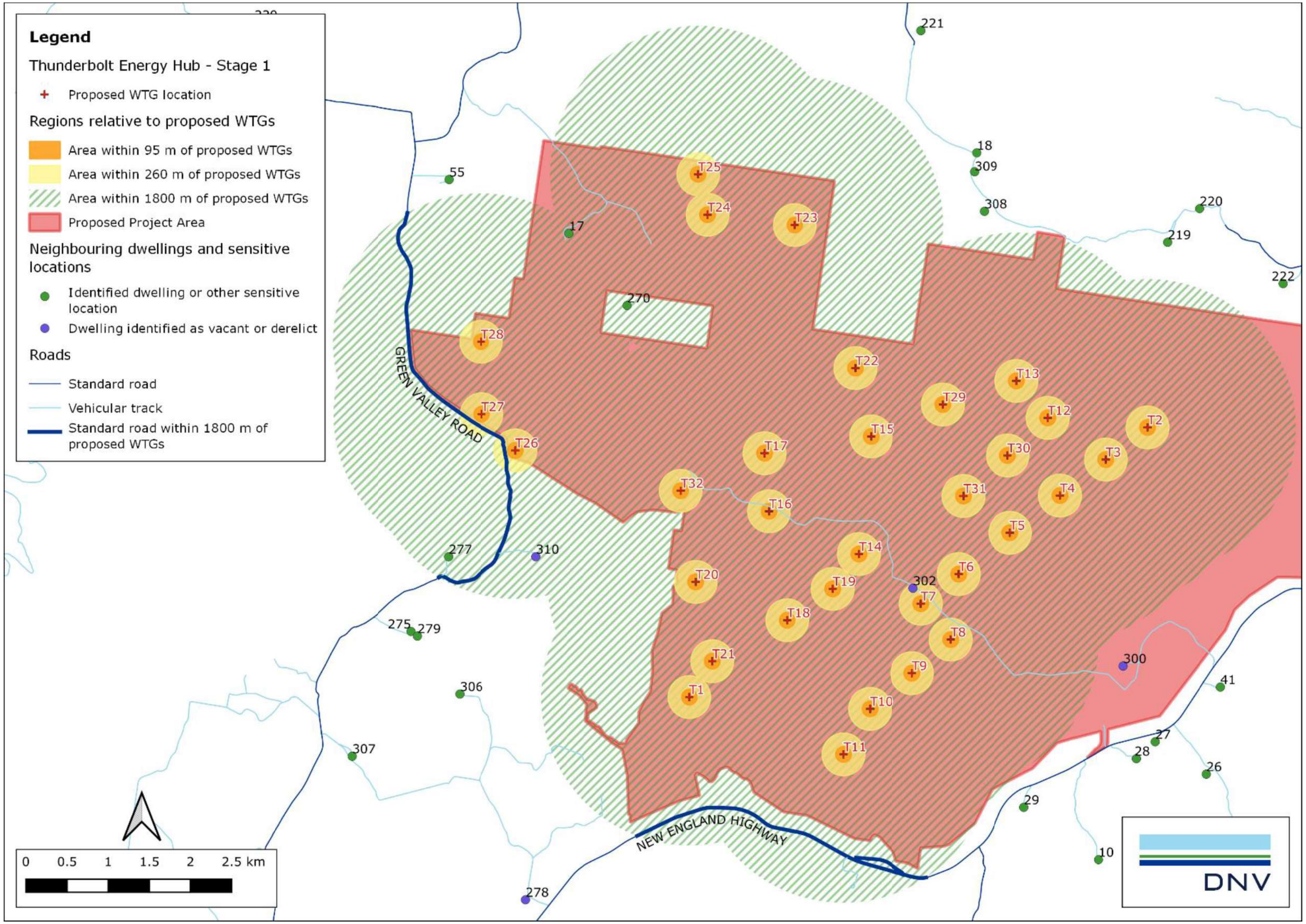

Figure 1 Locations of nearby dwellings and other sensitive locations, roads, and properties in relation to the proposed Project Area

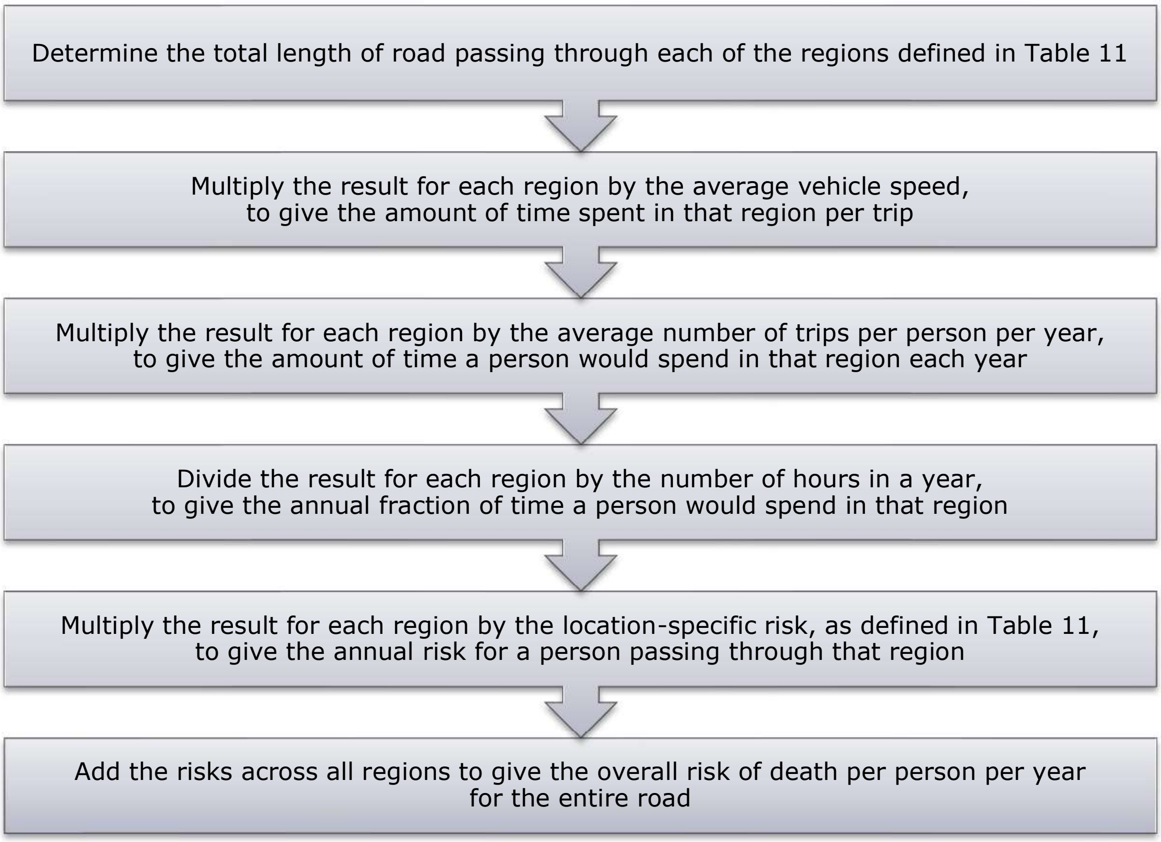

Figure 2 Steps involved in estimating the individual risk of death caused by blade throw from the Project for people travelling on Green Valley Road

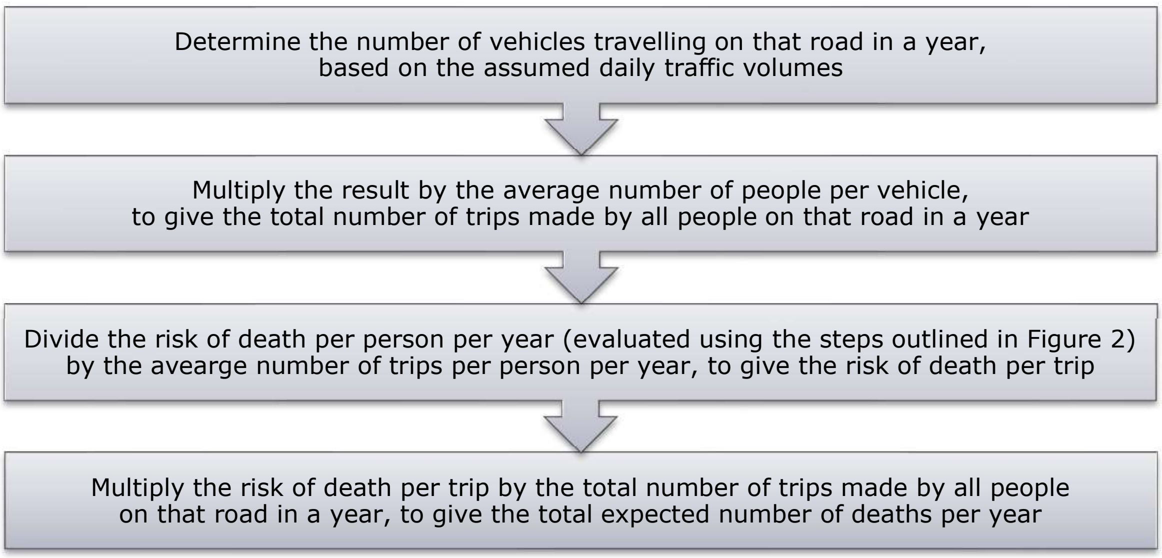

Figure 3 Steps involved in estimating the societal risk of death caused by blade throw from the Project for people travelling on Green Valley Road

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