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Wimmera Plains Energy Facility

Blade Throw Assessment

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Disclaimer

Executive Summary

BayWa r.e. wishes to connect a new 312 MW Wind Farm in Wimmera, Victoria. The project known as the Wimmera Plains Energy Facility is located approximately 10 km northeast of Horsham and is proposed to be connected to the 220 kV transmission network.

The project is expected to be operational by 2032. Currently, the project is in the development stage and consultation & planning with the Victorian Department of Transport & Planning has commenced.

The site has an existing planning permit for the use and development of a wind energy facility. It is understood that the proponent seeks to amend the existing planning permit under Section 72 of the Planning and Environment Act to remove Condition 1b, which requires that no turbine is located within 225 metres of a boundary of a road.

BayWa r.e. has engaged Environmental Resource Management (ERM) as their consultant to manage the planning permit amendment for the project. ERM have engaged Middleton Group Engineering (MGE) to conduct the Blade Throw study to assess the level of risk relevant to the project in support of removal of Condition 1b of the existing planning permit.

This Blade Throw study concluded that the likelihood of a fatal blade throw event at the project site is estimated to be once in 29.97 million years, which is comfortably within the bounds of what is considered to be broadly acceptable.

This estimate was based on the characterisation of the following:

- The likelihood of a blade failure, based on existing Australian wind turbines and reported blade failure events in Australia.
- The impact of such a blade failure.
- The likelihood that the impact extent of such a blade failure would be occupied.
- The likelihood that the blade failure impacts on an occupier within the impact extent.

The low likelihood of adverse outcome is due to the low incidence of failure and low rates of occupation in the vicinity of the WTGs.

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1 Abbreviations/Definitions

Table 1: Abbreviations and Definitions

Abbreviation / definition	Explanation
DPE	Department of Planning and the Environment
HIPAP4	Hazardous Industry Planning Advisory Paper No 4
km	Kilometre
km/h	Kilometres per hour
m	metre
MGE	Middleton Group Engineering
MW	Mega-Watt
MWh	Mega-Watt-hour
NSW	New South Wales
P(...)	Probability
QLD	Queensland
SEARs	Secretary's Environmental Assessment Requirements
VIC	Victoria
WTG	Wind Turbine Generator
WPEF; the Project	Wimmera Plains Energy Facility

2 Background

2.1 Defining Blade Throw

Blade throw is the instance where a turbine loses all or part of a turbine blade. Wind Turbines often suffer damage; however, this damage does not always result in blade throw. In their analysis, Branner and Gharidian (Branner & Ghadirian, 2014) identify four levels of blade damage:

0. Observation, no harm.
1. Damage to be repaired at an opportunity.
2. Damage must be repaired as soon as possible.
3. Serious damage, the turbine is stopped.

It is noted that blade defects, examples of which are described by Branner & Ghadirian (Branner & Ghadirian, 2014) – whether by manufacturing defect or by wear and tear, are not included in this assessment. This assessment focusses on catastrophic failure of a blade – that is, where they fall under the level 3 subset of damage.

Blade defect and/or degradation events are relatively commonplace in wind farms around the world, with Branner and Ghadirian (Branner & Ghadirian, 2014) identifying a mean outage per WTG due to blade or rotor issues between 9 and 62 hours per year, and a mean outage time per failure of between 0.9 h and 17.2 days. The majority of these events are dealt with in the course of the WTG's maintenance programme and pose no risk to human life. Even where serious damage occurs, WTG control systems will typically detect the failure and shutdown the WTG preventing a catastrophic failure, i.e., a Blade Throw event (MMI Engineering Ltd, 2013).

For the purposes of this study, Blade Throw is defined as a catastrophic blade failure, which is divided into two types of events: Blade Drop and Fragmentation.

- **Blade drop** – Blade Drop is defined as where the whole blade or the majority of the blade detaches from the WTG's hub.
- **Blade fragmentation** – Fragmentation is defined as an event where a smaller blade fragment such as a blade tip or part of the shell detaches from the blade.

The distinction between these two instances impacts the likelihood of blade throw as it is a determining factor of the distance thrown and the threat to human life.

Within Australia there has been five (5) instances of blade throw within Australia as seen in Table 2. The implications of these incidents on this study will be further investigated in section 5.1.

Table 2: Blade throw instances within Australia.

Wind Farm	Date	Classification
Windy Hill WF (QLD)	July 2005	General Failure: Unsure – Assume fragmentation.
Wonthaggi WF (VIC)	March 2012	General Failure: Fragmentation.
Lal Lal WF (VIC)	September 2019	Lightning Failure: Blade drop.
Bald Hills WF (VIC)	June 2020	General Failure: Assume fragmentation.
Dundonnell WF (VIC)	October 2020	General Failure: Blade drop.

2.2 Causes of Blade Throw

Blade throw can occur for a vast variety of reasons. The turbine's age is a contributing factor, as age leads to wear and increases the likelihood of damage. However, damage from age is unlikely to result in as catastrophic a consequence as blade throw. Additionally, extreme weather conditions such as lighting events, high wind speeds and natural disasters can cause damage which results in blade throw. Other causes include:

- Fatigue failure – cracking of the turbine rotor or structure due to high levels of cyclical stress.
- Installation issues – turbine installation defects causing blade throw.
- Manufacturing issues – turbine manufacturing defects causing blade throw.
- Wind turbine overspeed – a mechanical failure resulting in the turbine rotor spinning out of control and breaking. This is more likely to happen primarily for previously used stall-regulated wind turbines which run at constant speed unlike current pitch regulated turbines.

The likelihood of these contributing factors occurring and leading to a blade throw event will be considered within Middleton Group's blade throw assessment. The comparison between the domestic and international frequency and the relationship between frequency and the above contributing factors is further discussed in section 5.1.

3 Purpose and Scope

3.1 Project Background

The Wimmera Plains Energy Facility is located approximately 10 km north of the township boundary of Horsham in Victoria. The project comprises of 52 Wind Turbine Generators (WTGs), with a tip height of 247 m and a rotor diameter of 180 m.

The electrical ancillary infrastructure includes a battery energy storage system (BESS), main substation, collector station, underground cables and/or overhead powerlines and an overhead transmission line. The other ancillary infrastructure includes internal access tracks and drainage, O&M facilities including carpark, meteorological masts, with no additional infrastructure. The wind farm including BESS and other infrastructure is known collectively as the Wimmera Plains Energy Facility.

ERM has engaged Middleton Group Engineering (MGE) to undertake a blade throw desktop study for inclusion within the planning permit amendment application.

3.2 Requirements

The Department of Transport and Planning Victoria, under the Environment Effects Act 1978 requires assessment of the potential environmental impacts of a proposed development. Environmental impacts include harm to human health as it is considered an amenity impact under the Environment Protection Act 2017. The Victorian Planning Provisions ensure human health is a consideration in planning decisions.

Thus, the purpose of this study is to estimate risk to human life associated with a blade failure event, based on likelihood of a human occupying space within the potential impact zone and the likelihood of blade failure.

3.3 Mitigation Factors

Modern wind turbines are typically designed and certified by leading manufacturers and certified according to the International Standard IEC 61400-1 which ensures their structural integrity and safe operation throughout the turbine's lifespan.

To safeguard against potential risks relating to equipment selection, installation and maintenance issues, the following conceptual management measure options should be considered:

- Ensure all WTG are designed and certified to achieve relevant Australian and international safety standards (IEC 61400-23 and IEC 61400-24).
- Ensure all WTG are equipped with suitable measurement instrumentation that can detect and then respond to any rotor blade imbalances and shut down WTG if required.
- Ensure all WTGs will be suitably managed and maintained according to industry best-practice standards and are subject to a regular and comprehensive maintenance and servicing regime.

Based on these design and manufacturing standards, blade throw incidents should be infrequent in modern wind turbines. Nonetheless, given the potential consequences of such incidents, it remains crucial to acknowledge and assess the associated risks. The wind energy industry has gained insights into the likelihood, dynamics, and risks of blade throw through a blend of historical incident investigations and theoretical research.

4 Methodology

This assessment assesses two risks; the risk of blade throw to nearby dwellings and the risk of fatality by blade throw to people within the surrounding land. The following, high-level methodology applied is:

1. Assess the likelihood of blade failure based on domestic WTG operation statistics.
2. Identify the radii of impact, and the likelihood of impact within those respective radii.
3. Determine the likelihood of occupation by examining the average land usages surrounding each turbine for a representative wind turbine installed in the Wimmera Plains Energy Facility.
4. Determine the probability of the dwelling(s) within the radius of a WTG being struck by a blade thrown from that WTG.
5. Obtain the probability of fatality due to blade failure for a representative wind turbine installed in the Wimmera Plains Energy Facility. This considers project layout specifics such as number and location of dwellings and public roads.
6. Find the overall probability of both dwelling impact and fatality due to blade failure by multiplication of the probability for a representative wind turbine in the Wimmera plains Energy Facility by the total number of wind turbines in the Project.
7. Assess probability of fatality and probability of impact to the dwelling(s) against broadly accepted risk criteria.

4.1 Probability Equation

The probability of a fatality P(fatality) is described in the following equation:

$$P(fatality) = P(Blade\ Drop) \times P(Blade\ Drop\ on\ Particular\ Location) \times P(Blade\ Drop\ Area\ Inhabited) + P(Fragmentation) \times P(Fragmentation\ reaching\ Particular\ Location) \times P(Fragmentation\ Area\ Inhabited)$$

The probability of dwelling impact uses the same equation but negates the likelihood that the area is inhabited through the assumption of a 100% occupancy rate. Based on the above, it is possible to assess whether both the likelihood of injury/fatality and risk to residents falls within accepted community standards. Section 6 expands on the calculation methodology for each of the inputs of the equations.

4.2 Determining Probability Values

Various approaches have been employed to assess the risk associated with WTG blade throw around the world, based on a mix of empirical and kinematic models (e.g. [2] [3] [4] [6]). The methodology used here has been developed using data from these various models.

The methodology to identify the inputs to the *P(fatality)* equation for a *representative* wind turbine considers the following four factors:

- Likelihood of blade failure.
- Area of impact in the case of blade failure.
- Likelihood of the impact area being occupied.
- Likelihood of person within the impact area to be hit by blade fragment.

Likelihood of Blade Failure is developed by the following steps:

- Identify the number of operating years of WTGs in Australia.
- Identify and classify the number of blade failures in Australia.
    - Classification is based on whether blade drop is observed or whether there is fragmentation.

Impact Area is found by identifying the radii of impact for blade fragmentation and blade drop based on the kinematic and empirical models.

Likelihood that the Impact Area is Occupied is developed through conservative estimates of farming practices, traffic data, dwelling, and shed occupancy rates, and wind farm maintenance practice.

Likelihood that a person within the Impact Area is hit is found by combination of:

- For an area within 150 m to 300 m of the WTG (based on Rogers et al.'s kinematic model [6]), this is taken as the likelihood of blade drop plus the likelihood of blade fragmentation.
- For an area within 400 m to 800 m of the WTG (based on Rogers et al.'s kinematic model [6]), this is taken as the likelihood of blade fragmentation.

4.3 Risk Assessment Criterion

Risk is assessed as a combination of likelihood and consequence. Where a hazard has fatal consequences, such as WTG blade throw, the likelihood must be extremely low for the residual risk to be considered acceptable.

The British Health & Safety Executive identify that the boundary between "broadly acceptable" and "tolerable" risks is generally taken as a 1 in one million years fatality. The boundary between "tolerable" and "unacceptable" is generally taken for the public at large as a 1 in 10,000 years fatality (Health & Safety Executive, 2001), on the proviso that there is a broader benefit to society in accepting this higher risk.

For the purpose of this assessment, the relevant risk criterion which Wimmera Plains Energy Facility will need to pass is the 1-million-year return period due to limited information on Victorian risk criteria for residential areas, which will be in the form of dwellings.

5 Blade Throw Parameters

The probability of a fatality due to blade throw is modelled by assessing the likelihood that part of the blade will be thrown and the likelihood that a person will be within the impacted area. The following sections aim to justify the values used by Middleton Group for both blade throw and fragmentation frequency and the relevant impact radii.

5.1 Domestic Blade Throw Frequency

To gain perspective on the severity of the risk it is important to quantify the frequency of blade throw within Australia. Blade failure is inclusive of all blade damage resulting in failure with the most catastrophic of these being blade throw. Blade failures are generally not publicised by wind farm owners and WTG manufacturers; however, catastrophic failures such as blade throw events are mostly reported in the media, as WTGs tend to be prominently placed in the landscape.

Research by Brouwer et al. (Brouwer, Al-Jibouri, Cárdenas, & Halman, 2018) demonstrates that blade failure events have tended to reduce over time despite the rapid increase in the number of WTGs, as shown in Figure 1. This is owing to "improvements in wind turbine safety over time".

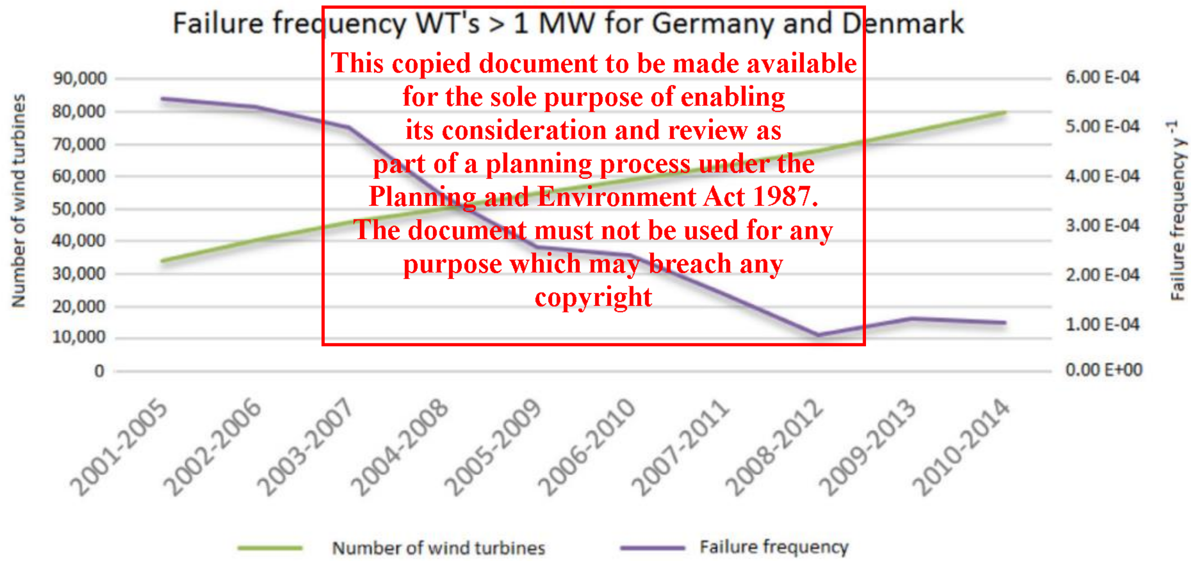

Figure 1: Estimated failure frequencies of wind turbines of 1 MW and above based on Germany and Denmark statistics. [10]

As demonstrated in Figure 1, the likelihood of blade throw is higher in older turbines, because of both manufacturing defects and age. In comparison to many other countries, most turbines within Australia are new, meaning that incidents of blade throw are less common. Additionally, as Wimmera Plains Energy Facility is a domestic project, it is going to be subject to the same weather conditions that preexisting Australian wind farms experience. As such, Middleton Group will be using Australian statistics for their assessment of blade throw likelihood because are they are of greater relevance to the Project than international data.

Five catastrophic blade failures have been identified in Australia and are assumed to represent Blade Throw events. These are described and classified in Table 3. It is noted that there is very little detail on the incidents in the public domain. Thus, details such as root cause analyses, projectile/debris scatter zones, and failure modes are not available. However, there are some broad data to suggest that manufacturing defects and lightning are two key causes of failure. There have been no injuries or fatalities associated with these events.

Of the failure events identified in Table 3, two failures are described as "blade drop", while the remaining three events are classified as "fragmentation".

In addition to these Blade Throw events, MGE are aware of several other catastrophic WTG failures, however, these failures did not constitute Blade Throw, and are beyond the scope of the current study.

For the purposes of this study, it is assumed that each of the events had the potential to be a life-threatening event. It is noted that in the case of the Wonthaggi Wind Farm blade failure event, reports describe debris, in the form of foam packing, being strewn across fields in the vicinity of the affected WTG. While details are scant, at face value the impact potential (that is, the potential to cause death or serious injury) for foam packing appears to be less than for fragments of a blade shell.

Table 3: Blade Failures in Australia

Event	Date	Description	Classification	Source
Windy Hill WF (QLD)	July 2005	Blade "sheared off" from wind turbine.	General Failure: Unsure – Assume fragmentation.	Herald Sun, 29 July 2005.
Wonthaggi WF (VIC)	March 2012	Blade cracked. Fibreglass delaminated. Blade fill strewn around vicinity of WTG.	General Failure: Fragmentation.	Wonthaggi Wind Farm – Wikipedia Various media reports.
Lal Lal WF (VIC)	September 2019	Blade broke and fell to the ground. Prior to incident, there was severe weather including lightning.	Lightning Failure: Blade drop.	Lal Lal Wind Farms Press Release: 23 September 2019
Bald Hills WF (VIC)	June 2020	No reliable details on cause.	General Failure: Assume fragmentation.	Turbine Trouble For Bald Hills Wind Farm – South Gippsland Sentinel-Times
Dundonnell WF (VIC)	October 2020	A single blade separated from the hub of a turbine and fell to the ground. Soon after mechanical completion.	General Failure: Blade drop.	Tilt Press Release: 6 October 2020 Dundonnell wind farm stops production after blade falls off turbine (wpengine.com)

The implications of this data on the inputs to the study will be further discussed in section 6.1.

5.2 Blade Throw Impact Radius

Two impact radii are considered – a 300 m radius to account for blade drop events and an 800 m radius to account for fragmentation. The calculation and justification of these values is found in sections 5.2.1 and 5.2.2.

5.2.1 Calculation of Impact Radii – Blade Drop

The values used for MGE's study are based on Rogers et al's (Rogers, Slegers, & Costello, 2012) simplified point-mass blade fragment model for maximum throwing distance that assumes a flat surface. The maximum blade throwing distance *D* is a function of tip velocity v_T, the sine and cosine of the launch angle θ_T, denoted as $s_{\theta T}$ and $c_{\theta T}$, gravitational acceleration, *g*, the hub height, *h*, and the rotor radius, *R*.

Thus, the maximum blade throwing distance is given as:

$$D = \frac{v_T^2 s_{\theta_T} c_{\theta_T} \pm v_T^2 \sqrt{v_{\theta_T}^2 c_{\theta_T}^2 + 2\frac{g}{v_T^2}(h - R c_{\theta_T}) c_{\theta_T}^2}}{g}$$

The frame of reference is provided in Figure 2 and results are plotted in Figure 3.

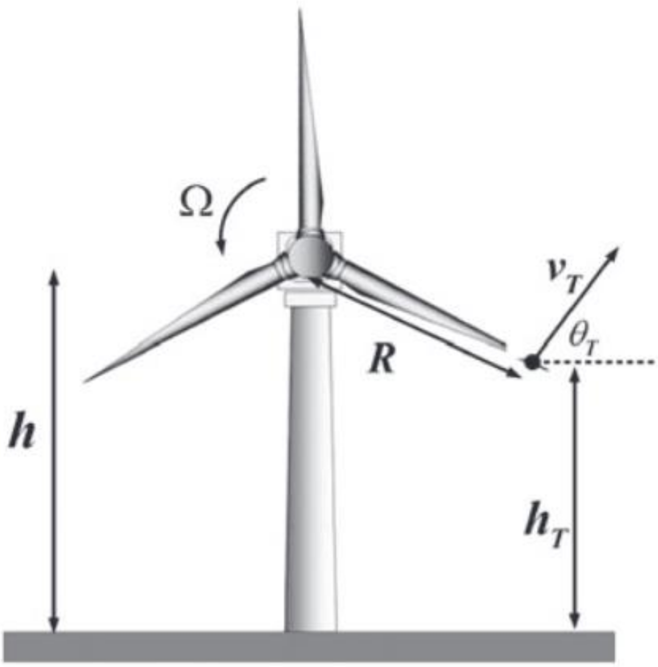

Figure 2: Frame of reference. Diagram from Rogers et al. [6].

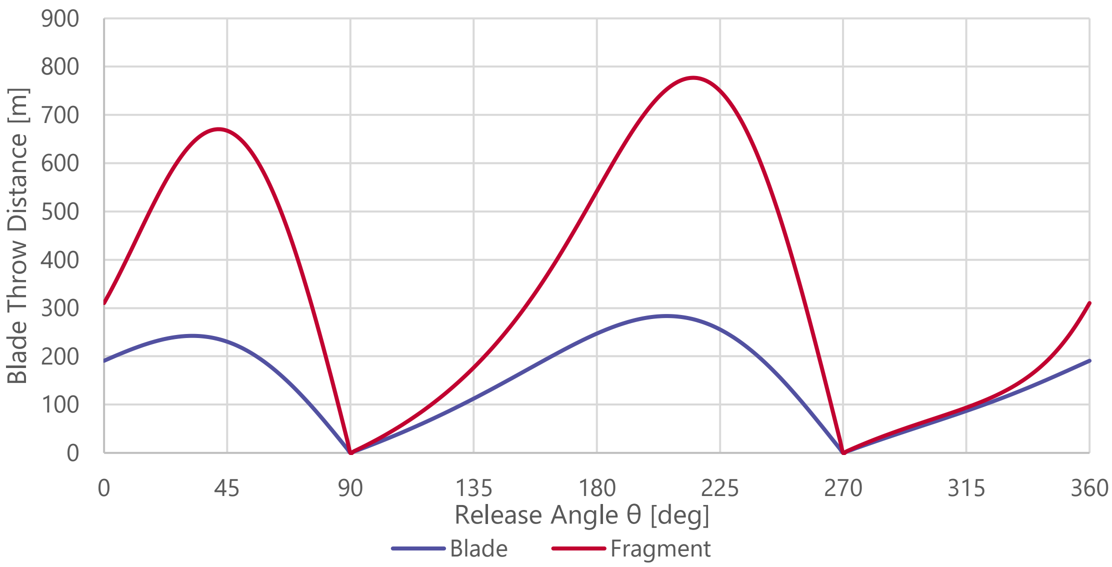

Figure 3: Maximum blade throw distance based on Rogers et al.'s kinematic model assuming a 75 m/s release velocity for the fragment, a 170 m hub height, and a 172 m rotor. The blade scenario is based on a 37.5 m/s release velocity and the effective radius being halfway along the blade.

Various sources provide a wide range of impact radii. For example, Braam & Rademakers (Braam & Rademakers, 2004) provide a commentary on the Dutch "Handbook Risk Assessment of Wind Turbines", which assessed 200 severe incidents that occurred over 43,000 WTG years in Germany, Denmark, and Holland until 2002 with WTGs having nameplate capacities ranging between 500 kW and 2 MW. Of those 200 incidents, 62 were relevant to the assessment of safety of nearby objects. Based on these data, the handbook identified "maximum throwing distances of a blade during overspeed" varying between 300 m and 400 m. Interestingly, the kinematic model developed by Rogers et al. (Rogers, Slegers, & Costello, 2012) highlights that "maximum throwing distance" is most dependent on the tip speed, rather than on the size of the WTG, suggesting that older studies such as Braam & Rademakers' (Braam & Rademakers, 2004) empirical assessment may have some level of applicability for much larger WTGs.

Alternatively, Persimia conducted Monte Carlo simulations using a WTG with rotor diameter of 158 m. The maximum simulated blade fragment throw distance was less than 475 m (Persimia, 2020).

While the empirical data is useful for sanity-checking the empirical models, there is simply insufficient empirical blade throw data on which to base a blade throw assessment. As such it would seem prudent to base modelling on Monte Carlo simulations.

Further, there is some conjecture regarding whether it is more or less conservative to model a larger area. In assuming a larger potential area of impact, the likelihood of impacting a person within that area of impact is reduced, assuming a homogenous distribution. However, by assuming a larger potentially impacted area, a greater number of people may be impacted. As such the conservatism is entirely dependent on the specific scenario modelled.

For the blade drop analysis, the impact area around a WTG is divided into two regions – a 50 m radius, and an outer area with radius of 300 m. It is assumed that while the level of human activity within these two areas differs, the likelihood of a blade dropping in a particular location within that 300 m radius is homogenous across the area.

Table 4: Characterisation of blade drop impact area.

Area	Radius [m]	Distribution	Area [m2]
1	50	2.8%	7,854
2	300	97.2%	274,890

5.2.2 Calculation of Impact Radii – Blade Fragmentation

The characterisation of the likelihood of a blade fragment landing in a particular location is assessed based on a Monte Carlo simulation. Persimia (Persimia, 2020), in their blade throw assessment for the Grove Park Wind Farm, used a Monte Carlo simulation to derive a probability density function, with the likelihood of a blade landing in a specific location generally decreasing as that location is farther from the WTG (Persimia, 2020). GE's Cypress platform with a 158 m rotor diameter was used as the candidate WTG; the result is shown in Figure 4. This study provides a helpful reference point as it is a recent-model utility-scale WTG. Figure 4, using 12.5 m distance bins, shows that within 50 m of a WTG, the likelihood of impact is approximately 75% higher for the 50 m to 200 m range. Beyond 200 m there is a steady decline in likelihood of impact.

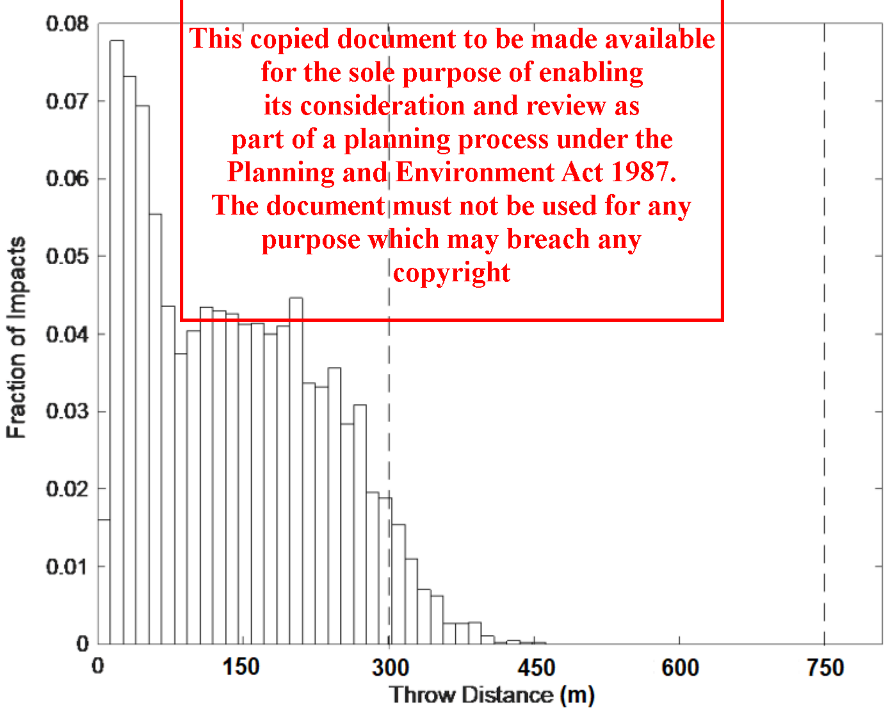

Figure 4: Histogram of blade fragment throw distance based on Monte Carlo simulations [4]. Throw distances converted from feet to metres.

Based on Figure 4, the impact area is broken up into four concentric circles and the respective likelihood of occurrence, as described in Table 5 for the blade fragment analysis, and Table 4 for the blade drop analysis, to give distance weightings. Examples of the concentric circles are shown in Figure 5. Table 5 is derived from the work of Persimia (Persimia, 2020), with some minor deviation to reflect the up to 800 m extent of the impact zone.

Table 5: Characterisation of fragmentation impact area.

Area	Radius Limits [m]	Distance weighting: Probability of Fragment within Area	Area [m2]
1	0 - 50	25%	7,854
2	50 - 275	65%	229,729
3	275 - 400	9.9%	265,072
4	400 - 800	0.1%	1,507,964

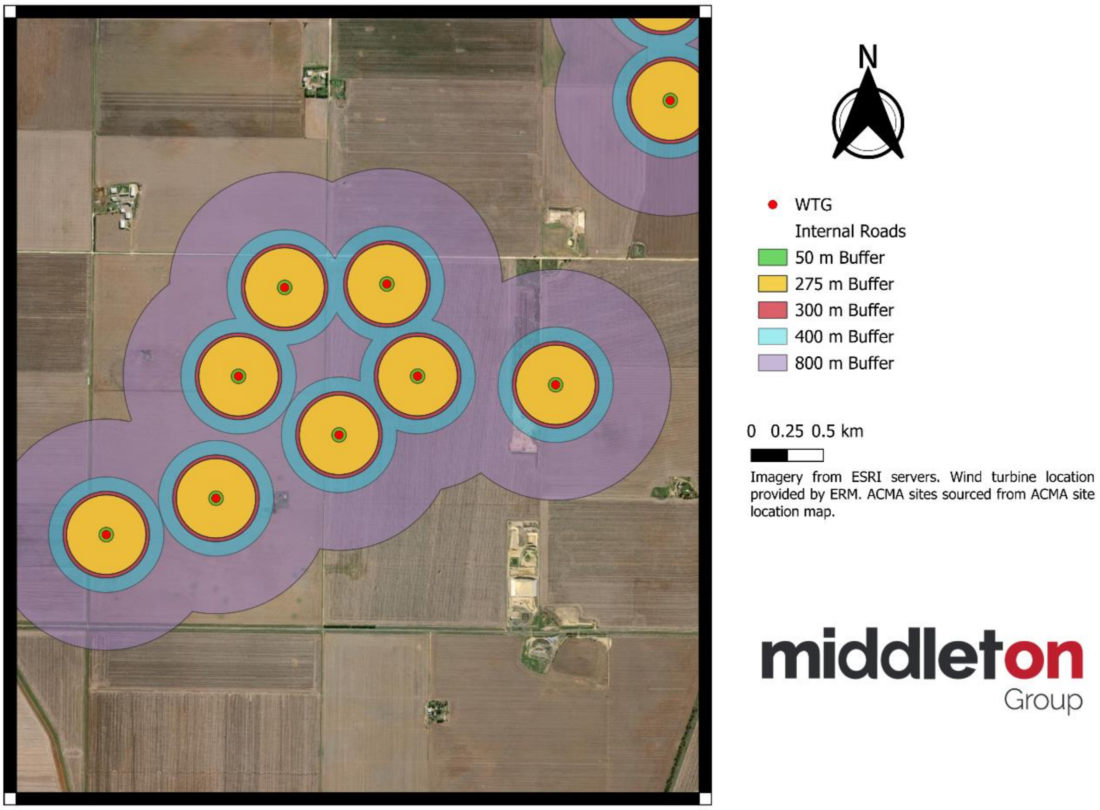

Figure 5: Concentric circles around turbines.

6 Probability Inputs

6.1 Likelihood of blade throw

As tabulated in Appendix A, the 4,183 WTGs in Australia have accumulated more than 40,126 years of operation in Australia since 1987 to 2024. Each year, these numbers increase with 4000 additional years of WTG operation in Australia as well as with newly installed wind farms.

Based on the two blade drop events across approximately 40,126 years of WTG operation, the return period for a catastrophic failure event resulting in fragmentation is 20,000 years of operation, or 0.000,050 year^{-1}. For application in the probability of fatality equation in section 4.1, the probability of blade drop or **P(Blade Drop) is 1 in 20,063 years**.

Similarly, based on the three fragmentation events, the return period for a catastrophic failure event resulting in blade drop is 13,000 years of operation, or 0.000,075 year^{-1}. For application in the probability of fatality equation in section 4.1, the probability of fragmentation or **P(Fragmentation) is 1 in 13,375 years**.

6.2 Land Uses and Occupancy Rates

The likelihood of a person being within the impact radius of a wind turbine blade drop or blade fragmentation is estimated by assessing the usage of land in the Project area.

The area around WTGs is divided between various categories of how the land is used. A significant portion of the land is used for vegetation, while smaller portions are occupied by buildings, roads, and farms.

The land use categories within Wimmera Plains Energy Facility are tabulated in Table 6. This table also shows the assumed occupancy rate used for the P(fatality) calculation, in section 0, for any given location within that land area category. When calculating the risk to dwellings specifically, in section 7.1, MGE assumes 100% occupancy.

Table 6: Land use categories and occupancy rate assumptions

Category	Occupancy Rate Assumption
Farmland – cropping and grazing	Ploughing/seeding/spraying/harvesting: assume coverage of area six times per year, at a rate of 20 km/h, at a width of 5 m. By default, all land is assumed to be farmland unless otherwise assigned.
Road – public	800 cars per day driving at 100 km/h.
Road – internal	4 cars per day driving at 40 km/h.
Native Vegetation, creeks, rivers, and dams.	Minimal human interaction
Wind farm maintenance	8 hours per day for 2 working weeks (10 days) for 4 people.
Associated Dwellings	16 hours per day for 3 people.

6.3 Representative Wind Turbine Values

By utilising GIS modelling, MGE found the area occupied by each land use within the different impact sectors of each turbine. Using these values, we created a representative turbine to complete the analysis. The following sections demonstrate the input values calculated for the representative turbine. The land use at the representative WTG of the Wimmera Plains Energy Facility is tabulated in Table 9. The total area of each sector is derived from Table 5.

It is not practical, for the purpose of this study, to exactly measure the area of land use for each category for each wind turbine. Conservative assumptions for land use are applied for a representative wind turbine and then scaled to the entire wind farm, as presented in the results section.

6.3.1 Roads

6.3.1.1 Internal Roads

Internal road describes access roads within the wind farm which connect wind turbines and may be used by farm personnel to traverse their land. Each WTG has an internal road. Reference to internal road also refers to unnamed roads within 1 km of WTGs. Internal roads are assumed to be of 5 m width. Internal road length within each impact area sector is shown in Table 7 and a project overview of blade throw radii and internal roads is provided in Figure 6.

Table 7: Length of internal road in Impact Areas for representative WTG

Impact area sector	Internal road length [m]	Calculation Method
800 m[1]	6,245	5,545 m of access road plus 700 m of internal farm roads
400 m[1]	2,182	2,162 m of access road plus 20 m of internal farm roads
300 m[2]	1,618	1,588 m of access road plus 30 m of internal farm roads
275 m[1]	1,385	1,365 m of access road plus 20 m of internal farm roads
50 m[1]	90	125 m of access road

[1] Fragmentation Impact Radius
[2] Blade drop Impact Radius

Figure 6: Internal Roads within impact radius

6.3.1.2 Public Roads

There is one (1) public road within the Project Boundary and the wind turbine generators (WTGs) located near these roads are as listed below:

- Henty Highway
  - 19 WTGs within 800 m (7, 8, 19, 20, 21, 22, 27, 28, 29, 30, 31, 32, 33, 34, 37, 38, 39, 40, 41)
  - 12 WTGs within 400 m (20, 21, 28, 29, 30, 31, 32, 34, 37, 38, 39, 41)
  - 10 WTGs within 300 m (20, 21, 28, 29, 31, 32, 34, 38, 39, 41)
  - 9 WTGs within 275 m (20, 21, 28, 29, 31, 34, 38, 39, 41)

Public roads are assumed to be of 20 m width. The input summary is provided in Table 8 and a project overview of blade throw radii and public roads is provided in Figure 7.

Table 8: Length of public road in Impact Areas for representative WTG

Impact area	Public road length [m]	Calculation Method
800 m[1]	1,559	19 out of 52 WTGs have a public road through with a maximum length of 5,957 m.
400 m[1]	725	12 out of 52 WTGs have a public road through with a maximum length of 3,085 m.
300 m[2]	496	10 out of 52 WTGs have a public road through with a maximum length of 1,775 m.
275 m[1]	431	9 out of 52 WTGs have a public road through with a maximum length of 1,459 m.
50 m[1]	0	None of 52 WTGs has a public road within 50 m of Henty Hwy

Figure 7: Public Roads within impact radius

6.3.2 Farming and Natural Environments

Native vegetation, creeks, and dams take up maximum approximately 85% of the impact area outside of 275 m from the WTG.

Farming is the land use allocated to the remaining land not used by roads or vegetation.

Table 9: Representative WTG surrounding land use area.

Impact area sector	Area of sector [m2]	Internal road [m]	Public road [m]	Native vegetation, creeks, dams [m2]	Farming [m2]
800 m	1,507,964	6,245	1,559	1,281,770	163,788
400 m	265,072	2,182	725	225,311	14,351
300 m	274889	1,618	496	233,655	23,223
275 m	229,729	1,385	431	195,270	18,914
50 m	7,854	90	0	6,675	729

6.3.3 Dwellings

There are twenty (20) dwellings within a 2 km radius of the WTGs and one (1) dwelling (ID number 4), is located within 800 m of the WTG ID 41, placing it within blade fragmentation zone. No dwellings are located within blade drop radius of the WTGs. The specific risk of strike to this dwelling will be assessed separately in section 7.1.

Figure 8: Dwellings near Project area

Table 10: Dwellings in the vicinity of WTGs

Impact area sector	WTGs with dwellings in the vicinity
800 m	41
400 m	-
300 m	-
275 m	-
50 m	-

6.3.4 Summary of Land Use Occupation Hours for Representative Wind Turbine

The assumed occupancy around the representative WTG is tabulated in Table 10Table 11 for the blade fragmentation case, with the equivalent analysis for the blade drop case shown in Table 12.

Table 11: Land use categories and assumed occupation rates for a representative WTG – for analysis of blade fragmentation.

Category	Occupancy details	Hours of occupation per year			
		800 m	400 m	275 m	50 m
Farmland – cropping and grazing	Ploughing/seeding/spraying/harvesting: assume coverage of area six times per year, at a rate of 20 km/h at a width of 5 m	9.8	0.9	1.1	0.0
Road – public	800 cars per day driving at 100 km/h.	4552.3	2117.0	1258.5	0
Road – internal	4 cars per day driving at 40 km/h.	227.9	79.6	50.6	3.3
Native Vegetation, creeks, rivers, and dams.	Minimal human interaction	0	0	0	0
Wind farm maintenance	8 hours per day for 2 working weeks (10 days) for 4 people.	0	0	0	320
Associated Dwellings	16 hours per day for 3 people.	336.9	0	0	0
TOTAL		5127.0 h	2197.5 h	1310.2 h	323.3 h

Table 12: Land use categories and assumed occupation rates for a representative WTG – for analysis of blade drop.

Category	Occupancy details	Hours of occupation per year	
		300 m	50 m
Farmland – cropping and grazing	Ploughing/seeding/spraying/harvesting: assume coverage of area six times per year, at a rate of 20 km/h, at a width of 5 m. By default, all land is assumed to be farmland unless otherwise assigned.	1.4	0.0
Road – public	800 cars per day driving at 100 km/h.	1372.9	0
Road – internal	4 cars per day driving at 40 km/h.	59.1	3.3
Native Vegetation, creeks, rivers, and dams.	Minimal human interaction	0	0
Wind farm maintenance	8 hours per day for 2 working weeks (10 days) for 4 people.	0	320
Associated Dwellings	16 hours per day for 3 people.	0	0
TOTAL		1433.4 h	323.3 h

6.4 Assumed Area Occupied

The area footprint of a person within the impact radius is assumed to be reflective of both the size of the person, and the potential landing area of debris should it pass through a person.

This area varies as a function of both the size and location of the person, the size of the blade or blade fragment, and the trajectory of the projectile. As a conservative measure, it is assumed that a person inhabiting the impact radius is 1 m wide, and that, due to the projectile's trajectory, a potential landing area of 3 m in length would impact on the occupant, as illustrated in Figure 9. Thus, an impact area of 3 m^2 is assumed.

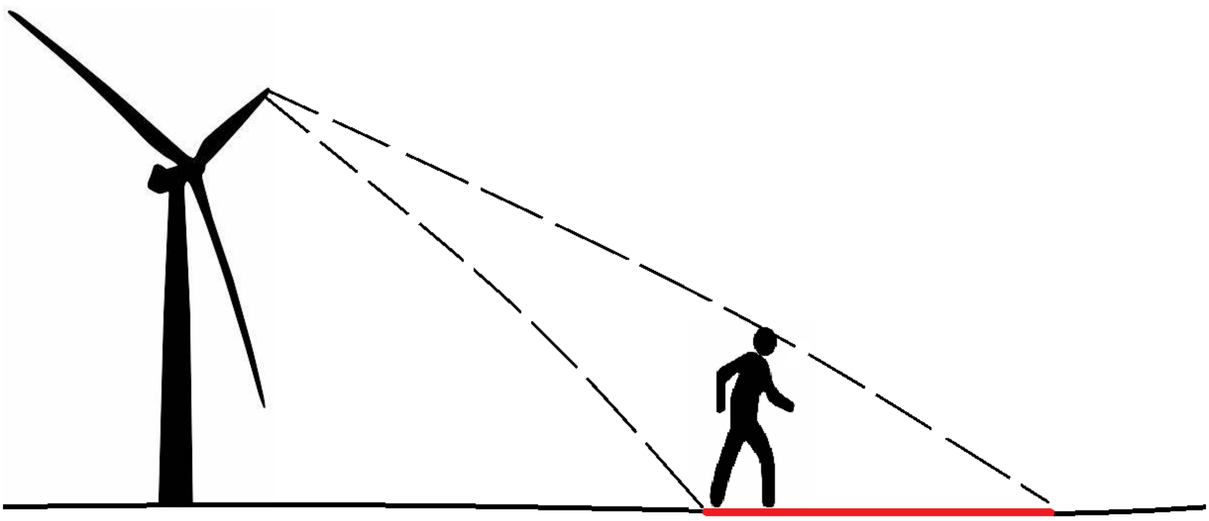

Figure 9: Illustration of potential landing area. The landing area is assumed to be longer than the occupant is tall.

7 Results

The probability of blade failure found by MGE is presented in Table 13.

Land use in the vicinity of the representative WTG is presented in Table 9, which is based on aerial imagery of the site, conservative estimates of traffic volumes and speed.

The numbers found in sections 7.1, 7.2 and 7.3 will be assessed in accordance to section 4.3.

Table 13: Blade Failure Probability

	Fragmentation	Blade Drop
Probability [years^{-1}]	1.974E-08	1.363E-08
Return Period [years]	50,669,206	73,340,512

7.1 Risk to Dwellings

MGE was provided with the location of several nearby dwellings. Twenty (20) dwellings lie within a 2 km radius of the WTGs and one (1) dwelling lies within 800 m radius of a WTG. Based on the analysis conducted in section 5.2 it is safe to assume that all dwellings outside of the 800 m radius will be safe from any potential blade throw instances.

Table 14 records the distances between a few of the closest dwelling to the nearest turbine to assess whether they are at risk of possible blade throw.

Table 14: Risk to Dwellings

Dwelling ID	Closest Turbine ID	Distance From Nearest Turbine	Is the dwelling within impact radius
4	41	658 m	Blade Drop: No Blade Fragmentation: Yes
3	43	1,010 m	Blade Drop: No Blade Fragmentation: No
1	7	1,117 m	Blade Drop: No Blade Fragmentation: No
18	33	1,040 m	Blade Drop: No Blade Fragmentation: No

As it can be seen in Table 14, one dwelling lies within the blade fragmentation impact zone of one turbine. Looking at the risk specifically to this dwelling, Table 15 summarises the probability of impact by blade fragmentation to this dwelling.

Table 15: Dwelling Impact Probability

WTG	Probability [years^{-1}]	Return Period (years)
41	2.9748E-13	3,361,000,000,000

Based on the available data, it is estimated that there is a 3.0-trillion-year return period for a blade failure impacting dwelling no. 4 located near WTG no. 41. The likelihood of such an event occurring is extremely low and the level of risk is well within the bounds of being considered broadly acceptable. Thus, the dwellings are appropriately located and comply with the risk fatality risk criterion.

7.2 Risk to Roads

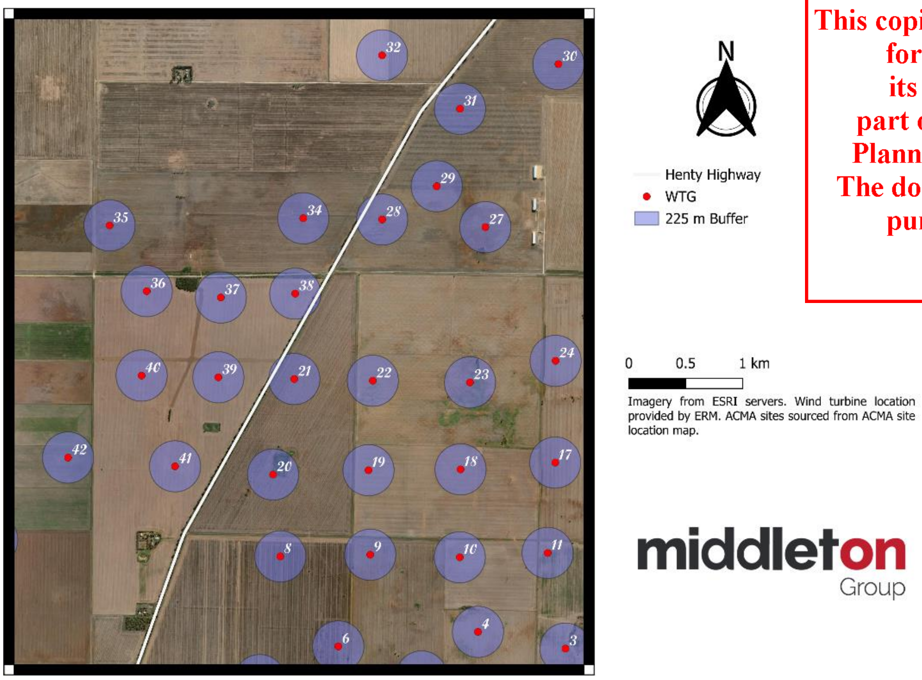

Figure 10: 225 m Impact radius of public road

Figure 10 depicts the turbines that are within the 225 m impact radius. Table 16 provides a summary of the distance of each turbine within the impact radius and the corresponding offset required for each.

Table 16: Distance to Public Road

WTG	Distance to Henty Highway	Offset required
28	165 m	60 m
38	180 m	45 m
21	182 m	43 m

With respect to the placement of the WTGs, MGE recommend the following:

- WTGs should be placed such that the blade tips do not extend beyond the edge of the road.
- The risk to roads of any given WTG is exceedingly small. The risks are:
  - Blade fragmentation (a blade or a fragment can be propelled up to 800 m from the WTG)
  - Blade drop (a blade falls up to 300 m from the WTG)
- Placing all WTGs at a distance from the road to prevent blade fragments from reaching them is impractical, given the extremely low probability of blade fragmentation causing fatalities.
- The probability that blade drop occurs is also extremely low, as it rarely occurs. Furthermore, our calculations consider road usage, and the likelihood of blade failure occurring at the same time a car is present on that section of the road.

The probability is summarised in **Error! Not a valid bookmark self-reference.** as follows:

1. Considering the worse case scenario: where the road is always occupied: (which is highly unlikely)
2. Considering the occupancy rate as assumed in Table 6.

Table 17: Road Impact Probability

Scenarios	Probability [years^{-1}]	Return Period (years)
1	5.56E-07	1,798,390
2	1.28E-07	7,819,064

With respect to development condition 1(b) of the Planning Permit (PA2000877) issued for Wimmera Plains Wind Farm from Planning and Environment Regulations 2015, the following is recommended:

- The assessment of WTGs risk to roads should consider the probability of blade failure causing fatalities as it serves as a more effective risk assessment tool and consider the length of the blades, rather than solely relying on a predetermined distance of 225 m.
- In particular, MGE suggests defining an acceptable risk threshold (in million-year return period) and positioning the WTGs' blades such that the blades do not protrude beyond the road's edge.

7.3 Risk of fatality

Table 18 summarises the probability of fatality found by MGE. The data is aggregated in Table 19 to represent blade fragmentation scenarios and in Table 20 to represent blade drop scenarios. The probability of these two scenarios is then summed to provide a final estimate of the probability of a fatal blade throw incident, and the corresponding return period.

Table 18: Blade Failure Probability

	Fragmentation	Blade Drop	Combined
P(fatality, single WTG) **[$years^{-1}$]**	2.61E-10	3.80E-10	6.42E-10
P(fatality, WPEF) **[$years^{-1}$]**	1.36E-08	1.97E-08	3.34E-08
Return Period Wimmera WF [years]	50,669,206	73,340,512	29,966,244

Table 19: Occupancy by sector and calculation of return period for fragmentation events.

Impact Area Sector	Hours of occupancy	% Time occupied	Occupier footprint/ Sector Area	Distance weighting	P(Location)	P(fatality) = % Time occupied × P(Location) × P(Blade Fragmentation)
800 m	5,127.0	58.53%	1.98944E-06	0.10%	1.98944E-09	8.70527E-14
400 m	2197.5	25.09%	1.13177E-05	9.90%	1.12045E-06	2.10142E-12
275 m	1310.2	14.96%	1.30589E-05	65%	8.48826E-06	9.49183E-11
50 m	323.3	3.69%	0.000381972	25%	9.5493E-05	2.63516E-10
			P(fatality, fragmentation, single WTG) [years⁻¹]			3.79536E-10
			P(fatality, fragmentation, WPEF) [years⁻¹]			1.97359E-08
			Return Period Wimmera WF [years]			50,669,206

Table 20: Occupancy by sector and calculation of return period for blade drop events.

Impact Area Sector	Hours of occupancy	% Time occupied	Occupier footprint/ Sector Area	Distance weighting	P(Location)	P(fatality) = % Time occupied × P(Location) × P(Blade Fragmentation)
300 m	1433.4	16.36%	1.09135E-05	97%	1.06103E-05	8.65348E-11
50 m	323.3	3.69%	0.000381972	3%	9.5493E-05	1.75677E-10
			P(fatality, blade drop, single WTG) [years⁻¹]			2.62212E-10
			P(fatality, blade drop, WPEF) [years⁻¹]			1.3635E-08
			Return Period Wimmera Plains Energy Facility [years]			73,340,511

8 Basis of Assessment

This report relies upon the following basis for the assessment:

- Blade throw return period
  - The study is based on the hours of operation to date of WTGs in Australia and the number of blade throw events reported is representative of Wimmera Plains Energy Facility and that a return period can be extrapolated from these data.
  - Blade throw events that have been reported are representative of all such events.
- Statistical independence
  - The site usage can be approximated as a simple occupancy likelihood while the likelihood of blade failure can also be described through a failure return period, and that the two events are statistically independent.
  - Blade failure is likely to occur during severe weather events, while occupancy within the vicinity of the WTG is likely to be reduced during severe weather.
  - The statistical independence is a source of conservatism in the model.
- Australian data
  - Analysis is confined to Australian data and Australian events.
- Representative WTG
  - Analysis is based on a representative WTG that is representative of an average WTG at the Wimmera Plains Energy Facility, with representative road distances, dwellings and buildings located within the impact zones.
- Traffic volumes and site occupation
  - Traffic volumes and site occupation specifications have been assumed based on consultation with ERM.

9 Conclusion

This study provides an estimate of the risk to human life associated with a blade failure event, based on likelihood of a human occupying space within the potential impact zone at the time of blade failure.

It is noted that the distance between the nearest non-associated dwelling to a proposed WTG location is beyond 400 m. The various models and empirical data examined demonstrate that the risk associated with blade drop and blade fragmentation for these dwellings is negligible as they are beyond the potential impact area. One dwelling is located within 800 m of one turbine, suggesting there is a possibility of risk to this dwelling from blade fragmentation.

There are three WTGs within 225 m of the road, suggesting there is a possibility of risk associated with blade fragmentation and blade drop which would occur a blade length away from the WTG. However, MGE has concluded that there is a 7.9-million-year return period risk to road assuming our occupancy rate in Table 6. Thus, the likelihood of such an event occurring is extremely low.

Based on the available data, it is estimated that there is a 29.97-million-year return period for a blade failure causing a fatality at Wimmera Plains Energy Facility. Thus, the likelihood of such an event occurring is extremely low and the level of risk is well within the bounds of being considered broadly acceptable. Table 21 provides a calculated summary for the project.

The low likelihood of adverse outcome is due to the low incidence of blade failure and low rates of occupation in the vicinity of any of the WTGs.

Table 21: Calculated return period for the Project for a fatality due to blade throw.

Land Use or Activity	Acceptable Risk/Return Period
Risk to Dwelling 4	3.4-trillion-year return period
Risk to Road	7.9-million-year return period
Wimmera Plains Energy Facility blade failure event	29.97-million-year return period

10 References

[1] Health & Safety Executive, "Reducing Risk, Protecting People: HSE's Decision Making Process," Her Majesty's Stationery Office, Norwich, 2001.

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[3] ERM, "Blade Throw Risk Assessment: Hills of Gold Wind Farm," Newcastle, 2020.

[4] J. Rogers, "P122020-3-002: Panther Grove Wind Project Ice Shed and Blade Throw Risk Assessment," Persimia, Atlanta, 2020.

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[6] J. Rogers, N. Slegers, and M. Costello, "A method for defining wind turbine setback standards," Wind Energy, vol. 15, no. 2, pp. 289-303, 2012.

[7] H. Braam and L. Rademakers, "Guidelines on the Environmental Risk of Wind Turbines in the Netherlands," Proceedings of the Global Wind Energy Conference, Paris, 2002, p. 4, 2004.

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[9] MMI Engineering Ltd, "RR968: Study and development of a methodology for the estimation of the risk and harm to persons from wind turbines," Health and Safety Executive, Warrington, 2013.

[10] S. R. Brouwer, S. H. Al-Jibouri, I. C. Cárdenas and J. I. Halman, "Towards analysing risks to public safety from wind turbines," Reliability Engineering and System Safety, vol. 180, pp. 77-87, 2018.

Appendix A Wind Turbine Years of Operation

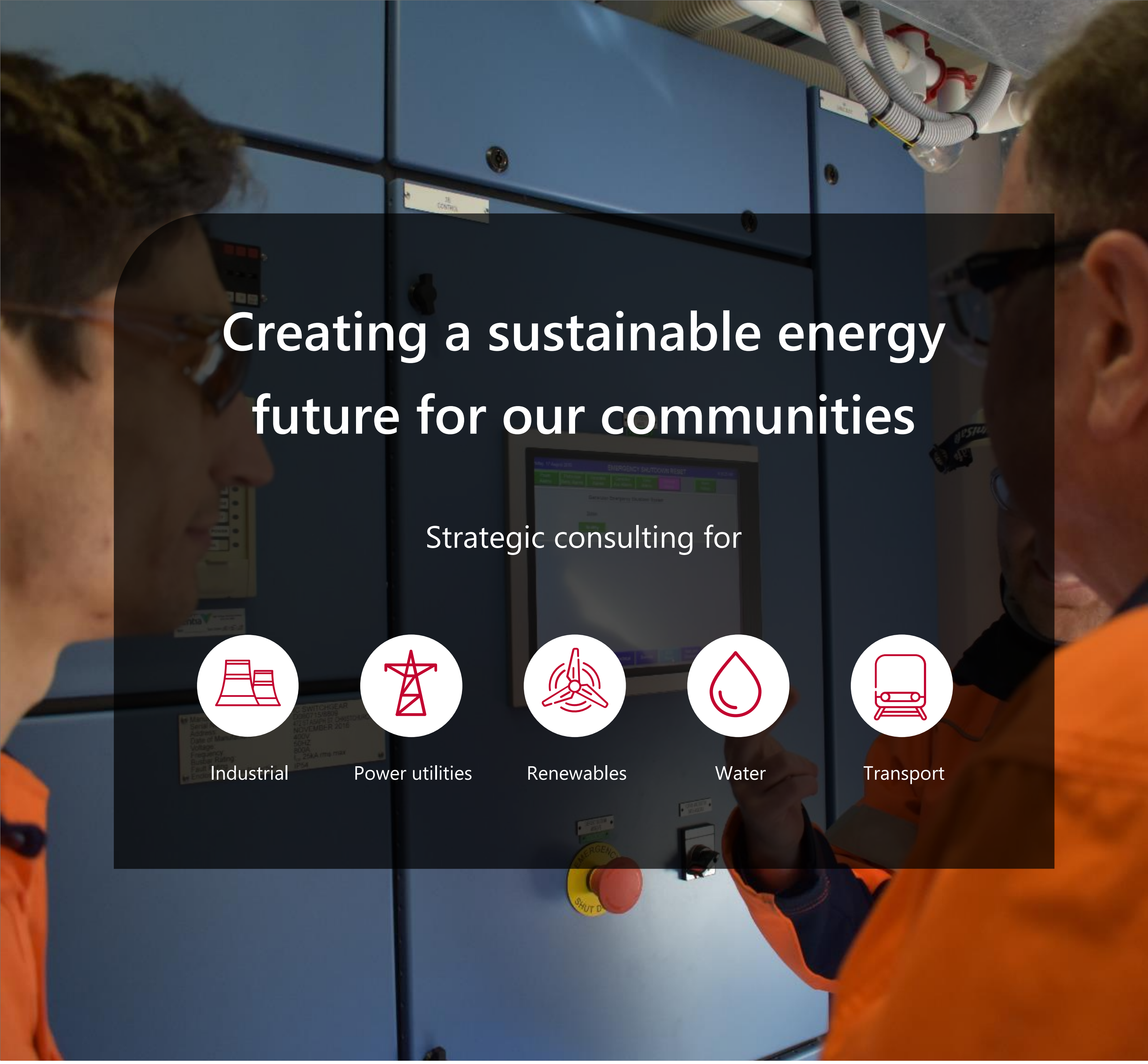
Wind Farm	No of WTGs	Year of Commencement	Years of Operation	WTG Years
Berrybank 2	26	2023	0	0
Dulacca Wind Farm	43	2023	0	0
Bango WF	46	2022	1	46
Crudine Ridge	37	2022	1	37
Esperence	2	2022	1	2
Mortlake South	35	2022	1	35
Berrybank 1	43	2021	2	86
Biala Wind Farm	31	2021	2	62
Collector Wind Farm	54	2021	2	108
Ferguson	3	2021	2	6
Kalbarri	2	2021	2	4
Murra Warra II Wind Farm	38	2021	2	76
Port Augusta	50	2021	2	100
Agnew	5	2020	3	15
Cherry Tree WF	16	2020	3	48
Coopers Gap Wind Farm[14]	123	2020	3	369
Diapur	2	2020	3	6
Dundonnel Wind Farm	80	2020	3	240
Moorabool Wind Farm (North & South)	104	2020	3	312
Stockyard Hill Wind Farm[16]	149	2020	3	447
Warradarge	51	2020	3	153
Yandin WF	51	2020	3	153
Badgingarra	37	2019	4	148
Beros Rd	19	2019	4	76
Bodangora Wind Farm	33	2019	4	132
Bulgana	56	2019	4	224
Cattle Hill Wind Farm[15]	48	2019	4	192
Kennedy	12	2019	4	48
Lal Lal Wind Farm	60	2019	4	240

Wind Farm	No of WTGs	Year of Commencement	Years of Operation	WTG Years
Murra Warra Wind Farm	61	2019	4	244
Port Gregory	5	2019	4	20
Silverton Wind Farm	58	2019	4	232
Willogoleche Wind Farm[13]	32	2019	4	128
Crookwell 2	46	2018	5	230
Crowlands Wind Farm	39	2018	5	195
Granville Harbour Wind Farm[5]	31	2018	5	155
Hornsdale 3	35	2018	5	175
Kiata	9	2018	5	45
Lincoln Gap Wind Farm	59	2018	5	295
Maroona	2	2018	5	10
Mount Emerald Wind Farm	53	2018	5	265
Mount Gellibrand Wind Farm[7]	44	2018	5	220
Salt Creek WF	15	2018	5	75
Sapphire Wind Farm[9]	75	2018	5	375
Timboon West	2	2018	5	10
Yaloak South	14	2018	5	70
Yawong Wind Farm	2	2018	5	10
Ararat Wind Farm	75	2017	6	450
Coober Pedy 2	2	2017	6	12
Flinders Island	1	2017	6	6
Hornsdale 1	32	2017	6	192
Hornsdale 2	32	2017	6	192
Waterloo 2	6	2017	6	36
White Rock Wind Farm (Stage I)[11]	70	2017	6	420
Coonooer Bridge	6	2016	7	42
Bald Hills Wind Farm	52	2015	8	416
Boco Rock Wind Farm	67	2015	8	536
Chepstowe	3	2015	8	24
Portland 4	23	2015	8	184
Taralga Wind Farm	51	2015	8	408

Wind Farm	No of WTGs	Year of Commencement	Years of Operation	WTG Years
Mount Mercer Wind Farm	64	2014	9	576
Snowtown 2	90	2014	9	810
Denmark community WF	2	2013	10	20
Gullen Range Wind Farm[4]	73	2013	10	730
Karakin	10	2013	10	100
Macarthur Wind Farm	140	2013	10	1400
Mortons Lane Wind Farm[6]	13	2013	10	130
Mumbida Wind Farm[8]	22	2013	10	220
Musselroe Wind Farm	56	2013	10	560
Sumich West Hills	10	2013	10	100
Hallett 5	25	2012	11	275
Hepburn	2	2012	11	22
Oaklands Hill Wind Farm	32	2012	11	352
Woodlawn Wind Farm	23	2012	11	253
Collgar Wind Farm	111	2011	12	1332
Grassmere WF (albany)	6	2011	12	72
Gunning WF	31	2011	12	372
Hallett 4	63	2011	12	756
Mount Barker	3	2011	12	36
Waterloo Wind Farm	37	2011	12	444
Clements Gap Wind Farm	27	2010	13	351
Hallett 2	34	2010	13	442
Lake Bonney 3	13	2010	13	169
Yambuk WF	20	2010	13	260
Capital Wind Farm	67	2009	14	938
Cullerin Range	15	2009	14	210
Portland 3	22	2009	14	308
Snowtown 1	47	2009	14	658
Waubra Wind Farm	128	2009	14	1792
Salmon beach wind farm	6	1987	15	90
Hallett 1	45	2008	15	675
Lake Bonney 2	53	2008	15	795

Wind Farm	No of WTGs	Year of Commencement	Years of Operation	WTG Years
Portland 2	29	2008	15	435
Nichols Poultry - Sassafras	1	2008	15	15
Cathedral Rocks Wind Farm	33	2007	16	528
Coral Bay Wind Farm	3	2007	16	48
Denham	4	2007	16	64
Hopetoun Bay WF 2	1	2007	16	16
Portland 1	20	2007	16	320
Woolnorth Studland Bay	25	2007	16	400
Kooragang	1	1997	17	17
Dulacca Wind Farm	48	2006	17	816
EMU Downs	48	2006	17	816
Mount Millar Wind Farm	35	2006	17	595
Walkaway Wind Farm	54	2006	17	918
Canunda Wind Farm	23	2005	18	414
Lake Bonney 1	46	2005	18	828
Wattle Point Wind Farm	55	2005	18	990
Wonthaggi WF	6	2005	18	108
Bremer Bay Wind Turbine	1	2004	19	19
Hopetoun Bay WF 1	1	2004	19	19
Rottnest Wind Turbine	1	2004	19	19
Woolnorth Wind Farm	37	2004	19	703
Challicum Hills Wind Farm	35	2003	20	700
Huxley Hill 2	2	2003	20	40
Nine Mile Beach	6	2003	20	120
Starfish Hill Wind Farm	22	2003	20	440
Toora	12	2002	21	252
Albany WF	12	2001	22	264
Codrington	14	2001	22	308
Hampton Wind Park	2	2001	22	44
Blayney Wind Farm	15	2000	23	345
Windy Hill	20	2000	23	460
Crookwell 1	8	1998	25	200

Wind Farm	No of WTGs	Year of Commencement	Years of Operation	WTG Years
Huxley Hill 1	3	1998	25	75
Coober Pedy 1	1	1991	26	26
Thursday Island	2	1997	26	52
Ten Mile Lagoon	9	1993	29	261
TOTAL	4183		1332	35960



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