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GOULBURN RIVER SOLAR FARM

Preliminary Hazard Analysis

FINAL

April 2023

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Prepared by
Umwelt (Australia) Pty Limited
on behalf of
Lightsource bp

Project Director:	Malinda Facey
Project Manager:	Jessica Henderson-Wilson
Technical Director:	Tim Procter
Technical Manager:	Chris Bonomini
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1.0 Introduction

1.1 Project Overview

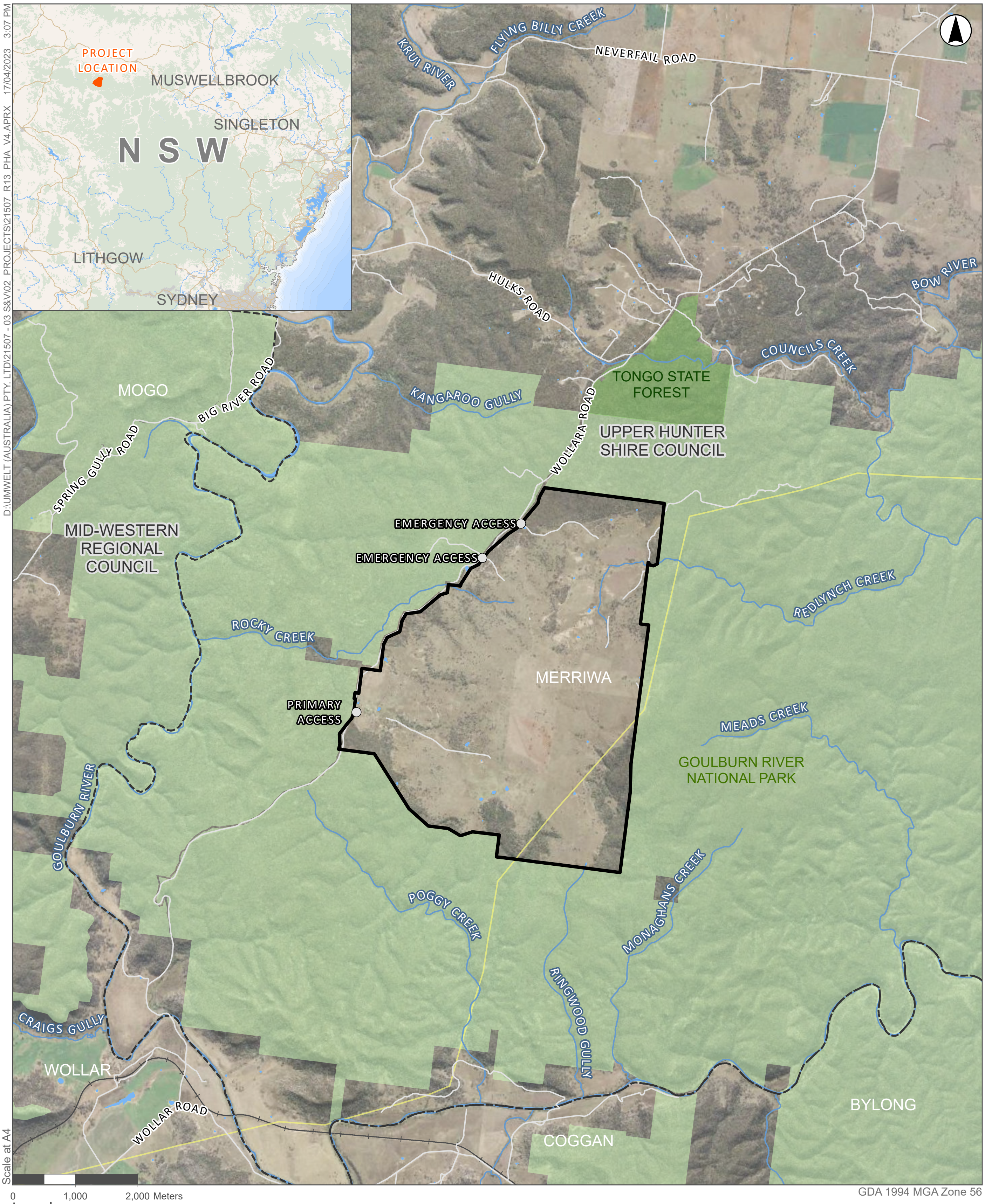
Lightsource Development Services Australia Pty Ltd (Lightsource bp) is seeking to develop the proposed Goulburn River Solar Farm (the 'Project') in New South Wales (NSW), approximately 28 kilometres (km) southwest of Merriwa within the Upper Hunter Shire Local Government Area (LGA) (refer to **Figure 1.1** and **Figure 1.2**).

The Project will involve the construction, operation and decommissioning of approximately 550-megawatt peak (MWp) of solar photovoltaic (PV) generation as well as a Battery Energy Storage System (BESS) with 280 MWp / 570 megawatt hour (MWh) capacity. The Project will also include a substation and connection to an existing 500 kilovolt (kV) transmission line. The Project will include various associated infrastructure, including road repairs and upgrades to Ringwood Road, temporary construction facilities, operation and maintenance buildings, internal access roads, civil works and electrical infrastructure to connect the Project to the existing transmission line which passes through the Project Area. The conceptual layout for the Project is shown in **Figure 1.2**.

The Project Area is situated on two freehold properties and sections of Crown Land, which is currently primarily used for grazing and cropping activities. The development footprint for the Project is approximately 799.5 hectares (ha).

The Project is expected to operate for 40 years following an approximately 27-month construction period. After the initial 40-year operating period, the solar farm would either be decommissioned, removing all above-ground infrastructure and returning the site to its existing land capability, or repurposed with new equipment subject to technical feasibility and planning consents.

The Project is a State Significant Development (SSD) under *State Environmental Planning Policy (Planning Systems) 2021* (Planning Systems SEPP) as the Project is development for the purposes of electric generating works and the capital value of the Project is over $30 million. A development application (DA) for the Project is required to be submitted under Part 4 of the NSW *Environmental Planning and Assessment Act 1979* (EP&A Act).



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1:85,000 Scale at A4

GDA 1994 MGA Zone 56

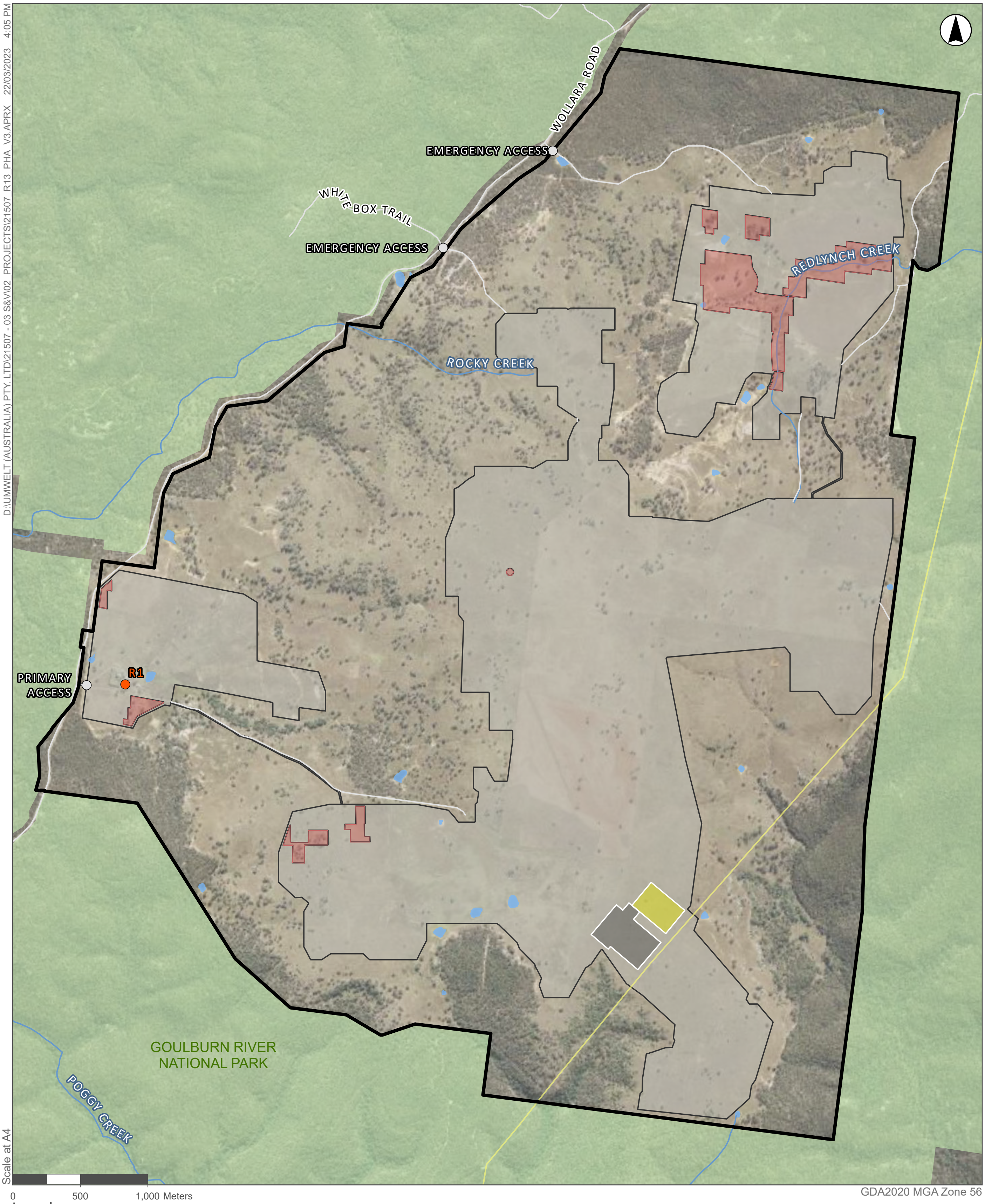
Legend

- Access Points
- Electricity Transmission Line
- Watercourse
- Roads and Tracks
- Railway
- Local Goverment Boundary
- Project Area
- NSW National Parks
- NSW State Forests
- Waterbodies

FIGURE 1.1

Locality

Image Source: ESRI Basemap (2022) **Data source:** NSW LPI (2022), NSW DSFI (2022); NPWS Estate (2022); Lightsource BP (2022)



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GDA2020 MGA Zone 56

Legend

- Involved Dwelling
- Access Points
- Electricity Transmission Line
- Watercourse
- Roads and Tracks
- Railway
- Local Goverment Boundary
- Project Area
- Exclusion Zones - Environmentally Sensitive Areas
- Battery Energy Storage System
- Battery Substation
- NSW National Parks
- NSW State Forests
- Waterbodies

FIGURE 1.2

Project Layout

Image Source: ESRI Basemap (2022) **Data source:** NSW LPI (2022), NSW DSFI (2022); NPWS Estate (2022); Lightsource BP (2022)

1.2 Purpose and Scope

This Preliminary Hazard Analysis (PHA) has been prepared by Umwelt (Australia) Pty Ltd (Umwelt), to satisfy relevant Secretary's Environmental Assessment Requirements (SEARs) issued by the former Department of Planning, Industry and Environment (DPIE) on 1 February 2022 and the requirements of *State Environment Planning Policy 33 – Hazardous and Offensive Development* (SEPP 33) which has now been superseded by *State Environmental Planning Policy (Resilience and Hazards)* 2021 (the Resilience and Hazards SEPP). The SEARs relating to this PHA are:

Table 1.1 Secretary's Environmental Assessment Requirements

Requirement	Where addressed in this report
Hazards and Risks – including:	
• a preliminary risk screening completed in accordance with State Environmental Planning Policy No. 33 – Hazardous and Offensive Development and Applying SEPP 33 (Department of Planning (DoP), 2011);	**Section 2.1**
• a Preliminary Hazard Analysis (PHA) must be prepared in accordance with Hazardous Industry Planning Advisory Paper No. 6 – Guideline for Hazard Analysis (DoP, 2011) and Multi-Level Risk Assessment (DoP, 2011). The PHA must consider all recent standards and codes and verify separation distances to on-site and off-site receptors to prevent fire propagation and compliance with Hazardous Industry Advisory Paper No. 4, Risk Criteria for Land Use Safety Planning (DoP, 2011); and	**Section 3.0, Section 4.0, Section 5.0, Section 6.0** and **Section 7.0**
• an assessment of potential hazards and risks including but not limited to bushfires, spontaneous ignition, electromagnetic fields or the proposed grid connection infrastructure against the International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines for limiting exposure to Time-varying Electric, Magnetic and Electromagnetic Fields.	**Section 5.0, Section 6.0** and **Section 7.0** EMF – See EIS **Section 6.11.4**

It should be noted that this PHA does not include an assessment of the hazards and risks associated with electric and magnetic fields or the proposed grid connection infrastructure against the International Commission on Non-Ionizing Radiation Protection (ICNIRP) *Guidelines for limiting exposure to Time-varying Electric, Magnetic and Electromagnetic Fields* (1998) or an assessment of bushfire risks (other than bushfire as a potential initiating event). Separate assessments have been undertaken to address time-varying electric and magnetic fields and bushfire, and are included in the Environmental Impact Statement (EIS).

The PHA considers the hazards and risks posed to off-site receivers and involved dwellings associated with the transport, storage and use of hazardous materials for the Project and has been prepared in general accordance with and/or with reference to:

- *Applying SEPP 33* (NSW Department of Planning (DoP), 2011a).
- *Multi-Level Risk Assessment* (DoP, 2011f).
- *Hazardous Industry Advisory Paper No. 4 – Risk Criteria for Land Use Safety Planning* (DoP, 2011d).
- *Hazardous Industry Planning Advisory Paper No. 6 – Guidelines for Hazard Analysis* (DoP, 2011e).

2.0 Preliminary Hazard Analysis

Under the Resilience and Hazards SEPP, a preliminary risk screening of a proposed development is required to determine the need for a PHA. The preliminary screening involves the identification and assessment of the storage of specific dangerous goods classes that have the potential for significant off-site effects. If, at the proposed location, and in the presence of controls, the risk level exceeds the acceptable criteria for impacts on the surrounding land use, the development is classified as ‘hazardous’ or ‘offensive’ industry and may not be permissible within most land use zones in NSW.

A ‘hazardous industry’ is one which, when all locational, technical, operational and organisational safeguards are employed, continues to pose a significant risk. An ‘offensive industry’ is one which, even when controls are used, has emissions which result in a significant level of offence e.g., odour or noise emissions. Separate air quality and noise and vibration assessments have been completed for this Project to address potential impacts. A proposal cannot be considered either hazardous or offensive until it is firstly identified as 'potentially hazardous' or 'potentially offensive' and subjected to the assessment requirements of Resilience and Hazards SEPP. A PHA is required if a proposed development is 'potentially hazardous'.

A proposed development may also be 'potentially hazardous' if the number of traffic movements for the transport of hazardous materials exceeds the annual or weekly criteria outlined in Table 2 of *Applying SEPP 33* (DoP, 2011a). If these thresholds are exceeded a route evaluation study is likely to be required.

Hazardous Industry Planning Advisory Paper No. 6 – Guidelines for Hazard Analysis (HIPAP 6) (DoP, 2011d) and *Multi-level Risk Assessment* (MLRA) (DoP, 2011f) note that a PHA should identify and assess all hazards that have the potential for off-site impact. The expectation is that the hazards would be analysed to determine the consequence to people, property and the environment and the potential for hazards to occur.

The methodology used to identify and assess the potential Project hazards and respective failure scenarios that have the potential for off-site impact is outlined in **Figure 2.1** and is based on the methodology detailed in HIPAP 6 (DoP, 2011e) and MLRA (DoP, 2011f). The details of how this methodology is implemented are discussed in the respective sections of this report.

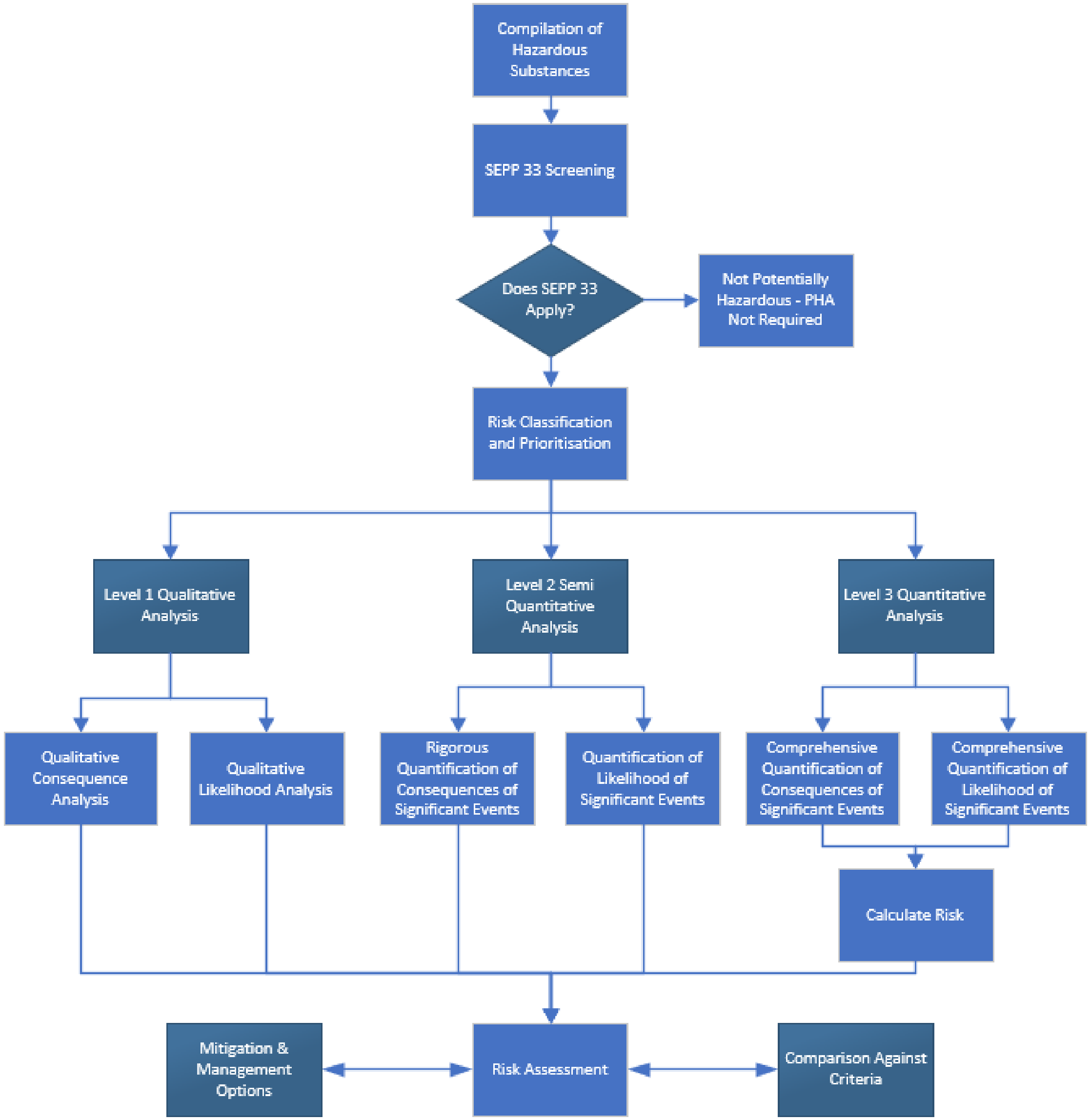


Figure 2.1 Overview of PHA Methodology

Preliminary Screening
SEPP 33 Screening involves compiling information on the quantity of hazardous materials used, the mode of storage and location with respect to off-site land users and the number and size of annual and weekly road movements of the hazardous material.

A proposed development should be considered potentially hazardous if the storage or transport of hazardous substances exceeds the respective screening thresholds and further risk assessment is required. If the storage and transport of hazardous materials does not exceed thresholds then no further analysis is necessary and the safety management regime should rely on observance of the requirements of engineering codes and standards.

Risk Classification and Prioritisation
Risk classification and prioritisation involves ranking of the facility using techniques to make broad estimates of the consequence and likelihood of accidents. The output may be expressed in terms of individual and societal risk and is compared against respective criteria for determining the appropriate level of analysis for further risk assessment.

Level 1 Analysis – Significant but not serious potential for harm
A Level 1 analysis is a qualitative assessment based on detailed hazard identification. The objective is to demonstrate that the activity does not pose a significant risk. Where the qualitative analysis cannot satisfactorily demonstrate there will be no significant risk, further analysis is required.

Level 2 Analysis – Medium potential for harm
A Level 2 analysis supplements the Level 1 analysis by quantifying the main risk contributors to show that their consequences are acceptable.

Level 3 – High potential for harm
A Level 3 quantitative analysis is required when the screening and hazard identification process and/or risk classification and prioritisation process has identified risk contributors with consequences beyond the site boundaries. The analysis requires a comprehensive quantification of significant consequences and their likelihood.

Risk Assessment
The Risk Assessment compares the results of the risk analysis with the respective risk criteria. Where the level of risk is not acceptable, risk minimisation, mitigation and management options need to be investigated.

2.1 Preliminary Risk Screening

Preliminary risk screening is undertaken to determine the requirement for a PHA. The Resilience and Hazards SEPP contains a number of assessment criteria for the storage and transport of hazardous materials that have the potential to create off-site impacts.

2.1.1 Storage Quantity Screening

The hazardous materials that will be stored and used for the Project include:

- approximately 2,280 tonnes[1] of lithium-ion batteries (LIBs), a Class 9 miscellaneous dangerous good.
- approximately 400,000 litres (approximately 360 tonnes based on an assumed specific gravity of 0.89) of electrical transformer insulating oil which is not classified as a dangerous good under the Australian Code for the Transport of Dangerous Goods (National Transport Commission, 2020).

Neither of these hazardous material types has a relevant screening threshold in the Resilience and Hazards SEPP. However, with the rapid proliferation of LIBs in portable devices, electric vehicles, energy storage systems and a range of other applications in recent years, the potential hazards associated with LIBs have become evident. It is known that LIBs may present fire, explosion and toxic gas release hazards as a result of manufacturing faults or a range of battery abuse scenarios (refer to **Section 4.3.1**).

Applying SEPP 33 indicates that the risk screening process for determining if a proposal is 'potentially hazardous' under the Resilience and Hazards SEPP should not be used in isolation and 'other factors' should be taken into account. While Applying SEPP 33 does not define 'other factors', the potential for hazardous events such as fire, explosion and toxic release involving LIBs and the large scale of the Project BESS (i.e., 570 MWh total storage capacity) are considered to be relevant. Further, given the limited global experience with large capacity, grid connected LIB BESSs, and to maintain a conservative approach with respect to the assessment of hazards and risk, further assessment is considered appropriate.

2.1.2 Transport Screening

As with the storage of LIBs and transformer insulating oil, there are no transport screening thresholds in the Resilience and Hazards SEPP for either of these hazardous materials. The transportation of LIBs to site in significant quantities and at a relatively high frequency will only occur during Project construction and decommissioning. Deliveries of LIBs to replace failed units will occur only in relatively small quantities and at less frequent intervals than during Project construction. LIBs will be transported to site by a suitably accredited freight company using dangerous goods licensed vehicles and drivers.

The transportation of transformer insulating oil to the Project will only occur in significant quantities during Project construction and maintenance when the oil is replaced to ensure safe and efficient transformer operation. Delivery of transformer insulating oil to the Project site during operations will be very infrequent.

Based on the very low frequency of hazardous materials transport to the Project site and the use of suitably accredited freight companies, no further assessment of transport risks (e.g., a transport route analysis) is considered necessary.

[1] Mass estimated based on 0.25 kWh/kg for a LIB cell from Bravo Diaz et al. (2020) and a total BESS capacity of 570 MWh.

3.0 Risk Classification and Prioritisation

Multi-level Risk Assessment (MLRA) (DoP, 2011f) suggests the use of a preliminary analysis of the risks related to a proposed development to enable the selection of the most appropriate level of risk analysis in the PHA. This preliminary analysis includes risk classification and prioritisation using a technique adapted from the *Manual for classification of risks due to major accidents in process and related Industries* (International Atomic Energy Agency (IAEA), 1996). A complete description of the technique is presented in the MLRA (DoP, 2011f). The technique is based on a general assessment of the consequences and likelihoods of accidents and their risks to individuals and society, and the comparison of these risks to relevant criteria to determine the level of assessment required, be it qualitative or quantitative.

3.1 Methodology

The objective of the risk classification and prioritisation process is to determine whether the risks identified as part of the Resilience and Hazards SEPP preliminary screening process are acceptable risks or whether further assessment is required. The assessment involves the following steps:

- classification of the type of activities and materials inventories
- estimation of consequences
- estimation of probabilities of major accidents for fixed installations
- estimation of societal risk
- evaluation of alternatives
- assessment using criteria to determine the required level of risk assessment.

For each potentially hazardous activity, information is required regarding the location, type, production and storage condition of the activity, as well as the name, physical state and the amount of hazardous substances involved. Table II of the *Manual for classification and prioritization of risks due to major accidents in process and related industries* (IAEA, 1996) provides a guideline of the required information.

If a facility has effective physical isolation and separation between the storage vessels with the same dangerous goods classification, then the content of the largest storage vessel would typically be used to estimate the effect of an incident.

When selecting the activities likely to have the potential to cause risk/damage, the following should be considered:

- if more than one substance in the same activity can cause damage independently from the other substances, analyse them separately
- if a group of substances may act together, consider them as a single (equivalent) substance
- if a flammable substance is also toxic, both effects have to be accounted for (after following the methodology within MLRA (DoP, 2011f) it will be clear whether flammable properties are important or not, compared with toxic properties).

3.1.1 Estimation of Consequences

Consequences of an accident depend on the type of substance, activity and the quantity involved, as well as the population exposed to its effect.

The external consequences ($C_{a,s}$) of major accidents to humans are calculated using equation (1) of *Manual for classification and prioritization of risks due to major accidents in process and related industries* (IAEA, 1996):

$$C_{a,s} = A \times d \times f_a \times f_m$$

where:

$C_{a,s}$	external consequences (fatalities per accident) where the subscript 'a' represents an activity and subscript 's' represents a hazardous substance
A	affected area (hectares; 1 ha = 10^4 m^2)
d	population density in defined populated areas (persons/ha)
f_a	correction factor for populated area
f_m	correction factor for mitigation effects.

Alternatively, if the population (N) within the affected area is known, the consequence can be estimated as follows:

$$C_{a,s} = N \times f_m$$

While the risk classification and prioritisation process does not lend itself directly to activities involving LIBs, the process has been applied to LIBs on the basis of toxic gas generation capacity for the entire battery inventory (i.e., 570 MWh battery storage capacity). For LIBs, the most toxic gas generated in significant quantities is understood to be hydrogen fluoride (HF) (refer to **Section 4.3.1**) and the consequence calculations outlined above have been based on HF. The result of this calculation for LIBs as a source of HF is provided in **Section 3.3**.

3.1.2 Estimation of Probabilities

The probability number (Ni,s) of major accidents to humans is calculated using equation (2) of *Manual for classification and prioritization of risks due to major accidents in process and related industries* (IAEA 1996):

$$N_{i,s} = N^*_{i,s} + n_l + n_f + n_0 + n_p$$

where:

$N^*_{i,s}$	the average probability number for the installation and the substance
n_l	probability number correction parameter for the frequency of loading/unloading operations
n_f	probability number correction parameter for the safety systems associated with flammable substances
n_0	probability number correction parameter for the organisational and management safety
n_p	probability number correction parameter for wind direction towards the populated area.

The probability number, $N_{i,s}$ is then converted into a probability $P_{i,s}$ by using the relationship between N and P which is defined as:

$$N = \log_{10}(P)$$

$P_{i,s}$ defines the frequency (number of accidents per year) of accidents involving a hazardous substance (subscript 's') for each hazardous fixed installation (subscript 'i'), which causes the consequences that have been estimated previously. The result of this calculation for LIBs as a source of HF is provided in **Section 3.3**.

3.2 Criteria for Multi-level Risk Assessment

The method for determining the assessment criteria recommended by DPE is outlined in Figure A1.3 of the MLRA (DoP 2011f). The figure shows three regions which are used to determine the level of assessment required by the PHA as follows:

- **Level 1 assessment** – can be justified if the analysis of the facility demonstrates the societal risk is negligible (i.e., falls below the lower criterion line) and there are no potential accidents with significant off-site consequences.
- **Level 2 assessment** – can be justified if the societal risk estimates fall within the middle region (i.e., between the upper and lower criteria lines) and the frequency of risk contributors having off-site consequences is relatively low. The assessment must demonstrate that the facility will comply, at least in principle, with the DPE risk criteria, based on broad quantification of the risk.
- **Level 3 assessment** – is required if the societal risk estimates are in the intolerable zone (i.e., above the upper criterion line) or where there are significant off-site risk contributors, or the level 2 assessment fails to demonstrate that risk criteria will be met.

According to Section 3.1 of MLRA (DoP, 2011f), quantification of the risk must be undertaken on any component identified in the risk classification and prioritisation process as having off-site consequences extending significantly beyond the site boundary at a frequency greater than 1×10^{-7} per year. **Section 3.3** presents the ranking and prioritisation results and the required level of risk assessment for the Project.

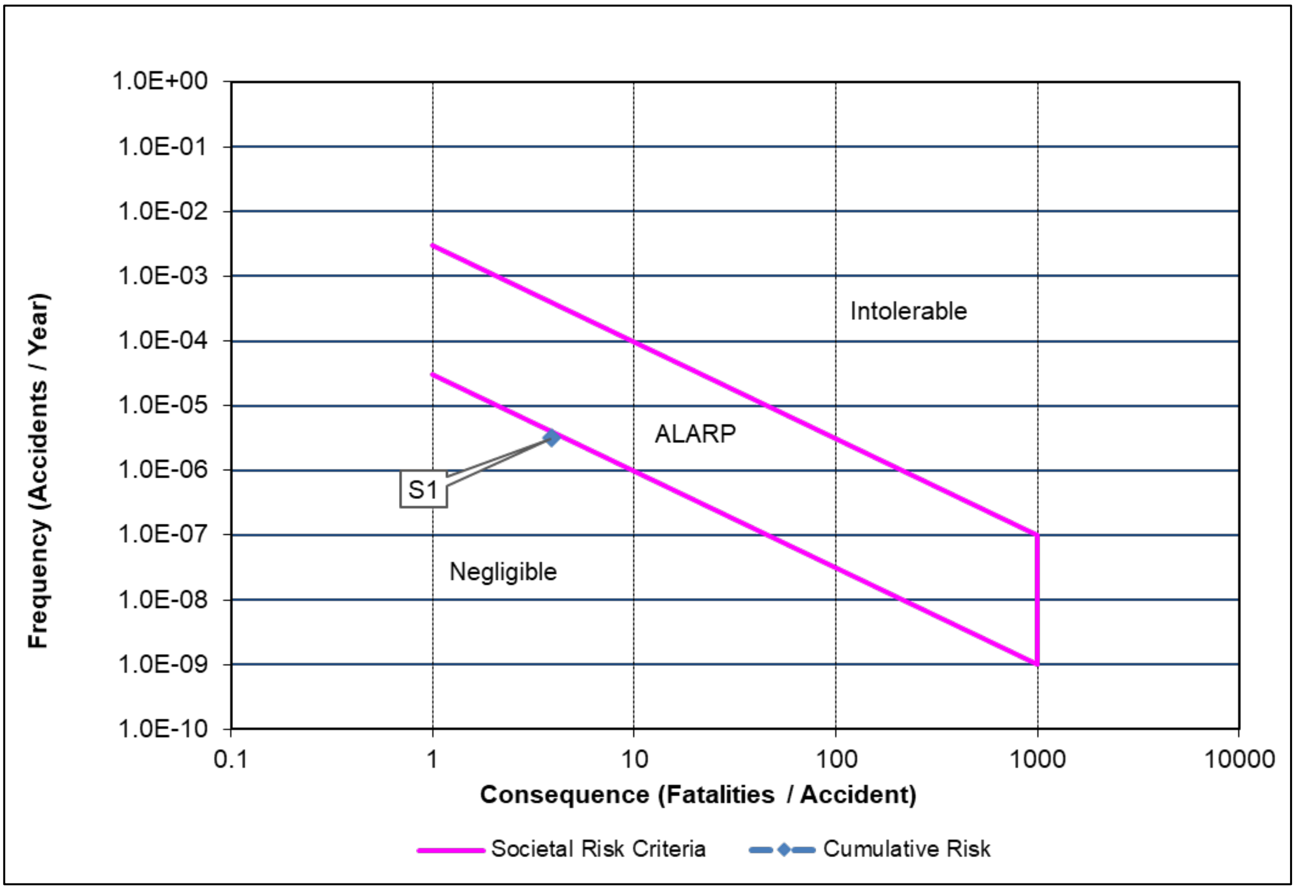
3.3 Estimation of Societal Risk

The risk to the public from each potentially hazardous activity is estimated by combining the estimated consequences to humans and the probabilities of major accidents.

Using the results of the assessments described in **Section 3.1.1** and **Section 3.1.2** the activities are classified and grouped according to *Manual for classification and prioritization of risks due to major accidents in process and related industries* (IAEA 1996). Details of the scenario modelled, and the consequence and probability number estimates are outlined in **Table 3.1**. **Appendix A** contains the consequence and probability number estimate calculations. The Consequence Number - Probability Number pair is shown plotted on a societal risk plot in **Graph 3.1**.

Table 3.1 Dangerous Goods Scenarios Modelled for Societal Risk

Descriptor	Substance	ADG/Division Class	Activity	Hazardous Event	Consequence Number (Ca,s)	Probability Number (Ni,s)
S1	LIBs (as HF source)	9	Plant	Toxic gas release	3.9	5.5



Graph 3.1 Societal Risk Plot

A cumulative risk plotted in the Intolerable region is considered undesirable regardless of whether individual risk criteria are met. Cumulative risk plotted in the Negligible region is not considered significant, while the focus for cumulative risk plotted within the As Low As Reasonably Possible (ALARP) region is on reducing risks as far as possible. Cumulative risk within the ALARP region is considered tolerable provided other quantitative and qualitative criteria of *HIPAP No 4 Risk Criteria for Land Use Safety Planning* (HIPAP 4) are met. The Consequence Number - Probability Number pair for the Project hazard scenario considered (refer to **Graph 3.1**) is on the border between the ALARP and the 'negligible' regions. HIPAP 4 notes that if the analysis of the societal risk is below the negligible line, provided other individual criteria are met, societal risk is not considered significant, and a qualitative analysis is sufficient.

MLRA (Department of Planning, 2011e) notes that no further quantification of risk would be required if:

- all points on the indicative societal risk curve produced from the risk classification and prioritisation are below the negligible line in **Graph 3.1**
- no events with consequences extending significantly beyond the site boundary at a frequency of greater than 1×10^{-7}
- the process/operation is well understood and covered by established and recognised standards and codes of practice
- if there are no off-site consequences that ill impact on any sensitive adjoining land use.

A higher level of analysis will be required if the qualitative analysis cannot demonstrate there will be no significant risk by satisfying the above requirements. Whereas in the ALARP region a Level 2 semi quantitative risk assessment is required to demonstrate that HIPAP 4 criteria can be met for the Project.

4.0 Level 1 Qualitative Risk Analysis

It was determined using the MLRA (Department of Planning, 2011e) risk classification and prioritisation process (refer to **Section 3.3**) that a Level 1 qualitative risk assessment should be sufficient to demonstrate that the Project can comply with relevant criteria in HIPAP 4 (Department of Planning, 2011c). However, as indicated in Section 3.1.2 of MLRA (Department of Planning, 2011e), a higher level of analysis may be required if the qualitative analysis cannot demonstrate there will be no significant risk of off-site consequences.

4.1 Methodology

A Level 1 assessment requires (as a minimum):

- hazard identification using word diagrams, simplified fault/event trees and checklists
- identification of key scenarios and qualitative assessment of risks
- evaluation of the risks against the following qualitative criteria from HIPAP 4 (DoP, 2011d):
  a. *All 'avoidable' risks should be avoided. This necessitates the investigation of alternative locations and alternative technologies, wherever applicable, to ensure that risks are not introduced in an area where feasible alternatives are possible and justified.*
  b. *The risk from a major hazard should be reduced wherever practicable, irrespective of the numerical value of the cumulative risk level from the whole installation. In all cases, if the consequences (effects) of an identified hazardous incident are significant to people and the environment, then all feasible measures (including alternative locations) should be adopted so that the likelihood of such an incident occurring is very low. This necessitates the identification of all contributors to the resultant risk and the consequences of each potentially hazardous incident. The assessment process should address the adequacy and relevancy of safeguards (both technical and locational) as they relate to each risk contributor.*
  c. *The consequences (effects) of the more likely hazardous events (i.e., those of high probability of occurrence) should, wherever possible, be contained within the boundaries of the installation.*
  d. *Where there is an existing high risk from a hazardous installation, additional hazardous developments should not be allowed if they add significantly to that existing risk.*
- demonstration of adequacy of the proposed technical and management controls to ensure ongoing safety of the proposed development
- should include all facilities which reported exceedances of initial screening thresholds.

4.2 Level 1 Risk Criteria

The risk criteria from Australian Standard *AS 4360:2004 – Risk Management* were used for this Level 1 assessment. The criteria for consequence severity, frequency estimation and the associated risk matrix used in the Level 1 assessment are presented in **Appendix A**.

4.3 Hazardous Materials

4.3.1 Lithium-Ion Batteries

The primary hazardous materials of concern to be located at the Project site are LIBs. LIBs comprise of:

- an anode (typically graphite) with a copper current collector
- a cathode (e.g., lithium iron phosphate - $LiFePO_4$ or LFP) with an aluminium current collector
- a porous separating layer between the anode and cathode (typically a polymer)
- an electrolyte comprised of a lithium salt (e.g., $LiPF_6$) dissolved in a flammable hydrocarbon solvent (e.g., one part Ethylene Carbonate and two parts Diethyl Carbonate).

4.3.1.1 LIB Hazards

During normal use LIBs are sealed and, unlike lead acid batteries, do not vent to the atmosphere during normal operation. However, if subject to abnormal heating (external or internal) or other abuse, flammable electrolyte and electrolyte decomposition products can vaporise, rupture the battery cell and be vented (Fire Protection Research Foundation, 2016). Vented electrolyte and electrolyte decomposition products may ignite if exposed to an ignition source including sparks, open flames and LIB cells undergoing thermal runaway.

Thermal runaway occurs when the internal temperature of a LIB cell increases beyond its operating range leading to exothermic decomposition reactions generating additional heat. If the additional heat is not dissipated, the cell temperature is further elevated, accelerating the process of decomposition and heat generation. LIBs are susceptible to thermal runaway which can be initiated by a range of mechanisms including electro-chemical abuse (e.g., from overcharging, over-discharging and over voltage charging), mechanical abuse (e.g., physical damage to cell causing a short circuit), thermal abuse (overheating from an external source), manufacturing defects (e.g., internal short circuits) and design faults (e.g., inadequate clearance between cells or modules to allow heat dissipation). Statistics for electric vehicle fires attribute 80% of fires to spontaneous ignition events (Bravo-Diaz et al., 2020) suggesting manufacturing defects, internal defects that develop over time and design faults are the primary cause of LIB fires.

The vented gases from LIBs during thermal runaway can exceed 600°C and are likely to include flammable (alkyl-carbonates, methane, ethylene, ethane, hydrogen gas) and toxic species (carbon monoxide, HF, phosphorus pentafluoride and phosphoryl fluoride), soot and particulates containing oxides of nickel, aluminium, lithium, copper and cobalt. Larsson et al. (2017) report on experimental work undertaken for a range of different LIB cell types including cells with a lithium cobalt oxide cathode ($LiCoO_2$ orLCO) and LFP cathode to determine toxic gas release rates and heat release rates. The experimental apparatus allowed for measurement of both phosphoryl fluoride and HF. However, phosphoryl fluoride was only detected during thermal runaway of the LCO type cell and indicates that phosphorus pentafluoride is rather short lived. It is understood that the most likely cell type to be used in the BESSs will be LFP. LFP cells are reported to have a greater thermal stability than LCO and lithium manganese oxide ($LiMn_2O_4$ or LMO) cells (Kong et al., 2018). The onset of thermal runaway in LFP cells has been reported as occurring at 246°C (Kong et al., 2018).

The flammable gases pose both a fire risk, if immediately ignited, and an explosion risk if accumulated in significant quantities within a confined space (e.g., in an enclosed module) prior to ignition.

A study to quantify the toxic gas emissions associated with LIB fires found that HF may be generated in amounts of approximately 20–200 mg/Wh of nominal battery capacity for a range of battery types and chemistries (Larsson et al., 2017). If the enclosed battery modules to be installed at the Project have a capacity of 0.1 to 0.3 MWh each, there is significant potential for generation of toxic HF which has a peak limited workplace exposure limit of 2.6 mg/m^3.

Abnormal events resulting in the venting of vaporised electrolyte and decomposition products from LIBs have the potential for fire, explosion and toxic gas hazards. **Figure 4.1** presents an event tree showing the potential hazard events associated with LIBs.

4.3.1.2 LIB Fire Response

There are a range of effective suppressants for extinguishing LIB fires (e.g., dry chemical powder, inert gas, foam, water), however events involving thermal runaway often re-ignite unless cooling is sufficient to inhibit the exothermic decomposition reactions. In one fire suppression test conducted on a full-scale model vehicle in 2013 by the Fire Protection Research Foundation, the battery reignited 22 hours after the open flame was extinguished (Kong et al., 2018). Studies have shown that water is the most effective method for extinguishing thermal runaway LIB fires and preventing re-ignition (Ghiji et al., 2020).

Where the installation permits, response to a LIB fire can involve allowing the battery pack to slowly burn itself out while applying cooling to nearby infrastructure as required. Tesla's emergency response guidance advises this fire response approach for Tesla Megapacks (Fisher Engineering and Energy Safety Response Group, 2022) which are designed and installed such that fire propagation between battery packs does not occur when subject to the conditions in *Underwriters Laboratory (UL) 9540A Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems* (Underwriters Laboratory, 2017) (UL 9540A). Fluence Energy (Fluence) (2022) reported that, in the unlikely event one of their Cube's goes into thermal runaway, an extreme internal battery failure is designed to be contain to a single Cube and not spread through an energy storage system. This was demonstrated by DNV where a large-scale fire test in the energy storage product surpassed the industry's UL9540A safety testing requirements.

4.3.1.3 Recent BESS Hazardous Events

Victorian Big Battery Fire

The Victorian Big Battery (VBB) facility is a 450 MWh grid scale BESS locate in Geelong, Victoria consisting of 212 Tesla Megapack units. A Tesla Megapack is a self-contained LIB BESS consisting of battery modules, power electronics, a thermal management system and control systems. Following is a summary of a fire incident that occurred at the VBB in July 2021, based on *Victorian Big Battery Fire: July 30, 2021, Report Of Technical Findings* (Fisher Engineering and Energy Safety Response Group, 2022).

On Friday 30 July 2021 at around 10:00 am while testing and commissioning was being undertaken at the facility, smoke was observed coming from one Megapack that had been manually shut down as it was not part of the testing and commissioning program for the day. At that time all Megapacks at the facility were electrically isolated and the Country Fire Authority (CFA) called to site. At approximately 10:30 am the CFA arrived at the facility and flames were observed coming from the Megapack. The CFA applied cooling water to nearby infrastructure but did not apply water directly to the burning Megapack in accordance with Tesla emergency response guidance. Flames were observed coming from an adjacent Megapack at approximately midday. Visible flames from the first Megapak to ignite subsided at approximately 12:30 pm and from the second Megapack at approximately 4:00 pm. A fire watch was maintained until approximately 3:00 pm on Monday 2 August 2021 at which time the CFA deemed the site under control.

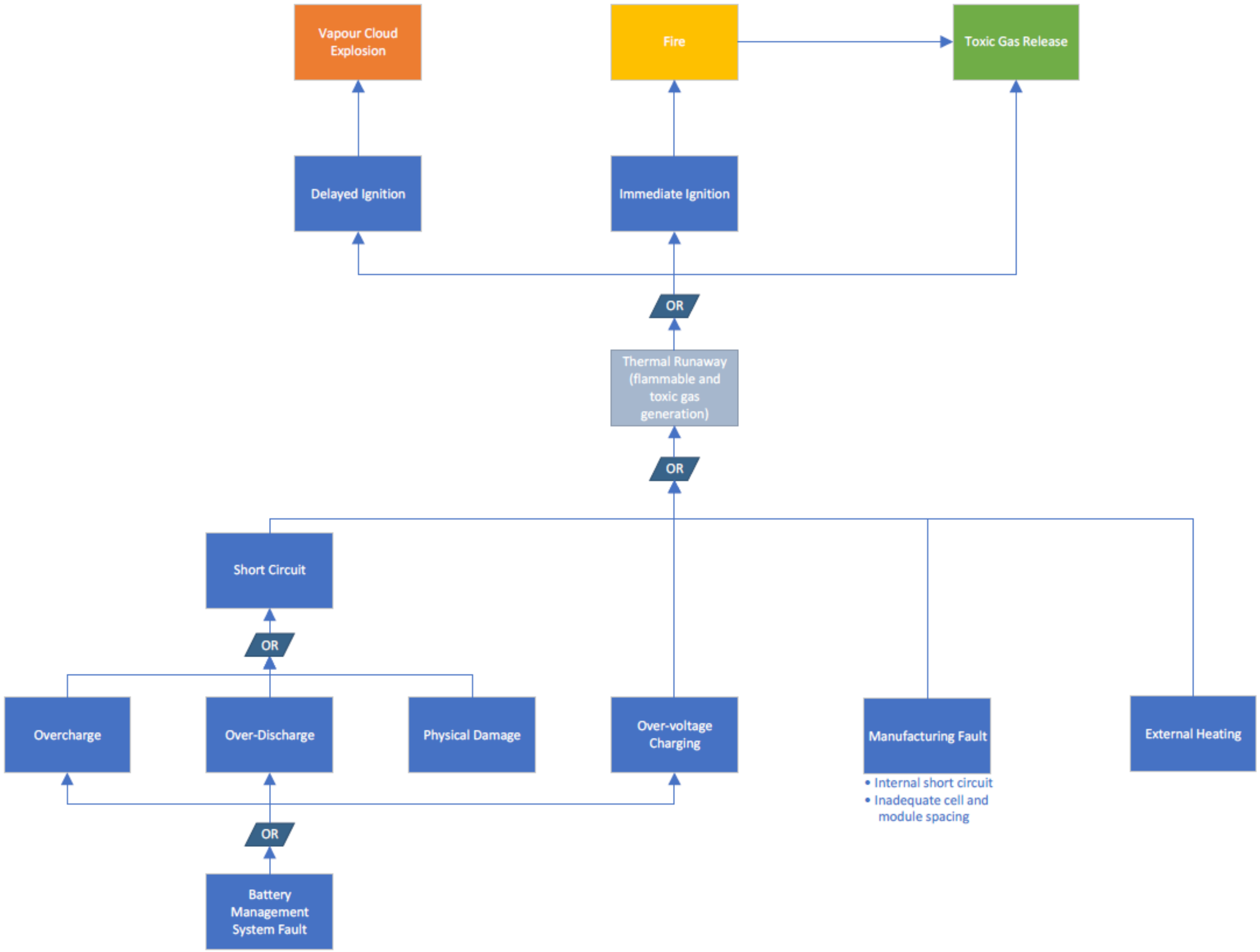


Figure 4.1 Lithium-Ion Battery Hazard Event Tree

The key findings from an investigation into the VBB fire relating to causes and contributing factors are summarised as follows:

- The most likely root cause of the fire was a leak within the liquid cooling system causing arcing in the power electronics of the Megapack's battery modules.
- A Megapack supervisory control and data acquisition (SCADA) system required 24 hours to setup a connection for new equipment and provide full telemetry data functionality and remote monitoring by Tesla operators. The Megapack that ignited had only been in service for 13 hours prior to being shut down via the keylock switch on the morning of the fire and as such, had not been on-line for the required 24 hours. This prevented the unit from transmitting telemetry data (internal temperatures, fault alarms, etc.) to Tesla's off-site control facility.
- The liquid coolant leak onto the battery modules is likely to have disabled the power supply to the circuit that actuates the pyro disconnect which is designed to interrupt a fault current passing through the battery module prior to it escalating into a fire event.
- Flames exiting the roof of first Megapack to ignite were impacted by 37 to 56 km/h winds which pushed the flames towards the roof of the second Megapack to ignite. This direct flame impingement on the thermal roof of the second Megapack ignited the plastic overpressure vents that seal the battery bay from the thermal roof. The burning overpressure vents provided a direct path for flames and hot gases to enter into the battery bays, exposing the battery modules to temperatures above their thermal runaway threshold. While Tesla Megapacks have been tested to UL9540A, the wind conditions during testing are limited to 19.3 km/h which is approximately two to three times lower than the wind conditions experienced during the VBB fire incident.

The key findings relating to the VBB fire response are summarised as follows:

- There was effective pre-incident planning at the VBB facility with an Emergency Action Plan (EAP) and an Emergency Response Plan (ERP) available to emergency responders. The EAP and ERP were found to have been effectively used during the VBB fire with all site employees and contractors following proper evacuation protocols during the fire.
- Pre-incident plans were in place that clearly identified the subject matter experts, how to contact them, their role and other key tasks. It is understood that the facility subject matter experts provided valuable information and expertise to the CFA incident controller throughout the VBB fire.
- Available data and visual observations of the fire indicate that water application had limited effectiveness in terms of limiting fire propagation between Megapacks. Thermal insulation appears to be the primary factor in reducing heat transfer to adjacent Megapacks, however, water was effectively used to protect other equipment which was not designed with the same level of thermal protection as a Megapack.

The investigation of the VBB fire identified several gaps in commissioning procedures, electrical fault protection devices and thermal roof design which has resulted in the implementation of a number of procedural, firmware, and hardware mitigations to address these gaps. Further, the investigation demonstrates the importance of understanding the limitations and parameters of testing undertaken to achieve certification (e.g., the wind speed parameters in UL9540A) with respect to the likely conditions that will be experienced on site.

McMicken Battery Energy Storage System Explosion

The 2 MWh McMicken BESS was located in Arizona, USA and housed in a container with over 10,000 LIB cells arranged in racks and modules (Institute of Electrical and Electronics Engineers Spectrum (IEEE Spectrum), 2020). On 19 April 2019, the Peoria Arizona Hazmat team responded to a call reporting smoke and odour in the area around the McMicken BESS. When the door of the BESS was opened by the Hazmat team captain, flammable gases that had accumulated in the container mixed with air to form an explosive mixture which ignited. The deflagration threw the captain approximately 22 m and another fire fighter 10 m from the BESS container door resulting in serious injuries.

Separate investigations into the explosion event were undertaken by a third party (DNV-GL) and the battery manufacturer (LG Chem). DNV-GL concluded that a single battery cell failure had initiated a cascading thermal runaway event that generated the flammable gases. LG Chem disputed this finding and concluded that external heating (e.g., electrical arcing) had initiated the thermal runaway event. While the event that triggered initiation of thermal runaway cannot be confirmed, there are a number of other factors that contributed to the resulting explosion including:

- the absence of adequate thermal barrier protections between battery cells allowing rapid propagation through the battery rack
- the container not being ventilated to the outside, therefore allowing for accumulation of flammable gases.

4.3.1.4 Project Batteries

As indicated in **Section 4.3.1.1** the LIB cell type that will most likely be utilised at the Project will be a LFP which is considered to have greater thermal stability compared to other typical LIB cell types (e.g. LCO or LMO). It is proposed the 570 MWh Project BESS will incorporate a fully integrated systems of battery racks and modules, controllers, cooling, solid aerosol fire suppression and deflagration panels.

4.3.2 Electrical Transformers

The Project will incorporate a 500 kW substation with one oil filled electrical transformer. There will also be 73 smaller 33 kV transformers distributed across the Project site. Transformer oils are typically combustible mineral oils that are used for their electrical insulating properties (thermally conductive) and stability at high temperature. The primary function of the mineral oil is to insulate and cool the transformer.

Leakage of transformer oil can result in environmental problems due to toxicity and fire and/or explosion accidents should leaking oil directly contact high-voltage elements or other ignition sources. Under abnormal operating conditions when the internal temperature of a transformer reaches 150 to 300°C the mineral oils produce hydrogen and methane gases due to chemical decomposition (El-Harbawi & Fahad Al-Mubaddel, 2020). When temperatures exceed 300°C ethylene is formed, and large amounts of both hydrogen and ethylene are produced when temperatures exceed 700°C (El-Harbawi & Fahad Al-Mubaddel, 2020). While contained in the transformer, these gases tend to dissolve in the mineral oil but will form flammable mixtures if released from the transformer oil compartment, potentially resulting in fire or explosion events (El-Harbawi & Fahad Al-Mubaddel, 2020).

4.4 Hazard Study

A hazard identification study was undertaken using guidewords as prompts to assist with identification of potential hazardous events and scenarios that could have off-site impacts. Credible hazardous events and scenarios were recorded, and risk scoring was applied for each. The hazard identification worksheets are attached in **Appendix B**.

The hazard study identified the following hazard scenarios with the potential for off-site consequences requiring further assessment (i.e., semi-quantitative assessment):

- a LIB fire
- a LIB vapour cloud explosion that requires:
    - the generation of gas from sufficient number of cells to form a significant mass of flammable gas due to thermal runaway
    - ignition of the vapour cloud.
- a toxic release of HF associated with a thermal runaway event in a LIB.

While the hazard study also identified a transformer fire as a scenario with the potential for off-site impacts, it was considered that substation design, installation, commissioning, operation and maintenance of the transformers in accordance with relevant Australian Standards will be adequate to ensure off-site risks from this scenario are acceptable.

The substation layout and plant installed will also comply with any specific development, regulatory, environmental or TransGrid design requirements applicable to the construction of the substation.

4.5 Qualitative Analysis

Based on the results of the hazard identification study the qualitative analysis cannot demonstrate that there will be no off-site consequences that could impact sensitive adjoining land uses. Therefor a Level 2 Semi-Quantitative Risk Assessment is warranted.

5.0 Level 2 Semi-Quantitative Risk Analysis

Based on the outcomes of the Level 1 Qualitative Risk Analysis (refer to **Section 4.5**) the following hazardous events have been further assessed by application of semi-quantitative risk analysis:

- a LIB fire
- a LIB vapour cloud explosion that requires:
    - the generation of gas from sufficient number of cells to form a significant mass of flammable gas due to thermal runaway
    - ignition of the vapour cloud.
- a toxic release of HF associated with a thermal runaway event in a LIB.

Fire, explosion and toxic gas release events have been modelled to determine the required distance that LIB units should be distanced from the site boundary and involved dwellings to ensure the risk criteria provided in HIPAP 4 (DoP, 2011d) are met.

Section 5.1 provides the relevant NSW risk criteria that apply to the Project. **Section 5.2** and **Section 5.3** detail the methodology and results of consequence and likelihood analysis. The results of the consequence and likelihood analysis are used to assess the Project risks against the relevant NSW risk criteria in **Section 6.0**.

5.1 Risk Criteria

HIPAP 4 (DoP, 2011d) provides individual risk criteria for fatality, injury, and property damage/accident propagation as described in the following sections.

5.1.1 Individual Fatality Risk

Individual fatality risk is estimated assuming that an individual is at the point of risk exposure (i.e., with exposure to a potentially fatal consequence, such as 23 kW/m^2 of thermal radiation, that is estimated to occur at a particular frequency) 24 hours per day, 365 days per year. The different individual fatality risk criteria applied by HIPAP 4 (DoP, 2011d) to various types of land use are presented in **Table 5.1**.

Table 5.1 Individual Fatality Risk Criteria

Land Use	Risk Criteria (fatalities/million/year)
Hospitals, schools, child-care facilities, old age housing	0.5
Residential, hotels, motels, tourist resorts	1
Commercial developments including retail centres, offices and entertainment	5
Sporting complexes and active open space	10
Industrial	50

Source: HIPAP No. 4 – Risk Criteria for Land Use Safety Planning (DoP, 2011d).

5.1.2 Individual Injury Risk

Individual injury risk is estimated assuming that an individual is at the point of risk exposure (i.e., with exposure to a potentially injurious consequence, such as 4.7 kW/m^2 of thermal radiation, that is estimated to occur at a particular frequency) 24 hours per day, 365 days per year. The HIPAP 4 injury risk criteria for different hazardous event consequences are presented in **Table 5.2**.

Table 5.2 Individual Injury Risk Criteria

Land Use	Risk Criteria (injuries/million/year)
Thermal radiation of 4.7 kW/m^2	50
Explosion overpressure of 7 kPa	50
Toxic concentrations (toxic gas, dust, smoke) resulting in serious injury	10
Toxic concentrations (toxic gas, dust, smoke) resulting in irritation	50

Source: HIPAP No. 4 – Risk Criteria for Land Use Safety Planning (DoP, 2011d).

5.1.3 Property Damage and Accident Propagation Criteria

Hazardous events may also result in damage to nearby structures as well as initiate further hazardous events such as fires and explosions at adjoining industrial developments. **Table 5.3** presents the HIPAP 4 (DoP, 2011d) criteria for exposure to thermal radiation and explosion overpressure consequences at neighbouring potentially hazardous installations or at land zoned to accommodate such installations.

Table 5.3 Property Damage and Accident Propagation Risk Criteria

Land Use	Risk Criteria (exposures/million/year)
Thermal Radiation of 23 kW/m^2	50
Explosion Overpressure of 14 kPa	50

Source: HIPAP No. 4 – Risk Criteria for Land Use Safety Planning (DoP, 2011d).

5.2 Consequence Analysis

The potential off-site impacts of the hazardous events identified for quantitative assessment of consequences (refer to **Section 4.4**) are exposure to damaging, injurious and fatal levels of thermal radiation, explosion overpressure and toxic gas. **Section 5.2.1**, **Section 5.2.2** and **Section 5.2.3** outline the potential impacts associated with radiation, explosion overpressure and toxic gas exposures and the modelled extent of various levels of impact for these hazardous scenarios.

5.2.1 Fire

This section details the methodology and results for the estimation of thermal radiation impact distances associated with a BESS fire scenario.

5.2.1.1 Impacts of Thermal Radiation Exposure

Table 5.4 presents the likely effects of various levels of thermal radiation on individuals and structures.

Table 5.4 Consequences of Thermal Radiation

Thermal Radiation (kW/m^2)	Effect
1.2	Received from the sun at noon in summer.
2.1	Minimum to cause pain after 1 minute.
4.7	Will cause pain in 15-20 seconds and injury after 30 seconds' exposure (at least second-degree burns will occur).
12.6	Significant chance of fatality for extended exposure. High chance of injury. Causes the temperature of wood to rise to a point where it can be ignited by a naked flame after long exposure. Thin steel with insulation on the side away from the fire may reach a thermal stress level high enough to cause structural failure.
23	Likely fatality for extended exposure and chance of fatality for instantaneous exposure. Spontaneous ignition of wood after long exposure. Unprotected steel will reach thermal stress temperatures which can cause failure. Pressure vessel needs to be relieved, or failure would occur.
35	Cellulosic material will pilot ignite within one minute's exposure. Significant chance of fatality for people exposed instantaneously.

Source: HIPAP No. 4 – Risk Criteria for Land Use Safety Planning (DoP, 2011d).

5.2.1.2 Fire Event Modelling

Fire scenario modelling was undertaken to estimate the incident heat flux experienced by a receiver at varying distances from the front of a LIB. Two representative sizes were considered: Option (1) 1 m wide x 2.2 m high x 1.3 deep and Option (2) up to 2.6 m wide x 2.6 m high x 2.3 m deep. This analysis is independent of the reported performance of proprietary LIB modules but is considered indicative of modules currently available on the market.

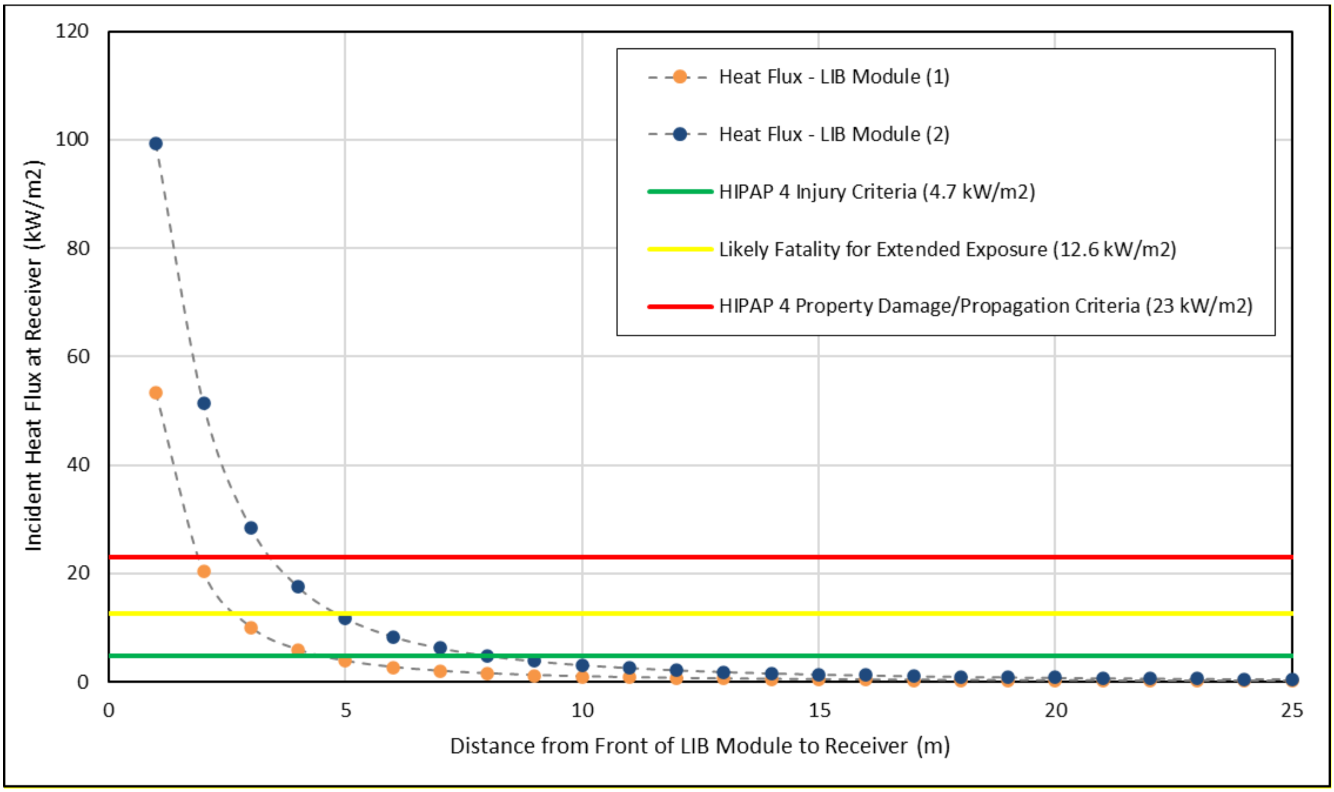
The emitted heat flux from a LIB module was estimated using the Stefan – Boltzmann equation based on the following conservative assumptions:

- an emitting surface temperature of 1,000°C (1,273.15 K)
- a surface emissivity of 1 (i.e., a black body).

Incident heat flux was estimated based on the estimated emitted heat flux and the configuration factors determined at varying distances from the centreline of the front of a representative LIB module. Incident heat flux results, showing the heat flux at varying distances from the LIB module are presented in **Graph 5.1** and the radiation calculations are contained in **Appendix C**.

The results in **Graph 5.1** indicate that the:

- incident heat flux falls below the HIPAP 4 (DoP, 2011d) property damage and propagation criteria of 23 kW/m^2 at a distance of approximately 4 m in front of the larger of the two LIB modules
- incident heat flux falls below the heat flux at which likely fatality will occur (i.e. 12.6 kW/m^2) at a distance of approximately 5 m in front of the larger of the two LIB modules
- incident heat flux falls below the HIPAP 4 (DoP, 2011d) injury criteria of 4.7 kW/m^2 at a distance of approximately 9 m in front of the larger of the two LIB modules.



Graph 5.1 Incident Heat Flux at Varying Distances from representative LIB Module Fires

The expected consequences associated with exposure to each level of thermal radiation for individuals and structures within the impact distance are outlined in **Table 5.4**. The maximum distance at which an individual exposed to thermal radiation from a BESS fire could experience an injury based on HIPAP 4 injury criteria (4.7 kW/m^2) is estimated to be 9 m.

5.2.2 Explosion

This section details the methodology and results for the estimation of overpressure impact distances associated with a BESS explosion scenario.

5.2.2.1 Impacts of Explosion Overpressure Exposure

Table 5.5 presents the likely effects of various levels of explosion overpressure on individuals and structures.

Table 5.5 Consequences of Explosion Overpressure

Explosion Overpressure (kPa)	Effect
3.5	90% glass breakage. No fatality and very low probability of injury.
7	Damage to internal partitions and joinery but can be repaired. Probability of injury is 10%, no fatality.
14	House uninhabitable and badly cracked.
21	Reinforced structures distort. Storage tanks fail. 20% chance of fatality to a person in a building.
35	House uninhabitable. Wagons and plants items overturned. Threshold of eardrum damage. 50% chance of fatality for a person in a building and 15% chance of fatality for a person in the open.
70	Threshold of lung damage. 100% chance of fatality for a person in a building or in the open. Complete demolition of houses.

Source: HIPAP No. 4 – Risk Criteria for Land Use Safety Planning (DoP, 2011d).

5.2.2.2 Explosion Overpressure Modelling

A representative LIB module explosion scenario was developed based on:

- generation of flammable gas species (ethylene, ethane, methane and carbon monoxide) and quantities for battery cells with one part ethyl carbonate and two parts diethyl carbonate was based on experimental test results presented in *In-situ analysis of gas generation in lithium ion batteries with different carbonate-based electrolytes* (Xin Teng et al., 2015)
- the free internal volume is filled with a flammable gas mixture at the UEL of ethylene (i.e., 36 % by volume) with other flammable gases in the same relative proportions (ethane, methane and carbon monoxide) as presented in *In-situ analysis of gas generation in lithium ion batteries with different carbonate-based electrolytes* (Xin Teng et al., 2015)
- a free internal volume of 7.8 m^3 of representative LIB module based on dimensions of up to 2.6 m high x 2.6 m wide x 2.3 m deep (Option (2) above) and 50% of the space within the unit being occupied by equipment.

Outputs from spreadsheet calculations to determine the quantities of the flammable gases in the representative LIB module are presented in **Appendix C**.

Explosion overpressures were estimated using the TNO Multi Energy Method in BREEZE® Incident Analyst (BREEZE®) hazardous incident modelling software.

The following parameters were applied in BREEZE® for the modelling of the explosion scenario described above:

- A 3.8 kg flammable gas mixture containing (by mass):
  - Carbon Monoxide, 31.3%.
  - Ethane, 1.2 %.
  - Ethylene, 67.4%.
  - Methane, 0.1%.
- Charge Strength of 10 due to confinement in the representative LIB module.

Table 5.6 presents the predicted overpressure impact distances (radii) from a representative LIB module explosion scenario described above.

Table 5.6 Estimated Explosion Overpressure Radii from a representative LIB Module

Overpressure (kPa)	Radius (m)
7	43
14	26
21	21

The expected consequences associated with exposure to each overpressure for individuals and structures within the overpressure radii are outlined in **Table 5.5**. **Appendix C** contains the BREEZE® input and output text file for the explosion scenario. The maximum distance at which an individual exposed to overpressure from a BESS explosion event could experience an injury based on HIPAP 4 injury criteria (i.e., 7 kPa) is estimated to be 43 m.

5.2.3 Toxic Gas

This section details the methodology and results for the estimation of toxic gas impact distances associated with a BESS toxic gas release.

5.2.3.1 Impacts of Toxic Gas Exposure

Acute Exposure Guideline Levels[2] (AEGLs) may be used by emergency planners and responders worldwide to guide land use planning for installations that have the potential to accidentally release hazardous chemicals into the air. AEGLs are expressed as specific concentrations of airborne chemicals; that when exposed to for a given period of time, are likely to cause health effects in the elderly, children, and other individuals who may be more susceptible than the majority of the population.

[2] The Acute Exposure Guideline Levels (AEGL) are similar but not the same as the Emergency Response Planning Guideline (ERPG) Levels. AEGL are expressed as exposure levels for periods of 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours. ERPG levels are the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour.

AEGLs are calculated for five relatively short exposure periods – 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours with AEGL 'levels' dictated by the severity of the toxic effects caused by the exposure. Level 1 AEGLs are the least severe and Level 3 are the most severe (refer to **Table 5.7**).

Table 5.7 Acute Exposure Guideline Levels and Health Effects

AEGL	Health Effect
1	Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
2	Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
3	Life-threatening health effects or death.

Source: About Acute Exposure Guideline Levels, United States Environmental Protection Agency, 2021.

As mentioned, AEGL values represent threshold levels for the general public that includes susceptible subpopulations, such as infants, children, the elderly, persons with asthma, and those with other illnesses. It should, however, be noted that individuals subject to unique or idiosyncratic responses could experience the effects described in **Table 5.7** at concentrations below the corresponding AEGL.

5.2.3.2 Toxic Gas Dispersion Modelling

As discussed in **Section 4.3.1**, LIBs in a thermal runaway event are known to release a range of toxic gases, in particular, fluoride gas species. Of the identified toxic gas species that may be released during a LIB thermal runaway/fire event with LFP type cells (i.e., the cells that are likely to be used in the Project BESSs), HF is the most toxic gas likely to be present in a significant release event that (refer to **Section 4.3.1**). As such, the toxic gas release consequence assessment has been based on HF emissions. **Table 5.8** presents the HF concentrations corresponding to the respective AEGL health effects for a one-hour exposure.

Table 5.8 Acute Exposure Guideline Levels - One-hour Exposure to Hydrogen Fluoride

AEGL	Health Effect	HF Concentration (ppm)
1	Irritation	1
2	Injury	24
3	Life-threatening health effects	44

Source: About Acute Exposure Guideline Levels, United States Environmental Protection Agency, 2021.

Given the highly toxic nature of HF, the consequence assessment for a toxic release scenario has been based on a release of HF. It is considered that if HIPAP 4 (DoP, 2011d) criteria are satisfied for a HF release then the criteria will be satisfied for other less toxic gases, neglecting any cumulative effects of different toxic species. The HF gas emission rate was based on the following experimental data:

- The maximum emission rate of HF from a battery pack with an energy capacity of 128 Wh and nominal capacity per LFP battery cell of 20 Ah in a thermal runaway/fire event is 198 mg/Wh which has been derived from experimental data presented in *Toxic fluoride gas emissions from lithium-ion battery fires* (Larsson et al., 2017). Note that while the LIB for the Project will be 280 Ah, experimental emission data does not indicate a relationship between HF emission rate and battery cell Ah capacity but with the burn rate of the battery cell (Wh/s). As such, the maximum HF emission rate (conservatively nominated at 200 mg/Wh burnt) has been applied to the toxic release scenario.

- The burn rate of a 100 kWh LIB module with LFP battery cells is 7.4 Wh/s which has been derived from experimental data published in *Hazard Assessment of Lithium Ion Battery Energy Storage Systems* (Fire Protection Research Foundation, 2016).

A HF emission rate of 1.48 g/s was determined using the above data as shown in the HF emission rate calculations presented in **Appendix C**. Dispersion modelling of the HF release was undertaken using the AFTOX Gaussian plume dispersion model in the BREEZE® software package based on the following conservative assumptions:

- the release is pure HF and at close to ambient temperature (non-buoyant) when released from a LIB module
- adverse meteorological conditions with a stability class of F (moderately stable) and a wind speed of 1.5 m/s (at a height of 10 m).

Table 5.9 Modelled Distance to Hydrogen Fluoride 1-hour AEGL Concentrations

AEGL	Health Effect	Modelled Distance to AEGL for HF Emission of 1.48 mg/s (m)
1	Irritation	573
2	Injury	68
3	Life-threatening health effects	42

The expected consequences associated with exposure to AEGL concentrations for individuals within the concentration impact distance are outlined in **Table 5.7**. **Appendix C** contains the BREEZE® input and output text file for the explosion scenario. The maximum distance at which an individual exposed to HF emissions from a BESS toxic release event could experience an injury (i.e., exposure to the AEGL Level 2 concentration of 24 ppm for 60 minutes) is estimated to be 68 m.

5.3 Frequency Analysis

Given large-scale stationary grid-connected LIB systems are only recently becoming prominent, there is limited data on the frequency of significant hazardous events associated with such systems. Statistics collected by agencies (Bravo Diaz et al., 2020) in specific sectors indicate the following:

- An average of 31 LIB electric vehicle fires are recorded in China every year.
- The USA National Transport Safety Board reported 17 Tesla and 3 BMWi3 LIB fires out of 350,000 and 100,000 electric vehicles respectively. This equates to fire frequencies of 4.9×10^{-5} for Teslas and 3.0×10^{-5} for BMWs.
- The USA Federal Aviation Authority has recorded 252 air and airport fire incidents involving LIBs in cargo or baggage since 2006.
- The USA Consumer Product Safety Commission reported 25,000 fires in more than 400 consumer products between 2012 and 2017.

A number of stationary grid-connected LIB fire incidents have been identified including:

- a fire and explosion at the Arizona Public Co. 2 MW Battery Storage System in 2019 which injured a team of firefighters (refer to **Section 4.3.1.3**)
- more than 20 battery storage system fires in South Korea from 2018 and 2019
- a battery storage system fire at a home in Brisbane in December 2018 (S&P Global Market Intelligence, 2019
- a fire at the 450 MWh Victorian Big Battery Project near Geelong in Victoria in July 2021 (refer to **Section 4.3.1.3**).

While the data presented above could be considered an indication of high LIB failure frequency, a representative of Underwriters Laboratories indicates that the failure rate of LIB cells is approximately one in 12 million (S&P Global Market Intelligence, 2019). However, as there are billions of LIB cells worldwide, failures will occur and some of these failures may lead to fire, explosion or toxic release events should appropriate layers of protection not be in place.

A variety of methods (e.g., failure mode analysis, physics-based model of prediction, empirical model of prediction) are used to predict BESS failure rates with varying success. Additionally, there are numerous factors that limit the accuracy and usefulness of predictions (Wong, 2022) including the following primary factors:

- there are many different failure modes for a BESS, and they are not uniformly defined due to the variance in the fire resistance and fire/explosion propagation characteristics of different LIB types and the wide range of operating conditions a BESS may be subjected to
- reliability data for BESSs is limited and the data is often based on fixed temperatures and cycling conditions that do not reflect real world use
- BESS development to increase energy density, efficiency and increased integrity is rapid and potentially renders the failure rate data of older designs obsolete.

Given the relatively recent proliferation of LIB technology for large-scale energy storage, numerical frequency data for LIB fire, explosion and toxic release events is limited and the reliability of predictive methods for failure rate uncertain. As such, a semi-quantitative approach to LIB hazardous event frequency estimation has been undertaken. Appendix F of Australian and New Zealand Standard, Pipelines – Gas and liquid petroleum Part 6: Pipeline safety management (AS/NZS 2885.6) provides a guide for semi-quantitative estimation of event frequencies as presented in **Table 5.10**. **Table 5.11** presents numerical frequency ranges that could be applied to qualitative descriptions of frequency sourced from Lee et al., 2011.

Consideration of the outcomes of the Level 1 Qualitative Risk Analysis (refer to **Section 4.5**) with respect to the descriptions and numerical frequencies presented in **Table 5.10** and **Table 5.11** suggests the numerical frequencies for a significant LIB fire, explosion or toxic gas release event that could result in off-site impacts is in the order of 10^{-5} (Remote to Hypothetical event in **Table 5.10**) to 10^{-8} (lower numerical frequency value for a Remote event in **Table 5.11)**. Based on the narrative above and for the purpose of this assessment a numerical frequency of 10^{-5} events/year has been adopted for a significant LIB fire, explosion or toxic gas release event that could result in off-site impacts.

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Table 5.10 AS/NZS 2885.6 Frequency Classes

Class	Description	Numerical Guidelines (events/1,000 km/year)
Frequent	Expected to occur once per year or more.	≥1
Occasional	May occur occasionally in the life of the pipeline.	1 to 0.1
Unlikely	Unlikely to occur within the life of the pipeline, but possible.	0.1 to 0.001 (10^{-1} to 10^{-3})
Remote	Not anticipated for this pipeline at this location.	0.001 to 0.00001 (10^{-3} to 10^{-5})
Hypothetical	Theoretically possible but would only occur under extraordinary circumstances.	<0.00001 ($<10^{-5}$)

Source: Australian and New Zealand Standard, Pipelines – Gas and liquid petroleum Part 6: Pipeline safety management.

Table 5.11 Qualitative and Numerical Frequencies

Qualitative Description	Numerical Frequency
Likely	$>10^{-2}$
Unlikely	10^{-2} to 10^{-4}
Very Unlikely	10^{-4} to 10^{-6}
Remote	10^{-6} to 10^{-8}

Source: Risk Ranking of Events by Frequency, Consequence and Attenuating Factor: A Three Variable Risk Ranking Technique (Lee et al., 2011).

6.0 Risk Assessment

The following risk assessment is based on a comparison of the results of the semi-quantitative risk analysis presented in **Section 5.2** and **Section 5.3** with HIPAP 4 (DoP, 2011d) risk criteria (refer to **Section 5.1**).

6.1 Individual Fatality Risk

The maximum modelled distances (refer to **Section 5.2**) from a LIB module to fatal impacts associated with fire, explosion and toxic gas release events are presented in **Table 6.1**.

Table 6.1 Maximum Modelled Distance to Fatal Impacts

Hazard Event	Distance (m)
Fire (12.6 kW/m^2 contour)	5
Explosion (14 kPa contour)*	26
Toxic Gas Release (HF AEGL 3 contour, 44 ppm contour)	42

**Conservative assumption that fatality will occur for all exposed individuals at the 14 kPa overpressure contour noting that HIPAP 4 indicates a 20% fatality likelihood at an overpressure of 21 kPa.*

The HIPAP 4 individual fatality risk criteria for residential land use (the most sensitive land use considered applicable for the majority of the land surrounding the Project) is 1 x 10^{-6} fatalities/year. As the estimated frequency of 10^{-5} for a LIB fire, explosion or toxic gas release is greater than the HIPAP 4 individual fatality risk criteria of 1 x 10^{-6} fatalities/year, the LIB modules will need to be located at a distance in excess of 42 m from the site boundary and any involved dwellings to meet HIPAP 4 (DoP, 2011d) individual fatality risk criteria. The proposed location of the BESS shown in **Figure 1.2** is over 1,000 m from the site boundary and over 3,000 m from the single involved dwelling to the west-northwest.

6.2 Injury and Irritation Risk

The maximum modelled distance (refer to **Section 5.2**) from a representative LIB module to injury impacts associated with fire, explosion and toxic gas release events are presented in **Table 6.2.**

Table 6.2 Maximum Modelled Distance to Injury and Irritation Impacts

Hazard Event	Distance (m)
Fire (4.7 kW/m^2 contour)	9
Explosion (7 kPa contour)*	43
Toxic Gas Release – Injury (HF AEGL 2 contour, 24 ppm contour)	68
Toxic Gas Release – Irritation (HF AEGL 1 contour, 1 ppm contour)	573

** Conservative assumption.*

The HIPAP 4 injury risk criteria for thermal radiation and explosion is 50 x 10^{-6} injuries/year which is greater than the estimated frequency of 10^{-5} events/year for a LIB fire or explosion.

The HIPAP 4 injury risk criteria for toxic concentrations is 10 x 10^{-6} injuries/year which is greater than the estimated frequency of 10^{-5} events/year for a LIB toxic gas release.

The HIPAP 4 irritation risk criteria for toxic concentrations is 50 x 10^{-6} injuries/year which is greater than the estimated frequency of 10^{-5} events/year for a LIB toxic gas release.

As such, the HIPAP 4 injury and irritation risk criteria for the Project is considered to be satisfied irrespective of the BESS location. However, Lightsource bp will locate the BESS at least 68 m from the Project site boundary and involved dwelling to minimise the likelihood of injurious off-site impacts.

6.3 Property Damage and Accident Propagation Risk

The maximum modelled distance (refer to **Section 5.2**) from a representative LIB module to property damage and propagation impacts associated with fire and explosion are presented in **Table 6.3**.

Table 6.3 Maximum Modelled Distance to Property Damage and Accident Propagation Impacts

Hazard Event	Distance (m)
Fire (23 kW/m^2 contour)	4
Explosion (14 kPa contour)*	26

* *Conservative assumption.*

The HIPAP 4 property damage and accident propagation risk criteria for thermal radiation and explosion is 50 x 10^{-6} exposures/year which is greater than the estimated frequency of 10^{-5} for a LIB fire or explosion. As such, the HIPAP 4 property damage and accident propagation risk criteria for the Project is considered to be satisfied irrespective of the BESS location. However, as Lightsource bp will locate the BESS at least 68 m from the Project site boundary and involved dwelling to minimise the likelihood of propagation in the highly unlikely event of the modelled worst case BESS fire or explosion occurring, risk of property damage and accident propagation is considered minimal.

With regard to accident propagation between BESS LIB modules it is important to note the conservative nature of both the modelled fire and explosion scenarios. To mitigate potential accident propagation, Lightsource bp will require that separation distances between the BESS and other critical site infrastructure is in accordance with contemporary international best practice guidelines and/or standards including *UL9540A Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems* (Underwriters Laboratory, 2017) and *NFPA 855 Standard for the Installation of Stationary Energy Storage Systems* (National Fire Protection Association, 2020).

7.0 Risk Management

The control of risks is a continuous process where strategies are put into place to eliminate risks wherever possible, mitigate the residual risks identified using appropriate control measures, safeguards and procedures, and, lastly, accept the residual risk and manage the impacts should the hazardous event occur. The risk control strategies and their effectiveness are broadly described as:

- engineering control to either completely eliminate the risk (100% effectiveness) or to implement physical controls and safeguards (minimum 90% effectiveness)
- administrative control based around procedures (maximum 50% effectiveness)
- personnel control using training and the control of work methods (maximum 30% effectiveness).

The qualitative risk assessment identified a range of technical control measures and non-technical safeguards and procedures that will be put in place to eliminate or mitigate the level of risk associated with the operation of the Project.

Technical safeguards are those controls that are incorporated into the process or control system hardware, software or firmware. Non-technical controls are management and operational controls, such as security policies, operational procedures, maintenance procedures and training. Technical and non-technical safeguards can also be divided into preventive controls which inhibit or prevent hazardous events from occurring and detective controls such as control system alarms that warn of unacceptable process deviations, or security monitoring systems that initiate an alarm in the event of violations of security protocols.

There are four key components to mitigating LIB thermal runaway events (Bravo-Diaz et al., 2020):

- Prevention, which is addressed in the system design stage and may be achieved with control of heat generation by:
    - avoiding short circuits with cushioning or isolation materials for cell spacing to avoid mechanical abuse
    - applying cell internal safety design such as shut down separators to reduce or cut off current when short circuit occurs
    - using more thermally stable cathode materials such as LFP instead of LCO.
- Compartmentation, which involves containing or delaying fire propagation within a battery pack once ignition occurs. This may be achieved by increasing cell spacing, dividing battery packs into several compartments with barriers that reduce heat transfer and mechanical impact between compartments.
- Detection of battery conditions (e.g., abnormal terminal voltages, cell temperatures, gas emissions) by the Battery Management System which indicate the onset of thermal runaway and ignition to allow appropriate system shutdowns and preparation for emergency response.
- Suppression, which may involve chemical suppression, cooling (i.e., water mist) or fire isolation.

The following sections outline the technical and non-technical control measures that will be implemented as part of the Project to address the four key components for mitigation of LIB thermal runaway events as well as the control measures relating to electrical transformer hazards.

7.1 Technical Control Measures

The technical control measures that will be implemented as part of the Project will address the key components with regard to LIB hazards and will include:

- Separating the BESS from the site boundary and involved dwelling by at least 68 m which exceeds the maximum predicted fatality, injury and property damage/accident propagation consequence distances for the modelled LIB hazardous events (refer to **Section 6.2**). When the specific battery cell type (i.e., chemistry and capacity) has been determined, a Final Hazard Analysis (FHA) will be completed to confirm the adequacy of separation distances between the BESS and the site boundary/involved dwellings.
- Purchasing a BESS that is designed and constructed to meet the requirements of *UL 9540 Standard for Safety of Energy Storage Systems and Equipment* (UL 9540) (Underwriters Laboratory, 2020).
- Purchasing a BESS that has been demonstrated to avoid fire propagation by being type tested in accordance with *UL9540A Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems* (UL 9540A) (Underwriters Laboratory, 2017). The configuration of the LIB modules for the 'as constructed' Project will be consistent with a configuration determined by the UL9540A testing to achieve no propagation.
- Ensuring the BESS system components purchased have been subject to rigorous factory acceptance testing prior to dispatch from the supplier.
- Ensuring the BESS and Battery Management System (BMS) incorporate adequate instrumentation, interlocks and alarms to minimise the risk of the LIB incubation period (the time at a particular temperature at which thermal runaway is likely to initiate) being approached by shutting down modules/racks and alarming unsafe temperatures or other unsafe conditions such as:
  - loss of cooling
  - charge/discharge voltage or current outside design parameters
  - internal electrical resistance outside design parameters during charging or discharge
  - rack fail-to-trip detected
  - inverter/charge fail-to-trip detected.
- Maintaining the separation distances between LIB module to reduce the risk of accident propagation in accordance with manufacturer's instructions, *NFPA 855 Standard for the Installation of Stationary Energy Storage Systems*, (NFPA 855) (National Fire Protection Association, 2020) and in line with testing conditions set during type testing for UL9540A.
- Ensuring the LIB modules have a solid aerosol fire suppression system.
- Installing the BESS with a freeboard of 300 mm above the 1% AEP flood level.

- Incorporating lightning protection at the Project site to reduce the risk of lightning initiating a LIB hazard event.
- Provisioning the Project site with adequate fire safety systems (e.g., provision of fire water tanks and hydrant booster sets) that will be determined following completion of Project design based on the results of a Fire Safety Study (FSS). The FSS will be prepared in accordance with *HIPAP No. 2 Fire Safety Study Guidelines* (DoP, 2011c) in consultation with NSW Fire and Rescue and will also determine the requirement for any fire water containment systems.
- Ensuring the Project site layout provides emergency services with clear access to all areas of the site that may require an emergency response, in particular to BESS components.

It is noted that Australian and New Zealand Standard *AS/NZS 5139:2019 Electrical Installations – Safety of battery systems for use with power conversion equipment* is only applicable to BESSs with a maximum capacity of 200 kWh and therefore does not apply to the Project BESSs. Further, while international standards such as *EC 62933-5-2:2020 Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems* and *IEC 62619:2017 Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications* are available, Lightsource bp does not consider that they address the full scope of UL 9540, UL 9540A and NFPA 855. *Property Loss Prevention Data Sheet 5-33, Electrical Energy Storage Systems*, (FM Global, 2020) provides general guidance on LIB storage systems, however, the content of the data sheet does not provide a basis for the detailed design of a BESS. *IEC 62897 Stationary Energy Storage Systems with Lithium Batteries - Safety requirements* were a standard understood to be under development, however, it has not been released and it is unclear whether it will be released. As such, Lightsource bp considers UL 9540, UL 9540A and NFPA 855 as the most comprehensive and applicable standards for the design and installation of the Project BESS. In cases where these standards contradict applicable Australian Standards, applicable Australian Standards will take precedence.

The technical control measures that will be implemented as part of the Project to address the hazards associated with electrical transformers are:

- The substation and transformers will be designed, installed, operated and maintained in accordance with:
  - AS/NZS 60076.1:2014 Power transformers General.
  - AS/NZS 60076.6:2013 Power transformers Loading guide for oil-immersed power transformers.
  - AS/NZS 60076.2:2013 Power transformers Temperature rise for liquid immersed transformers.
  - AS 2374.8-2000 Power Transformers – Application Guide.
  - AS1767.1-1999 Insulating liquids - Specification for unused mineral insulating oils for transformers and switchgear.
  - AS/NZS 60076.5:2012 Insulated bushings for alternating voltages above 1000 V.
  - AS 2067-2008 Substation and High Voltage Installations exceeding 1 kV AC.

7.2 Non-Technical Control Measures

The non-technical measures to be implemented for the Project include:

- LIBs will be transported to site by a suitably accredited freight company using dangerous goods licensed vehicles and drivers.
- A detailed Emergency Plan (EP) will be prepared for the Project consistent with *Hazardous Industry Planning and Advisory Paper No. 1 – Emergency Planning* (HIPAP 1) (DoP, 2011b) in consultation with relevant emergency services organisations (i.e., Fire and Rescue NSW (FRNSW), NSW Rural Fire Service (RFS), NSW Ambulance) and the Local Emergency Management Committee (LEMC). The EP will detail the management measures to minimise the risk of hazardous events as well as emergency response procedures including an evacuation plan for site personnel, the involved dwelling and surrounding premises. **Section 7.3** provides an outline of the anticipated EP that will be prepared should the Project proceed.
- First responders will be made aware of Project hazards (including those specific to LIBs and electrical hazards that pose a threat during emergency response) and appropriate responses to Project hazard events in post construction inductions for first responders. Handbooks will be provided detailing appropriate response methods for hazard events and the precautions for first responders.
- Site security will include perimeter fencing and CCTV monitoring.
- A combustible materials (including vegetation) exclusion zone of 20 m will be maintained around the BESS to reduce the risk of external fire initiating LIB hazard events.
- On site vehicle speed will be limited to between 20 and 40 km/h, depending on site conditions, with designated traffic flow directions.
- Training will be provided for all personnel responsible for operations, maintenance and emergency response.
- Hot work/safe work procedures will be prepared for any maintenance works on LIB modules or electrical transformers.
- Routine preventative maintenance, interlock testing and condition monitoring (e.g., thermography, insulating oil analysis) of BESS LIB modules and electrical transformers will be undertaken.
- All waste batteries will be disposed of in a safe and responsible manner by suitably licensed waste contractors.

7.3 Emergency Plan Outline

A comprehensive EP and detailed emergency procedures consistent with HIPAP 1 and the RFS *Planning for Bushfire Protection* (or equivalent) will be developed and implemented should the Project be approved. Reference will also be made to *Australian Standard AS 3745-2010 Planning for emergencies in facilities* for the preparation of the EP. Prior to preparation of a draft EP, an initial round of consultation will be undertaken with RFS, FRNSW and the LEMC to determine any specific issues that the RFS, FRNSW and LEMC would like addressed in the EP and establish key contacts for ongoing consultation.

A hazard identification workshop involving key Project personnel and key stakeholders will be undertaken to identify emergency scenarios that could arise during Project construction and operation as well as hazard and risk mitigation measures (including the requirement to develop particular emergency response procedures).

The EP will have the following general structure:

- Introduction – general outline of the Project and location and the definition of an emergency.
- Aim and Objectives – a statement of the aims and objectives of the plan.
- Roles of Agencies, Industry, Community and Other Groups – define the roles and requirements of key stakeholder groups (e.g., RFS and FRNSW) and when consultation is required (e.g., EP review and update).
- Hazards – detail the identified hazards that could have a significant impact on emergency events and the ability to respond to such events including dangerous goods/hazardous materials, electrical hazards and natural hazards (a figure (or figures) detailing the location of hazards will be included).
- Emergency Events – the types and level of emergency events that may occur on site or impact the site.
- Emergency Organisational Structure and Responsibilities – list of Lightsource bp personnel and external agencies with emergency management functions, including contact details, their respective responsibilities in emergency planning and emergency events and how they can be identified in an emergency event.
- Site Security and Access – details and provisions for 24/7 access for emergency services.
- Emergency Procedures – clear, concise and practical procedures for the prevention and management of emergency events, likely to include:
    - Asset Protection Zone (APZ) management.
    - Bushfire response.
    - Hot work procedures including requirements for notifications to RFS and detailing work that cannot be undertaken in a total fire ban.
    - Dangerous goods storage and handling.
    - EP activation initial advice to emergency authorities and emergency termination.
    - Site evacuation (including evacuation plan drawings showing the evacuation routes).
- Emergency Resources – details of the resources (e.g., communication equipment, alarms, fire fighting equipment, material safety data sheets, PPE, water supplies) that are available for use in an emergency event (a figure (or figures) showing the location of emergency response equipment and other resources will be included).
- Reporting of Emergency Events – requirements for internal and external reporting of emergency events and post-emergency investigations.

- EP Testing and Training Requirements – requirements for training of personnel in emergency response, periodic drills to test the preparedness and effectiveness of the EP and relevant record keeping.
- EP Review, Update and Document Control – requirements/triggers (periodic or event based) for EP review and update and associated document control.
- Glossary – glossary of terms and abbreviations.
- Appendices:
  - Emergency Services Information Package.
  - Material Safety Data Sheets.
  - FRNSW, RFS and LEMC consultation records.

The draft EP will be submitted to RFS, FRNSW and the LEMC for comment prior to finalisation.

8.0 Conclusions

The PHA prepared for the Project identified a number of hazard events involving LIBs and electrical transformers with the potential for harmful off-site impacts. Other than LIBs and transformer oil, there will be no hazardous materials stored at, or transported to, the Project in significant quantities. Consequence modelling of thermal radiation, explosion overpressure and toxic gas dispersion was undertaken for a LIB fire/thermal runaway scenario resulting in either a fire, explosion or toxic gas release (refer to **Section 5.2**). The modelling estimated the distances to fatal, injurious, irritation, property damage and accident propagation impacts (refer to **Section 5.2**). An estimate of the likelihood of a LIB fire/thermal runaway scenario resulting in either a fire, explosion or toxic gas release was semi-quantitatively estimated (refer to **Section 5.3**).

The semi quantitative analysis undertaken estimated that the greatest distance from a representative LIB module at which an individual could be subject to injurious impact is 68 m, as a consequence of a LIB explosion scenario at a frequency of less than 10^{-5} events per year. Given Lightsource bp will locate the BESS at least 68 m from the site boundary and involved dwellings, no off-site impacts with the potential to cause injury or fatality are predicted.

A risk assessment considering the results of the consequence modelling and the estimated likelihood of a LIB fire/thermal runaway scenario resulting in either a fire, explosion or toxic gas release (refer to **Section 6.0**) indicated that the Project would comply with HIPAP 4 risk criteria for land use planning provided adequate separation distances between the BESS and the site boundary/involved dwellings are maintained. Lightsource bp will implement a range of technical and non-technical risk mitigation and management measures including rigorous design standards and maintenance practices (refer to **Section 7.0**). Compliance with HIPAP 4 criteria is conditional on these technical and non-technical risk mitigation and management measures being implemented.

It is considered that the fire and explosion risks associated with the substation can be adequately managed provided electrical transformers are designed, installed, operated and maintained in accordance with relevant Australian Standards (refer to **Section 4.0** and **Section 7.0**).

A FHA and FSS will be undertaken as the Project design progresses toward completion to ensure the final Project design adheres to the risk management measures outlined in **Section 7.0** and that the separation distances to the site boundary/involved dwellings are appropriate for the specific battery cell type (i.e., chemistry and capacity) to be used at the Project.

9.0 References

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APPENDIX A

Risk Classification and Prioritisation Calculations

IAEA Risk Classification and Prioritisation

Estimation of External Consequences

Hazardous Material: Lithium Ion Batteries

Select the appropriate effect category from Table II

IAEA Table II(a): Classification of Substances by Effect Categories

Ref. No.	Type of substance	Description of substance	Activity	Quantity (t) 0.2-1	1-5	5-10	10-50	50-200	200-1000	1000-5000	5000-10000	>10000
1	Flammable liquid	Vapour pressure <0.3 bar at 20°C	Storage with tank pit	-	-	-	-		AI	BI	BI	CI
2			Pipeline	-	_	-	-	-	-	-	-	-
3			Other	-	-	-	AI	BI	CI	DII	X	X
4		Vapour Pressure 0.3 bar at 20°C	Storage with tank pit	-	-	-	-	-	BI	CII	CII	DII
6			Other	-	-	-	BII	CII	DII	E II	X	X
7	Flammable gas	Liquefied by pressure	Rail, road, overground storage	-	AI	BI	C I	D I	E I	X	X	X
9			Other	-	BII	CIII	CIII	DIII	E III	X	X	X
10		Liquefied by cooling	Storage with tank pit	-	-	-	-	-	BI	CII	CII	DII
11			Other		-	-	BII	CII	DII	E II	X	X
13		Under pressure > 25 bar: high toxicity	Storage of cylinders (25-100kg)	-	-	CIII	CII	CI	CI	X	X	X
14	Explosive	In bulk (causing single explosion)		AI	BI	BI	CI	CI	DI	X	X	X
15		In packages (e.g. shells)		BIII	BIII	CIII	CI	CI	DI	X	X	X
16	Toxic liquid	Low toxicity	Storage with tank pit	-	-	-	-		A II	A II	B II	C III
17			Other	-	-	-	A III	A II	B II	C II	C II	C II
18		Medium toxicity	Storage with tank pit	-	-	-	A III	B III	D III	E III	F III	F III
21			Other	-	BII	C III	D III	E III	F III	F III	X	X
22		High toxicity	Storage with tank pit	-	-	A II	B III	C III	E III	F III	G III	G III
25			Other	BII	CII	D III	E III	F III	F III	G III	X	X
26		Very high toxicity	Storage with tank pit	AII	BII	C III	E III	F III	G III	G III	H III	H III
29			Other	CIII	DIII	E III	F III	G III	H III	H III	X	X
30	Toxic gas	Liquefied by pressure: low toxicity		AII	BII	B II	CIII	C II	DIII	D III	D III	E III
31		medium toxicity		BII	CII	C II	DIII	E III	F III	F III	G III	H III
32		high toxicity		CII	DIII	E III	E III	F III	G III	G III	X	X
33		very high toxicity		DIII	EIII	F III	G III	G III	H III	.	X	X
34		extreme toxicity		EIII	FIII	G III	H III	H III	X	X	X	X
35		Liquefied by cooling: low toxicity	In the case of activities on water use 30-34 instead of 35-39	-	-	-	A II	A II	B II	B II	C II	DIII
36		medium toxicity		-	AII	B II	C II	D III	D III	E III	F III	G III
37		high toxicity		BII	CII	D III	E III	E III	F III	F III	G III	H III
38		very high toxicity		DIII	EIII	F III	F III	G III	G III	X	X	X
39		extreme toxicity		EIII	FIII	G III	H III	H III	X	X	X	X

***Note**: For flammable liquids in underground tanks, the quantity should be divided by 5 and the substance treated as 'other' i.e. Refs 3 or 6.*

***Symbols**: 'X' means the combination of that substance and that amount does not usually exist in practice. It is suggested that a full QRA should be carried out in any such case. '-' means that the effects are small enough to be ignored.*

Effect Category: EIII

Comments regarding selection

Based on 570 MWh capacity BESSs and a hydrogen fluoride generation rate of 200 mg/Wh (50-200t @ worst case HF generation for $LiFePO_4$ battery in study by Larsson et al., 2017) and activity reference number of 31 for HF as per IAEA Table II.

Based on the selected effect category, identify maximum effect distance and/or area from Table III.

IAEA Table III: Effect Categories: Maximum Distance and Area of Effect (A)

Effect distance (m)		Effect area category (ha)		
Category	**Max. Distance (m)**	**I**	**II**	**III**
A	0-25	0.2	0.1	0.02
B	25-50	0.8	0:4	0.1
C	50-100	3	1.5	0.3
D	100-200	12	6	1
E	200-500	80	40	8
F	500-1000	-	-	30
G	1000-3000	-	-	300
H	3000-10 000	-	-	1000

Maximum Effect Distance (m): 500

Effect Area (ha): 8

Comments

Maximum distance E111 = 500m, A = 8ha
and Notation III is estimated as 1/10 of the area of the circle dues to the elongated cloud caused by dispersion.

If known enter population density of surrounding land or use Table IV as an estimate.

IAEA Table IV: Population Density (*d*)

Description of the area	Density (persons/ha)
Farmland, scattered houses	5
Individual dwellings	10
Village, quiet residential area	20
Residential area	40
Busy residential area	80
Urban area, shopping centres, centre of city	160

Comments

Very sparsely populated area. While a 5 person/ha is likely to be an overestimate of population density, it has been used to provide for a conservative assessment.

Population Density (persons/ha): 5

Select population correction factor from Table V.

IAEA Table V: Population Correction Factor (f_A)

Effect area	Populated fraction (%) of circular area				
Category	100%	50%	20%	10%	5%
I	1	0.6	0.2	0.1	0.05
II	1	1	0.4	0.2	0.1
III	1	1	1	1	1

Comments

Population Correction Factor, f_A: 1

Select mitigation correction factor from Table VI.

IAEA Table VI: Correction Factor for Mitigation (f_m)

Substances (reference numbers)	Factor
Flammables (1-12)	1
Flammables (13)	0.1
Explosives (14, 15)	1
Toxic liquid (16-29, 43-46)	0.05
Toxic gas (30-34, 37-39, 40-42)	0.1
Toxic gas (35-36)	0.05

Comments

Mitigation Correction Factor, f_m: 0.1

ESTIMATE OF EXTERNAL CONSEQUENCES

$C_{a,s} = A \times d \times f_A \times f_m$

$C_{a,s} = 3.9$

IAEA Risk Classification and Prioritisation

Estimation of Probability and Frequency

Select the average probability number from Table VI

IAEA Table VII: Average Probability Number ($N^*_{i,s}$)

Substances (reference numbers)	Activity: Storage	Activity: Plant
Flammable liquid (1-3)	8	7
Flammable liquid (4-6)	7	6
Flammable gas (7)	6	5
Flammable gas (9)	7	6
Flammable gas (10,11)	6	-
Flammable gas (13)	4	-
Explosive (14,15)	7	6
Toxic liquid (16-29)	5	4
Toxic gas (30-34)	6	5
Toxic gas (35-39)	6	-
Toxic gas (42)	5	4
Combustion products (43-46)	3	-

Comments

Average Probability Number, $N^*_{i,s}$: 5 — Batteries in operation, i.e. charging and discharging.

Select probability number correction parameter for frequency of loading/unloading operations from Table VIII

IAEA Table VIII: Probability Number Correction Parameter (n_l) For Loading/Unloading Operations Frequency

Frequency of loading/ unloading (per year)	Parameter
1-10	+0.5
10-50	0
50-200	-1
200-500	-1.5
500-2000	-2

Note *that this does not apply to cylinders (Ref No 13)*

Comments

Loading/Unloading Correction Parameter, nl 0.5 — Loading very infrequent as batteries are in use for many years prior to replacement at end of life.

If the hazardous material is flammable select appropriate correction parameters from Table IX

IAEA Table IX: Probability Number Correction Parameter (n_f) for Flammables

Substance	Safety measures	Factor
Flammable gas (7, 13)	Sprinkler system	+0.5
Flammable gas (10)	Double containment	+1
Flammable gas (13)	Fire wall	+1
	Sprinkler system	+0.5
	5-50 stored cylinders	+1
	50-500 stored cylinders	0
	>500 stored cylinders	-1

Comments

Flammables correction Parameter, nf 0 — Not being treated as flammable material for the purpose of this calculation.

Select organisational safety probability correction parameter from Table X.

IAEA Table X: Probability Number Correction Parameter (n_o) for Organisational Safety

Above average industry practice	+0.5
Average industry practice	0
Below average industry practice	-0.5
Poor industry practice	-1
Non-existent safety practices	-1.5

Note: *Several factors are included: safety management, age of the plant, maintenance, documentation and procedures, safety culture, training, emergency planning etc.*

Comments

Organisational Safety Correction Parameter, no: 0

Select wind direction correction parameter from Table XI.

IAEA Table XI: Probability Number Correction Parameter (n_p) for Wind Direction Towards Populated Area(s) in the Affected Zone

Effect area category	Part of the area (%) where people are living				
	100%	50%	20%	10%	5%
I	0	0	0	0	0
II	0	0.5	0.5	0.5	0.5
III	0	0.5	0.5	1	1.5

Comments

Wind Direction Correction Parameter, n_p: 0

ESTIMATE OF PROBABILITY NUMBER AND FREQUENCY

$N_{i,s} = N^*_{i,s} + n_l + n_f + n_o + n_p$

$N_{i,s} = 5.5$

$P = 3.2E-06$

Reference
Multi Level Risk Assessment , NSW Department of Planning, January 2011.

Consequence Estimation

Scenario	Substance	Activity	Physical Harm	Effect Category Table II(a)	Maximum Distance (m)	Affected Area (ha)	Population Density	Affected Population, N	Mitigation Factor, fm	External Consequences, Ca,s
S1	LIBs as hydrogen fluoride	Plant	Toxic	EIII	200	12.6	5.0	63	0.1	3.9
						0.0				0.0
						0.0				0.0

Probability Estimation

Scenario	Substance	Activity	Physical Harm	Average Probability Number, N*i,s Table VII(a)	Loading Unloading Frequency	Loading/Unloading Correction Parameter, nl	Organisational Safety Correction Parameter, no	Flammable Correction Factor, nf	Population Fraction	Wind Direction Correction Parameter, np	Probability Number, Ni,s	Frequency, P (events/yr)
S1	LIBs as hydrogen fluoride	Plant	Toxic	5	0	0.5	0	0	100%	0	5.5	3.2E-06

APPENDIX B

Qualitative Analysis Worksheets and Risk Matrix

Hazard Identfication Workshop

Date of Workshop: 17-Aug-22
Location: Umwelt - 75 York Street Teralba

Job Title: Goulburn River Solar Farm **Job Number:** 21507

Job Description:	Lightsource bp is seeking to develop the proposed Goulburn River Solar Farm in the in New South Wales (NSW), approximately 28 kilometres (km) southwest of Merriwa within the Upper Hunter Shire Local Government Area (LGA). The Goulburn River Solar Farm includes up to 550 megawatts peak (MWp) of solar electricity generation with a Battery Energy Storage System (BESS) of up to approximately 570 MWh (the Project). The type of batteries within the BESS are anticipated to be lithium ion which pose potential fire, explosion and toxic gas release hazards when subject to abuse conditions (electro-chemical, thermal, mechanical) or as a result of internal manufacturing defects. The BESS will be comprised of 3,600 Gridstack Fluence Cube units with each cube housing 2,300 x 280 Ah lithium iron phosphate cells and equipped with a liquid cooling rack. There will also be a main electrical transformer at the site which poses a potential explosion and fire hazard as well as 70 twin skid inverters with an associated transformer (per inverter pair) throughout the site.
Purpose, Scope and Context:	The purpose of this workshop is to identify associated with the Project hazards that may have off-site impacts on people,property and the envcironment. NSW Department of Planning Secretary's Environmental Assessment Requirements (SEARs) have identified hazard and risk as an area to be addressed in the EIS. Risk screening, classification and prioritisation has shown that a Level 2 Semi Quantitative risk assesment is required and as such all aspects of a Level 1 Qualititative risk assessment are required. The risk assessment will focus on health and safety risks posed to the surrounding off-site land users and the risks posed to the surrounding biophysical environment. i.e. the risk rankings are relevant to off-site land users not on-site personnel.

Workshop Attendees

Name	Company	Position/Role
Chris Bonomini	Umwelt	Principal Engineer - Risk
Tim Procter	Umwelt	Lead Process Engineer

AS 4360 Risk Scoring System

Scoring Matrix

Likelihood		1	2	3	4	5
Level		Insignificant	Minor	Moderate	Major	Catastrophic
A	Almost Certain	11	16	20	23	25
B	Likely	7	12	17	21	24
C	Possible	4	8	13	18	22
D	Unlikely	2	5	9	14	19
E	Rare	1	3	6	10	15

Legend

18 to 25:	EXTREME RISK; immediate action required;
10 to 17:	HIGH RISK; senior management attention needed;
6 to 9:	MODERATE RISK; management responsibility must be specified; and
1 to 5:	LOW RISK; managed by routine procedures.

Qualitative Measures of Likelihood

	Level	Description
A	Almost Certain	The event is expected to occur in most circumstances
B	Likely	The event will probably occur in most circumstances
C	Possible	The event might occur at some time
D	Unlikely	The event could occur at some time
E	Rare	The event may occur only in exceptional circumstances

Qualitative Measures of Consequence or Impact or Severity

	Level	People Losses	Environmental Harm	Equipment Damage	Production Loss
1	Insignificant	No injuries	No-off site effects	Low financial loss	No production loss
2	Minor	First aid treatment	On-site release immediately contained	Medium financial loss	Up to 1 day production loss
3	Moderate	Medical treatment	On-site release contained with outside assistance	High financial loss	Between 1 to 5 days production loss
4	Major	Extensive injuries	Off-site release with no detrimental effects	Major financial loss	Between 5 to 20 days production loss
5	Catastrophic	Death	Toxic release off-site with detrimental effect	Huge financial loss	More than 20 days production loss

Hazard Identification

Date 17-Aug-22 **Job:** Goulburn River Solar Farm **Job #:** 21507

Section/Area: Solar Farm

Ref	Asset	Guideword	Hazard Event Description	Threat (cause of hazard event)	Consequence	Current Barriers	C	L	R	Action
1	BESS Container	Natural Hazards	Fire or explosion in BESS unit as a result of thermal runaway in battery cells leading to possible battery fire, explosion or toxic release.	Bushfire external to site heats BESS container or lightning strike intiates fire in BESS. Flood event casues short circuit and thermal runaway.	Possible injury or fatality on and off-site. Damage to off-site structures and/or equipment. Propagation to other BESS containers or transformers.	Site will have lightning protection installed Routine site maintenance will include bushfire mitigation and combustible materials management to prevent propagation from external fires to BESS containers. Batteries to be installed >20m from 3rd oder streams. Separation distance from site boundary will be maintained to ensure fire, explosion and toxic gas release off-site impacts are within NSW land use planning risk criteria. BESS to be designed and constructed by supplier to UL 9540 Standard for Safety of Energy Storage Systems and Equipment BESS will have met the large scale fire testing requirements of UL9540A Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems. BESS will be installed in accordance with NFPA 855 Standard for the Installation of Stationary Energy Storage Systems BESS monitoring and interlocks for early detection of unsafe conditions (e.g. high temperatures), thermal runaway and trips to disconnect/shutdown impacted racks. Each BESS unit has a liquid cooling system to mimimise the risk of overheating. Pre-commissioning testing and hold point	3	E	6	Complete consequence modelling to determine potential extent of fire and explosion impacts. Locate BESS units at a distance from the site boundary to ensure NSW land use planning risk criteria is achieved. Ensure first responders are aware of hazards and appropriate response to hazard events - will have post construction inductions for first responders and provide access for emergency services, handbooks will be provided detailing how to respond to hazard events. Ensure safe/responsible disposal of batteries including transport.

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2	BESS Container	Fire/Explosion	Fire or explosion in BESS container as a result of thermal runaway in battery cells leading to possible battery fire, explosion or toxic release.	Manufacturing fault. Failure of BMS controls resulting in electro-chemical abuse of cells.	Possible injury or fatality on and off-site. Damage to off-site structures and/or equipment. Propagation to other BESS containers or transformers.	Separation distance from site boundary will be maintained to ensure fire, explosion and toxic gas release off-site impacts are within NSW land use planning risk criteria. BESS to be designed and constructed by supplier to UL 9540 Standard for Safety of Energy Storage Systems and Equipment BESS units will have met the large scale fire testing requirements of UL9540A Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems. BESS will be installed in accordance with NFPA 855 Standard for the Installation of Stationary Energy Storage Systems BESS monitoring and interlocks for early detection of unsafe conditions (e.g. high temperatures), thermal runaway and trips to disconnect/shutdown impacted racks. Each BESS unit has a liquid cooling system to mimimise the risk of overheating. Pre-commissioning testing and hold point testing whereby full site capacity is gradually brought online. Site layout has been designed to allow clear access for emergency services in the event of an event requiring emergency response. Site security includes perimeter fencing for security and CCTV monitoring to reduce the risk of malicious damage initiating hazardous	3	E	6	Complete consequence modelling to determine potential extent of fire, explosion impacts and locate BESS units at a distance from the site boundary to ensure NSW land use planning risk criteria is achieved. Ensure first responders are aware of hazards and appropriate response to hazard events holding post construction inductions for first responders and providing handbooks detailing how to respond to hazard events involving Li ion batteries. Ensure first responders are given ability to independently access the site 24/7.

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Hazard Identification

3	BESS Container	Fire/Explosion	Fire or explosion in BESS container as a result of thermal runaway in battery cells leading to possible battery fire, explosion or toxic release.	Vehicles and mobile plant impacts. Maintenance activities within container.	Possible injury or fatality on and off-site. Damage to off-site structures and/or equipment. Propagation to other BESS containers or transformers.	On-site vehicle speed limits. All personnel (operations, maintenance, contractors) will be trained in regard to the hazards of Li ion batteries and safe work procedures. Batteries to be installed above 200 year flood level. Separation distance from site boundary will be maintained to ensure fire, explosion and toxic gas release off-site impacts are within NSW land use planning risk criteria. BESS to be designed and constructed by supplier to UL 9540 Standard for Safety of Energy Storage Systems and Equipment BESS will have met the large scale fire testing requirements of UL9540A Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems. BESS will be installed in accordance with NFPA 855 Standard for the Installation of Stationary Energy Storage Systems BESS monitoring and interlocks for early detection of unsafe conditions (e.g. high temperatures), thermal runaway and trips to disconnect/shutdown impacted racks. Each BESS unit has a liquid cooling system to mimimise the risk of overheating. Pre-commissioning testing and hold point testing whereby full site capacity is gradually	3	E	6	Complete consequence modelling to determine potential extent of fire, explosion impacts and locate BESS containers at a distance from the site boundary to ensure NSW land use planning risk criteria is achieved. Ensure first responders are aware of hazards and appropriate response to hazard events holding post construction inductions for first responders and providing handbooks detailing how to respond to hazard events involving Li ion batteries. Ensure first responders are given ability to independently access the site 24/7.

4	BESS	Natural Hazards	Rainfall runoff and soil contaminated by leached toxicants (heavy metals) from damaged solar panels.	Hail storm. Physical damage associated with vehicle collision of during installtion and maintenance activities on site.	Contamination of soils. Receiving water quality degradation.	Leaching of metals from damaged panels is a relatively slow process and concentrations of metals in broader catchment runoff would be negligible. Routine inspections of panels for damage will be undertaken on a regular basis and and damaged panels willl be removed as well as soil with damaged panel debris.	2	E	3	Ensure maintenance regime includes routine inspections for damaged solar panels.

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Hazard Identification

Date 18-Aug-21 **Job:** Goulburn River Solar Farm **Job #:** 21507

Section/Area: Transformers

Ref	Asset	Guideword	Hazard Event Description	Threats (causes of hazard event)	Consequence	Current Barriers	C	L	R	Action
1	Transformers	Toxicity	Oil leakage	Pipe fitting failures, tank corrosion, physical damage and bunding failure.	Harm to environment - possible soil and waterway contamination.	Transformers transported to site empty, i.e. no oil. Routine maintenance and inspections will be undertaken to minimise likelihood of oil leakage. Main transformer will be contained in bunds in accordance with relevant Australian Standards and anyother federal, state or local requirements. Distributed inverters/transformers will have integrated oil retention. Spill response kits will be maintained on-site and all relevant personnel will be trained in	3	E	6	
2	Transformers	Fire/Explosion	Fire/explosion involving transformer oil	Insulation breakdown.	Possible injury or fatality on and off-site.	Transformers will be designed and installed in accordance with relevant federal, state and local standards. Routine preventative maintenance, inspections and condition monitoring (ie.g. oil analysis to detect insulation breakdown) will be undertaken	4	E	10	

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APPENDIX C

Quantitative Consequence Analysis

LIB Module Heat Flux Caclulations

Emitted Heat Flux

Stefan-Boltzmann Equation

$$E = e\,\sigma T^4$$

where:

Symbol	Description	Value	Units
e	Emissivity	1.0	-
σ	Stefan-Boltzmann constant	5.67E-08	$W/m^2/K^4$
T	Absolute temperature of emitting surface	1273.15	K
E	Emitted heat flux	149.0	kW/m^2

Incident Heat Flux at Receiver

$$q = \phi_{total} E$$

$$\phi_{total} = \phi_A + \phi_B + \phi_C + \phi_D$$

$$\phi = \frac{1}{2\pi}\left[\frac{a}{(1+a^2)^{1/2}}\tan^{-1}\frac{b}{(1+a^2)^{1/2}} + \frac{b}{(1+b^2)^{1/2}}\tan^{-1}\frac{a}{(1+b^2)^{1/2}}\right]$$

$$a = \frac{0.5 \times L_2}{d} \qquad b = \frac{0.5 \times L_1}{d}$$

where:

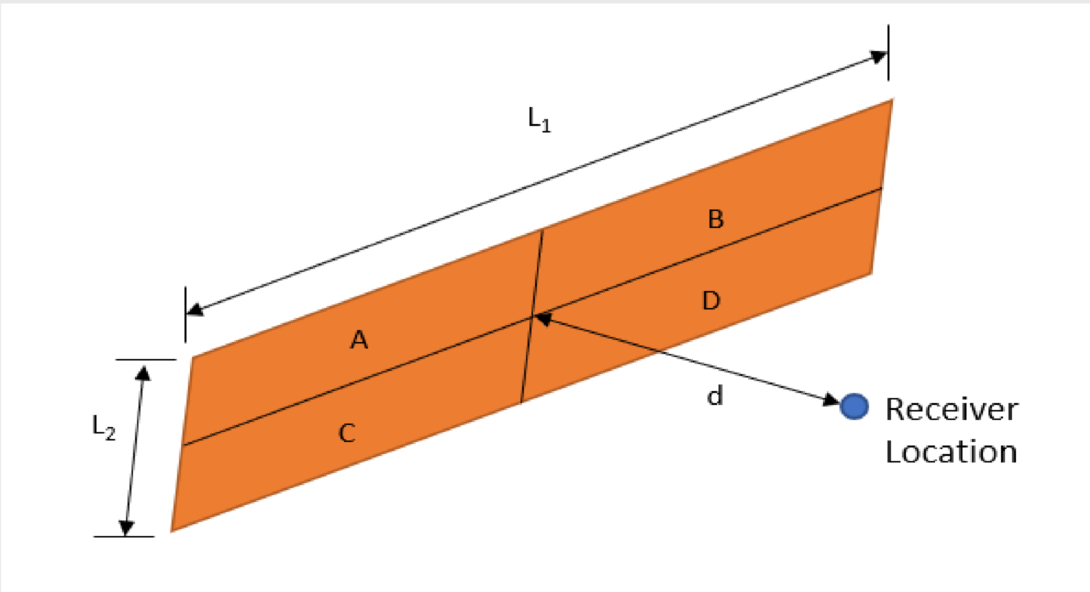
Symbol	Description	Units
ϕ_{total}	Configuration factor at receiver location	-

As the receiver is located perpendicular to the centreline of the container surface:

$$\phi_A = \phi_B = \phi_C = \phi_D$$

$$\phi_{total} = 4\,\phi_A$$

$$q = 4\,\phi_A E$$



	Wide	High	Deep
Opt 1	1.0	2.2	1.3
Opt 2	2.6	2.6	2.3

BESS Unit Front	L_1 (m)	L_2 (m)	
BESS Unit Side		L_2 (m)	L_1 (m)

BESS Unit Front				q (kW/m²)	
Distance (	**a**	**b**	ϕ_A	**Opt 1**	**Opt 2**
1	1.30	1.30	0.166	53.3	99.2
2	0.65	0.65	0.086	20.4	51.4
3	0.43	0.43	0.048	10.1	28.5
4	0.33	0.33	0.029	5.9	17.6
5	0.26	0.26	0.020	3.9	11.8
6	0.22	0.22	0.014	2.7	8.4
7	0.19	0.19	0.010	2.0	6.3
8	0.16	0.16	0.008	1.5	4.8
9	0.14	0.14	0.006	1.2	3.9
10	0.13	0.13	0.005	1.0	3.1
11	0.12	0.12	0.004	0.8	2.6
12	0.11	0.11	0.004	0.7	2.2
13	0.10	0.10	0.003	0.6	1.9
14	0.09	0.09	0.003	0.5	1.6
15	0.09	0.09	0.002	0.4	1.4
16	0.08	0.08	0.002	0.4	1.2
17	0.08	0.08	0.002	0.3	1.1
18	0.07	0.07	0.002	0.3	1.0
19	0.07	0.07	0.001	0.3	0.9
20	0.07	0.07	0.001	0.3	0.8
21	0.06	0.06	0.001	0.2	0.7
22	0.06	0.06	0.001	0.2	0.7
23	0.06	0.06	0.001	0.2	0.6
24	0.05	0.05	0.001	0.2	0.6
25	0.05	0.05	0.001	0.2	0.5
26	0.05	0.05	0.001		0.5
27	0.05	0.05	0.001		0.4
28	0.05	0.05	0.001		0.4
29	0.04	0.04	0.001		0.4
30	0.04	0.04	0.001		0.4

BESS Unit Side				q (kW/m²)	
Distance (	**a**	**b**	ϕ_A	**Opt 1**	**Opt 2**
1	1.30	1.15	0.23	109.0	136.2
2	0.65	0.58	0.09	29.8	53.3
3	0.43	0.38	0.05	14.2	27.3
4	0.33	0.29	0.03	8.2	16.3
5	0.26	0.23	0.02	5.3	10.7
6	0.22	0.19	0.01	3.7	7.6
7	0.19	0.16	0.01	2.7	5.6
8	0.16	0.14	0.01	2.1	4.3
9	0.14	0.13	0.01	1.7	3.4
10	0.13	0.12	0.00	1.4	2.8
11	0.12	0.10	0.00	1.1	2.3
12	0.11	0.10	0.00	0.9	1.9
13	0.10	0.09	0.00	0.8	1.7
14	0.09	0.08	0.00	0.7	1.4
15	0.09	0.08	0.00	0.6	1.3
16	0.08	0.07	0.00	0.5	1.1
17	0.08	0.07	0.00	0.5	1.0
18	0.07	0.06	0.00	0.4	0.9
19	0.07	0.06	0.00	0.4	0.8
20	0.07	0.06	0.00	0.3	0.7
21	0.06	0.05	0.00	0.3	0.6
22	0.06	0.05	0.00	0.3	0.6
23	0.06	0.05	0.00	0.3	0.5
24	0.05	0.05	0.00	0.2	0.5
25	0.05	0.05	0.00	0.2	0.5
26	0.05	0.04	0.00	0.2	0.4
27	0.05	0.04	0.00	0.2	0.4
28	0.05	0.04	0.00	0.2	0.4
29	0.04	0.04	0.00	0.2	0.3
30	0.04	0.04	0.00	0.2	0.3

MULTI-ENERGY EXPLOSION MODEL

INPUT DATA

Modeled Chemical	LIB_Flammable_Gas
Heat Combustion	35557.168

Results data

Subcloud1:

Absolute Coordinates (metres)	0 0
Explosive Mass (kilograms)	3.8
Charge Strength	10
Energy (Btu)	128066.414

CALCULATED DISTANCES AT SPECIFIED OVERPRESSURES

Overpressure Pa (g)	Distance meters
7.00E+03	42.362
1.40E+04	25.547
2.10E+04	20.336

BREEZE MULTI-ENERGY EXPLOSION MODEL

INPUT DATA

Modeled Chemical	LIB_Flammable_Gas
Heat Combustion	35557.168

Results data

Subcloud1:

Absolute Coordinates (metres)	0 0
Explosive Mass (kilograms)	3.8
Charge Strength	10
Energy (Btu)	128066.414

CALCULATED DISTANCES AT SPECIFIED OVERPRESSURES

Overpressure Pa (g)	Distance meters
7.00E+03	42.362
1.40E+04	25.547
2.10E+04	20.336

Lithium Ion Battery Gas Generation Species and Volumes

Reference

In-situ analysis of gas generation in lithium ion batteries with different carbonate-based electrolytes
Xin Teng, Chun Zhan, Ying Bai, Lu Ma, Qi Liu, Feng Wu, Yusheng Tang, Jun Lu and Khalil Amine
ACS Applied Materials and Interfaces, 2015

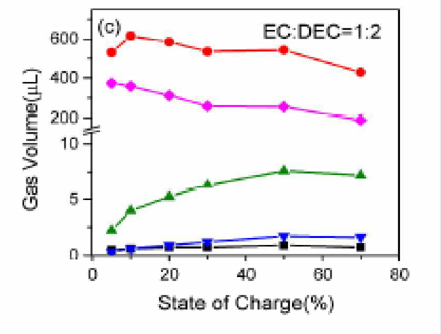
Battery Cells Tested

Type	Pouch
Capacity/cell	900 mAh
Anode	Graphite
Cathode	$LiCoO_2$
Electrolyte	$LiPF_6$ dissolved in binary carbonate solvents

Electrolyte in Battery Type Used to Calculate Flammable Gas Generation

1 part Ethyl Carbonate, 2 parts Diethyl Carbonate

Chart 1



Source: *In-situ analysis of gas generation in lithium ion batteries with different carbonate-based electrolytes* (Teng et al.)

BESS Unit Volume

Capacity	2 to 4	MWh
Depth	2.3	m
Width	2.6	m
Height	2.6	m
% Occupied	50%	-
Free Volume	7.8	m3

Assumed Conditions in Container

Gas Temperature	373.15	K
Pressure	101325	Pa

BREEZE Incident Analyst (version 4.0.0.28)
AFTOX Summary Output File

Meteorological data:	
Ambient temperature (C)	5
Ambient pressure (mmHg)	760
Relative humidity (%)	50
Wind direction (degrees)	270
Wind speed (m/s)	1.5
Anemometer height (metres)	10
Surface roughness (metres)	0.03
Stability option	Stability class
Stability class(1=A - 6=F)	F (6)
Computed Monin-Obukhov length (metres)	14.264
Inversion layer height (metres)	None
Chemical data:	
Name	Hydrogen fluoride (anhydrous)
Molecular weight (g/g-mole)	20.006
Vapor heat capacity at constant pressure (J/kg-K)	1450
Boiling point (C)	19.55
Heat of vaporization (J/kg)	373200
Liquid heat capacity (J/kg-K)	2528
Liquid density (kg/m**3)	973.5
Release data:	
Source type	Gas release
Release type	Continuous
Emission rate (g/s)	1.481
Release height (metres)	1.5
Output data:	
Concentration level 1 (ppm	1
Concentration level 2(ppm)	24
Concentration level 3(ppm)	44
Concentration averaging time (seconds)	3600
Height of interest (metres)	1.5

BREEZE Incident Analyst (version 4.0.0.28)
AFTOX Summary Output File

Results data:

MAXIMUM DISTANCE TO LEVELS OF CONCERN (LOC)

Concentration (ppm)	Distance (meters)
1.000	572.897
24.000	67.965
44.000	41.866

Toxic corridor:

Maximum Distance (metres)	1203.084
Direction and width (circle)	90

MAXIMUM CONCENTRATION AT GIVEN HEIGHT AND TIME

Downwind Distance metres	Concentration ppm	Concentration mg/m**3
30.00	69.23	60.68

***THE MAXIMUM CONCENTRATION IS WITHIN 30 M (100 FT) OF THE SOURCE. AFTOX ONLY GIVES THE CONCENTRATION AT 30 METRES**

Estimation of Hydrogen Fluoride (HF) Gas Release Rate from a LIB Module Fire

Basis

Battery Cathode – Lithium Iron Phosphate

The HF generation rate for a range of LIB battery packs is described in *Toxic fluoride gas emissions from lithium-ion battery fires* (Larsson et al., 2017). For a battery pack with an energy capacity of 128 Wh and a nominal capacity per battery of 20 Ah the detected HF generation rate during the fire test was 150 to 198 mg/Wh depending on the State of Charge (SoC).

Specific HF Generation Rate

Battery Capacity (Ah)	HF Generation Range (mg/Wh)	Nominated Maximum Generation Rate, HF_{gen} (mg/Wh) based on 0% Charge
20 Ah	150 [1] – 198 [2]	200

Source: *Toxic fluoride gas emissions from lithium-ion battery fires* (Larsson et al., 2017)

Note: [1] 100% SoC.

[2] 0% SoC.

The estimated burn rate of a LIB battery pack based on the Tesla battery pack fire test results presented in *Hazard Assessment of Lithium Ion Battery Energy Storage Systems* (Fire Protection Research Foundation, 2016). The results of the test are summarised as follows:

- Battery Pack Capacity – 100 kWh.
- Burn Time – 225 minutes from the initiation of heating to last visible flame.
- All battery pods reported as being damaged and no stranded energy within pack.

Calculations

Battery Burn Rate, R is:

$$R = \frac{100\ kWh \times \frac{1{,}000\ Wh}{kWh}}{225\ min \times \frac{60\ s}{min}}$$

$$R = 7.41\ \frac{Wh}{s}$$

HF Release Rate, m_{HF} is:

$$m_{HF} = R \times HF_{av}$$

Where the nominated maximum HF generation rate, HF_{gen} = 200 mg/Wh

$$m_{HF} = 7.41\ \frac{Wh}{s} \times 200\ \frac{mg}{Wh} \times \frac{g}{1{,}000\ mg}$$

$$m_{HF} = 1.48\ \frac{g}{s}$$

Environmental & Social Consultants

Umwelt (Australia) Pty Limited

T| 1300 793 267 E| info@umwelt.com.au www.umwelt.com.au