Preliminary Hazard Analysis

Marulan Solar Farm

Terrain Solar Pty Ltd
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Executive Summary

Background

Terrain Solar Pty Ltd (Terrain Solar) has proposed to develop the Marulan Solar Farm, being a new solar farm with battery storage at 740 Carrick Road, Carrick NSW. The project will comprise up to 152 MWac of installed Photovoltaic (PV) panels along with up to 600 MWh of Battery Energy Storage System (BESS) along with associated infrastructure (i.e., substations, transformers, etc.).

The Secretary Environmental Assessment Requirements (SEARs) require the preparation of a Preliminary Hazard Analysis (PHA) to assess the risk profile of the development in accordance with the Hazardous Industry Planning Advisory Paper (HIPAP) No. 6 (Ref. [1]) utilising criteria from HIPAP No. 4 (Ref. [2]).

Terrain Solar has engaged Riskcon Engineering Pty Ltd (Riskcon) to prepare a PHA for the project as part of the State Significant Development Application (SSDA).

Conclusions

A hazard identification table was developed for the Marulan Solar Farm PV & BESS project to identify potential hazards that may be present at the site as a result of operations or storage of materials. Based on the identified hazards, scenarios were postulated that may result in an incident with a potential for offsite impacts. Postulated scenarios were discussed qualitatively and any scenarios that would not impact offsite were eliminated from further assessment. Scenarios not eliminated were then carried forward for consequence analysis.

Incidents carried forward for consequence analysis were assessed in detail to estimate the impact distances. Impact distances were developed into scenario contours and overlaid onto the site layout diagram to determine if an offsite impact would occur. The consequence analysis showed that several scenarios impacted over the site boundary depending upon where the boundary was identified (i.e. security fence or property boundary).

Where an offsite impact was identified, a frequency analysis and risk assessment was conducted to identify the potential for fatality, injury and irritation to occur as a result of the development. The results indicated that the fatality risks would not exceed the acceptable criteria. Similarly, the injury and irritation criteria were not exceeded. Finally, the potential for incident propagation as assessed at the 23 kW/m^2 contour which didn't show any potential for off-site impact and thus incident propagation would not be considered to occur.

Based on the analysis conducted, it is concluded that the risks at the site boundary are not considered to exceed the acceptable risk criteria; hence, the project would only be classified as potentially hazardous and would be permitted within the current land zoning for the site.

Recommendations

Notwithstanding the conclusions drawn, the following recommendations have been made:

- The site induction shall include information regarding the gas pipeline including location and protections to identify the gas pipeline (i.e., marker tape, etc.).
- All personnel working at the site shall be inducted prior to commencing any work.
- Appropriate marking shall be provided along the length of the gas pipeline as required to minimise the potential for unauthorised works occurring within the vicinity of the gas pipeline, in conjunction with the Site Induction and relevant site-specific construction management plans.

- The transformers spill containment shall be designed according to the requirements of AS 2067:2016 – “Substations and *high voltage installations exceeding 1 kV a.c’*
- Battery equipment shall be located away from external site boundaries (property owner’s site boundary) as much as possible *to maximise distance to sensitive receptors from downwind* dispersion in the event of a fire.
- A final hazard analysis shall be conducted once a detailed design has been completed to demonstrate the risk criteria are not exceeded.

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Abbreviations

Abbreviation	Description
AC	Alternating Current
ADG	Australian Dangerous Goods Code
AS	Australian Standard
BESS	Battery Energy Storage System
CBD	Central Business District
DC	Direct Current
DGs	Dangerous Goods
ELF	Extra Low Frequency
EMF	Electric and Magnetic Field
ERPG	Emergency Response Planning Guideline
FCAS	Frequency Control Ancillary Services
HF	Hydrogen Fluoride
HIPAP	Hazardous Industry Planning Advisory Paper
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IDLH	Immediately Dangerous to Life and Health
PCU	Power Control Unit
PHA	Preliminary Hazard Analysis
Pmpy	Per million per year
PV	Photovoltaic
SEARs	Secretary’s Environmental Assessment Requirements
SEP	Surface Emissive Power
SEPP	State Environmental Planning Policy
SOC	State of Charge
SSDA	State Significant Development Application
STEL	Short Term Exposure Limit

1.0 Introduction

1.1 Background

Terrain Solar Pty Ltd (Terrain Solar) has proposed to develop the Marulan Solar Farm, being a new solar farm with battery storage at 740 Carrick Road, Carrick NSW. The project will comprise up to 152 MWac of installed Photovoltaic (PV) panels along with up to 600 MWh of Battery Energy Storage System (BESS) along with associated infrastructure (i.e., substations, transformers, etc.).

The Secretary Environmental Assessment Requirements (SEARs) require the preparation of a Preliminary Hazard Analysis (PHA) to assess the risk profile of the development in accordance with the Hazardous Industry Planning Advisory Paper (HIPAP) No. 6 (Ref. [1]) utilising criteria from HIPAP No. 4 (Ref. [2]).

Terrain Solar has engaged Riskcon Engineering Pty Ltd (Riskcon) to prepare a PHA for the project as part of the State Significant Development Application (SSDA).

1.2 Objectives

The key objectives of this PHA are to:

- Complete the PHA according to the Hazardous Industry Planning Advisory Paper (HIPAP) No. 6 – Hazard Analysis (Ref. [1]);
- Assess the PHA results using the criteria in HIPAP No. 4 – Risk Criteria for Land Use Planning (Ref. [2]); and
- Demonstrate compliance of the site with the relevant codes, standards and regulations (i.e. Planning and Environment Regulation, WHS Regulation, 2017 Ref. [3]).

1.3 Scope of Services

The scope of work is to complete a PHA study for the Terrain Solar PV and BESS project located at 740 Carrick Road, Carrick NSW. No other Terrain Solar projects are included within the scope of work.

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2.0 Methodology

2.1 Multi-Level Risk Assessment

The Multi-Level Risk Assessment approach (Ref. [4]) published by the NSW Department of Planning, Industry and Environment, has been used as the basis for the study to determine the level of risk assessment required. The approach considered the development in context of its location, the quantity and type (i.e. hazardous nature) of Dangerous Goods stored and used, and the project's technical and safety management control. The Multi-Level Risk Assessment Guidelines are intended to assist industry, consultants and the consent authorities to carry out and evaluate risk assessments at an appropriate level for the project being studied.

There are three levels of risk assessment set out in Multi-Level Risk Assessment which may be appropriate for a PHA, as detailed in **Table 2-1**.

Table 2-1: Level of Assessment PHA

Level	Type of Analysis	Appropriate If:
1	Qualitative	No major off-site consequences and societal risk is negligible
2	Partially Quantitative	Off-site consequences but with low frequency of occurrence
3	Quantitative	Where 1 and 2 are exceeded

The Multi-Level Risk Assessment approach is schematically presented in **Figure 2-1**.

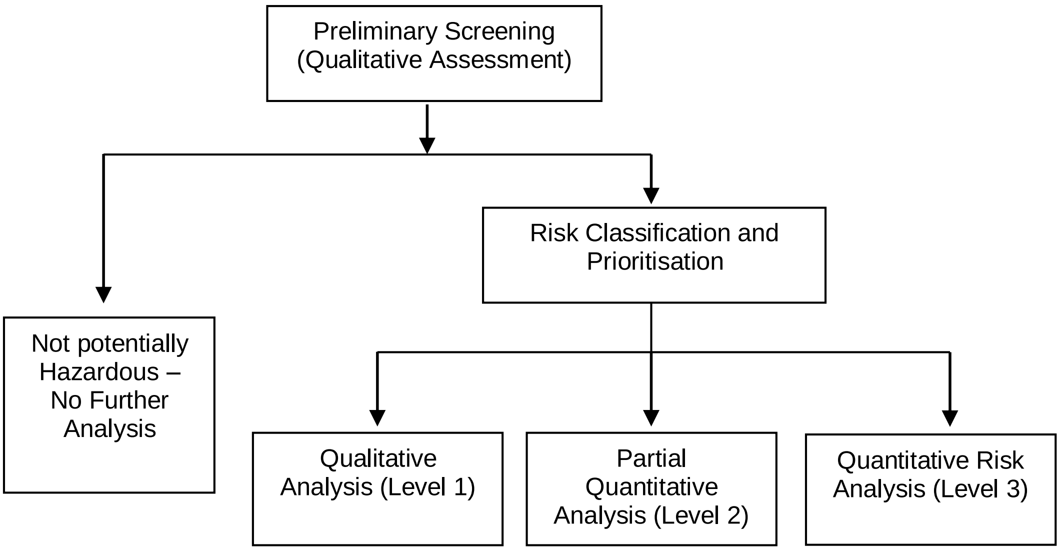

Figure 2-1: The Multi-Level Risk Assessment Approach

Based on the type of DGs to be used and handled at the proposed project, a **Level 2 Assessment** was selected for the Site. This approach provides a qualitative assessment of those DGs of lesser quantities and hazard, and a quantitative approach for the more hazardous materials to be used on-site. This approach is commensurate with the methodologies recommended in "Applying SEPP 33's" Multi Level Risk Assessment approach (DPIE, 2011).

2.2 Risk Assessment Study Approach

The methodology used for the PHA is as follows;

Hazard Analysis – A detailed hazard identification was conducted for the site facilities and operations. Where an incident was identified to have a potential off-site impact, it was included in the recorded hazard identification word diagram (**Appendix A**). The hazard identification word diagram lists incident type, causes, consequences and safeguards. This was performed using the word diagram format recommended in HIPAP No. 6 (Ref. [1]).

Each postulated hazardous incident was assessed qualitatively in light of proposed safeguards (technical and management controls). Where a potential offsite impact was identified, the incident was carried into the main report for further analysis. Where the qualitative review in the main report determined that the safeguards were adequate to control the hazard, or that the consequence would obviously have no offsite impact, no further analysis was performed. **Section 3.1** of this report provides details of values used to assist in selecting incidents required to be carried forward for further analysis.

Consequence Analysis – For those incidents qualitatively identified in the hazard analysis to have a potential offsite impact, a detailed consequence analysis was conducted. The analysis modelled the various postulated hazardous incidents and determined impact distances from the incident source. The results were compared to the consequence criteria listed in HIPAP No. 4 (Ref. [2]). The criteria selected for screening incidents is discussed in **Section 3.1**.

Where an incident was identified to result in an offsite impact, it was carried forward for frequency analysis. Where an incident was identified to not have an offsite impact, and a simple solution was evident (i.e. move the proposed equipment further away from the boundary), the solution was recommended, and no further analysis was performed.

Frequency Analysis – In the event a simple solution for managing consequence impacts was not evident, each incident identified to have potential offsite impact was subjected to a frequency analysis. The analysis considered the initiating event and probability of failure of the safeguards (both hardware and software). The results of the frequency analysis were then carried forward to the risk assessment and reduction stage for combination with the consequence analysis results.

Risk Assessment and Reduction – Where incidents were identified to impact offsite and where a consequence and frequency analysis was conducted, the consequence and frequency analysis for each incident were combined to determine the risk and then compared to the risk criteria published in HIPAP No. 4 (Ref. [2]). Where the criteria were exceeded, a review of the major risk contributors was performed, and the risks reassessed incorporating the recommended risk reduction measures. Recommendations were then made regarding risk reduction measures.

Reporting – On completion of the study, a draft report was developed for review and comment by Terrain Solar. A final report was then developed, incorporating the comments received by Terrain Solar for submission to the regulatory authority.

3.0 Site Description

3.1 Site Location

The site is located 740 Carrick Road, Carrick NSW which is southwest of Sydney and is approximately 60 km northwest of Nowra. **Figure 3-1** shows the regional location of the site in relation to Nowra. A site layout has been provided in **Figure 3-5**.

Figure 3-1: Site Location

3.2 Adjacent Land Uses

The land is located in a regional / rural area surrounded by the following land uses, which are adjacent to the site:

- North – Farmland (rural)
- South – Farmland (rural)
- East – Farmland (rural)
- West – Farmland (rural)

3.3 Sensitive Receptors

The nearest residential locations are as follows and shown in **Figure 3-2**:

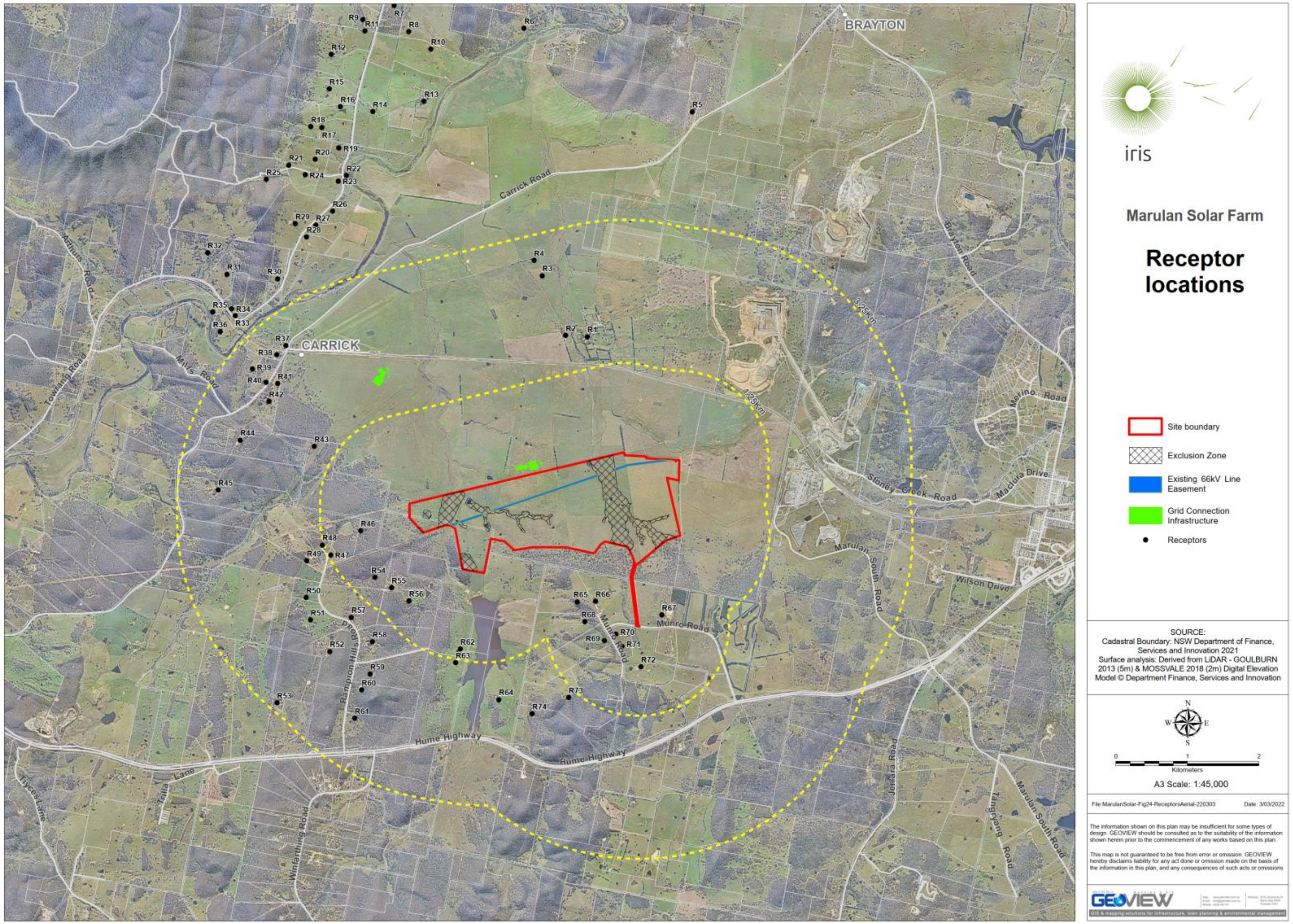

Figure 3-2: Sensitive Receptors

3.4 Detailed Description

The purpose of the project is to provide clean renewable energy to the NSW grid, and contribute further renewable generation towards the goals of the NSW government's NSW Electricity Infrastructure Roadmap.

The energy will be generated from the circa 152 MWac installed capacity of PV panels, and the up to 600 MWh BESS will enable storage of this clean renewable energy to be dispatched to help accommodate electricity demand fluctuations and ensure supply when demand is highest. This is achievable due to the fast response times achieved through lithium-ion battery storage which can fill peak demands due to the quick dispatchability of battery storage. The project will have capacity to store up to 150 megawatts (MW) of energy for 4 hours resulting in a storage of 600 MWh.

3.4.1 PCUs

Power Conversion Units, or PCUs, house transformers and inverters which will be sited between the PV Module Arrays, along the solar farm's internal access tracks. There will be approximately 38 PCUs across the site which typically comprise:

1. 1 x PCU transformer
2. 3 x inverters
3. 1 x DC/DC converter

The inverters convert the Direct Current (DC) to Alternating Current (AC), while the transformers increase the voltage from Low Voltage to a Medium or High Voltage, as required for the electricity grid connection. PCUs are a compact, containerised product, with each unit measuring approximately 2.5 metres wide by 2.9 metres high, with a depth of 12.2 metres (equivalent to a 40 foot shipping container for the double inverter units).

The exact height of these PCUs will be subject to detailed design. The location of the PCUs are identified in **Appendix C** showing all potential configurations of the PCU storage locations. **Figure 3-3** provides an example of a typical PCU.

Figure 3-3: Typical Single Inverter

3.4.2 Battery Storage

The proposed BESS will be located within containerised units and will either be co-located with PCUs distributed around the site or aggregated in one BESS storage area depending on detailed project design.

The BESS will enable the solar farm to be a flexible energy generation source, providing energy when it is required the most. The BESS electrical energy into chemical energy and stores the energy internally. It may also contribute towards network security Frequency Control Ancillary Services (FCAS) in the Region. A typical BESS is shown in **Figure 3-4** and layout for the BESS are contained in the layout shown in **Figure 3-5** which shows all potential BESS storage configurations (i.e. PCU dispersed around the site (denoted by small green dots on the site layout) or aggregated).

Figure 3-4: Typical BESS

3.5 Quantities of Dangerous Goods Stored and Handled

The classes and quantities of DGs to be approved in the project are summarised **Table 3-1**.

Table 3-1: Maximum Classes and Quantities of Dangerous Goods Stored

Area	Class	Description	Quantity
BESS	9	Lithium Batteries	3,492 T
PCU Transformer	C1	Transformer oils	190,000 L*
Substation Transformer	C1	Transformer oils	40,000 L

*Approximately 5,000 L per transformer.

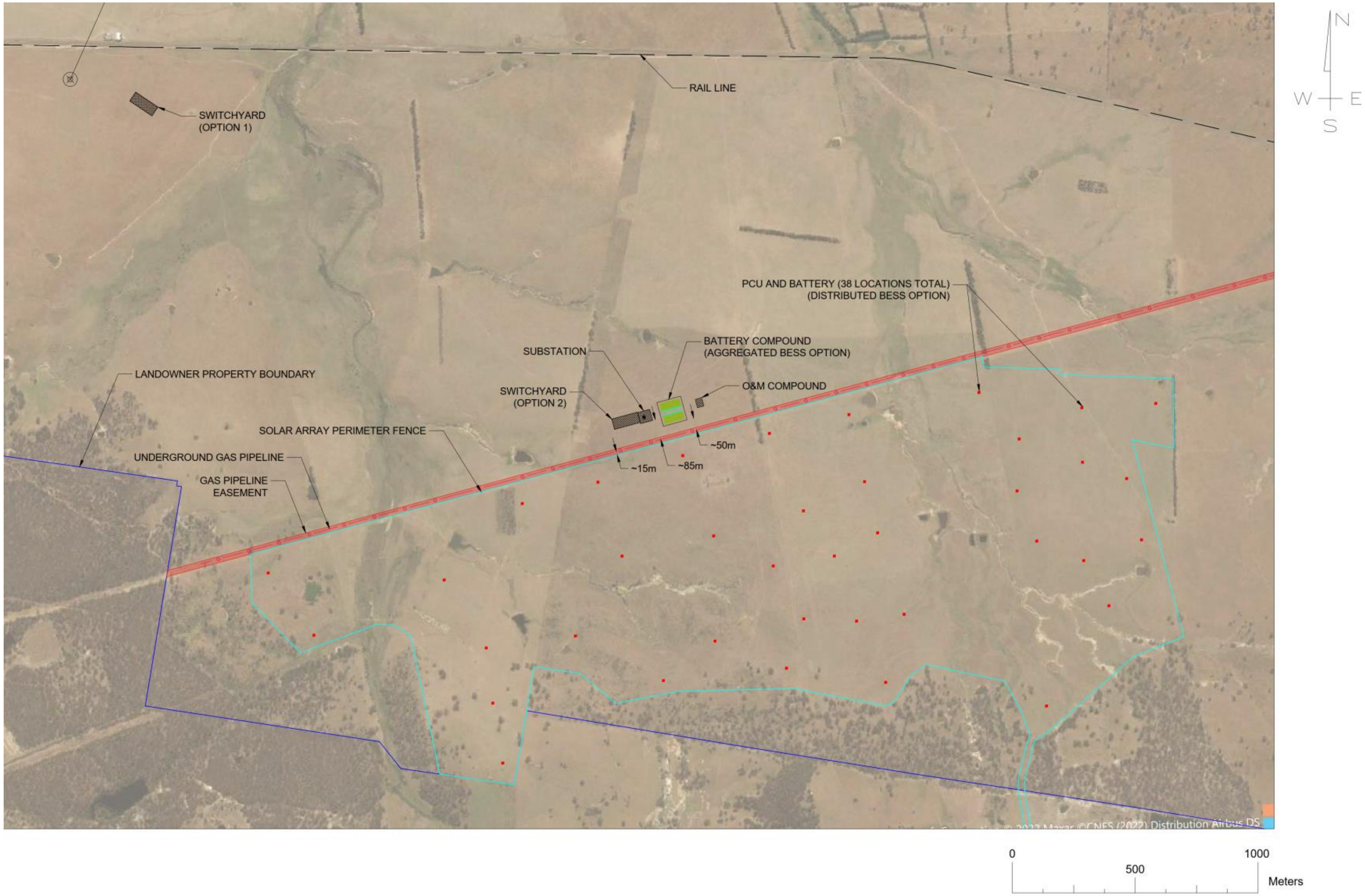

Figure 3-5: Site Layout

4.0 Hazard Identification

4.1 Introduction

A hazard identification table has been developed and is presented at **Appendix A**. This table has been developed following the recommended approach in Hazardous Industry Planning Advisory Paper No .6, Hazard Analysis Guidelines (Ref. [1]). The Hazard Identification Table provides a summary of the potential hazards, consequences and safeguards at the site. The table has been used to identify the hazards for further assessment in this section of the study. Each hazard is identified in detail and no hazards have been eliminated from assessment by qualitative risk assessment prior to detailed hazard assessment in this section of the study.

In order to determine acceptable impact criteria for incidents that would not be considered for further analysis, due to limited impact offsite, the following approach has been applied:

- *Fire Impacts* - It is noted in Hazardous Industry Planning Advisory Paper (HIPAP) No. 4 (Ref. [2]) that a criterion is provided for the maximum permissible heat radiation at the site boundary (4.7 kW/m^2) above which the risk of injury may occur and therefore the risk must be assessed. Hence, to assist in screening those incidents that do not pose a significant risk, for this study, incidents that result in a heat radiation less that at 4.7 kW/m^2, at the site boundary, are screened from further assessment.

  Those incidents exceeding 4.7 kW/m^2 at the site boundary are carried forward for further assessment (i.e. frequency and risk). This is a conservative approach, as HIPAP No. 4 (Ref. [2]) indicates that values of heat radiation of 4.7 kW/m^2 should not exceed 50 chances per million per year at sensitive land uses (e.g. residential). It is noted that the closest residential area is approximately 700 m from the site, hence, by selecting 4.7 kW/m^2 as the consequence impact criteria (at the adjacent industrial site boundary) the assessment is considered conservative.

- *Explosion* - It is noted in HIPAP No. 4 (Ref. [2]) that a criterion is provided for the maximum permissible explosion over pressure at the site boundary (7 kPa) above which the risk of injury may occur and therefore the risk must be assessed. Hence, to assist in screening those incidents that do not pose a significant risk, for this study, incidents that result in an explosion overpressure less than 7 kPa, at the site boundary, are screened from further assessment. Those incidents exceeding 7 kPa, at the site boundary, are carried forward for further assessment (i.e. frequency and risk). Similarly, to the heat radiation impact discussed above, this is conservative as the 7 kPa value listed in HIPAP No. 4 relates to residential areas, which are over approximately 700 m from the site.

- *Toxicity* – Toxic bi-products of combustion may be generated by a BESS fire; hence, toxicity has been assessed with criteria based upon the Emergency Response Planning Guidelines (ERPG).

- *Property Damage and Accident Propagation* - It is noted in HIPAP No. 4 (Ref. [2]) that a criterion is provided for the maximum permissible heat radiation/explosion overpressure at the site boundary (23 kW/m^2/14 kPa) above which the risk of property damage and accident propagation to neighbouring sites must be assessed. Hence, to assist in screening those incidents that do not pose a significant risk to incident propagation, for this study, incidents that result in a heat radiation heat radiation less than 23 kW/m^2 and explosion over pressure less than 14 kPa, at the site boundary, are screened from further assessment. Those incidents exceeding 23 kW/m^2 at the site boundary are carried forward for further assessment with respect to incident propagation (i.e. frequency and risk).

- *Societal Risk* – HIPAP No. 4 (Ref. [2]) discusses the application of societal risk to populations surrounding the proposed project. It is noted that HIPAP No. 4 indicates that where a development proposal involves a significant intensification of population, in the vicinity of such a project, the change in societal risk needs to be taken into account. In the case of the project, there is currently no significant intensification of population around the proposed site; hence, societal risk has not been considered in this assessment.

4.2 Properties of Dangerous Goods

The type of DGs and quantities stored and used at the site has been described in **Section 3**. **Table 4-1** provides a description of the DGs to be stored and handled at the site, including the Class and the hazardous material properties of the DG Class.

Table 4-1: Properties* of the Dangerous Goods and Materials Stored at the Site

Class	Hazardous Properties
9 – Miscellaneous DGs	Class 9 substances and articles (miscellaneous dangerous substances and articles) are substances and articles which, during transport present a danger not covered by other classes. Releases to the environment may cause damage to sensitive receptors within the environment. It is noted that the Class 9s stored within this project are lithium ion batteries which may undergo thermal runaway (i.e. escalating reaction resulting in heat which ultimately leads to failure of the battery and a fire).
Combustible Liquids	Combustible liquids are typically long chain hydrocarbons with flash points exceeding 60.5ºC. Combustible liquids are difficult to ignite as the temperature of the liquid must be heated to above the flash point such that vapours are generated which can then ignite. This process requires either sustained heating or a high-energy ignition source.

* The Australian Code for the Transport of Dangerous Goods by Road and Rail (Ref. [5]

4.3 Hazard Identification

Based on the hazard identification table presented in **Appendix A**, the following hazardous scenarios have been developed:

- Li-ion battery fault, thermal runaway and fire.
- Li-ion battery fire and toxic gas dispersion.
- Electrical equipment failure and fire.
- Transformer internal arcing, oil spill, ignition and bund fire.
- Electromagnetic field Impacts.
- Gas pipeline impacts.

Each identified scenario is discussed in further detail in the following sections.

4.4 Li-Ion Battery Fault, Thermal Runaway and Fire

Lithium ion (Li-ion) batteries are composed of a metallic anode and cathode which allows for electrons released from the anode to travel to the cathode where positively charged ions in the solute migrate to the cathode and are reduced. The flow of electrons provides the source of energy which is discharged from a battery and used for work. In a Li-ion battery, the lithium metal composites (a composite of lithium with other metals such as cobalt, manganese, nickel, or any combination of these metals) oxidises (loses an electron) becoming a positively charged ion in solution which migrates through the battery separator to the cathode. At the same time, the lost electron travels through the circuit to the cathode. The lithium ions in solution then recombine with the electron at the cathode forming lithium metal within the cathodic metal composite. This process is shown in **Figure 4-1**.

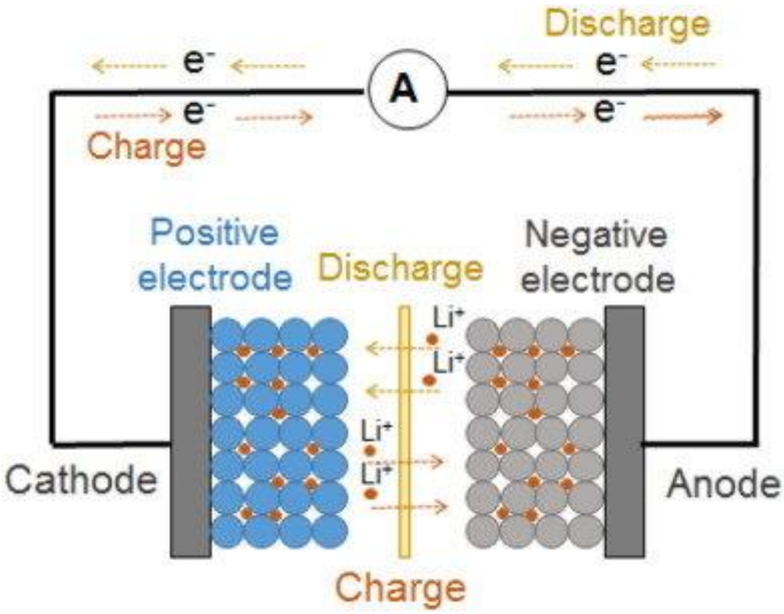

Figure 4-1: Cathode and Anode of a Battery (Source Research Gate)

Initial lithium batteries were designed around lithium metal (i.e. no composite structure) due to the high energy density yielded by the metal. However, when overcharging a battery, lithium ions can begin to plate on the anode in the form of lithium dendrites. Eventually, the dendrites pierce the separator within the battery resulting in a short of the battery which could result in heat, fire, or explosion of the battery. The technology evolved to move away from lithium metal to lithium ions (held within composite materials) which reduced the incidence of lithium dendrites forming resulting in an overall safer battery.

Despite the improvement in battery technology, there are several degradation mechanisms that are still present within the battery which can result in thermal runaway. These include:

- Chemical reduction of the electrolyte at the anode
- Thermal decomposition of the electrolyte
- Chemical reduction of the electrolyte at the cathode
- Thermal decomposition by the cathode and the anode
- Internal short circuit by charge effects

These effects arise primarily as a result of high discharge, overcharging, or water ingress into the battery which results in a host of bi-products being formed within the battery during charge and discharge cycles.

As a result, Li-ion batteries are equipped with several safety features to prevent the batteries from charging or discharging at voltages which result in battery degradation, leading to shorting of the battery and thermal runaway. Safety features generally include:

- Shut-down separator (for overheating)
- Tear-away tab (for internal pressure relief)
- Vent (pressure relief in case of severe outgassing)
- Thermal interrupt (overcurrent/overcharging/environmental exposure)

These features are designed to prevent overcharging or excessive discharge, pressurisation arising from heat generated at the anode or from battery contamination. Protection techniques for Li-ion batteries are standard; hence, the potential for thermal runaway to occur in normal operation is incredibly low with the only exceptions being where batteries are manufactured poorly or due to manufacturing faults, or battery damage (i.e. battery cell is ruptured as this can short circuit the battery resulting in thermal runaway).

Given the ubiquitous nature of Li-ion batteries, thermal runaway is not considered a credible threat when used in a battery storage. In terms of physical damage, the batteries are contained within in modules which are located within a fenced area; therefore, there is a low potential for damage to occur to the batteries which may initiate an incident.

Notwithstanding this, there is the potential for thermal runaway to occur which may consume the whole battery module which may result in offsite impacts or propagation risks to adjacent modules. Therefore, this incident has been carried forward for further analysis.

4.5 Li-ion Battery Fire and Toxic Gas Dispersion

As noted in **Section 4.4**, there is the potential for a BESS failure to occur resulting in a fire which may result in toxic bi-products of combustion to form. A literature review was conducted on lithium-ion battery fires to identify the toxic gases which may be generated in the event of a fire. The review identified the following gases or classes of gases can form:

- Carbon dioxide;
- Carbon monoxide; and
- Fluorine gases.

Each of these have been discussed in further detail in the following subsections.

4.5.1 Carbon Dioxide

Carbon dioxide is a colourless, odourless, dense gas which is naturally forming and is present in the atmosphere at concentrations around 415 ppm (0.0415%). At low concentrations carbon dioxide is physiologically impotent and at low concentrations does not appear to have any toxicological effects. However, as the concentration grows it increases the respiration rate with short term Exposure Limit (STEL) occurring at 30,000 ppm (3%), above 50,000 ppm (5%) a strong respiration effect is observed along with dizziness, confusion, headaches, and shortness of breath. Concentrations in excess of 100,000 ppm (10%) may result in coma or death.

Carbon dioxide is a by-product of combustion where hydrocarbon or carbon-based materials are involved. A typical combustion reaction producing carbon from a hydrocarbon has been provided in **Equation 4-1**. This reaction proceeds when there is an excess of oxygen to the fuel being consumed and is known as complete combustion as it is the most efficient reaction pathway.

$$C_3H_8(g) + 5O_2(g) \rightarrow 3Co_2(g) + 4H_2O(g)$$ **Equation 4-1**

The lithium-ion batteries are predominantly composed of metal structures. However, during a fire event ancillary equipment and materials within the batteries will be involved in the fire including wiring, plastics, anodes, etc. which will liberate carbon dioxide. However, a review of the toxicological impacts indicates high concentrations would be required to result in injury or fatality. Based upon a review of the sensitive areas, and the similar BESS fires, it is not considered that the formation of carbon dioxide in a fire would be sufficient to result in downwind impacts sufficient to cause injury or fatality. In other words, there would be insufficient production of carbon dioxide to generate a plume of sufficient concentration to displace the required oxygen for a significant downwind consequence to occur. Therefore, this incident has not been carried forward for further analysis.

4.5.2 Carbon Monoxide

Carbon monoxide an odourless, colourless gas which is slightly denser than air and occurs naturally in the atmosphere at concentrations around 80 ppb. Carbon monoxide is a toxic gas as it irreversibly binds with haemoglobin which prevents these molecules from carrying out the function of oxygen / carbon dioxide exchange. The loss of 50% of the haemoglobin may result in seizures, coma or death which can occur at concentration exposures of approximately 600 ppm (0.06%).

Carbon monoxide is by-product of combustion if there is insufficient oxygen to enable complete combustion. The reaction pathway for the formation of carbon monoxide is provided in **Equation 4-2**.

$$2C_3H_8(g) + 7O_2(g) \rightarrow 6CO(g) + 8H_2O(g)$$ **Equation 4-2**

As noted, in **Section 4.5.1** there is the potential for a fire to occur with the BESS units which could form carbon monoxide if there is insufficient oxygen to sustain complete combustion. However, it is noted that the combustible load within the BESS which could result in the formation of carbon monoxide is relatively low compared to the available oxygen in the surrounding atmosphere. Therefore, it is considered that the formation of carbon monoxide at levels which would result in a substantial downwind impact are not considered credible. Therefore, this incident has not been carried forward for further analysis.

4.5.3 Fluorine Gases

The electrolyte used in Li-ion batteries typically is lithium hexafluorophosphate ($LiPF_6$) or other li-salts containing fluorine. In the event of a thermal runaway, the electrolyte will expand and be vented from the battery. In the event of a fire, the vented gas and other components such as the polyvinylidene fluoride binders may form gases such as hydrogen fluoride (HF), phosphorous pentafluoride (PF_5) and phosphoryl fluoride (POF_3) (Ref. [6]).

The decomposition of $LiPF_6$ can be promoted by the presence of water / humidity according to reactions **Equation 4-3** to **Equation 4-5**.

$$LiPF_6 \rightarrow LiF + PF_5$$ **Equation 4-3**

$$PF_5 + H_2O \rightarrow POF_3 + 2HF$$ **Equation 4-4**

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF$$ **Equation 4-5**

Of the fluorine gases formed, PF_5 is a short-lived gas while POF_3 is a reactive intermediate. Thermal destruction of a several battery chemistry, configurations and State of Charge (SOC) indicated the vast majority of these did not produce observable POF_3 with the only observance occurring in a specific battery chemistry at 0% SOC (Ref. [6]). Therefore, the main fluorine gas of concern in a Li-ion battery fire is HF.

HF gas is hydroscopic readily dissolving into water vapour / humidity or moisture in airways forming hydrofluoric acid. Hydrofluoric acid is a weak acid although is highly corrosive and may result in chemical burns. In addition, it is calcium scavenging. Hence, it will readily bind with calcium in cells and tissues disrupting the nerve signalling.

The immediately dangerous to life or Health (IDLH) for HF is 30 ppm and the 10-minute lethal concentration is 170 ppm. Based upon the volumes of electrolyte in the battery cells, along with other fluorine containing compounds used within the batteries, the potential to generate HF at levels which may exceed these concentrations is considered credible. Hence, this incident has been carried forward for further analysis.

4.6 Electrical Equipment Failure and Fire

Electrical equipment is located within the switch room which may fail resulting in overheating, arcing, etc. which could initiate a fire. In the event of a fire, it may begin to propagate to adjacent combustible materials (i.e. wiring). It is noted that electrical equipment fires typically start by smouldering before flame ignition occurs resulting in a slow fire development.

The type of equipment used within the project is ubiquitous throughout the world and across industry segments and is therefore not a unique fire scenario. Based upon fire development within switch rooms the fire would be considered to be relatively slow in growth and would be unlikely to result in substantial impacts in terms of offsite impact or incident propagation. Therefore, this incident has not been carried forward for further analysis.

4.7 Transformer Internal Arcing, Oil Spill, Ignition and Bund Fire

Transformers contain oil which is used to cool the units during operation. If arcing occurs within the transformer (e.g. due to a low oil level), the high energy passing through the coolant vaporises the oil into light hydrocarbons (methane, ethane, acetylene, etc.) resulting in rapid pressurisation within the reservoir. To minimise the likelihood of such occurrence, transformers are fitted with a low oil pressure switches and a pressure surge switch (Buckholtz relay). These devices identify potential oil and pressure events within the transformer, isolating power and alarming operators.

Notwithstanding the protection systems, if the pressure rise exceeds the structural integrity of the reservoir, and the installed pressure relief devices, the reservoir can rupture allowing the release of oil into the bund. The rupture also allows oxygen to enter the reservoir. The temperature of the gases is above the auto ignition point, but this does not occur until oxygen is present. When oxygen enters the reservoir, the gases auto ignite which generates sufficient heat to ignite the oil in the bund.

As there is the potential for a fire to occur within the substation transformers, this incident has been carried forward for further analysis.

The transformers haven't been subject to detailed design at this stage; hence, the following recommendation has been made:

- The transformers spill containment shall be designed according to the requirements of AS 2067:2016 – "Substations and high voltage installations exceeding 1 kV a.c'

4.8 Electromagnetic Field Impacts

4.8.1 Introduction

Electric and Magnetic Fields (EMFs) are associated with a wide range of sources and occur both naturally as well as man-made. Naturally occurring EMFs, occurring during lightning storms, are generated from Earth's magnetic field. Man-made EMFs are present wherever there is electricity; hence, EMFs are present in almost all built environments where electricity is used.

Extremely low frequency (ELF) electric and magnetic fields (EMF) occupy the lower part of the electromagnetic spectrum in the frequency range 0-3,000 Hz which is the current will change direction 0-3,000 times a second. ELF EMF result from electrically charged particles. Artificial sources are the dominant sources of ELF EMF and are usually associated with the generation, distribution and use of electricity at the frequency of 50 Hz in Australia. The electric field is produced by the voltage whereas the magnetic field is produced by the current.

Solar farms create EMFs from operational electrical equipment, such as transmission lines, substations and the electrical components found within BESS units, inverts, etc. This equipment has the potential to produced ELF EMF's in the range of 30 to 300 Hz.

4.8.2 Existing Standards

There are currently no existing standards in Australia for governing the exposure limits to ELF EMFs; however, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has provided some guidelines around exposure limits for prolonged exposure which limits the exposure to 2,000 milligauss (mG) for members of the public in a 24 hour period (Ref. [7]).

Table 4-2 provides typical magnetic field measurements and ranges associated with EMF sources. It is noted that electric fields around devices are generally close to 0 due to the shielding provided around the equipment. In addition, EMF levels drop away quickly with distance; hence, while a value may be measurable at the source, within a short distance the EMF is undetectable.

Table 4-2: EMF Sources and Magnetic Field Strength

Source	Typical Measurement (mG)	Measurement Range (mG)
Television	1	0.2 – 2
Refrigerator	2	2 – 5
Kettle	3	2 – 10
Personal computer	5	2 – 20
Electric blanket	20	5 – 30
Hair dryer	25	10 – 70
Distribution powerline (under the line)	10	2 – 20
Transmission power line (under the line)	20	10 – 200

Source	Typical Measurement (mG)	Measurement Range (mG)
Edge of easement	10	2 – 50

4.8.3 Exposure Discussion

A review of the site indicates there are no immediate residences adjacent to the area where the solar farm or BESS will be developed providing substantial distance for attenuation of EMFs. Based upon the typical levels which may be generated by transmission equipment the cumulative effect would not exceed the 2,000 mG limit for prolonged exposure. In addition, the closest residence is approximately 700 m away from the EMF generating sources at the solar farm; hence, the potential for the EMF to exceed the accepted levels is considered negligible.

As the potential for exposure to EMF exceeding the international guidelines is negligible, this incident has not been carried forward for further analysis.

4.9 Gas Pipeline Impacts

A review of the surrounding area indicates there is a buried gas pipeline running through the site. Incidents arising from the BESS and transformers may have an impact upon the gas pipeline which could result in a loss of containment and associated incidents (i.e. jet fire, flash fire, explosions, etc.).

Based upon the hazard identification conducted, the only real threats to the gas pipeline during operation are from BESS fires which will emit radiant heat. However, as the pipeline is buried, the earth above the pipeline will provide shielding from the radiant preventing heating or thermal damage to the pipeline.

The only other threats to the pipeline occur during the construction of the BESS and solar farm whereby any excavation works may result in the pipeline being impacted and damaged and subsequent loss of containment or create a point where corrosion can take hold resulting in an eventual failure as the metal pipework is corroded. Typical protection systems around pipelines include “dial before you did” to identify the location of pipelines, marker signs and marker tape. The aim is to identify a pipeline before undertaking work or to alert site personnel the presence of a pipeline, or in the worst case if excavation occurs the marker tape is dragged to the surface before excavation impacts the actual pipeline.

The location of the pipeline is already known; hence, there is a low potential for excavation work to occur around the pipeline. In the event of a site error resulting in excavation along the pipeline, the marker tape should be identified prior to impact; however, this may only be the case if the operator is aware of what the marker tape means. Assuming, the protection systems work as intended, the potential damage to the gas pipeline should be minimised preventing damage and potential incident escalation.

It is noted, the protection of the gas pipeline relies on personnel working in the area to be aware of the gas pipeline and the protections associated with it. Therefore, to improve site personnel knowledge, the following recommendations have been made:

- The site induction shall include information regarding the gas pipeline including location and protections to identify the gas pipeline (i.e., marker tape, etc.).
- All personnel working at the site shall be inducted prior to commencing any work.

- Appropriate marking shall be provided along the length of the gas pipeline as required to minimise the potential for unauthorised works occurring within the vicinity of the gas pipeline, in conjunction with the Site Induction and relevant site-specific construction management plans.

Based upon the low risk of interaction with the gas pipeline based upon the protection systems incorporated and the recommendation induction, training and markings, it is considered that the potential for an offsite incident to occur as a result of the gas pipeline is negligible; hence, this incident has not been carried forward for further analysis.

5.0 Consequence Analysis

5.1 Incidents Carried Forward for Consequence Analysis

The following incidents were identified to have potential to impact off site:

- Li-ion battery fault, thermal runaway and fire.
- Li-ion battery fire and toxic gas dispersion.
- Transformer internal arcing, oil spill, ignition and bund fire.

Each incident has been assessed in the following sections.

5.2 Li-Ion Battery Fault, Thermal Runaway and Fire

There is potential that a Li-Ion battery may fault resulting in thermal decomposition and fire which may spread throughout the whole fire unit if not isolated / protected. A detailed analysis has been conducted in **Appendix B** and the radiant heat impact distances estimated for this scenario are shown in **Table 5-1**. The radiant heat contours associated with a fire occurring within a Li-Ion battery module are shown in **Figure 5-1**.

Table 5-1: Radiant Heat from a Li-Ion Battery Fire

Heat Radiation (KW/m^2)	Distance (m)
35	0
23	6
12.6	6
4.7	9

Figure 5-1 is based upon the BESS storage area which depending upon the end configuration could be in numerous locations around the site. It is noted that the solar farm site resides within a larger parcel of farmland; hence, the site boundary for the solar farm development is technically the security fence of the BESS (for the aggregated BESS) or the security fence of the solar array (for the distributed BESS option). It is noted that the more conservative design option for offsite impact is the aggregated BESS option as the security fence is provided around the BESS while the distributed option the BESS are further from the fence. Therefore, this has been reviewed in further detailed with respect to the aggregated BESS as the risk profile from the distributed BESS would not impact over the site boundary. A review of **Figure 5-1** indicates that the 4.7 kW/m^2 contour would impact offsite; hence, this incident has been carried forward for further analysis.

A review of the 23 kW/m^2 contour indicates it does not impact offsite; however, the distance calculated from the model indicates a distance of 6 m. The adjacent battery units are 2 m away; hence, the 23 kW/m^2 contour would impact these units which may result in incident propagation. It is noted that the battery units are containerised and the metal enclosure would prevent direct radiant heat impact onto the battery units within the adjacent unit. Therefore, it is considered that incident escalation is unlikely to occur; however, cosmetic damage to the adjacent battery units may occur.

It is noted that the contours shown in **Figure 5-1** are offset from the release point due to the presence of wind which results in an offset of the radiant heat from the source due to the tilt of the flame.

Figure 5-1: Li-Ion Battery Module Fire Radiant Heat Contours

5.3 Li-ion Battery Fire and Toxic Gas Dispersion

In the event of a BESS fire, decomposition of solvents and additives used within the batteries will result in the formation of HF gas which will disperse downwind of the fire source. The impacts associated with exposure to a toxic gas are broken down based upon the effects which occur when exposed to a concentration. The values used in this analysis are based upon the Emergency Response Planning Guidelines (ERPG) tiers which are summarised below

- **ERPG-3** is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.
- **ERPG-2** is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action.

- **ERPG-1** is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient adverse health effects or without perceiving a clearly defined objectionable odour.

Provided in **Table 5-2** is a summary of the concentration limits for each ERPG value for ammonia.

Table 5-2: HF ERPG Concentrations

ERPG Tier	Translation	Concentration (ppm)
3	Fatality	34.5
2	Injury	13.8
1	Irritation	1.38

A detailed analysis of a HF dispersion has been prepared in **Appendix B** with the results shown in **Table 5-3**.

Table 5-3: HF Dispersion Results for F1.5 and D3 Conditions

ERPG Level	Downwind Distance (m)	
	F1.5	D3
ERPG-3	1,427	479
ERPG-2	2,554	824
ERPG-1	13,504	3,223
1% Fatality	781	275

A review of the impact distances indicates that there is the potential for a fatal exposure concentration to impact offsite; hence, this incident has been carried forward for further analysis.

5.4 Transformer Internal Arcing, Oil Spill, Ignition and Bund Fire

There is potential that arcing may occur within the transformers which may lead to generation of gases and pressure above the structural integrity of the oil reservoir which may rupture leaking oil into the bund. As a result of the arcing and rupture, the oil may ignite leading to a bund fire within the dimensions of the bund. A detailed analysis has been conducted in **Appendix B** and the radiant heat impact distances estimated for this scenario are shown in **Table 5-4**. The radiant heat contours associated with a fire occurring within a transformer bund are shown in **Figure 5-2**. It is noted the contours are located at the worst-case location within the substation with respect to the site boundary.

Table 5-4: Radiant Heat from a Transformer Bund Fire

Heat Radiation (KW/m^2)	Distance (m)
35	9
23	10
12.6	11
4.7	17

As can be seen in **Figure 5-2** the radiant heat contours at 4.7 kW/m^2 do not impact over the security fence and would therefore not impact over the site boundary. It is noted that under different wind conditions and directions there may be a minor impact over the site boundary at 4.7 kW/m^2; however, as only a minor incursion over the site boundary could occur in such a condition and the site is located within the boundaries of a private property, it is not expected that a fatality would occur. Therefore, this incident has not been carried forward for further analysis.

The 23 kW/m^2 contour is associated with incident propagation which also does not impact over the boundary nor the site boundary. Therefore, incident propagation offsite would not be expected to occur from transformer bund fire.

It is noted that there may be other transformer locations around the site along the PV arrays depending upon the final layout selected; however, these are located >20 m from the main private property boundary and therefore would not result in impacts off site. As the contours for fatality and incident propagation do not impact over the site boundaries this incident has not been carried forward for further analysis.

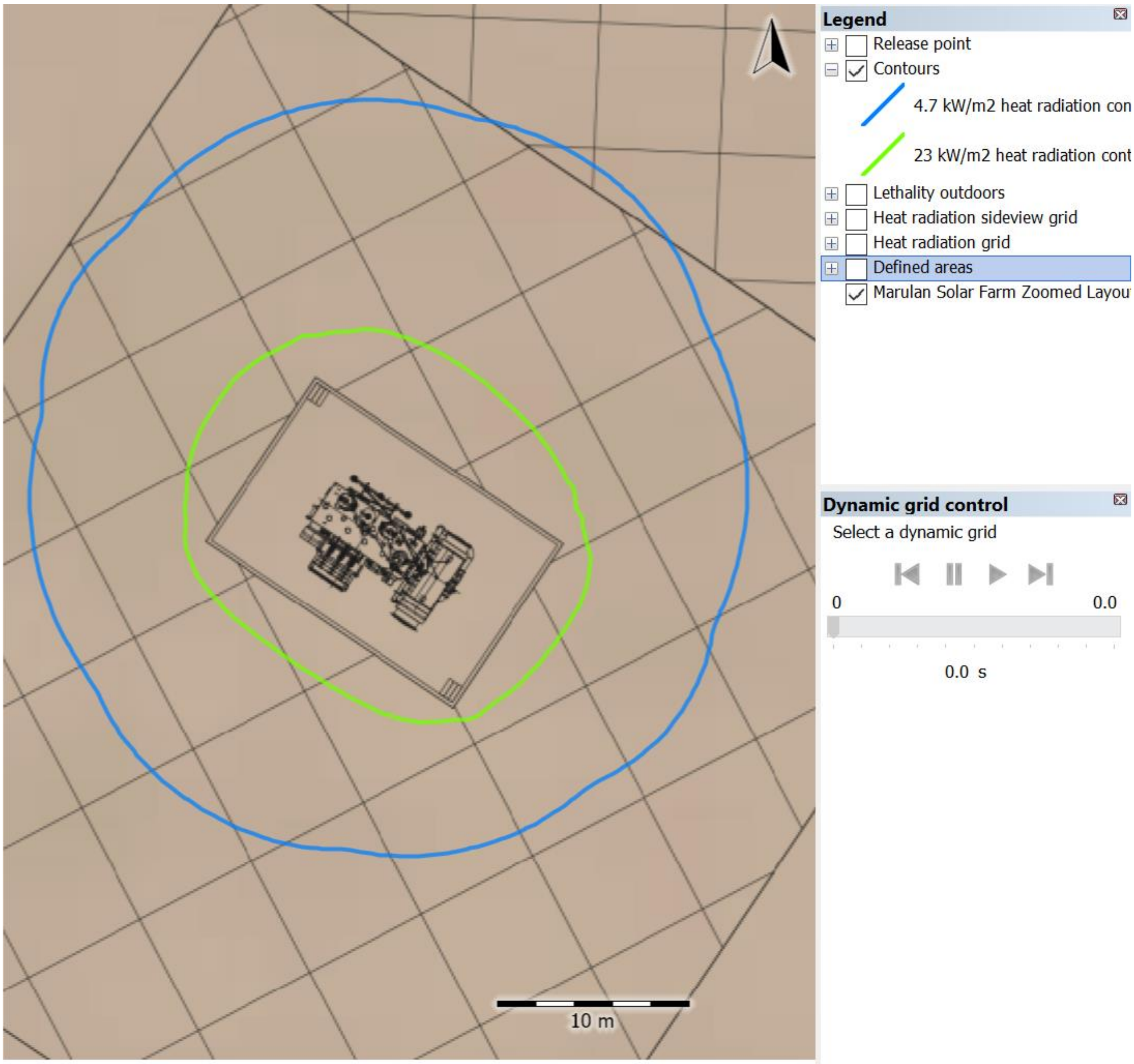

Figure 5-2: Transformer Bund Fire Radiant Heat Contours

6.0 Frequency Analysis and Risk Assessment

6.1 Incidents Carried Forward for Frequency Analysis

The following incidents have been carried forward for frequency analysis and risk assessment:

- Li-ion battery fault, thermal runaway and fire.
- Li-ion battery fire and toxic gas dispersion.

Each of these incidents have been assessed in the following sections.

6.2 Li-Ion Battery Fault, Thermal Runaway and Fire

To estimate the potential for a fatality to occur it is necessary to estimate the initiating event frequency. A detailed analysis has been prepared in **Appendix D** which identified an initiating event frequency of 1.1×10^{-4} per MWh/year. Based upon the number of BESS units and the total installed capacity for this project, each individual unit was estimated to have a storage capacity of 3.75 MWh; therefore, the potential for a fire to occur within a BESS unit is $1.1 \times 10^{-4} \times 3.75 = 4.13 \times 10^{-4}$ p.a.

A fatality can only occur if a person is exposed to radiant heat which would result in a fatality. Therefore, it is necessary to have a person to be located at the site boundary of the BESS (i.e. the security fence). It is noted that the BESS is located within a security fence within the boundaries of a private property. Therefore, the potential for personnel to be located at the boundary (i.e. outside the security boundary but on the private property) would be drastically minimised. Given the land is farmland, it has been assumed that the property owners or their employees may be within the vicinity of the BESS 1 hour per week or 52 hours/year resulting in an exposure probability of 0.006.

To estimate the probability of fatality it is necessary to review the susceptibility to personnel exposed to radiant heat that may occur at the site boundary. Tolerance to an exposure (i.e. radiant heat or toxicity) differs across a population which may be estimated using Probit analysis. For radiant heat exposure, the Probit equation is shown in **Eqn 6-1**.

$$Y = K_1 + K_2 lnV \qquad \textbf{Eqn 6-1}$$

Where:

- K1 = -36.38
- K2 = 2.56
- V = $I^{4/3t}$
- I = radiant heat intensity (W/m^2)
- t = time (seconds)

The value obtained from the Probit equation is then read from the graph shown in **Figure 6-1**. Which yields the percentage of fatality for personnel exposed to the input radiant heat.

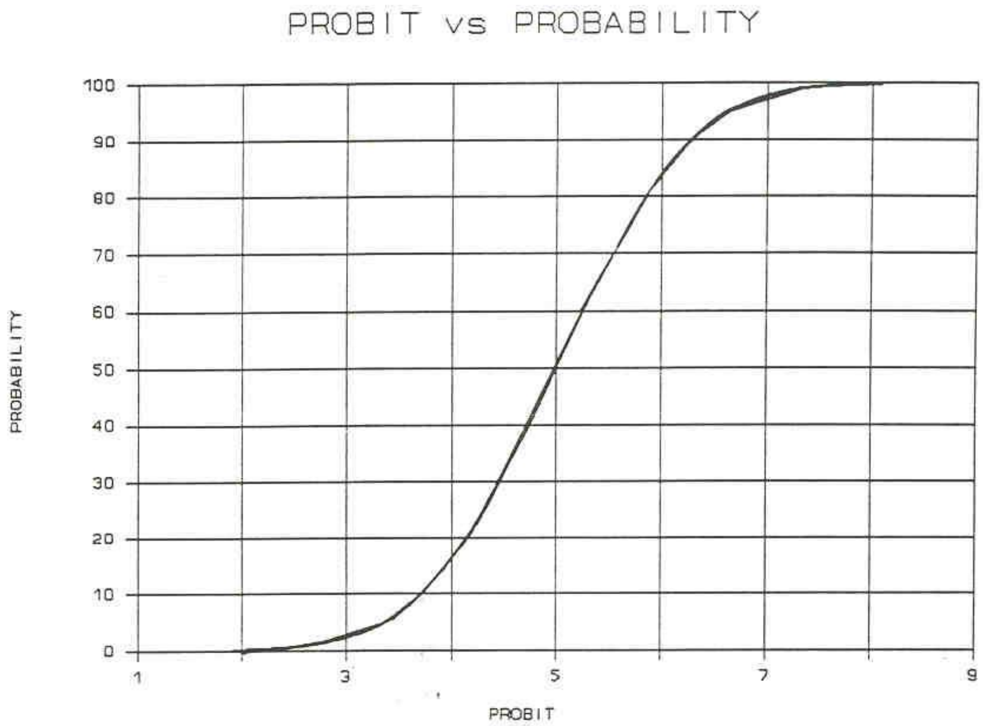

Figure 6-1: Probit vs Probability

The radiant heat calculated at the site boundary is approximately 8 kW/m^2 which when substituted into **Eqn 6-1** with an exposure period of 30 seconds results in a probit of 3 which translates into a probability of 3% reading from **Figure 6-1**.

The probability of fatality at the site boundary becomes $4.13 \times 10^{-4} \times 0.006 \times 0.03 = 7.4 \times 10^{-8}$ p.a.

6.3 Li-ion Battery Fire and Toxic Gas Dispersion

6.3.1 Introduction

There are two components to determining the fatality risk from the dispersion, the first is within the immediate vicinity of the release which where the site boundary (between the BESS infrastructure the private land) occurs and the second is the downwind dispersion which may impact residences. Each of these has been reviewed to determine the potential for a fatality to occur.

6.3.2 Immediate Vicinity

As with the battery fire, the initiating event frequency is 4.13×10^{-4} and the probability of a person been within the vicinity is the same as 0.006. The potential for a fatality to occur within the immediate vicinity becomes $4.13 \times 10^{-4} \times 0.006 = 2.48 \times 10^{-6}$ p.a.

6.3.3 Residential

The initiating event frequency is the 4.13×10^{-4} p.a. as previously discussed. **Table 5-3** identifies the lethality frequency of 1% at 781 m which is for outdoor situation in highly stable conditions (i.e. F1.5). A review of the D3 conditions indicates the lethal impact distances only occur in the highly stable F1.5 conditions. It has been assumed that F conditions occur 30% of the time.

The lethality for indoor situations is typically an order of magnitude lower than for outdoors as the structure of a building reduces the potential for pollutants to enter thereby resulting in a lower concentration and thus a lower potential for fatality. Therefore, at 781 m the probability of fatality would become 0.1% or 0.001.

Multiplying through the modifiers results in an overall fatality potential at the closest residences as defined in **Figure 3-2** which are approximately 700 m from the site of $4\times10^{-4} \times 0.3 \times 0.001 = 1.2\times10^{-7}$ p.a.

6.4 Total Fatality Risk

The fatality risks for the immediate vicinity and residences have been tabulated in **Table 6-1** and **Table 6-2.**

Table 6-1: Total Fatality Risk Immediate Vicinity

Incident	Fatality Risk (p.a.)
Li-Ion Fire	7.4×10^{-8}
Li-ion Toxic Gas Dispersion	2.48×10^{-6}
Total	$\mathbf{2.55\times10^{-6}}$

Table 6-2: Total Fatality Risk Residences

Incident	Fatality Risk (p.a.)
Li-Ion Fire	0
Li-ion Toxic Gas Dispersion	1.2×10^{-7}
Total	$\mathbf{1.2\times10^{-7}}$

6.5 Comparison Against Risk Criteria

6.5.1 Fatality Risk

The acceptable criteria have been taken from the NSW Department of Planning, Industry and Environment *Hazardous Industry Planning Advisory Paper No. 4 – Risk Criteria for Land Use Safety Planning* (Ref. [2]). The acceptable risk criteria published in the guideline relates to injury, fatality and property damage. The values in the guideline present the maximum levels of risk that are permissible at the land use under assessment as defined in **Table 6-3**.

Table 6-3: Individual Fatality Risk Criteria

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

The private property surrounding the solar farm and BESS units is not neatly described by the criteria shown in **Table 6-3**; however, the most applicable based upon the description would be active open spaces with a criterion of 10 pmpy. While the criteria at the residences would be 1 pmpy.

The fatality risk estimated for the immediate vicinity was calculated to be 2.55 pmpy which is below the criteria of 10 pmpy. Similarly, the criteria at the residential area were estimated to be 0.12 pmpy which is below the 1 pmpy criteria. Therefore, from a fatality risk perspective the development does not result in an exceedance of the criteria and would be considered acceptable for the proposed location.

6.5.2 Injury / Irritation

HIPAP No. 4 outlines that concentrations that would result in injury or irritation should not exceed 10 pmpy and 50 pmpy respectively. A review of the injury concentrations indicates the residences may be impacted by these for both the F1.5 and D3 scenarios. Therefore, it can be concluded that provided the wind direction blows toward residences injury may occur. However, as noted previously, the concentration indoors is typically a tenth of what is experienced outdoors; therefore, the injurious concentrations would not be experienced indoors under D3 conditions and would therefore likely only occur in F conditions. As assumed before, F conditions occur 30% of the time.

For the impact occur at a residence the plume must blow in the direction of the residence such that the residence is impacted. For the purpose of conducting generalised assessment, it is assumed the wind may blow in all directions equally, therefore, for an impact to occur at a residence the plume width must impact the residence. The plume has a width of 123 m and the circumference with a radius of 700 m is 4400 m; hence, the geometric probability of wind impacting a residence is 123/4400 = 0.03. Therefore, the potential for injury is $4.13 \times 10^{-4} \times 0.3 \times 0.03 = 3.78 \times 10^{-6}$ or 3.78 pmpy which is less than the 10 pmpy.

Undertaking a similar assessment for irritation, it is likely that under all conditions the concentration may result in an irritation impact at the residences. Therefore, the probability of irritation would be $4.13 \times 10^{-4} \times 0.03 = 12.5 \times 10^{-6}$ or 12.5 pmpy which is less than the 50 pmpy criteria.

6.6 Incident Propagation

The same guidelines provide acceptable risk criteria (Ref. [2]) for incident propagation as 50 chances pmpy. A review of the scenarios that may lead to incident propagation shows that the 23 kW/m^2 contour was not observed to impact offsite; hence, the potential for incident propagation is zero (0) which is less than the acceptable risk criteria for incident propagation.

7.0 Conclusion and Recommendations

7.1 Conclusions

A hazard identification table was developed for the Marulan Solar Farm PV & BESS project to identify potential hazards that may be present at the site as a result of operations or storage of materials. Based on the identified hazards, scenarios were postulated that may result in an incident with a potential for offsite impacts. Postulated scenarios were discussed qualitatively and any scenarios that would not impact offsite were eliminated from further assessment. Scenarios not eliminated were then carried forward for consequence analysis.

Incidents carried forward for consequence analysis were assessed in detail to estimate the impact distances. Impact distances were developed into scenario contours and overlaid onto the site layout diagram to determine if an offsite impact would occur. The consequence analysis showed that several scenarios impacted over the site boundary depending upon where the boundary was identified (i.e. security fence or property boundary).

Where an offsite impact was identified, a frequency analysis and risk assessment was conducted to identify the potential for fatality, injury and irritation to occur as a result of the development. The results indicated that the fatality risks would not exceed the acceptable criteria. Similarly, the injury and irritation criteria were not exceeded. Finally, the potential for incident propagation as assessed at the 23 kW/m^2 contour which didn't show any potential for off-site impact and thus incident propagation would not be considered to occur.

Based on the analysis conducted, it is concluded that the risks at the site boundary are not considered to exceed the acceptable risk criteria; hence, the project would only be classified as potentially hazardous and would be permitted within the current land zoning for the site.

7.2 Recommendations

Notwithstanding the conclusions drawn, the following recommendations have been made:

- The site induction shall include information regarding the gas pipeline including location and protections to identify the gas pipeline (i.e., marker tape, etc.).
- All personnel working at the site shall be inducted prior to commencing any work.
- Appropriate marking shall be provided along the length of the gas pipeline as required to minimise the potential for unauthorised works occurring within the vicinity of the gas pipeline, in conjunction with the Site Induction and relevant site-specific construction management plans.
- The transformers spill containment shall be designed according to the requirements of AS 2067:2016 – "Substations and *high voltage installations exceeding 1 kV a.c'*
- Battery equipment shall be located away from external site boundaries (property owner's site boundary) as much as possible to maximise distance to sensitive receptors from downwind dispersion in the event of a fire.
- A final hazard analysis shall be conducted once a detailed design has been completed to demonstrate the risk criteria are not exceeded.

8.0 References

[1] Department of Planning, Industry and Environment, "Hazardous Industry Planning Advisory Paper No. 6 - Guidelines for Hazard Analysis," Department of Planning, Industry and Environment, Sydney, 2011.

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[11] Marsh Commercial, "Battery energy storage systems fire risks explained," Marsh Commercial, 2021 February 23. [Online]. Available: https://www.marshcommercial.co.uk/articles/battery-energy-storage-fire-risks-explained/. [Accessed 2022 March 3].

Appendix A

Hazard Identification Table

Appendix A

A1. Hazard Identification Table

Area/Operation	Hazard Cause	Hazard Consequence	Safeguards
Battery Storage	• Failure of Li-ion battery protection systems	• Thermal runaway resulting in fire or explosion • Incident propagation through battery cells • Toxic smoke dispersion	• Batteries are tested by manufacturer prior to sale / installation • Overcharging and electrical circuit protection • Battery monitoring systems • Batteries composed of subcomponents (i.e. BBU, cells) reducing risk of substantial component failure • Batteries are not located in areas where damage could easily occur (i.e. within the fenced property) • Electrical systems designed per AS/NZS 3000:2007 (Ref. [8])
Switch rooms, communications, etc.	• Arcing, overheating, sparking, etc. of electrical systems	• Ignition of processors and other combustible material within servers and subsequent fire	• Fires tend to smoulder rather than burn • Isolated location • Switch room separation from other sources of fire
Substation	• Arcing within transformer, vaporisation of oil and rupture of oil reservoir	• Transformer oil spill into bund and bund fire	• Bunded • Isolated location
EMF	• Electric and magnetic equipment	• Generation of ELF EMF and injury / nuisance to surrounding area	• Large separation distances allow for attenuation of EMFs • Cumulative impacts from equipment below acceptable thresholds. • Low occupancy density within vicinity of the development
Gas pipeline	• Damage to pipeline during construction	• Failure of pipeline and loss of containment and fire, vapour cloud explosion, jet fire, flash fire	• Underground pipeline protects against damage / radiant heat • Marker tape, marker signs

Area/Operation	Hazard Cause	Hazard Consequence	Safeguards
	• Fire from solar farm equipment impacts pipeline		• Dial before you dig • Known location of pipeline

Appendix B

Consequence Analysis

B1. Incidents Assessed in Detailed Consequence Analysis

The following incidents are assessed for consequence impacts.

- Li-ion battery fault, thermal runaway and fire.
- Li-ion battery fire and toxic gas dispersion.
- Transformer internal arcing, oil spill, ignition and bund fire.

Each incident has been assessed in the sections below.

B2. Gexcon - Effects

The modelling was prepared using Effects which is proprietary software owned by Gexcon which has been developed based upon the TNO Coloured books and updated based upon CFD modelling tests and physical verification experiments. The software can model a range of incidents including pool fires, flash fires, explosions, jet fires, toxic dispersions, warehouse smoke plumes, etc.

B3. Radiant Heat Physical Impacts

Appendix Table B-1 provides noteworthy heat radiation values and the corresponding physical effects of an observer exposed to these values (Ref. [2]).

Appendix Table B-1: Heat Radiation and Associated Physical Impacts

Heat Radiation (kW/m^2)	Impact
35	• Cellulosic material will pilot ignite within one minute's exposure • Significant chance of a fatality for people exposed instantaneously
23	• Likely fatality for extended exposure and chance of a 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
12.6	• Significant chance of a 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
4.7	• Will cause pain in 15-20 seconds and injury after 30 seconds exposure (at least second degree burns will occur)
2.1	• Minimum to cause pain after 1 minute

B4. Li-Ion Battery Fault, Thermal Runaway and Fire

The battery units are spaced out throughout the site to provide energy storage when drawing energy from the grid and discharging back to the grid. For conservatism, a Li-Ion battery fire has been based upon a fire originating within a battery pack and propagating to the closest batteries resulting in a full container fire. The dimensions of the battery containers are 12 m x 3 m resulting in an area of 36 m^2.

The battery fire model has been based upon the properties of the organic solvents used within the battery. A review of typical organic solvents used batteries indicates there is a range including chemicals such as dimethoxyethane and gamma-butyrolacton. For the purposes of this assessment dimethoxyethane has been selected.

It is noted that the BESS units are contained in containerised metal shipping containers which will provide a level of shielding to the fire. A typical 20 ft shipping container has a height of 2.9 m; hence this has been input as a shielding value.

The input file used to model this scenario has been provided in

Parameters	
Inputs	
Process Conditions	
Chemical name	1,1-DIMETHOXYETHANE (DIPPR)
Calculation Method	
Type of pool fire calculation	Two zone model Rew & Hulbert
Type of pool fire source	Instantaneous
Fraction combustion heat radiated (-)	0.35
Soot definition	Calculate/Default
Source Definition	
Total mass released (kg)	10000
Temperature of the pool (°C)	25
Process Dimensions	
Type of pool shape (pool fire)	Polygon
Non burning area within pool (m2)	0
Height of the confined pool above ground level (m)	0
Include shielding at bottomside flame	Yes
Height of shielding at bottomside flame (m)	2.9
Meteo Definition	
Wind speed at 10 m height (m/s)	2
Predefined wind direction	S
Environment	
Ambient temperature (°C)	25
Ambient pressure (bar)	1.0151
Ambient relative humidity (%)	60
Amount of CO2 in atmosphere (-)	0.0004

Appendix Figure B-1: BESS Fire Input File

The above information was input into Effects which calculated the following outputs:

- SEP – 95.8 kW/m^2
- Flame height – 10.6 m

The results of the analysis are shown in **Appendix Table B-2.**

Appendix Table B-2: Heat Radiation Impacts from a Li-Ion Battery Fire

Heat Radiation (KW/m^2)	Distance (m)
35	0
23	6
12.6	6
4.7	9

B5. Li-ion Battery Fire and Toxic Gas Dispersion

B5.1 Atmospheric Conditions

The atmospheric conditions will vary from stable conditions (generally night-time) to unstable conditions (high insolation from solar radiation) which results in substantial vertical mixing, aiding in the dispersion. Contributing to this is the impact of wind speed which will limit the vertical rise of a plume but may exacerbate the downwind impact distance.

The atmospheric conditions are classified as Pasquill Guifford's Stability categories which are summarised in **Appendix Table B-3** (Ref. [9]).

Appendix Table B-3: Pasquill's Stability Categories

Surface wind speed at 10 m height (m/s)	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast or ≥50% cloud	<50% cloud.
<2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Generally, the most onerous conditions are F conditions which result in stable air masses and typically have inversion characteristics. Inversion characteristics occur when a warm air mass sits above a cold air mass. Typically, hot air will rise due to lower density than the bulk air. However, in an inversion, a warm air mass sits above the cooler denser air. Hence, as the warm air rises through the cold mass it hits a 'wall' of warmer air preventing vertical mixing above this point.

F conditions occur a minority of the time with conditions typically residing within the neutral bounds which are covered by D stability classes. High insolation conditions have increased vertical mixing which results in reduced downwind dispersion. Notwithstanding this, for conservatism the plume dispersion has been modelled using F conditions at a wind velocity of 1.5 m/s per the industry standard.

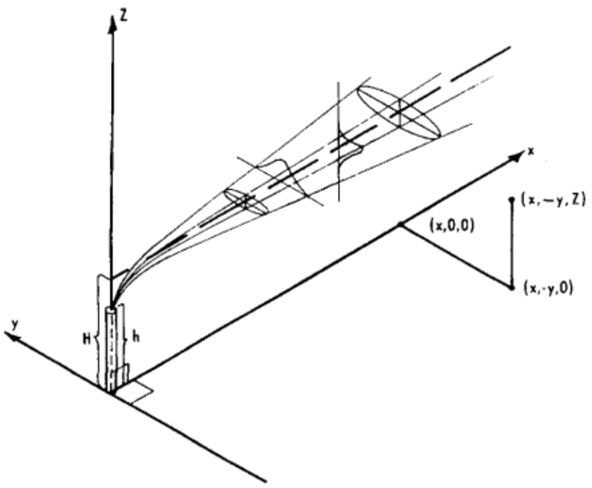
While F conditions are conservative, a D3 condition has been run in tandem as a sensitivity as part of the analysis.

B5.2 Temperature

The temperature had been proposed to be modelled at the average annual minimum and maximum. However, running the model at different temperatures did not show any significant variability in the results. Therefore, the temperature has been modelled at the average minimum temperature as conceptually this would provide a more conservative analysis as the hot plume will not rise as high allowing the dispersion to occur closer to ground level. The lowest minimum throughout the year occurs in July at a value of 9.1°C as taken from the Goulburn Airport (Weather station 070330).

B5.3 Dispersion Model Selection

As discussed in **Section 4.5** the representative chemical for modelling is HF which is neutrally buoyant meaning the molecular weight is similar to the average atmospheric molecular weight which eliminates any bias to rise or fall within the air mass. The neutrally buoyant model within Gexcon Risk Effects utilises a Gaussian dispersion which is graphically as shown in **Appendix Figure B-2**.



Appendix Figure B-2: Co-ordinate System for Gas Dispersion

B5.4 Wind Direction

For the purposes of understanding the impact at the closest resident, the wind direction has been selected in the direction of that closest residence. A review of the surrounding area indicates the closest residents are to the southeast at a distance of approximately 700 m. Therefore, the wind direction has been modelled coming from the northwest to result in an impact in the direction of these residences.

B5.5 Release Rate

It is estimated that the amount of HF which is released from a 1 MWh battery ranges from 20 kg – 200 kg depending upon the type of battery (Ref. [6]). The project is up to 600 MWh which is contained across approximately 160 battery units. Therefore, each battery unit has an energy storage of 3.75 MWh. The range of HF which could be released from each battery unit would therefore be 80 kg – 750 kg. For conservatism, it has been assumed that the HF present within the battery is at the higher end of this range. Hence, a total of 800 kg may be released over the course of a fire.

The rate of release is dependent upon the SOC with the greater charge resulting in higher initial release rates of HF. At a 75% charge approximately 60% of the HF was released at roughly halfway through the course of the experiment (Ref. [6]). For the purposes of modelling, it has been assumed the majority of the HF is released in the first hour with the remaining HF being released over the remaining duration of the fire. Therefore, the average release rate of HF in the first hour is 0.6 x 750 = 450 kg/h or 0.125 kg/s.

Provided in **Appendix Figure B-3** is the input file used for the model.

Parameters	
Inputs	
Process Conditions	
Chemical name	HYDROGEN FLUORIDE (DIPPR)
Source Definition	
Type of neutral gas release	Semi-continuous
Type of continuos source	User defined window
Mass flow rate of the source (kg/s)	0.125
Duration of the release (s)	3600
Length source in wind (x) direction (m)	0
Width source in crosswind (y) direction (m)	3
Height source in vertical (z) direction (m)	2.5
Process Dimensions	
Height of release (Z-coordinate) (m)	2.5
Offset X direction (distance) start dispersion (m)	0
Offset Z direction (height) start dispersion (m)	0
Meteo Definition	
Meteorological data	Pasquill
Pasquill stability class	F (Very Stable)
Wind speed at 10 m height (m/s)	1.5
Predefined wind direction	NW
Environment	
Ambient temperature (°C)	9.1
Ambient pressure (bar)	1.0151
North/South latitude of the location (deg)	-34.69
Roughness length description	Open flat terrain; grass, few isolated objects.
Vulnerability	
Toxic exposure duration based on	Time limit of release
Max. duration release (s)	3600
Perform toxic indoors calculation	No
Accuracy	
Grid resolution	Low
Reporting	
Concentration averaging time (s)	600
Distance from release centre (m)	5000
Reporting/receiver height (Zd) (m)	1.5
Use defined dose contour	No
Use dynamic concentration presentation	Yes

Appendix Figure B-3: BESS Plume Model Inputs

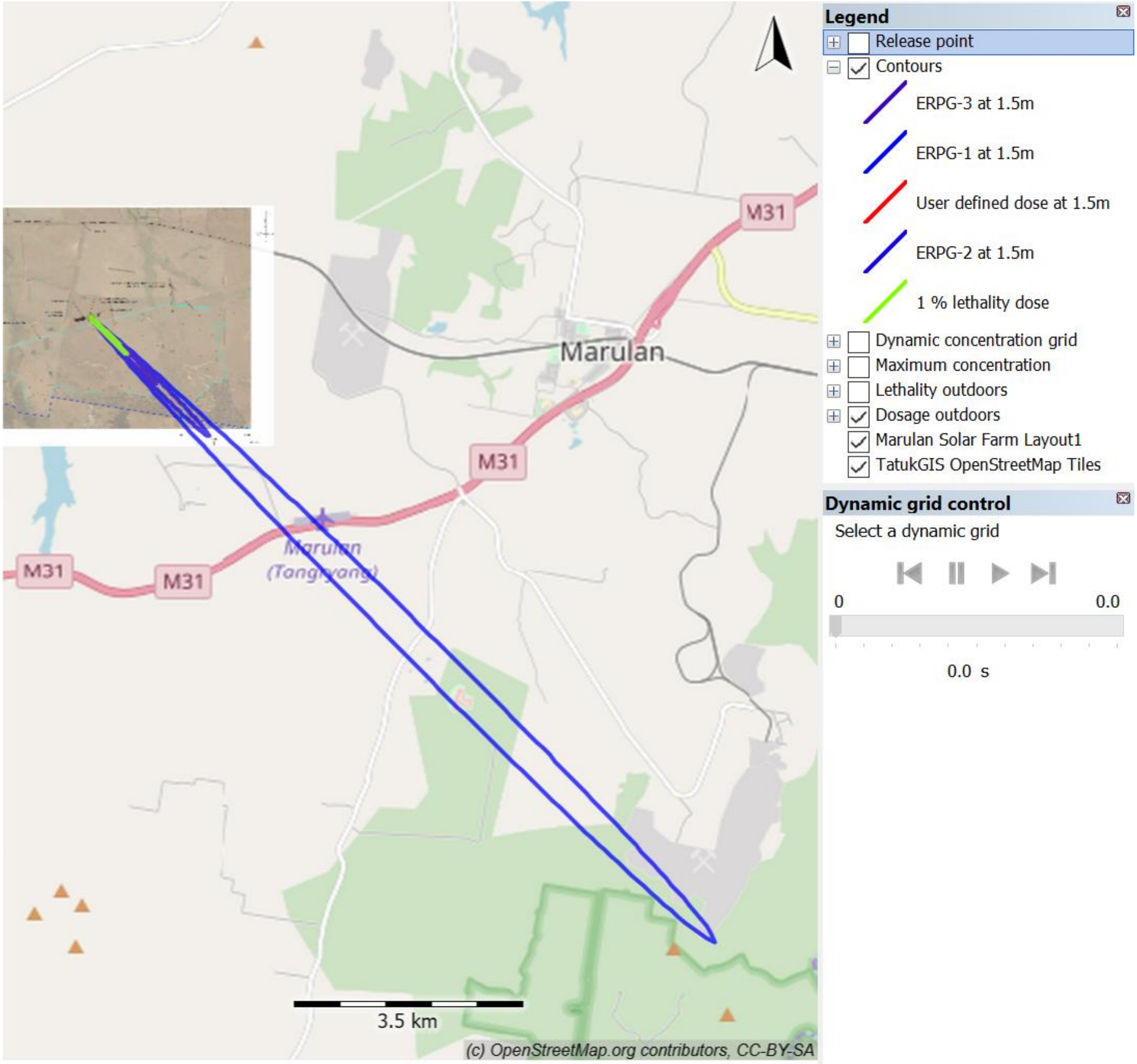
B5.6 Dispersion Results

The downwind distances to the ERPG values for the F1.5 and D3 scenarios have been summarised in **Appendix Table B-4**.

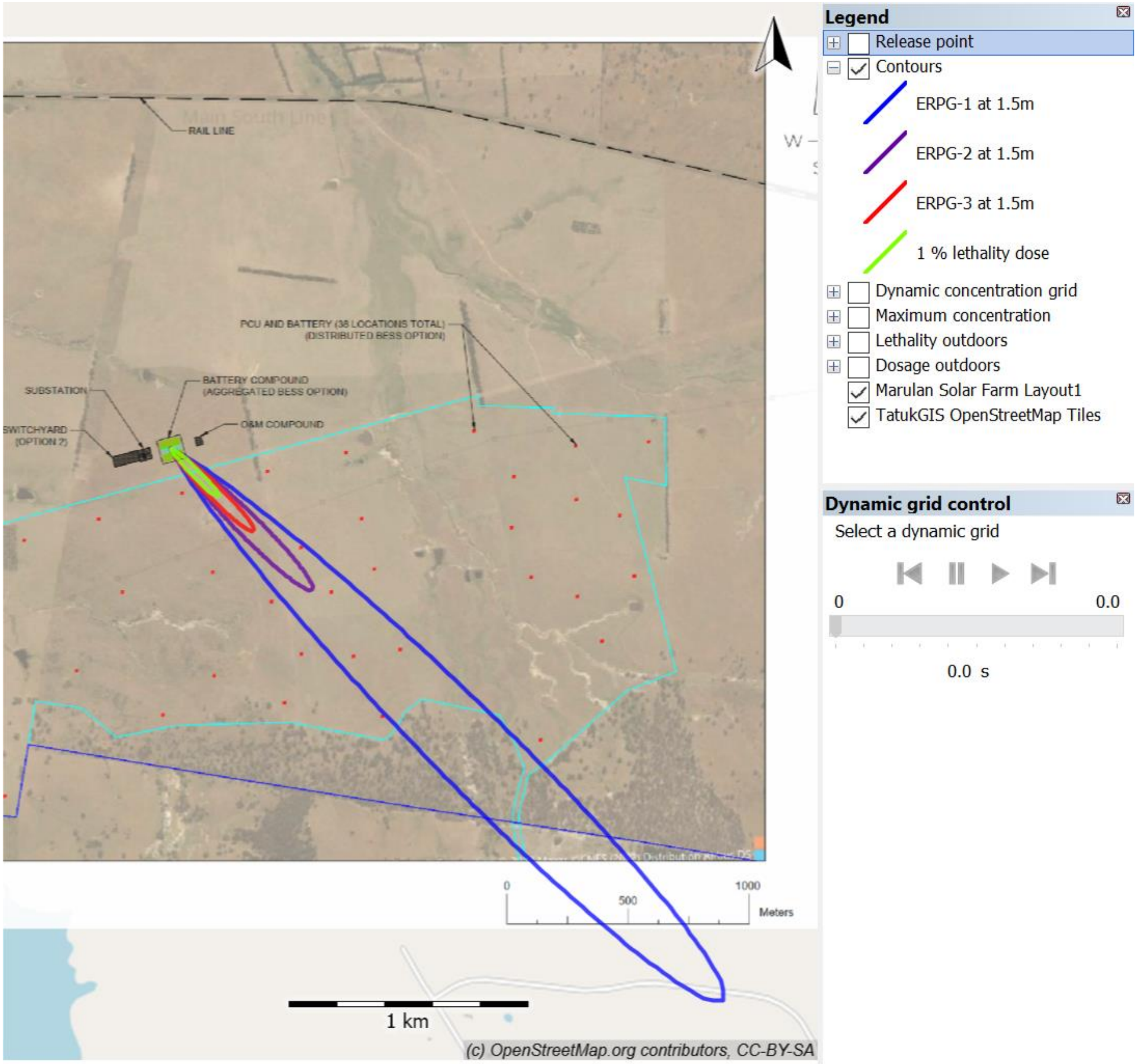
Appendix Table B-4: HF Dispersion Results at F1.5 and D3 Conditions

ERPG Level	Downwind Distance (m)	
	F1.5	D3
ERPG-3	1,427	479
ERPG-2	2,554	824
ERPG-1	13,504	3,223
1% Fatality	781	275

The downwind impact distances and plume width for the F1.5 and D3 scenarios are shown in **Appendix Figure B-4** and **Appendix Figure B-5**.



Appendix Figure B-4: F1.5 Plume Dispersion



Appendix Figure B-5: D3 Plume Dispersion

B6. Transformer Internal Arcing, Oil Spill, Ignition and Bund Fire

Transformers contain oil to provide cooling and insulation. If arcing occurs within the transformer, the oil will rapidly heat generating gases above their auto ignition point. The pressure of the gases may rupture the reservoir allowing oxygen to enter resulting in the gases auto igniting. The oil is released from the reservoir and is ignited by the burning gases.

It has been assumed that the transformer has bund dimensions of approximately 10 m x 15 m; hence, if a spill from the transformer was to occur it would fill the base of the bund resulting in a pool fire with the dimensions of the bund.

Transformer oil is typically a combustible liquid of some formulation which have high flash points. For the purposes of providing a conservative analysis, fuel/bunker oil sample has been selected.

The above information was input into Effects which calculated the following outputs:

- SEP – 67 kW/m^2

- Flame height – 13.0 m

The results of the analysis are shown in **Appendix Table B-5.**

Appendix Table B-5: Heat Radiation Impacts from a Transformer Bund Fire

Heat Radiation (KW/m^2)	Distance (m)
35	9
23	10
12.6	11
4.7	17

Appendix C

Estimation of BESS Fire Frequency

Appendix C

C1. Introduction

A literature review to identify the frequency with which BESS fires occur did not yield any definitive results nor are there any databases which were identified containing this information. Subsequently, it is necessary to undertake a review of the BESS industry and fire incidents to estimate the frequency with which BESS units fail resulting in fire.

C2. Methodology

It has been proposed to identify the failure rate of BESS units on an installed capacity basis and identify how many BESS fires have occurred globally. This failure rate could then be applied to the installed capacity at a particular site as the basis for undertaking a quantitative assessment of fatality risk.

C3. BESS Fire Frequency Estimation

The International Energy Agency (IEA) produces a report of the total installed energy storage system around the world. The report from 2021 indicated the total installed capacity was around 17 GW following 5 GW of capacity installed in 2020 which was a 50% increase from the mediocre installation levels in 2019. Assuming a similar installation of 5 GW occurred in 2021, then the total installed capacity would be in the order of 22 GW or 22,000 MW.

Consistent information detailing the size of the battery storages was unable to be identified; hence, it has been assumed that the 22,000 MW of installed capacity represents grid scale deployment requiring 4 hours of storage resulting in total installed capacity of 88,000 MWh.

An extensive search to identify the number of BESS fires which have occurred since large scale BESS commenced being deployed did not provide a definitive number; however, data reported by S&P Global (Ref. [10]) and Marsh Commercial (Ref. [11]) indicated fires indicated around 20 - 30 fires had occurred since 2017. As it is not clear if there is a centralised database documenting BESS fires, the number of BESS fires has been estimated at 50 since large scale BESS have been deployed which commenced around 2012.

Therefore, there has been approximately 50 BESS fires per 88,000 MWh of installed capacity or a rate of 0.00057 per MWh of total installed capacity. While the rate of installation is proceeding exponentially, for the purposes of identifying a failure rate, it has been assumed that the deployment has been linear and that the failure rate per annum becomes 0.00057 fires per total MWh installed divided by 5 years = 0.00057 / 5 = 1.1×10^{-4} per MWh/y.