Regional and Remote Communities Reliability Fund Microgrid

MyTown Microgrid

Neighbourhood batteries in Heyfield – technical analysis of impacts and benefits

Heyfield local energy options: techno-economic analysis

Milestone 5.3b – June 2023

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About the project

MyTown Microgrid is an innovative, multi-year, multi-stakeholder project that aims to undertake a detailed data-led microgrid feasibility for the town of Heyfield (Victoria), built on a platform of deep community engagement and capacity building.

The project received funding under the Australian Government's Regional and Remote Communities Reliability Fund Microgrids stage 1 funding round. It also received funding from the Latrobe Valley Authority as part of the Gippsland Smart Specialisation Strategy.

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1. Executive Summary

The MyTown Microgrid project is developing an innovative data-led approach to local energy solutions, starting with the town of Heyfield in Victoria. Built on a platform of deep community engagement and capacity building, the project is also creating the knowledge and tools to make it faster, easier, and cheaper for other regional communities to understand the proposition for microgrids for their towns.

This report is built on Milestone 4.2, initial feasibility results for a town microgrid, and complementary to Milestone 5.3b – Neighbourhood batteries in Heyfield – initial feasibility. The report evaluates the technical feasibility of integrating batteries on the selected low-voltage feeders. Specifically, it evaluates the potential of neighbourhood batteries to support the distribution grid and increase the amount of solar which can be added to the system without violating the limits of the distribution grid.

Methodology

A multi-step methodology was used consisting of four main steps:

Step 1: Identify the low voltage feeders for testing and analysis, then model the selected LV feeders using data from a model provided by AusNet Services.

Step 2: Develop the integration scenarios for the front-of-the-meter (FTM) and behind-the-meter (BTM) batteries for the selected low-voltage feeders.

Step 3: Model the battery energy storage for powerflow simulation studies.

Step 4: Simulate the selected low voltage feeders for voltage profile and hosting capacity.

One residential and one mixed commercial/residential low voltage feeder were modelled and analysed for integration of battery energy storage. The following cases were evaluated:

- Case 1: FTM on a residential feeder.
- Case 2: A fleet of distributed BTM on a residential feeder with the same capacity as the FTM battery.
- Case 3: FTM on a mixed feeder (commercial and residential feeder).
- Case 4: Large BTM at the commercial customer.

All scenarios assumed the current installation of solar-PVs for the system benefit analysis. Two extreme network conditions were considered for the simulations:

- Maximum load/minimum PV – this is the network condition with greatest potential for under-voltage and overload on transformer lines. Batteries are assumed to inject power (i.e., discharge) in this condition.
- Minimum load/maximum PV – this is the network condition with greatest potential for over-voltage. Batteries are considered to absorb power (i.e., charge) in this condition.

Results

While these are only the initial findings, the results indicated:

- There is no voltage limit violation with the integration of FTM and BTM batteries on the selected low-voltage feeders. The system voltage remained within limits without the battery. However, as loads and/or PV penetration increases in the future (for example, as EVs become commonplace), the deployment of batteries could prevent voltage problems from occurring.
- Integration of a FTM battery would allow the residential feeder to host 221 kW more than the current penetration of PV (an increase of 240%), and 123 kW more than the base case (i.e., hosting capacity assessment without the battery).
- Integration of a fleet of BTM batteries would allow the residential feeder to host 241 kW more PV than the current penetration (an increase of 250%), and 143 kW more than the base case (i.e., hosting capacity assessment without battery).

- Integration of a FTM battery would allow the mixed feeder to host 358 kW more than the current penetration of PV (an increase of 180%), and 200 kW more than the base case (i.e., hosting capacity assessment without battery).
- The network transformer is the main limiting factor to hosting more PV on the selected feeders.

The technical analysis results are summarized in the table below. It was found that all of the batteries studied support the network voltage, with larger batteries having a greater impact. To achieve the best voltage characteristics and highest hosting capacity for a residential feeder, a fleet of BTMs is recommended.

If a commercial customer wants to use the battery for emergency power in islanded mode, additional investment in equipment is necessary, which may cost between $4,985 and $7,514. The customer would be required to submit the connection request to the DNSP to operate in islanded mode, which may require further technical studies on voltage level (including power factor), fault level analysis, load-flow, and projection grading assessment. While operating in islanded mode is technically feasible for FTM batteries, the cost is likely to be prohibitive.

Table E1: Summary of technical feasibility results

Case	Voltage characteristics	Hosting capacity	Islanded operation
100 kW FTM battery on residential feeder	Improved; best result from battery located at end of feeder	PV installations could double without a battery, or treble with a battery (from 89 kW to 310 kW)	Not commercially feasible
Fleet of BTM batteries on residential feeder (100 kW in total)	Improved somewhat more than FTM	PV installations could increase somewhat more with BTM batteries (to 330 kW).	Not investigated
100 kW FTM battery on mixed residential/ commercial feeder	Improved; best result from battery located at end of feeder	PV installations could increase by 80% without a battery (from 202 kW to 360 kW), or by 170% with the battery (to 560 kW)	Not commercially feasible
BTM battery at commercial premises, 10 kW – 100 kW	Improved; dependant on size and location (assumed same as FTM case if 100 kW)	Improved, dependent on the size of battery (assumed same as FTM case if 100 kW)	Feasible for additional cost of $4,985 - $7,514.

Conclusion

This analysis aimed to find out the technical feasibility of integrating batteries in selected low-voltage feeders. The following conclusions can be drawn:

- Is there technical potential for neighbourhood batteries to support the distribution network within and downstream from a feeder, including management of network constraints? Yes, the neighbourhood battery supports the voltage of the system both upstream and downstream. However, depending on the position in the network, the benefit could be varied. The distributed fleet of behind-the-meter batteries provided somewhat better network support compared to the FTM battery.
- Are there any physical limitations to the power flows within distinct low voltage sub-regions of the distribution network (i.e., downstream from a feeder)? No, the power flow studies show no physical limitations with neighbourhood batteries until a very high penetration of solar-PVs into the system. Technically, battery management can mitigate congestion and voltage issues.
- Is there any expected impact on solar consumption or solar capacity (e.g., how much additional solar capacity can be integrated into the system)? Yes, solar-PV penetration can be increased. However, the increment depends on the network type and the position of the battery in the network.
- Is it possible to use the battery for emergency power in islanded mode? This is likely for a commercial customer, provided there is additional investment in equipment, with an estimated cost of $4,985 - $7,514. While this could be technically possible for the FTM batteries, the cost is likely to be prohibitive.

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3. List of abbreviations

Abbreviation	Description
BESS	Battery energy storage system
BTM battery	Behind-the-meter battery
DERs	Distributed Energy Resources
DNSPs	Distribution network service providers (e.g., AusNet Services, PowerCor)
EV	Electric vehicle
FTM battery	Front-of-the-meter battery
kV	Kilovolts
kVA	Kilo-volt ampere
kW	Kilowatt (a measure of power or load)
kWh	Kilowatt per hour
LV	Low voltage
MV	Medium voltage
MVA	Mega-volt ampere
MW	Megawatt (a measure of power or load)
NB	Neighbourhood battery
T & D	Transmission and Distribution
Solar-PV	Solar photovoltaic
USE	Unserved energy
VAR	Volt ampere reactive

1. Introduction

The Heyfield MyTown Microgrid project is conducting a comprehensive data-based investigation into the feasibility of microgrid and energy solutions for the town of Heyfield in Victoria. The project is founded on a deep engagement with the community and aims to build their capacity. Over three years, the project will develop the necessary knowledge and tools to enable other regional communities to more easily and affordably explore microgrids and energy solutions for their communities.

The MyTown Microgrid project provides a range of reports and resources, including documenting Heyfield's journey to explore a microgrid and other local energy solutions[1].

This report complements Milestone 5.3b, which focuses on the initial feasibility of neighbourhood batteries in Heyfield, and outlines the technical feasibility results related to integrating neighbourhood batteries into the chosen low-voltage (LV) feeders.

1.1 Purpose

The purpose of this report is to assess whether it is technically feasible to incorporate batteries into certain LV feeders. The focus is on the potential of neighbourhood batteries (NBs) to bolster the distribution grid, overcoming the physical constraints of adding more solar energy to the system without breaching the grid's limits. This version of the report aims to provide answers to the following questions:

- What is the technical potential for neighbourhood batteries to support the distribution network within and downstream from a feeder, including management of network constraints (e.g., operational limits for voltage, assets utilisations)?
- What are the physical limitations of the powerflows within distinct LV sub-regions of the distribution network (i.e., downstream from a feeder)?
- What is the expected impact on solar consumption, solar capacity (e.g., how much additional solar capacity can be integrated into the system)?
- What are the technical implications of allowing the feeders to operate in an islanded mode in times of grid disconnection (subject to AusNet Services operational approval for islanded operation)?

1.2 Background definitions

These are some definitions used throughout the report, and these are:

PV hosting capacity: the maximum capacity of PV that a given section of a distribution network can host without negatively affecting normal operation (i.e., voltage limits, line and transformer loading).

Front-of-the-Meter (FTM) battery: these batteries are directly integrated into the electricity network rather than being connected via a customer meter that also serves as that customer's load. Utility, grid, community, and neighbourhood batteries are all examples of front-of-the-meter as they are not on customer premises.

Behind-the-Meter (BTM) battery: these batteries are connected via electricity meters for residential, commercial, or industrial customers. These BTM batteries range in size from 3 kW to 5 MW; residential batteries are typically installed with rooftop solar-PV, as they can maximise value from the PV.

1.3 Cases for analysis

The following cases are considered for the analysis:

- **Case 1:** Front-of-the-meter battery on a residential feeder.
- **Case 2:** Fleet of behind-the-meter batteries on the same residential feeder.

[1] https://www.uts.edu.au/isf/explore-research/projects/mytown-microgrid-heyfield-victoria

- **Case 3:** Front-of-the-meter battery in a mixed commercial/residential feeder.
- **Case 4:** Behind-the-meter battery at a commercial premises (i.e., the pub).

The cases mentioned above are compared against the base case in the selected LV feeders. The base case represents the current level of solar-PV penetration in those LV feeders. These cases will be evaluated for their maximum and minimum loading conditions.

1.4 Outline of report

The rest of the report is structured as follows:

- Section 2 of the report gives some background on the potential network benefit and the technical background relevant to assessing the impact of battery storage in the LV distribution network.
- Section 3 describes the method and scenario assumptions used for this study.
- Sections 4-7 provides the case study results.
- Section 8 gives the conclusions.

The Appendices of this report include the additional case study results for further comparisons as well as a mathematical overview of the distribution system voltage regulation and control.

2. Background

2.1 Potential network benefits from batteries on distribution feeders

Distributed energy resources (DERs) such as solar-PVs and batteries are essential to distribution network service providers (DNSPs) and customers. With these DERs, consumers can fulfil 60-80% of their electricity requirements on average and become partially independent from the power grid [1] - [3].

However, the steady increase of DERs such as solar-PVs could result in significant operational challenges to the distribution network. Among these challenges, violation of over and under-voltage limits, voltage imbalance, asset congestion (e.g., transformer and line loading), and protection system malfunction, are considered the key issues faced by DNSPs [4].

These issues mainly result from significant powerflow created by the uncoordinated power export from DERs, as the LV networks are not designed to support the significantly high level of bi-directional powerflow. Batteries can play a role in managing the bi-directional powerflows with intelligent and coordinated management. According to [6], battery helps reduce the stress on the grid due to increased self-consumption.

Grid reinforcement is one of the approaches used by the DNSPs to overcome voltage violations and asset congestion and increases the hosting capacity of the network. However, this will incur additional costs for DNSPs, which will be pushed onto the customers by increasing network tariffs [7]. The integration of batteries defers the requirement for grid reinforcement in the LV network. Batteries provide an alternative to improve the hosting capacity of the distribution network (e.g., PV, electric vehicle) by storing and releasing energy as required through the control algorithm.

The distributed batteries can also mitigate voltage violation issues in LV-distributed networks due to the high penetration of solar-PVs under the minimum loading condition [8]. In addition, the overloading of the medium voltage (MV) distribution transformer can be minimised by the slow charging of the battery using solar-PV. The system benefits from installing batteries in the LV network are outlined below:

- Deferral of new generation, peaking plant, and grid reinforcement.
- Fuel saving, emission reduction.
- Maximising the utilisation of the assets.
- Decreasing the unserved energy.
- Deceasing the transmission and distribution losses.
- Increasing the hosting capacity of PV and EV.
- Deferral of transmission and distribution augmentation.

2.2 Distributed energy resources impact on system

In Figure 1, a traditional LV feeder is displayed. As shown in Figure 2, the voltage drop along the length of the line in this type of distribution feeder gradually increases towards the endpoint. This means that the customer located farthest from the source may experience a decrease in voltage. To minimise this voltage drop, voltage regulators can be installed. However, this can be a costly practice for DNSPs to implement in all LV feeders.

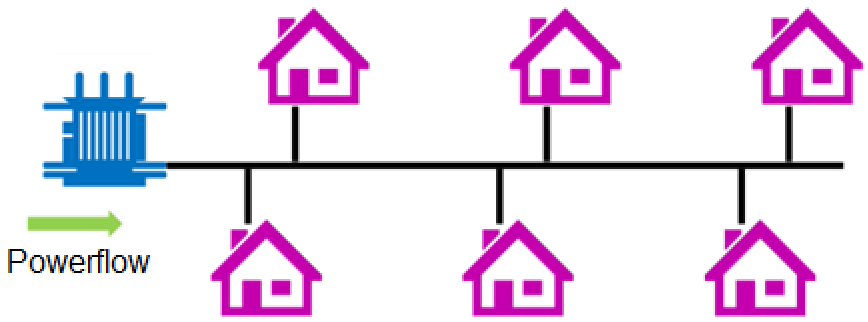

Figure 1. Traditional distribution feeder.

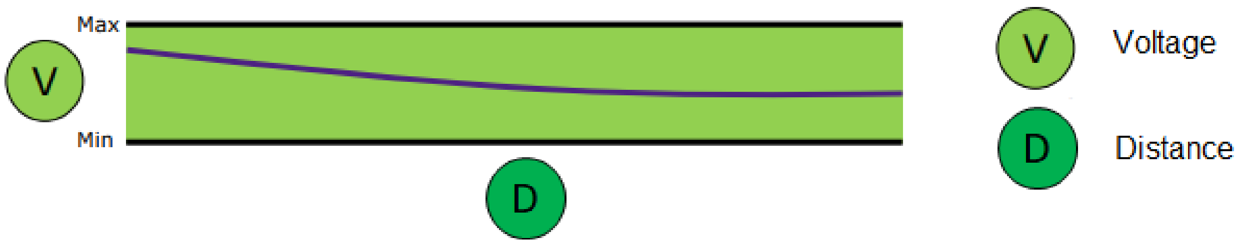

Figure 2. Traditional distribution feeder voltage profile vs distance.

If the solar-PVs are installed in the LV feeder (as in Figure 3), the solar-PV generation and the load will determine the direction and amount of the powerflow. Hence, the voltage could either decrease or increase along the feeder.

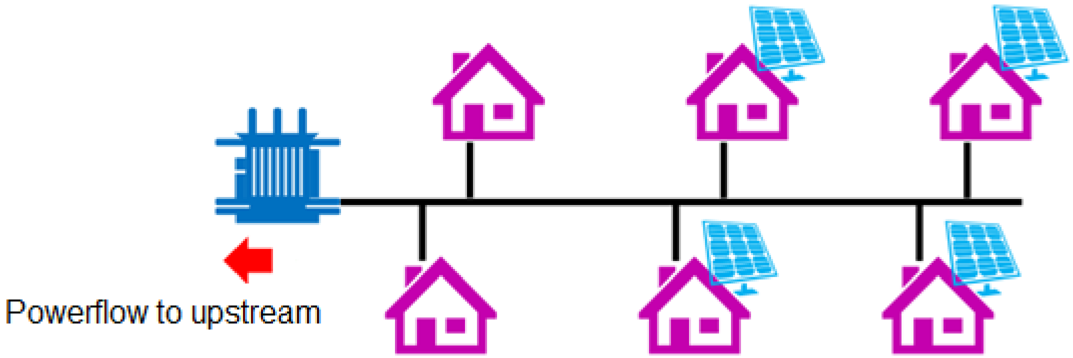

Figure 3. Distribution feeder with solar-PVs.

At times when the solar-PV generation is greater than the load, the voltage would increase (Figure 4). This rise would be highest in the minimum loading condition. When the solar-PV generation is less than the load, the voltage would decrease. The voltage between two adjacent buses (i.e., electrical connection point, poles) can be affected by the energy storage system's active and reactive power injection. The location, charging and discharging time would impact the adjacent buses' voltage variation and asset utilisation.

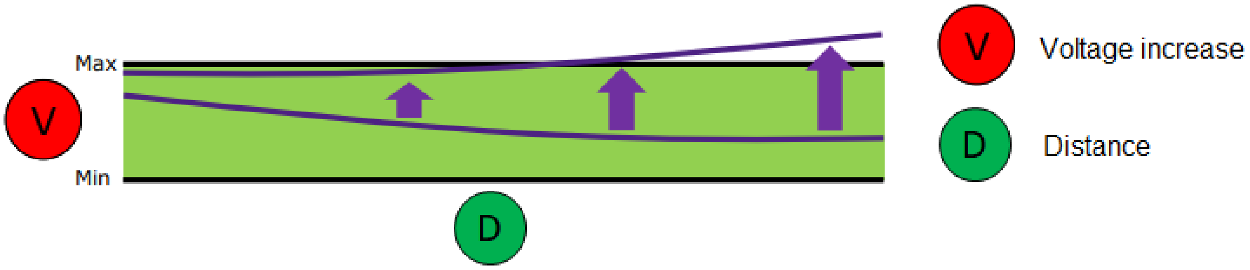

Figure 4. Voltage profile of distribution system with solar-PVs.

As previously discussed, the integration of DERs can have an impact on the voltage profile of the network. In order to ensure the network operates safely and securely, it's important to maintain the voltage within the legal limits of 0.94 to 1.06 per unit (pu). PU stands for ‘per unit’, meaning that the actual voltage should not differ by more than 6% from the nominal system voltage. For the simulation cases outlined in Section 1.3, we have adhered to these statutory voltage limits of 0.94 to 1.06 pu. It is worth noting that the network voltage characteristics with solar-PVs and batteries are highly non-linear, unpredictable, and mainly depend on PV penetrations and operation mode.

3. Methodology

3.1 Overview

In Figure 5, a flowchart is presented to show the process of the technical feasibility study. It outlines the key assumptions, primary data sources, steps taken during modelling and simulations, and the key indicators used to draw preliminary conclusions. The method consists of four main steps and these are:

Step 1: Identify the LV feeders for testing and analysis. Then, model the selected LV feeders using the data from AusNet Services.

Step 2: Develop the integration scenarios for FTM and BTM battery for the selected LV feeders.

Step 3: Model the battery energy storage for powerflow simulation studies.

Step 4: Simulate the selected LV feeders for voltage profile and hosting capacity.

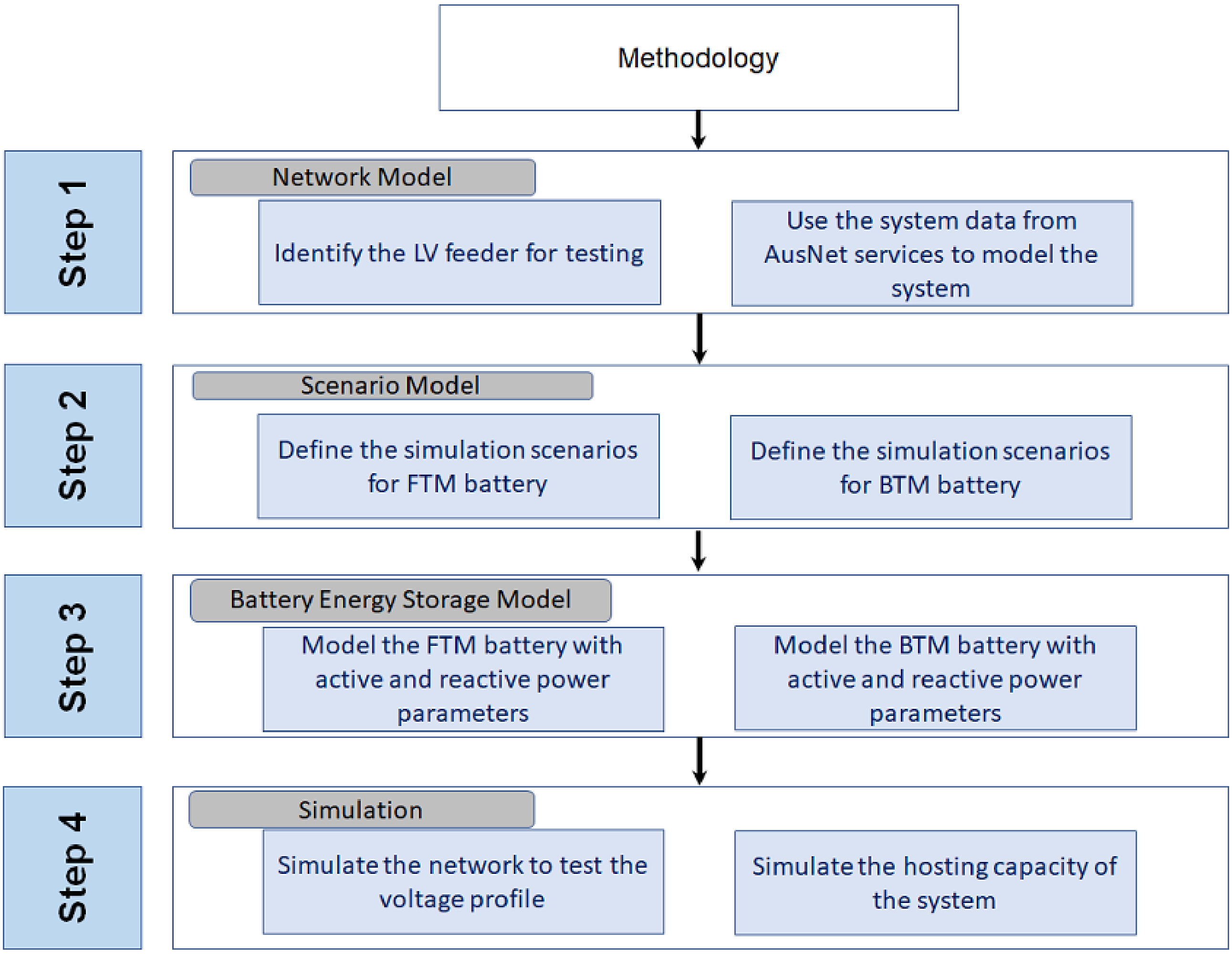

Figure 5. Methodology -overview.

The system was modelled using various combinations of data. The network and distribution substation locations are adopted from the PSS SINCAL model provided by AusNet Services. The distribution transformers' kVA ratings are estimated based on the substations' statistical load data. The technical feasibility analysis has been conducted using the DIgSILENT Power Factory, a leading power system analysis software application for analysing generation, transmission, distribution, and industrial systems (e.g., mines, wastewater treatment plants). Various tools are available for such studies [9]. However, DIgSILENT provides flexibility to model both conventional and power electronics-based systems with high accuracy. It also offers various analytical toolboxes, including steady-state analysis, dynamic stability analysis, reliability assessment, time series analysis, power quality, and techno-economic analysis. The DIgSILENT Power Factory distribution system analysis toolbox has been used for this analysis.

Powerflow analysis is used to determine statutory voltage limits and asset utilisation of the distribution feeder for various cases and integration scenarios. The LV feeder has been developed considering the AusNet Services LV network characteristics [10]. The actual feeder length of all selected feeders for the study has been considered for the modelling. The overhead line impedances of 0.24+j0.0716 ohm and 0.281+j0.0716 ohm are used for the mixed and residential feeder development, as reported in [11]. In addition, the following solar size is used for the residential customer, as reported in [12].

- 5 kW active power and 6 kVA inverter for the residential customer.
- Actual size of solar for the commercial customer.

The BTM battery of 3 kW active and 4 kVA inverter is considered for residential customers. This sizing would be considered for the distributed fleets of BTM batteries case studies (See Section. 1.3).

The powerflow simulations are carried out to characterise and analyse the voltage behaviour of the distribution feeder under various integration scenarios. Once the voltage limit is satisfied, the hosting capacity of PV is assessed for the cases given in Section 1.3.

3.2 Scenarios

Four integration scenarios (ISs) are considered in this study (as shown in Figures 6-9), to study the impact of the front-of-the-meter and the fleet of the behind-the-meter batteries in the distribution network.

- IS-1 FTM at the substation: the battery is located at the substation.
- IS-2 FTM mid feeder: the battery is located at the middle of the feeder/line.
- IS-3 FTM end of feeder: the battery is located near the end of the feeder/line.
- IS-4 BTM: considers the same total capacity of storage deployed in a fleet of BTM batteries.

All scenarios assume the current installation of solar-PVs for the system benefit analysis.

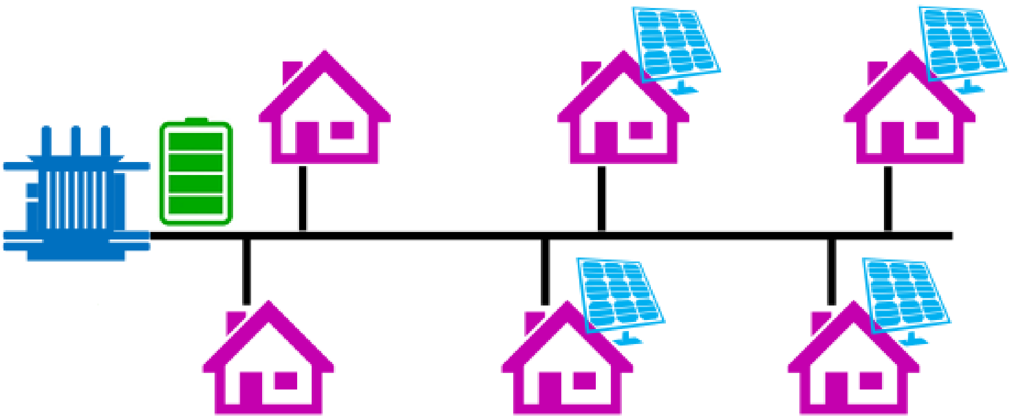

Figure 6. Front-of-the-meter battery at the substation – IS1.

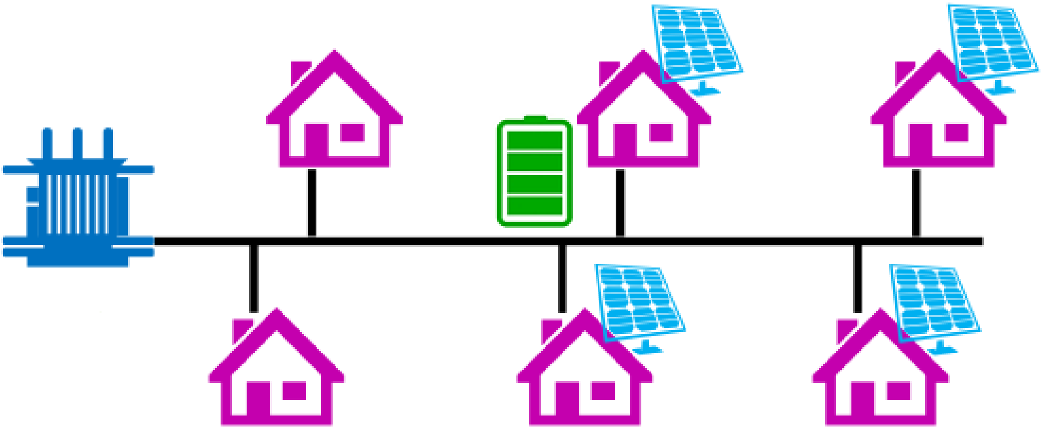

Figure 7. Front-of-the-meter battery at the middle of the feeder-IS2.

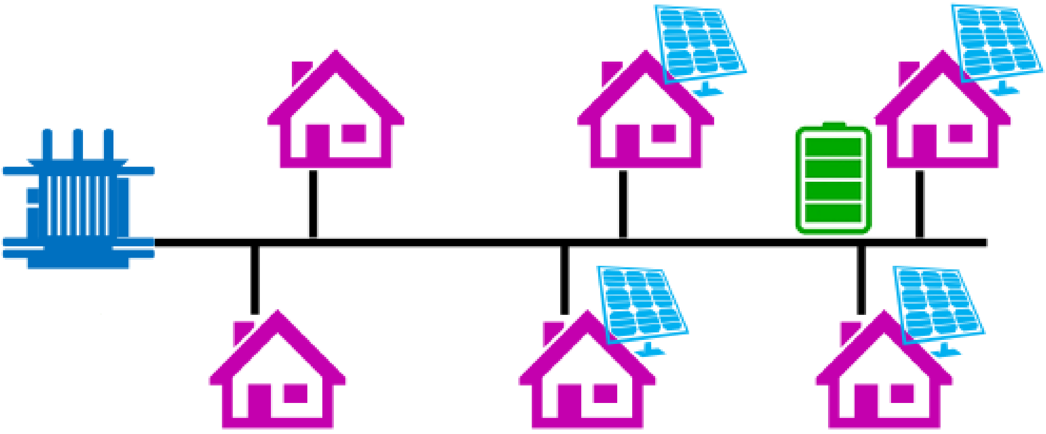

Figure 8. Front-of-the-meter battery near the end of the feeder-IS3.

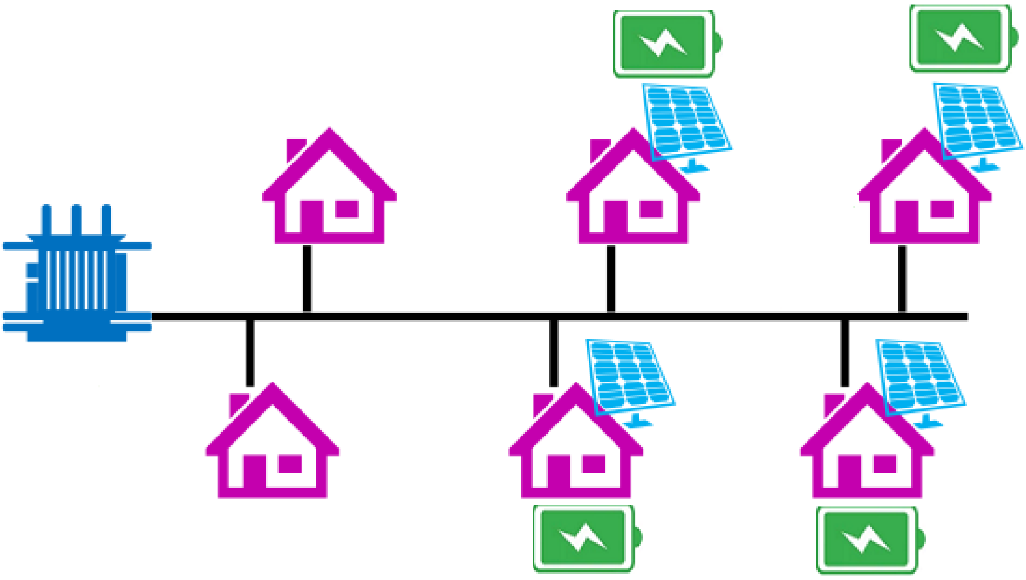

Figure 9. Behind-the-meter battery with solar consumer - IS4.

Also, a special integration scenario has been considered for the mixed commercial/residential feeder where a range of large BTM batteries are considered for the large commercial consumers (i.e., the pub) with PV to see the implication of the battery integration into feeder voltage and utilisation factor as well as the hosting of the PV (See Figure 10).

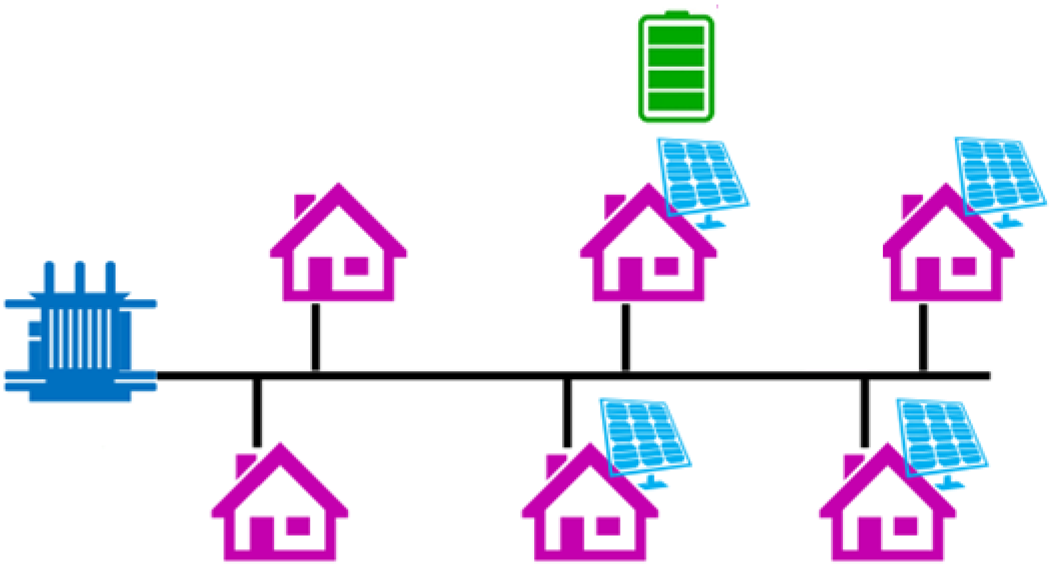

Figure 10. Large behind-the-meter battery in commercial consumers.

Two boundary conditions are considered for the simulations. These conditions show the most stressed network conditions. These are –

- Maximum load/minimum PV – This condition defines the network condition with under-voltage and overload on transformers and lines. Batteries are considered to inject power (i.e., discharge) in this condition.

- Minimum load/maximum PV – This condition defines the network condition with potential over-voltage. Batteries are considered to absorb power (i.e., charge) in this condition.

3.3 Battery model for simulation studies

The battery energy storage system is equipped with active and reactive power control. The active power control is based on the dispatch condition set in Section 3.2. On the other hand, reactive power control aims to regulate the local voltage by injecting or absorbing reactive power. The battery's inverter offers two modes of control - constant power factor and Volt-VAr. The constant power factor mode enables the inverter to supply reactive power per the specified power factor. Conversely, the Volt-VAr mode adjusts the reactive power output based on the grid voltage. In this study, we will use the Volt-VAr control to dispatch reactive power for the battery storage system in the simulations.

4. Case study 1: Front-of-meter battery on a residential feeder

4.1 Overview

In this section, we will discuss the possibility of integrating a FTM battery into one of the LV residential feeders in Heyfield. The research team has considered the MV/LV transformer 2125260400 that supplies power to residential customers. Based on the data provided by AusNet Services, there are three lines that supply the residential loads connected to this transformer. To analyse the technical feasibility, we have listed the key feeder parameters in Table 1. The approach outlined in Section 3 is considered for the analysis.

Table 1. System parameters used in case 1

Parameter	Value
MV transformer rating	300 kVA
Number of PV	31
Total capacity of PV	89 kW
Feeder length	Line 1: 500 m; Line 2: 400 m; Line 3: 315 m;
Number of customers	107
Battery power capacity	100 kW (200 kWh)
Feeder description	Residential, AusNet ID: 2125260400

4.2 Grid impact studies

4.2.1 Voltage profile

Figures 11-12 summarise the voltage profiles of the feeder for the following integration scenarios (ISs).

- IS-1 FTM at the substation: the battery is located at the substation.
- IS-2 FTM mid feeder: the battery is located at the middle of the feeder/line.
- IS-3 FTM end of feeder: the battery is located near the end of the feeder/line.

It is important to note that three lines serve residential customers, but only the voltage profiles for the longest line, line 1, are provided here. This is because longer LV lines are more likely to violate statutory limits. Based on Figures 11-12, it is clear that the voltage profiles of the system are within the allowable limit. Figure 11 displays the voltage characteristics under maximum load and minimum PV. Under the base case (i.e., current PV and no battery), a voltage reduction along the line can be observed, with the lowest recorded voltage being 0.96 pu. However, with the FTM battery placed at the entrance of the feeder, the lowest terminal voltage increases to 0.985 pu. If the FTM battery is placed in the middle of the feeder, the lowest terminal voltage increases to 0.99 pu. Furthermore, if the FTM is placed at the end of the line, the lowest terminal voltage increases to 1.01 pu.

The voltage characteristics of the line under minimum load and maximum PV condition are displayed in Figure 12. The terminal voltage decreases with FTM compared to the base case (i.e., current PV and no battery). The highest terminal voltage in the base case is 1.035 pu, which decreases to 1.02 when the FTM is placed at the entrance of the line. When the FTM is placed at the middle of the line, the highest terminal voltage reduces to 1.012 pu and decreases to 1.011 pu when placed at the end of the line. The battery charging during the minimum load and maximum PV condition helps manage the over-voltage issue. The battery located at the middle or end of the line has a more significant influence on the voltage characteristics compared to the battery at the upstream of the line.

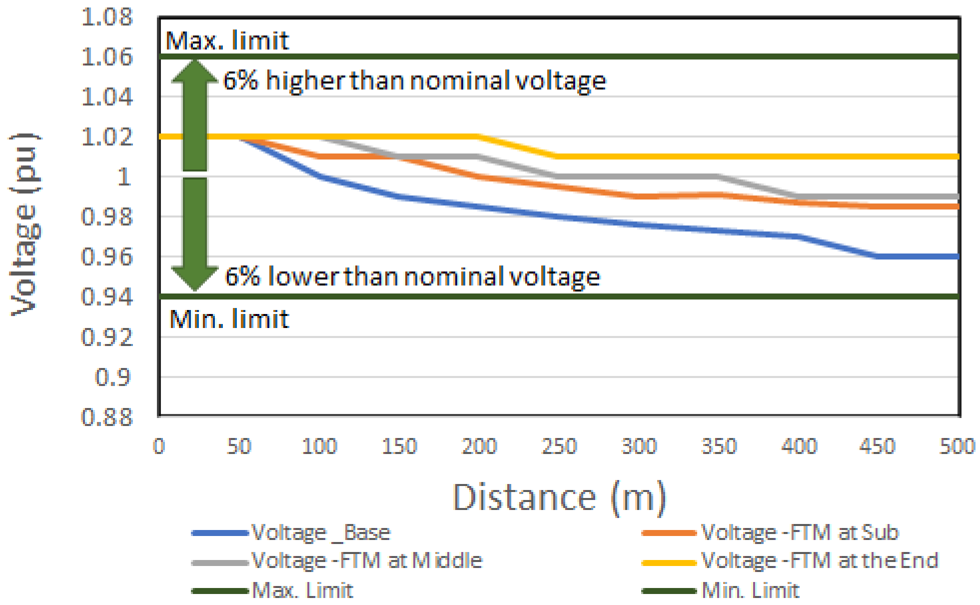

Figure 11. Voltage profile for FTM battery (max load/min PV).

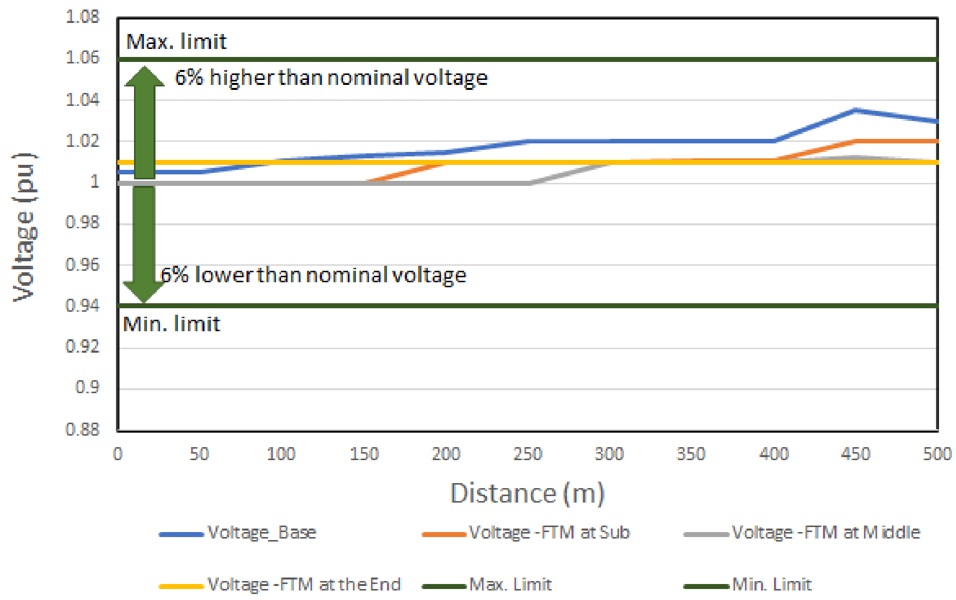

Figure 12. Voltage profile for FTM battery (min load/max PV).

4.2.2 Hosting capacity

Table 2 summarises the hosting capacity results for a FTM integration into the feeder. Voltage profiles and network utilisation are used to assess the hosting capacity of PV to the network. The results of the PV hosting capacity are compared against the base case (PV hosting of the selected feeder without battery). The current PV penetration to this feeder is 89 kW (total 31 customers with PV). The network can host another 98 kW of PV without integrating a battery to the system (before transformer and line become overloaded). The system could host total 310 kW of PV with battery into the system before being reaching the line and transformer limits.

Table 2. Hosting capacity with FTM in residential feeder (89kW installed currently)

IS		89 kW	120 kW	140 kW	160 kW	180 kW	187 kW	200 kW	220 kW	240 kW	260 kW	280 kW	310 kW	340 kW
No battery (base case)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X	X
	Transformer	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X	X
FTM at start	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
FTM mid-feeder	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
FTM end-feeder	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X

✓: Within the limit/no overloading; **X**: Outside the limit/overloading

4.3 Islanded operation

The islanded operation appears economically non-feasible. However, the research team has performed additional simulations to test the network performance under the islanded operation. Table 3 outlines the constraints for the islanded operation. It is apparent from Table 3 that the load needs to be reduced under maximum load/minimum PV operating condition for the islanded operation. The system would experience slightly high voltage at the end of the feeder during the islanded operation when the FTM battery is located at the end of the feeder. However, the voltage of the buses is within the acceptable limits defined by the DNSPs.

Table 3. Overview of islanded operation with FTM battery in the residential feeder

Integration scenario		Min load /max PV	Max load/min PV
IS1: FTM at the substation	Load	No load reduction	Reduction
	Voltage	Voltage within the limits	Voltage within the limits
IS2: FTM mid-feeder	Load	Reduction	Reduction
	Voltage	Voltage within the limits	Voltage within the limits
IS3: FTM end of feeder	Load	No load reduction	Reduction
	Voltage	Higher voltage at end of feeder	Higher voltage at end of feeder

4.4 Conclusion – residential feeder FTM battery technical impacts

- Different voltage distributions could be noticed along the LV line depending on the location of the FTM battery. However, the voltages in the network are within the limits. The battery charging/discharging scenario considered for this study improves the voltage profiles during the maximum and minimum loading of the feeder. Furthermore, the battery located at the middle or end of the line has a more significant influence on the voltage characteristics compared to the battery at the upstream of the line.

- By integrating the FTM battery into the power system, it would be possible to host a total of 310 kW of PV. This represents an increase of 221 kW more PV than what is currently available and 123 kW more than the base case. This can be done without exceeding the line and transformer limits as defined by the DNSPs.

- The transformer is the main limiting factor for the network to host more DERs. This is similar to other rural networks in Victoria.

5. Case study 2: Fleet of behind-the-meter batteries on a residential feeder

5.1 Overview

In this section, we present the results of our technical feasibility study on connecting BTM battery fleets in one of the LV residential feeders in Heyfield. For our simulation, we used the same feeder parameters as described in Section 4.1 (refer to Table 4). The MV/LV transformer 2125260400 supplies power to residential customers, and according to the data provided by AusNet Services, there are three lines that supply the residential customers to this transformer. We focused on the BTM battery of 3 kW active and 4 kVA inverter for residential customers.

Table 4. System parameters used in case 2

Parameter	Value
MV transformer rating	300 kVA
Number of PV	31
Total capacity of PV	89 kW
Feeder length	Line 1: 500 m; Line 2: 400 m; Line 3: 315 m;
Number of customers	107
Total battery power capacity	100 kW (200 kWh)
Feeder description	Residential, AusNet ID: 2125260400

5.2 Grid impact studies

5.2.1 Voltage profile

It is important to note that three lines serve residential customers, but only the voltage profiles for the longest line, line 1, are provided here. This is because longer LV lines are more likely to violate statutory limits. Looking at Figures 13-14, we can see that the voltage profiles are within the allowable limit. Figure 13 shows the voltage characteristics under maximum load and minimum PV. Under the base case, which has no battery, a voltage reduction is observed along the line, with the lowest recorded voltage being 0.96 pu. However, with the BTM batteries distributed along the line, the lowest terminal voltage increases to 0.995 pu. Figure 14 shows the voltage characteristics of the line under minimum load and maximum PV condition. The terminal voltage decreases with BTM batteries compared to the base case. The highest terminal voltage in the base case is 1.035 pu, which decreases to 1.012 pu with the distributed fleets of batteries along the line.

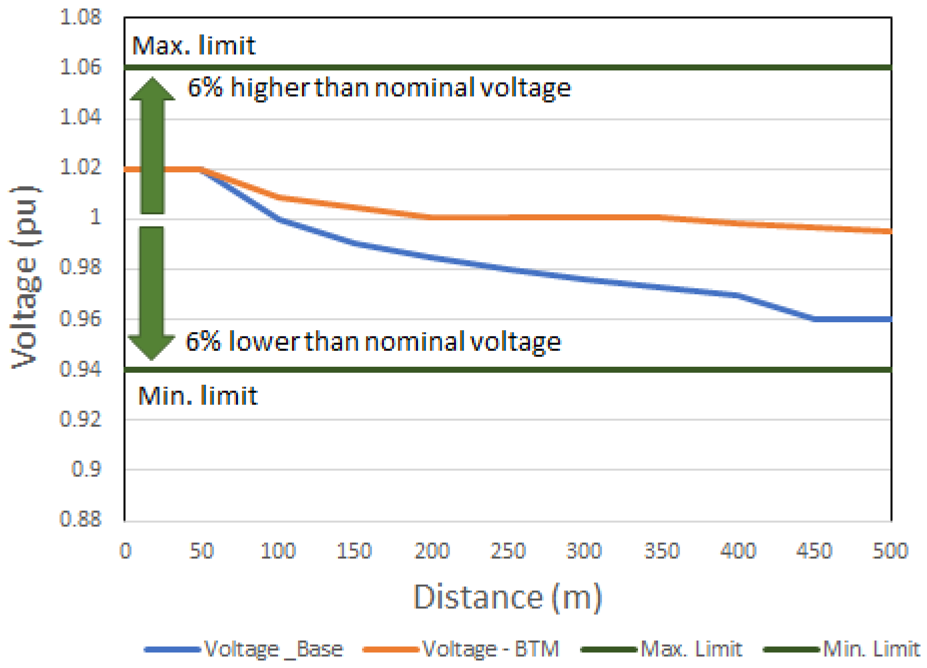

Figure 13. Voltage profile for distributed BTM in residential feeder (max load/min PV).

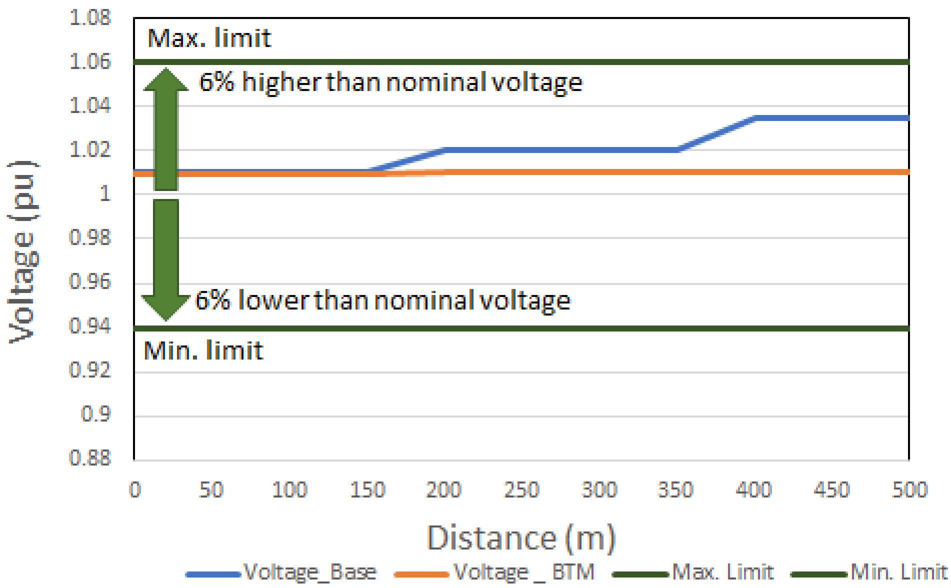

Figure 14. Voltage profile for distributed BTM in residential feeder (min load/max PV).

5.2.2 Hosting capacity

Table 5 summarises the hosting capacity results for the fleet of BTM batteries in the feeder. Voltage profiles and network utilisation are used to assess the hosting of PV into the network. The results of the PV hosting capacity are compared against the base case (PV hosting of the selected feeder without battery). The current PV penetration to this feeder is 89 kW (total 31 customers with PV). The network can host another 98 kW of PV without integrating the battery into the system (before transformer and lines become overloaded). The system could host 330 kW of PV with the fleets of BTM batteries into the system before being reaching the line and transformer limits.

Table 5. Hosting capacity with BTM batteries in the residential feeder (89 kW current level)

IS		89 kW	120 kW	140 kW	160 kW	180 kW	187 kW	200 kW	220 kW	240 kW	260 kW	280 kW	330 kW	350 kW
No battery (base case)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X	X
	Transformer	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X	X
BTM in the feeder	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X

✓: Within the limit/no overloading; **X**: Outside the limit/overloading

5.3 Conclusion – residential feeder BTM battery technical impacts

- Integrating BTM battery fleets into the system would allow for the hosting of 330 kW of PV, which is 241 kW more than the current PV penetration and 143 kW more than the base case. The voltage characteristics under maximum load and minimum PV improves with BTM batteries as compared to the base case. Furthermore, under minimum load and maximum PV condition, the terminal voltage decreases with BTM batteries compared to the base case.

- In order to allow for more DERs, the transformer is currently the main limiting factor for the network. This is a common problem, similar to other rural networks across Victoria.

6. Case study 3: Front-of-meter battery mixed commercial / residential feeder

6.1 Overview

This section presents the technical feasibility of integrating a FTM in one of the mixed LV feeders in Heyfield. The MV/LV transformer 215302700 supplies power to commercial and residential customers. According to the data provided by DNSP, two lines supply the commercial and residential loads under this transformer. Table 6 illustrates the key feeder parameters used for the modelling and technical feasibility analysis. This uses the approach outlined in Section 3.

Table 6. System parameters -mixed feeder (Case 3)

Parameter	Value
MV transformer rating	500 kVA
Number of PV	12
Total size of PV	202 kW
Feeder length	Line 1: 366 m; Line 2: 300 m;
Number of customers	59
Battery Power Capacity	100 kW (200 kWh)
Feeder description	Mixed commercial and residential, AusNet Services ID. 215302700

6.2 Grid impact studies

6.2.1 Voltage profile

Figures 15-16 summarise the voltage profiles of the feeder for the following integration scenarios (ISs).

- IS-1 FTM at the substation: the battery is located at the substation.
- IS-2 FTM mid feeder: the battery is located at the middle of the feeder/line.
- IS-3 FTM end of feeder: the battery is located near the end of the feeder/line.

It is important to note that two lines serve the customers in this selected feeder, but only the voltage profiles for the longest line, line 1, are provided here. This is because longer LV lines are more likely to violate statutory limits. Based on Figures 15-16, it is clear that the voltage profiles are within the allowable limit. Figure 15 displays the voltage characteristics under maximum load and minimum PV. Under the base case (i.e., current PV and no battery), a voltage reduction along the line can be observed, with the lowest recorded voltage being 0.97 pu. However, with the FTM battery placed at the beginning of the feeder, the lowest terminal voltage increases to 0.988 pu. If the FTM battery is placed in the middle of the feeder, the lowest terminal voltage increases to 0.995 pu. Furthermore, if the FTM is placed at the end of the line, the lowest terminal voltage increases to 1.005 pu.

The voltage characteristics of the line under minimum load and maximum PV condition are displayed in Figure 16. The terminal voltage decreases with FTM compared to the base case. The highest terminal voltage in the base case is 1.04 pu, which decreases to 1.018 when the FTM is placed at the entrance of the line. When the FTM is placed at the middle of the line, the highest terminal voltage reduces to 1.013 pu and decreases to 1.011 pu when placed at the end of the line. The battery charging during the minimum load and maximum PV condition helps manage the over-voltage issue. Similar to case 1, the battery located at the middle or end of the line has a more significant influence on the voltage characteristics when compared to the battery at the upstream of the line.

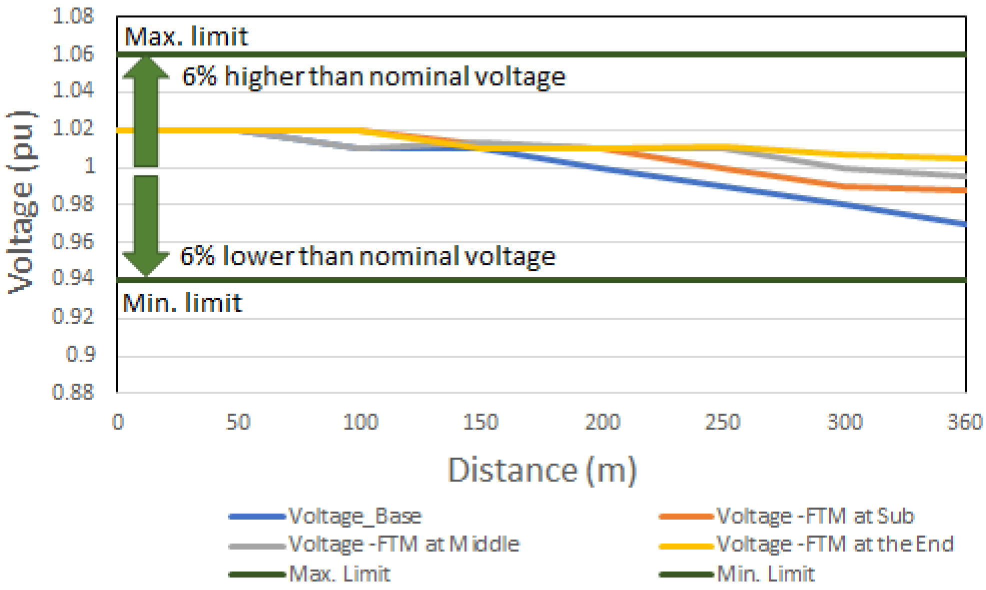

Figure 15. Voltage profile for front-of-the-meter battery (max load/min PV).

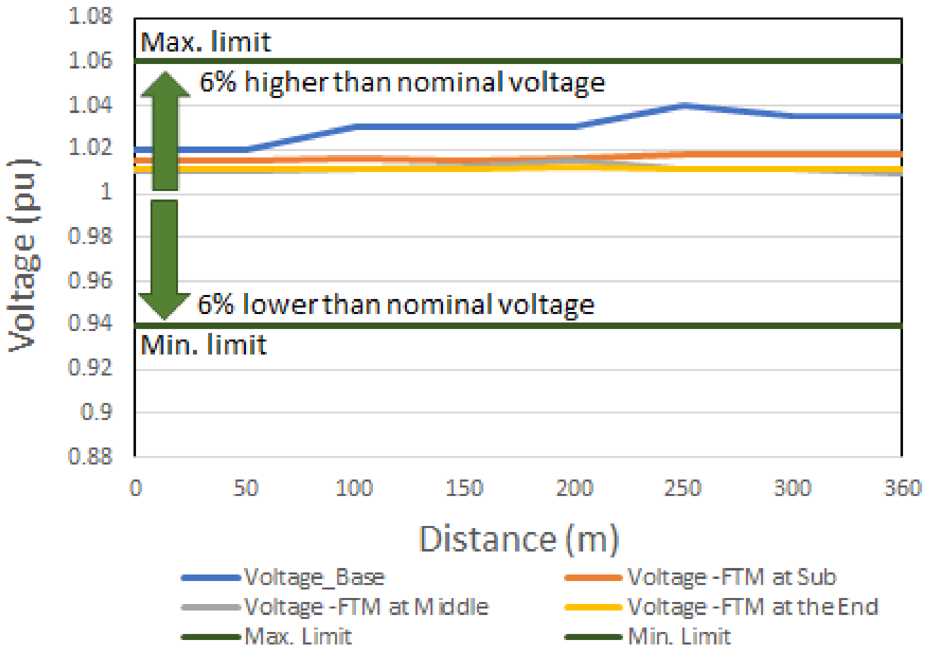

Figure 16. Voltage profile for front-of-the-meter battery (min load/max PV).

6.2.2 Hosting capacity

Table 7 shows the hosting capacity results for a FTM battery into the feeder. The voltage profiles and network utilisation are used to assess the hosting of PV. Similar to the prior cases, the results of the PV hosting capacity are compared against the base case (PV hosting of the selected feeder without battery). The current PV penetration to this feeder is 202 kW (total of 12 customers with PV). The network can host another 178 kW of PV (total 380 kW) to this feeder without integrating the battery to the system (before transformer and line become overloaded). The system could host a total 560 kW of PV with the integration of battery into the system before reaching line and transformer limits.

Table 7. Hosting capacity with FTM in the mixed feeder (202 kW current level)

IS		202 kW	240 kW	280 kW	320 kW	358 kW	380 kW	420 kW	460 kW	500 kW	520 kW	540 kW	560 kW	580 kW
No battery (base case)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X	X
	Transformer	✓	✓	✓	✓	✓	X	X	X	X	X	X	X	X
FTM at start	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
FTM mid-feeder	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
FTM end-feeder	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X

✓: Within the limit/no overloading; **X**: Outside the limit/overloading

6.3 Islanded operation

The islanded operation appears economically non-feasible. However, the research team has performed additional simulations to test the network performance under the islanded operation. Table 8 outlines the constraints for the islanded operation with a FTM into this LV feeder. It is apparent from the Table 8 that the load needs to be reduced under maximum load/minimum PV operating condition for the islanded operation of the mixed feeder. Moreover, a slight overvoltage is noticed with the FTM battery at the end of the feeder. However, the voltages are within the acceptable limits. Similar to case 1 and 2, the islanded operation required changes in converter control to define the voltage and frequency along the feeder, as well as power electronic-based seamless switchover.

Table 8. Overview of islanded operation with FTM battery in the mixed feeder

Integration scenario		Min load/max PV	Max load/min PV
IS1: FTM at the substation	Load	No load reduction	Reduction
	Voltage	Voltage within the limits	Voltage within the limits
IS2: FTM mid-feeder	Load	Reduction	Reduction
	Voltage	Voltage within the limits	Voltage within the limits
IS3: FTM end of feeder	Load	No load reduction	Reduction
	Voltage	Over voltage at end of feeder	Over voltage at end of feeder

6.4 Conclusion – mixed feeder FTM battery technical impacts

- Depending on the placement of the FTM battery, varied voltage distributions can be observed along the line. Nonetheless, all integration scenarios maintain voltages within acceptable limits as defined by the DNSPs.
- By integrating the FTM battery, the system could host up to 560 kW of PV. This is an increase of 358 kW, compared to the current PV penetration and 200 kW more than the base case.

7. Case study 4: Battery at the commercial customer (behind-the-meter)

7.1 Overview

This section presents the technical feasibility of integrating the ranges of large BTMs (e.g., 10 kW, 20 kW, 40 kW, 50 kW, and 100 kW) at the commercial consumer in one of the mixed LV feeders in Heyfield. The feeder is supplied by the MV/LV transformer 215302700. According to the data provided by DNSP, two lines supply the commercial and residential consumers under this transformer. Table 9 illustrates the key feeder parameters used for the modelling and technical feasibility analysis. This uses the approach set out in Section 3.

Table 9. System parameters – mixed feeder (Case 4)

Parameter	Value
MV transformer rating	500 kVA
Number of PV	12
Total size of PV	202 kW
Feeder length	Line 1: 366 m; Line 2: 300 m
Number of customers	59
Battery Power Capacity	10 kW (20 kWh), 20 kW (40 kWh), 40 kW (80 kWh), 50 kW (100 kWh), 100 kW, 200 kWh
Feeder description	Mixed commercial and residential, AusNet Services ID. 215302700

7.2 Key assumptions

This case study examines the impact of several BTMs (ranging from 10 kW to 100 kW) at a commercial customer's location with a PV system. We are analysing their effect on the power system voltage characteristics and the network hosting of solar-PVs. The effect of the battery on the network depends on the location in the feeder (i.e., one location or distributed), mode of operation, and penetration level, regardless of whether it is a FTM or BTM battery.

From the powerflow study perspective, we have modelled the BTM battery as if it was FTM at the node (in this case near to the substation), so the analysis is simply showing the change in voltage support for different sizes of battery. Actual voltage support will vary according to the location on the feeder and the mode of operation of the battery.

7.3 Grid impact studies

7.3.1 Voltage profile

Please note that while two lines are available for mixed feeder customers, we have only provided voltage profiles for the longest line, line 1. This is because longer LV lines run a higher risk of violating statutory limits. It should be noted that from the powerflow study perspective, we have modelled the BTM battery as if it was FTM at the node (which is near to the substation), so the analysis is simply showing the change in voltage support for different sizes of battery. Our recorded voltage profiles are for batteries ranging from 10 kW to 100 kW. However, we have included voltage profiles for 10 kW and 100 kW batteries at the commercial customer to demonstrate network performance under maximum and minimum battery size.

Figures 17-18 show that the voltage profiles remain within allowable limits. Figure 17 displays voltage characteristics under maximum load and minimum PV for 10 and 100 kW BTM. Under the base case (i.e., current PV and no battery), there is a noticeable voltage reduction along the line, with the lowest recorded voltage being 0.97 pu. With a 100 kW BTM, the lowest terminal voltage increases to 0.987 pu. With a 10 kW BTM battery at the commercial customer, the lowest terminal voltage increases to 0.972 pu.

Figure 18 displays the voltage characteristics of the line under minimum load and maximum PV condition. It is observed that the terminal voltage decreases with battery in comparison to the base case. In the base case, the highest terminal voltage recorded is 1.04 pu, but this drops to 1.014 pu when a 100-kW battery is installed for the commercial customer. Similarly, the highest terminal voltage reduces to 1.034 pu when a 10-kW battery is considered for the commercial customer, as shown in Figure 20.

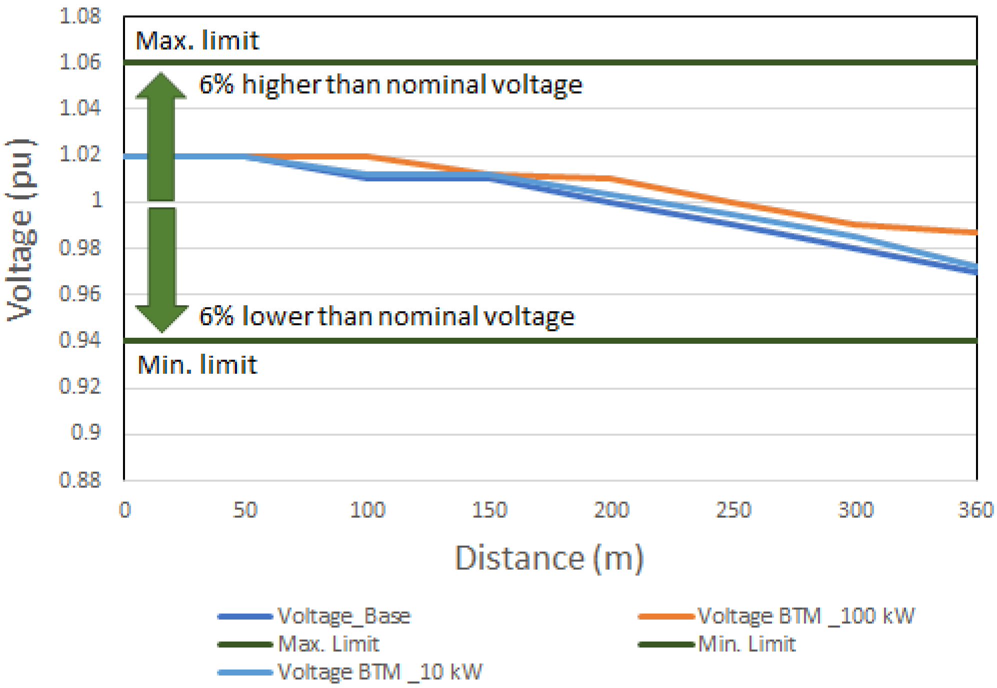

Figure 17. Voltage profile with large BTM (max load/min PV) - 10 kW and 100 kW BTM.

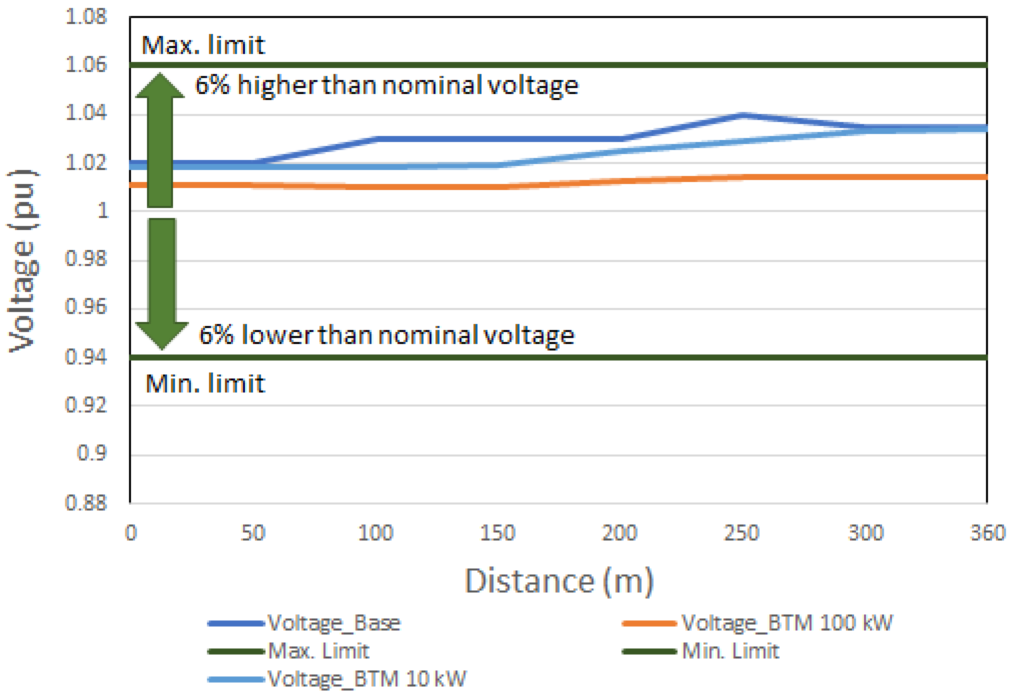

Figure 18. Voltage profile with large BTM (min load/max PV) – 10 kW and 100 kW BTM.

7.3.2 Hosting capacity

Table 10 shows the network's hosting capacity of PV with various sizes of batteries. It should be noted that from the powerflow and hosting capacity study perspective, we have modelled the BTM battery as if it was FTM at the node (in this case, it is located near the substation), so the analysis is simply showing the change in the hosting of PV for different sizes of battery. The capacity to host (PV) is evaluated through voltage profiles and network utilisation. The results of PV hosting capacity are compared to the base case, which is the PV hosting of the selected feeder without a battery.

Currently, the feeder has a total of 12 customers with PV, which results in a penetration of 202 kW. Without integrating a battery, the network can host an additional 178 kW of PV, reaching a total of 380 kW, before overloading the transformer and line. However, with the integration of a large 100 kW battery, the network's capacity to host PV can reach up to 560 kW before reaching the line and transformer limits.

The integration of batteries ranging from 10 kW to 50 kW could contribute to increasing the PV hosting capacity in the feeder considered, although there isn't much difference in hosting capacity with the smaller batteries. For the batteries ranging from 10 kW to 20 kW, the hosting capacity of the network could be increased up to 370 kW - 390 kW.

We note that the impact of BTM and FTM batteries on the feeder is not significantly different. If the size of the battery is the same, impact on hosting capacity will be very similar.

Table 10. Hosting capacity of the network with various sizes of battery installed (current PV 202 kW)

IS		202 kW	340 kW	360 kW	380 kW	400 kW	420 kW	440 kW	460 kW	480 kW	500 kW	520 kW	560 kW	580 kW
No battery (Base case)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	X	X	X	X	X	X	X	X	X
	Transformer	✓	✓	X	X	X	X	X	X	X	X	X	X	X
BTM battery (10 kW)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	X	X	X	X	X	X	X	X	X	X
	Transformer	✓	✓	✓	X	X	X	X	X	X	X	X	X	X
BTM battery (20 kW)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	X	X	X	X	X	X	X	X	X
	Transformer	✓	✓	✓	✓	X	X	X	X	X	X	X	X	X
BTM battery (40 kW)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	X	X
BTM battery (50 kW)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	X
BTM battery (100 kW)	Voltage	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Line	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	Transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X

✓: Within the limit/no overloading; **X**: Outside the limit/overloading

7.4 Islanded operation

The research team has evaluated the potential for operating the commercial premises in an isolated mode in order to provide backup power in times of outage. We analysed the load and PV generation time series data with and without batteries, in order to assess the potential for islanded operation.

In summary, Table 11 outlines the islanded operation options for powering the load using batteries ranging from 10 kW to 100 kW. However, for battery cases with 10-20 kW, the load may need to be reduced when operating with minimum or no PV.

To operate the system in an isolated mode, the following components are required (see Table 12), which would result in additional investment from the customer. These costs are estimated to be between $4,985 and $7,514.

Table 11. Overview of islanded operation of commercial customer with large BTM batteries

Integration scenario		Min load /max PV	Max load/min PV
BTM battery (10 kW, 20 kWh)	Load	No load reduction	Reduction
BTM battery (20 kW, 40 kWh)	Load	No load reduction	Reduction
BTM battery (40 kW, 80 kWh)	Load	No load reduction	No load reduction
BTM battery (50 kW, 100 kWh)	Load	No load reduction	No load reduction
BTM battery (100 kW, 200 kWh)	Load	No load reduction	No load reduction

Table 12. Equipment required to operate the load in islanded mode#

Equipment	Description	Costs (AUD)
Interlocking	Inverter integrated protection	184 – 254 (per unit)
Inverter and inverter control	Inverter with control must comply with AS/NSS4 777.2	2535-4500 (per 6 kVA unit)
Mechanical Isolation	Mechanical isolation switch complies with AS/NZS 5033 standard	253 -280 (per unit)
Islanding protection	This scheme permits customer to do the islanding operation	1324 – 1540 (per unit)
Energy management system	Energy management system of battery (usually comes with battery)	Usually comes with the battery storage system
Earthing protection (50/51)	Protection scheme to break the circuit when earth fault occurs	689 – 940 (per unit)
Estimated total cost for enabling islanded mode		**$4,985 - $7,514**

Low voltage embedded network access standard, UE-ST-2008, 2020.

The customer would be required to submit the connection request to the DNSP to operate in islanded mode during the grid outage. This may require further technical studies on voltage level (including power factor), fault level analysis, load-flow and projection grading assessment.

7.5 Conclusion – battery at the commercial consumer technical impacts

- Smaller battery at the commercial consumer has less impact on the voltage characteristics of the feeder.
- The hosting capacity of the entire feeder does not change much compared to the base case for the battery ranging from 10 to 20 kW.

- The large battery of 100 kW at the commercial customer reveals almost a similar performance as the battery at the beginning of the feeder, since both cases have considered batteries in close proximity with similar operation mode.
- Islanded operation of the commercial consumer is possible with a small battery, as small as 10 kW. However, it requires some changes in the electrical system of the consumer. This would incur further costs to the consumer.

8. Discussion and conclusion

This study assesses the impact of the FTM and BTM battery integration on selected LV feeders. The following cases are simulated to evaluate the technical potential of batteries to support the distribution grid and increase the capacity of solar which can connect to the system without violating the technical limits of the distribution grid. The following cases were evaluated:

- Case 1: FTM on a residential feeder.
- Case 2: A fleet of distributed BTM on a residential feeder with the same capacity as the FTM battery.
- Case 3: FTM on a mixed feeder (commercial and residential feeder).
- Case 4: Large BTM at the commercial customer.

FTM battery on a residential feeder and a mixed residential/ commercial feeder

The results for both feeders were very similar. From the initial simulation results, the following conclusions can be drawn:

- The battery supports the voltage of the LV system. Two conditions were considered in this work, that of maximum load/minimum PV generation and minimum load/maximum PV generation, as these conditions are most likely to trigger under- or over-voltage conditions. The batteries improve or maintain the voltage profiles of the system for all operating conditions. Three locations were tested, with the battery either at the substation, midway along the feeder, or at the extreme end of the feeder. In general, locating the battery at the extreme end of the feeder had the most beneficial effect. We note that system voltage remained within limits without the battery. However, as loads and/ or PV penetration increases in the future (for example, as EVs become commonplace), the deployment of batteries could prevent voltage problems occurring.
- On the residential feeder, the analysis showed that in the base case (without batteries), physical limitations of PV installation started at about double the current penetration of 89 kW, with both the line and the transformer breaching limits. The installation of a 100 kW battery meant that PV installation could treble to 310 kW.
- On the mixed commercial residential feeder, PV capacity could increase by 80% (from 202 kW to 360 kW) without breaching limits on the line or the transformer. The installation of a 100 kW battery increased the hosting capacity by 180%, to 560 kW.

FTM battery vs fleet of household-level BTM batteries on a residential feeder

The following key comparisons can be made based on the initial simulation results:

- The distributed fleet of BTM batteries provides somewhat better voltage support along the feeder/line compared to the FTM battery.
- The hosting capacity of PV is increased by 20 kW for the distributed fleet of BTM batteries compared to the FTM battery (330 kW rather than 310 kW).

FTM battery vs fleet of BTM batteries on a commercial feeder

The impact of the FTM battery on the commercial feeder compared to a fleet of BTM batteries of the same capacity could not be compared, as there was insufficient data on the specific commercial loads and PV installation, to undertake the detailed modelling. However, both could have beneficial impacts on the voltage characteristics and hosting capacity of the feeder.

BTM batteries at a commercial premises

The following conclusions can be drawn based on the initial simulation results:

- The voltage benefits offered to the network vary according to the size and location of the BTM battery.
- The increase in PV hosting capacity differs depending on the capacity of BTM battery. However, there isn't much change in PV hosting compared to the base case until the BTM battery is larger than 40 kW.
- It appears that commercial consumers can operate in islanded mode without having to restrict their power usage when using BTM batteries that range from 20 kW to 100 kW. However, additional costs of approximately $4,985 - $7,514 would be incurred to enable this operation.

Summary

Table 13 presents a summary of the technical analysis results. All of the batteries studied support the network voltage, with greater impact from larger batteries. For the residential feeder, the best voltage characteristics and highest hosting capacity can be achieved with a fleet of BTM batteries.

The fleet of BTM batteries on the residential feeder displays somewhat better network support and somewhat better hosting capacity for PV than the FTM battery. While the effect is relatively small, it is sufficient to warrant further investigation.

The location of the FTM battery was significant for the network support offered, with batteries located both at the middle and the end of the feeder offering better network performance compared to batteries located at the substation. In general, locating the battery at the extreme end of the feeder had the most beneficial effect. Further detailed modelling should be undertaken for the feeders in question to determine optimum location as loads and/ or PV penetration increases in the future (for example, as EVs become commonplace).

It is possible for a commercial customer to use the battery for emergency power in islanded mode, provided there is additional investment in equipment, with an estimated cost of $4,985 - $7,514. While this could be technically possible for the FTM batteries, the higher cost is likely to be prohibitive.

Table 13. Summary of technical analysis results

Case	Voltage characteristics	Hosting capacity	Islanded operation
100 kW FTM battery on residential feeder	Improved; best result from battery located at end of feeder	PV installations could double without battery, or treble with a battery (from 89 kW to 310 kW)	Not commercially feasible
Fleet of BTM batteries on residential feeder (100 kW in total)	Improved somewhat more than FTM	PV installations could increase somewhat more with BTM batteries (to 330 kW).	Not investigated
100 kW FTM battery on mixed residential/ commercial feeder	Improved; best result from battery located at end of feeder	PV installations could increase by 80% without a battery (from 202 kW to 360 kW), or by 170% with the battery (to 560 kW)	Not commercially feasible
BTM battery at commercial premises, 10 kW – 100 kW	Improved; dependant on size and location (assumed same as FTM case if 100 kW)	Improved, dependent on size of battery (assumed same as FTM case if 100 kW)	Feasible for additional cost of $4,985 - $7,514.

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Appendix Additional information: voltage deviation in distribution feeder

This appendix gives more information on the impact of batteries on voltage deviation in distribution feeders with loads and solar-PVs.

The voltage and current at any *m^th* bus of the traditional distribution feeder (Figure 20) can be expressed as follows:

$$I_m = \sum_{m=1}^{n} \frac{P_{Lm} - jQ_{Lm}}{E_m} \tag{1}$$

$$E_m = E_s - \sum_{m=1}^{n} (R_m + jX_m) I_m \tag{2}$$

In (1) and (2), E, P_L, Q_L, I, R, X present voltage, current, load active power, load reactive power, current, feeder resistance, feeder reactance, respectively. The subscript s, m and n represent the sending end, *m^th* bus, and last bus.

Now, the voltage difference or voltage deviation between two buses can be expressed,

$$\Delta E_m = E_{m+1} - E_m = \sum_{n=1}^{m} \frac{P_{Lm} R_m + Q_{Lm} X_m}{E_m} \tag{3}$$

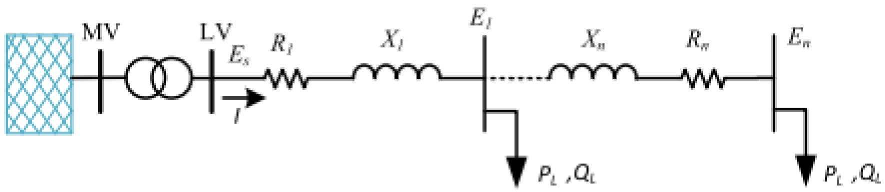

Figure 19. Distribution Feeder with loads.

For the case of solar-PVs into the system as shown in Figure 21, the current equation at *m^th* bus can be expressed as follows:

$$I_m = \sum_{m=1}^{n} \frac{(P_{Lm} - P_{Gm}) - j(Q_{Lm} - Q_{Gm})}{E_m} \tag{4}$$

In (4), P_G and Q_G represent the active and reactive power injected by the solar-PV. Therefore, the voltage at the m^th bus can be expressed as in (5).

$$E_m = E_s - \sum_{m=1}^{n} (R_m + jX_m) I_m \tag{5}$$

The voltage difference between two buses can be expressed as

$$\Delta E_m = E_{m+1} - E_m = \sum_{n=1}^{m} \frac{(P_{Lm} - P_{Gm}) R_m + (Q_{Lm} - Q_{Gm}) X_m}{E_m} \tag{6}$$

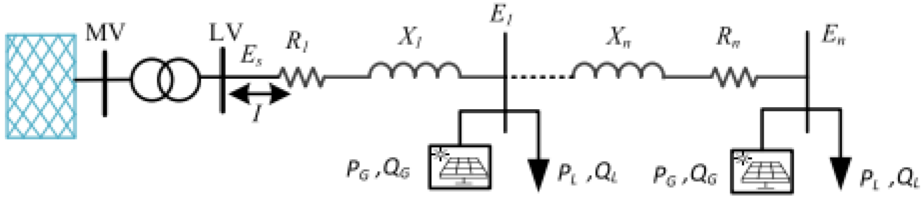

Figure 20. Distributor feeder with load and solar-PVs.

For the case of the system with battery energy storage (see Figure 22), the voltage difference between two buses can be expressed as in (7):

$$\Delta E_m = E_{m+1} - E_m = \sum_{n=1}^{m} \frac{(P_{Lm} - P_{Gm} - P_B) R_m + (Q_{Lm} - Q_{Gm} - Q_B) X_m}{E_m} \tag{7}$$

In (7), P_B and Q_B represent the active and reactive power injected or absorbed by the battery.

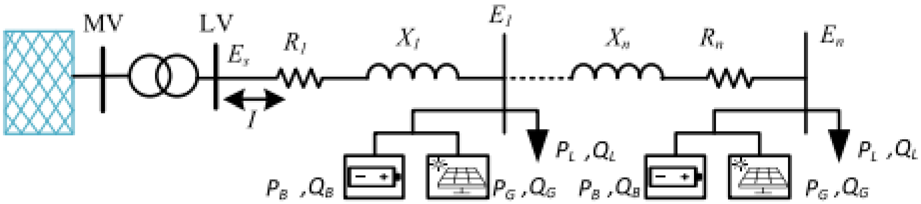

Figure 21. Distribution feeder with load, solar-PV and batteries.