Battery Energy Storage Systems

Vector Limited

Independent Review of Lithium Ion Battery Lives

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Contents

Executive Summary

Vector engaged Jacobs to prepare an independent report outlining the expected life of Vector owned grid-connected utility-scale and behind-the-load residential Lithium Ion batteries depending on their mode of operation. The report focuses on a class of Lithium ion batteries that are typically provided by a number of manufacturers for stationary applications that require daily cycling of energy (e.g. for solar energy storage).

The current regulatory life span for "DC Supplies, Batteries and Inverters" in the ODV Handbook is set to 20 years, based on low usage backup lead acid batteries. This report is specifically focused on a class of batteries being utilised by Vector for network load management purposes at the zone substation level as well as at the residential level. These can be broadly characterised as follows:

- The batteries are based on Lithium ion chemistry (as opposed to lead acid).
- The batteries are part of an overall energy storage system (ESS) that is connected to the grid via a bi-directional inverter.
- The primary operational mode of the ESS is anticipated to typically involve daily discharging and charging of the batteries.

Battery life is typically defined as the number of full charge-discharge cycles before significant capacity loss. Battery manufacturers typically provide performance warrantees that warrant a minimum level of performance over a set period (in this case ten years), provided that the operational use of the system does not exceed pre-defined operational limits of the manufacturer.

At the end of the performance warranty period, while the ESS might still have a remaining technical life, albeit at a reduced capacity, it can no longer meet the functional and commercial objectives of its original purpose. At this point the ESS either needs to be replaced or supplemented with additional battery capacity.

Jacobs modelled the ten year duty cycle and throughput of both utility-scale network and residential Tesla batteries under a range of anticipated operational scenarios:

- 1 MW, 2.3 MWh Tesla Powerpack 1 ESS at a zone substation – monthly peak demand management vs. heavy usage to maximise utilisation.
- 3 kW, 6.4 kWh Tesla Powerwall 1 – maximise solar PV self-consumption, reserving some battery capacity for back-up, and solar storage plus network peak management.

Utility-Scale Energy Storage

Based on the expected functionality of the Tesla Powerpack 1 units on Vector's network (i.e. primarily for peak demand management), there is unlikely to be excessive duty cycles imposed on the batteries which would prematurely shorten their operational life / capacity. Likewise, the modelling showed that even if the batteries are utilised outside of peak demand months for other purposes on a regular basis they are not likely to exceed the throughput that would reduce the warranted performance, or shorten the warranty.

The primary driver of life for these batteries will therefore be driven by their warranted degraded performance. Once they have lost up to 30-50% of their storage capacity, their ability to meet Vector's functional requirements (i.e. the ability to contain load peaks at a specific site) will be significantly reduced, which will require either replacement of the battery, increasing battery capacity or investment in the network upgrade that the battery was helping to defer.

Based on this, the expected usable and economic life of a utility-scale Lithium ion battery energy storage system (such as the Tesla Powerpack 1) would be 10 years.

Residential Energy Storage

Like the grid-connected network batteries, the expected life of the Tesla Powerwall 1 units deployed to customers on Vector's network will be driven by their warranted degraded performance. This is potentially impacted by the operational mode and configuration they are used for. The typical usage scenarios considered

by Jacobs resulted in battery throughput over ten years lower than the operational limits set by the manufacturer (i.e. the batteries would not be expected to degrade at an advanced rate and reduce life expectancy).

While a future scenario of solar self-consumption with overnight charging for peak demand management could potentially exceed this operating limit, in practice it is expected that the settings for grid based charging would be used sparingly to avoid excessive “solar spill” and therefore would be unlikely to exceed the manufacturer’s operating limits.

It is unlikely that the operating scenarios envisaged will prematurely age the batteries to less than ten years. However at the end of ten years, the reduced warranted capacity of the battery would mean that the home owner would likely to be exporting significant quantities of solar energy to the grid, so would be economically incentivised to replace the battery at this point.

Based on this, the expected usable and economic life of a residential-scale Lithium battery energy storage system (such as the Tesla Powerwall 1) would be 10 years.

Inverters

The life span of inverters is not impacted by the number of cycles of the batteries or solar panels that are connected to them. An inverter is a fairly well established electronic device for converting direct current electricity supply into alternating current supply, and vice versa.

There is no correct answer on inverter life span, but in normal operating environments, a good quality inverter such as the Dynapower PCS and SolarEdge inverters used by Vector that is regularly maintained should comfortably last between 10 and 15 years.

Conclusions

The warranted performance of the Tesla Powerwall was considered to be typical of those provided by manufacturers of Lithium batteries being utilised for similar purposes. While these warranted performance curves may be conservative compared to real world performance, they are bankable. That is, a developer seeking funding for a project incorporating these batteries can rely on the performance warranty, provided they are operating the batteries in the manner and in the environmental conditions specified in the warranty.

Based on the expected range of utility and residential applications that Vector are intending to use these batteries for, it is not expected that the batteries will be subject to excessive cycling that would shorten their warranted life span of ten years.

On the flipside, in situations where such batteries might be cycled a lot less due to a greater level of capacity being reserved for infrequent back up purposes, the impact of calendar aging processes on storage capacity will be more predominant. The total amount of storage capacity decline for a lowly utilised Lithium battery over ten years from calendar aging processes is not well understood but Jacobs anticipate that capacity loss could still be significant, particularly as a commercially focused utility such as Vector would seek to maximise the value obtained from a utility scale battery to benefit its customers. .

On this basis, Jacobs recommend the use of a ten year life span for regulatory purposes for both utility-scale and residential-scale Lithium batteries deployed by Vector.

As it is likely that the associated inverters would be replaced at the same time as the batteries in the network and residential systems above, a commercial lifespan of ten years for inverter would also be considered appropriate.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to provide a report on the expected lives of Lithium Ion batteries in accordance with the scope of services set out in the contract between Jacobs and the Client. That scope of services, as described in this report, was developed with the Client. This report is for Vector's regulatory compliance purposes and is not intended to be relied upon by third parties.

Jacobs derived the data in this report from information sourced from the Client (if any) and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context.

This report has been prepared on behalf of, and for the exclusive use of, Jacobs' Client, and is subject to, and issued in accordance with, the provisions of the contract between Jacobs and the Client. Jacobs accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

1. Introduction

Vector engaged Jacobs to prepare an independent report outlining the expected life of Vector owned grid-connected utility-scale and behind-the-load residential Lithium Ion batteries depending on their mode of operation.

The current regulatory life span for "DC Supplies, Batteries and Inverters" in the ODV Handbook[1] is set to 20 years, based on low usage backup lead acid batteries. This regulatory lifespan does not reflect the different mode of operation and chemistry of the batteries that are being deployed by Vector.

The independent report covers:

- Expected life cycle curves for Lithium Ion batteries utilised for regular cycling applications (such as residential solar storage or utility-scale peak demand management).
- Review of proposed (and existing) operation of utility-scale grid-connected batteries being utilised at zone substations (such as Glen Innes).
- Review of operation of behind-the-load residential batteries being utilised at customer homes.
- Expected impact of the No of Cycles and depth of discharge on maximum battery capacity over time and expected life given the above modes of operation.
- Review of expected life of inverters utilised at zone substations and in-home.

Vector provided the following information for review:

- Historical histogram of usage for batteries at Glen Innes zone substation.
- Expected operating parameters of grid-connected batteries at zone substations and in the home.
- Battery datasheets and warranty information.
- Inverter data sheets and warranty information.

It should be noted that Jacobs have relied on public domain information in preparing this report. Certain aspects such as the potential chemistry of the Tesla batteries that have been deployed on Vector's network have been assumed and are indicative of the expected performance of a range of Lithium based batteries that are being brought to market by various suppliers.

[1] Commerce Commission (2004).

2. Battery Technology

2.1 General

This report is specifically focused on a class of batteries being utilised by Vector for network load management purposes at the zone substation level as well as at the residential level. These can be broadly characterised as follows:

- The batteries are based on Lithium Ion chemistry (as opposed to lead acid).
- The batteries are part of an overall energy storage system (ESS) that is connected to the grid via a bi-directional inverter.
- The primary operational mode of the ESS is anticipated to typically involve daily discharging and charging of the batteries.

2.1.1 Defining End of Life

Battery life is typically defined as the number of full charge-discharge cycles before significant capacity loss.

In the context of utilising energy storage systems for maximising household solar energy self-usage or managing network peak loads, a reduction of storage capacity affects the economic benefits of ESS as follows:

- Increasing export of excess solar power to the grid at low (or zero) feed-in tariffs during the day.
- Reducing the amount of time that a network battery can offset peak loads on a feeder or zone substation (or alternatively reducing the size of the peak reduction possible for the same time period).

In either situation while the ESS might still have a remaining technical life, albeit at a reduced capacity, it can no longer meet the functional and commercial objectives of its original purpose. At this point the ESS either needs to be replaced or supplemented with additional battery capacity.

2.1.2 Battery Chemistries

Lithium-ion batteries are a class of rechargeable batteries that involve lithium ions moving from the negative electrode to the positive electrode during discharge and back when charging. They generally have a higher energy density, smaller memory effect and lower self-discharge than other types of batteries (e.g. lead acid, nickel cadmium).

They utilise a range of different lithium chemistries for the electrodes depending on the functional requirements and required performance of the battery. Each has a different specific energy density, specific power (maximum charge / discharge rate), safety, performance, cost and life span.

Some of the key Lithium-ion technologies include:

- Lithium cobalt oxide ($LiCoO_2$) – typical in handheld electronics, broad use.
- Lithium iron phosphate ($LiFePO_4$) – typical in power tools, automotive hybrid systems, some home energy storage systems (e.g. Enphase batteries).
- Lithium manganese oxide ($LiMn_2O_4$, Li_2MnO_3, or LMO) – hybrid electric vehicles, cell phones, laptops.
- Lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$ or NCA) – high energy density and power discharge but shorter life – suitable for electric vehicles.
- Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$ or NMC) – lower energy density but long cycle life – suitable for daily usage (e.g. storing excess solar energy).
- Lithium titanate ($Li_4Ti_5O_{12}$ or LTO) – electric vehicles (particularly for rapid charging applications).

2.1.3 Degradation Curves

The maximum storage capacity of rechargeable batteries degrades over time depending on a number of factors:

- Battery chemistry
- Number of times the battery is cycled (i.e. charged and discharged).
- The depth of discharge (i.e. how much the battery is drained during each discharge cycle).
- How rapidly the battery is charged and discharged.
- The operating environment (i.e. ambient temperature).

Figure 2.1 below shows a NMC-based Lithium Ion battery that is charged and discharged to no more than 80% depth of discharge and at a 1C charge rate can achieve a cycle life performance of 10,000 cycles up to 70% of the original capacity.

Figure 2.1 : Cycle Life Performance for a typical NMC Battery Cell charged and discharged (at 1C/1C) to 80% DoD, 23±3˚ C

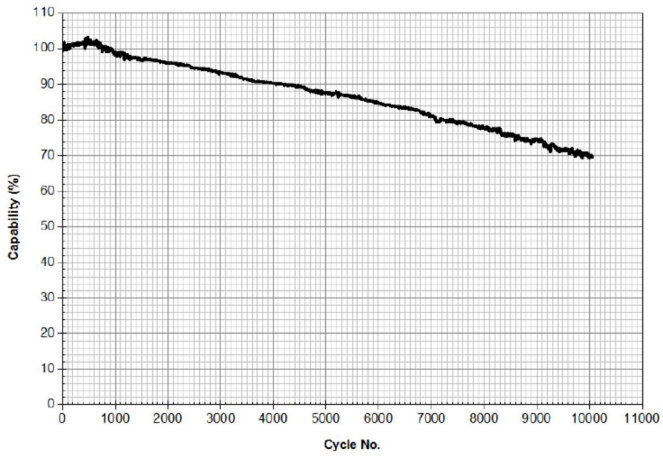
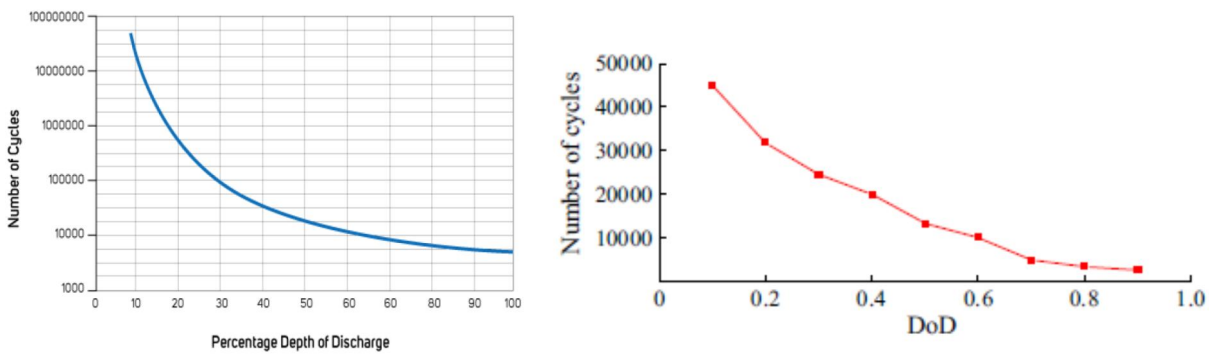


Figure 2.2 provides a couple of examples that show the significance of depth of discharge on the number of life cycles of NMC batteries.

Figure 2.2 : Examples of Cycle Life vs Depth of Discharge for a typical NMC Battery Cell



Temperature can also have a significant effect on battery life. Keeping a fully charged Lithium ion battery in a 40˚C environment would result in it losing about 35% of its capacity in a year without being used[2].

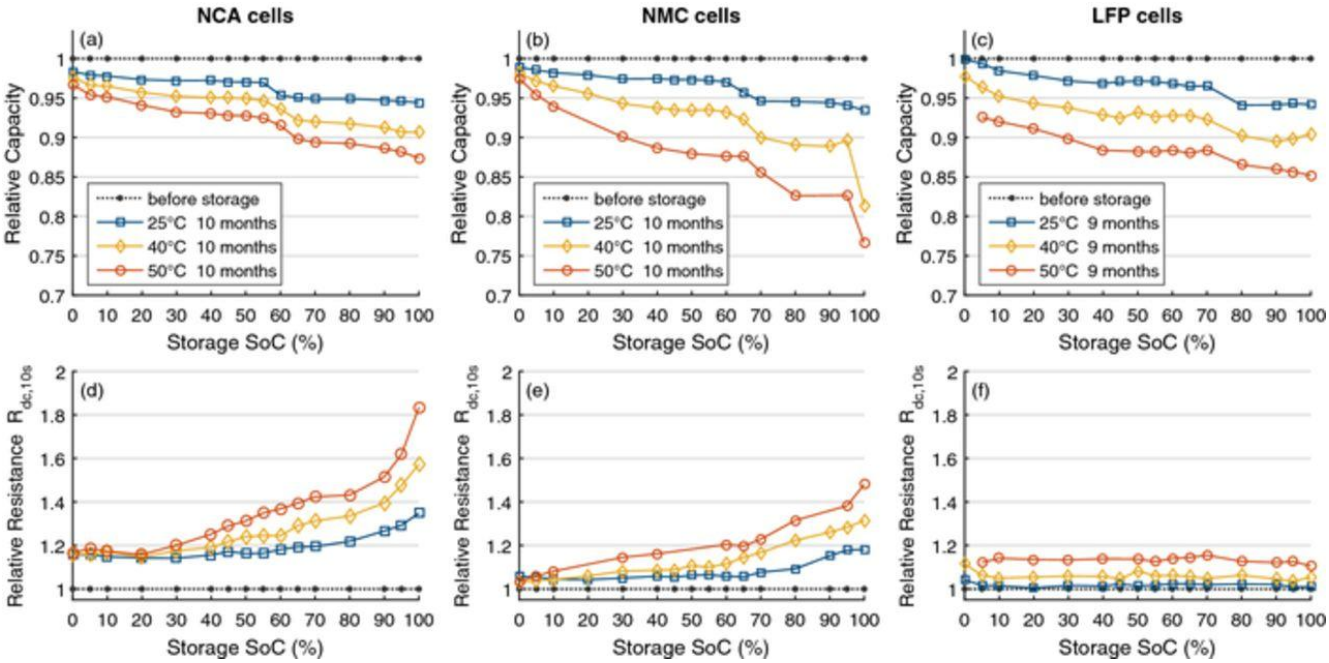
[2] http://batteryuniversity.com/learn/article/how_to_define_battery_life

2.1.4 Calendar Aging

In addition to loss of energy capacity due to cycling, it is important to note that batteries also undergo calendar aging. This comprises all aging processes that lead to a degradation of a battery cell independent of charge-discharge cycling and is an important factor in situations where the operational periods are shorter than the idle periods. It has been found that calendar aging can be more predominant in cycle aging studies when cycle depths and current rates are low.

Figure 2.3 below shows the reduction in storage capacities for three different types of Lithium ion batteries (NCA, NMC and LFP) that are held (without cycling) at various states of charge (from 0 to 100%) and temperatures (25˚C, 40˚C and 50˚C) for 9-10 months. For NMC and NCA cells that were at an initial state of charge (SoC) of between 70 to 100%, the reduction in storage capacity at the end of 10 months was about 5%. (Keil et al, 2016). There is no publicly available information to indicate whether or not this trend would continue over ten years.

Figure 2.3 : Battery Degradation after 9-10 months of storage at various States of Charge and Temperatures (Keil et al. 2016)



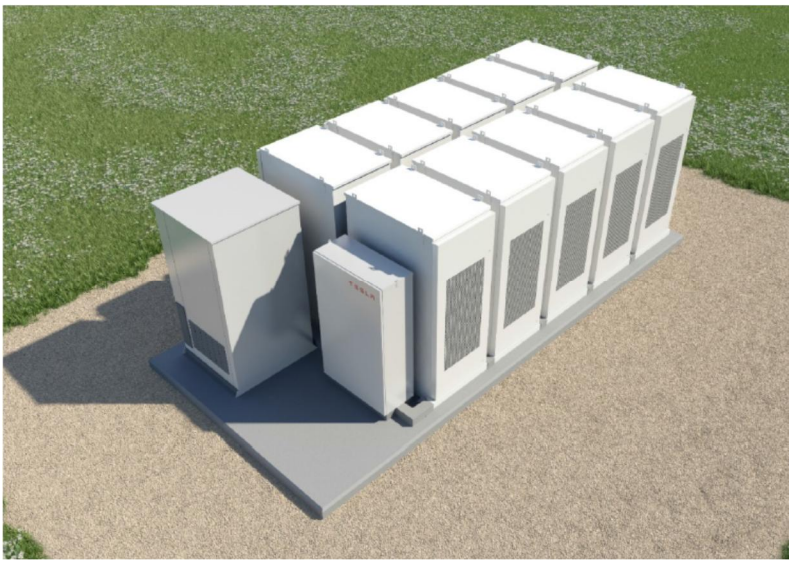
2.2 Utility-Scale Energy Storage (Tesla Powerpack)

2.2.1 Overview

The Tesla Energy Powerpack 1 System utilised by Vector at Glen Innes Zone Substation is based on a modular and scalable energy storage system, comprising:

- Rechargeable lithium-ion battery packs (Tesla Powerpacks)
- Bi-directional power conversion system (Dynapower MPS-250 inverters)
- DC combiner panels
- Site Master Controller

Figure 2.4 : Tesla 250kW 4 hour Powerpack System with bidirectional PCS (left), DC Combiner Panel and 10 Powerpacks



The configuration of the Glen Innes ESS is based on four Tesla Powerpack 1 System blocks to provide a total capacity of 1 MW, 2.3 MWh.

2.2.2 Tesla Powerpack System

The Tesla Powerpack 1 that Vector has installed at Glen Innes comes with a 10 year product warranty in relation to defects and a 10 year energy retention warranty. As is typical for these types of batteries, this includes a warranted storage capacity curve with a guaranteed minimum at the end of ten years, provided that the aggregate discharge of the battery has not been exceeded a certain limit[3].

2.2.3 Dynapower PCS

The Dynapower MPS-250 inverter has been designed to be seamlessly integrated with the Tesla Powerpack 1.

The inverter is covered by the Tesla Powerpack 1 ten year product warranty.

2.2.4 Glen Innes ESS Operational Modes

There are a number of potential uses for the ESS each of which would result in a different level of duty for the battery:

- Peak demand management to defer network investment at the zone substation level (e.g. defer replacement of transformers).
- Peak demand management to manage aggregated demand peaks at grid exit points.
- Demand response for other market participants (e.g. Transpower, generator / retailers).
- Voltage support.
- Instantaneous reserves.
- Energy arbitrage (i.e. purchasing energy in low price periods and selling during high price periods).

These are not necessarily mutually exclusive opportunities, although given the nature of the NZ power system these opportunities are highly correlated e.g. peak demand on residential networks occur during cold wind evenings, impacting grid exit point demand, availability of generation and instantaneous reserves, and system voltages.

[3] This curve and warranty details are commercially sensitive so cannot be replicated in this report.

At present the Powerpack 1 at Glen Innes Substation is undergoing an operational trial, with charge and discharge set points being adjusted regularly to increase utilisation of the battery and explore the commercial benefits of the above modes.

The impact of this and these potential modes on cycling of the battery and aggregate discharge are discussed further in Section 3.1.

2.3 Residential Energy Storage (Tesla Powerwall)

2.3.1 Specifications

Vector have deployed first generation 6.4 kWh Tesla Powerwall 1 batteries with SolarEdge Inverters to a number of its customers. The key specifications of the Powerwall battery and SolarEdge inverter are as follows:

Table 2.1 : 6.4kWh Tesla Powerwall 1 Home Battery Key Specifications

Specification	Value
Power, continuous and peak	3.3 kW
Energy	6.4 kWh
Round Trip Efficiency (Beginning of Life)	92.5%
Operating Temperature Range	-20˚C to 50˚C Humidity: <95% condensing

Table 2.2 : 3kW SolarEdge Single Phase Inverter Key Specifications

Specification	SE3000	SE5000
Rated and Maximum AC Power	3.0 kVA	4.985 kVA
Maximum DC Power	3.375 kW	6.75 kW
Maximum Inverter Efficiency	97.6%	97.4%
Operating Temperature Range	-20˚C to 50˚C	-20˚C to 50˚C

2.3.2 Warranty Conditions

Tesla provides a ten year warranty for the 6.4 kWh Powerwall 1 as follows[4]:

- 10 years free of defects from initial installation date.
- Maintain minimum energy capacity as shown in Table 2.3 below.

Table 2.3 : Warranty Conditions for Tesla Powerwall (1st Generation)

Application	Energy Retention	Operating Limitation
Solar self-consumption / backup only	60% at 10 years following initial installation date	Unlimited cycles
Any other application or combination of applications	60% at 10 years following initial installation date	18 MWh of aggregate throughput (measured at the battery DC output)

It is assumed that the energy retention is roughly a linear decline from an initial capacity of 6.4 kWh at installation to 3.84 kWh in year 10.

[4] https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall_Warranty_Australia_New_Zealand_2-1.pdf

SolarEdge provide a 12 year warranty for its inverters[5] commencing on the earlier of:

i. 4 months from shipping date from SolarEdge

ii. Installation date

2.3.3 Operational Modes

Vector predominantly uses the following profiles for the network-owned Powerwalls. The profile is currently selected based on the purpose of the install and arrangement with the end consumer.

1) **Battery only profile:** same schedule every day of the year, reserves 50% of the battery energy storage for backup purposes (i.e. only 3.2kWh of energy is available for cycling). Charge battery in off peak periods (e.g. early morning) and discharge during evening peak.

2) **Solar with battery (no backup) profile**:

This uses the following rules for 100% of the energy storage in the battery (with 0% backup).
The solar system size is either 2.5 or 3 kW (most of the systems installed by Vector are 3 kW).

- If Solar Generation > Home Consumption: Solar supply home demand with excess solar energy stored in battery
- If Home Consumption > Solar Generation: Solar supply home with excess demand supplied from battery
- If Battery is empty: Supply home from any available solar energy and excess from grid
- If Battery full AND Solar Generation > Home Consumption: Solar supply home and excess solar generation is exported to grid

3) Solar with battery (backup capable) profile:

This uses the same rules as profile 2 above for 70% of the energy storage in the battery (with 30% backup and not cycled).

These types of profiles are typical of a range of solar home batteries being supplied on the market at present and a number of suppliers are developing intelligent controllers with the intent to optimise solar energy storage and battery utilisation based on network or electricity pricing signals, weather forecasts etc.

[5] https://www.solaredge.com/us/service/warranty

3. Life Cycle Modelling

3.1 Utility-Scale Energy Storage

The ESS control system is currently set up to charge the battery when the load at Glen Innes drops below 4.2MW and to discharge up to a maximum of 1MW when the Glen Innes load exceeds 6.5 MW. It is understood that Vector have been adjusting these set points regularly to ensure that the battery achieves a high level of utilisation.

Figure 3.1 : Glen Innes Powerpack Performing Peak Shaving on 23 April 2017

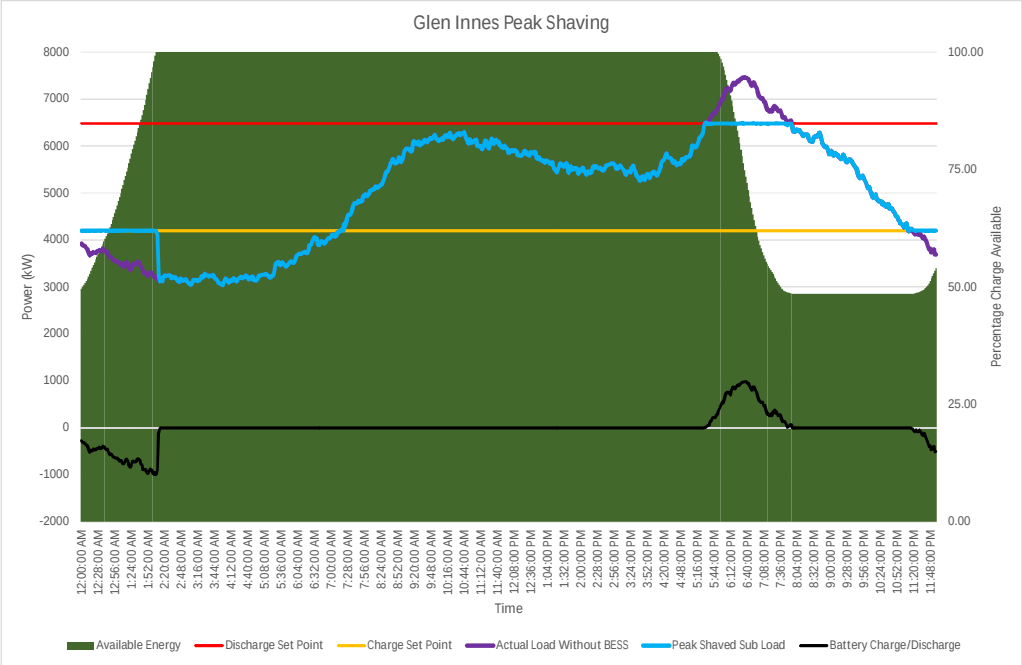
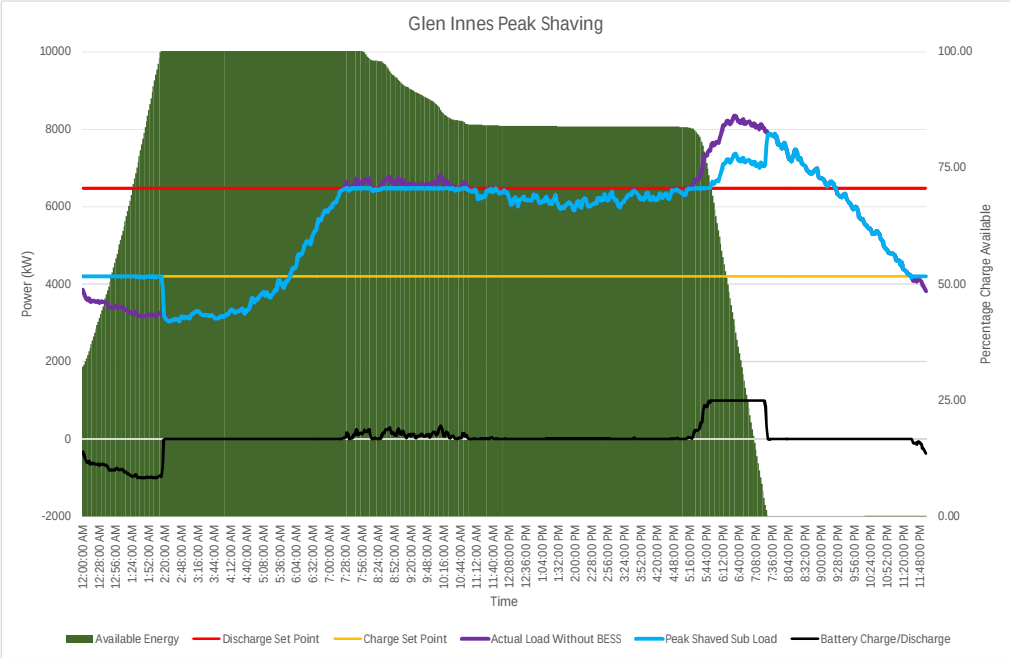


Figure 3.2 : Glen Innes Powerpack Performing Peak Shaving on 26 April 2017



Vector provided Jacobs with half hourly load data for the Glen Innes substation for the year prior to the installation of the Tesla Powerpack. Based on this Jacobs developed a battery model to calculate the expected number of cycles when operating under the following modes:

- Set points aimed at reducing the highest substation peak each month by 1 MW.
- Set points designed to reduce the annual highest peak in August by 1MW and during other months set at a lower level to maximise the number of cycles (to achieve ~80% usage over life time).

The total throughput of the Glen Innes 2.3 MWh ESS battery energy storage system was modelled over 10 years and is shown in Table 3.1 below, assuming an annual substation load growth of 2% per annum. This is contrasted against a larger capacity 4 hour (4 MWh) ESS under the same scenarios.

Table 3.1 : Network Battery Usage Under Different Operating Scenarios

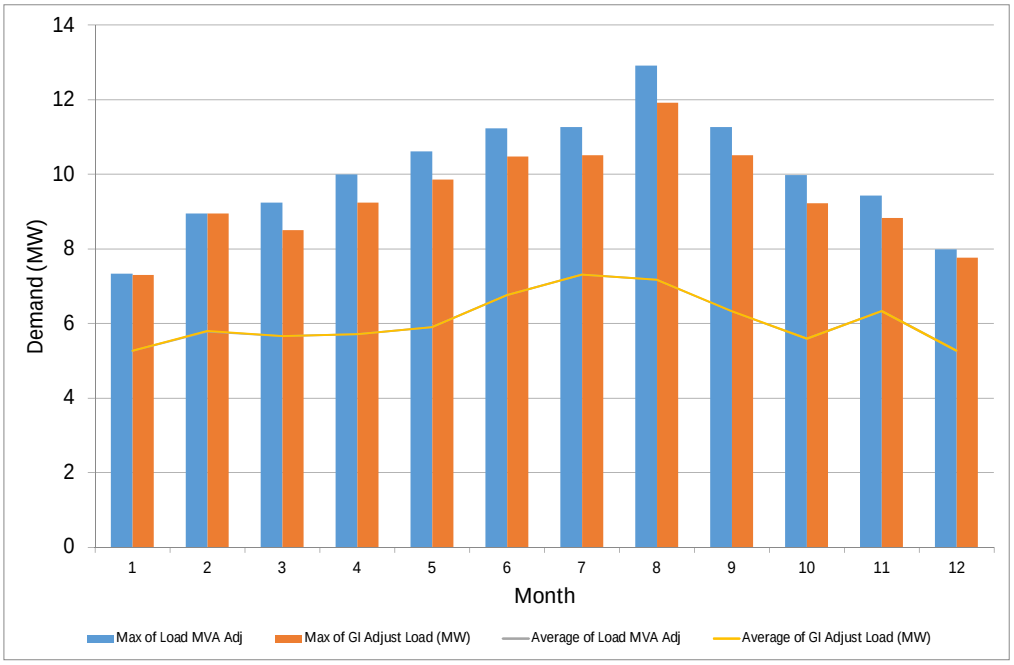
Scenario	Energy Stored / Lost (MWh year 1)		Energy Discharged (MWh y1)	10 Year Throughput (MWh)	No. full cycles	Peak Savings Y1 (MW)	Peak Savings Y10 (MW)
Highest Peak per Month (2.3 MWh)	91 MWh	16 MWh	72 MWh	2,269 MWh	986	1.0	0.49
Maximise Usage (2.3 MWh)	782 MWh	141 MWh	640 MWh	5,329 MWh	2,316	1.0	0.49
Highest Peak per Month (4 MWh)	107 MWh	19 MWh	84 MWh	3,230 MWh	808	1.0	0.92
Maximise Usage (4 MWh)	1,199 MWh	216 MWh	983 MWh	8,709 MWh	2,177	1.0	0.84

Based on the above results, it was found that if the ESS is only utilised to contain network peaks on a residential substation then over ten years the throughput of the battery is likely to be well within the performance warranty. Figure 3.3 below shows the impact on network peaks for each month of the first year. In January and February the battery is unable to reduce the peaks by a full 1 MW due to a number of days where the loads were above the discharge set point for more than four hours.

Over the period of 10 years the ability of the 2.3 MWh battery to reduce peaks by 1 MW is halved due to the shortened storage capacity resulting from modelled degradation. The larger 4 MWh battery would still have enough capacity to reduce network peaks by about 900 kW at the end of ten years.

The second scenario which was based on setting the charge and discharge set point at arbitrarily low levels for each month (except August), resulted in a higher throughput of the 2.3 MWh and 4 MWh batteries over the ten years. This was still likely to be within the performance warranty limit of the battery and achieved an annual peak demand reduction of 1MW in the first year which dropped off to 0.49 MW and 0.84 MW respectively in year 10 as reducing battery storage capacity made it increasingly difficult to contain peaks.

Figure 3.3 : Glen Innes Substation Peak Demand Reduction with Monthly Target Setting

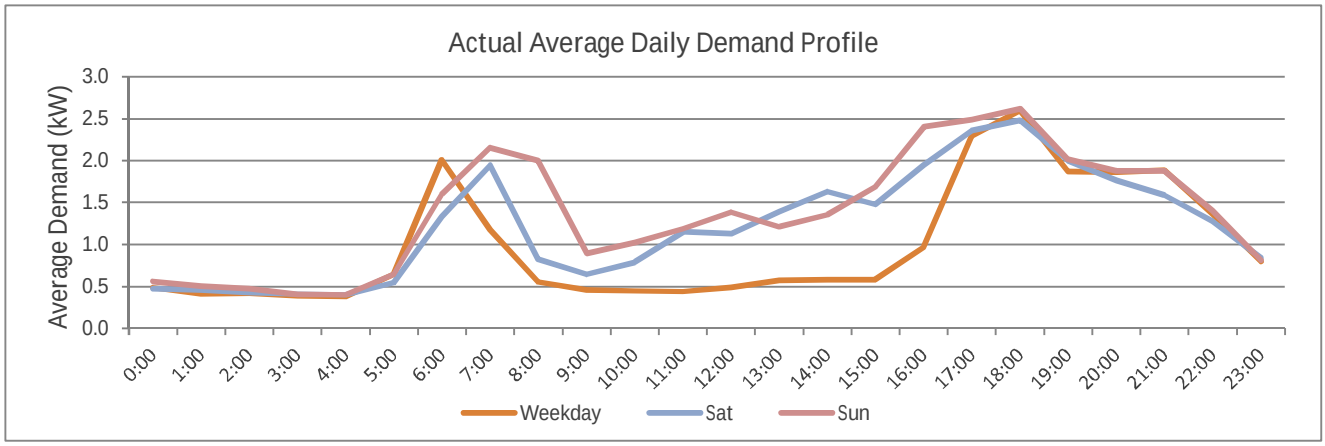


3.2 Residential Energy Storage

Jacobs developed an hourly residential solar / battery model based on the following parameters:

- 2016 half hourly load data for a residential property in Auckland (2 adult household, gas hot water, electric heat pumps, no one home during week days) with total annual load of 9,456 kWh and average daily load of 25.91 kWh – as shown in Figure 3.4 below.
- Hourly solar data for Auckland, 3.2 kWp solar array north facing at 30 degrees tilt for an average year.
- 6.4 kWh Tesla Powerwall 1 battery with maximum charge and discharge capacity of 3.3 kW and DC-DC round trip efficiency of 92.5%.
- 3kW$_{ac}$ SolarEdge Inverter with maximum efficiency of 97.6% - giving AC-AC roundtrip efficiency of 88%.

Figure 3.4 : Average Weekday and Weekend day time load profiles for Auckland Residential Household for 2016



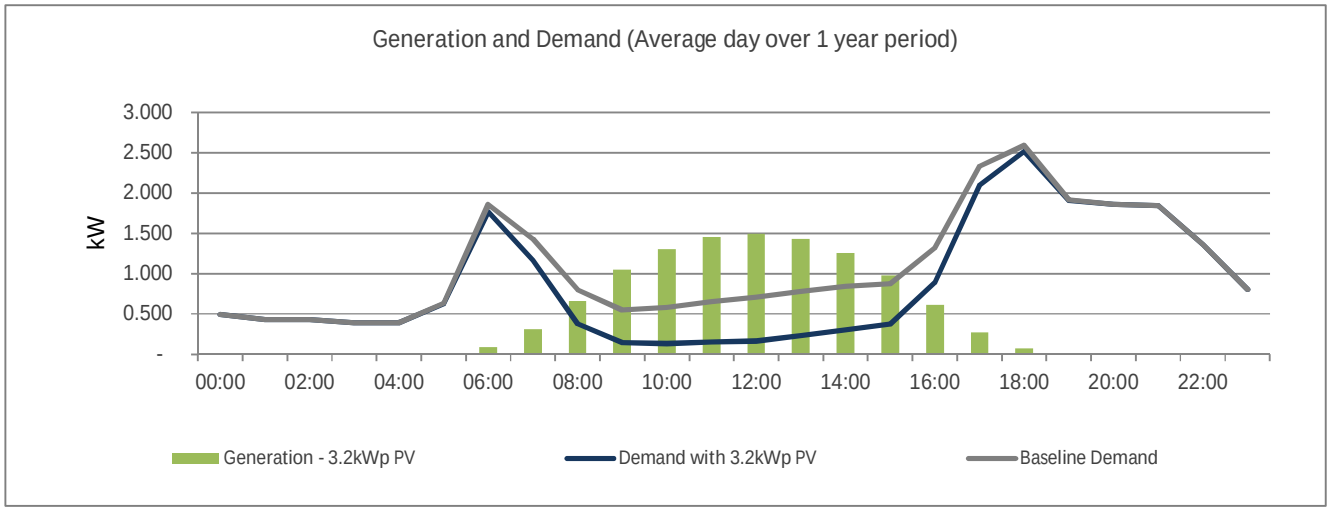
The battery modes programmed into the model included:

- Maximise solar consumption – store any solar energy in excess of base load in the battery, and discharge up to meet excess load until the minimum battery storage setting is reached.
- Overnight charging – charge the battery between 12 am and 6 am with grid power until the maximum overnight storage level is reached. This maximum overnight level was a variable parameter to ensure that the battery was not too full after the morning peak to store excess solar, resulting in excessive export of solar energy.

The throughput of the battery was calculated over the course of ten years, accounting for annual degradation of the solar panels of 0.5% per annum and battery storage capacity of 0.256 kWh per annum (assuming a linear decline from 6.4 kWh to 3.84 kWh / 60% capacity at the end of year 10).

The average annual production from the 3.2kW solar array was calculated as 4,025 kWh per annum (in year 1). Without storage the impact was that only 46% of the solar energy would be utilised in the home with the rest exported to the grid at the prevailing solar feed in tariff. The impact of the solar array on the average household load profile is shown in Figure 3.5 below, showing very little impact on peak demands in the morning and evening when the homeowner is home and typically operating the heat pumps.

Figure 3.5 : Impact of 3.2kWp solar system without storage on average load profile



A number of scenarios of minimum battery storage for back up supply in an outage, and overnight charging were modelled and are summarised in Table 3.2 below. For completeness these are compared against a scenario of solar PV without battery storage available.

Table 3.2 : Solar Energy Utilised and Battery Usage Under Different Operating Scenarios

Scenario	Solar used in home (kWh pa – year 1)		Solar Exported (kWh pa – year 1)		Energy Stored / Lost (kWh pa – year 1)		10 Year kWh	No. full cycles
PV only (no battery)	1,838 kWh	46%	2,187 kWh	54%	N/A	N/A	N/A	N/A
PV + battery (Max. Solar)	3,604 kWh	90%	420 kWh	10%	1,767 kWh	212 kWh	14,195 kWh	2,218
Max. solar – reserve 30% cap[6].	3,252 kWh	81%	773 kWh	19%	1,415 kWh	170 kWh	11,364 kWh	1,776
N/T charge to 25% capacity[7]	3,490 kWh	87%	535 kWh	13%	2,276 kWh	273 kWh	18,283 kWh	2,857
N/T charge to 50% capacity	3,254 kWh	81%	771 kWh	19%	2,689 kWh	323 kWh	21,606 kWh	3,376

[6] i.e. only discharge battery down to 30% level to reserve a minimum of 1.9 kWh of stored energy for a possible network outage
[7] i.e. charge the battery from the grid up to 25% capacity between 12 pm and 6 am, discharge from 6 am to reduce morning peak. Store excess solar energy and discharge once sun goes down to meet household load. No minimum backup storage level modelled.

This shows that for this particular household the combination of a 3.2kWp solar array and 6.4kWh Powerwall battery would nearly double the self-usage of available solar energy (versus a scenario of solar without a storage battery) if the battery is operated in maximise solar mode with no back up reserve capacity. The throughput of the battery over 10 years is about 78% of the operating limitation of 18 MWh, so the battery can be expected to meet its >60% performance guarantee over this period.

Figure 3.6 below shows the average impact of the solar plus battery combination in reducing the evening peak on average. It should be noted however that although the graph appears to show a considerable reduction in evening peak loads, it is an average over 365 days. The underlying model detail shows there are some days in June where the solar energy is very low due to cloud cover, resulting in a battery only charged to 15% and quickly consumed in the first hour of the evening peak.

Reserving 30% of the capacity for back up purposes reduces cycling of the battery but results in an additional 9% of the solar resource exported to the grid.

Figure 3.7 shows the impact of adding overnight charging to 25% capacity to reducing the morning peak on average. However, as shown in Table 3.2, even this modest additional partial charging cycle pushes the aggregate through put of the battery past the operating limitation of 18 MWh.

Figure 3.6 : Impact of 3.2kWp solar plus 6.4 kWh storage system in "Max. Solar Self Usage" mode on average load profile

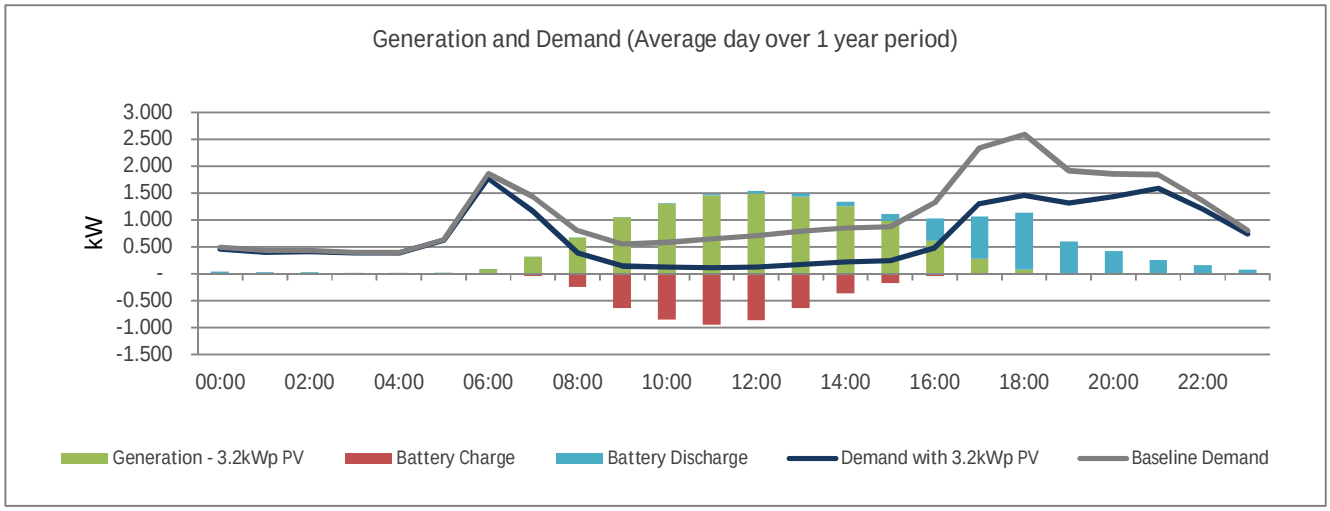
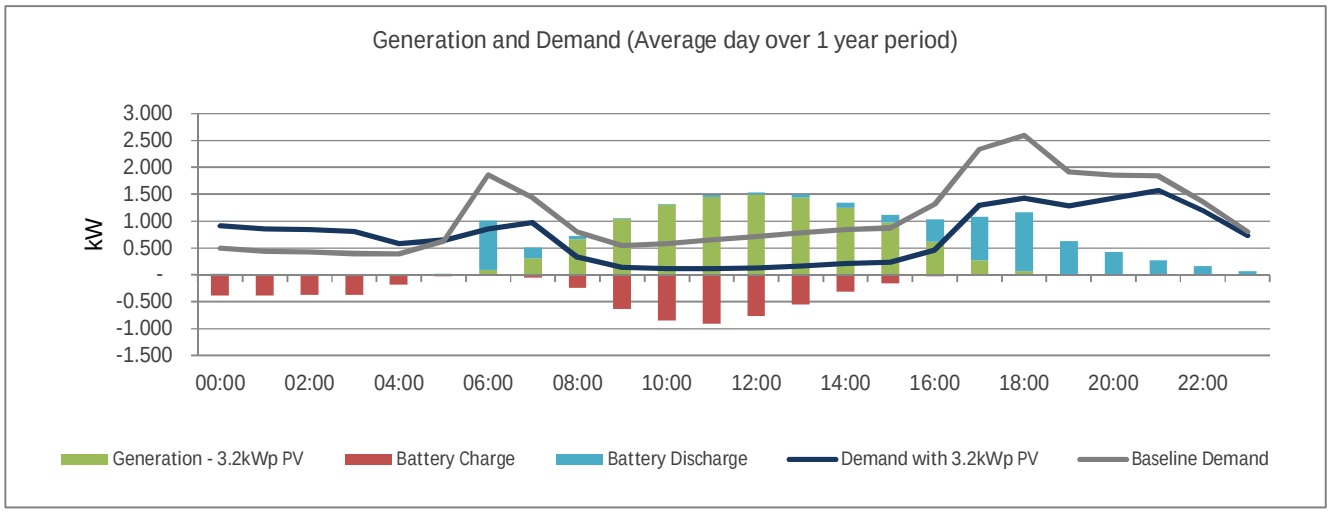


Figure 3.7 : Impact of 3.2kWp solar plus 6.4 kWh storage system in "25% overnight charge" mode on average load profile



3.3 Inverters

The lifespan of inverters is not impacted by the number of cycles of the batteries or solar panels that are connected to them. An inverter is a fairly well established electronic device for converting direct current electricity supply into alternating current supply, and vice versa.

The life span is typically effected by the quality of the components and manufacturing process, the environment that the inverter is located in (ambient temperature, salt air corrosion, ingress of insects etc.) and the adequacy of ongoing maintenance (typically routine such as ensuring cooling fans are cleared of dust etc.). The other factor that might affect the life of an inverter is the grid environment that it is connected to. For example how often it is exposed to grid conditions that are outside the norm (i.e. voltage and frequency fluctuations, and high levels of harmonics).

There is no correct answer on inverter life span, but in normal operating environments, a good quality inverter should comfortably last between 10 and 15 years.

4. Conclusions

4.1 Battery Life

4.1.1 Utility-Scale Energy Storage

Based on the expected functionality of the Tesla Powerpack 1 units on Vector's network (i.e. primarily for peak demand management), there is unlikely to be excessive duty cycles imposed on the batteries which would prematurely shorten their operational life / capacity. Likewise, the modelling showed that even if the batteries are utilised outside of peak demand months for other purposes on a regular basis they are not likely to exceed the throughput that would reduce the warranted performance, or shorten the warranty.

The primary driver of life for these batteries will therefore be driven by their warranted degraded performance. Once they have lost up to 30-50% of their storage capacity, their ability to meet Vector's functional requirements (i.e. the ability to contain load peaks at a specific site) will be significantly reduced, which will require either replacement of the battery, increasing battery capacity or investment in the network upgrade that the battery was helping to defer.

In situations where these utility batteries might be cycled a lot less due to being utilised for infrequent peak demand or back up purposes, the impact of calendar aging processes on storage capacity will be more predominant. The total amount of storage capacity decline for a lowly utilised Lithium battery over ten years from calendar aging processes is not well understood but Jacobs anticipate that capacity loss could still be significant, particularly as a commercially focused utility such as Vector would seek to maximise the value obtained from a utility scale battery to benefit its customers.

Based on this, the expected usable and economic life of a utility-scale Lithium ion battery (such as the Tesla Powerpack 1) would be 10 years.

4.1.2 Residential Energy Storage

Like the network batteries, the expected life of the Tesla Powerwall 1 units deployed to customers on Vector's network will be driven by their warranted degraded performance. This is potentially impacted by the operational mode and configuration they are used for:

- Solar self-consumption – total throughput over 10 years would be around 80% of the operational limits of the Tesla performance warranty, so expected to last 10 years at which point warranted performance would be at 60%.
- Solar self-consumption with 30% reserve for backup – this effectively reduces the storage capacity of the battery, resulting in greater loss of solar energy to the grid and total throughput to 63% of the 10 year operating limit.
- Solar self-consumption plus network management – this is not a mode currently being employed by Vector. Modelling of the additional charging of batteries up to 25% capacity overnight to manage a morning peak would result in total throughput over ten years in excess of the 10 year operating limit. Increasing overnight charging beyond this level would further exceed this operating limit, reducing the term of the performance warranty below 10 years.

However it should be noted that future in-home control devices with smart load and weather monitoring would likely only seek to charge the battery from the grid at certain times of the year (e.g. during winter months) to reduce the likelihood of exceeding operating limits and optimising solar storage.

It is unlikely that the operating scenarios envisaged will prematurely age the batteries to less than ten years. However at the end of ten years, the warranted capacity of the battery at 60% would mean that the home owner would likely to be exporting significant quantities of solar energy to the grid, so would be economically incentivised to replace the battery at this point.

As with utility-scale batteries, in situations where residential batteries are being utilised a lot less due to a greater level of capacity being reserved for infrequent back up purposes, the impact of calendar aging processes on storage capacity will be more predominant. Jacobs anticipate that storage capacity loss from a combination of calendar aging and lower cycling could still be significant.

Based on this, the expected usable and economic life of a residential-scale Lithium ion battery (such as the Tesla Powerwall 1) would be 10 years.

4.1.3 Inverters

There is no correct answer on inverter life span, but in normal operating environments, a good quality inverter such as the Dynapower PCS and SolarEdge inverters used by Vector that is regularly maintained should comfortably last between 10 and 15 years. However, it is likely that the inverters would be replaced at the same time as the batteries in the network and residential systems above, so a commercial lifespan of ten years would be considered appropriate.

5. Glossary of Terms

Term	Description
Charge rate (C-rate)	The C-rate specifies the speed at which a battery is charged or discharged. At 1C the battery is charged / discharged at a current that is on par with its Ah rating. At 2C the current is doubled and the charging time is halved, and at 0.5C the current is halved and charging time is doubled.
Depth of Discharge (DoD)	How much of the battery storage capacity is utilised in a discharge cycle. At 80% DoD, the battery is discharged until only 20% of capacity is remaining, at 100% DoD the whole range of storage is utilised. Utilising 100% DoD typically shortens battery life and is not recommended.
ESS / BESS	Energy Storage System / Battery Energy Storage System
Lithium Nickel Manganese Cobalt Oxide (NMC)	A class of Lithium ion batteries using a cathode based on this chemical compound and graphite based anode. Designed for high power applications such as EVs, e-scooters, e-bikes and home energy storage.
Lithium Nickel Cobalt Aluminium Oxide (NCA)	A class of Lithium ion batteries using a cathode based on this chemical compound and graphite based anode. High energy density and power discharge but shorter life – suitable for electric vehicles.
Power Conversion System (PCS) / Inverter	The bi-directional power conversion system, or inverter, which couples the battery system (DC power) with the power grid (AC power). The PCS can consist of one or multiple units, depending on the system size.
SoC / State of Charge	The current level of storage at which a battery is being held at.

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