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# Public Report 6

## Lithium Ion Battery Testing

ENGINEERING | STRATEGY | ANALYTICS | CONSTRUCTION



June 2019



# About ITP Renewables

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ITP Renewables (ITP) is a global leader in energy engineering, consulting and project management, with expertise spanning the breadth of renewable energy, storage, efficiency, system design and policy.

We work with our clients at the local level to provide a unique combination of experienced energy engineers, specialist strategic advisors and experts in economics, financial analysis and policy. Our experts have professional backgrounds in industry, academia and government.

Since opening our Canberra office in 2003 we have expanded into New South Wales, South Australia and New Zealand.

ITP are proud to be part of the international ITP Energised Group—one of the world's largest, most respected and experienced specialist engineering consultancies focussed on renewable energy, energy efficiency and climate change.

Established in the United Kingdom in 1981, the Group was among the first dedicated renewable energy consultancies. In addition to the UK it maintains a presence in Spain, Portugal, India, China, Argentina and Kenya, as well as our ITP offices in Australia and New Zealand.

Globally, the Group employs experts in all aspects of renewable energy, including photovoltaics (PV), solar thermal, marine, wind, hydro (micro to medium scale), hybridisation and biofuels.

## About this report

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Supported by an \$870,000 grant from the Australian Renewable Energy Agency under its Emerging Renewables Program, the Lithium Ion Battery Test Centre involves performance testing of conventional and emerging battery technologies. The aim of the testing is to independently verify battery performance (capacity fade and round-trip efficiency) against manufacturers' claims.

Six lithium-ion, one conventional lead-acid, and one advanced lead-acid battery packs were installed during Phase 1 of the trial. The trial was subsequently expanded to include an additional eight lithium-ion packs, a zinc bromide flow battery, and an Aquion "saltwater" battery bank.

This report describes testing results and general observations or issues encountered thus far with both the Phase 1 and 2 batteries.

This report, earlier reports (Reports 1 to 5), and live test results are published at [www.batterytestcentre.com.au](http://www.batterytestcentre.com.au)

# Report Control Record

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# List of Abbreviations

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<b>AC</b>	Alternating Current
<b>AIO</b>	All-in-one (referring to a battery unit which is combined with a battery inverter and PV inverter)
<b>ARENA</b>	Australian Renewable Energy Agency
<b>AUD</b>	Australian Dollar
<b>BESS</b>	Battery Energy Storage System
<b>BMS</b>	Battery Management System
<b>BOS</b>	Balance of System
<b>C (number)</b>	“C Rate” (charge rate), is a measure of the rate at which the battery is charged/discharged relative to its nominal capacity. Conversely, it can be thought of as the time over which the entire (nominal) battery capacity is charged/discharged (ie. a C10 rate indicates a charge/discharge rate at which a full charge/discharge takes 10 hours. A 2C rate indicates a charge/discharge rate at which a full charge/discharge takes only 0.5 hours)
<b>CAN (bus)</b>	Controller Area Network (a message-based communications protocol allowing microcontrollers and devices to communicate without a host computer)
<b>DC</b>	Direct Current
<b>DOD</b>	Depth of Discharge of a battery
<b>ELV</b>	Extra Low Voltage
<b>IR</b>	Infra-Red (region of the electromagnetic radiation spectrum used in thermal imaging)
<b>ITP</b>	IT Power (Australia) Pty Ltd, trading as ITP Renewables
<b>kW</b>	Kilowatt, unit of power
<b>kWh</b>	Kilowatt-hour, unit of energy (1 kW generated/used for 1 hour)
<b>kWp</b>	Kilowatt-peak, unit of power for PV panels tested at STC
<b>LFP</b>	Lithium Iron Phosphate (a common li-ion battery chemistry)
<b>Li-ion</b>	Lithium ion (referring to the variety of battery technologies in which lithium ions are intercalated at the anode/cathode)
<b>LMO</b>	Lithium Manganese Oxide (a common li-ion battery chemistry)
<b>MODBUS</b>	A serial communication protocol for transmitting information between electronic devices
<b>NMC</b>	Nickel Manganese Cobalt (a common li-ion battery chemistry)
<b>NCC</b>	National Construction Code
<b>PbA</b>	Lead Acid
<b>PMAC</b>	Permanent Magnet Alternating Current (a variety of Electric motor)
<b>PV</b>	Photovoltaic
<b>RE</b>	Renewable Energy
<b>SOC</b>	State of Charge of a battery
<b>UPS</b>	Uninterruptable Power Supply
<b>VRB</b>	Vanadium Redox Battery, a type of flow battery
<b>VRLA</b>	Valve Regulated Lead Acid

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# Executive Summary

ITP Renewables (ITP) is testing the performance of residential and commercial scale battery packs in a purpose-built, climate-controlled enclosure at the Canberra Institute of Technology. Eight batteries were installed initially, and a further ten installed in a second phase. This is the sixth public six-monthly report outlining the progress of the results, and includes a performance summary of the eight batteries in Phase 1, which concluded at the end of March 2019.

Overall, the Sony (Phase 1) and Pylontech (Phase 2) battery packs are demonstrating excellent capacity retention based on cycles completed to date. The Sony, Samsung, Tesla (Phase 1), BYD and Pylontech (Phase 2) battery packs have generally demonstrated high reliability, with minimal issues encountered throughout the testing period, while the Samsung and BYD battery packs in particular have demonstrated consistently high round-trip efficiency.

Round-trip efficiency between 85-95% has been observed for both the lead-acid and lithium-ion technologies, while linear extrapolation of capacity retention to date suggests that between 2,000 - 6,000 cycles can be delivered by properly functioning lithium-ion battery packs.

Unfortunately, many battery packs installed in the Test Centre have had to be removed or replaced prematurely owing to faults. These issues are symptomatic of new technology and a new market, and are expected to improve over time.

With respect to the market at large, price reductions have stalled in recent months owing to production constraints and high raw material prices. Nevertheless, most analysts predict that manufacturers will substitute away from high cost inputs, and that the large amount of production capacity currently under construction will put downward pressure on prices in the medium-term.

These price reductions are required for mass-market uptake, alongside improvements in products, interfaces, and technical support.



# 1. PROJECT BACKGROUND

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ITP Renewables (ITP) is testing the performance of residential and commercial scale battery packs in a purpose-built, climate-controlled enclosure at the Canberra Institute of Technology. The aim of the testing is to independently verify battery performance (capacity fade and round-trip efficiency) against manufacturers' claims.

Six lithium-ion, one conventional lead-acid, and one advanced lead-acid battery packs were installed during Phase 1 of the trial, which commenced in August 2016. The trial was subsequently expanded with a Phase 2 to include an additional eight lithium-ion packs, a zinc bromide flow battery, and an Aquion "saltwater" battery bank. Phase 2 commenced in July 2017.

This is the sixth public report outlining the progress and results of the trial thus far. A summary of the five previous reports is provided below. Complete reports are accessible on the Battery Test Centre website at [www.batterytestcentre.com.au/reports](http://www.batterytestcentre.com.au/reports).

## 1.1. Report 1 – September 2016

Report 1 was published in September 2016 and outlined the background of the project. The intended audience of the trial included the general public, research organisations, commercial entities, and government organisations who are considering investment in battery energy storage.

The report described conventional lead-acid and lithium-ion technologies, the process of battery selection, and the testing procedure. The implementation process from procurement through installation to commissioning was also described for the eight Phase 1 batteries listed in Table 1 below.

Table 1. Phase 1 Battery Packs

Product	Country of Origin	Chemistry	Total Installed Capacity (kWh)
<b>CALB CA100</b>	China	Lithium Iron Phosphate	10.24
<b>Ecoult UltraFlex</b>	USA	Lead Acid Carbon	14.8
<b>GNB Sonnenschein</b>	Germany	Lead Acid	15.84
<b>Kokam Storaxe</b>	Korea	Nickel Manganese Cobalt	8.3
<b>LG Chem RESU 1</b>	Korea	Nickel Manganese Cobalt	9.6
<b>Samsung AIO</b>	Korea	Nickel Manganese Cobalt	11.6
<b>Sony Fortelion</b>	Japan	Lithium Iron Phosphate	9.6
<b>Tesla Powerwall 1</b>	USA	Nickel Manganese Cobalt	6.4



At the completion of this first report testing had been underway for roughly three months. At that early stage of testing, data did not provide meaningful insight into long-term battery performance. As such, the report focussed on the lessons learned during the procurement, installation and commissioning phases and set out the structure in which results would be released in future reports.

## 1.2. Report 2 – March 2017

By the publication of Report 2 in March 2017, Phase 1 battery cycling had been ongoing since August 2016. Capacity and efficiency tests were conducted in each of the six months between September 2016 and February 2017.

It was reported that the Kokam Storaxe battery pack had suffered irreversible damage during that time, due to improper low-voltage protection provided by the built-in Battery Management System (BMS).

It was also reported that the CALB pack required a replacement cell and thereafter was functional, but still showing evidence of either a weak cell or poor battery management by the external BMS.

The main lessons learned included that capacity fade was evident for some of the battery packs under test, as expected. However, for others, long-term trends were not yet discernible owing to the inherent variability in individual capacity test results, attributed to imprecision in SOC estimation.

In terms of round-trip efficiency, despite the limited data, already it could be observed that lithium-ion out-performs the conventional lead-acid battery pack, despite lead-acid efficiency appearing higher than general expectations. Refer to the complete report for details.

## 1.3. Report 3 – November 2017

Report 3 was published in November 2017. It described the process of procuring and installing the 10 x Phase 2 battery packs listed in Table 2 below, and outlined preliminary testing results and general observations or issues encountered with the Phase 1 batteries.

Table 2. Phase 2 Battery Packs

Product	Country of Origin	Chemistry	Total Installed Capacity (kWh)
<b>Alpha ESS M48100</b>	China	Lithium Iron Phosphate	9.6
<b>Ampetus Super Lithium</b>	China	Lithium Iron Phosphate	9.0
<b>Aquion Aspen</b>	USA	Aqueous Hybrid Ion	17.6
<b>BYD B-Box</b>	China	Lithium Iron Phosphate	10.2
<b>GNB Lithium</b>	Germany	Nickel Manganese Cobalt	13.6
<b>LG Chem RESU HV</b>	Korea	Nickel Manganese Cobalt	9.8
<b>Pylontech US2000B</b>	China	Lithium Iron Phosphate	9.6
<b>Redflow ZCell</b>	USA	Zinc-Bromide Flow	10
<b>SimpliPhi PHI 3.4</b>	USA	Lithium Iron Phosphate	10.2
<b>Telsa Powerwall 2</b>	USA	Nickel Manganese Cobalt	13.5

In particular, Report 3 described how battery supply and installation issues continued to hamper the progress of the market as a whole, and that a number of manufacturers had either exited the market or substantially changing their product offerings. Of further note was that market leaders Tesla and LG Chem had aggressively cut wholesale pricing, and introduced second generation battery packs.

In terms of Phase 1 pack performance, one EcoUlt Cell failure and general SOC recalibration issues with the GNB lead-acid battery were reported.

Integration of battery packs with inverters continued to be problematic for battery products generally, with the communications interface being the most common challenge encountered. There was still no standardised approach to battery-inverter communications and the report described the expectation that installation and commissioning issues would remain common until communications interface protocols were standardised.

Results from Phase 1 battery pack testing indicated that capacity fade was continuing with nascent trends discernible, and that lithium-ion batteries continued to demonstrate higher efficiency.

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## 1.4. Report 4 – March 2018

Report 4 was published in March 2018. It outlined the preliminary testing results and general issues encountered with both Phase 1 and Phase 2 batteries. This report provided particular detail on the ongoing commissioning challenges with the Tesla Powerwall 2 and Aquion saltwater battery packs, the replacement of the malfunctioning Redflow and Ecoults packs, and upgrades to the Ampetuss pack.

Ongoing erratic behaviour of the CALB lithium-ion and GNB lead-acid battery packs were observed, but generally higher round-trip efficiency for lithium-ion technology over conventional lead-acid and zinc-bromide technologies continued to be demonstrated.

Capacity test results showed characteristic capacity fade for all Phase 1 battery packs (1,000+ cycles completed) still in operation. Significant variability between packs was observed, and the potential role of temperature effects in contributing to these results was discussed. Phase 2 battery packs (500+ cycles completed) showed similar initial trends and variability in capacity fade.

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## 1.5. Report 5 – September 2018

With testing of both Phase 1 and 2 batteries well under way by the time Report 5 was published in September 2018, capacity fade trends were well-established with significant variation in performance between packs becoming apparent. DC round-trip efficiency varied less between packs, with average values of 85-95%.

Although several batteries continued to perform well, the report described performance and reliability issues with some battery packs. In most cases the issues were attributed to inadequate product development and/or a lack of understanding on the part of local salespeople/technicians in regard to product integration (i.e. with inverters or control systems).

In particular, the report described the replacement of the Redflow ZCell and SimpliPhi PHI 3.4 packs, ongoing challenges controlling the Tesla Powerwall 2, the insolvency of Aquion and Ampetuss, and some operational issues with the CALB, LG Chem, EcoUlt and GNB lead-acid battery packs.

## 2. Battery Operation Overview

Figure 1 gives an overview of the issues experienced by battery packs installed in the trial. Note that only issues inhibiting all cycling are displayed, including commissioning difficulties, failures requiring replacement, and removal of batteries.

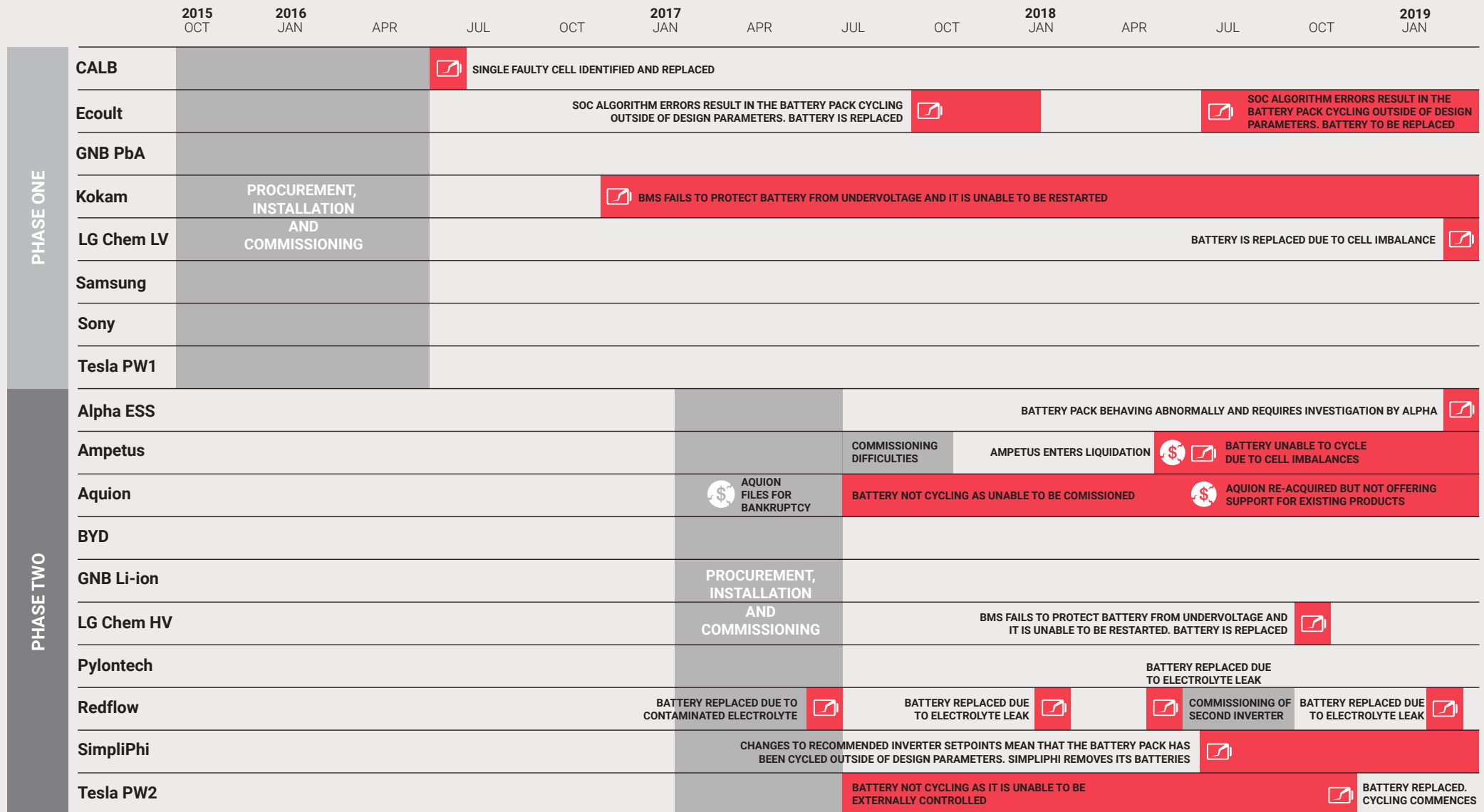


Figure 1: Overview of battery operation

# 3. PHASE 1 SUMMARY

This section provides a summary of the performance for each of the Phase 1 batteries tested. It includes information provided in previous reports, but also describes any developments in the past six months.

## 3.1. General Performance

### CALB CA100

#### Operational Issues

The CALB capacity test cycles continue to show that the external BMS is cutting off charge cycles before the maximum SOC setpoint is reached. Pack voltage appears to reach its upper limit while the SOC estimated by the external BMS remains low. The CALB pack still cycles acceptably, but the issues create significant variability between discharge cycles and it is generally unclear how much of the pack's actual residual capacity has been discharged in any one cycle.

#### Capacity Fade

The operational challenges associated with the CALB pack compromise the reliability of individual capacity tests. Nevertheless, it is informative to view the degradation in energy discharged each "cycle", where a cycle is defined as a continuous discharge of more than 40 minutes duration (Figure 2). Note that while no x-axis is shown, cycles are ordered chronologically.

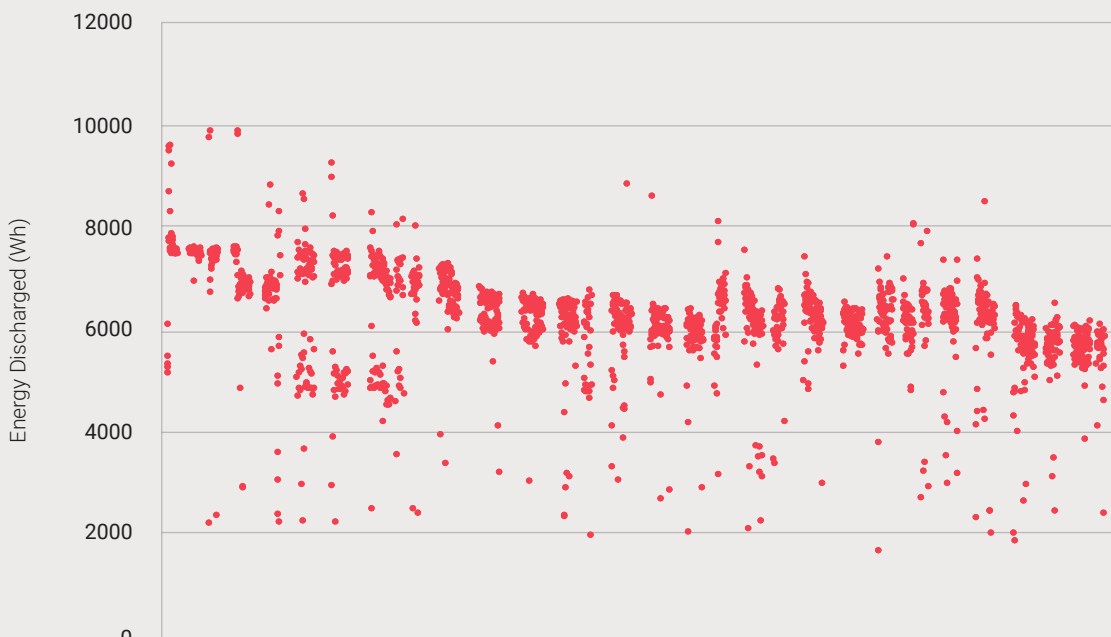


Figure 2. Energy discharged per "cycle" by the CALB battery pack

Figure 2 suggests initial usable capacity of around 7,500 W and current usable capacity of around 5,700 W; ~76% of its initial value after ~1,500 equivalent 100% DOD cycles. If this average rate of degradation continues, a 60% SOH can be expected after ~2,500 equivalent full cycles, though the data suggests some non-linearity which may invalidate this extrapolation.

**Round-Trip Efficiency**

Analysis of the monthly energy into and out of the CALB battery pack suggests an average round-trip efficiency of 90%, with no discernible trend over time. Individual monthly efficiency is depicted in Figure 3.

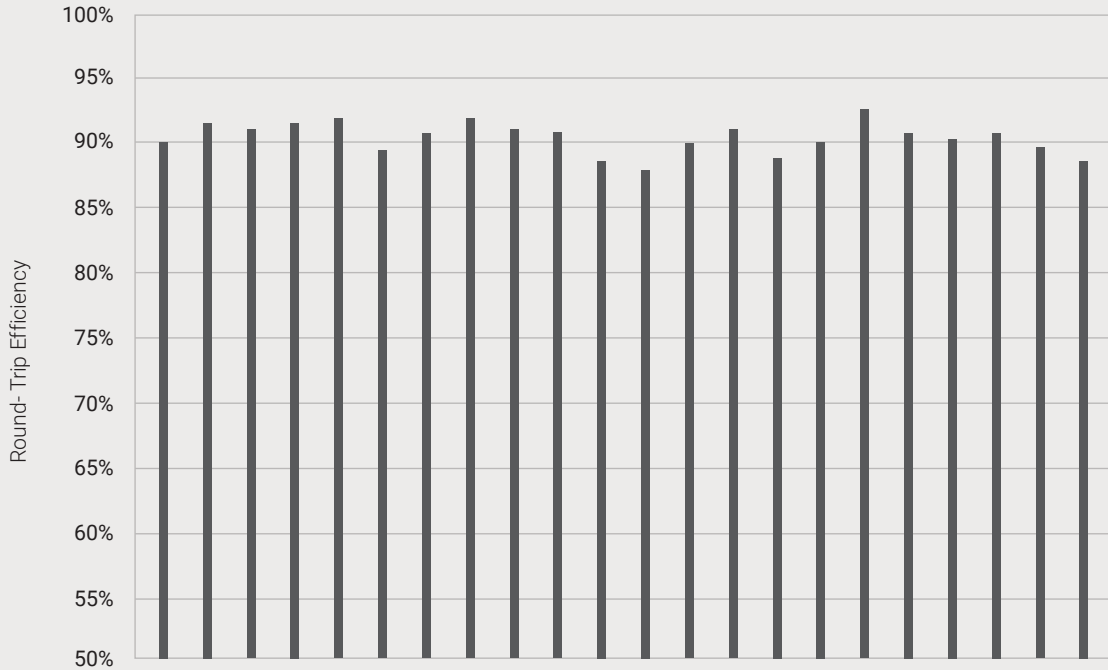


Figure 3. Round-trip efficiency of CALB battery pack by month

## EcoUlt UltraFlex

In September 2017 EcoUlt removed some underperforming battery units from the Test Centre for analysis and identified that the BMS was allowing some cells to stray beyond their minimum SOC limits for extended periods, accelerating capacity fade. EcoUlt updated their SOC algorithm and replaced all batteries under warranty. Cycling of the new batteries commenced in January 2018.

From May onwards, the new pack was unexpectedly low on capacity, failing to cycle down to the target 30% SOC due to low voltage cut-off. EcoUlt attributed this loss of capacity to over-discharging caused by incorrect SOC estimation, and believe that the effect has been exacerbated due to the unusual cycling regime employed at the Battery Test Centre. EcoUlt have subsequently updated the algorithm and conducted maintenance cycles in an effort to restore as much lost capacity as possible. Despite this, EcoUlt has communicated to ITP that the battery capacity has been permanently damaged and that they will be replacing all batteries.



# GNB Sonnenschein Lead-Acid

## Operational Issues

The Sonnenschein lead-acid batteries have demonstrated reduced capacity and ongoing SOC estimation issues throughout the trial. SOC estimation (conducted by the SMA inverter) frequently adjusts downwards (to ~20%) during discharge, triggering low-SOC protection modes in the inverter that prevent further discharge. The opposite is true during charging, where the SOC rapidly adjusts upwards.

Due to the poor charge acceptance of conventional lead-acid batteries in the absorption charging phase, and the low allowable DOD, the GNB lead-acid battery pack has completed only ~480 equivalent full cycles over the course of the trial. Moreover, these cycles are inconsistent owing to the SOC estimation issues described above.

## Round-Trip Efficiency

Analysis of the monthly energy into and out of the Sonnenschein lead-acid battery pack suggests an average round-trip efficiency of 87%, with no discernible trend over time. Individual monthly efficiency is depicted in Figure 4.

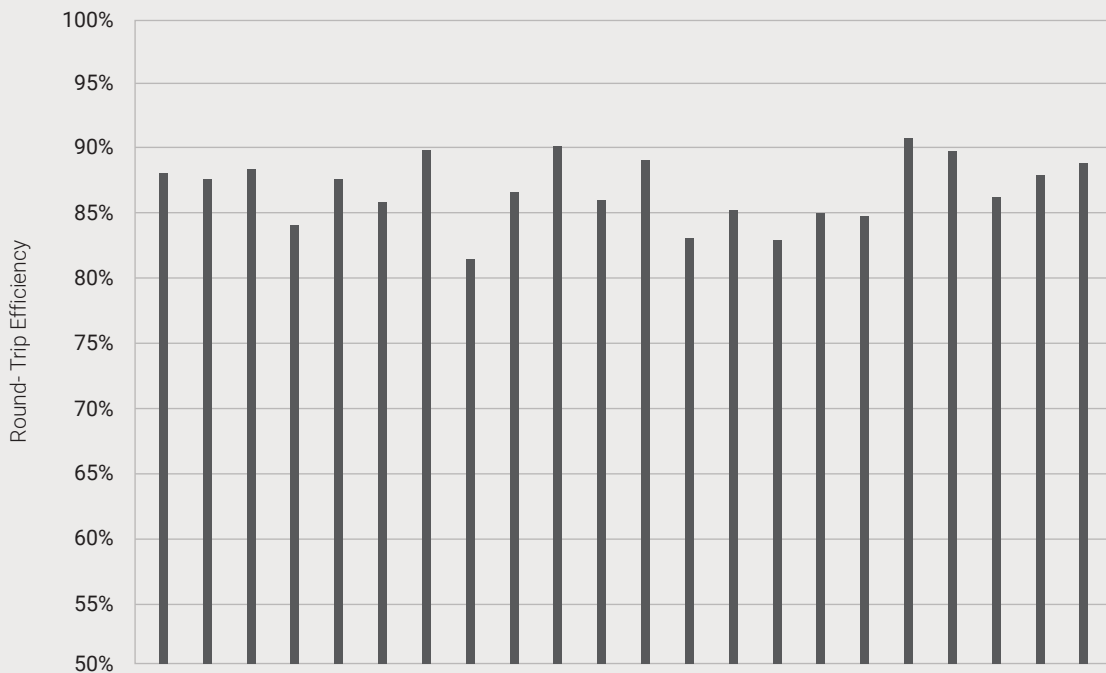


Figure 4. Round-trip efficiency of Sonnenschein lead-acid battery pack by month

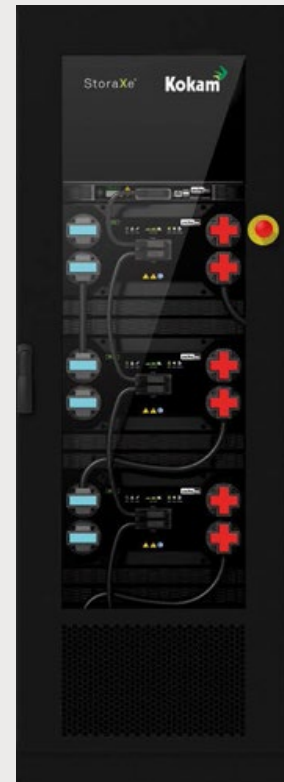
## Kokam StoraXe

In early November 2016, the StoraXe battery pack containing the Kokam battery cells and ADS-TEC BMS produced an error code indicating that the battery pack had entered a low voltage protection mode, whereby contactors on the BMS open to protect the battery from further discharge.

ITP inspected the pack and found a pack voltage of 44.6V. With no ability to manually close the contactors and allow the inverter to charge the battery pack, the manufacturer advised that the battery pack would have to be charged manually using a constant 50VDC voltage source (max 20A current), until the charge current decayed to 5A. ITP was also advised that the cells would not discharge further, and the system could be left online to allow for remote diagnostics by the manufacturer.

When ITP arrived to site to manually charge the pack the following week, the pack voltage had fallen from 44.6V to 6.8V. It appears that during the intervening period, re-energising the BMS drained the remaining energy from the cells, causing them to over-discharge.

Once lithium-ion cells fall below some minimum voltage they cannot be recharged owing to increased risk of a short-circuit across battery electrodes. Due to this early failure, insufficient cycles were completed to provide meaningful results.



## LG Chem RESU 1

### Operational Issues

Throughout the trial the LG Chem RESU battery has exhibited temperature de-rating in hotter conditions. This was attributed to the high charge/discharge rates used in the trial, coupled with the battery pack's high density and lack of active cooling mechanisms (i.e. fans, coolant loops etc.).

Throughout the summer temperature regime of 2018/19, the LG Chem RESU shut down multiple times, with the BMS reporting both over-temperature and cell imbalance faults. The periodic shutdowns interrupted cycling and in February 2019, LG Chem communicated that the battery pack should be returned to the service centre due to the cell imbalance.

The pack has since been replaced by LG Chem, albeit with a newer model (LG Chem's second generation RESU10) as the original LG Chem RESU is no longer in production. The replacement battery is yet to be installed.

### Capacity Fade

While the original battery pack has now been removed from the test centre, it is informative to view the degradation in energy discharged each cycle over the lifetime of the testing (Figure 5), which shows initial usable capacity of ~7,700 Wh fading to ~6,000 Wh (78%) after 1,183 cycles (the time of the cell imbalance fault).





Figure 5. Energy discharged per cycle by the LG Chem RESU 1 battery pack

The operational issues are apparent in the data, with the temperature de-rating restricting the energy discharged per cycle in the hotter months, and the cell imbalance restricting it in the latter months.

### Round-Trip Efficiency

Analysis of the monthly energy into and out of the LG Chem RESU 1 battery pack suggests an average round-trip efficiency of 92%, with no discernible trend over time. Individual monthly efficiency is depicted in Figure 6.

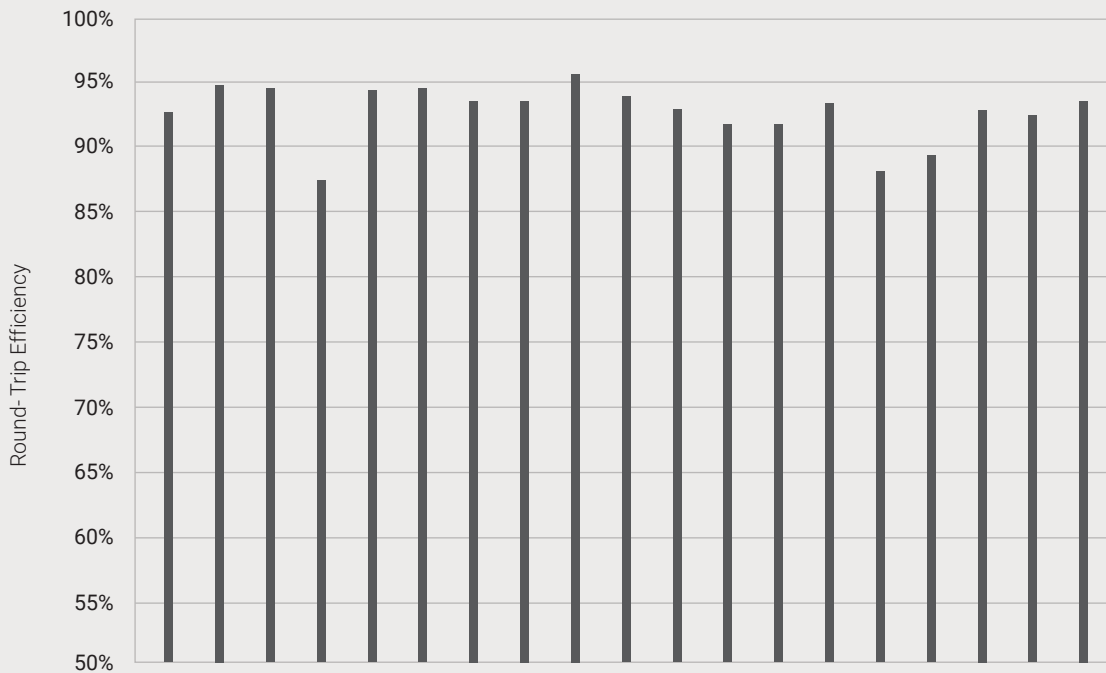


Figure 6. Round-trip efficiency of LG Chem RESU 1 battery pack by month



# Samsung AI010.8

## Operational Issues

The Samsung AI010.8 has completed a high number of cycles due to high reliability. No operational issues have been experienced during testing.

## Capacity Fade

The average energy discharged each cycle (Figure 7) can be seen to have generally decreased over time, with greater variance between cycles also evident. The data suggests initial usable capacity of ~9,500 Wh and current usable capacity of ~8,250 Wh (87%) after 1,808 cycles. If this average rate of degradation continues, a 65% SOH can be expected after ~4,810 equivalent full cycles and a 60% SOH can be expected after ~5,500 equivalent full cycles. However, the data suggests some non-linearity which may invalidate this extrapolation.

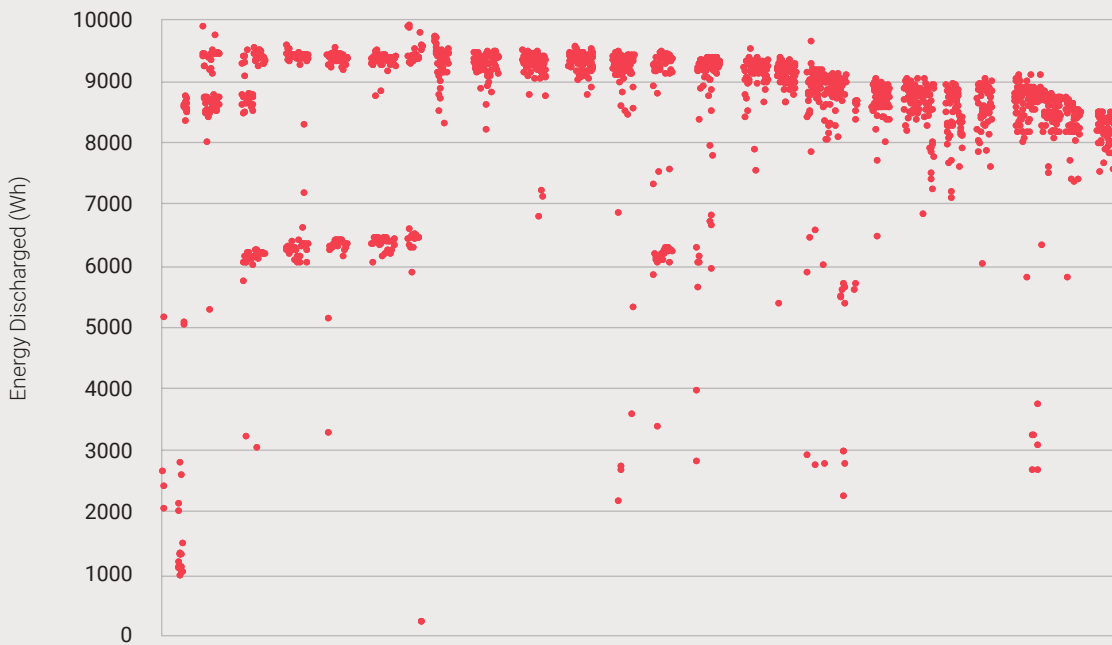


Figure 7. Energy discharged per cycle by the Samsung battery pack

## Round-Trip Efficiency

Analysis of the monthly energy into and out of the Samsung battery pack suggests an average round-trip efficiency of 95%, with no discernible trend over time. Individual monthly efficiency is depicted in Figure 8.

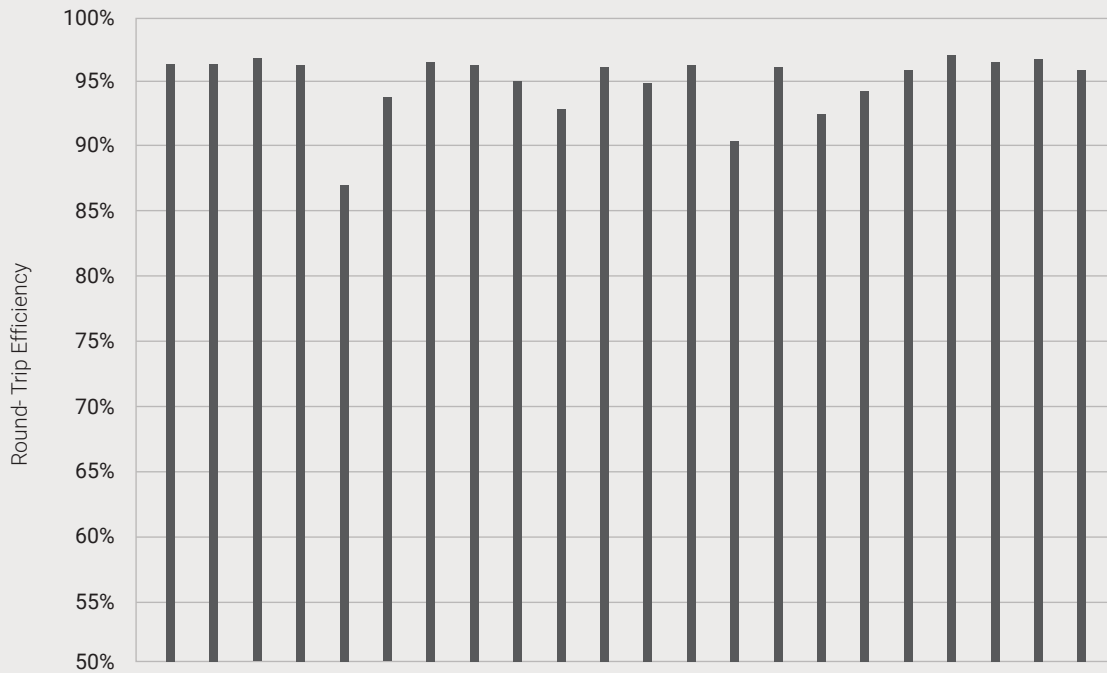


Figure 8. Round-trip efficiency of Samsung battery pack by month

## Sony Fortelion

### Operational Issues

The Sony pack has completed a high number of cycles due to high reliability. No operational issues have been experienced during testing.

### Capacity Fade

The average energy discharged each cycle (Figure 9) can be seen to have generally decreased over time, with greater variance between cycles also evident. The data suggests initial usable capacity of ~7,500 Wh and current usable capacity of ~6,500 Wh (87%) after ~1,790 cycles. If this average rate of degradation continues, a 60% SOH can be expected after ~5,380 equivalent full cycles, though the data suggests some slight non-linearity which may invalidate this extrapolation.



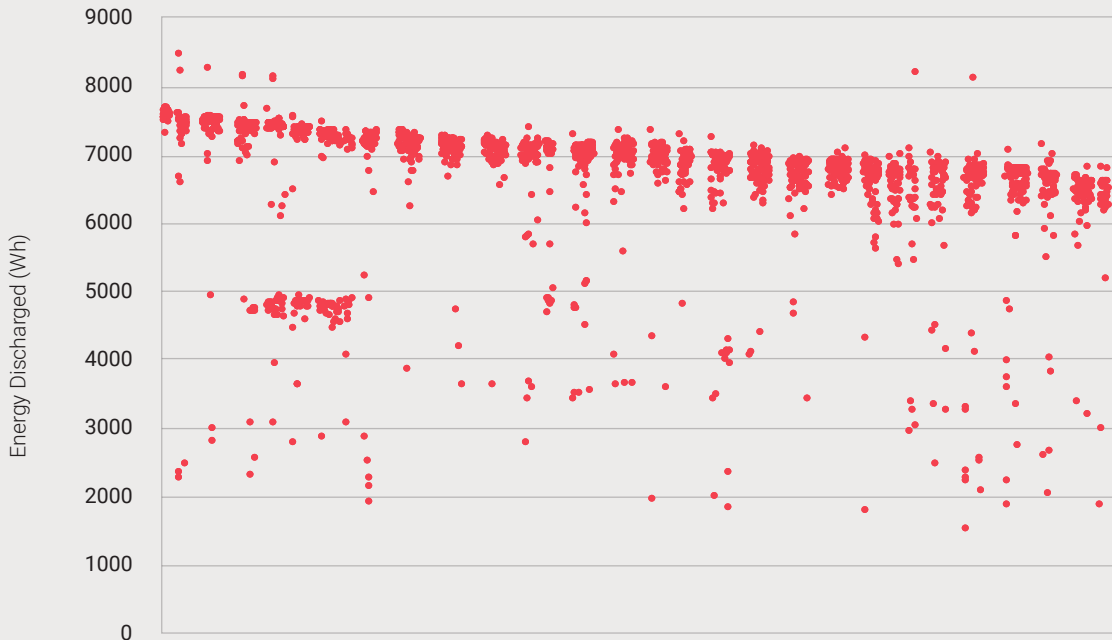


Figure 9. Energy discharged per cycle by the Sony battery pack

### Round-Trip Efficiency

Analysis of the monthly energy into and out of the Sony battery pack suggests an average round-trip efficiency of 87%, with a slight downward trend over time. Individual monthly efficiency is depicted in Figure 10.

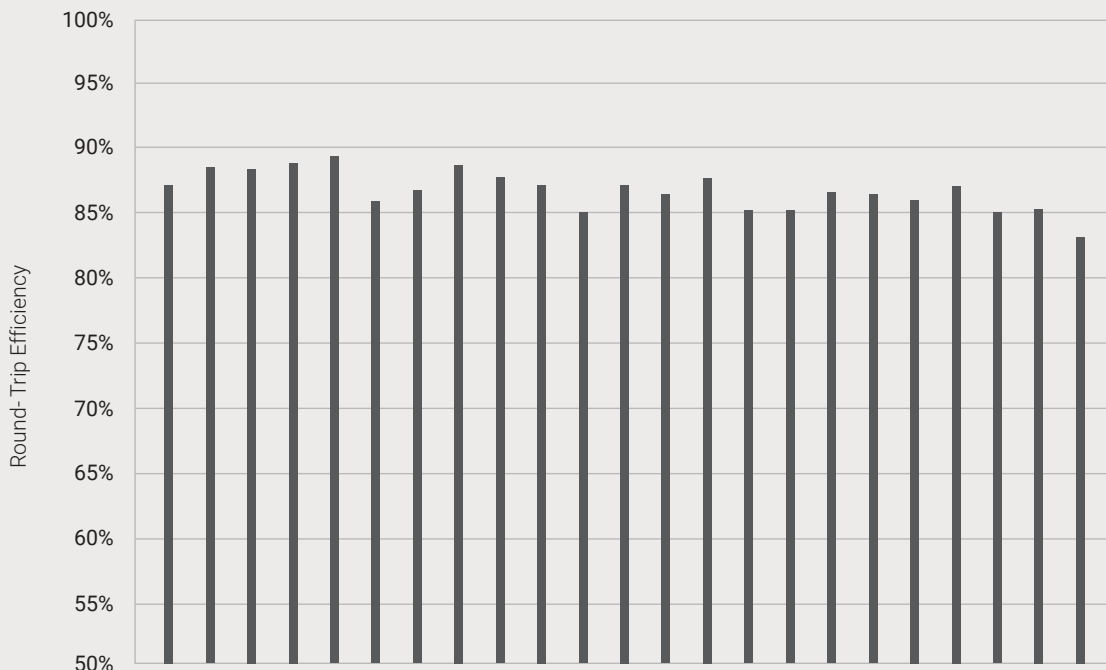


Figure 10. Round-trip efficiency of Sony battery pack by month

# Tesla Powerwall 1

## Operational Issues

At the beginning of the trial (Phase 1), Tesla's Powerwall 1 was only compatible with a Solar Edge inverter. All other Phase 1 packs, excluding the Samsung, were compatible with the market-leading SMA Sunny Island inverter, which the control system had been designed to control. While ITP was able to control the Solar Edge/Powerwall system via an online portal, the rate of charge and discharge was not able to be controlled. Hence, the Powerwall 1 is charging and discharging at its maximum rate (~2hr full charge/discharge) while other batteries charge and discharge over ~3hrs. This means the Powerwall has less time to dissipate heat built up during charge/discharge, which may be causing higher battery cell temperatures leading to accelerated capacity fade. Efficiency may also be affected, as the Tesla's cooling system will be more heavily loaded. ITP is unable to confirm these hypotheses as the Tesla system allows for no data access.

Nevertheless, the Tesla Powerwall 1 has proven highly reliable and, in conjunction with the high allowable DOD, this has allowed the battery pack to have completed the high number of cycles. No operational issues have been experienced during testing.

## Capacity Fade

The average energy discharged each cycle (Figure 11) can be seen to have generally decreased over time. The data suggests initial usable capacity of ~5,600 Wh and current usable capacity of ~4,050 Wh (72%) after ~ 1,820 cycles. If this average rate of degradation continues, a 60% SOH can be expected after ~2,631 equivalent full cycles, though the data suggests some non-linearity which may invalidate this extrapolation.

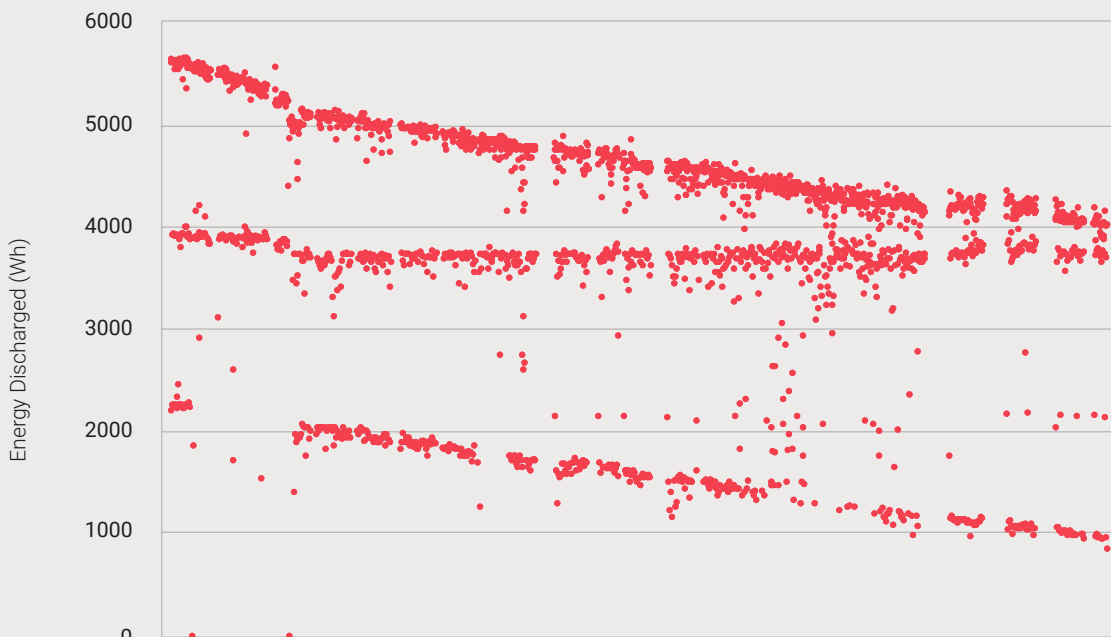


Figure 11. Energy discharged per cycle by the Tesla Powerwall 1 battery pack

### Round-Trip Efficiency

Analysis of the monthly energy into and out of the Tesla Powerwall 1 battery pack suggests an average round-trip efficiency of 87%. Individual monthly efficiency is depicted in Figure 12.

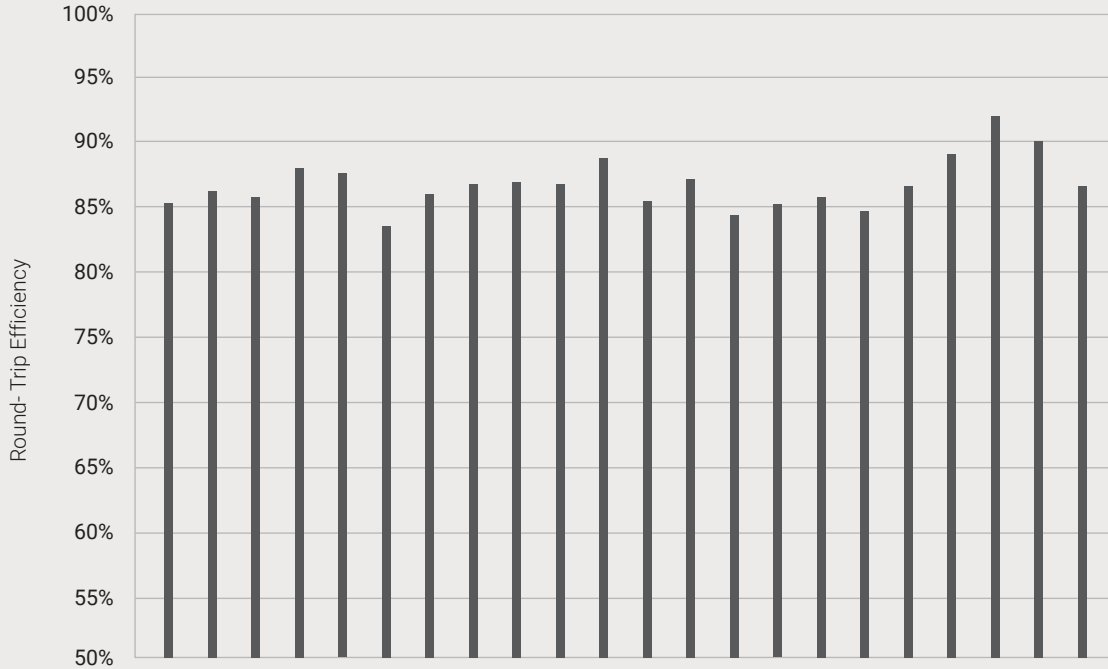


Figure 12. Round-trip efficiency of Sony battery pack by month

## 3.2. Capacity Test Performance

Testing the capacity of a battery cell involves discharging the cell between an upper and lower voltage limit at a fixed current, and at a given ambient temperature. Because ITP is conducting pack-level testing, the upper and lower voltage limits are not accessible, and hence the maximum and minimum SOC must be used as a proxy. The result is that the precision of a single capacity test depends on the precision of the SOC estimation, conducted either by the battery inverter/charger or the in-built BMS.

Throughout the trial, ITP has observed imprecision in SOC estimation resulting in significant variability in the energy discharged each cycle. As such, this report provides data and analysis based on both the energy discharged during the monthly capacity tests (below), as well as on the energy discharged each “cycle” over the course of the trial (see Section 3.1 above, where a cycle is defined as a continuous discharge exceeding 40 minutes in length). Both data sets should be considered before drawing conclusions.

Figure 13 shows the estimated state of health (SOH) against cycles completed for each Phase 1 battery pack still cycling reliably. In this case, SOH is estimated by dividing the energy delivered at each capacity test by the energy delivered in the first capacity test.

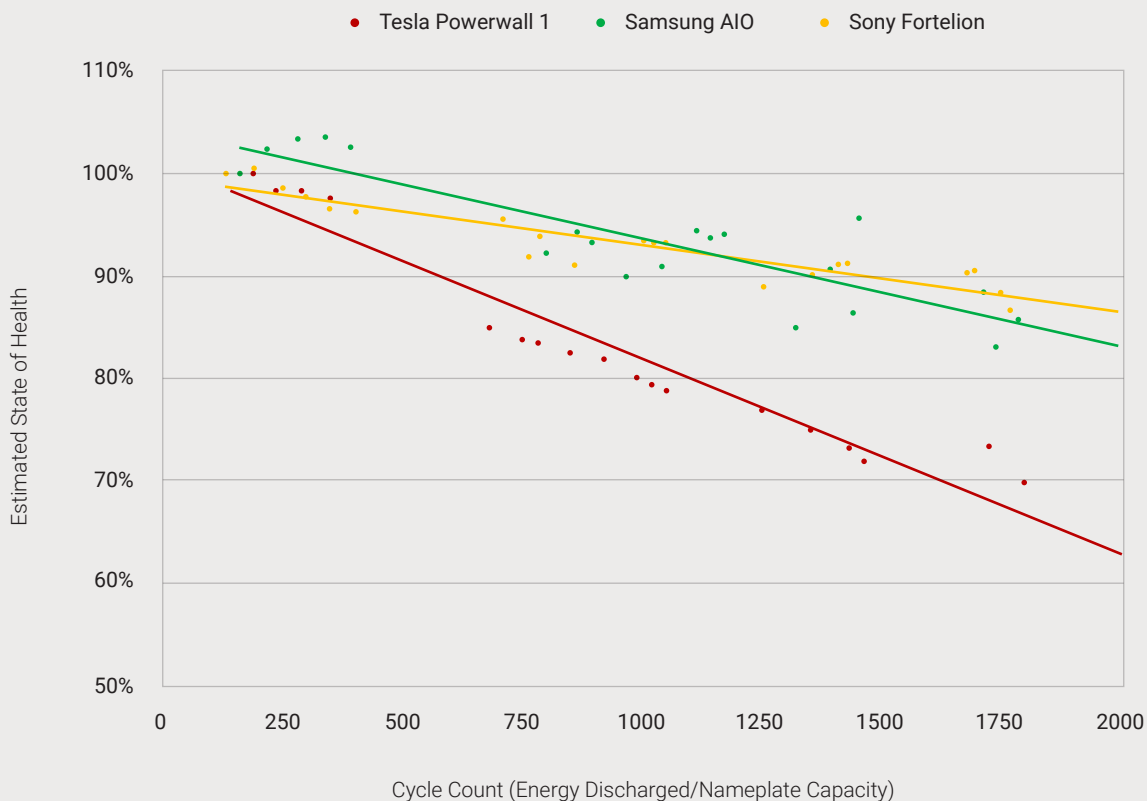


Figure 13. Capacity fade of Phase 1 battery packs based on monthly capacity tests

It should be noted that Figure 13 includes lines-of-best-fit that are determined by simple linear regression. While a linear regression provides good fit to the capacity test data collected thus far, extrapolating these trends into the future may not be appropriate.

## Samsung AI010.8

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The most recent capacity test suggests a SOH of 86%, in accordance with the 87% SOH estimated from cycle data (described in Section 3.1).

Based on the linear regression between estimated SOH and cycles completed (Figure 13), the Samsung AIO pack is on track for 65% SOH at 3,720 cycles and 60% SOH at 4,190 cycles. As above, the cycle data suggests some non-linearity which may invalidate this extrapolation.



## Sony Fortelion

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The most recent capacity test suggests a SOH of 87%, in accordance with the 87% SOH estimated from cycle data (described in Section 3.1).

Based on a linear regression between estimated SOH and cycles completed (Figure 13), the Sony Fortelion pack is on track for 60% SOH at 6,070 cycles. As above, a linear extrapolation may not be appropriate.



## Tesla Powerwall 1

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The most recent capacity test suggests a SOH of 70%, in accordance with the 72% SOH estimated from cycle data (described in Section 3.1).

Based on a linear regression between estimated SOH and cycle count (Figure 13), the Tesla Powerwall 1 is on track for 60% SOH at 2,150 cycles. As above, the cycle data suggests some non-linearity which may invalidate this extrapolation.



## 3.3. Discussion

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### CALB CA100

CALB product information describes a cell lifetime of 2,000 x 80% DOD cycles and 0.3C. Despite the operational issues apparent, the CALB cells appear to be outperforming this specification.

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### EcoUlt UltraFlex

Owing to the issues described in Section 3.1, it is difficult to draw any conclusions on the EcoUlt technology.

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### GNB Sonnenschein Lead-Acid

It is expected that the operational issues described in Section 3.1 are the result of sulfation. To avoid sulfation, lead-acid batteries should be fully charged regularly (and periodically equalised). However, owing to the poor charge acceptance of lead-acid technology at high SOC, reaching full charge can take many hours, making it unsuited to accelerated testing such as that employed in the Battery Test Centre.

In solar-storage applications, these limitations are typically managed by over-sizing the battery bank (to ensure shallow cycles only) and solar system (to ensure full charging on poor solar days), but this adds capital cost and increases the fraction of solar energy that must be curtailed or exported.

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### Kokam StoraXe

Owing to the issues described in Section 3.1, minimal cycles were ever completed by the Kokam battery pack and it is therefore difficult to draw any conclusions on the technology.

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### LG Chem RESU 1

The rate of capacity fade demonstrated by both cycling and capacity tests is considerably faster than that described in LG Chem RESU datasheets and user manuals available at the time. These documents specified a cycle life (to 60% SOH) of 6,000 x 90% DOD cycles (5,400 x 100% DOD cycles), and 10,000 x 80% DOD cycles (8,000 x 100% DOD cycles), but the warranty contains no capacity retention guarantee.

It is unclear how much of the accelerated degradation can be attributed to the cell imbalance, but ITP expects the primary cause of the accelerated capacity fade to be the high pack temperatures brought on by the combination of the pack's high energy density and lack of active cooling, and the aggressive cycling regime employed by the trial. The same pack could be expected to perform better in real-world applications with lower-duty cycling.





### Samsung AIO10.8

Samsung AIO product information includes a chart depicting capacity retention against time (Figure 14). It can be seen that >80% capacity retention is expected after 10 years, but the conditions of these estimates are not described.

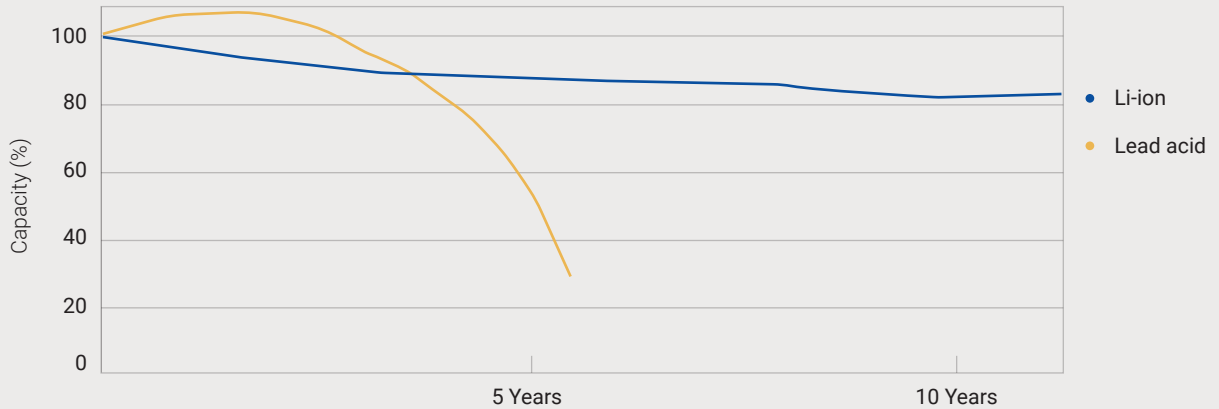


Figure 14. Samsung SDI AIO Product Information

Samsung's warranty for the AIO unit is described in its User Manual and includes a performance guarantee that 65% of the initial capacity will remain after 10 years or 6,000 x 90% DOD cycles (equivalent to 5,400 x 100% DOD cycles), provided that usage complies with "the Operating Conditions under specification". No Operating Conditions are clearly laid out in the document, though an operating temperature range of -10°-40°C is described under General Data in the Technical Specifications.

Linear extrapolation of capacity test and cycle data to date suggests that these specifications will not quite be met. However, a linear extrapolation may not be appropriate. While the data suggests the rate of capacity fade is accelerating, Samsung SDI's ESS brochure suggests capacity fade should decelerate (Figure 15).

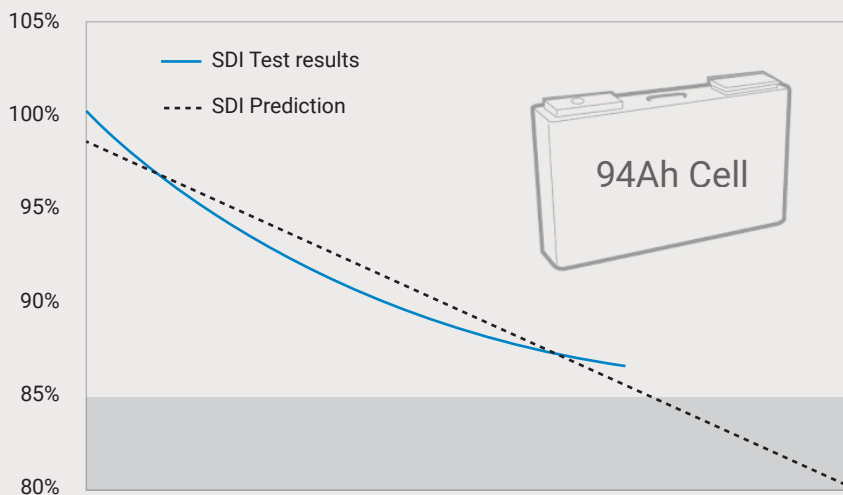


Figure 15. Samsung SDI ESS product information

Whatever the case, the capacity retention, efficiency and reliability of the Samsung SDI battery pack is among the best in the Battery Test Centre.



### Sony Fortelion

Sony warrants 60% capacity retention after 7 years, provided the ambient temperature remains between 0-35°C at all times, and that the battery is cycled no more than once per day (ie. a maximum of 2,557 x 100% DOD cycles). The performance to date in both cycling and capacity tests suggests that the battery pack will easily exceed these conditions, despite ambient temperatures in the test centre peaking at 36°C.

However, Sony product information includes a chart showing capacity retention against cycles (Figure 16). The chart shows an expected SOH of ~90% after 2,000 x 100% DOD cycles at 1 cycle per day and 23°C ambient temperature. The capacity retention to date does not meet this specification, though the conditions of this trial are harsher than the conditions described in the product information, with higher temperatures, temperature swings, and accelerated cycling (3 per day).

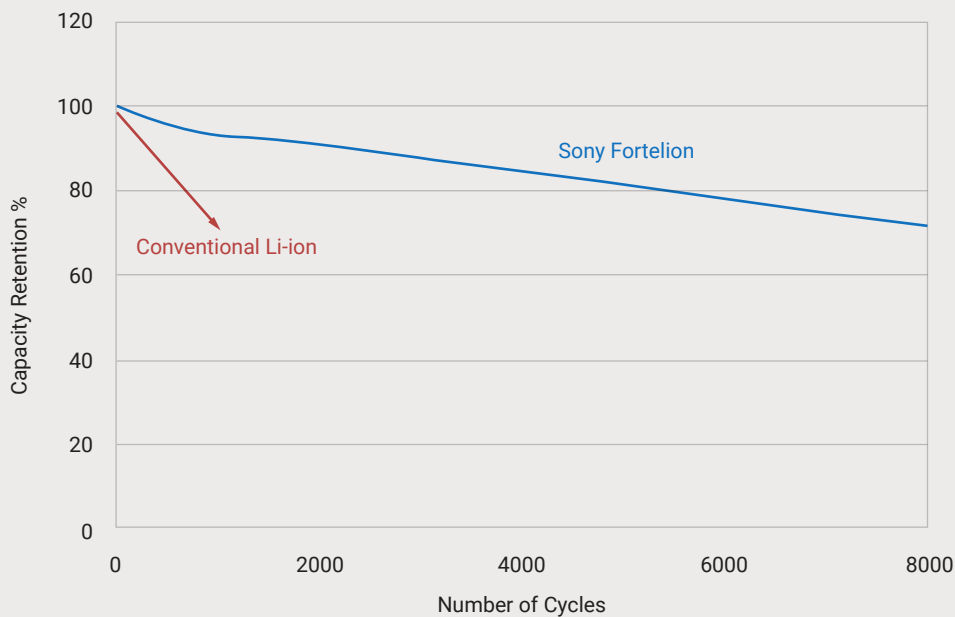


Figure 16. Sony ESS Product Information

Nevertheless, the capacity retention and reliability of the Sony battery pack is the best in the Battery Test Centre, and is consistent with the product's premium pricing.



### Tesla Powerwall 1

Tesla's warranty statement at the time of installation includes a capacity retention guarantee for:

- 85% SOH at 4MWh of accumulated discharge (625 x 100% DOD cycles)
- 72% SOH at 9MWh of accumulated discharge (1,406 x 100% DOD cycles)
- 60% SOH at 18MWh of accumulated discharge (2,813 x 100% DOD cycles)

The cycle and capacity test data collected to date suggest the Powerwall 1's capacity retention is in line with the guaranteed performance prescribed in its warranty. While a linear extrapolation of the capacity fade to date suggests the pack will not satisfy its performance guarantee for 60% SOH, it is notable that the guaranteed performance suggests that the rate of capacity fade should now slow.

When comparing between battery packs, it should be kept in mind that the Powerwall 1 is charging/discharging at a higher rate (~C/2) than the other batteries under test (~C/3). All else equal, this would increase the cell temperature and increase the rate of capacity fade. In practice, the Powerwall 1 includes a thermal management system that reticulates heat transfer fluid through the battery pack to manage battery cell temperature. Unfortunately, ITP is unable to assess the effectiveness of this system owing to the limited data made available by the battery pack. In terms of operation, the pack has consistently demonstrated high reliability.

## 4. PHASE 2 UPDATE

This section provides a performance update for each of the Phase 2 batteries tested. It focuses on developments in the past six months.

### 4.1. General Performance

Some battery packs have demonstrated challenges that affect cycling and capacity testing. These issues are described below.

#### Alpha ESS M48100

##### Operational Issues

During the 2018/19 summer temperature regime, ITP observed that the Alpha battery pack was constraining the charge and discharge rate below the rate requested by the test centre's control system. Alpha has stated that this behaviour is abnormal, and collected the battery pack for analysis in March 2019.

ITP understands that the battery pack being tested in the trial is no longer a current model.

##### Capacity Fade

The energy discharged per cycle is shown in Figure 17. The increased variance in energy discharged for some months (hotter) is apparent in the data.

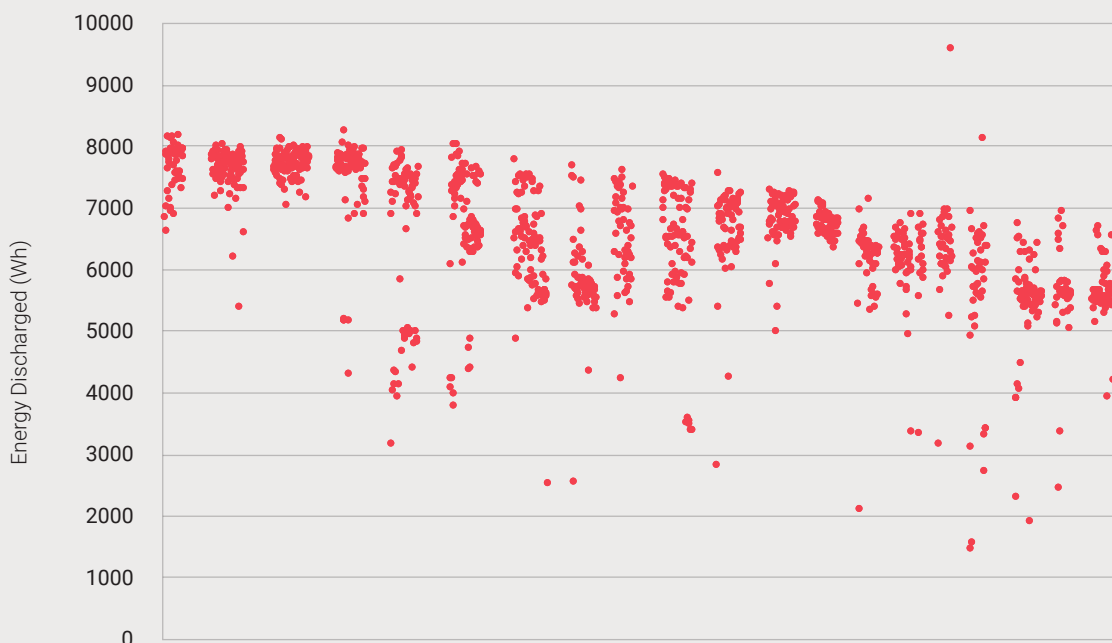


Figure 17. Energy discharged per cycle by the Alpha battery pack

# Ampetus Super Lithium

ITP encountered difficulties with commissioning of the Ampetus battery pack. As cycling continued the pack continued to demonstrate issues with reliability, frequently shutting down and requiring cell re-balancing. ITP understands that these issues are not isolated to ITP's battery pack, and that Sinlion were not willing to honour their product warranty with regards to this fault. Ampetus were forced to bear this liability with their Australian customers and subsequently went into receivership in May 2018.



# Aquion Saltwater Battery

Aquion's bankruptcy in early March 2017 continues to leave ITP without support for final commissioning of the battery bank with the Victron inverter. ITP has set all parameters detailed in existing documentation but is unable to complete commissioning. Although Aquion was bought out in July 2017, it is not supporting existing products in any way, and all existing warranties are void.



# BYD B-Box

## Operational Issues

ITP has not experienced any operational issues with the BYD battery pack.

## Capacity Fade

The energy discharged per cycle is shown in Figure 18. The data suggests a SOH of 75% after 1,470 cycles, with capacity fade appearing to accelerate.

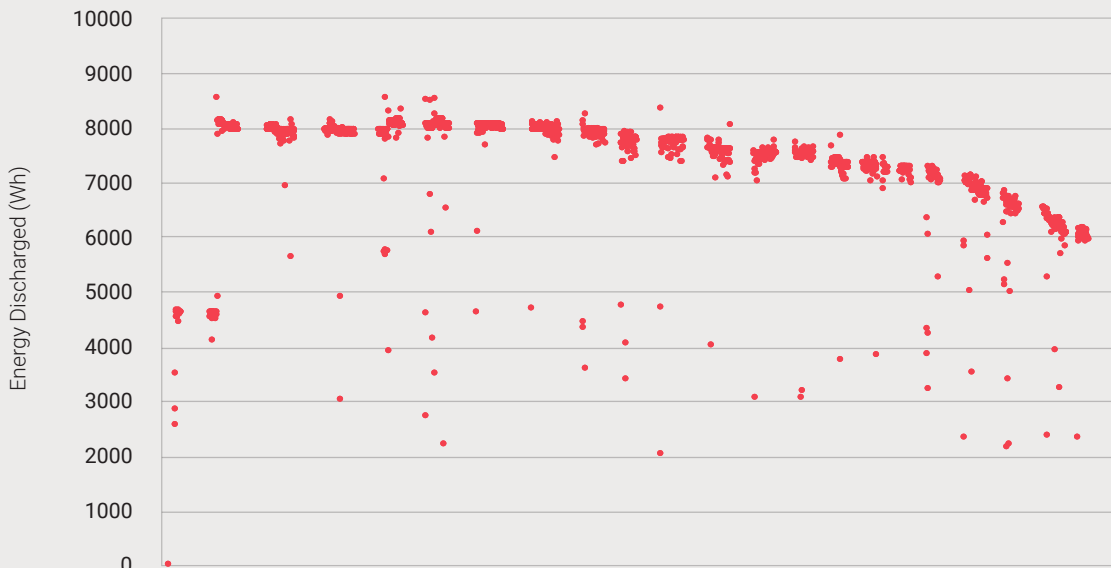


Figure 18. Energy discharged per cycle by the BYD battery pack

# GNB Lithium

## Operational Issues

ITP has not experienced any operational issues with the GNB Lithium battery pack.

## Capacity Fade

The energy discharged per cycle is shown in Figure 19. It is apparent that some cycles show capacity has been retained far above the average capacity delivered each cycle. While this suggests a fault, GNB have advised that no such fault is apparent.

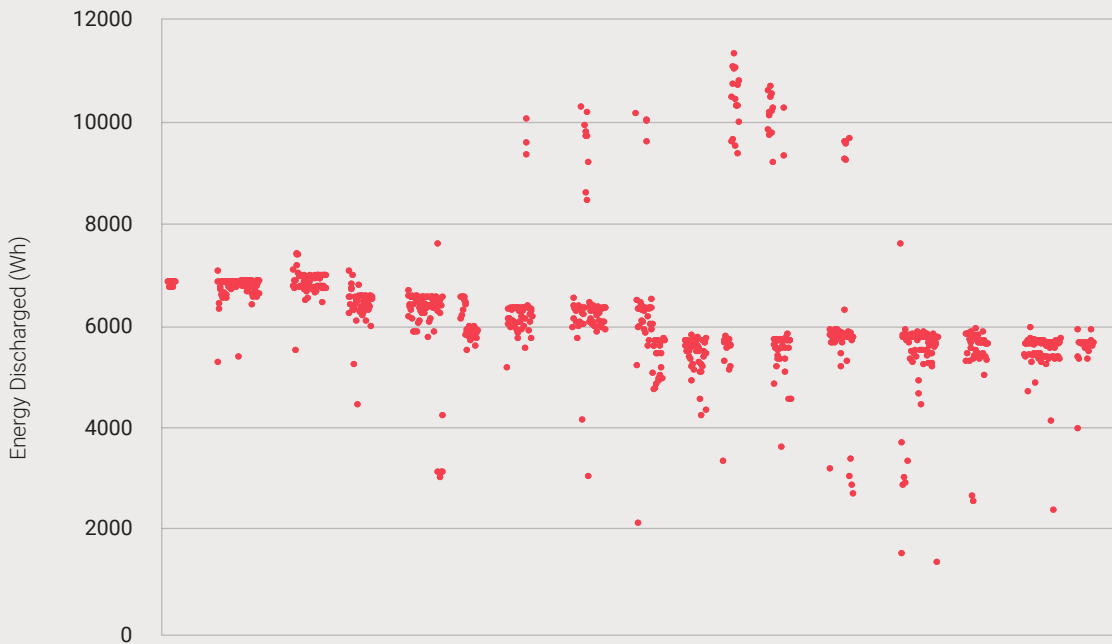


Figure 19. Energy discharged per cycle by the GNB LFP battery pack

# LG Chem RESU HV

## Operational Issues

In September 2018 ITP attempted to turn the LG Chem RESU HV battery back on after a scheduled outage, but was unsuccessful as the battery voltage was too low. ITP was able to recharge the battery pack to an acceptable starting voltage with a high voltage charger dispatched by LG Chem support, but the battery pack was physically unable to be reconnected as it had emerged from the battery enclosure when opened and could not be re-enclosed.

LG Chem attributed this to swelling of the battery cells, which can occur when the voltage drops too low, although LG Chem did note that it normally occurs at a lower voltage than what was experienced by the battery pack in question.

The battery pack was replaced by LG Chem. Cycling of the new pack commenced in October 2018 but the data collected to date reveals little regarding capacity retention.



# Pylontech US2000B

## Operational Issues

ITP has not experienced any operational issues with the Pylontech battery pack.

## Capacity Fade

The energy discharged per cycle is shown in Figure 20. The data suggests a SOH of 88% after ~1,150 cycles.

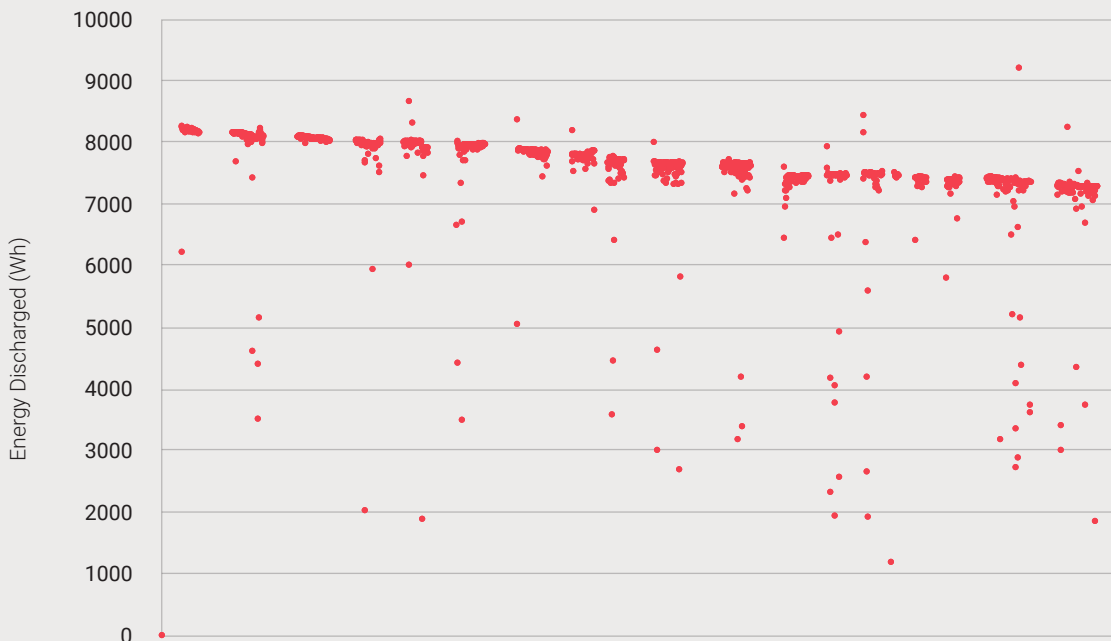


Figure 20. Energy discharged per cycle by the Pylontech battery pack

# Redflow ZCell

The Redflow battery suffered an electrolyte leak and was replaced in February 2019. This is the fourth time the Redflow battery has been replaced in this trial, and the third time it has been replaced due to an electrolyte leak. The first replacement was due to contaminated electrolyte.

Redflow attributed the leak to a step in their manufacturing process in which the electrolyte tank was washed with a particular soap after manufacture, causing brittleness in the plastic and therefore increased risk of cracks. This apparently only affected a specific batch of products.

The previous leaks were attributed to micro-cracking of the electrolyte tank that occurred during road transport. The problem identified was that the electrolyte trays were not sufficiently supported on the sides to withstand the weight of the electrolyte. Redflow state that they have since modified their transport techniques and believe this problem will be avoided in the future. Data on the replacement Redflow unit is not provided below due to the low number of cycles completed to date.



## SimpliPhi PHI 3.4

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In the Battery Test Centre Report 5 – September 2018, it was noted that ITP was awaiting replacement of the SimpliPhi batteries after SimpliPhi advised ITP that the original inverter setpoints were no longer consistent with their operating guidelines, causing the battery pack to be cycled beyond what SimpliPhi now considers to be 100% depth of discharge. After picking up the original batteries in September 2018, SimpliPhi has since chosen to issue ITP with a refund rather than replace them. The SimpliPhi battery is therefore no longer included in this trial.



## Tesla Powerwall 2

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In September 2018, the Tesla Powerwall 2 identified a 'welded relay' fault. Tesla suggested that this may have been related to the burnt-out terminal block discovered following installation, although this was not confirmed and it is unclear what caused the fault. Both the Powerwall 2 and associated Gateway were subsequently replaced by Tesla. Cycling of the replacement Powerwall 2 commenced in late November.

ITP still have no direct control over the battery (as Tesla do not allow this level of control of their products), but rely on Tesla to implement the cycling schedule. Monitoring of Tesla Powerwall's is only possible via mobile app. Tesla are yet to publish a local API for direct access to data. Nevertheless, community groups of have published a tutorial on how to take data from the battery online.<sup>1</sup> The data used by ITP in monitoring and analysis is obtained from this API but is not provided below due to the low number of cycles completed to date.



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<sup>1</sup> [mikesgear.com/2017/12/07/monitoring-teslas-powerwall2-on-pvoutput-org/](https://mikesgear.com/2017/12/07/monitoring-teslas-powerwall2-on-pvoutput-org/)

## 4.2. Capacity Test Performance

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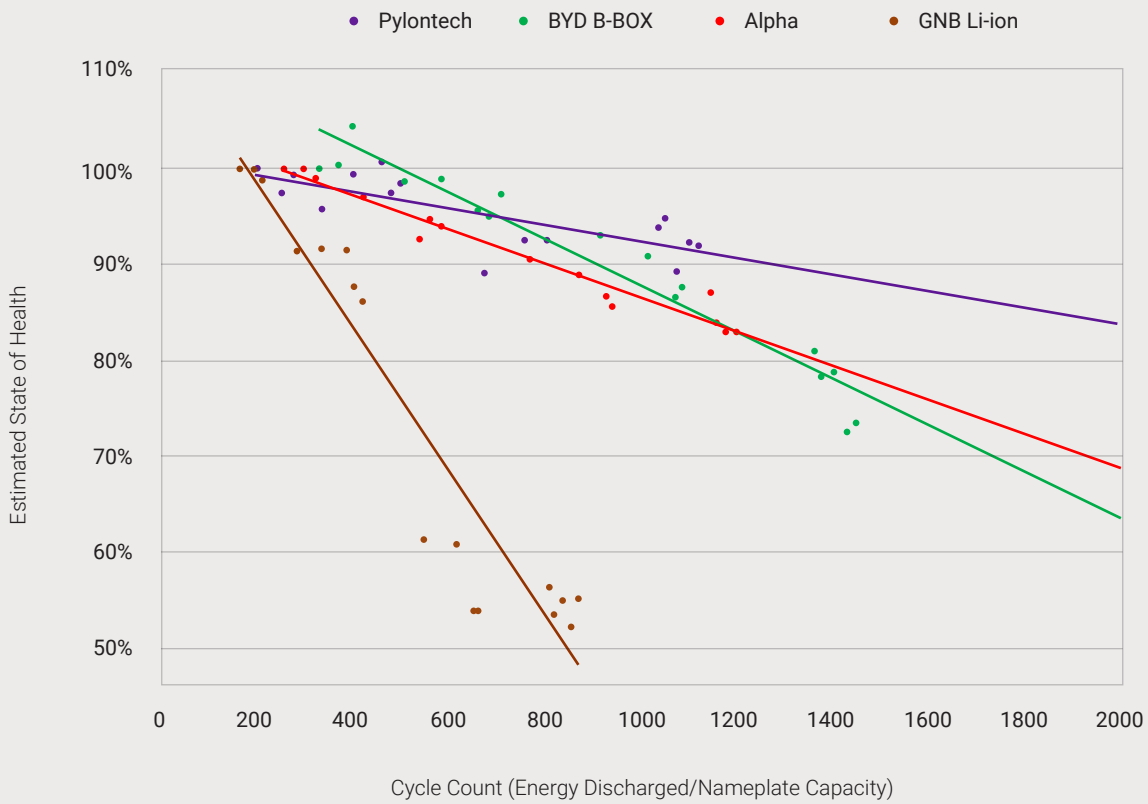


Figure 21. Capacity fade of Phase 2 battery packs

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The results of the capacity tests broadly align with the observations that can be made based on cycle data. In particular, the Pylontech battery pack is demonstrating excellent capacity retention while the capacity of the BYD battery pack appears to have degraded more rapidly in recent months.

It should be noted that the Alpha pack has been confirmed as faulty by Alpha, while the GNB LFP pack appears faulty to ITP. Therefore, the capacity fade demonstrated is not necessarily the result of cell degradation, and could be made available once more if these faults are identified and rectified.

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## 4.3. Round-Trip Efficiency Comparison

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While there is variance in the efficiency of each battery pack each month, no trend is apparent. Lifetime round-trip efficiency (i.e. lifetime energy in vs. lifetime energy out) is depicted in Figure 22, which shows all Phase 2 technologies still in operation delivering between 85-95% DC round-trip efficiency.

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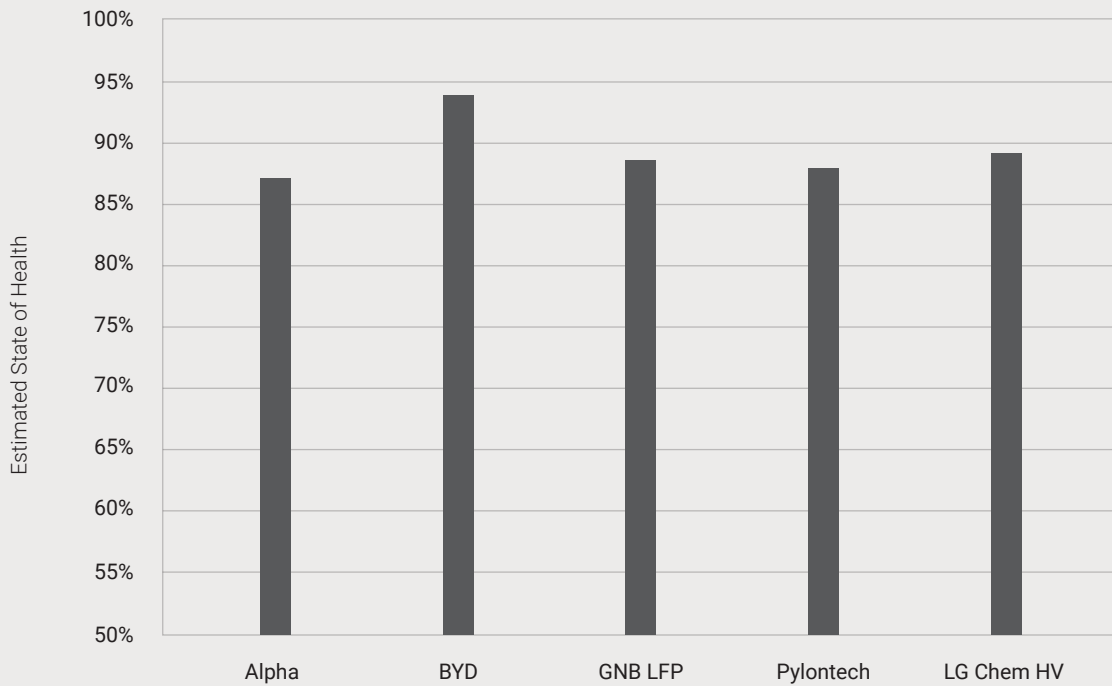


Figure 22. Lifetime round-trip efficiency of various battery packs

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# 5. MARKET DEVELOPMENT

## 5.1. Cost Trajectory

Since the beginning of the project, the cost of residential and commercial scale lithium-ion battery packs has fallen significantly. Further, throughout that period, many manufacturers have significantly altered their product offering, and several have exited the market or become insolvent. In recent periods, cost progress has slowed, owing to capacity constraints at the manufacturing level and increasing raw material costs (cobalt, in particular).

At the same time, the established conventional lead-acid market has been stable, with product prices following currency and lead price fluctuations.

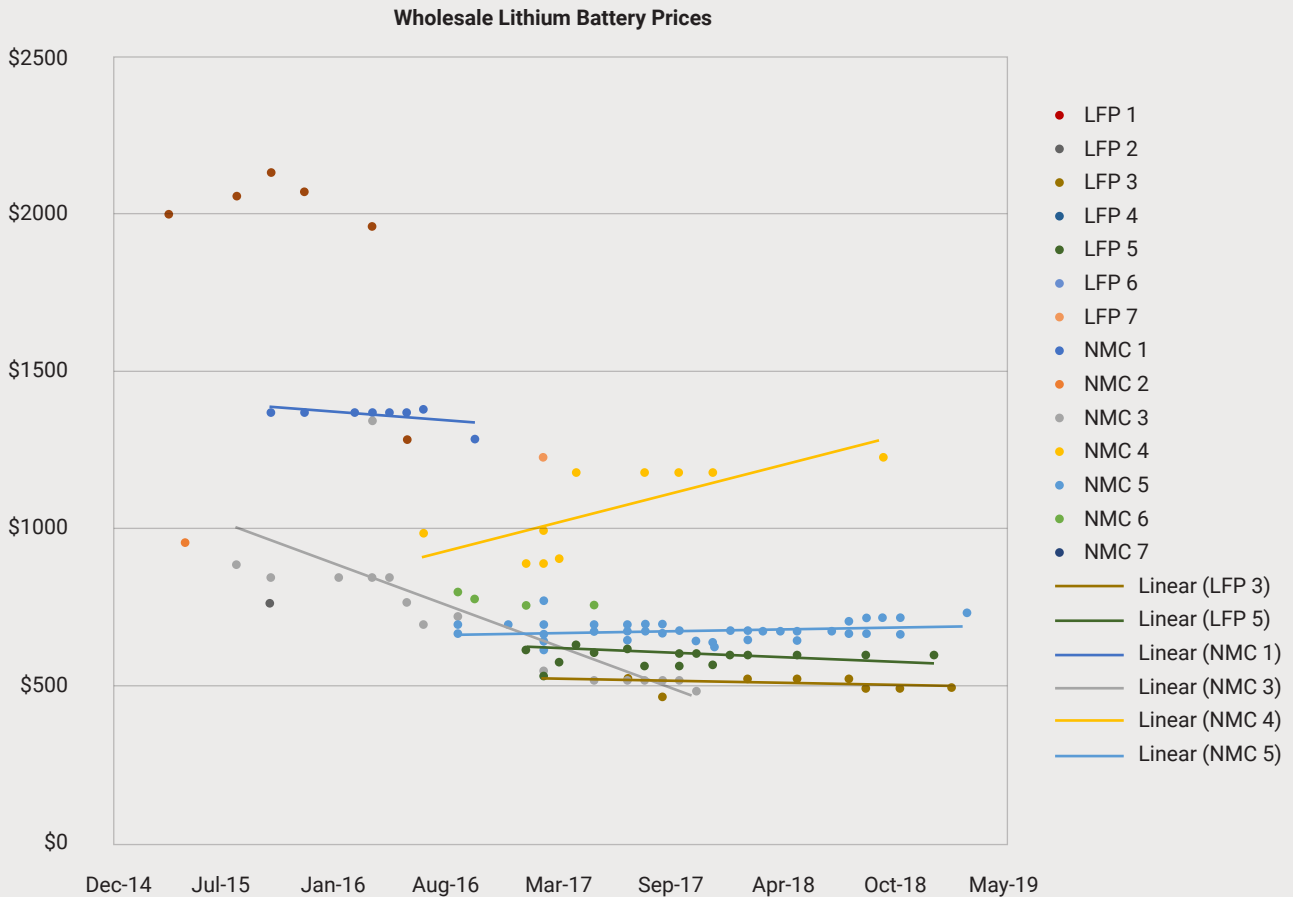


Figure 23: Wholesale prices for lithium-ion battery products installed in the Battery Test Centre

Significant lithium-ion production capacity is coming online in the medium term, and manufacturers are increasingly substituting cobalt out of their cells. The effect should be falling lithium-ion costs in the medium-term.

## 5.2. Uptake

The rate of lithium-ion battery installations in stationary and non-stationary applications is increasing both within Australia and globally. Figure 24 shows projected electricity storage energy capacity growth to 2030, as predicted by the International Renewable Energy Agency (IRENA).

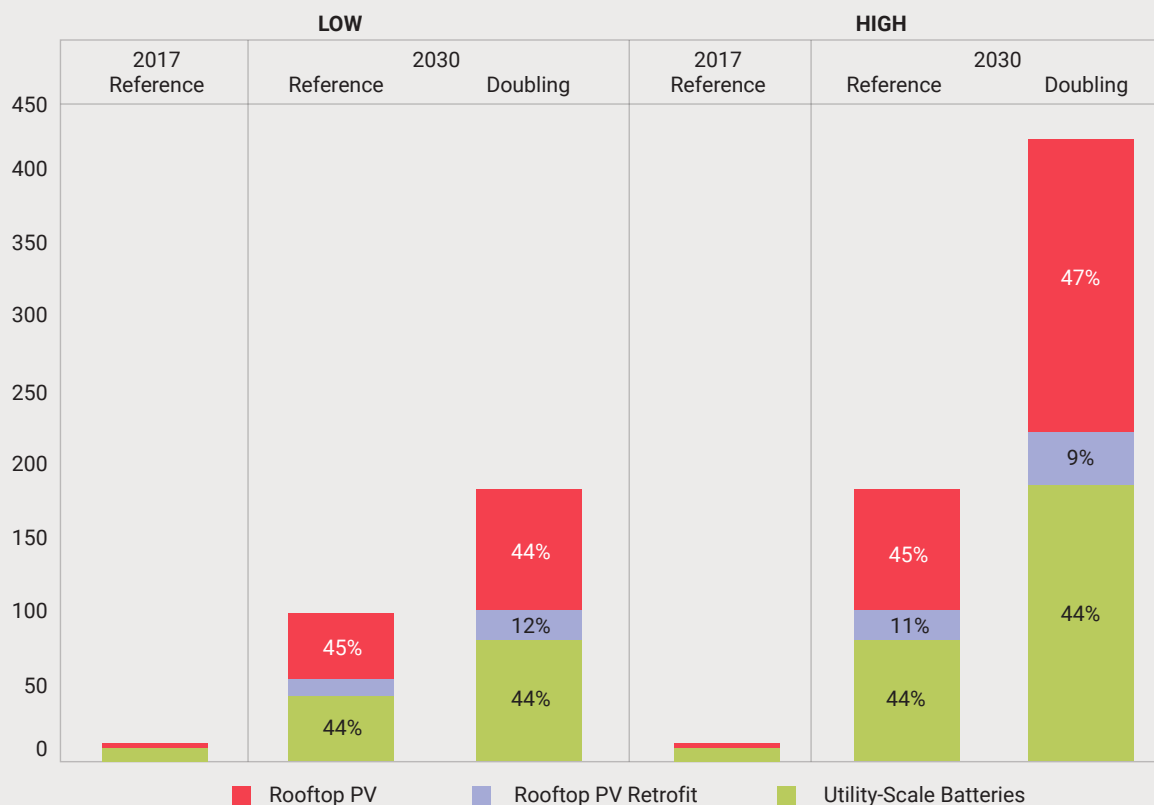


Figure 24: Battery electricity storage energy capacity growth in stationary applications by sector, 2017-2030.<sup>2</sup> 'Reference' projects business-as-usual and 'Doubling' projects a doubling in the global share of renewables from 2010 to 2030.

The size of the Australian storage market has grown rapidly in recent years, a trend which is projected to continue, both due to declining retail prices and the introduction of multiple state government-supported subsidies. While the lack of a national register of energy storage systems makes it impossible to state definitive figures, the Smart Energy Council estimates that 25,000 battery storage systems were installed in Australia from 2010 to 2015; 7,500 in 2016; and 20,000 in 2017.<sup>3</sup> The latest figure aligns with Sunwiz's estimate of approximately 21,000 battery installations in 2018.<sup>4</sup>

<sup>2</sup> irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA\_Electricity\_Storage\_Costs\_2017.pdf

<sup>3</sup> [https://www.smartenergy.org.au/sites/default/files/uploaded-content/field\\_f\\_content\\_file/australian\\_energy\\_storage\\_market\\_analysis\\_report\\_sep18\\_final.pdf](https://www.smartenergy.org.au/sites/default/files/uploaded-content/field_f_content_file/australian_energy_storage_market_analysis_report_sep18_final.pdf)

<sup>4</sup> Sunwiz Australian Battery Market Report for 2018

Projections for future uptake generally all assume growth, with disparity in the rate. Sunwiz estimates that battery installation will double between 2017 and 2018. In a recent report, Bloomberg New Energy Finance (BNEF) estimated that 70,000 Australian households would install battery storage in 2019, making it the largest home battery market in the world. The Smart Energy Council estimates that 150,000-450,000 energy storage systems could be installed by 2020. Figure 25 from the Smart Energy Council's latest Australian Energy Storage Market Analysis shows forecasts from a range of sources.

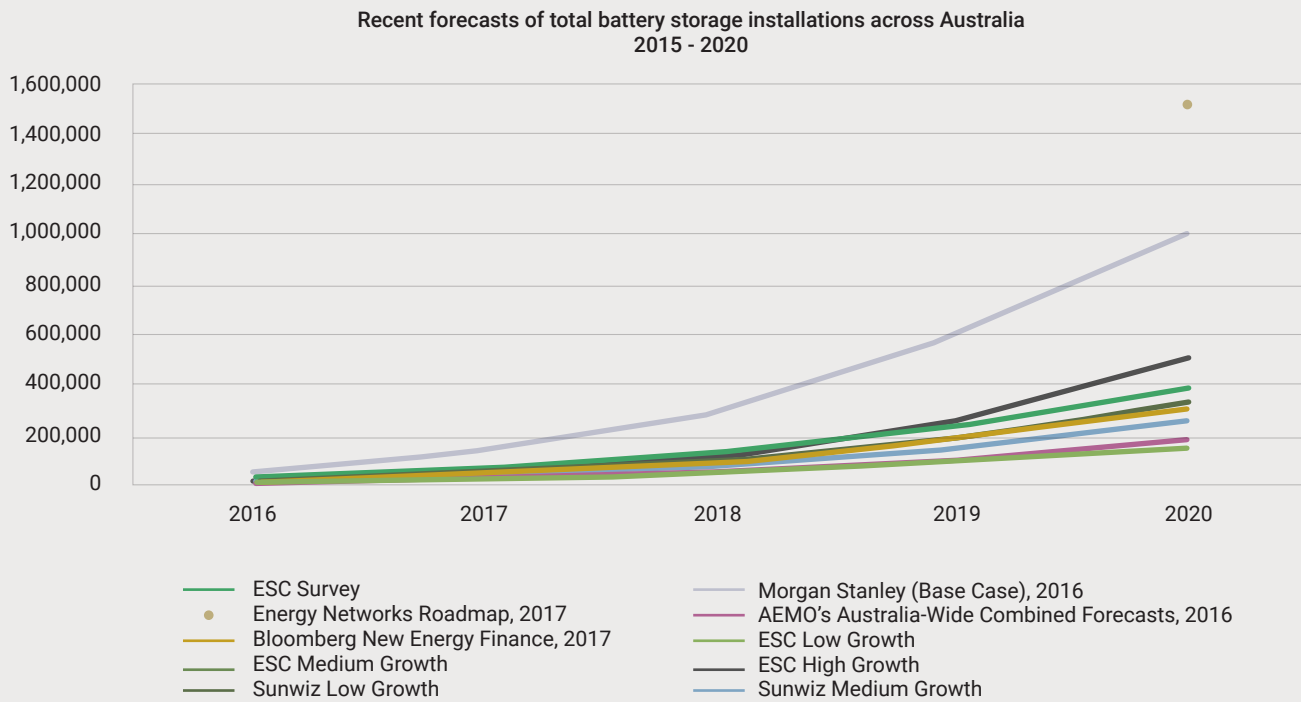


Figure 25: Forecasts of battery storage cumulative installs 2015-2020 according to various sources<sup>5</sup>

The recent and projected uptake of home energy storage systems in Australia is supported by subsidies and other incentives offered by multiple state governments. These are summarised in Table 3: Programmes supporting residential and commercial battery systems Table 3. Notably, the SA Home Battery Scheme has led to multiple battery manufacturers committing to establishing manufacturing facilities in SA, including sonnen, Alpha, and Eguana.

<sup>5</sup> [https://www.smartenergy.org.au/sites/default/files/uploaded-content/field\\_f\\_content\\_file/australian\\_energy\\_storage\\_market\\_analysis\\_report\\_sep18\\_final.pdf](https://www.smartenergy.org.au/sites/default/files/uploaded-content/field_f_content_file/australian_energy_storage_market_analysis_report_sep18_final.pdf)

Table 3: Programmes supporting residential and commercial battery systems<sup>6</sup>

	<b>Programme name</b>	<b>Overview</b>	<b>Status</b>
<b>ACT</b>	Next Generation Energy Storage	Up to 5,000 homes to receive discounted battery storage systems	In effect since 2016 (currently on third tranche)
<b>NSW</b>	Smart Energy for Homes & Businesses	\$50 million for up to 200 MW (home & business - \$1,000 incentive per home)	Introduced Nov 2018, date in effect TBA
<b>NSW</b>	Smart Batteries for Key Government Buildings	\$20 million for up to 13 MW (gov buildings)	Introduced Nov 2018, date in effect TBA
<b>SA</b>	Home Battery Scheme	\$100 million for up to 40,000 battery systems with a VPP-ready requirement	In effect from Oct 2018
<b>SA</b>	Home Battery Scheme	\$100 million for up to 40,000 battery systems with a VPP-ready requirement	In effect from Oct 2018
<b>VIC</b>	Battery storage incentive	\$40 million for up to \$5,000 off as many as 10,000 battery systems (on homes with pre-existing solar)	Introduced Sept 2018
<b>VIC</b>	Solar Homes Package	\$1.34 billion for up to \$2,225 off as many as 650,000 solar systems	In effect from Aug 2018
<b>QLD</b>	Interest-free loans for solar & storage	Loans up to \$4,500 for up to 3,500 home solar systems. Loans up to \$6,000 and grants up to \$3,000 for as many as 500 battery systems. Loans up to \$10,000 and grants up to \$3,000 for as many as 1,000 solar+battery systems.	In effect from Aug 2018

Projections for future uptake generally all assume growth, with disparity in the rate. Sunwiz estimates that battery installation will double between 2017 and 2018. In a recent report, Bloomberg New Energy Finance (BNEF) estimated that 70,000 Australian households would install battery storage in 2019, making it the largest home battery market in the world. The Smart Energy Council estimates that 150,000-450,000 energy storage systems could be installed by 2020. Figure 25 from the Smart Energy Council's latest Australian Energy Storage Market Analysis shows forecasts from a range of sources.

<sup>6</sup> <https://onestepoffthegrid.com.au/battery-incentive-programs-around-australia-existing-proposed/>

## 5.3. Installation

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Over the past three years, there has been significant development in the design of lithium battery products with regards to form factor and installation. Unlike lead acid batteries, lithium-ion batteries require monitoring and management via a dedicated Battery Management System (BMS). This complicates the installation process as it involves both DC power and communications integration between the inverter and battery.

Lithium ion batteries are typically available in one of the following configurations:

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### **Wall-mounted**

Wall-mounted products are specifically designed for residential installations and are usually a fixed capacity.

### **Ground-mounted**

These products are similar to wall-mounted products, but generally don't require a load bearing wall for mounting. Some products are able to be either wall-mounted or ground-mounted, with particular supports available for each option.

### **Server rack mounted**

These are typically modules used in larger commercial installations. This design allows flexibility in battery capacity as the system is modular. Some residential systems are also adopting this design, with a specialised enclosure containing a small number of racks. The enclosure may be indoor- or outdoor-rated, and does not generally require any kind of fixing to a surface.

### **Individual cells**

These can be used to build a battery pack. However, installation is more complex as the packs need to be integrated with a BMS.

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The physical battery design has a significant impact on how the product is installed.

Early lithium battery products were typically a server rack mountable design, as this provided flexibility in system size. This led to complexity in installation as communication and power wiring between battery modules became part of the installation process.

As lithium-ion batteries became a consumer product, aesthetics became an important design feature. Wall- and floor-mounted battery packs with less modularity became the norm for residential installations. Customers were given fewer options in terms of pack capacity and configuration, leading to a simplified installation process. This allowed installers to become more familiar and efficient.

Battery packs with a single power connection and a single communications connection to the inverter simplifies installation and reduces the likelihood of mistakes.

Some battery products such as the Samsung All-In-One or the Tesla Powerwall 2 integrate an inverter and battery internally. This greatly simplifies the installation process as the installer only has to make a single electrical connection (as well as whatever external communications connection is required for monitoring purposes).



## 6. LESSONS LEARNED

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Having been in operation for almost three years now, the Battery Test Centre project has revealed a number of valuable lessons. The lessons learned relate not only to the performance of the batteries throughout the trial (analysed in Sections 3 and 4), but also to the following.

### 6.1. Battery Trial Design

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- At the inception of Phase 1, there were relatively few technologies commercially available, limited mainly to LFP, NMC and the lead-acid chemistries. In Phase 2 a larger range of technologies could be chosen for inclusion. In both cases, inverter compatibility was a key criterion for consideration of inclusion, as the trial aimed to minimise the number of inverter models and therefore differences in testing set-up between batteries.
- By the time of inception of Phase 2 of the trial, the inverters used in Phase 1 were no longer compliant for new grid connections according to Australian standards. New inverter models were therefore chosen, which had the result of allowing batteries to be included in the trial which previously could not have been considered.
- Unfortunately, information on inverter compatibility from battery manufacturers was often ambitious or misrepresented, leading to integration and commissioning delays later on.
- Due to the budgetary constraints of the project, only one unit of each battery was installed. While this did result in a large number of different products included in the trial, the results obtained for each product are not statistically significant or necessarily a reliable indication of the performance of installations of each product as a whole.
- The accelerated cycling methodology was designed to enable analysis of battery performance over a shorter timescale than would be possible in a typical installation. However, this did result in the batteries being worked harder (although still within manufacturer specifications) than would normally be the case in solar-storage applications. This led to de-rating and failures that might not normally arise, particularly related to heat management.
- This cycling regime was also more suitable for certain technologies; specifically, lithium technologies proved to be better suited to the accelerated cycling regime than lead-acid technology. The lead-acid battery (not including the advanced lead-acid chemistry) was therefore at an inherent disadvantage in the trial.

- With regards to the design of the testing facility, a fireproof enclosure was required for batteries installed in a Class 9 building. This added cost and complexity to the project. It is understood that the requirements for this have since changed with the introduction of the National Construction Code (NCC) 2019, which will be adopted from 1 May 2019.
  
  - Monitoring and control of the systems was highly challenging, for multiple reasons. These included:
    - A lack of consistent protocols for inverter communications and control
  
    - The need to control multiple inverters types including, in some cases, integrated inverters in 'all-in-one' systems
  
    - A change of data collection system for the Phase 2 batteries. Having two different data collection systems increased the infrastructure to be maintained. Both systems were also highly bespoke.
-



## 6.2. Procurement, Construction, Installation and Commissioning

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- Delays in battery availability and delivery were common, particularly for products that were just entering the Australian market. This caused further project delays as it was planned that all batteries would be installed in the same timeframe. In addition, the shelf life of batteries had to be considered; some battery warranties were even dependent on the date of manufacture as opposed to the date of installation or purchase.
- When the products did arrive, they sometimes did not include all the necessary instructions or even components. This made installation even more difficult for electricians who were, at the time, unfamiliar with lithium-ion battery products. At the time of Phase 1 and Phase 2 installation, manufacturer or installation support was often non-existent or difficult to access. This has improved with maturation of the market.
- Builders and electricians alike were unfamiliar with the requirements for fire-rated buildings.
- Communications was the most difficult aspect of commissioning for most of the products installed. This was due to a number of factors, including incomplete product integration between batteries and inverters, and installers' lack of familiarity with battery and inverter communications. Registration and product-specific monitoring possibilities varied widely between products and has also developed significantly since the time of Phase 1 and Phase 2 installation. Some products even required online registration in order for the warranty to be valid.
- At the time of Phase 1 installation, both the distribution network and electrical installation regulatory service were generally unfamiliar with battery installations, and did not have a standard approach. Both parties adopted a very risk-averse approach at the time of the Phase 1 installation, but were much more accommodating at the time of the Phase 2 installation (although this may have still stemmed from a lack of standard approach). Regulatory requirements are now becoming clearer; there is now an Australian Standard under development for electrical installations with battery systems, which may be released in the second half of 2019 (AS/NZS 5139).
- The commissioning time required for control and monitoring systems was longer than expected, due to the complexity discussed above. This difficulty should not be underestimated in future projects.

## 6.3. Ongoing Operation

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- The amount of time required for managing maintenance issues during ongoing operation was significantly underestimated. As discussed above, it is possible that the demanding cycling regime may have contributed to more issues and/or failures than might be generally expected. However, even with this taken into account, the failure rate far exceeded expectations. The reactive and unpredictable nature of the maintenance call-outs, combined with the (off-site) location of the testing facility, resulted in more time spent on troubleshooting maintenance than was planned.
- The level of support received from manufacturers varied widely. Some were very engaged and willing to assist while others were dismissive or inaccessible. It is possible that the status of these particular installations as a tested product with public exposure may have influenced some manufacturers' approach to support, although to what extent is unclear. Residential homeowners may not, for example, always receive the same level of service.
- In many cases issues with battery performance were first noticed by ITP and raised with the manufacturer, rather than the other way around. While it is expected that commercial installations might be similarly closely monitored, residential homeowners may not necessarily keep such a close eye on their systems. It is conceivable that problems arising with residential installations could go unnoticed for significant periods, particularly if the issue is not one resulting in absolute failure.
- Although the number of problems experienced with battery operation was both higher than expected and disruptive to the testing regime, they are also a significant indicator in themselves of the state of the products on the market.

## 7. KNOWLEDGE SHARING

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An important part of the battery testing project has been to maximise the demonstration value of the trial by:

- Sharing the knowledge with the largest possible audience
- Publishing data in a way that is highly accessible and user friendly
- Adding value to the raw data through expert analysis and commentary

The Knowledge Sharing seeks to publicise data and analysis generated by the battery testing in order to help overcome the barriers impeding the up-take of battery storage technology. In particular, it seeks to overcome the barrier that there are no known published studies of side-by-side battery comparisons which test manufacturers' claims about battery performance. This lack of independent verification contributes to investor uncertainty.

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The intended users of the information generated by the project include:

- Future energy project developers, including technology providers and financiers, who will be examining the investment case of a range of energy storage options.
- Energy analysts involved in projecting future renewable energy costs and uptake rates.
- Electricity industry stakeholders including generators, TNSPs, DNSPs, and regulators.

The Battery Test Centre website<sup>7</sup> was established as the key mechanism for this Knowledge Sharing. The website includes background on the project, live tracking of battery status, and a virtual reality component that replicates the battery test facility. To date the site has had over 131,000 page views with an average of 2:00 minutes spent per page and 4:08 minutes spent on the reports page.

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<sup>7</sup> [batterytestcentre.com.au/reports/](http://batterytestcentre.com.au/reports/)

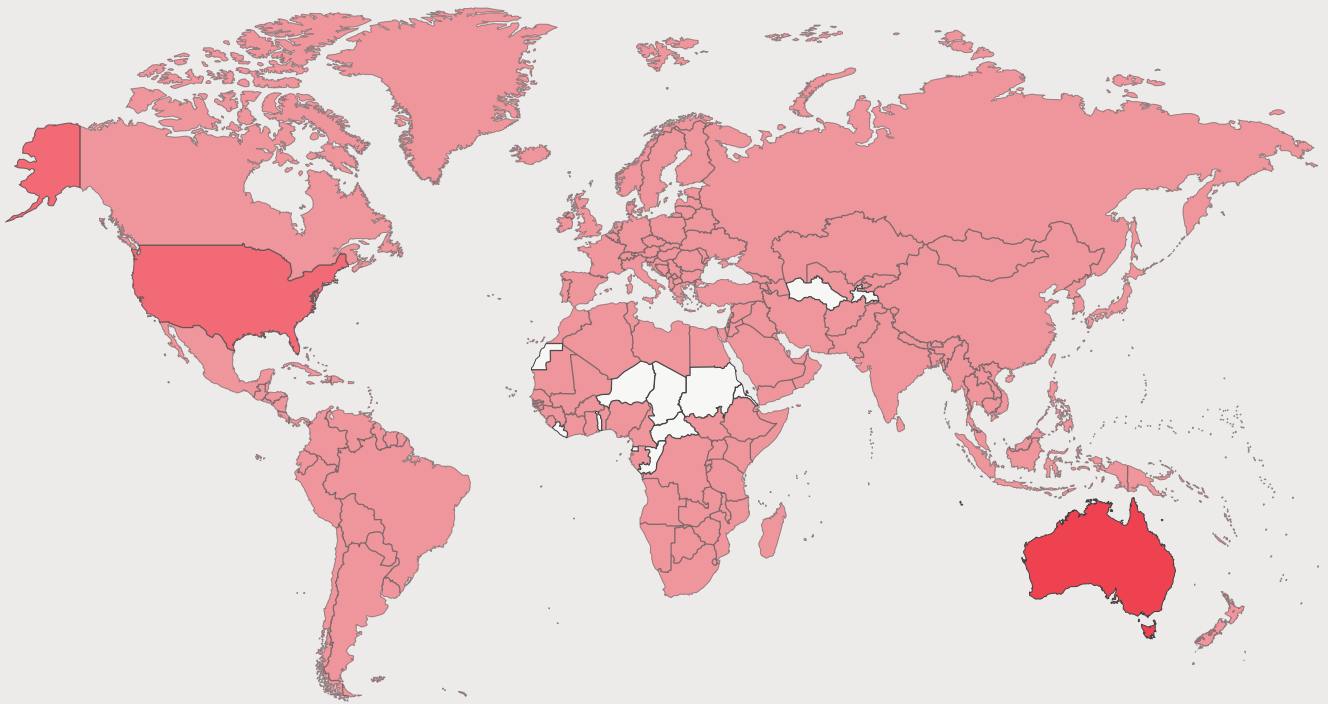


Figure 26: Number of sessions by country

The data from the website shows that the key audience is Australia, with Australian IP addresses accounting for 32,437 sessions (51%). A session is logged as a single viewer who may view multiple pages within a restricted period (periods are normally reset after 30 minutes of inactivity). Australia is followed by 6,997 sessions from the United States, 2,067 from Germany and the United Kingdom not far behind on 2,048. It is interesting to note, however, that the content has been accessed from right across the globe.



Figure 27: Weekly active users

Figure 27 above shows the number of weekly active users that have accessed the website and there is a clear rise between the Phase 1 figures at around 250 weekly users, to the launch of Phase 2 in August of 2017 when the weekly averages nearly doubled to around 500 active weekly users. The peaks coincided with media articles that were distributed on those dates.

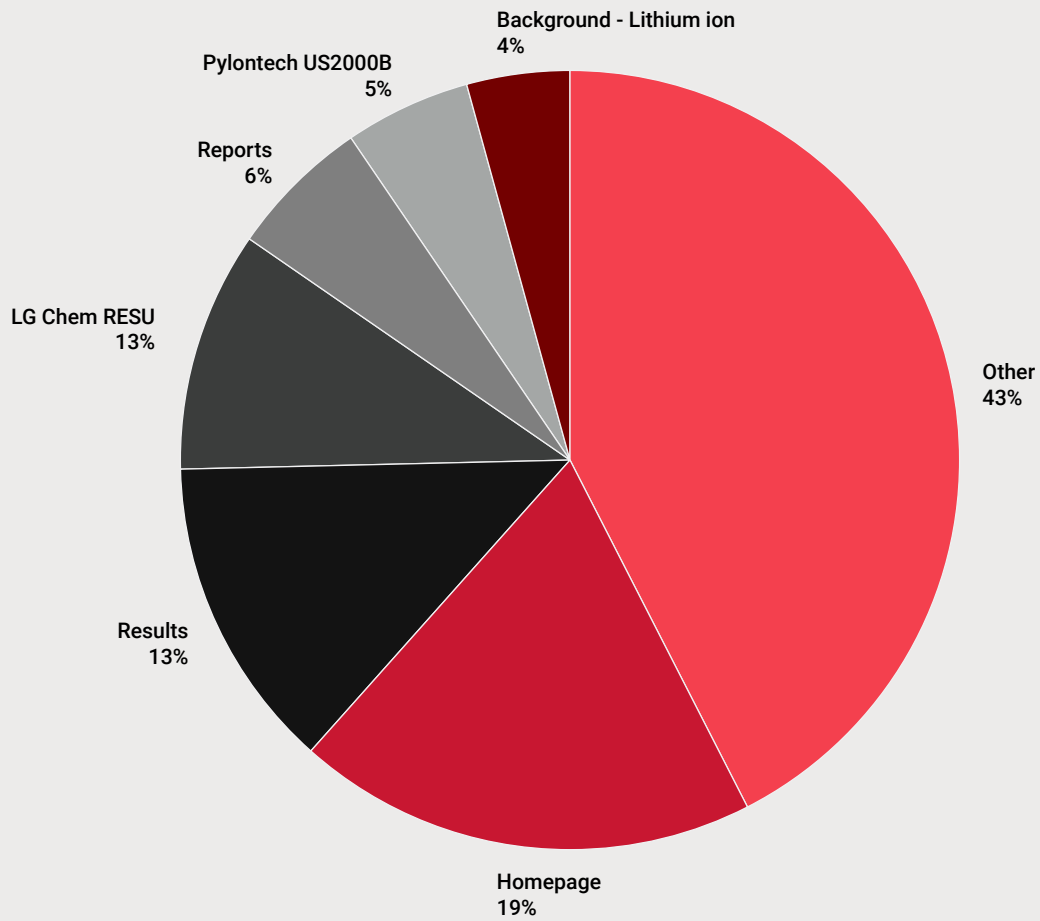


Figure 28: Breakdown of the 131,150 page views

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There is a good spread of views across the website, particularly the technology and results pages; the top five most viewed pages after the homepage (19%) are the results page (13%), LG Chem RESU (10%), the reports page (6%), Pylontech US2000B (5%) and the background page on lithium-ion technology (4%).

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# APPENDIX A. TESTING PROCEDURE

The key objective of the testing is to measure the batteries' decrease in storage capacity over time and with energy throughput. As the batteries are cycled they lose the ability to store as much energy as when they are new.

To investigate this capacity fade, the lithium-ion batteries are being discharged to a state of charge (SOC) between 5% and 20% (depending on the allowable limits of the BMS), while the lead-acid batteries are being discharged to a 50% SOC (i.e. 50% of the rated capacity used). The advanced lead battery is being be cycled between 30% and 80% SOC. These operating ranges are in line with manufacturers' recommendations for each technology.

Each battery pack is charged over several hours (mimicking daytime charging from the PV), followed by a short rest period, then discharged over a few hours (mimicking the late afternoon, early evening period) followed by another short rest period. In total, there are three charge/discharge cycles per day.

## Temperature Profile

The ITP lithium-ion battery trial aims to test batteries in 'typical' Australian conditions. It is expected that most residential or small commercial battery systems will be sheltered from rain and direct sunlight, but still be exposed to outdoor temperatures; therefore, the ambient temperature in the battery testing room is varied on a daily basis, and varies throughout the year. The high and low temperatures are given in Table 1.

ITP implements 'summer' and 'winter' temperature regimes for the three daily charge/discharge cycles. In the summer months the batteries undergo two cycles at the monthly high temperature and the third at the monthly low temperature, and in the winter months the batteries undergo two cycles at the monthly low temperature and the third at the monthly high temperature.

Table 4: Daily high and low ambient temperatures throughout the year

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
<b>Low</b>	22	20	18	16	14	12	10	12	14	16	18	20
<b>High</b>	36	34	32	30	28	26	24	26	28	30	32	34
<b>Regime</b>	S	S	S	S	W	W	W	W	W	W	S	S

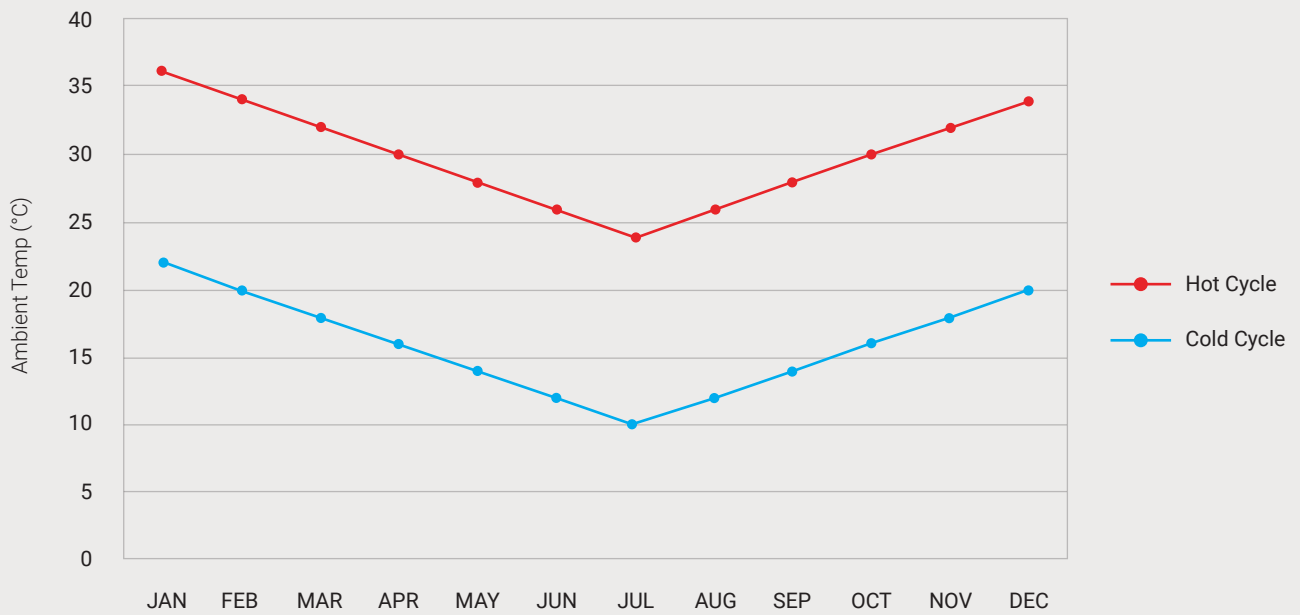


Figure 29: Daily hot and cold cycle temperatures throughout the year

Given the focus on energy efficiency and low energy consumption at the CIT Sustainable Skills Training Hub, the timing of the high and low temperature cycles is matched with the variations of outdoor temperatures, to allow transitions between high and low temperature set-points to be assisted by outdoor air. The schedule of charge and discharge cycles is show in Figures 2 and 3.

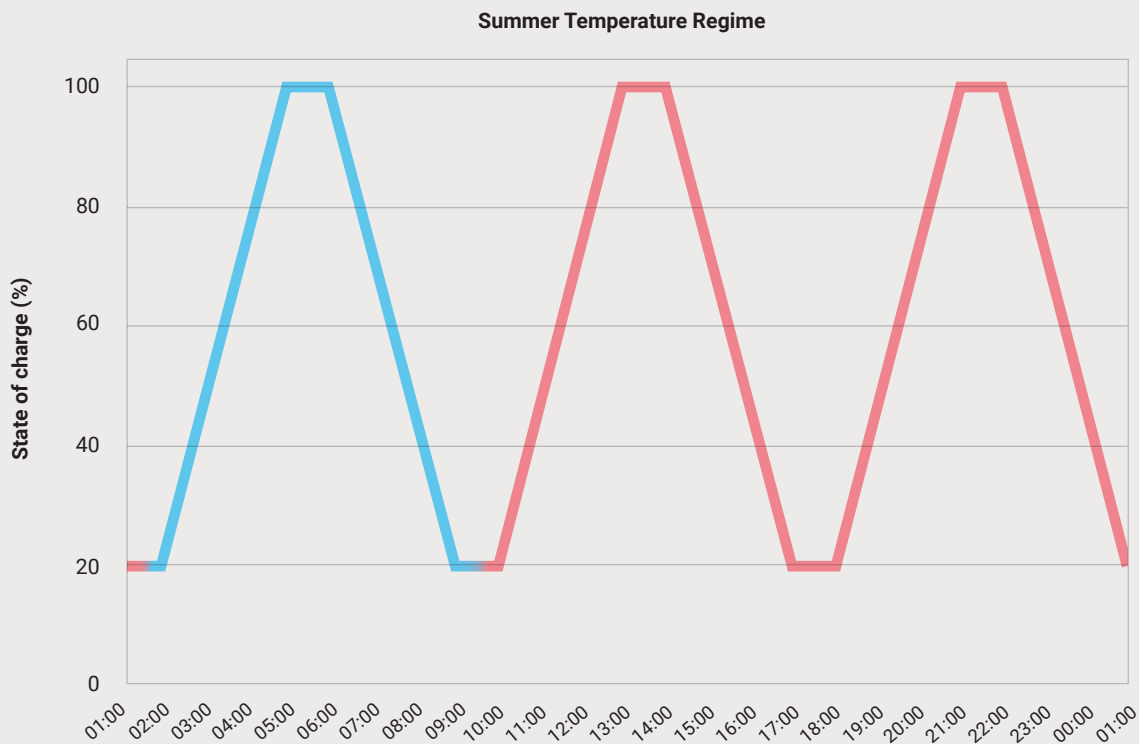


Figure 30: Summer temperature regime and charge regime

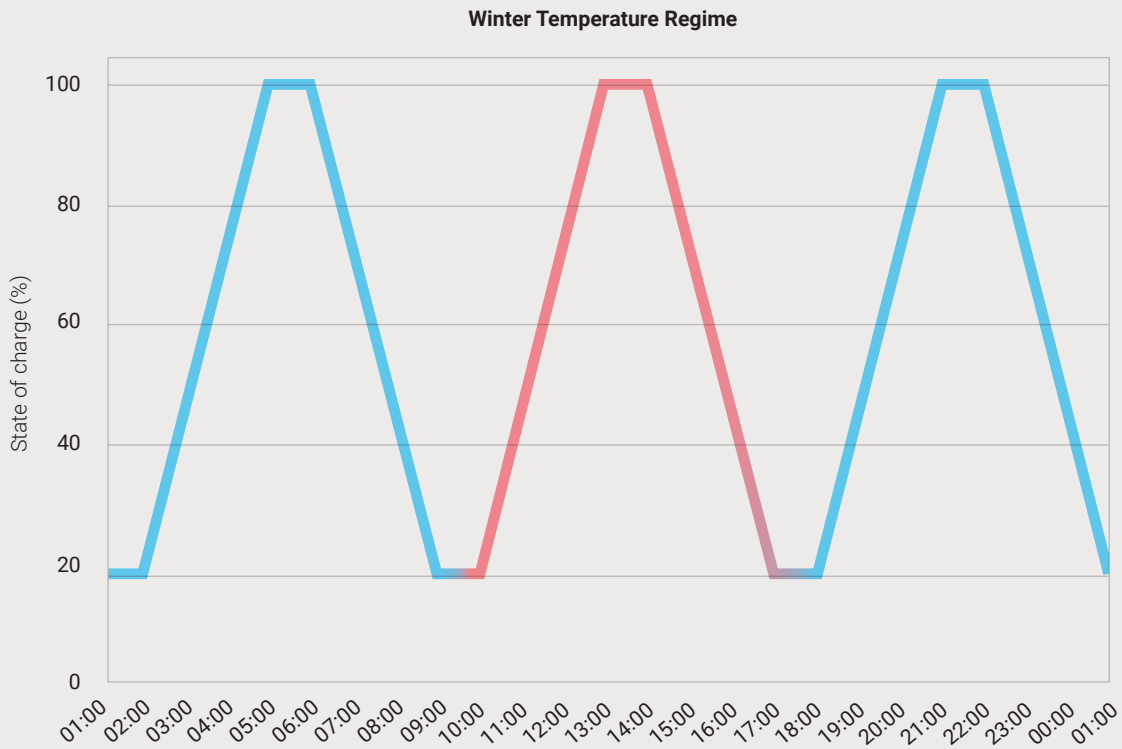


Figure 31: Winter temperature regime and charge regime

On the last day of each month, the batteries undergo a charge/discharge cycle at 25 °C as this is the reference temperature at which most manufacturers provide the capacity of their batteries. From this, an up-to-date capacity of the battery can be obtained and compared to previous results to track capacity fade. Although the duration of a month varies between 28 and 31 days, ITP does not expect this to make a statistically relevant difference to the results.







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