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# Public Report 10

## Lithium-ion Battery Testing

ENGINEERING | STRATEGY | ANALYTICS | COMPLIANCE

March 2021

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# 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 a \$1.29m grant from the Australian Renewable Energy Agency under its Advancing Renewables Program, the Lithium-Ion Battery Test Centre program 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

This report describes testing results and general observations or issues encountered thus far for each battery pack.

This report, earlier reports, and live test results are published at [batterytestcentre.com.au](https://batterytestcentre.com.au).

*This Project received funding from ARENA as part of ARENA's Advancing Renewables Program. The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained within this report.*

# 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 (nomi- nal) 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>LTO</b>	Lithium Titanate (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

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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. Eight batteries were installed initially, followed by a further ten installed in a second phase. Another eight battery packs, including a lithium-titanate battery and a sodium-nickel battery, were installed in late 2019. This is the tenth public six-monthly report.

While many battery packs have experienced faults and/or failed prematurely, the Sony battery pack from Phase 1 has proven highly reliable to date, alongside the Pylontech and GNB Lithium battery packs from Phase 2.

The Sony battery pack (Phase 1) has retained over 80% of its initial capacity after nearly 3,000 cycles. The Pylontech battery pack (Phase 2) has also retained over 80% of its initial capacity after nearly 2,000 cycles.

Phase 3 batteries have completed less than 1,000 cycles to date. The three batteries without communications to the inverter have tended to accumulate cycles slowly owing to shallow discharges.

Round-trip efficiency is fairly consistent between battery packs and has been observed between 78-95% (DC).

No major cost progress has been observed since the previous report. Most analysts continue to believe that the large amount of lithium-ion production capacity currently under development will put downward pressure on prices in the medium-term. ITP's opinion is that these price reductions are required for mass-market uptake, alongside improvements in products, interfaces, and technical support.

# 1. PROJECT BACKGROUND

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 retention 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. Phase 2 commenced in July 2017 with the addition of eight lithium-ion packs, a zinc-bromide flow battery, and a "saltwater" battery bank. Phase 3 commenced in late 2019 with the addition of a further eight battery packs, including a lithium-titanate (LTO) battery and a sodium-nickel battery. The batteries tested by ITP are listed below.

Product	Type	Nameplate Capacity (kWh nominal)	Phase	Status
CALB CA100	Lithium Iron Phosphate	10.24	1	Testing Concluded
Ecoulx UltraFlex	Lead Carbon	14.8	1	Testing Concluded
GNB Sonnenschein	Lead Acid	14.4	1	Testing Concluded
Kokam Storaxe + ADS-TEC BMS	Lithium Nickel Manganese Cobalt	8.3	1	Testing Concluded
LG Chem RESU 1	Lithium Nickel Manganese Cobalt	9.6	1	Testing Concluded
Samsung AIO	Lithium Nickel Manganese Cobalt	10.8	1	Testing Concluded
Sony Fortelion	Lithium Iron Phosphate	9.6	1	Testing Ongoing
Tesla Powerwall 1	Lithium Nickel Manganese Cobalt	6.4	1	Testing Concluded
Alpha ESS M48100	Lithium Iron Phosphate	9.6	2	Testing Concluded
Ampetys Super Lithium	Lithium Iron Phosphate	9.0	2	Testing Concluded
Aquion Aspen	Aqueous Hybrid Ion	17.6	2	Testing Concluded
SimpliPhi PHI 3.4	Lithium Iron Phosphate	10.2	2	Testing Concluded

Product	Type	Nameplate Capacity (kWh nominal)	Phase	Status
BYD B-Box	Lithium Iron Phosphate	10.24	2	October 2020 Replaced by BYD B-Box LVS (8 kWh) Testing Ongoing
GNB Lithium	Lithium Nickel Manganese Cobalt	12.7	2	Testing Ongoing
LG Chem RESU HV	Lithium Nickel Manganese Cobalt	9.8	2	Testing Ongoing
Pylontech US2000B	Lithium Iron Phosphate	9.6	2	Testing Ongoing
Redflow ZCell	Zinc-Bromide Flow	10.0	2	Testing Ongoing
Telsa Powerwall 2	Lithium Nickel Manganese Cobalt	13.5	2	Testing Ongoing
BYD B-Box HV	Lithium Iron Phosphate	10.2	3	June 2020 Replaced by BYD B-Box HVM (11.04 kWh) Testing Ongoing
DCS PV 10.0	Lithium Iron Phosphate	10.0	3	Testing Ongoing
FIMER REACT 2	Lithium Nickel Manganese Cobalt	8.0	3	Testing Ongoing
FZSoNick	Sodium Nickel Chloride	9.6	3	Testing Ongoing
PowerPlus Energy LiFe Premium	Lithium Iron Phosphate	9.9	3	Testing Ongoing
SolaX Triple Power	Lithium Nickel Manganese Cobalt	12.6	3	Testing Ongoing
sonnenBatterie	Lithium Iron Phosphate	10.0	3	Testing Ongoing
Zenaji Aeon	Lithium Titanate	9.6	3	Testing Ongoing

Table 1: Summary of battery packs tested by ITP at the test centre

2. BATTERY OPERATION OVERVIEW

Figure 1 gives an overview of the issues experienced by battery packs installed in the trial. Note that only issues causing a complete interruption to cycling are displayed.

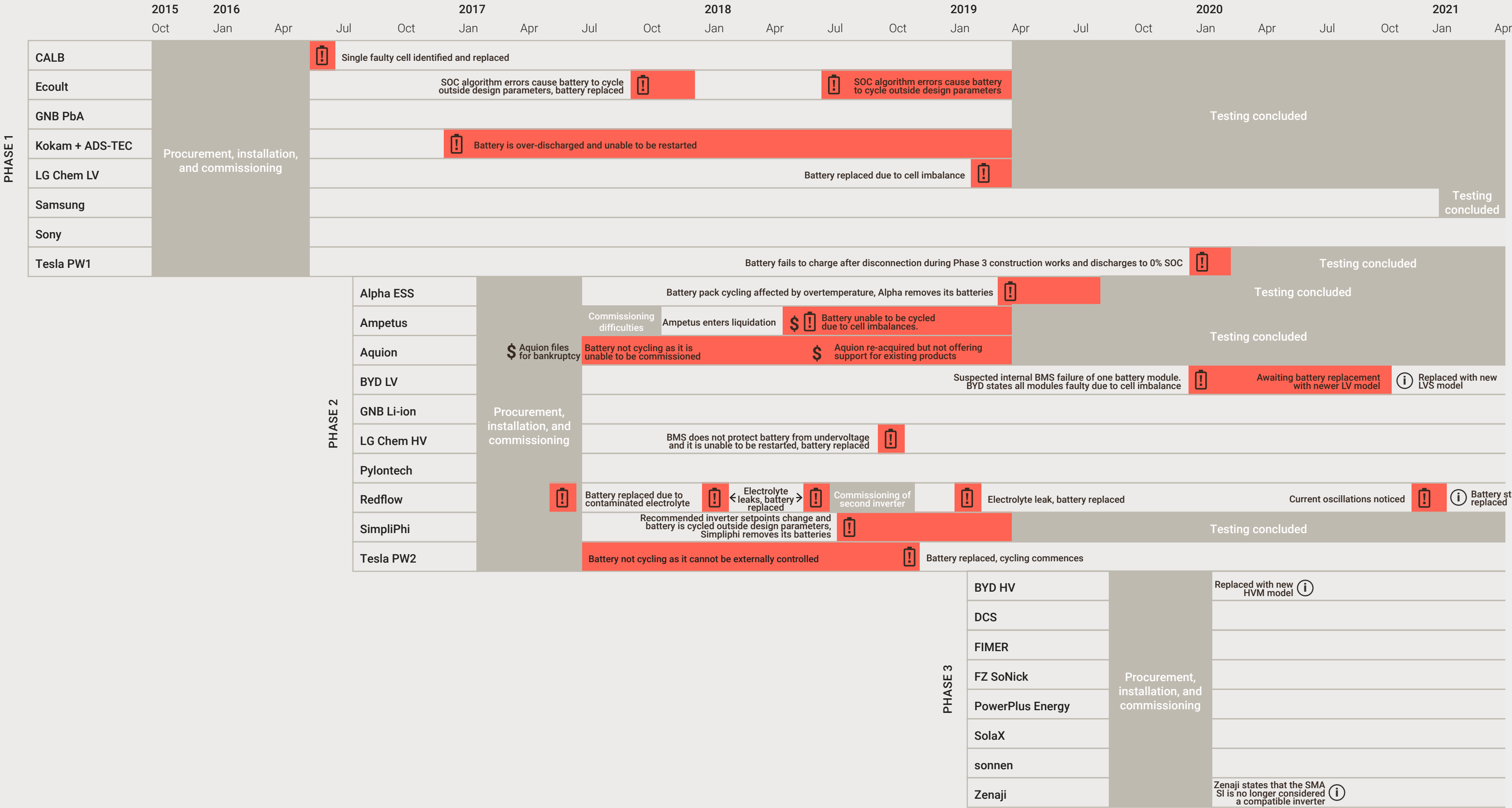


Figure 1: Overview of battery operation

## 3. PHASE 1 UPDATE

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This section provides a summary of any developments in the past six months for the remaining Phase 1 batteries and gives an update on cycling progress overall.

### 3.1. Samsung AIO 10.8

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#### Operational Issues

The Samsung AIO10.8 has generally been highly reliable since installation in 2016. However, in late 2020 the battery began to frequently enter standby mode, requiring manual reset. The Samsung was also demonstrating SOC recalculation when reaching the end of both the charge and discharge periods, jumping from 70% SOC to 90-95% SOC during charging and from 20% SOC to 5% SOC during discharge. Moreover, the power to the Samsung was seen to oscillate between charging and discharging towards the end of charge cycles.

Samsung's technical support team advised that the power oscillations are the BMS attempting to balance cells. ITP believes that the SOC recalculation during the discharge cycle triggers standby mode and expects that these issues are due to cell voltage imbalances, which are typically exacerbated by aging.

As the Samsung now requires frequent intervention to enable cycling, ITP has decided to conclude the testing for the battery. Overall, the battery has generally been very reliable and has completed more cycles than most of the other batteries in the test centre.

#### Capacity Fade

The energy discharged per cycle (Figure 2) can be seen to have decreased over time, with increasing variance between cycles also evident. This is attributed to the issues with SOC estimation described above.

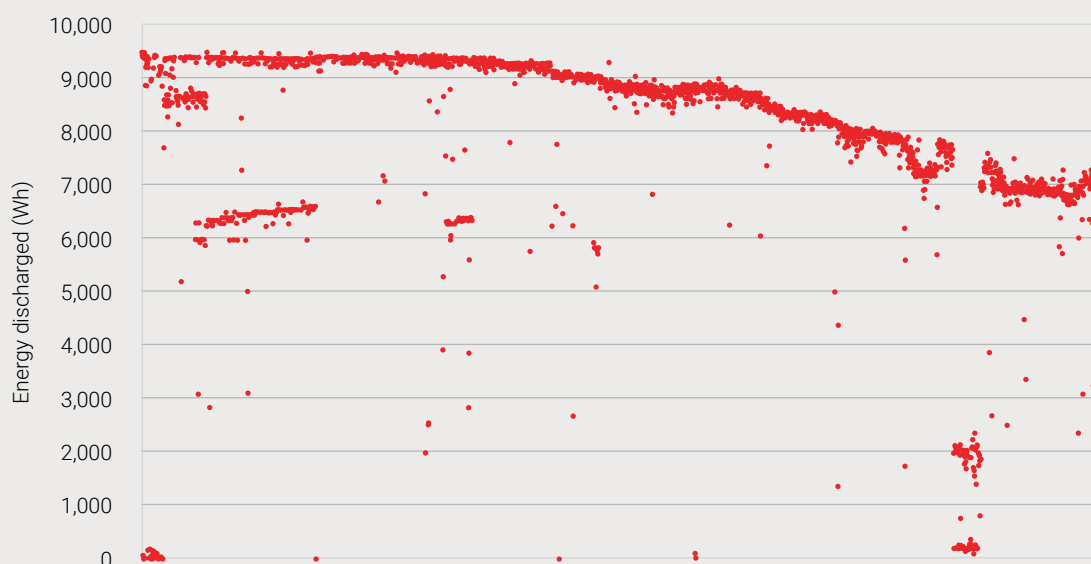


Figure 2: Energy discharged per cycle by the Samsung battery pack

Residual capacity at the conclusion of cycling can be seen to be around 73% of initial capacity (ie. suggesting a 73% SOH) after ~2,790 cycles<sup>1</sup>.

### 3.2. Sony Fortelion

#### Operational Issues

The Sony pack has completed a high number of cycles. No faults have been experienced in the past six months or at any time during testing, and it is still cycling extremely well. There is a small jump in SOC at the end of the charge cycle as it recalculates from 95% to 100%.



#### Capacity Fade

The energy discharged per cycle is depicted in Figure 3. Capacity appears to have decreased linearly over time with a SOH of ~84% after ~2,965 cycles apparent.

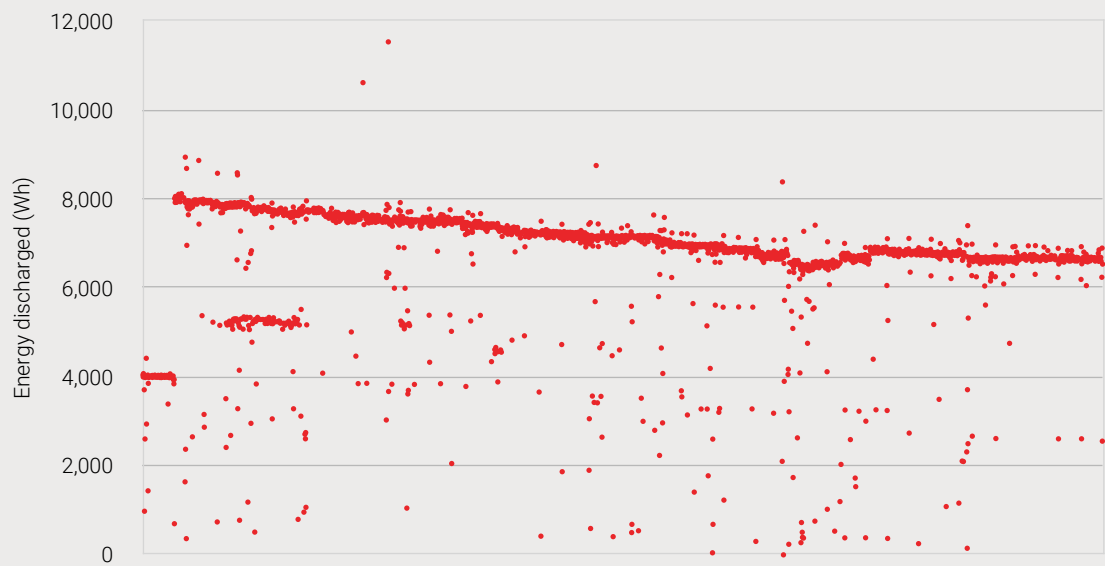


Figure 3: Energy discharged per cycle by the Sony battery pack

<sup>1</sup> In this report, a cycle is defined by the nameplate capacity of the battery. Therefore, a 10kWh battery that completes 2 x 5kWh discharges has completed only 1 cycle.

# 4. PHASE 2 UPDATE

This section provides a summary of any developments in the past six months for the remaining Phase 2 batteries and gives an update on progress overall.

## 4.1. BYD B-Box LVS

### Operational Issues

The BYD B-Box LV was replaced by BYD at the end of October 2020 with a newer model (BYD B-Box LVS) and has been cycling without issues since then. The issues encountered with the previous model are described in previous reports.

### Capacity Fade

No capacity fade is apparent from the small number of cycles completed thus far (~330).



Figure 4: Energy discharged per cycle by the BYD LVS battery pack

## 4.2. GNB Lithium

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### Operational Issues

ITP has not experienced any operational issues with the GNB Lithium battery pack but approached GNB regarding the rapid capacity fade. ITP revised the cycling range after receiving clarification from GNB on the battery's minimum SOC limits, and operational requirements to keep its SOC counter accurate. This appears to have resulted in a slight boost in calculated capacity.

### Capacity Fade

The energy discharged per cycle is depicted in Figure 5. The data suggests a SOH of ~54% after ~1,610 cycles. A slight improvement in capacity is apparent in the most recent data.

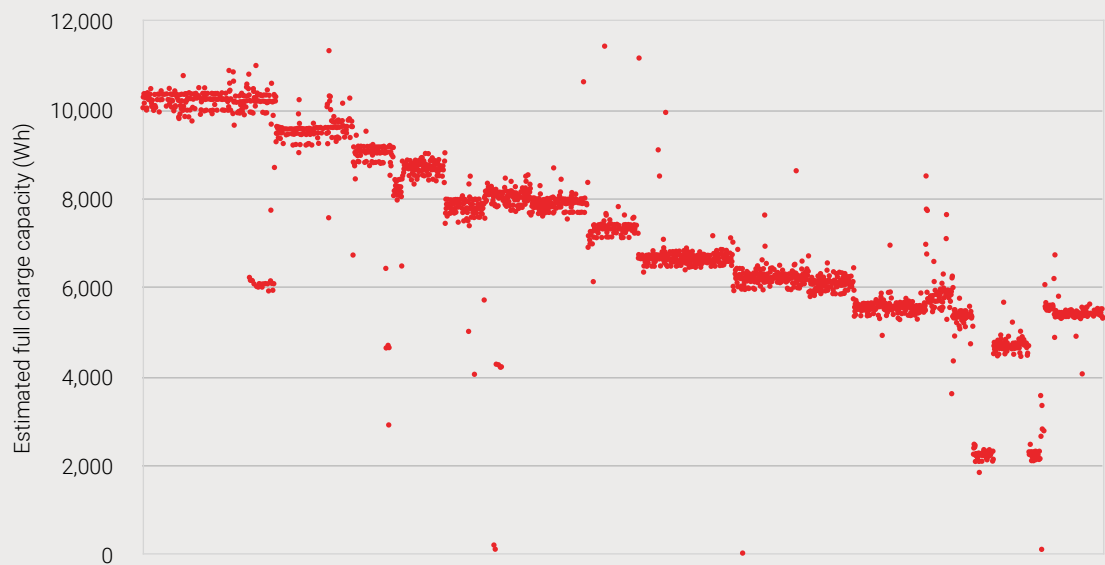
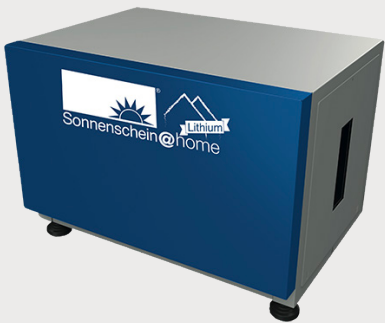


Figure 5: Estimated full charge capacity per cycle by the GNB LFP battery pack

## 4.3. LG Chem RESU HV

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### Operational Issues

No operational issues have been experienced since replacement of this battery in October 2018. The issues encountered with the previous model are described in previous reports.

### Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 6. The data suggests a SOH of ~80% after ~1,430 cycles.



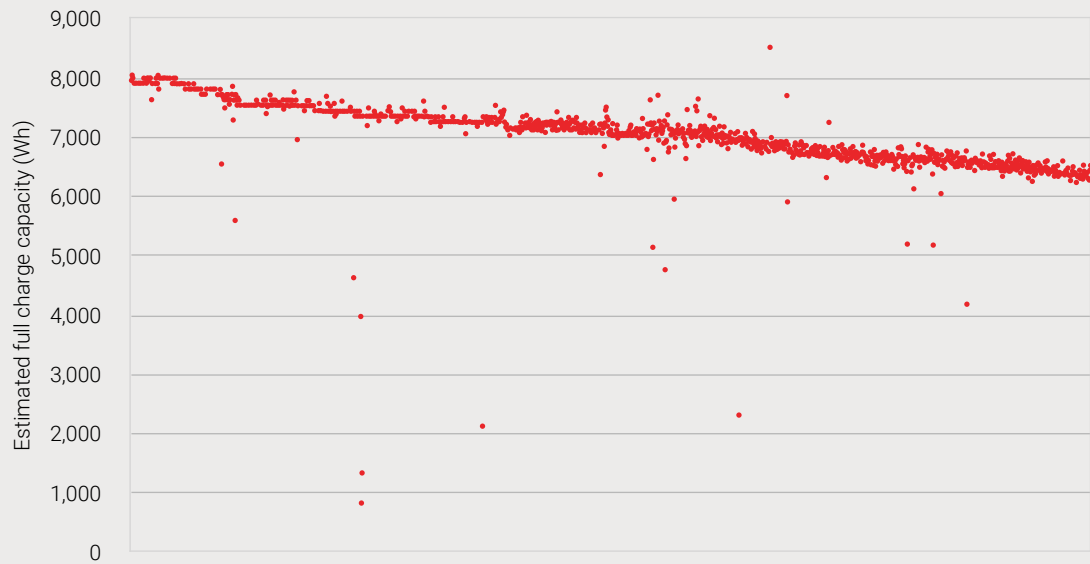


Figure 6: Estimated full charge capacity per cycle by the LG Chem RESU HV battery pack

## 4.4. Pylontech US2000B

### Operational Issues

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



### Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 7. The data suggests a SOH of ~80% after ~2,250 cycles.

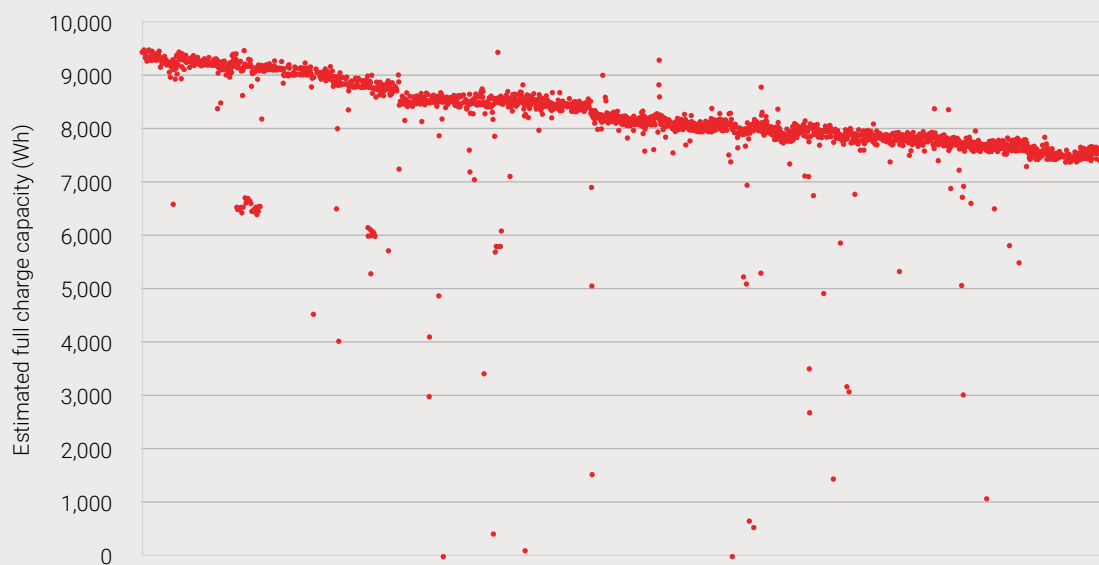


Figure 7: Estimated full charge capacity per cycle by the Pylontech battery pack

## 4.5. Redflow ZCell

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### Operational Issues

This is the fifth Redflow battery to be installed in the test centre, with four replacements previously due to contaminated electrolyte and electrolyte leaks.

In November 2020, Redflow noticed oscillations in the inverter current at the end of a discharge cycle. After running maintenance and testing cycles, Redflow concluded that the issue was caused by a fault in the battery stack. The battery stack was replaced by Redflow in Feb 2021 and the battery has returned to normal cycling. The electrolyte and tanks were retained but ITP reset the cycle count as replacement of the battery stack is a major overhaul.

The Redflow battery operates on a slightly different cycling regime to other batteries in the trial. Due to battery charge rate limits, as well as the requirement for regular maintenance cycles during which normal operation is paused, the Redflow only completes two full cycles per day (instead of three).

The purpose of the maintenance cycle is to remove all zinc from the electrode stack so the next charge cycle starts with a “clean slate”. The maintenance cycle requires the battery be fully discharged before the maintenance can occur. For the trial, this is scheduled to occur at the end of each day (after two complete cycles).

### Capacity Fade

No capacity fade is apparent from the small number of cycles completed thus far.



## 4.6. Tesla Powerwall 2

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### Operational Issues

The Powerwall 2 was replaced by Tesla in September 2018 and has been cycling without issues since then. The issues encountered with the previous model are described in previous reports.

ITP 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. This requires intermittent contact with Tesla as it appears that the control is only set for a finite period each time it is implemented.

User-friendly monitoring of the Tesla Powerwall 2 is only possible via Tesla's mobile app. Some data is available from the Tesla Powerwall 2's local web interface. However, detailed data is only able to be accessed via the Application Programming Interface (API). Although Tesla has not published local API documentation, online community groups have published a tutorial on how to take data from the battery<sup>2</sup>. The data used by ITP in monitoring and analysis is obtained from this API.

The Tesla Powerwall 2 is experiencing small jumps in SOC at the end of the discharge cycle (7% to 0%) and the start of the charge cycle (0% to 9%) but this does not impact cycling.



<sup>2</sup> <https://mikesgear.com/2017/12/07/monitoring-teslas-powerwall2-on-pvoutput-org/>

Capacity Fade

The energy discharged per cycle is depicted in Figure 8. The data suggests a SOH of ~85% after ~1,690 cycles.

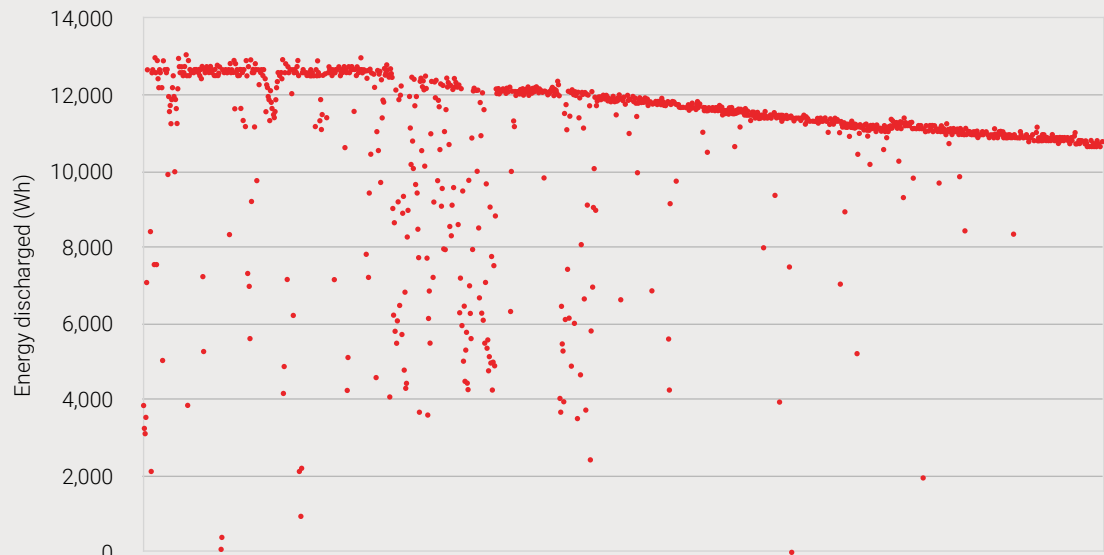


Figure 8: Energy discharged per cycle by the Tesla Powerwall 2 battery pack

## 5. PHASE 3 UPDATE

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This section provides a summary of any developments in the past six months for the remaining Phase 3 batteries, and gives an update on progress overall.

### 5.1. BYD B-Box HVM

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#### Operational Issues

The BYD B-Box HV was replaced with BYD's more recent HVM model in June 2020. There were no issues experienced with the original B-Box HV installed, but the testing period had only just begun and ITP considered it more valuable to replace it with the latest model. The original B-Box HV is no longer commercially available.

In mid-July 2020, the HVM was shut down as part of a scheduled outage. However, this caused the battery to enter a 'stuck' state where it could no longer be turned off or on. BYD was helpful in assisting and the battery started operating again after the BCU was temporarily disconnected from the modules.

In late August 2020, the battery's internal DC breaker tripped during normal cycling and continued to trip after only a few minutes after reconnection to the SMA Sunny Boy inverter. BYD concluded that the battery stopped working due to the Sunny Boy Storage firmware being out of date and incompatible with the HVM battery. SMA and BYD were helpful and provided support to get the battery cycling again in November 2020. Since then, the battery has been cycling reliably.

#### Capacity Fade

No capacity fade is apparent after ~400 cycles.





Figure 9: Estimated full charge capacity per cycle by the BYD HVM battery pack

## 5.2. Deep Cycle Systems (DCS) PV 10.0

### Operational Issues

The DCS battery in this trial is connected to an SMA Sunny Island inverter. Although the battery has a BMS, it does not communicate with the inverter. Therefore, the inverter is responsible for estimating SOC based on battery parameters entered, and its own measurements (e.g. voltage, temperature, Coulombs etc.).

The DCS battery is cycled between minimum and maximum battery voltage limits (as per DCS advice), as well as a minimum inverter SOC (to avoid inverter shutdown), meaning that the end of the discharge cycle is determined by whichever of the minimum battery voltage or inverter SOC is reached first. When discharging the battery at a C3 rate, the battery voltage and inverter-estimated SOC was dropping to their cut-off levels well before the expected energy was discharged. Early in the testing period DCS sent a DC charger to ITP to confirm that there were no issues with the battery, by performing a slow 1 kW discharge down to minimum voltage. This test indicated that the battery was still at full capacity. However, as ITP had difficulty discharging this full capacity at higher discharge rates. To maximise the energy discharged per cycle while maintaining three cycles per day, ITP reduced the charge/discharge rate as well as the rest time between cycles. The slower discharge rate allows more energy to be discharged each cycle before the cut-off limits are reached; however, the 'full' capacity of the battery is still not discharged through this cycling.



### Capacity Fade

A trend in capacity is difficult to determine after ~600 cycles.

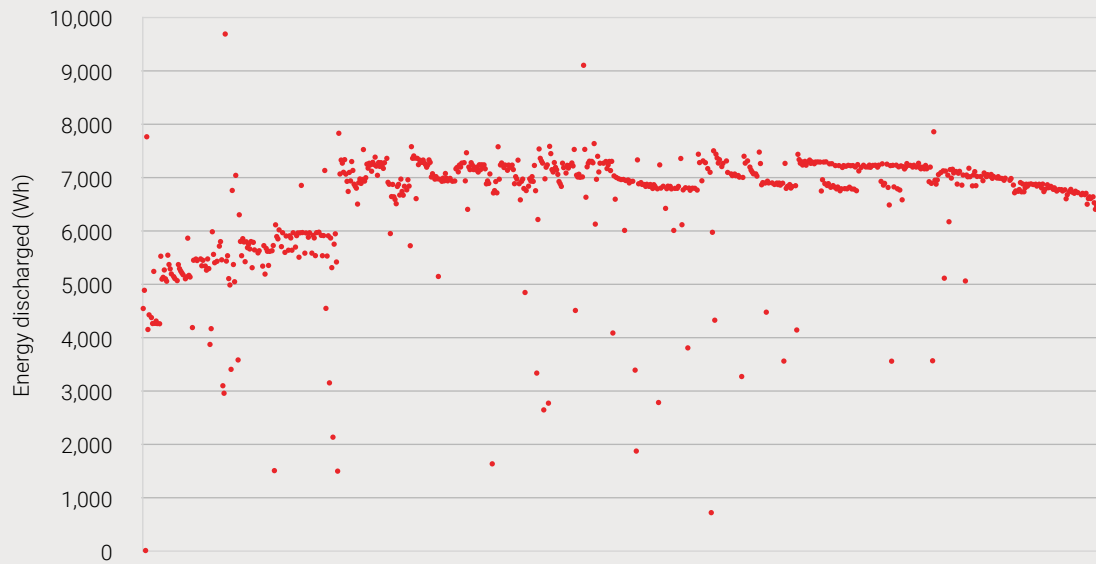


Figure 10: Energy discharged per cycle by the DCS battery pack

## 5.3. FIMER REACT 2

### Operational Issues

ITP has not experienced any operational issues with the FIMER REACT 2 battery.

### Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 11. The data suggests a SOH of 91% after ~890 cycles.

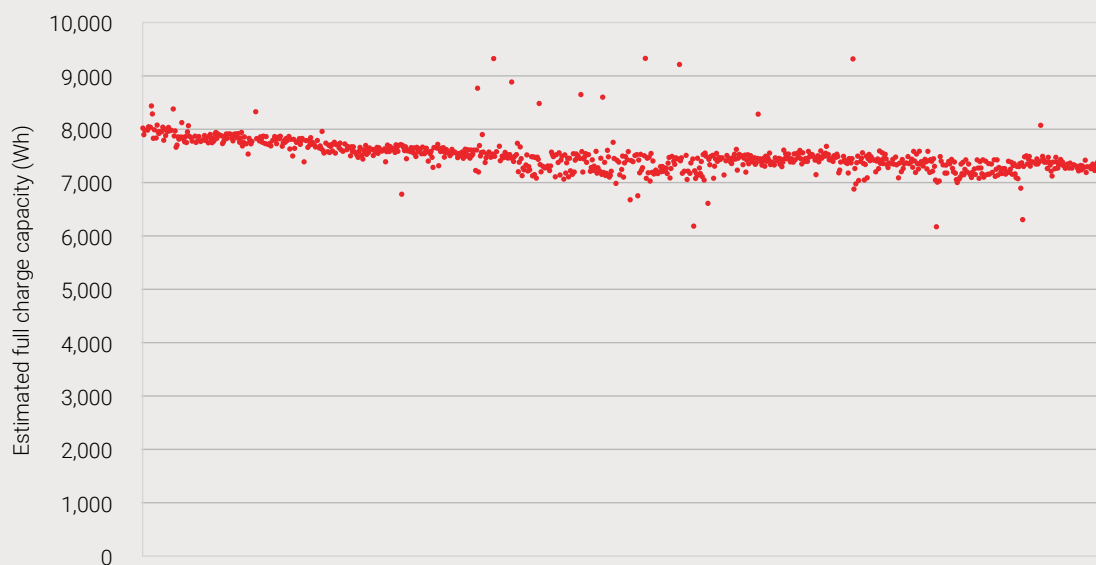


Figure 11: Estimated full charge capacity per cycle by the FIMER battery pack

# 5.4. FZSoNick

## Operational Issues

The FZSoNick is connected to a Victron inverter. The battery operates on a slightly different cycling regime to other batteries in the trial. Due to battery charge rate limits, it only completes two full cycles per day (instead of three).

There are no direct communications from the FZSoNick BMS to the inverter, so the Victron inverter does not know the battery SOC as communicated from the BMS. The Victron inverter does estimate SOC based on battery measurements; however, it is not clear how accurate this figure is, and ITP does not use it as a parameter in inverter cycling control. With support from the Australian distributor GridEdge, ITP has implemented a system which reads the battery SOC directly from the BMS, and uses this value to determine and communicate to the inverter whether it should charge or discharge.

FZSoNick also advised that the battery should undertake a weekly cycle with prolonged charge periods and discharge down to 0% SOC, in order to preserve battery capacity and keep the BMS SOC calculator accurate. These operational differences mean that the FZSoNick battery accumulates cycles at a slower rate than other batteries in the trial.

Other than these requirements, ITP has not experienced any operational issues with the FZSoNick battery.

## Capacity Fade

Minimal capacity fade is apparent after ~440 cycles.

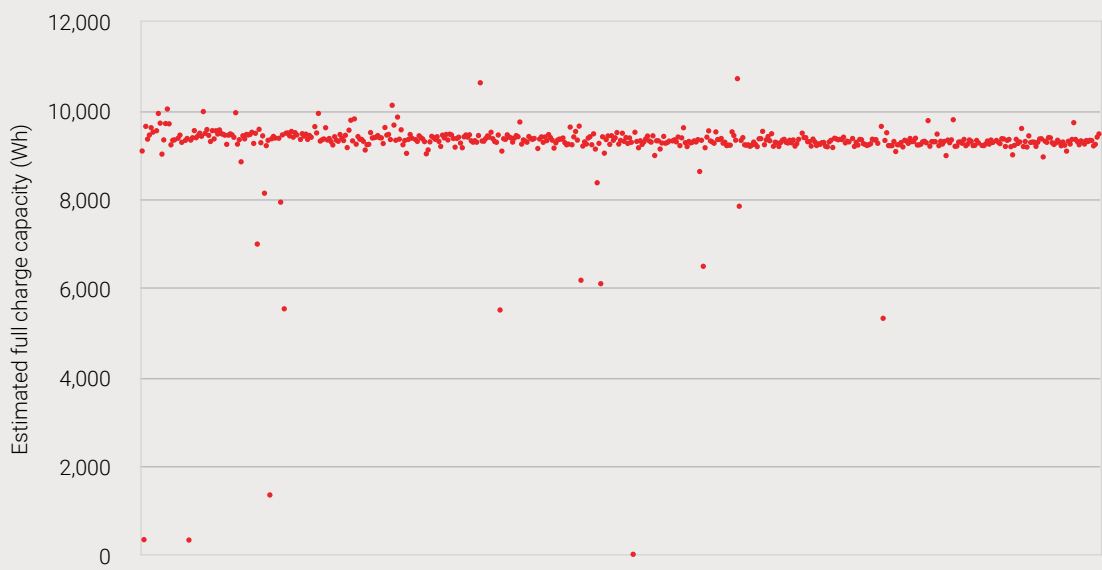


Figure 12: Estimated full charge capacity per cycle by the FZSoNick battery pack

# 5.5. PowerPlus Energy LiFe Premium

## Operational Issues

The PowerPlus batteries in the trial are connected to an SMA Sunny Island inverter. Although each battery has a BMS, the BMS does not communicate with the inverter. Therefore, the inverter is responsible for estimating SOC based on battery parameters entered, and its own measurements (e.g. voltage, temperature, Coulombs etc.).



However, the inverter does not appear to be able to accurately estimate the SOC as SOC jumps at the end of discharge cycles (in line with the battery voltage), and there is also an upwards jump at the end of the charge cycle. The end of each discharge cycle is in practice limited by the inverter minimum SOC setpoint (to avoid shutdown) rather than the minimum voltage the battery can reach.

ITP found that when cycling at C3 rates, the energy discharged during each cycle was not close to the maximum apparently available, due to inverter SOC limits being reached first. The battery is now cycling at closer to a C4 rate and the battery discharges more energy at this rate before reaching minimum SOC.

The battery warranty is dependent on the battery not being cycled below 20% SOC. Given SOC data is not being directly communicated from the BMS to the inverter, it appears that PowerPlus is depending on the inverter to either accurately or conservatively estimate the battery SOC. ITP's experience with this inverter suggests inverter SOC estimation should not be relied upon.

The PowerPlus battery also requires a 100% recharge every 7 to 14 days to keep the external SOC counter accurate.

## Capacity Fade

No capacity fade is apparent after ~530 cycles but each cycle can be seen to be delivering much less energy than the nameplate capacity. This is likely a result of the issues described above.

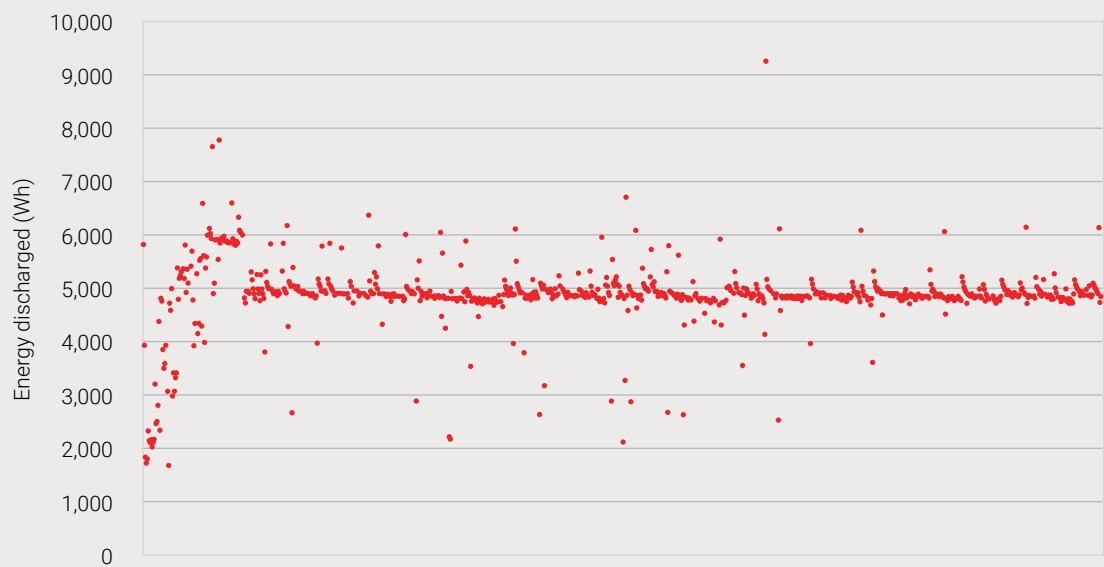


Figure 13: Energy discharged per cycle by the Powerplus battery pack

# 5.6. SolaX Triple Power

## Operational Issues

The SolaX battery has been cycling reliably but the energy and SOC discharged per cycle has started to drop off rapidly. ITP has reached out to SolaX and is awaiting a response after they complete their investigation.

## Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 14. The data suggests a SOH of 88% after ~880 cycles.

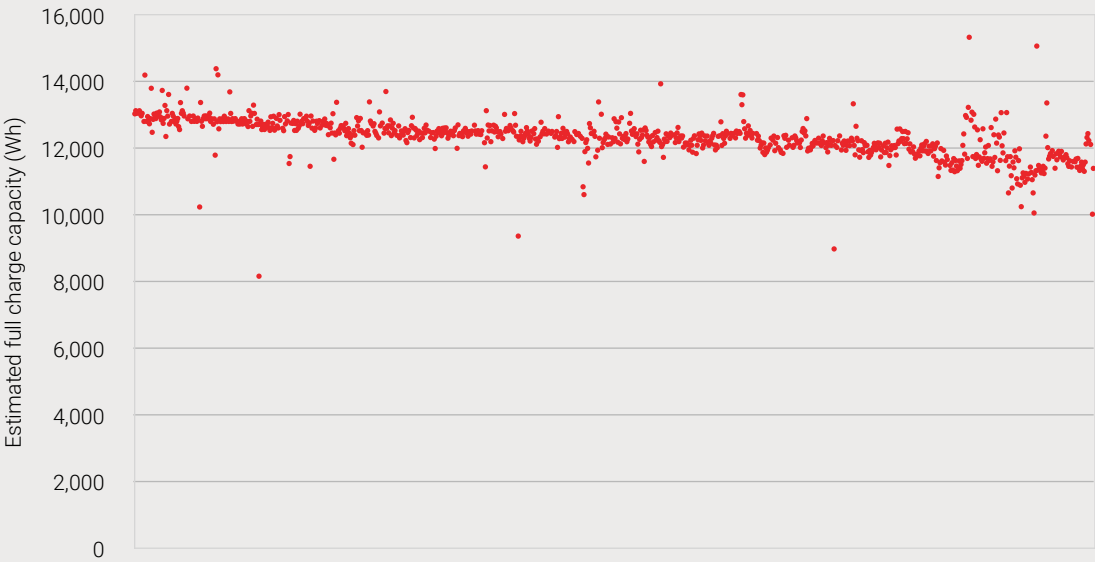


Figure 14: Estimated full charge capacity per cycle by the SolaX battery pack

# 5.7. sonnenBatterie

## Operational Issues

Following some issues establishing control of the battery during commissioning, ITP has not experienced any operational issues with the sonnenBatterie.

## Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 15. No significant capacity fade is apparent after ~800 cycles.

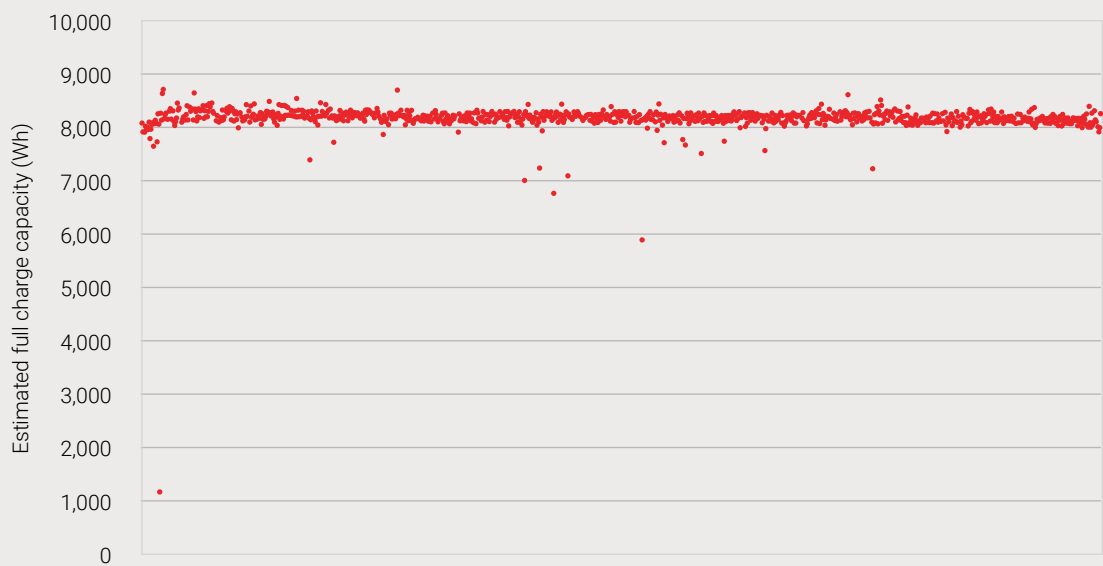


Figure 15: Estimated full charge capacity per cycle by the Sonnen battery pack

# 5.8. Zenaji Aeon

## Operational Issues

The Zenaji batteries in the trial are connected to an SMA Sunny Island inverter. Although each unit has a BMS, the BMS does not communicate with the inverter. Therefore, the inverter is responsible for estimating SOC based on battery parameters entered, and its own measurements (e.g. voltage, temperature, Coulombs etc.).

However, the inverter does not appear to be able to accurately estimate the SOC as SOC jumps at the end of discharge cycles (in line with the battery voltage) and then re-calculates downwards. There is also a sharp upwards jump partway through the charge cycle. The SOC does not generally go higher than 85%, and the end of each discharge cycle is limited by the inverter SOC setpoint (to avoid shutdown) rather than the minimum voltage the battery can reach.



This behaviour has made it difficult to cycle the batteries according to the test methodology (i.e. 3x full cycles per day). The energy discharged during each cycle is not close to the maximum apparently available.

ITP has communicated with Zenaji about these difficulties and the best settings to use. In early July 2020 Zenaji informed ITP that it no longer recommends the SMA Sunny Island inverter for use with the Aeon batteries and was removing it from its list of compatible inverters. ITP requested that Zenaji replace the inverter with a Victron MultiPlus-II, the only other compatible inverter which is also used in the trial. However, Zenaji stated that it is not in a position to offer any model other than a Schneider inverter at this point in time. Since the Schneider model is not used in the lab, ITP will continue to use the SMA Sunny Island until such time as Zenaji can replace it with a Victron inverter.

### Capacity Fade

Owing to the issues described above, the trend in capacity fade is unclear after ~380 cycles.

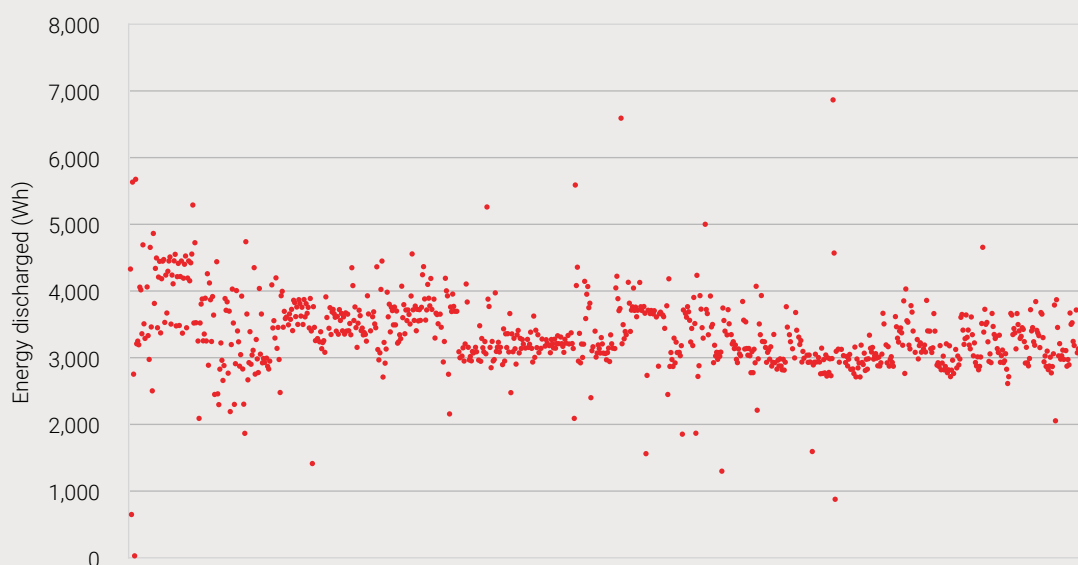


Figure 16: Energy discharged per cycle by the Zenaji battery pack

# 6. PERFORMANCE COMPARISON

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

Throughout the trial, ITP has observed erratic 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 Sections 3, 4 and 5 above). Both data sets should be considered before drawing conclusions.

## 6.1. Phase 1 Capacity Test Results

Figure 17 shows the estimated state of health (SOH) against cycles completed for each Phase 1 battery pack still cycling. SOH is estimated by dividing the energy delivered during each capacity test by the energy delivered in the first capacity test.

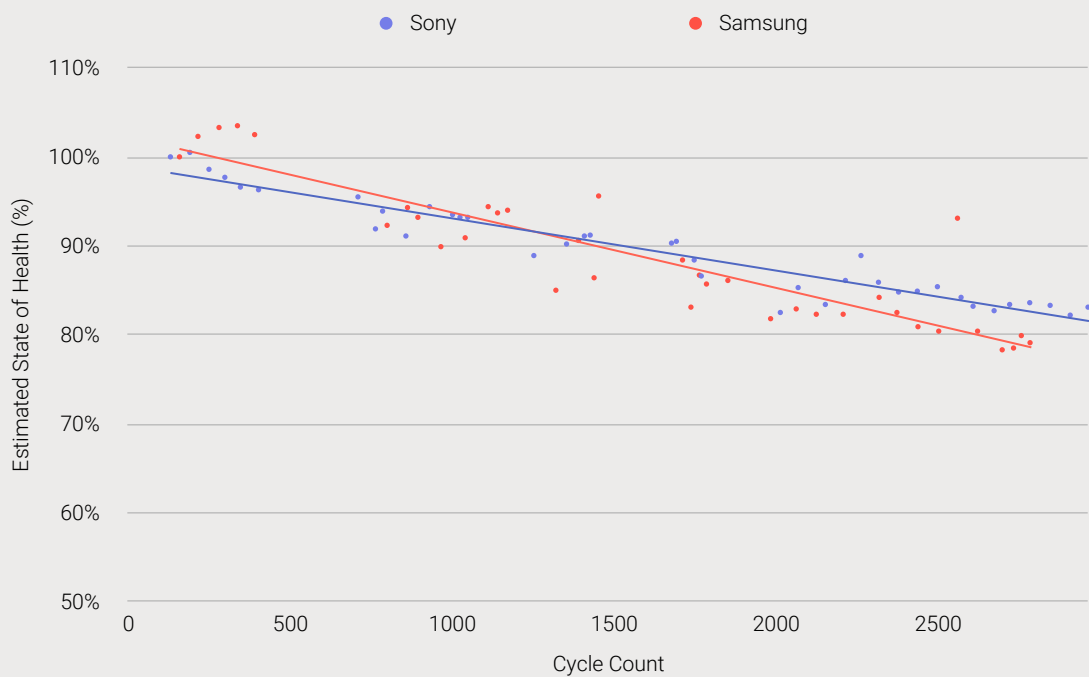


Figure 17: Capacity fade of Phase 1 battery packs based on monthly capacity tests

It should be noted that Figure 17 includes lines of “best fit” that are determined by simple linear regression between cycles and SOH. While a linear relationship appears to provide a good fit to the capacity test data collected to date, extrapolating linearly into the future may not be appropriate.

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## Samsung AI010.8

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Based on the linear regression between estimated SOH and cycles completed (Figure 17), the Samsung AI0 pack is on track for 60% SOH at ~4,380 cycles. However, the battery pack is no longer usable and has been retired before this point.

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## Sony Fortelion

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Based on a linear regression between estimated SOH and cycles completed (Figure 17), the Sony Fortelion pack is on track for 60% SOH at ~6,640 cycles. As above, however, a linear extrapolation may not be appropriate.

## 6.2. Phase 2 Capacity Test Results

Figure 18 shows the estimated state of health (SOH) against cycles completed for each Phase 2 battery pack still cycling. SOH is estimated by dividing the energy delivered at each capacity test by the energy delivered in the first capacity test.

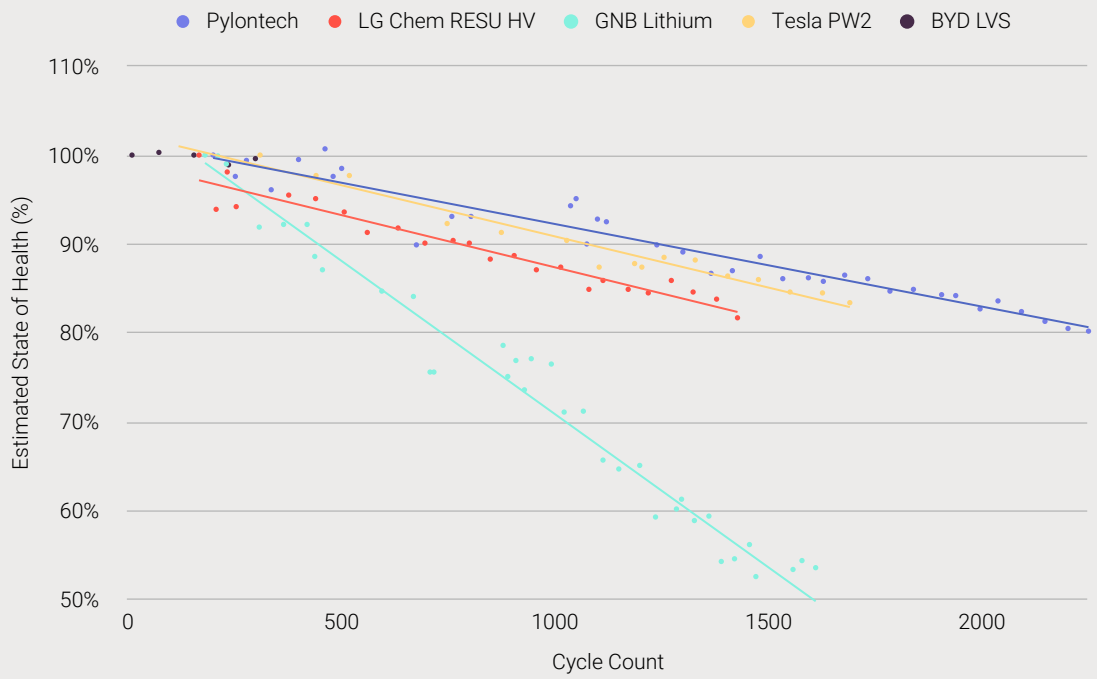


Figure 18: Capacity fade of Phase 2 battery packs based on monthly capacity tests

It should be noted that Figure 18 includes lines of “best fit” that are determined by simple linear regression between cycles and SOH. While a linear relationship appears to provide a good fit to the capacity test data collected to date, extrapolating linearly into the future may not be appropriate.

### GNB Lithium

Based on a linear regression between estimated SOH and cycles completed (Figure 18), the GNB Lithium reached 60% SOH at ~1,315 cycles. As above, however, the data suggests some non-linearity which may invalidate this extrapolation. In this case, the SOH appears to already be below 60%.

### LG Chem RESU HV

Based on the linear regression between estimated SOH and cycles completed (Figure 18), the LG Chem RESU HV is on track for 60% SOH at ~3,330 cycles. As above, however, a linear extrapolation may not be appropriate.

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## Pylontech US2000B

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Based on the linear regression between estimated SOH and cycles completed (Figure 18), the Pylontech US2000B is on track for 60% SOH at ~4,470 cycles. As above, however, a linear extrapolation may not be appropriate.

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## Tesla Powerwall 2

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The Tesla Powerwall 2 cycling regime is implemented by Tesla, based on requests from ITP. This requires intermittent communication with Tesla as their implemented schedules periodically expire.

Based on the linear regression between estimated SOH and cycles completed (Figure 18), the Tesla Powerwall 2 is on track for 60% SOH at ~3,680 cycles. As above, however, a linear extrapolation may not be appropriate.

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## Redflow ZCell

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The Redflow ZCell is controlled via the ZCell portal, where it follows a daily cycling regime. The portal does not currently allow for monthly scheduled changes to implement the capacity test regime.

## 6.3. Phase 3 Capacity Test Results

Figure 19 shows the estimated state of health (SOH) against cycles completed for each Phase 3 battery pack. SOH is estimated by dividing the energy delivered at each capacity test by the energy delivered in the first capacity test.

It should be noted that Figure 19 includes lines of “best fit” that are determined by simple linear regression between cycles and SOH. While a linear relationship appears to provide a good fit to the capacity test data collected to date, extrapolating linearly into the future may not be appropriate. No line of best fit has been included for batteries with less than 500 cycles or if the trend is highly non-linear.

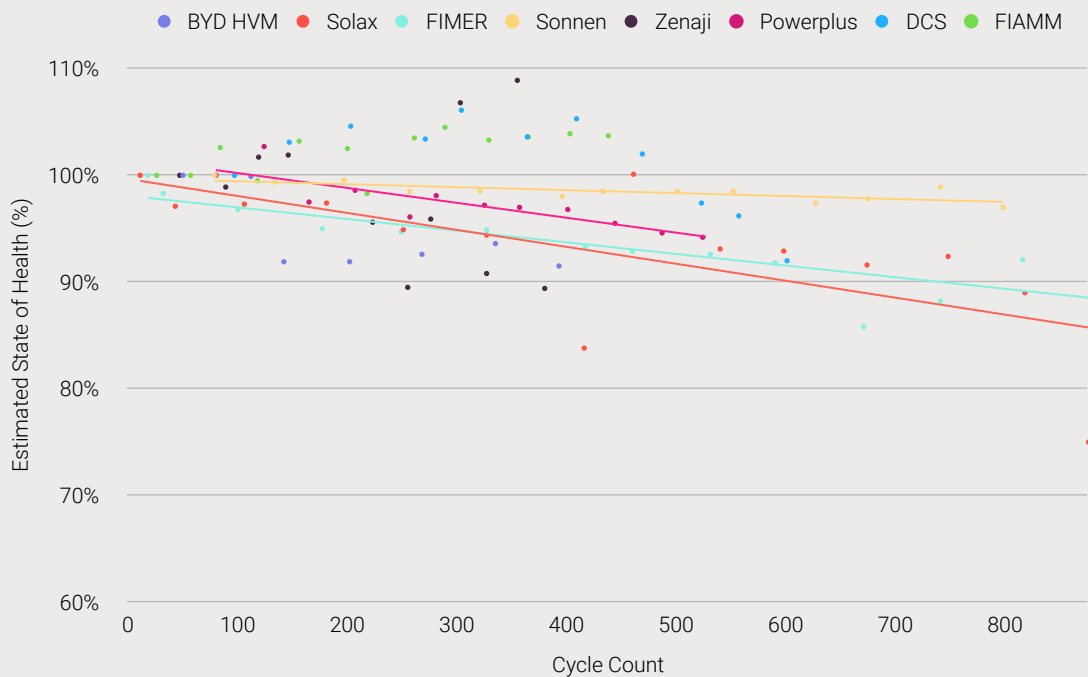


Figure 19: Capacity fade of Phase 3 battery packs based on monthly capacity tests

### FIMER REACT 2

Based on the linear regression between estimated SOH and cycles completed (Figure 19), the FIMER REACT 2 is on track for 60% SOH at ~3,480 cycles. As above, however, a linear extrapolation may not be appropriate.

### PowerPlus Energy LiFe Premium

Based on the linear regression between estimated SOH and cycles completed (Figure 19), the PowerPlus Energy LiFe Premium is on track for 60% SOH at ~2,995 cycles. As above, however, a linear extrapolation may not be appropriate.

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## SolaX Triple Power

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Based on the linear regression between estimated SOH and cycles completed (Figure 19), the SolaX Triple Power is on track for 60% SOH at ~2,495 cycles. As above, however, a linear extrapolation may not be appropriate.

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## sonnenBatterie

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Based on the linear regression between estimated SOH and cycles completed (Figure 19), the sonnenBatterie is on track for 60% SOH at ~14,370 cycles. As above, however, a linear extrapolation may not be appropriate.

# 6.4. Round-Trip Efficiency

The lifetime round-trip efficiency results are shown for each battery in Figure 20. Note that the results shown for the sonnenBatterie and Tesla PW2 are in orange as these values are AC round-trip efficiency. DC values are not available, but can be assumed to be higher.

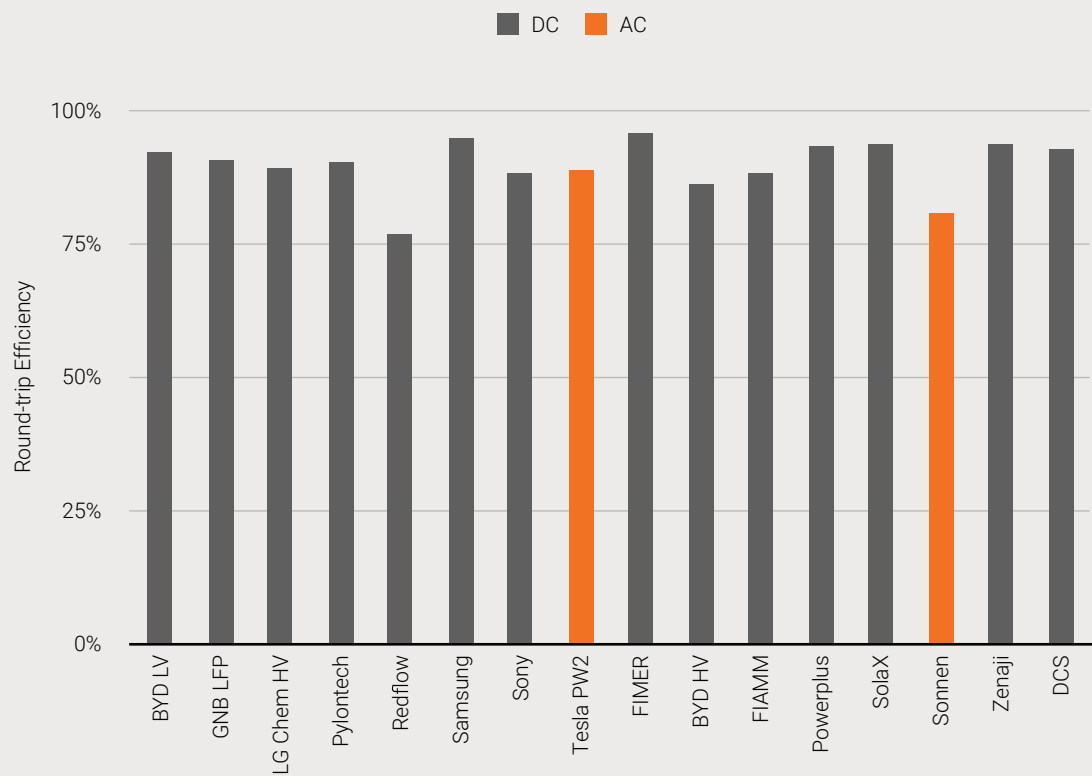


Figure 20: Lifetime round-trip efficiency for each battery pack

## 7. MARKET DEVELOPMENT

Since the beginning of the trial in 2016, most manufacturers have significantly altered their product offering, and many have exited the market or become insolvent. The cost of residential and commercial scale lithium-ion battery packs has fallen but cost progress has slowed in recent years owing to high battery demand from the EV sector. Figure 21 shows wholesale battery pack prices for NMC, LFP and LTO battery models installed in the Battery Test Centre over time.

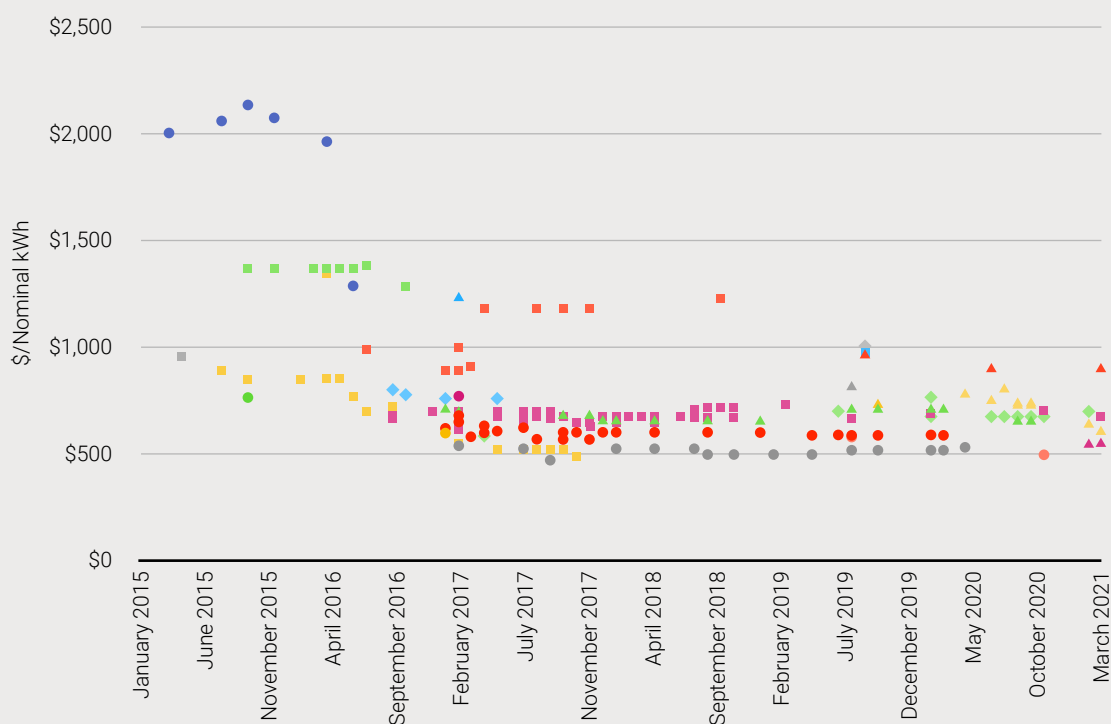


Figure 21: Wholesale prices for lithium-ion battery products installed in the Battery Test Centre

Globally, significant additional lithium-ion battery production capacity is under development as both the EV and stationary storage markets expand. As this supply catches up with demand, further reductions in lithium-ion battery prices are expected.

## 8. LESSONS LEARNED

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Having been in operation for over five 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, but also to the performance of suppliers in delivering products and providing technical support during commissioning and operation. These lessons have been described in previous reports, available at [www.batterytestcentre.com.au](http://www.batterytestcentre.com.au). While all of those lessons are still pertinent, the following additional observations have been made since the last Public Report.

- Some of the batteries installed under Phase 3 have no communications between the BMS and inverter, meaning the inverter is responsible for SOC estimation. This has presented challenges cycling these batteries according to the test methodology.
- The capability of the manufacturer to diagnose faults remotely has proven valuable for some batteries. Ideally, this would not be required, but faults have proven common throughout the trial.

# Appendix A: Knowledge Sharing

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.

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>3</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 268,750 page views with an average of 2:09 minutes spent per page overall and 3:53 minutes spent on the reports page.

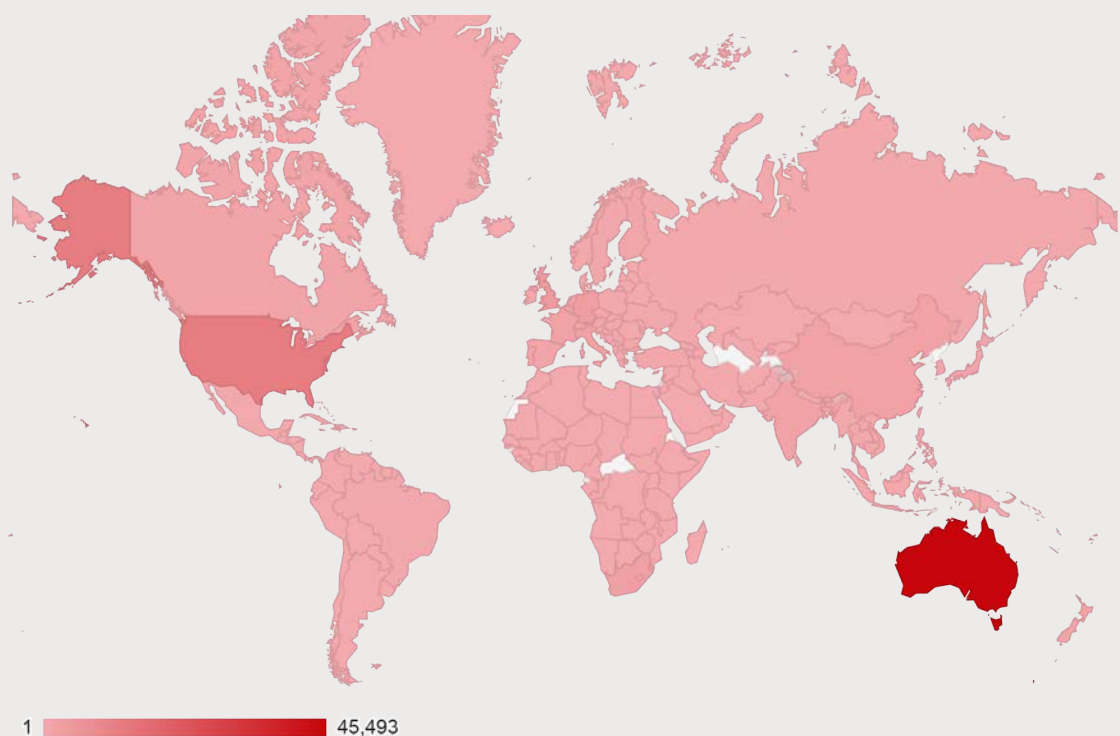


Figure 22: Number of sessions by country

<sup>3</sup> [batterytestcentre.com.au](https://batterytestcentre.com.au)

The data from the website shows that the key audience is Australia, with Australian IP addresses accounting for 66,013 sessions (47.1%). 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 14,709 sessions from the United States, 4,785 from the United Kingdom and Germany not far behind on 4,439. It is interesting to note, however, that the content has been accessed from right across the globe.

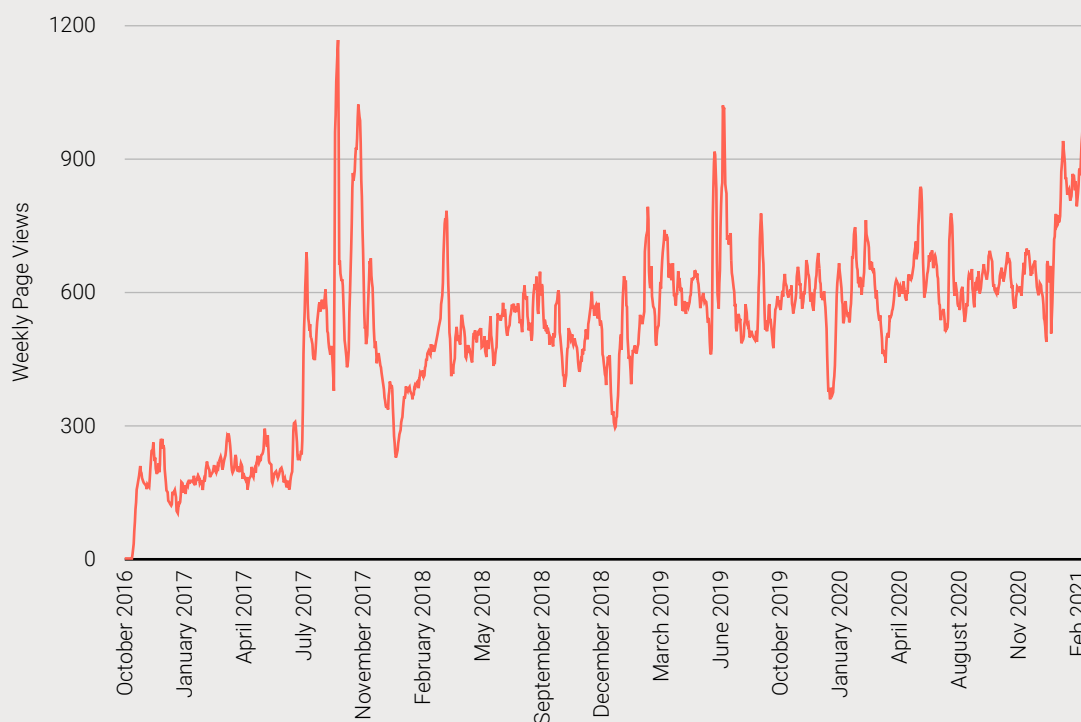


Figure 23: Weekly active users

Figure 23 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. Since then the number of users has been on a gradual upwards trajectory, with an increase noted after the release of Report 6 and associated media articles in June 2019. Around April 2020 there was a small decline in viewers, likely due to the focus on COVID-19 related news at that time. In the long term, interest in the site has remained reasonably constant with the number of weekly users hovering around an average of 600. But interest in the website has been spiking again starting from this year with the no. of weekly users going up to 900.

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 (18%) are the reports page (12%), the batteries page (11%), Pylontech US2000B (10%), LG Chem RESU (4%) and the background page on lithium-ion technology (4%).

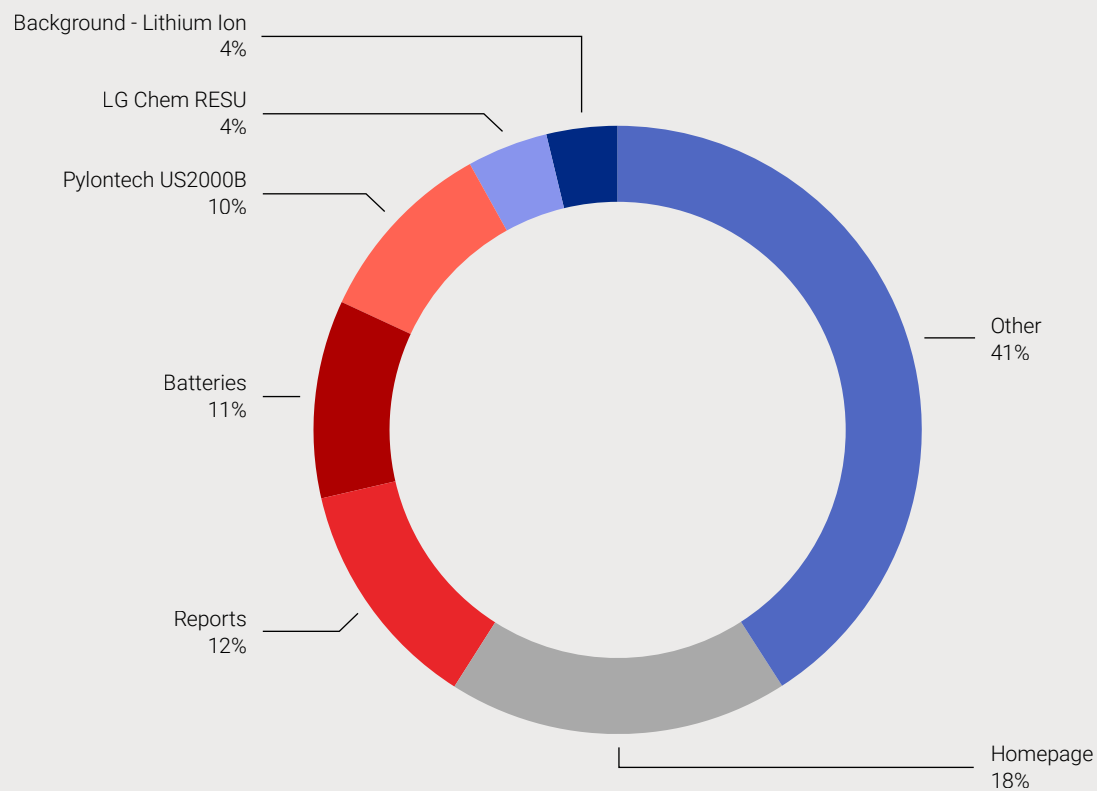


Figure 24: Breakdown of the 268,750 page views

# Appendix B: 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.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Low (°C)	22	20	18	16	14	12	10	12	14	16	18	20
High (°C)	36	34	32	30	28	26	24	26	28	30	32	34
Regime (°C)	S	S	S	S	W	W	W	W	W	W	S	S

Table 2: Daily high and low ambient 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.

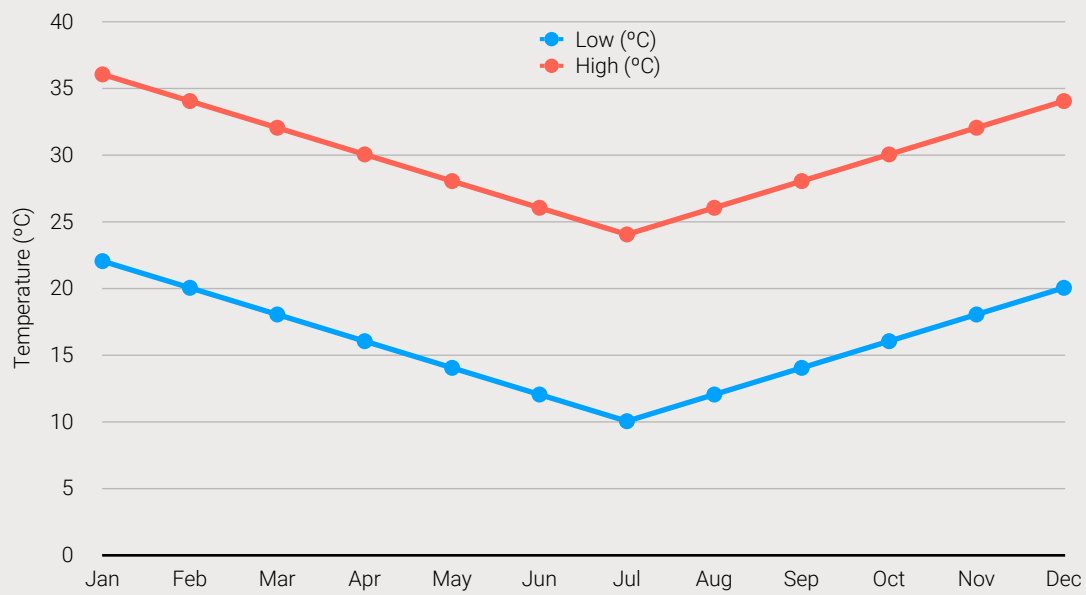


Figure 1: Daily hot and cold cycle temperatures throughout the year

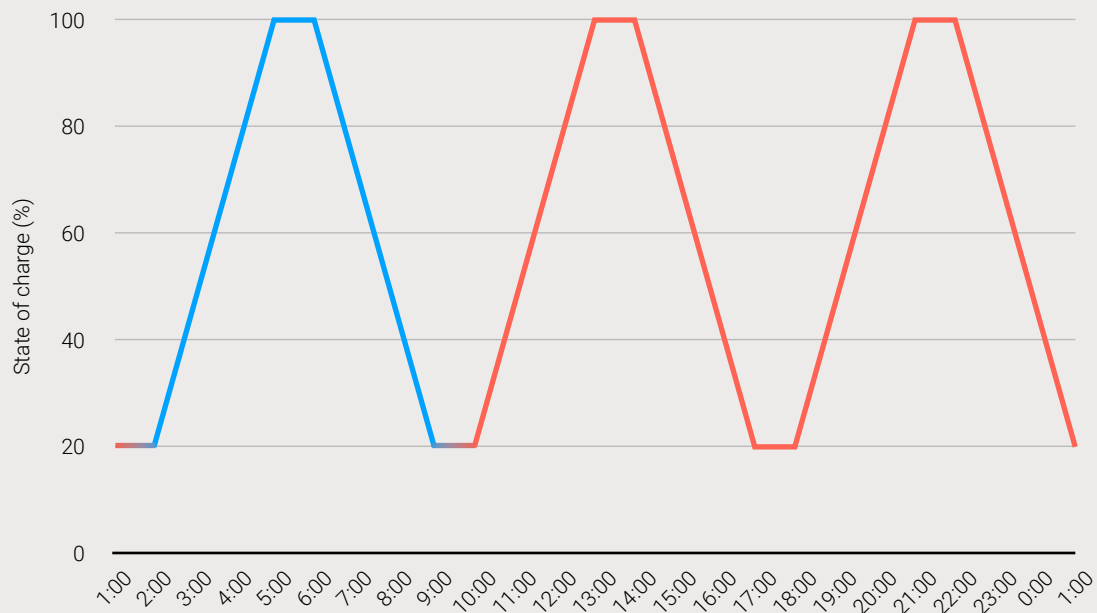


Figure 2: Summer temperature regime and charge regime

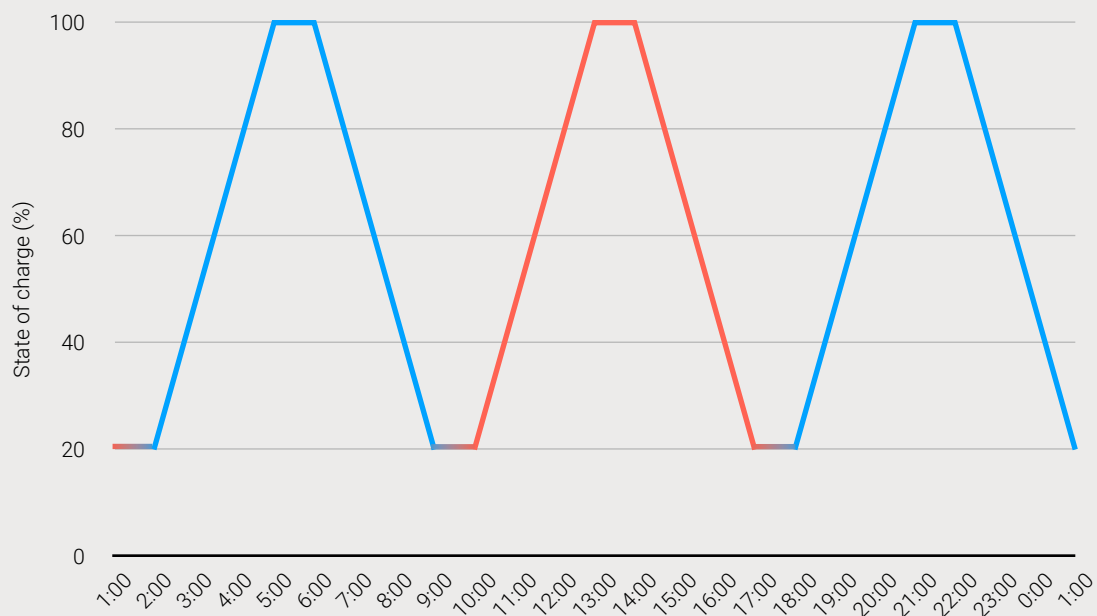


Figure 3: Winter temperature regime and charge regime

## Appendix C: Previous Report Summary

### 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 3 below.

Product	Type	Nameplate Capacity (kWh nominal)
CALB CA100	Lithium Iron Phosphate	10.24
Ecoul UltraFlex	Lead Carbon	14.8 (C8)
GNB Sonnenschein	Lead Acid	14.4 (C100)
Kokam Storaxe + ADS-TEC BMS	Lithium Nickel Manganese Cobalt	8.3
LG Chem RESU 1	Lithium Nickel Manganese Cobalt	9.6
Samsung AIO	Lithium Nickel Manganese Cobalt	10.8
Sony Fortelion	Lithium Iron Phosphate	9.6
Tesla Powerwall 1	Lithium Nickel Manganese Cobalt	6.4

Table 3: Phase 1 battery packs

At the completion of the first report, battery cycling 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.

### Report 2 March 2017

Capacity tests were conducted in each of the six months between September 2016 and February 2017, and the results

were published in Public Report 2.

During that time, the Kokam battery was over-discharged and was unable to be restarted.

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.

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.

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## Report 3

### November 2017

Report 3 described the process of procuring and installing the 10 x Phase 2 battery packs listed in Table 4 below, and outlined testing results and general observations or issues encountered with the Phase 1 battery packs.

Product	Type	Nameplate Capacity (kWh nominal)
Alpha ESS M48100	Lithium Iron Phosphate	9.6
Ampetus Super Lithium	Lithium Iron Phosphate	9.0
Aquion Aspen	Aqueous Hybrid Ion	17.6
BYD B-Box	Lithium Iron Phosphate	10.24
GNB Lithium	Lithium Nickel Manganese Cobalt	12.7
LG Chem RESU HV	Lithium Nickel Manganese Cobalt	9.8
Pylontech US2000B	Lithium Iron Phosphate	9.6
Redflow ZCell	Zinc-Bromide Flow	10.0
SimpliPhi PHI 3.4	Lithium Iron Phosphate	10.2
Telsa Powerwall 2	Lithium Nickel Manganese Cobalt	13.5

Table 4: Phase 2 battery packs

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 was reported and general SOC estimation issues with the

GNB lead-acid battery and Sunny Island inverter were described.

Integration of battery packs with inverters continued to be problematic 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 nascent capacity fade trends were discernible, and that lithium-ion batteries continued to demonstrate higher efficiency.

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## **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 battery packs, the replacement of the malfunctioning Redflow and EcoUlt packs, and upgrades to the Ampetus pack.

Ongoing SOC estimation issues for the CALB 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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## **Report 5**

### **September 2018**

With testing of both Phase 1 and 2 batteries well under way by the time Report 5 was published, capacity fade trends were well-established with significant variation in performance between packs 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 Ampetus, and some operational issues with the CALB, LG Chem, EcoUlt and GNB lead-acid Phase 1 battery packs.

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## **Report 6**

### **June 2019**

With Phase 1 testing concluding at the end of March 2019, Report 6 included a comprehensive analysis of the

performance of those batteries, as well as an update on Phase 2 batteries. Overall, the Sony (Phase 1) and Pylontech (Phase 2) battery packs demonstrated excellent capacity retention, and the Sony, Samsung, Tesla (Phase 1), BYD and Pylontech (Phase 2) battery packs demonstrated high reliability. The Samsung and BYD battery packs in particular demonstrated consistently high round-trip efficiency.

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

The report also discussed the high number of battery packs installed in the Test Centre which had been 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.

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## Report 7 September 2019

Report 7 included analysis and commentary of the three batteries from Phase 1 (Sony, Samsung, and Tesla Powerwall 1) and seven batteries from Phase 2 (Alpha ESS, BYD LV, GNB Lithium, LG Chem HV, Pylontech, Redflow, and Tesla Powerwall 2) which were still in testing.

While some battery packs had experienced faults and/or failed prematurely, the Sony, Samsung, Tesla Powerwall 1, BYD, Pylontech, and GNB Lithium battery packs had generally demonstrated high reliability, with minimal issues encountered throughout the testing period.

Linear extrapolation of capacity fade to date suggested cycle life varied significantly between products. The Sony, Samsung, and Pylontech battery packs continued to demonstrate good capacity retention over a large number of cycles. Following replacements, the current Tesla Powerwall 2 and Redflow ZCell were also demonstrating excellent capacity retention, though the number of cycles completed was low at the time.

Variability in round-trip efficiency was lower, and had generally been observed between 85-95% for both the lead-acid and lithium-ion technologies.

## Report 8 April 2020

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Report 8 included analysis and commentary of the three batteries from Phase 1 (Sony, Samsung, and Tesla Powerwall 1) and six batteries from Phase 2 (BYD LV, GNB Lithium, LG Chem HV, Pylontech, Redflow, and Tesla Powerwall 2) which were still in testing, as well as an overview of the procurement and installation of eight batteries added to testing for Phase 3.

The Sony and Samsung battery packs from Phase 1 have proven reliable, alongside the Pylontech and GNB Lithium battery packs from Phase 2. Both the Tesla Powerwall 1 and the BYD B-Box LV stopped cycling due to operational issues, in the period covered by this report.

For the Sony and Samsung battery packs (Phase 1), over 80% of initial capacity has been retained after over 2,000 cycles. Linear extrapolation suggests the Pylontech battery pack (Phase 2) is currently on a similar trajectory. Following replacements, the current Tesla Powerwall 2 and Redflow ZCell (Phase 2) are also demonstrating excellent capacity retention.

Round-trip efficiency is more consistent between battery packs, and has generally been observed between 85-95% for both the lead-acid and lithium-ion technologies.

The Phase 3 procurement exercise highlighted the movement of the market towards either integrated battery and inverter products, or battery products that are only compatible with inverters from the same manufacturer; as well

as an increased requirement for product registration. Both point towards an increasingly strong preference from manufacturers for reduced interfaces with, and dependence on, external associated systems.

Product	Type	Nameplate Capacity (kWh nominal)
BYD B-Box HV	Lithium Iron Phosphate	10.2
DCS PV 10.0	Lithium Iron Phosphate	10.0
FIMER REACT 2	Lithium Nickel Manganese Cobalt	8.0
FZSoNick	Sodium Nickel Chloride	9.6
PowerPlus Energy LiFe Premium	Lithium Iron Phosphate	9.9
SolaX Triple Power	Lithium Nickel Manganese Cobalt	12.6
sonnenBatterie	Lithium Iron Phosphate	10.0
Zenaji Aeon	Lithium Titanate	9.6

Table 5: Phase 3 battery packs

## Report 9 September 2020

Report 9 included analysis and commentary on two batteries from Phase 1 (Sony and Samsung), six batteries from Phase 2 (BYD LV, GNB Lithium, LG Chem HV, Pylontech, Redflow, and Tesla Powerwall 2) and eight batteries from Phase 3 (BYD HV, DCS, FIMER, FZSoNick, PowerPlus, SolaX, and sonnen).

ITP had experienced difficulties commissioning and controlling the three Phase 3 battery packs that do not communicate their SOC to the inverter.

The Sony battery pack from Phase 1 had continued to operate reliably, alongside the Pylontech and GNB Lithium battery packs from Phase 2. Both the Sony and Pylontech batteries were also showing excellent capacity retention after a high number of cycles. The Phase 3 batteries had not completed many cycles at that point.

Round-trip efficiency was more consistent between battery packs, with DC values as high as 95% for some lithium-ion battery packs, and as low as 78% for Redflow's zinc bromine battery.



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