



Public Report 9

Lithium-ion Battery Testing

ENGINEERING | STRATEGY | ANALYTICS | COMPLIANCE

September 2020

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About ITP Renewables

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

Supported by a \$1.29m grant from the Australian Renewable Energy Agency (ARENA) 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.

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 with a Phase 2 to include an additional eight lithium-ion packs, a zinc bromide flow battery, and an aqueous hybrid ion battery bank. Recently a Phase 3 comprising another seven lithium-ion packs and a sodium nickel battery was also installed.

According to original testing timelines, this would be the Final Report to include results for the Phase 2 batteries; however, this will be completed in 2022 in line with the extension of the testing period to match Phase 3 batteries. This report describes testing results and general observations or issues encountered thus far with the Phase 1, Phase 2, and Phase 3 batteries.

This report, earlier reports, and live test results are published at batterytestcentre.com.au.

List of Abbreviations

AC	Alternating Current
AIO	All-in-one (referring to a battery unit which is combined with a battery inverter and PV inverter)
ARENA	Australian Renewable Energy Agency
AUD	Australian Dollar
BESS	Battery Energy Storage System
BMS	Battery Management System
BOS	Balance of System
C (number)	“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)
CAN (bus)	Controller Area Network (a message-based communications protocol allowing microcontrollers and devices to communicate without a host computer)
DC	Direct Current
DOD	Depth of Discharge of a battery
ELV	Extra Low Voltage
IR	Infra-Red (region of the electromagnetic radiation spectrum used in thermal imaging)
ITP	IT Power (Australia) Pty Ltd, trading as ITP Renewables
kW	Kilowatt, unit of power
kWh	Kilowatt-hour, unit of energy (1 kW generated/used for 1 hour)
kWp	Kilowatt-peak, unit of power for PV panels tested at STC
LFP	Lithium Iron Phosphate (a common li-ion battery chemistry)
Li-ion	Lithium-ion (referring to the variety of battery technologies in which lithium ions are intercalated at the anode/cathode)
LMO	Lithium Manganese Oxide (a common li-ion battery chemistry)
LTO	Lithium Titanate (a common li-ion battery chemistry)
MODBUS	A serial communication protocol for transmitting information between electronic devices
NMC	Nickel Manganese Cobalt (a common li-ion battery chemistry)
NCC	National Construction Code
PbA	Lead Acid
PMAC	Permanent Magnet Alternating Current (a variety of electric motor)
PV	Photovoltaic
RE	Renewable Energy
SOC	State of Charge of a battery
UPS	Uninterruptable Power Supply
VRB	Vanadium Redox Battery, a type of flow battery
VRLA	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, 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 ninth 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. Phase 3 batteries have not yet completed enough cycles to draw conclusions on reliability.

The Sony battery pack (Phase 1) has retained over 80% of its initial capacity after more than 2,500 cycles. The Pylontech battery pack (Phase 2) has also retained over 80% of its initial capacity after nearly 2,000 cycles. Following replacements, the Redflow ZCell (Phase 2) is also demonstrating excellent capacity retention, albeit after a lower number of cycles (~860).

Round-trip efficiency is more consistent between battery packs, and has generally been observed between 85-95% (DC) for both the lead-acid and lithium-ion technologies. The Redflow ZCell efficiency is lower, at ~78%, as expected.

With respect to the market at large, price reductions have stalled in recent months, with this generally attributed to cell production constraints and the weak Australian dollar. Nevertheless, most analysts believe that the large amount of production capacity currently under construction will continue to put downward pressure on prices in the medium-term. ITP's opinion is that price reductions are still 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. The trial was subsequently expanded 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.

Nine battery packs from Phase 1 and 2 were removed from testing after March 2019, having either concluded the original testing period or ceased testing for various reasons. The remaining nine batteries from Phase 1 and 2 are continuing testing and discussed in this report. These include:

- Samsung AIO (Phase 1)
- Sony Fortelion (Phase 1)
- Tesla Powerwall 1 (Phase 1)
- BYD B-Box LV (Phase 2)
- GNB Lithium (Phase 2)
- LG Chem RESU HV (Phase 2)
- Pylontech US2000B (Phase 2)
- Redflow ZCell (Phase 2)
- Tesla Powerwall 2 (Phase 2)

In late 2019 a further eight battery packs, including a lithium-titanate (LTO) battery and a sodium-nickel battery, were installed in the facility for testing under Phase 3 of the project. These batteries have begun cycling and are listed below:

- BYD Battery Box HV
- Deep Cycle Systems (DCS) PV 10.0
- FIMER REACT2
- FZSoNick
- PowerPlus Energy LiFe Premium
- SolaX Triple Power
- sonnenBatterie
- Zenaji Aeon

This is the ninth public report outlining the progress and results of the trial thus far. A summary of the eight previous reports is provided in Appendix C. Complete reports are accessible on the Battery Test Centre website at batterytestcentre.com.au/reports/.

2. BATTERY OPERATION OVERVIEW

Figure 1 below 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.

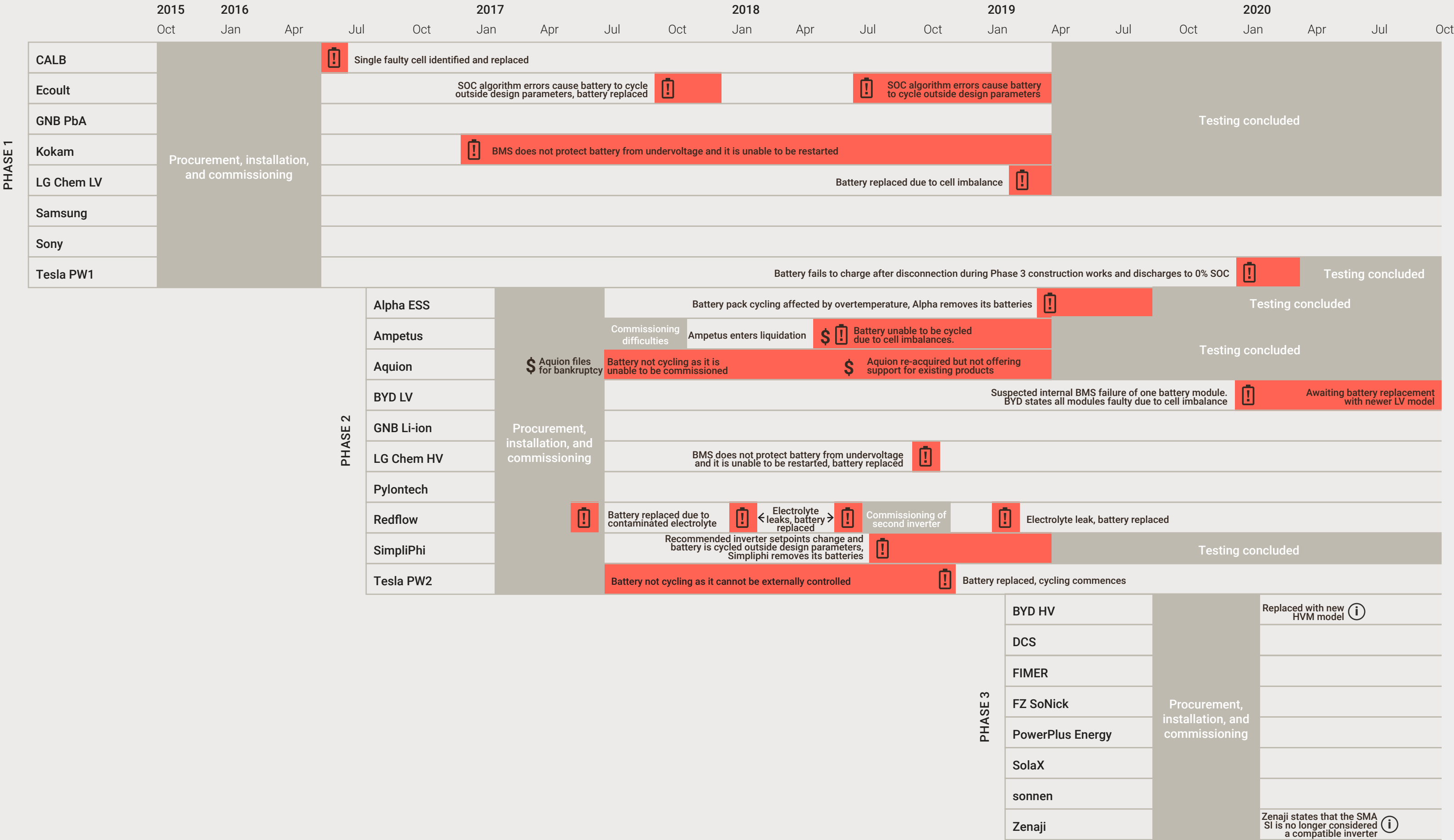


Figure 1: Overview of battery operation

3. PHASE 1 UPDATE

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

3.1. Samsung AIO 10.8

Operational Issues

The Samsung AIO10.8 has completed a high number of cycles¹ (~2,730 cycles). While it has generally been highly reliable, in the last month or so it has sometimes stopped responding to charge/discharge commands, and only operates again once power cycled. The cause for this is not yet known. Moreover, towards the end of charge cycles, the power to the Samsung is oscillating between charging and discharging.

The Samsung now appears to experience SOC recalculation when reaching the end of both the charge and discharge periods. As a result, even though it is reaching a maximum SOC of approximately 90% each cycle, this may not be accurate as it is jumping from close to 70% SOC. Similarly, during discharge the SOC jumps from approximately 20% to 10%. ITP expects that these issues are due to cell voltage imbalances, which are typically exacerbated by aging.



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

¹ 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.

This variance in this dataset makes state-of-health (SOH) estimation difficult, but residual capacity can be seen to be around 73% of initial capacity (ie. suggesting a 73% SOH) after ~2,730 cycles.

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. It can be seen that capacity has generally decreased over time. The data suggests a SOH of ~85% after ~2,610 cycles.

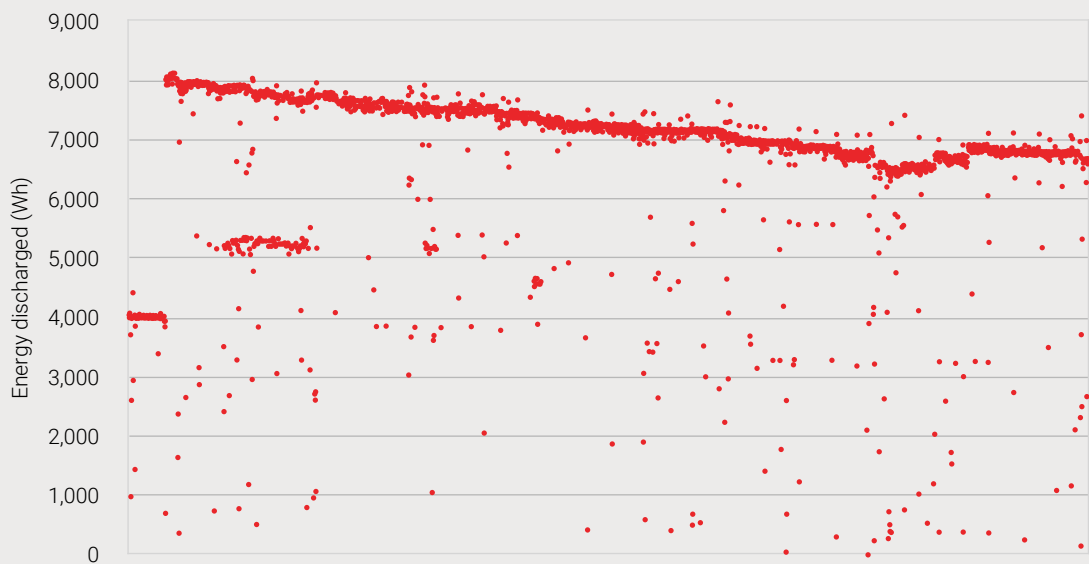


Figure 3: Energy discharged per cycle by the Sony battery pack

3.3. Tesla Powerwall 1

Operational Issues

The previous Public Report described the failure of the battery to charge when it was turned back on after Phase 3 construction works. Tesla no longer stocks the Powerwall 1 model and this battery is no longer being tested under the trial.



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.

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

4.1. BYD B-Box LV

Operational Issues

The previous Public Report described the failure of one the four B-Box battery modules, and BYD's statement that the cell imbalance observed in all four modules indicated that they were faulty. BYD is currently liaising with ITP to replace the B-Box model with its most recent modular LV offering, which is planned to be cycling before the release of the next Public Report.



4.2. GNB Lithium

Operational Issues

ITP has not experienced any operational issues with the GNB Lithium battery pack. When performing diagnostic tests on the battery with GNB's proprietary software, a 'Battery Internal Voltage Too High' error is returned. When ITP last contacted GNB, they stated that the errors were regular notifications.

Capacity Fade

The energy discharged per cycle is depicted in Figure 4. The data suggests a SOH of ~54% after ~1,470 cycles.



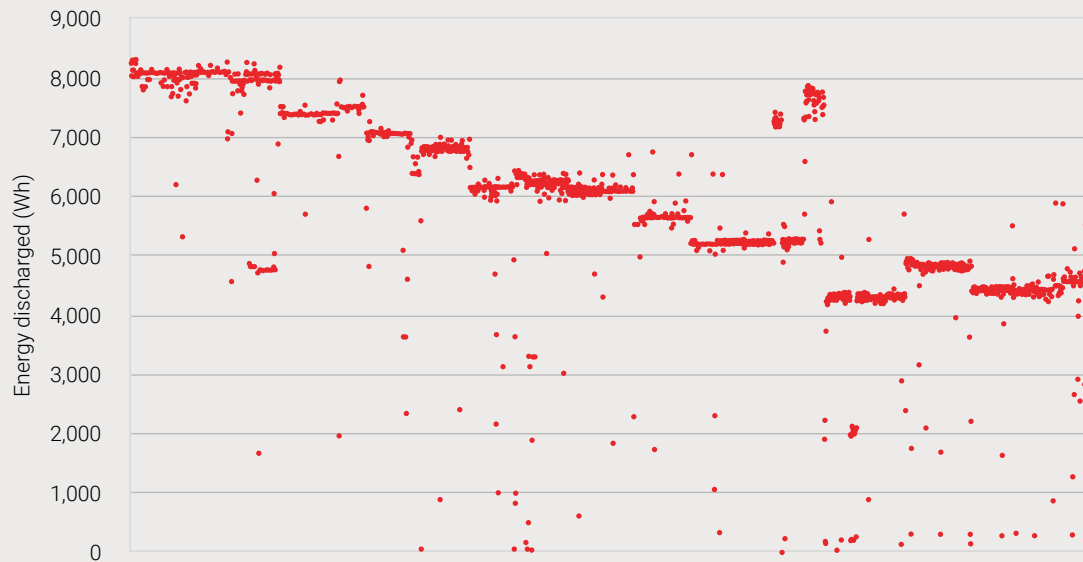


Figure 4: Energy discharged per cycle by the GNB LFP battery pack

4.3. LG Chem RESU HV

Operational Issues

In Public Report 7, ITP described deep self-discharge of the LG Chem RESU HV battery pack, and LG Chem's subsequent design improvements. Prior to Phase 3 construction works, the LG Chem battery was turned off while at a high SOC, and the internal DC-DC converter was disconnected according to LG Chem's instructions. The battery was turned back on without issue after construction works were completed. No operational issues have been experienced since replacement of the battery in October 2018.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 5. The data suggests a SOH of ~84% after ~1,110 cycles.



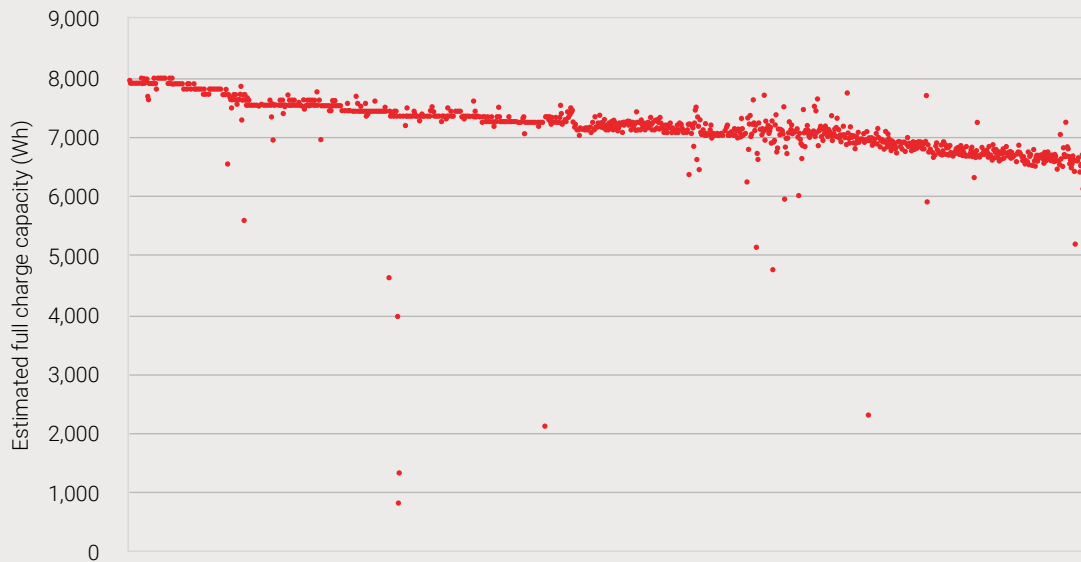


Figure 5: Estimated full charge capacity per cycle by the LG Chem RESU HV battery pack

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 6. The data suggests a SOH of ~82% after ~1,940 cycles.

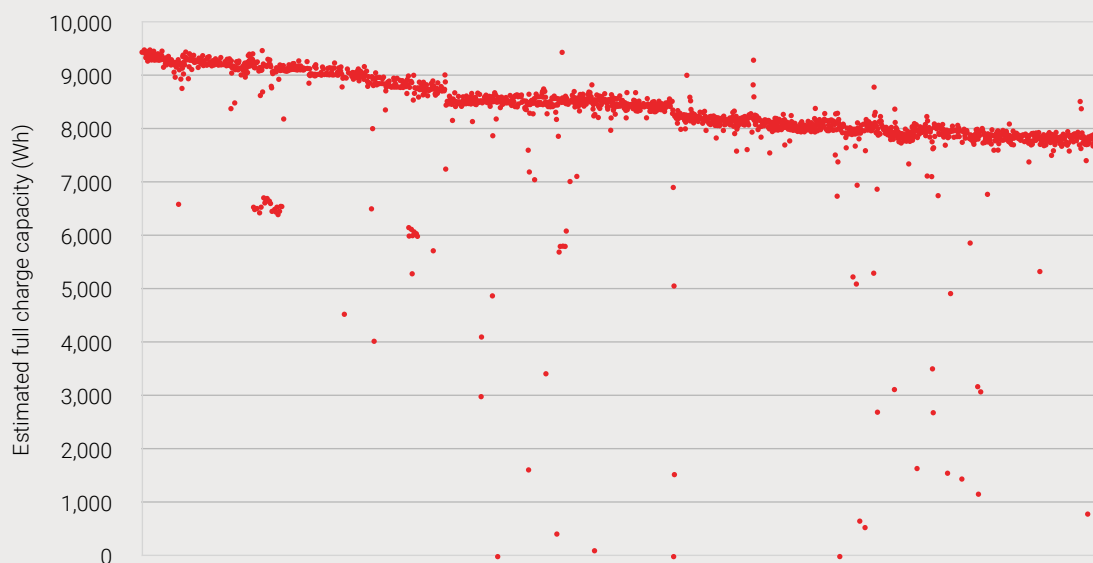


Figure 6: Estimated full charge capacity per cycle by the Pylontech battery pack

4.5. Redflow ZCell

Operational Issues

The Redflow battery has not experienced any operational issues since it was last replaced in February 2019. This is the fifth Redflow battery to be installed in the test centre, with replacements due to contaminated electrolyte, and electrolyte leaks.

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 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, and in the trial set-up this occurs at the end of each day (after two complete cycles).



Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 7. The data suggests some minor capacity fade (i.e. a SOH of 97%) after ~860 cycles.

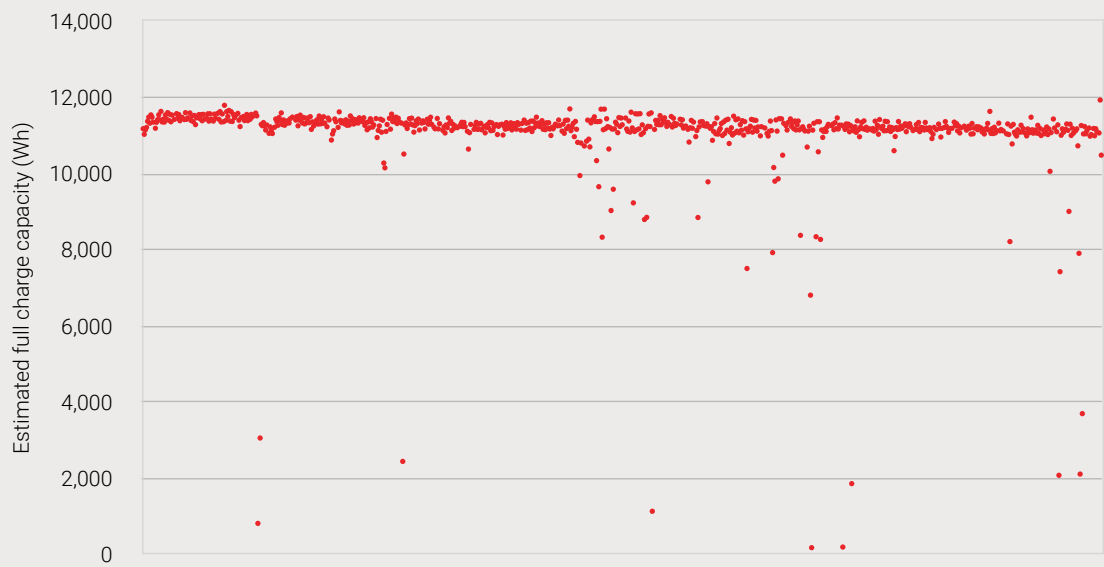


Figure 7: Estimated full charge capacity per cycle by the Redflow battery pack

4.6. Tesla Powerwall 2

Operational Issues

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 (communications and energy management hardware) were subsequently replaced by Tesla. Cycling of the replacement Powerwall 2 commenced in late November 2018.

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. 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 mobile app. Data is available from the Tesla Powerwall 2’s local web interface. Although Tesla has not published local API documentation, community groups of have published a tutorial on how to take data from the battery online.² 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%).

Capacity Fade

The energy discharged per cycle is depicted in Figure 8. The data suggests a SOH of ~88% after ~1,250 cycles.

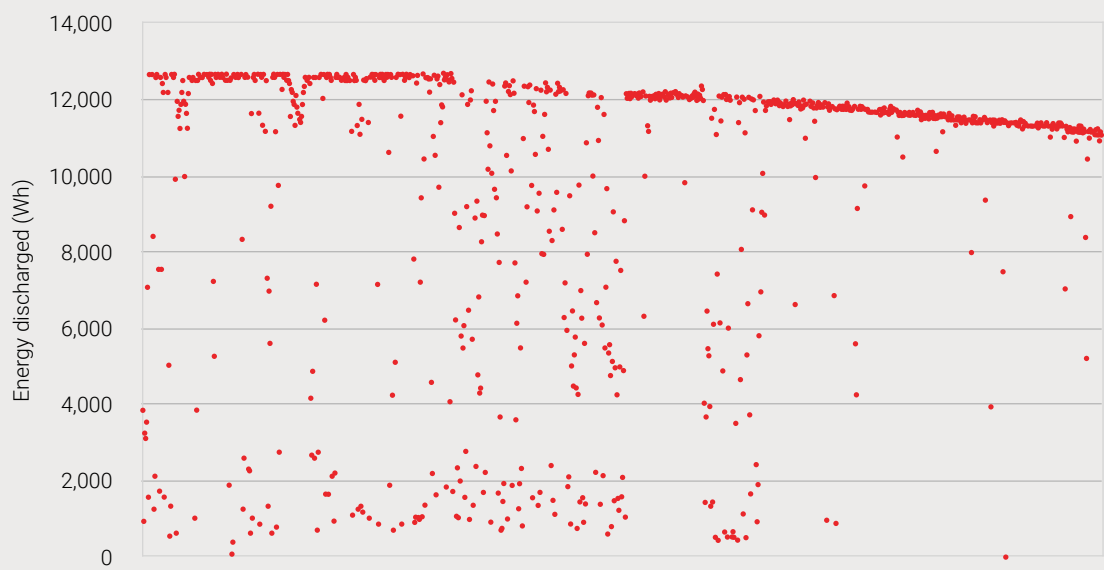


Figure 8: Energy discharged per cycle by the Tesla Powerwall 2 battery pack

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

5. PHASE 3 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.

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

5.1. BYD B-Box HVM

Operational Issues

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

In mid-July, 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, the battery's internal DC breaker tripped during normal operation. Following this, the system has been unable to be turned back on with connection to the inverter for more than a few minutes before the battery's DC breaker trips again. The battery LED sequence indicates an error code; however, at present BYD is unsure of the nature of the error and undertaking further investigation.



Capacity Fade

Performance analysis will be included in the next Public Report, but no capacity fade is apparent after ~140 cycles.

5.2. Deep Cycle Systems (DCS) PV 10.0

Operational Issues

The DCS battery in the trial is installed with an SMA Sunny Island inverter. Although the system has a BMS, it is not designed with any communications between the BMS and 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 inverter cycles are controlled with both battery voltage limits (as per DCS advice) and inverter SOC limits (to avoid inverter shutdown). When cycling the battery at a C3 rate, the battery voltage and estimated SOC would drop to

their cut-off levels well before the expected energy was discharged. DCS sent a DC charger to ITP to assist in testing that the battery was still operating as expected, by performing a slow discharge down to minimum voltage. The test discharge was performed at 1kW rate, and indicated that the battery was still at full capacity. However, ITP had difficulty discharging this full capacity at higher discharge rates. The battery is now cycled at closer to a C5 rate with four-hour charge and discharge rates, rather than three hours as per other batteries in the lab.

The last Public Report described how the battery must be 'woken up' with a 48V battery charger both before operation can begin, and also after any period of time without operation (during which the battery will re-enter the hibernation mode). DCS subsequently contacted ITP to clarify that the hibernation state was particularly designed to allow a very low draw on the battery during periods of inactivity, so that it can remain in that state for years without destroying the cells. DCS also noted that most battery inverters do have a 'battery awoken' button (i.e. do not require a ~48V voltage from the battery to start), but the SMA Sunny Islands do not.



Capacity Fade

Performance analysis will be included in the next Public Report, but no capacity fade is apparent after ~325 cycles.

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 9. The data suggests some minor capacity fade (i.e. a SOH of 95%) after ~475 cycles.

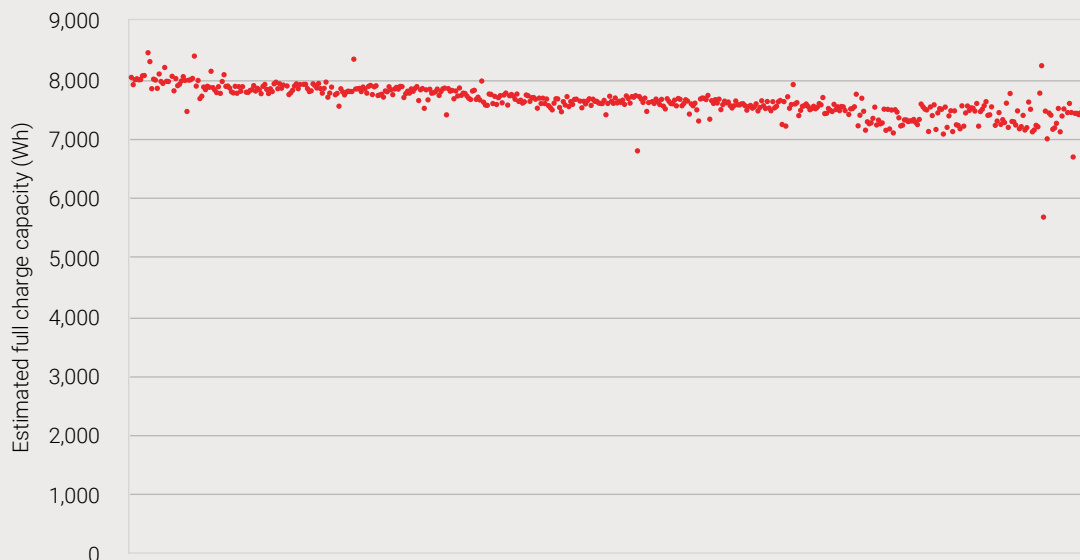


Figure 9: Estimated full charge capacity per cycle by the FIMER battery pack

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) 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.



ITP has not experienced any operational issues with the FZSoNick battery.

Capacity Fade

Performance analysis will be included in the next Public Report, but no capacity fade is apparent after ~225 cycles.

5.5. PowerPlus Energy LiFe Premium

Operational Issues

The PowerPlus batteries in the trial are installed with an SMA Sunny Island inverter. Although each battery has a BMS, the system is not designed with any communications between the BMS and 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 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.

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

Capacity Fade

Performance analysis will be included in the next Public Report, but no capacity fade is apparent after ~290 cycles.

5.6. SolaX Triple Power

Operational Issues

ITP has not experienced any operational issues with the SolaX Triple Power battery.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 10. The data suggests some minor capacity fade (i.e. a SOH of 95%) after ~475 cycles.

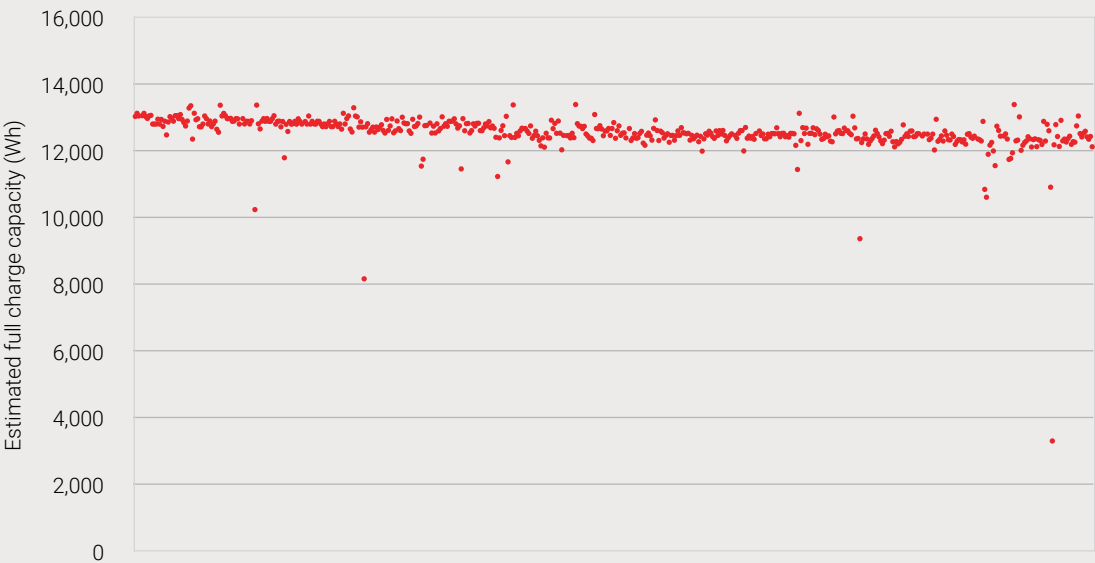


Figure 10: Estimated full charge capacity per cycle by the SolaX battery pack

5.7. sonnenBatterie

Operational Issues

ITP experienced some small difficulties in controlling the sonnenBatterie (specifically, the inverter) during the commissioning phases, when the inverter would sometimes stop responding to commands until power cycled. This may have been due to either high grid voltages, or firmware updates, and the issue has not been observed since Sonnen disabled automatic updates. These issues may have been specifically related to third-party control commands and may not have resulted in any change to operation for a regular installation.

Since then 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 11. No capacity fade is apparent after ~445 cycles.

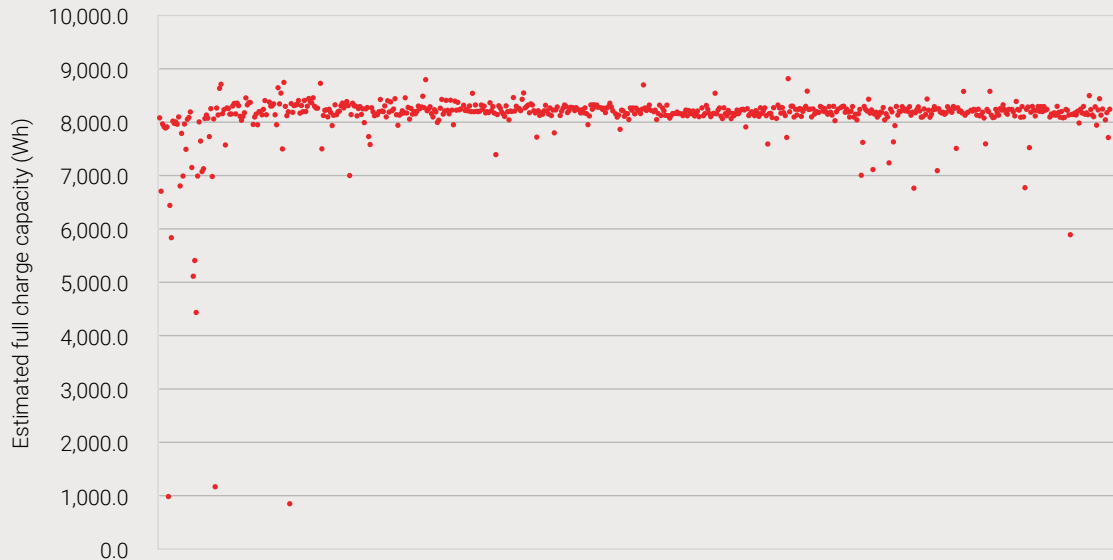


Figure 11: Estimated full charge capacity per cycle by the Sonnen battery pack

5.8. Zenaji Aeon

Operational Issues

The Zenaji batteries in the trial are installed with an SMA Sunny Island inverter. Although each unit has a BMS, the system is not designed with any communications between the BMS and 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 could only offer 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

Performance analysis will be included in the next Public Report. The trend in capacity fade is unclear after ~240 cycles.

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 and 4 above). Both data sets should be considered before drawing conclusions.

6.1. Phase 1 Capacity Test Results

Figure 12 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 at each capacity test by the energy delivered in the first capacity test.

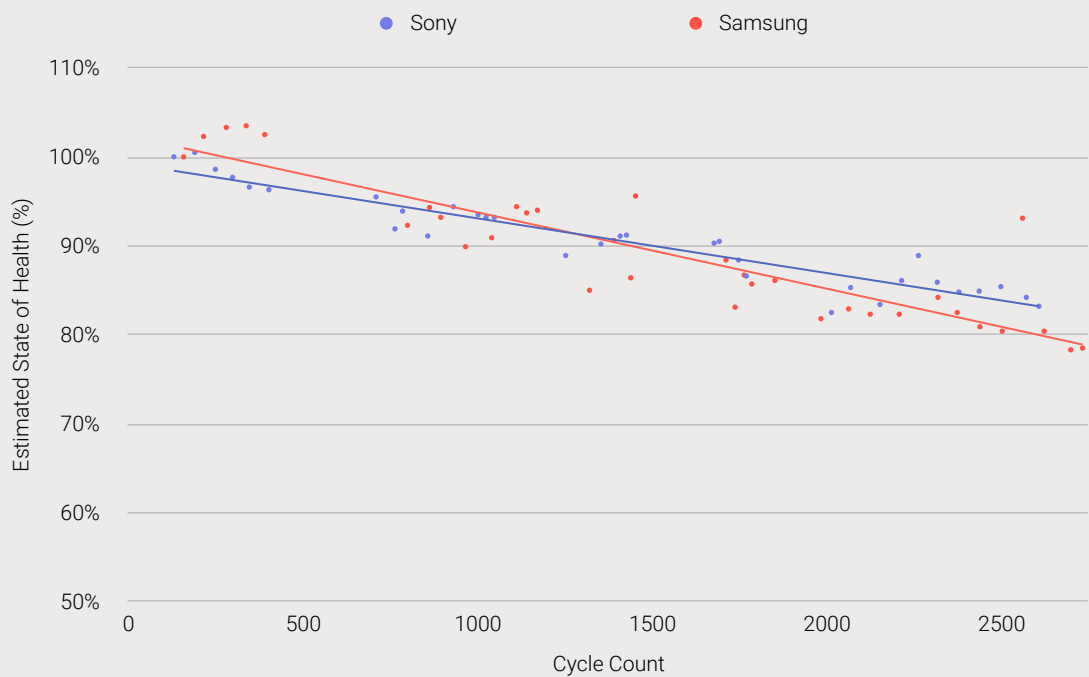


Figure 12: Capacity fade of Phase 1 battery packs based on monthly capacity tests

It should be noted that Figure 12 includes lines-of-best-fit that are determined by simple linear regression. While a linear regression appears to provide a good fit to the capacity test data collected thus far, extrapolating linearly into the future may not be appropriate.

Samsung AI010.8

Based on the linear regression between estimated SOH and cycles completed (Figure 12), the Samsung AI0 pack is on track for 60% SOH at ~4,400 cycles. As above, however, the cycle data suggests some non-linearity which may invalidate this extrapolation.

Sony Fortelion

Based on a linear regression between estimated SOH and cycles completed (Figure 12), the Sony Fortelion pack is on track for 60% SOH at ~6,400 cycles. As above, however, a linear extrapolation may not be appropriate.

6.2. Phase 2 Capacity Test Results

Figure 13 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.

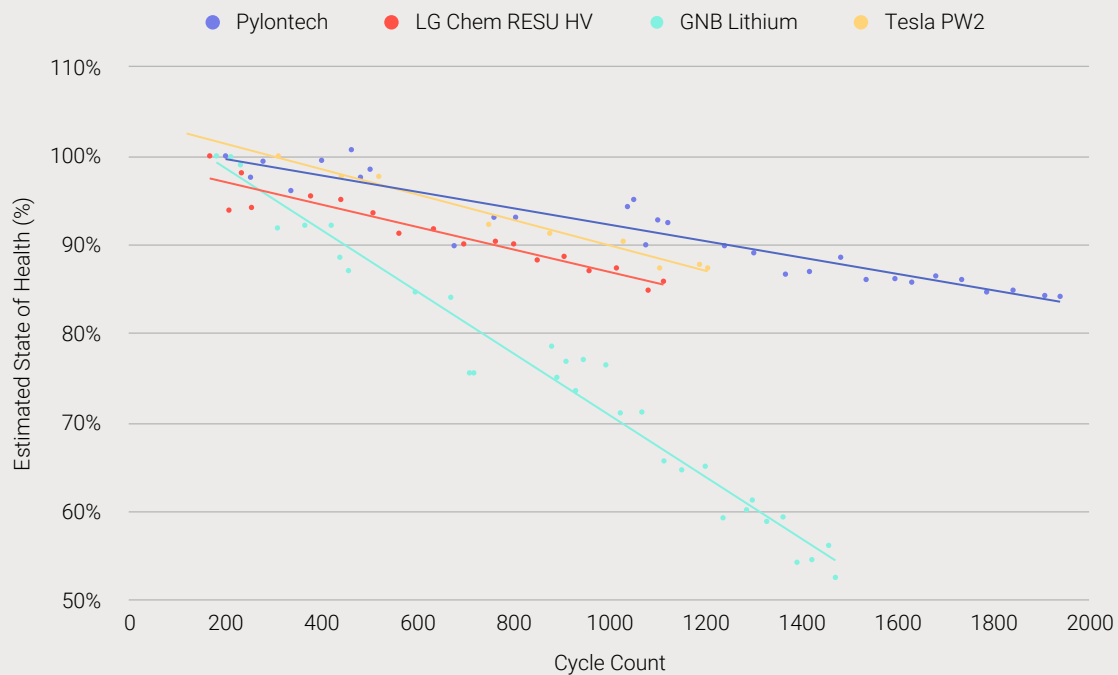


Figure 13: Capacity fade of Phase 2 battery packs based on monthly capacity tests

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

GNB Lithium

Based on a linear regression between estimated SOH and cycles completed (Figure 13), the GNB Lithium is on track for 60% SOH at ~1,300 cycles. As above, however, the data suggests some non-linearity which may invalidate this extrapolation.

LG Chem RESU HV

Based on the linear regression between estimated SOH and cycles completed (Figure 13), the LG Chem RESU HV is on track for 60% SOH at ~3,100 cycles. As above, however, a linear extrapolation may not be appropriate.

Pylontech US2000B

Based on the linear regression between estimated SOH and cycles completed (Figure 13), the Pylontech US2000B is on track for 60% SOH at ~4,340 cycles. As above, however, a linear extrapolation may not be appropriate.

Tesla Powerwall 2

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 13), the Tesla Powerwall 2 is on track for 60% SOH at ~3,100 cycles. As above, however, a linear extrapolation may not be appropriate.

Redflow ZCell

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

Capacity tests data has been collected for the new Phase 3 batteries but the low number of cycles completed by each battery means that trends relating to capacity fade cannot be determined. This data will be depicted in the next Public Report.

6.4. Round-Trip Efficiency

The lifetime round-trip efficiency results are shown for each battery in Figure 14. 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.

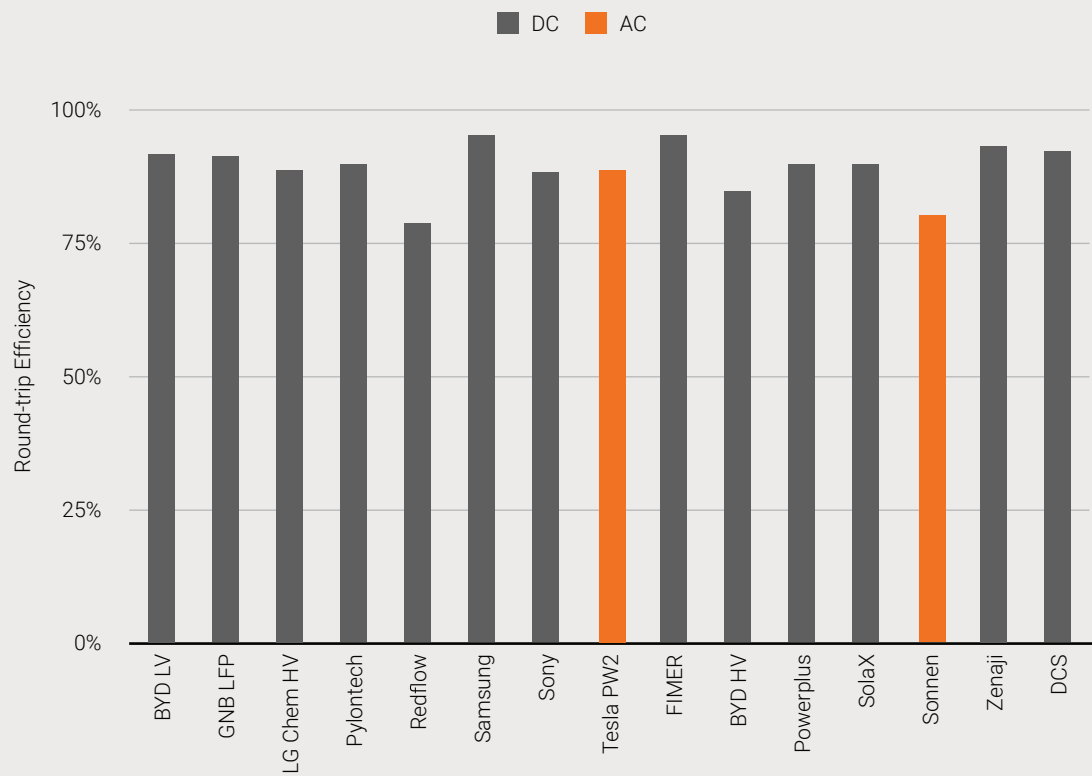


Figure 14: Lifetime round-trip efficiency for each battery pack

7. MARKET DEVELOPMENT

Since the beginning of the project, the cost of residential and commercial scale lithium-ion battery packs has fallen. 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, attributed to capacity constraints at the manufacturing level, increasing raw material costs (cobalt, in particular), and a weakening Australian dollar.

These trends have continued since publication of the last Public Report. Figure 15 shows prices for NMC and LFP battery models installed in the Battery Test Centre over time.

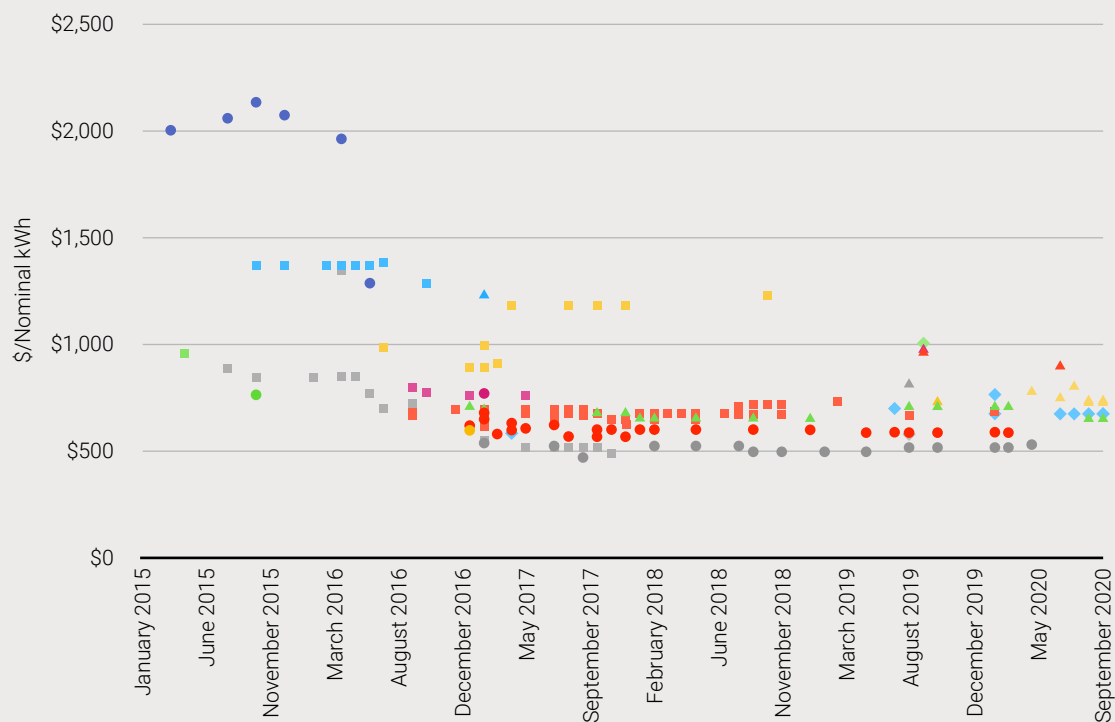


Figure 15: Wholesale prices for lithium-ion battery products installed in the Battery Test Centre

Globally, significant additional lithium-ion production capacity is expected to be developed over the medium term, and manufacturers are increasingly substituting cobalt out of their cells. This production capacity expansion is in part related to the expected demand from electric vehicle manufacturers. The effect should be falling lithium-ion battery costs in the medium-term.

8. LESSONS LEARNED

Having been in operation for over four 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. While all of those lessons are still pertinent, the following additional observations have been made since the last Public Report.

- Some of the new batteries installed under Phase 3 have no communications between the BMS and inverter. This approach relies on the inverter to safely and accurately manage operation for optimal performance. All three of these batteries are installed with SMA Sunny Island inverters. ITP has encountered some difficulty in commissioning these batteries to cycle according to the test methodology.
- Previous Public Reports have described difficulties in commissioning batteries and inverters to work together despite statements of compatibility from manufacturers (particularly battery manufacturers, rather than inverter manufacturers). Some battery manufacturers do not appear to comprehensively test their product with inverters before declaring compatibility, and this can result in stated battery specifications (e.g. energy capacity with certain charge/discharge rate) not being realised in practice.

Appendix A: Knowledge Sharing

An important part of ITP’s 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 website³ was established as the key mechanism for sharing knowledge. 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 231,800 page views with an average of 2:07 minutes spent per page overall and 3:55 minutes spent on the reports page.

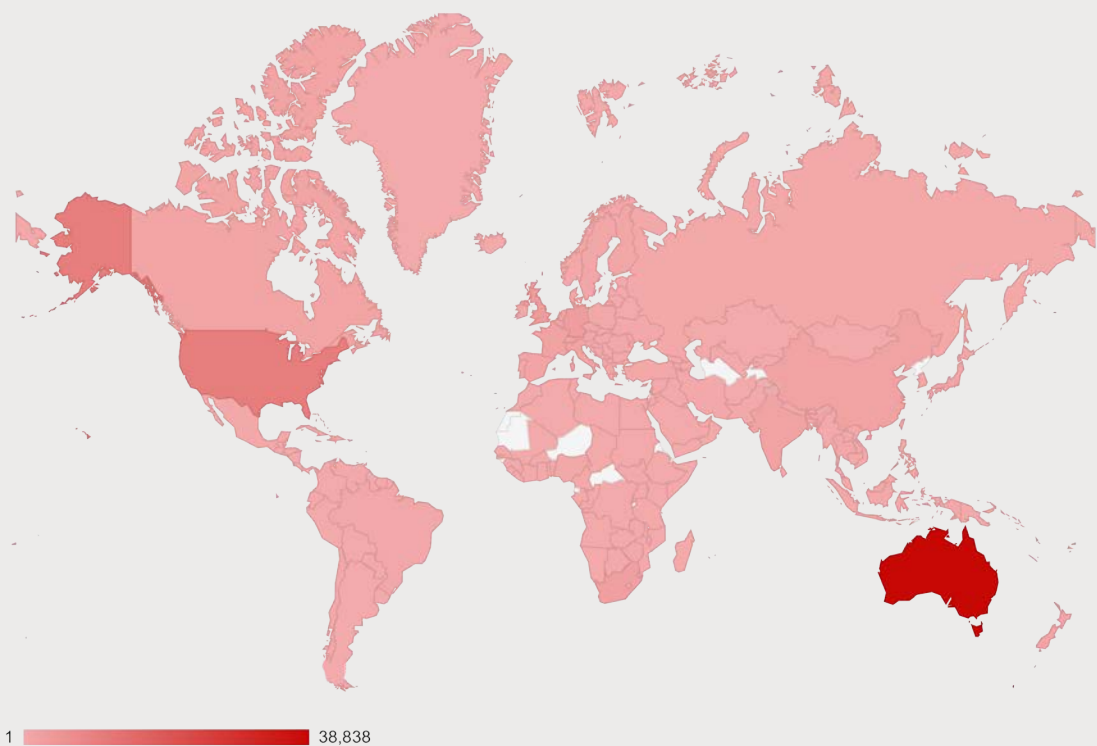


Figure 16: Number of sessions by country

³ batterytestcentre.com.au

The data from the website shows that the key audience is Australia, with Australian IP addresses accounting for 56,972 sessions (48%). 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 12,809 sessions from the United States, 3,974 from the United Kingdom and Germany not far behind on 3,799. It is interesting to note, however, that the content has been accessed from right across the globe.

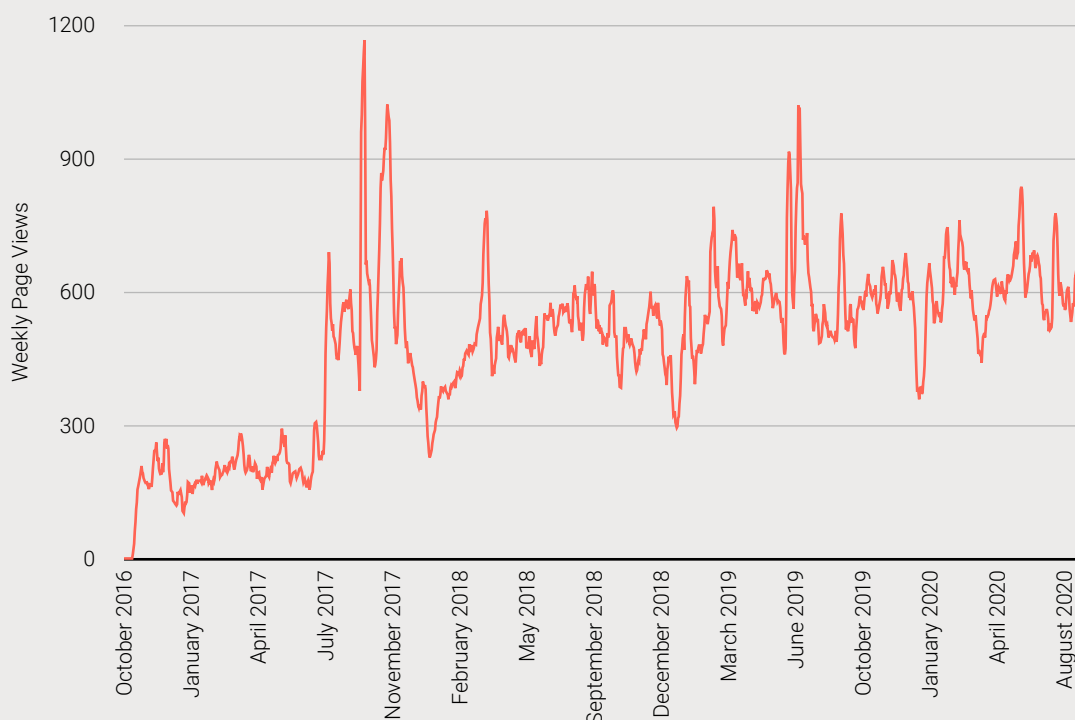


Figure 17: Weekly active users

Figure 17 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. Overall though, interest in the site has remained reasonably constant in the last six months, with the number of weekly users hovering around 600.

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 batteries page (11%), the reports page (11%), LG Chem RESU (7%), Pylontech US2000B (7%) and the background page on lithium-ion technology (4%).

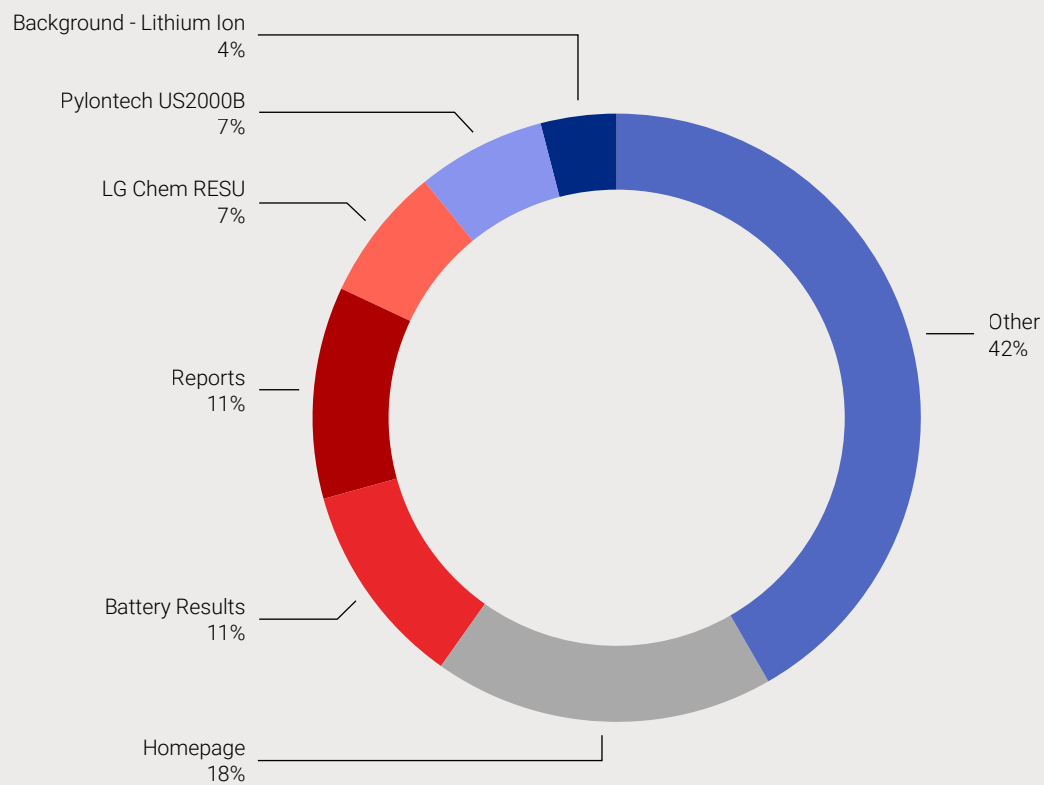


Figure 18: Breakdown of the 231,800 page views

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 1: 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.

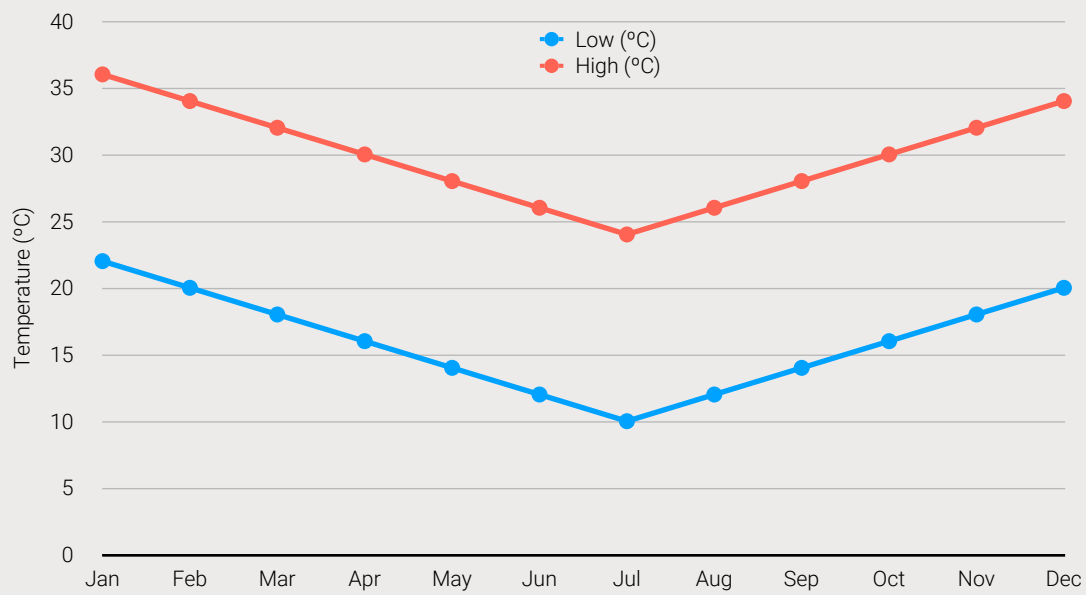


Figure 1: Daily hot and cold cycle temperatures throughout the year

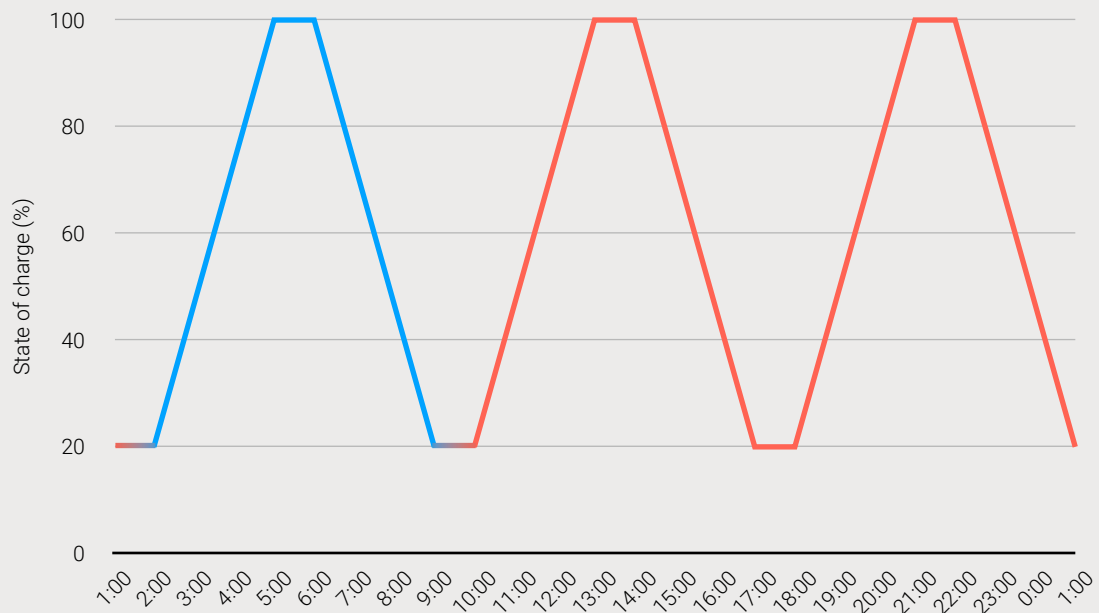


Figure 2: Summer temperature regime and charge regime

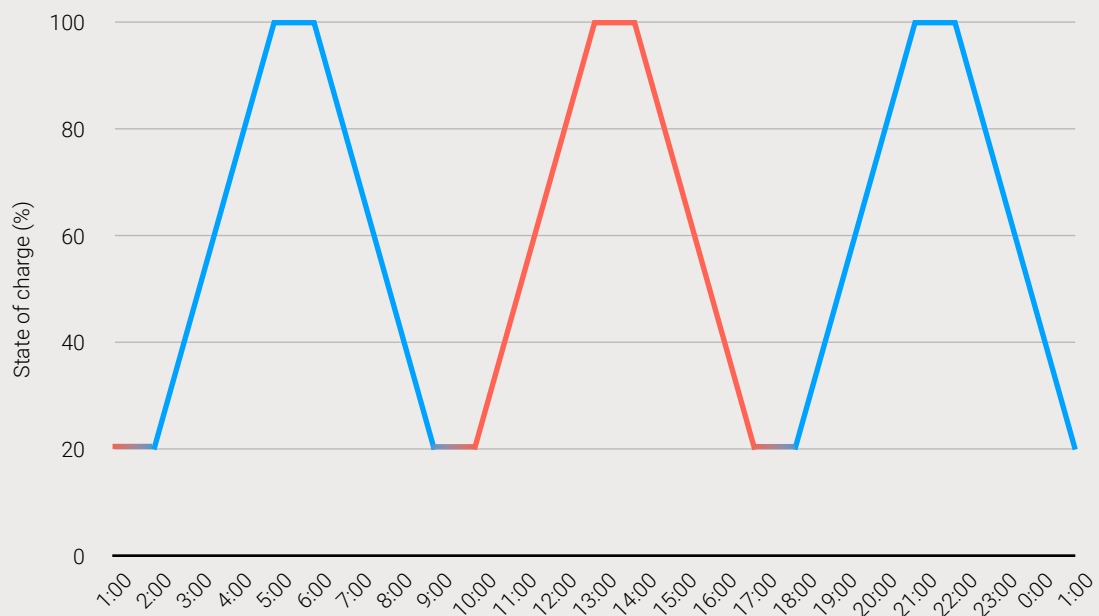


Figure 3: Winter temperature regime and charge regime

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 2 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	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 2: 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.

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.

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.

Report 3

November 2017

Report 3 described the process of procuring and installing the 10 x Phase 2 battery packs listed in Table 3 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 3: 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.

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.

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.

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.

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

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 4: Phase 3 battery packs



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