Public Report 8
Lithium-ion Battery Testing

ENGINEERING | STRATEGY | ANALYTICS | CONSTRUCTION

April 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 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.

This report describes testing results and general observations or issues encountered thus far with both the Phase 1 and 2 batteries, and installation experiences with the Phase 3 batteries.

This report, earlier reports, and live test results are published at **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

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

Contents

Executive Summary

ITP Renewables (ITP) is testing the performance of residential and commercial scale battery packs in a purpose-built, climate-controlled enclosure at the Canberra Institute of Technology. Eight batteries were installed initially, and a further ten installed in a second phase. This is the eighth public six-monthly report.

While some battery packs have experienced faults and/or failed prematurely, the Sony, Samsung and Tesla battery packs from Phase 1 have proven reliable, alongside the Pylontech and GNB Lithium battery packs from Phase 2.

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.

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.

A third phase of battery testing has recently begun and comprises another eight battery packs, including a lithium-titanate battery and a sodium-nickel battery. These replace batteries from Phases 1 and 2 which are no longer cycling for various reasons. Testing of the remaining Phase 1 and 2 batteries is continuing.

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:

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

This is the eighth public report outlining the progress and results of the trial thus far. A summary of the seven 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.

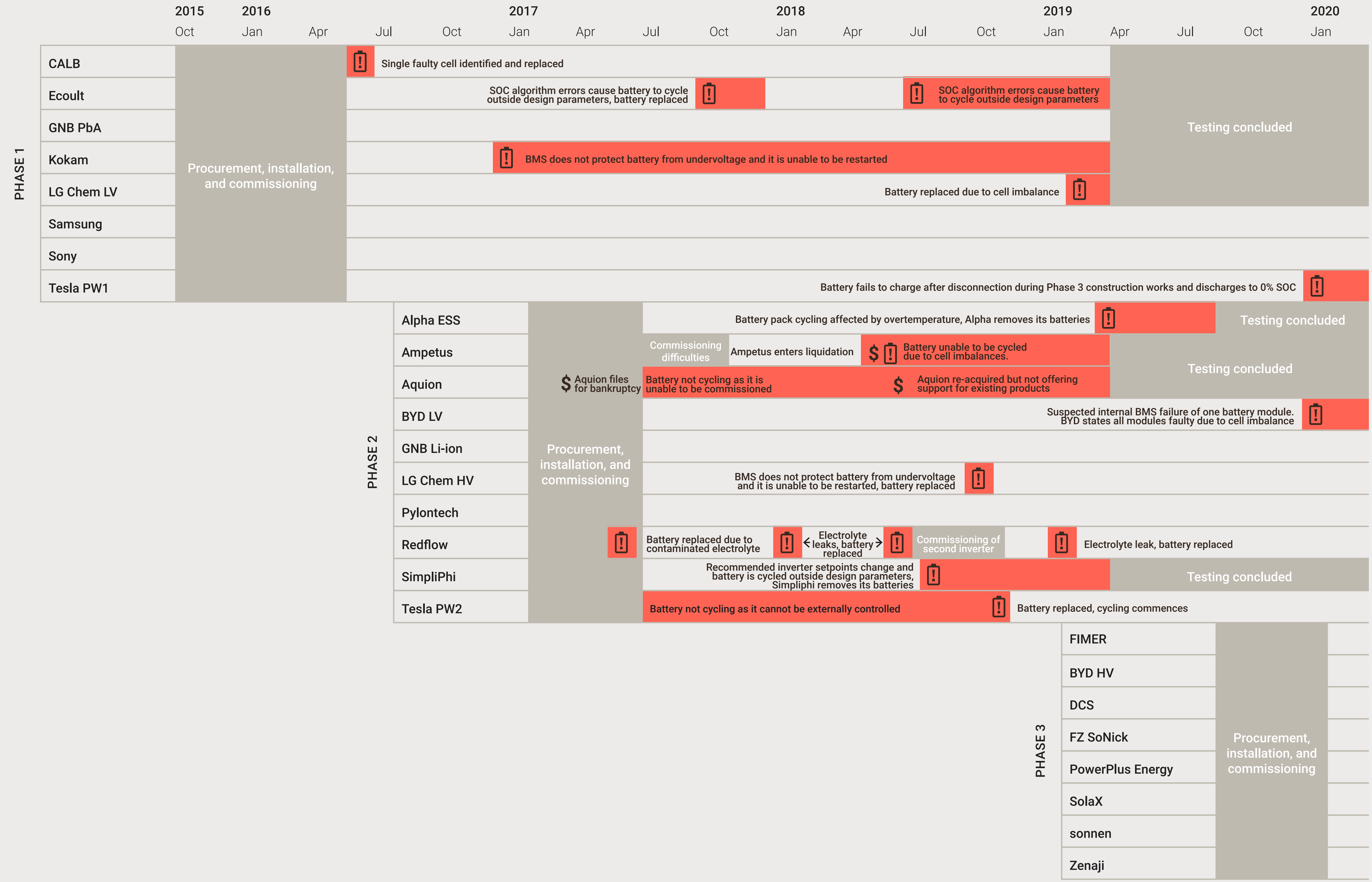

Figure 1: Overview of battery operation

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 cycles. No faults have been experienced in the past six months or at any time during testing.

The Samsung does appear to sometimes experience SOC recalculation when reaching the end of its discharge cycle. It is also not charging past approximately 85% SOC. ITP expects that these issues are due to aging.

Capacity Fade

The energy discharged each 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.

This variance in this dataset makes state-of-health (SOH) estimation difficult, but residual capacity can be seen to be around 70% of initial capacity (ie. suggesting a 70% SOH).

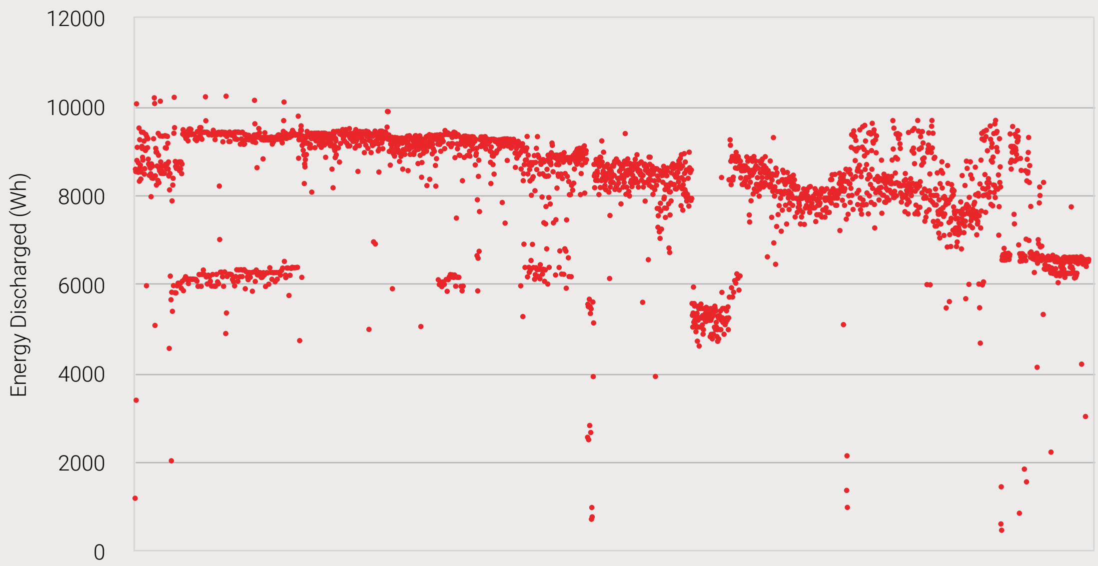

Figure 2: Energy discharged per cycle by the Samsung battery pack

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.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 3. It can be seen that capacity has generally decreased over time. The data suggests a SOH of ~86% after ~2,350 cycles.

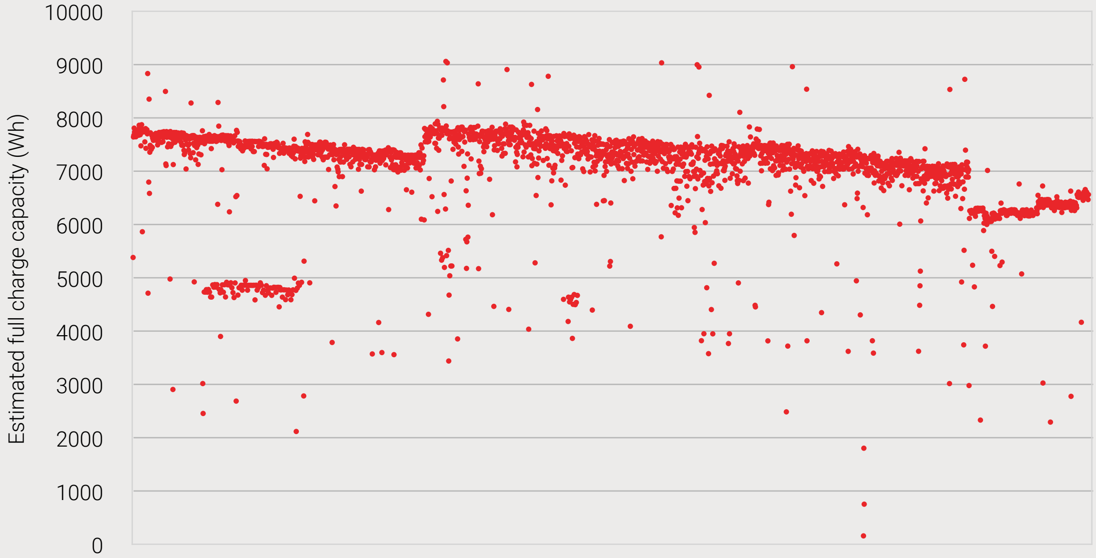

Figure 3: Estimated full charge capacity per cycle by the Sony battery pack

3.3. Tesla Powerwall 1

Operational Issues

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

The Tesla Powerwall 1 and associated SolarEdge inverter were turned off in October 2019 prior to Phase 3 construction works in the lab. The battery was at a high SOC (95%) at the time it was shut down. It was turned back on in November 2019 after construction works were complete. At this time, the battery reported SOC error codes to the inverter, and failed to charge, discharging to 0% SOC. Tesla support staff visited site to inspect the battery in February 2020, and concluded that one of the cells was no longer recoverable and that the battery was inoperable. Tesla has since stated that when the battery started up in November, it either did not receive the correct charge commands (from the inverter) or was unable to charge, but continuously attempted to charge up until mid-December when it went into a deep sleep mode.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 4. It can be seen to have generally decreased over time. The data suggests an end-of-life SOH of ~59% after ~2,540 cycles.

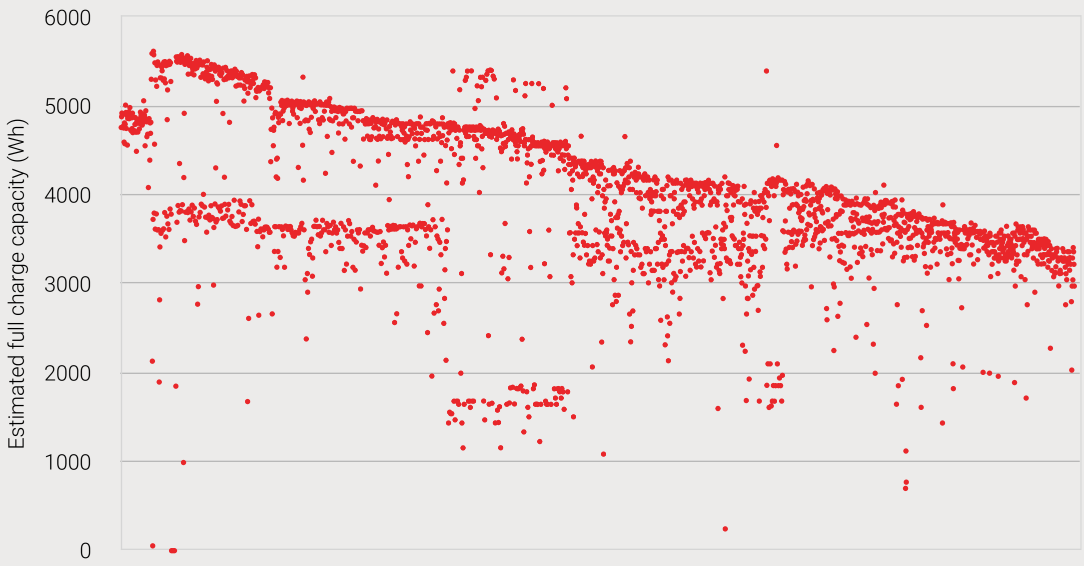

Figure 4: Estimated full charge capacity per cycle by the Tesla Powerwall 1 battery pack

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

BYD performed firmware updates on the BMU in June and August 2019 in an effort to mitigate cell imbalance issues evident from its performance. The BMU was replaced after the second time as it was unable to accept the firmware update.

In mid-November 2019, one of the four battery modules indicated a fault and stopped cycling. According to BYD, the issue was likely to be a failure of the internal BMS component; however, as the battery has not yet been inspected by them this has not been confirmed.

BYD has since stated that the cell imbalance observed in all four modules is not normal behaviour, could not be rectified by the firmware update, and that the modules are faulty. BYD has noted that the modules installed in the test are an older generation model, and new models have since been released which have an improved BMS. BYD has offered replacement of the battery pack.

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, GNB stated that the errors were regular notifications.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 5. The data suggests a SOH of ~55% after ~1,325 cycles.

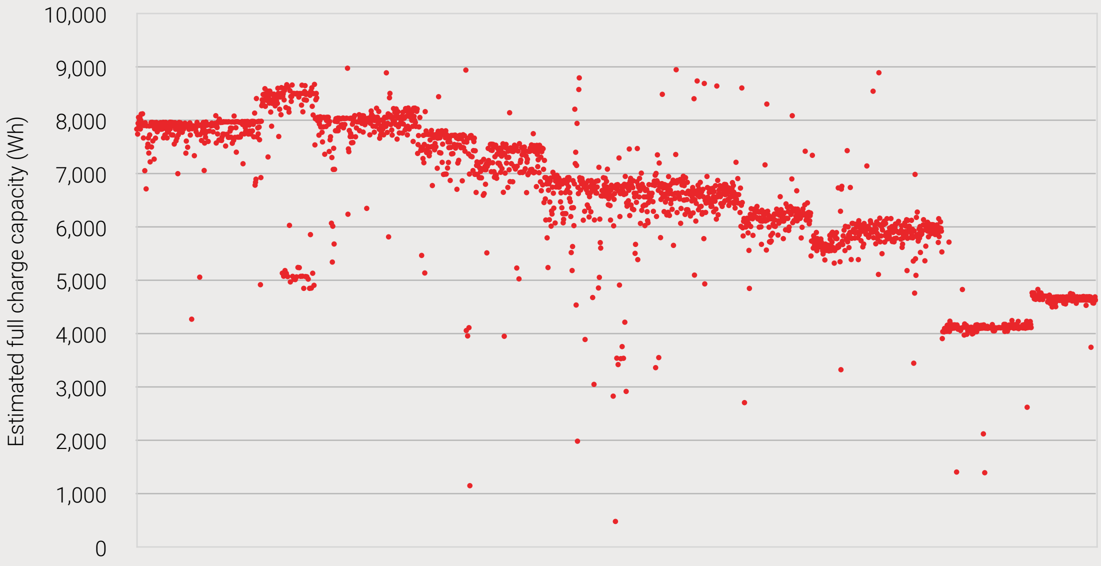

Figure 5: Estimated full charge capacity per cycle by the GNB LFP battery pack

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 DC-DC converter 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 6. The data suggests a SOH of ~88% after ~850 cycles.

The capacity appears to have dropped during the period in which the battery was disconnected for Phase 3 construction works.

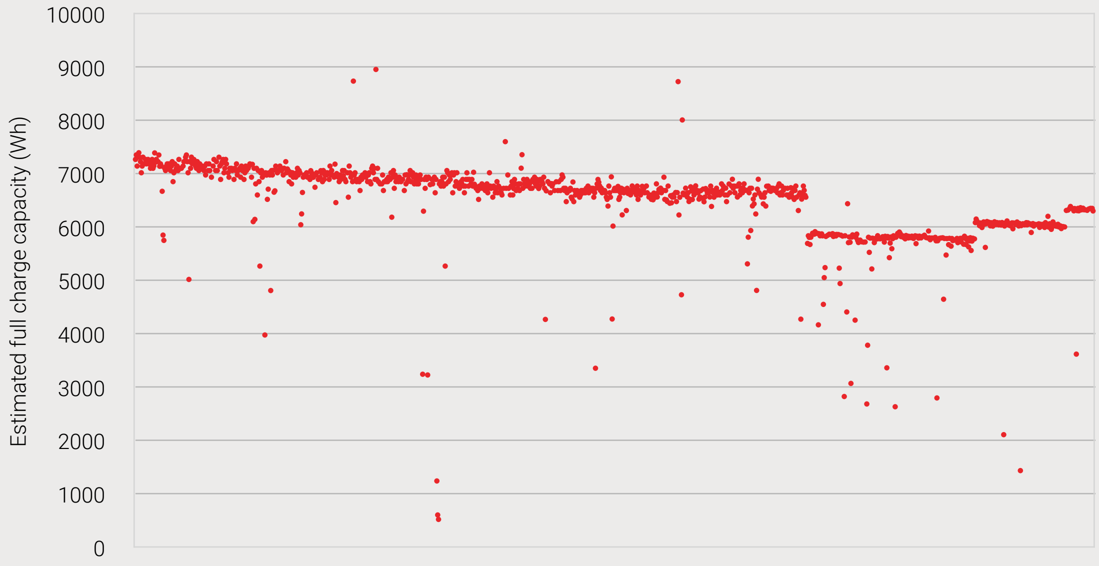

Figure 6: Estimated full charge capacity per cycle by the LG Chem RESU HV battery pack

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 ~85% after ~1,675 cycles.

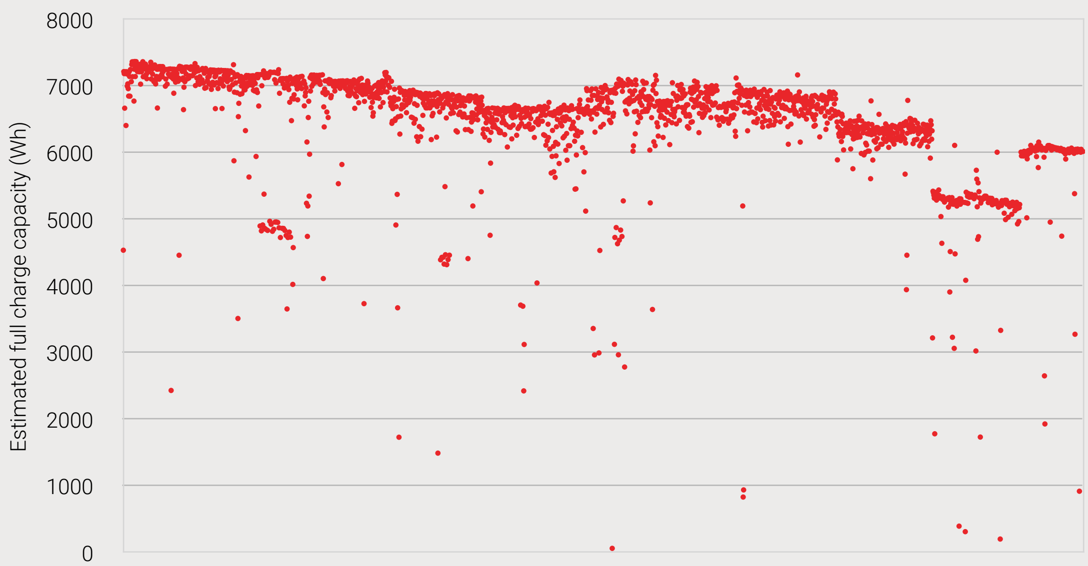

Figure 7: Estimated full charge capaciy per cycle by the Pylontech battery pack

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 8. The data suggests no capacity fade (i.e. a SOH of 100%) after ~600 cycles.

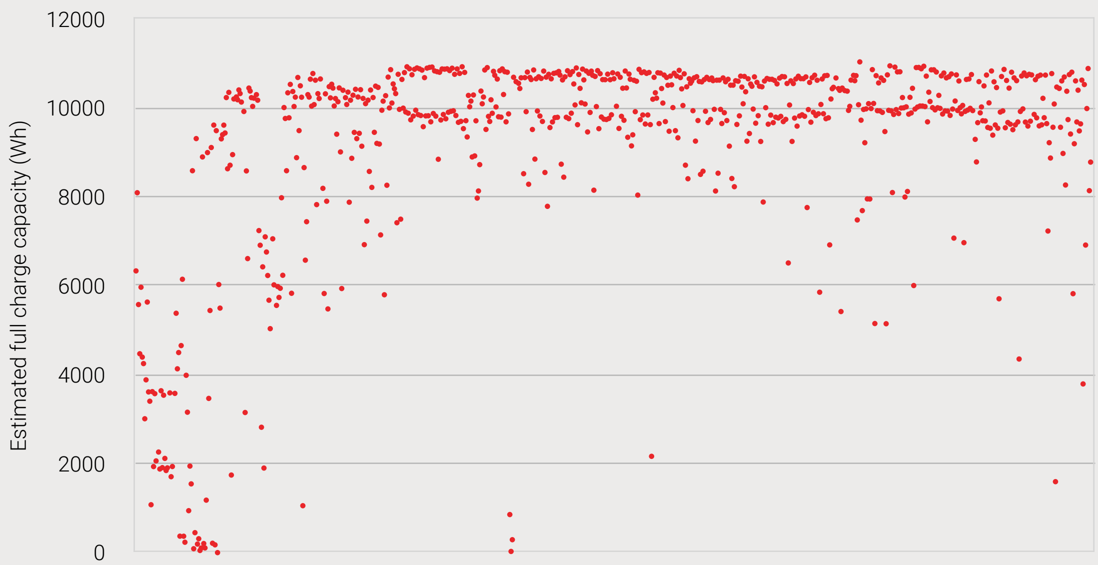

Figure 8: Estimated full charge capacity per cycle by the Redflow battery pack

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. The data used by ITP in monitoring and analysis is obtained from this API.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 9. The data suggests a SOH of ~92% after ~975 cycles.

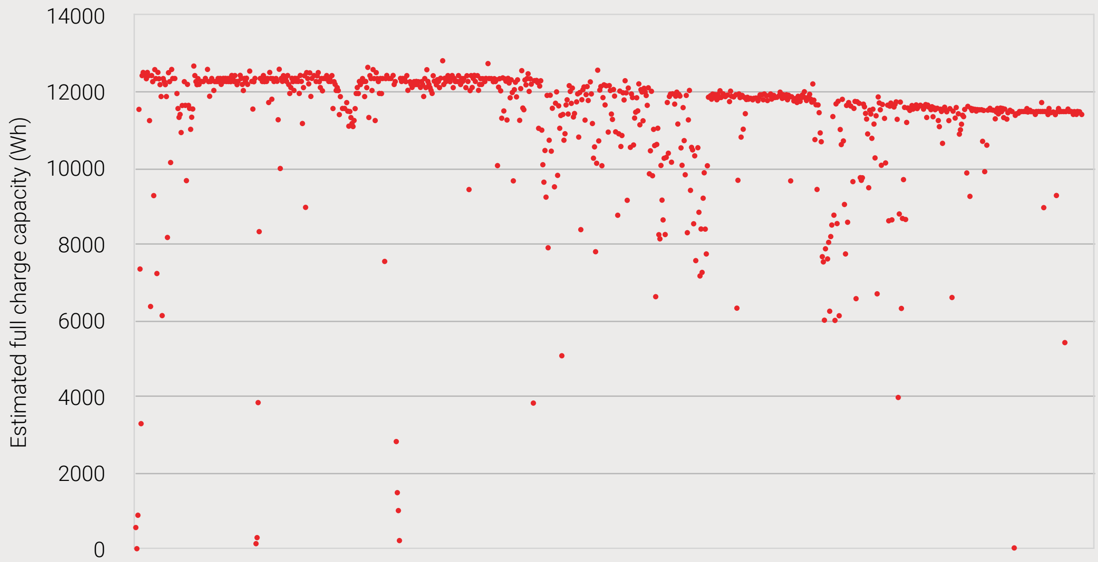

Figure 9: Estimated full charge capacity per cycle by the Tesla Powerwall 2 battery pack

5. 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 not accessible, and hence the maximum and minimum SOC must be used as a proxy. The result is that the precision of a single capacity test depends 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, where a cycle is defined as a continuous discharge exceeding 40 minutes in length). Both data sets should be considered before drawing conclusions.

5.1. Phase 1 Capacity Test Results

Figure 10 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.

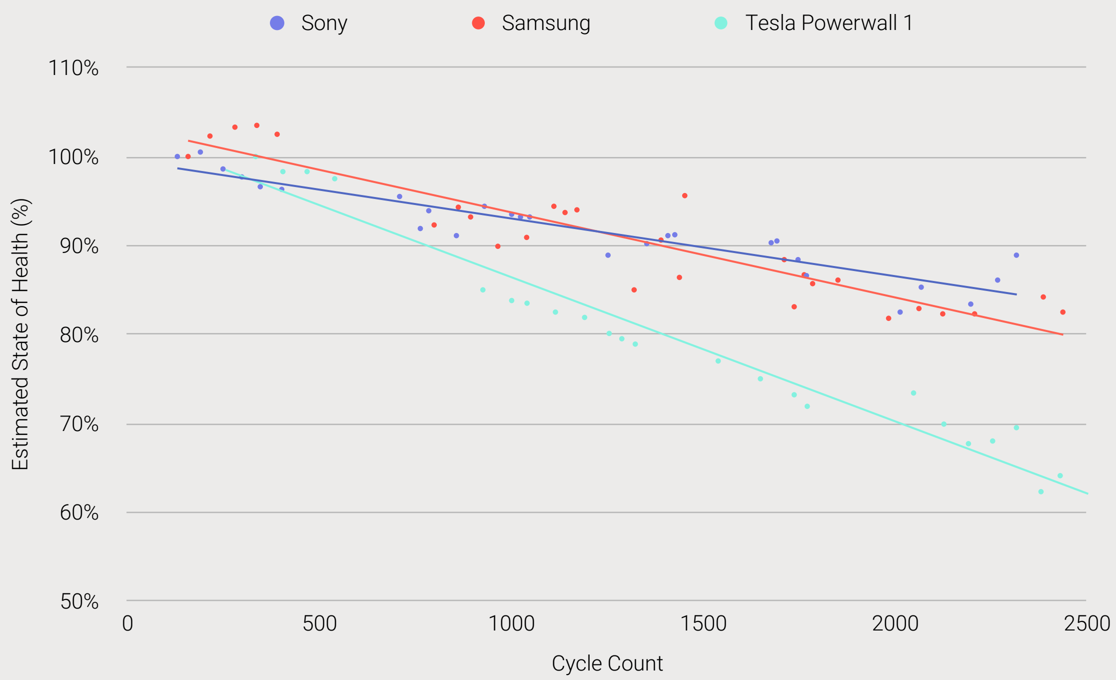

Figure 10: Capacity fade of Phase 1 battery packs based on monthly capacity tests

It should be noted that Figure 10 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 AIO10.8

Based on the linear regression between estimated SOH and cycles completed (Figure 10), the Samsung AIO pack is on track for 60% SOH at ~4,000 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 10), the Sony Fortelion pack is on track for 60% SOH at ~6,000 cycles. As above, however, a linear extrapolation may not be appropriate.

Tesla Powerwall 1

A linear regression between estimated SOH and cycle count (Figure 10) shows a 60% SOH at ~2,630 cycles, while the battery ceased to operate after ~2,540 cycles.

5.2. Phase 2 Capacity Test Results

Figure 11 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.

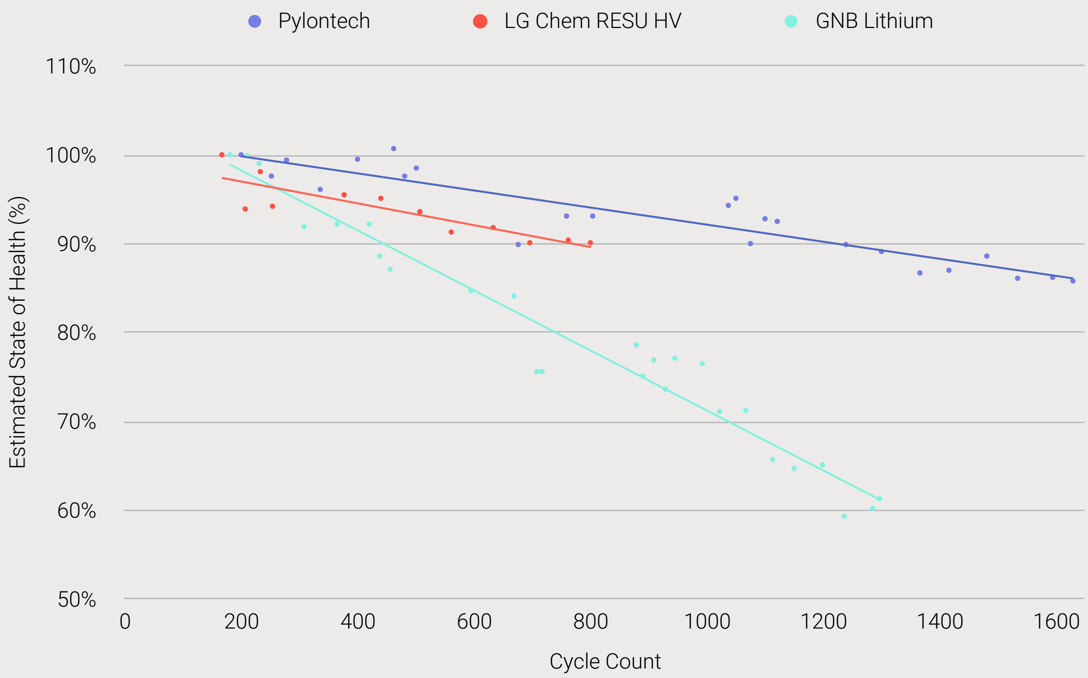

Figure 11: Capacity fade of Phase 2 battery packs based on monthly capacity tests

It should be noted that Figure 11 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

The most recent capacity test suggests a SOH of ~60%, and a linear regression between estimated SOH and cycles completed (Figure 11) estimates a 60% SOH at ~1,330 cycles. As above, however, the data suggests some non-linearity which may invalidate this extrapolation.

LG Chem RESU HV

The most recent capacity test suggests a SOH of 90%. Based on the linear regression between estimated SOH and cycles completed (Figure 11), the LG Chem RESU HV is on track for 60% SOH at ~3,220 cycles. As above, however, a linear extrapolation may not be appropriate.

Pylontech US2000B

The most recent capacity test suggests a SOH of 86%. Based on the linear regression between estimated SOH and cycles completed (Figure 11), the Pylontech US2000B is on track for 60% SOH at ~4,340 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.

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. Due to periodic lack of cycling on capacity test dates, and disconnection during Phase 3 construction works, the number of recent capacity tests completed is low and results have not been included here.

5.3. Round-Trip Efficiency

The lifetime round-trip efficiency results are shown for each battery in Figure 12. Note that the result shown for the Tesla PW2 in orange is the AC round-trip efficiency. DC values are not available for the PW2, but can be assumed to be higher.

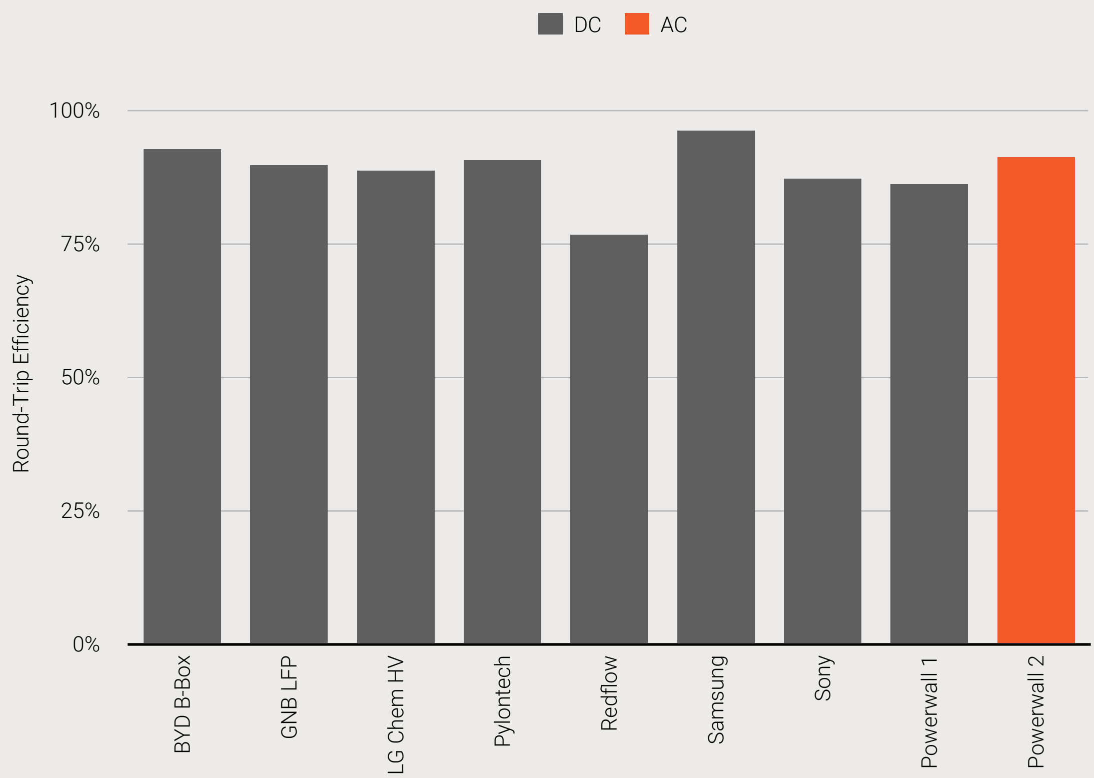

Figure 12: Lifetime round-trip efficiency for each battery pack

It is apparent that the lithium-ion battery packs outperform the Redflow zinc-bromide flow battery pack.

6. PHASE 3 IMPLEMENTATION

Additional project funding from ARENA has enabled a Phase 3 of the trial, which involves removal of existing battery packs no longer cycling and the addition of eight new battery packs.

6.1. Removal of Existing Batteries

A total of nine battery packs have been removed from testing since their installation in the facility. A mix of batteries installed during Phases 1 and 2, some of these have finished their original testing period, while others have been removed for other reasons. The batteries that have been removed are:

- Alpha ESS (Phase 2)
- Ampetus (Phase 2)
- Aquion (Phase 2)
- CALB (Phase 1)
- Ecoult (Phase 1)
- GNB Sonnenschein PbA (Phase 1)
- Kokam (Phase 1)
- LG Chem LV (Phase 1)
- SimpliPhi (Phase 2)

In order to make room for the new Phase 3 batteries to be installed, the batteries still physically remaining in the facility had to be uninstalled. ITP looked into the option of disposing of the batteries and recycling where possible; however, an opportunity which allowed the batteries to be continued to be used was preferable. Therefore, ITP and ARENA reached an agreement with the Canberra Institute of Technology (CIT), which has taken ownership of the removed batteries for educational purposes within its Trade Skills and Vocational Learning department.

6.2. Procurement and Installation of New Batteries

FIMER REACT 2

The FIMER REACT 2 is a photovoltaic energy storage system, with storage options available from 4-12 kWh (one to three modules). The internal cells are manufactured by Samsung.

At the time of procurement of these units for the Battery Test Centre, the batteries and inverter systems were sold by ABB. The REACT 2 battery was its product for the residential energy storage market and became available in Australia in mid-2019. However, FIMER completed acquisition of ABB's solar inverter business in March 2020. FIMER started developing inverter technologies in 1983 and established a solar inverter division in 2007.

The Battery Test Centre installation consists of two REACT 2-BATT batteries (8 kWh of nominal capacity) connected to a 5 kW FIMER REACT 2-UNO inverter, the only inverter with which the batteries are compatible.

Although stock was available in Australia at the time ITP was beginning procurement, there was a delay in receiving the Modbus documentation from ABB which would allow ITP to monitor and control the battery as required for the testing. In September, ITP was informed that the documentation would be available in October. Due to delays of the firmware release which the Modbus documentation was related to, the documentation was received in December, at which time ITP was informed that the current firmware would not allow third party control of inverter power setpoints. This functionality was released in a later firmware update in February 2020. At this time, ABB provided support in updating the inverter's firmware and following up to ensure that ITP was able to monitor and control the battery as required. ITP began testing this battery in February 2020 once the new firmware was loaded onto the inverter.

Initial contact with ABB regarding the battery and inverter's capabilities were made with local staff in Australia. Once the batteries and inverter were purchased, ITP was put in touch with specialist product managers in Italy.

The REACT 2 batteries and inverter were straightforward to install. They are designed to be the same size and shape, which provides a more homogenous aesthetic as well simpler installation. The units at the ITP facility are wall-mounted in a single row on brackets which are attached to the wall first and designed to interlink with each other. Documentation was comprehensive and easy to understand. Cables for connection between the batteries and inverter were pre-made and easy to connect. The system also includes an inbuilt DC switch, which reduces cost and installation time since a separate switch is not required.

BYD B-Box HV

The BYD B-Box HV contains five to nine stackable LFP modules with a BMS. BYD (Build Your Dreams) is a large Chinese manufacturer of LFP cells for electrical vehicles and communications industries. The B-Box HV is one of their products for the residential and commercial energy storage market and is rated for outdoor installation.

The Battery Test Centre installation consists of eight B-Plus-H modules with a total capacity of 10.24kWh. The BYD B-Box HV is connected to an SMA Sunny Boy Storage inverter.

BYD batteries are stocked by multiple distributors and procurement was simple; there were no issues with stock shortages or other delays.

The modular nature of the battery pack makes installation easier as the installer only has to handle smaller, lighter units. However, having such a large number of modules does result in a lot of packaging, as every part comes individually packaged. The battery did not come with any cables, but being a HV battery, this is not as critical. The smaller HV cables (the same type of cable used for solar PV installations) are easier for installers to work with, and allow more flexibility in locating the battery and inverter a further distance from each other.

Documentation provided was good and included specific reference to the inverter model for installation (SMA Sunny Boy Storage).

The BYD HV battery includes a port for hard-wired connection to the internet, allowing for remote access to the BYD battery portal and updates to the battery firmware. This is unusual for batteries, as it is usually the inverter which is connected. The battery can operate without being connected to the internet.

Since the installation of this battery pack, BYD has since released a newer generation of HV battery modules.

Deep Cycle Systems (DCS) PV 10.0

Deep Cycle Systems (DCS) is an Australian company based in Queensland. Its batteries are engineered in Australia, with internal cells manufactured in China and the BMS manufactured in Japan. Assembly has been undertaken in Hong Kong, but in 2019 the company had plans to bring this step to Australia. Floor-mounted and wall-mounted options are available.

The installation at the ITP facility consists of a 10kWh nominal capacity PV 10.0 battery connected to an SMA Sunny Island inverter.

The battery was procured directly from the manufacturer in Australia, and there were no issues with stock shortages or other delays.

The model at the test facility is floor-mounted. Although the battery did not come with any cables or lugs, installation was very simple, and only required bolting on DC cables to the terminals. The installation documentation is a little out-of-date (some information contained does not match more recent datasheets), but in any case, very little instruction is required for successful installation. The battery also has large handles which make manoeuvring of the floor-mounted unit easier.

The battery does not have communications between its BMS and the inverter, which further simplifies installation, as it eliminates the need for a communications cable between the battery and inverter.

Before operation can begin, the battery must first be 'woken up' with a 48V DC charger. No voltage appears across the terminals until this is done, presumably for safety reasons. The documentation does not include information or instructions on this requirement. While some battery installers may own or have access to such a DC charger, it is not a common tool for most (grid-connected) installers. The battery will also enter back into this inactive mode after a period of time without operation; therefore, should some error occur which causes the system to shut down for a period, the charger is required to start it again.

FZSoNick

This Sodium Nickel Chloride $NaNiCl_2$ battery is manufactured by FZSONICK, a partnership between Swiss battery manufacturer FIAMM and Switzerland-based MES-DEA. The batteries are promoted for their high density, ability to operate over a large temperature range, and lack of fire risk. The battery is 100% recyclable in Australia.

The model installed in the Battery Test Centre is a 9.6 kWh 48TL200. The FZSoNick battery is connected to two Victron MultiPlus-II inverters in order to meet the required charge rate.

GridEdge is the only distributor of FZSoNick batteries in Australia. ITP began conversations with GridEdge early to discuss system design; although it sells the FZSoNick batteries with Victron inverters, there is not actually any direct communications from the FZSoNick BMS to the inverter. Instead, GridEdge have developed their own unit to sit between the two. Without it, the Victron inverter does not know the battery SOC as communicated from the BMS. GridEdge was very amenable to providing support to ITP in setting up its own control and monitoring. FZSoNick itself does not appear to have a list of inverters it claims to be compatible with.

Procurement was straightforward, and there were no issues with stock shortages or other delays.

The unit itself is physically reasonably small, but quite dense; large handles on the sides make it easier to manoeuvre. The installation at the test facility is floor-mounted, although there did not seem to be an optimal way to manage the cables with the unit on the floor. Installation instructions were clear, although again did not include any instruction on connection to particular inverters or which settings should be used with them.

The battery operates at a temperature of 265°C. From the outside, the battery is warm to the touch, but does not feel overly hot. When first turned on, it takes some time to reach this operating temperature before it can be used. When discharging, if it reaches the End of Discharge condition at 0% SOC, it will begin to cool after two minutes. It must then be warmed up before it can operate again.

ITP has been working with both FZSoNick and the Australian distributor to ensure optimal system operation. This included installing a capacitor between the battery and the inverter, on the advice that the Victron inverter has been known to cause DC 'ripples' which can affect the BMS. This condition is apparently also required for regular installations. The battery is also unable to charge at the C3 rate required as per the cycling methodology; the battery does two cycles per day (as opposed to three) over a reduced SOC window.

The manufacturer also states that a 15-hour charge is required every week in order to preserve battery capacity and keep the BMS SOC calculator accurate.

PowerPlus Energy LiFe Premium

PowerPlus Energy is an Australian company founded in 2017 and based in Melbourne. The PowerPlus LiFe batteries are rack-mounted and come in 24V, 48V, and 120V DC models. The LFP cells are produced by overseas manufacturers, but the battery packs are assembled within Australia and come with a 10 year warranty.

The Battery Test Centre installation consists of three 3.3kWh modules connected to an SMA Sunny island inverter.

The batteries were purchased directly from PowerPlus Energy in Australia. PowerPlus Energy wished to wait for a newer model with improved BMS to become available. Originally a lead time of two to three weeks was estimated; unfortunately, the new product was not ready after six weeks and the current version was delivered instead.

When the battery packs arrived, there were no DC cables included. PowerPlus states that it does usually provide cables with the battery, but in this case hadn't as it was not a regular installation and not clear that we required them. It was happy to send ITP the cables on request. The batteries came with an earth post but no interlinking earth cables; although these aren't necessarily expected, they would be easy to manufacture since the batteries are rack-mounted, and would reduce installation time if provided.

The battery does not have communications between its BMS and the inverter, which further simplifies installation, as it eliminates the need for a communications cable between the battery and inverter.

SolaX Triple Power

SolaX is a Chinese inverter manufacturer founded in 2003 and is prominent within the Australian residential inverter market. The SolaX Triple Power is its high voltage battery solution, containing 1-4 4.5 kWh or 6.3 kWh modules with a BMS. The internal cells are manufactured by Chinese company Shezhen BAK Power.

The SolaX Triple Power installation in the test facility consists of a Master Box and two 6.5kWh nominal capacity battery modules connected in series. The SolaX Triple Power is connected to a high voltage SolaX X1 hybrid inverter, the only inverter that it is compatible with.

As a major brand in the solar industry, the batteries were procured from a third-party distributor. At the time of order, the distributor did note that the SolaX Triple Power systems have had some issues when additional battery packs are added to the system at a later time. There were no delays in procurement, although the batteries and inverter arrived before the Master Box.

The battery units are floor-mounted, but attached to the wall via a pre-mounted plate. Multiple modular units make installation easier than with a single, physically larger unit. The batteries came with DC cables, and a kit with tubes to run cables between the two battery modules; however, these cables were a fixed length which resulted in the batteries being further apart than might otherwise be desired. Documentation was easy to follow. The Master Box, which is fixed to the top of one of the battery modules, includes a DC switch which eliminates the need for installation of a separate breaker between the batteries and inverter.

ITP initially had some problems controlling the SolaX X1 inverter as required for the testing. Although SolaX was initially responsive in providing support (and had provided support in the past for the X-Hybrid inverters in the facility), there was a long period where no progress was made, despite repeated contact from ITP since late October 2019. According to SolaX this was due in part to staff turnover and then difficulty contacting the software team in Wuhan during the COVID-19 epidemic that was occurring there at the time. After three months SolaX was able to provide the necessary information required for successful control.

sonnenBatterie

The sonnenBatterie system is an LFP battery pack with a DOD of 90%. The sonnenBatterie is an all-in-one system made up of the battery modules, BMS and inverter. sonnen was founded in 2010 in Germany, and has a manufacturing plant in South Australia.

The Battery Test Centre hybrid 9.53 model contains four 2.5kWh nominal capacity battery modules distributed across two cabinets.

sonnen only allows installation of its products by installers who have completed an in-depth online training course. The installer then receives an identifying number, which must be documented during the sonnen registration process.

The batteries do not come pre-installed in the cabinets and must be connected together by the installer; however, this is a simple process and also means that the installer does not have to manoeuvre a single large, heavy unit. DC and earth cables are supplied, and there are plenty of spare parts provided. The documentation provided was comprehensive. The installation at ITP's test facility is floor-mounted but attached to the wall via a keyhole slot in the back of the cabinets. This design requires a high level of accuracy in placing the battery; however, a full-size cardboard template is also provided by sonnen so that the exact placement can be marked on the wall before installation.

Zenaji Aeon

Zenaji is an Australian company who have designed the LTO Aeon battery, which is warranted for 20 years or 22,000 cycles. Proponents claim lithium titanate is a promising chemistry with excellent thermal stability and lifespan, and the ability to deliver energy over an extremely short period. Each module contains an inbuilt BMS. The Zenaji Aeon battery cells are manufactured overseas.

The Battery Test Centre installation consists of five modules with a total nominal capacity of 9.65kWh. The Zenaji Aeon battery is connected to an SMA Sunny Island inverter.

Zenaji advised a lead time of three weeks, but shipping delays meant that the batteries arrived two months from the date of order. Dispatch once the batteries arrived in Australia was quick.

Physically, the Zenaji Aeon batteries can be described as long triangular prismatic 'tubes'. Zenaji provides mounting brackets and DC cables. Nothing is provided to combine the cables from multiple batteries, although the requirement for this would vary based on what the cables are connecting into. Documentation was reasonable, although not much is required since installation is quite simple.

The manufacturer has advised that it is possible to install the battery 'tubes' either horizontally or vertically; however, this is not clear from the documentation, which references a 'Top Mounting Bracket' and 'Bottom Mounting Bracket'. Product IP ratings are dependent on installation according to documentation, so it is not clear that a regulator would accept horizontally mounted batteries as meeting the specified IP without further information from the manufacturer.

The battery does not have communications between its BMS and the inverter, which further simplifies installation, as it eliminates the need for a communications cable between the battery and inverter.

Since initial installation in the ITP test facility, Zenaji staff have visited to install updated protection boards in each of the battery packs. According to the manufacturer, these will switch off the battery when the BMS reports alarms in response to certain conditions.

7. MARKET DEVELOPMENT

7.1. Cost Trajectory

Since the beginning of the project, the cost of residential and commercial scale lithium-ion battery packs has fallen significantly. Further, throughout that period, many manufacturers have significantly altered their product offering, and several have exited the market or become insolvent. In recent periods, cost progress has slowed, 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 13 shows prices for NMC and LFP battery models installed in the Battery Test Centre over time.

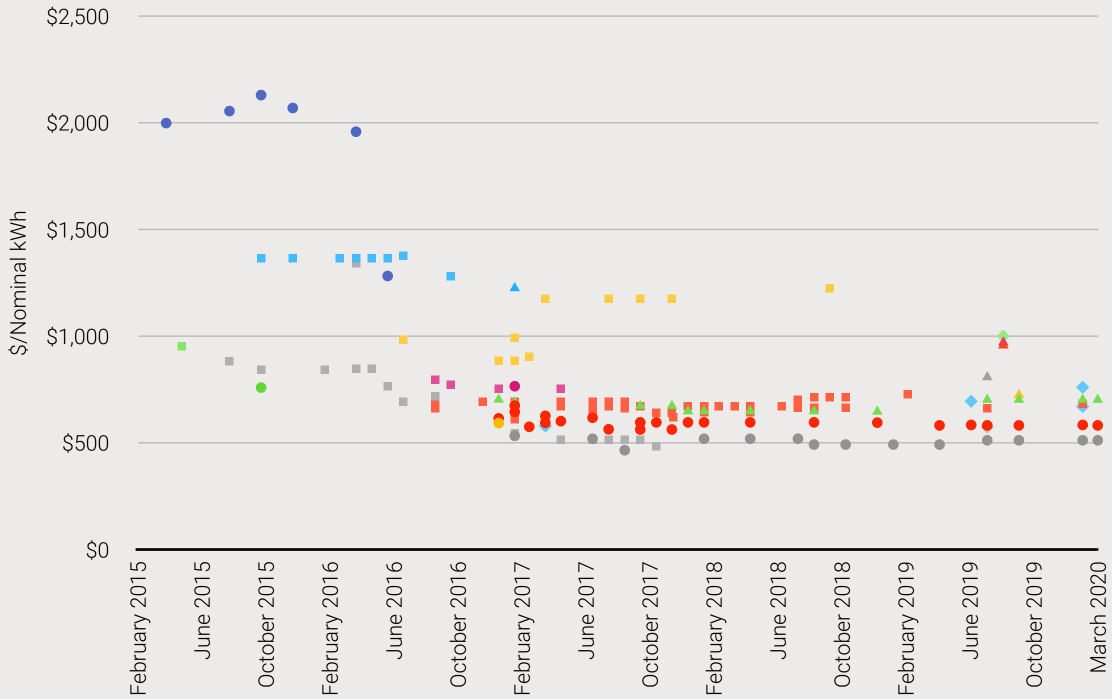

Figure 13: Wholesale prices for lithium-ion battery products installed in the Battery Test Centre

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 costs in the medium-term.

8. LESSONS LEARNED

Having been in operation for almost three years now, the Battery Test Centre project has revealed a number of valuable lessons. The lessons learned relate not only to the performance of the batteries throughout the trial, 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:

- The previous Public Report noted that the market appears to be moving towards either integrated battery and inverter products, or battery packs that are only compatible with inverters from the same manufacturer. As a result of this, there are an increased number of inverter models now contained within the battery trial. As a result, ITP has had to work closely with a number of manufacturers to integrate several different methods of monitoring and control into its IT systems. While the main method of control remains via Modbus over TCP to the inverters, other inverters utilise APIs, proprietary portals, and external control (such as Tesla). ITP has upgraded its overall lab monitoring and control system to best manage this complexity. While noted that the vast majority of applications will not involve having to manage control of multiple different batteries, it remains the case that the communication methods are neither standardised nor trivial. Third-party 'smart' DER devices would encounter similar difficulties in integrating with a large number of inverter models; for some 'black box' all-in-one systems, any kind of integration at all remains very difficult (e.g. Tesla Powerwall 2).

  Where possible, ITP has chosen inverter models which are the same as those products already installed.

- Some of the new batteries installed under Phase 3 are lithium batteries without 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. So far ITP has encountered some difficulty in commissioning these batteries and inverters to cycle according to the test methodology, and is working with SMA and the manufacturers.

  At least one of the manufacturers has stated that communications between the BMS and inverter will be included in future product development plans.

- More battery manufacturers are requiring product registration in order for warranty conditions to be valid. Details to be provided may include installer name/company, date of installation, and system configuration. This acts as a QA measure to ensure system installations meet manufacturer requirements. It is possible that in the future manufacturers may move towards requiring batteries to be directly connected to the internet and available for external monitoring, reducing the risk of honouring warranty claims when the conditions of operation are unknown by the manufacturer.

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[1] 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 200,850 page views with an average of 2:05 minutes spent per page overall and 3:54 minutes spent on the reports page.

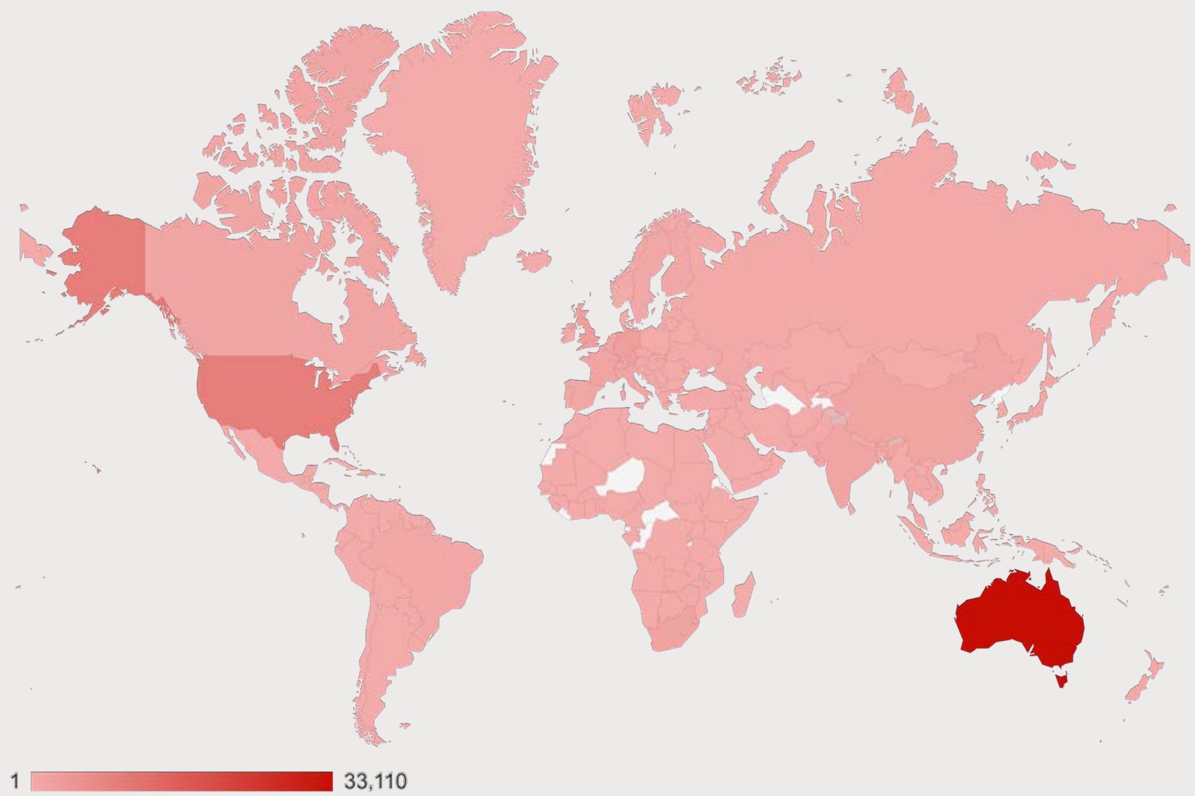

Figure 14: Number of sessions by country

1. batterytestcentre.com.au

The data from the website shows that the key audience is Australia, with Australian IP addresses accounting for 49,188 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 11,238 sessions from the United States, 3,382 from the United Kingdom and Germany not far behind on 3,316. It is interesting to note, however, that the content has been accessed from right across the globe.

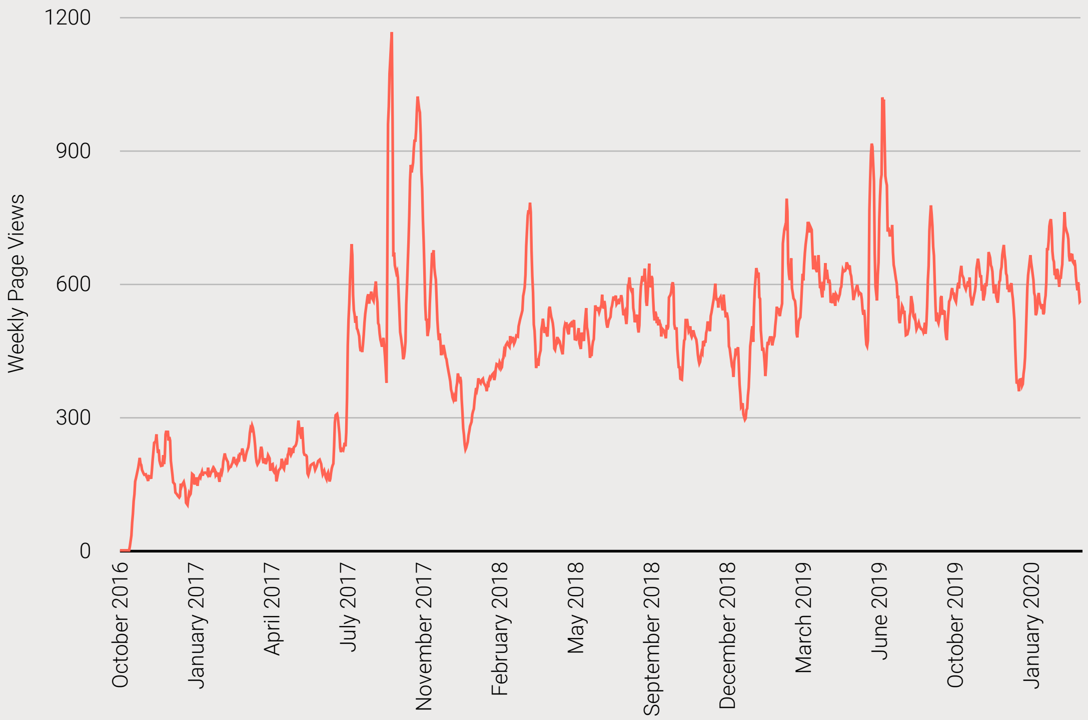

Figure 15: Weekly active users

Figure 15 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. The number of weekly users currently hovers 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 (12%), the reports page (10%), LG Chem RESU (8%), Pylontech US2000B (7%) and the background page on lithium-ion technology (4%).

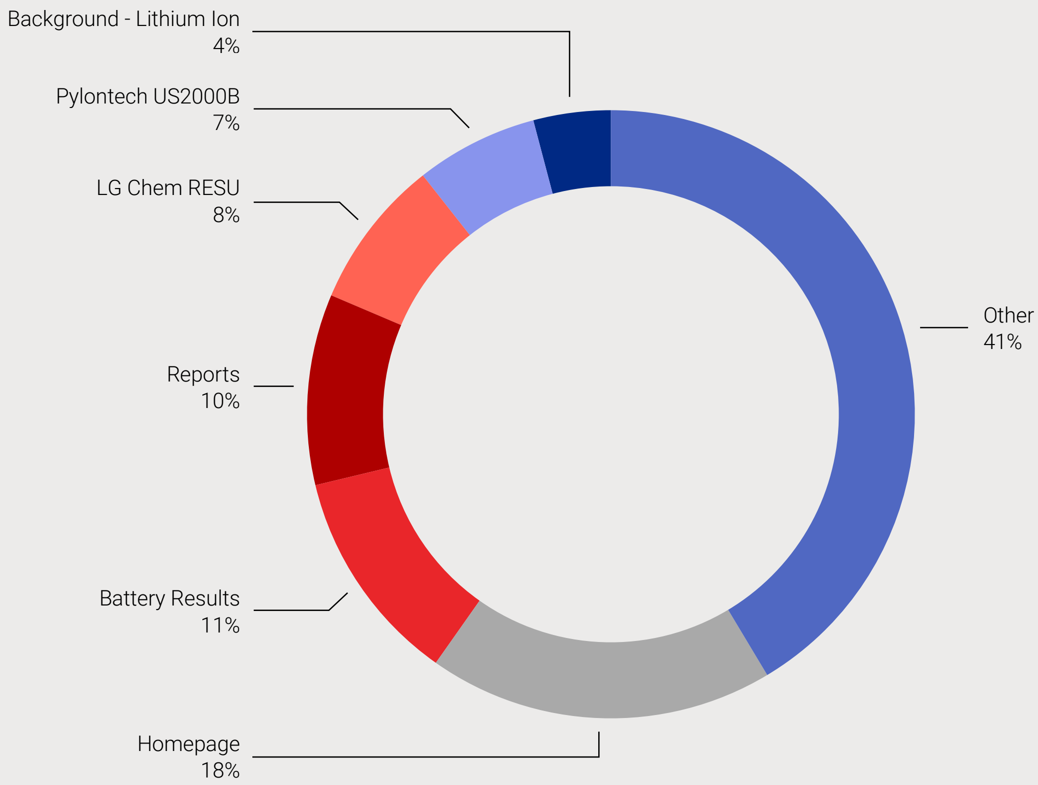

Figure 16: Breakdown of the 200,850 page views

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.

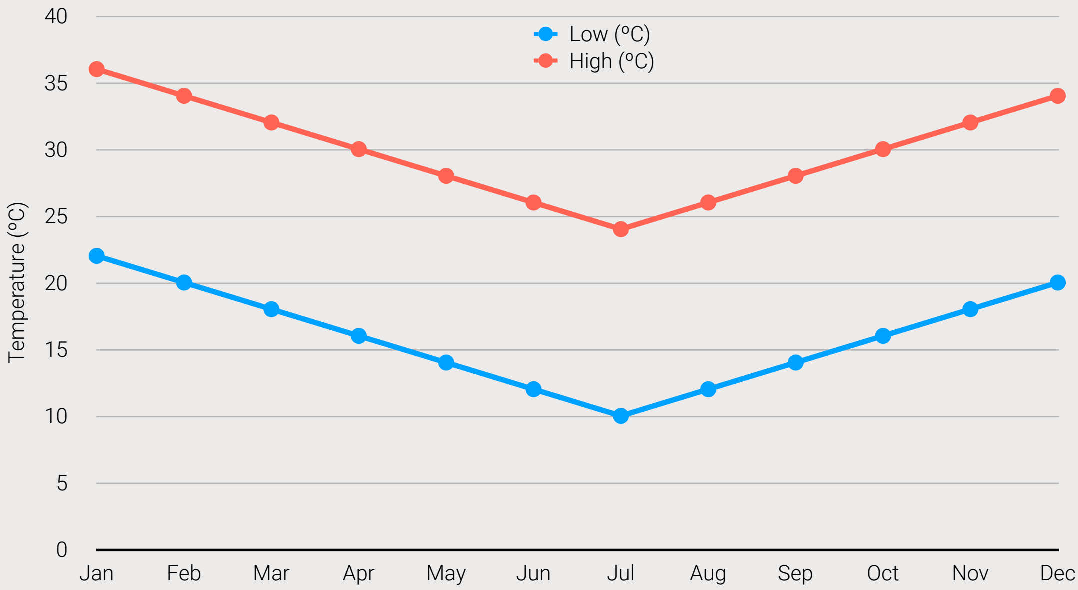

Figure 17: Daily hot and cold cycle temperatures throughout the year

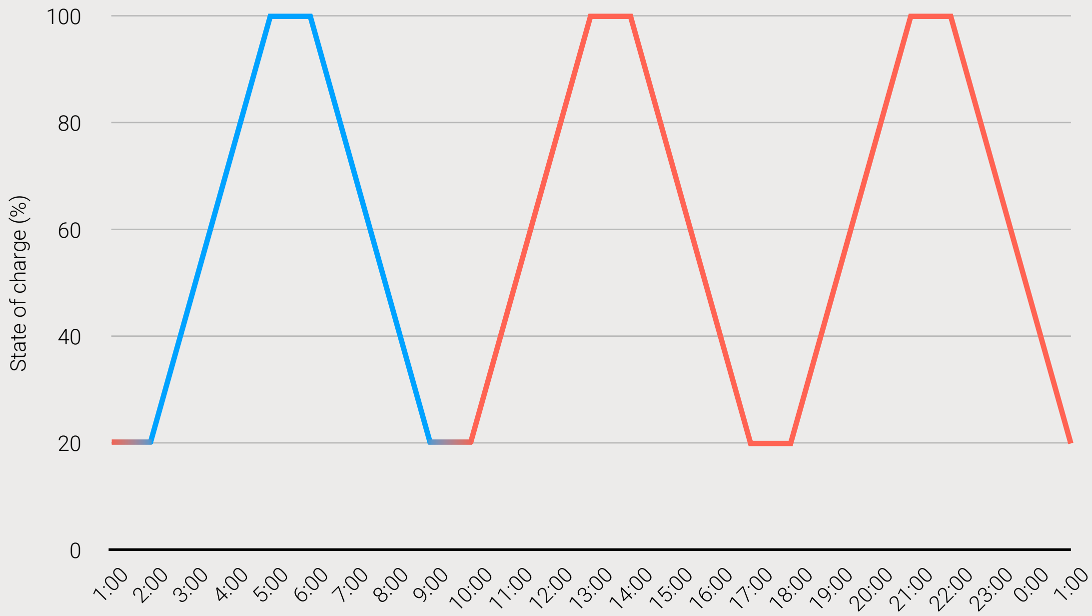

Figure 18: Summer temperature regime and charge regime

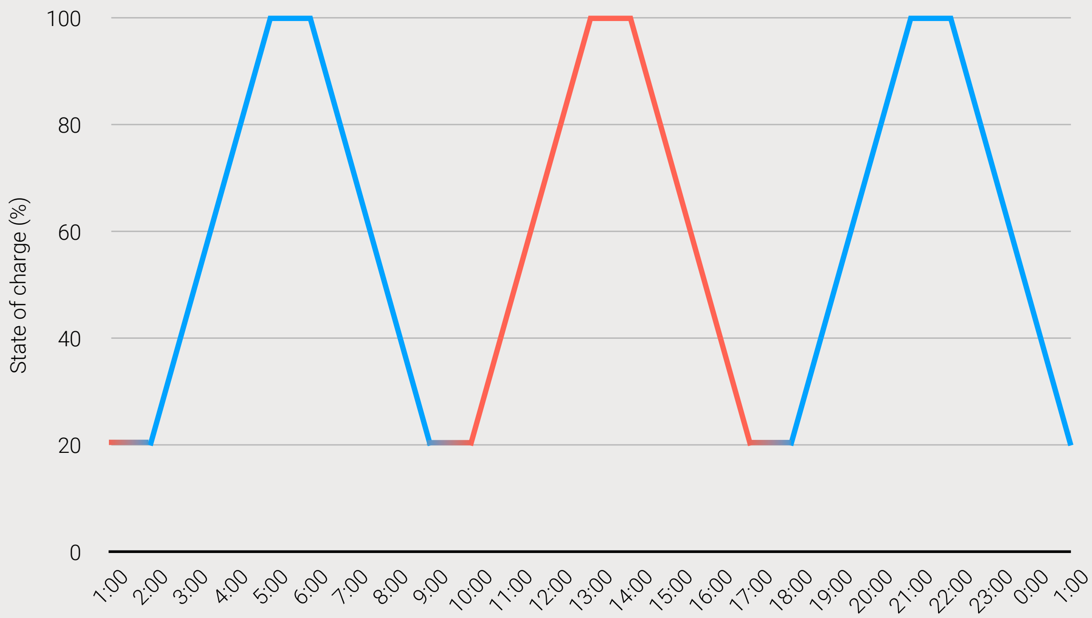

Figure 19: Winter temperature regime and charge regime

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
Ecoult 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.

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