Public Report 12 (Final Report)
Lithium-ion Battery Testing

ENGINEERING | STRATEGY & ADVISORY | ANALYTICS

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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. Eight batteries were included in the original Phase 1 project in 2015, with ten batteries added in Phase 2 in 2017, and a further eight in Phase 3 in 2019. The aim of the testing was to independently verify battery performance (capacity fade and round-trip efficiency) against manufacturers' claims. With a total of over six years of testing completed at the end of March 2022, the Battery Test Centre has provided valuable insights into battery performance beyond this original aim.

This final report describes testing results and general observations or issues encountered for each battery pack still cycling, to the end of testing in March 2022.

This report and earlier reports 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) tested 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 twelfth and final 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, alongside the Pylontech and GNB Lithium battery packs from Phase 2.

The Sony battery pack (Phase 1) has retained over 80% of its initial capacity after nearly 3,700 cycles. The Pylontech battery pack (Phase 2) has also retained over 75% of its initial capacity after nearly 2,800 cycles.

Most Phase 3 batteries have completed around 1,000 cycles, except the FIMER REACT2, which has retained over 85% of its initial capacity after nearly 1,750 cycles. The FZSoNicK battery shows minimal capacity fade but its lower discharge rate means it hasn't completed as many cycles as other batteries installed in the same phase. The three batteries without communications to the inverter have accumulated cycles more slowly owing to shallow discharges.

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

No major cost progress has been observed since the previous report. Indeed, cell and module costs have increased in the EV and commercial/utility-scale storage sector owing to high lithium and nickel prices, and high logistics costs. Nevertheless, most analysts continue to believe that the large amount of lithium-ion production capacity currently under development, alongside advances in manufacturing, will put downward pressure on prices in the medium-term. ITP's opinion is that these price reductions are required for mass-market uptake, alongside improvements in products, interfaces, and technical support.

The key findings of the trial over the last six years have been summarised below:

- There is a disconnect between communication from manufacturers and distributors and ITP's experiences on product capability (particularly integration and compatibility).
- Significant delays were experienced in battery availability and delivery, particularly for new models.
- Manufacturers appear to be moving towards either integrated battery and inverter products or battery packs that are only compatible with inverters from the same manufacturer. During commissioning in all three phases, ITP experienced many integration issues between batteries and inverters and this step removes the requirement for manufacturers to undertake R&D and testing with external partners.
- In terms of market development, more high-voltage battery inverters and battery packs are now available. High-voltage battery products are generally simpler to install, due to smaller cables being required. Higher-voltage inverters are generally more efficient and have higher power density, meaning cheaper equipment and easier/cheaper installation.
- The number of battery failures and required replacements during the trial has been greater than originally estimated. This has been across products, i.e. a mix of established and emerging manufacturers. Although there have been a few batteries which have not experienced any issues over the trial period, this indicates an overall continuing state of development of the technologies. Some manufacturers have become insolvent during the trial period, highlighting the importance of choosing manufacturers who will be likely to endure any issues and honour warranties where required.
- The amount of time required for managing maintenance issues during operation was significantly underestimated and the level of support received from manufacturers varied widely.

1. PROJECT BACKGROUND

Over the last six years, ITP Renewables (ITP) has been testing the performance of residential and commercial-scale battery packs in a purpose-built, climate-controlled enclosure at the Canberra Institute of Technology.

Six lithium-ion, one conventional lead-acid, and one advanced lead-acid battery packs were installed during Phase 1 of the trial, which commenced in August 2016. Phase 2 commenced in July 2017 with the addition of eight lithium-ion packs, a zinc-bromide flow battery, and a "saltwater" battery bank. Phase 3 commenced in late 2019 with the addition of a further eight battery packs, including a lithium-titanate (LTO) battery and a sodium-nickel battery. Testing of all batteries was completed at the end of March 2022.

The batteries tested by ITP are listed below.

Product	Type	Nameplate Capacity (kWh nominal)	Phase	Status
CALB CA100	Lithium Iron Phosphate	10.24	1	Testing Previously Concluded
Ecoult UltraFlex	Lead Carbon	14.8	1	Testing Previously Concluded
GNB Sonnenschein	Lead Acid	14.4	1	Testing Previously Concluded
Kokam + ADS-TEC	Lithium Nickel Manganese Cobalt	8.3	1	Testing Previously Concluded
LG Chem RESU 1	Lithium Nickel Manganese Cobalt	9.6	1	Testing Previously Concluded
Samsung AIO	Lithium Nickel Manganese Cobalt	10.8	1	Testing Previously Concluded
Sony Fortelion	Lithium Iron Phosphate	9.6	1	Testing Concluded in March 2022
Tesla Powerwall 1	Lithium Nickel Manganese Cobalt	6.4	1	Testing Previously Concluded
Alpha ESS M48100	Lithium Iron Phosphate	9.6	2	Testing Previously Concluded
Ampetus Super Lithium	Lithium Iron Phosphate	9.0	2	Testing Previously Concluded
Aquion Aspen	Aqueous Hybrid Ion	17.6	2	Testing Previously Concluded
SimpliPhi PHI 3.4	Lithium Iron Phosphate	10.2	2	Testing Previously Concluded

Product	Type	Nameplate Capacity (kWh nominal)	Phase	Status
BYD B-Box	Lithium Iron Phosphate	10.24	2	October 2020 – Replaced by BYD B-Box LVS (8 kWh) Testing Concluded in March 2022
GNB Lithium	Lithium Nickel Manganese Cobalt	12.7	2	Testing Concluded in March 2022
LG Chem RESU HV	Lithium Nickel Manganese Cobalt	9.8	2	Testing Concluded in March 2022
Pylontech US2000B	Lithium Iron Phosphate	9.6	2	Testing Concluded in March 2022
Redflow ZCell	Zinc-Bromide Flow	10.0	2	Testing Concluded in March 2022
Telsa Powerwall 2	Lithium Nickel Manganese Cobalt	13.5	2	Testing Concluded in March 2022
BYD B-Box HV	Lithium Iron Phosphate	10.2	3	June 2020 – Replaced by BYD B-Box HVM (11.04 kWh) Testing Concluded in March 2022
DCS PV 10.0	Lithium Iron Phosphate	10.0	3	Testing Concluded in March 2022
FIMER REACT 2	Lithium Nickel Manganese Cobalt	8.0	3	Testing Concluded in March 2022
FZSoNick	Sodium Nickel Chloride	9.6	3	Testing Concluded in March 2022
PowerPlus Energy LiFe Premium	Lithium Iron Phosphate	9.9	3	Testing Concluded in March 2022
SolaX Triple Power	Lithium Nickel Manganese Cobalt	12.6	3	Testing Concluded in March 2022
sonnenBatterie	Lithium Iron Phosphate	10.0	3	Testing Concluded in March 2022
Zenaji Aeon	Lithium Titanate	9.6	3	Testing Concluded in March 2022

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

The objectives of this project include:

- increased skills, capacity and knowledge in emerging battery technologies within Australia;
- increased insight into the validity of claims made by battery manufacturers about the performance of their products
- increased publicly-accessible material or tools to inform the design of projects using battery technology;
- increased understanding of the performance of battery technologies when exposed to real-world temperatures;
- increased understanding of battery performance among potential investors and researchers;
- increased collaboration between ARENA-funded projects and renewable energy sector projects (by industries and/or universities) in the field of emerging battery technologies.

Project information has been disseminated in six-monthly public reports, and a project website (**batterytestcentre.com.au**) with information on each of the batteries under test and live testing results. In doing so the project has contributed to public knowledge and awareness of battery performance, and provided consumers with tools to assist them in making investment decisions.

2. BATTERY OPERATION OVERVIEW

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

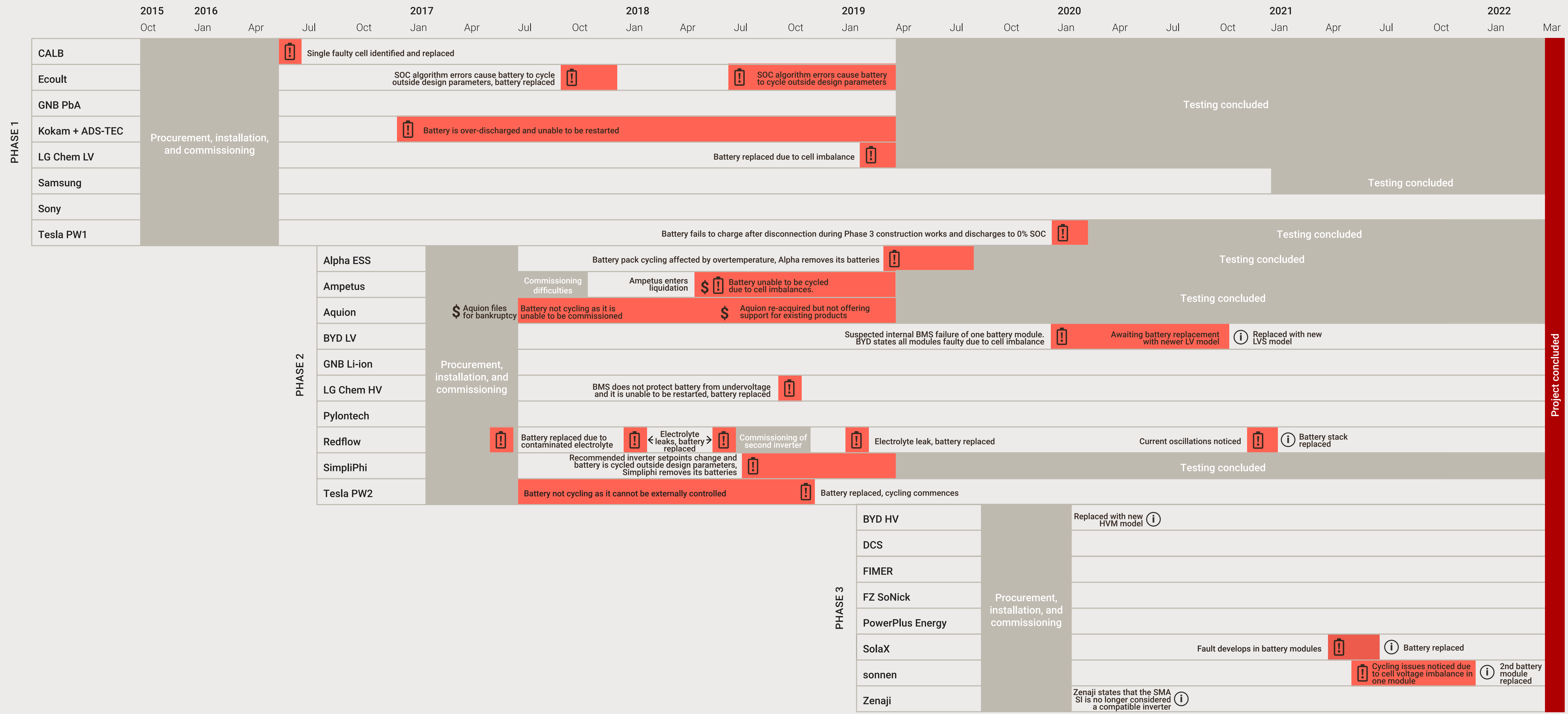

Figure 1: Overview of battery operation

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 cycling progress overall.

3.1. Sony Fortelion

Operational Issues

The Sony pack has completed a high number of cycles. No faults were experienced in the past six months or at any time during testing. There is a small jump in SOC at the end of the charge cycle as it recalculates from 93% to 100%.

Capacity Fade

The energy discharged per cycle is depicted in Figure 2. Capacity appears to have decreased linearly initially, but has stabilised recently. A SOH of ~81% after ~3,680 cycles[1] is apparent.

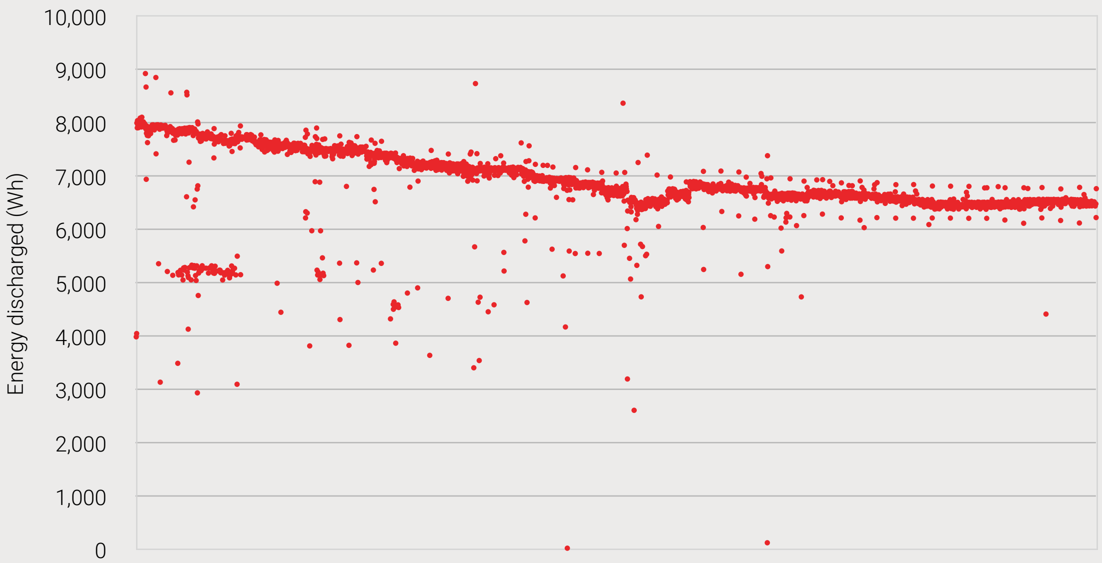

Figure 2: Energy discharged per cycle by the Sony battery pack

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

4. PHASE 2 UPDATE

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

4.1. BYD B-Box LVS

Operational Issues

The BYD B-Box LV was replaced by BYD at the end of October 2020 with a newer model (BYD B-Box LVS). The issues encountered with the previous model are described in previous reports.

In September 2021, ITP noticed that the battery SOC would regularly drop below the minimum SOC setpoint while the battery was idling. This would trigger the Sunny Island inverter's battery protection functions, putting the inverter on standby. BYD checked battery logs and advised that there was an issue with the battery's SOC-voltage calibration. Changes in cycling parameters were suggested but did not resolve the issue. To keep the battery cycling without interruptions, ITP was advised to lower the Sunny Island battery protection (SOC%) settings, while BYD continue to monitor the battery performance.

BYD is still monitoring the battery but has not yet provided any further feedback. Nevertheless, the battery is operational and cycling as expected.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 3. Only minor capacity fade is apparent and the data suggests a SOH of ~ 93% after ~1,060 cycles.

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

4.2. GNB Lithium

Operational Issues

ITP has not experienced any operational issues with the GNB Lithium battery pack but in September 2020 approached GNB regarding the rapid capacity fade. ITP revised the cycling range after receiving clarification from GNB on the battery's minimum SOC limits, and operational requirements to keep its SOC counter accurate. This boosted calculated capacity initially, but SOH has subsequently dropped.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 4. The data suggests a SOH of ~37% after ~1,940 cycles.

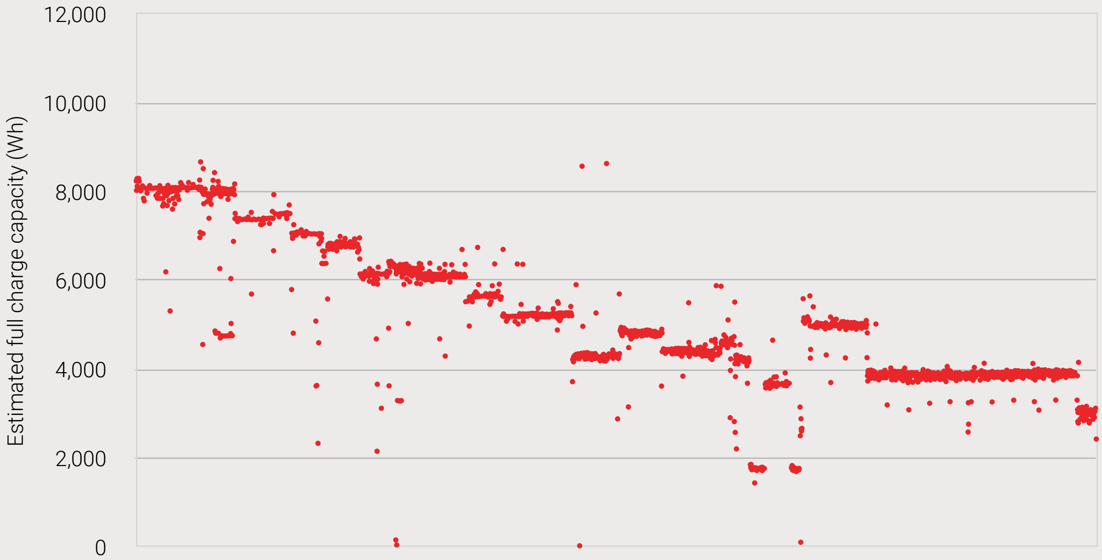

Figure 4: Estimated full charge capacity per cycle by the GNB LFP battery pack

4.3. LG Chem RESU HV

Operational Issues

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

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 5. Linear capacity fade is apparent and the data suggests a SOH of ~75% after ~2,040 cycles.

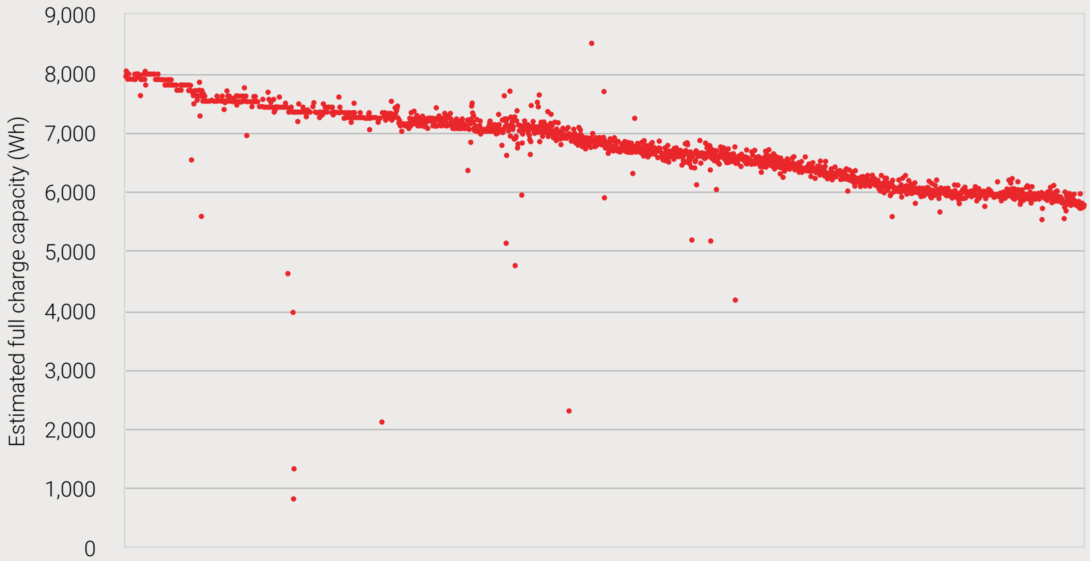

Figure 5: Estimated full charge capacity per cycle by the LG Chem RESU HV battery pack

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 rate of capacity fade appears to have reduced over time. The data suggests a SOH of ~77% after ~2,830 cycles.

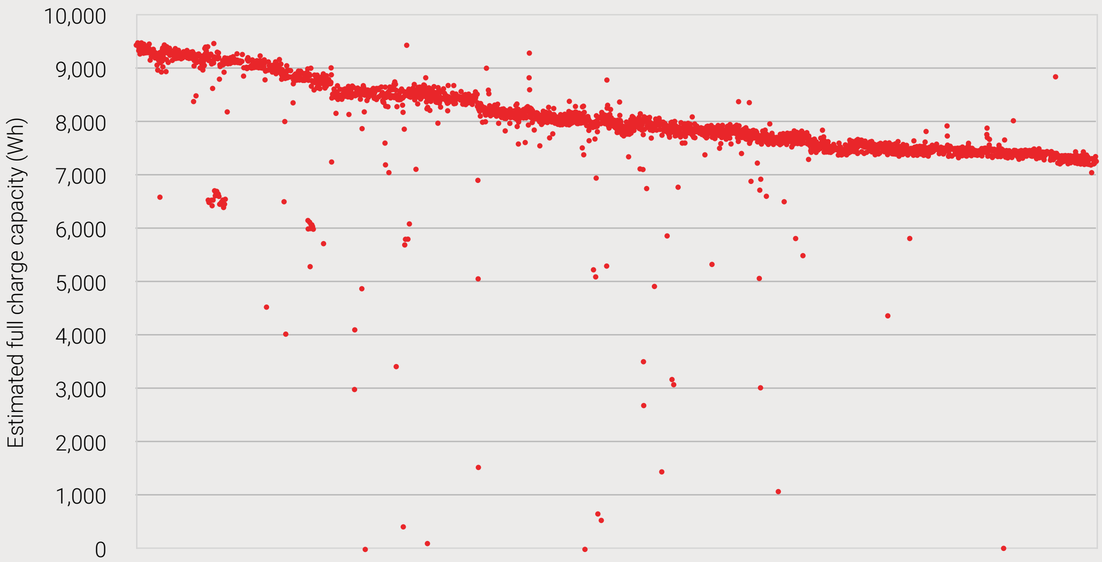

Figure 6: Estimated full charge capaciy per cycle by the Pylontech battery pack

4.5. Redflow ZCell

Operational Issues

This is the fifth Redflow battery to be installed in the Test Centre. Issues with the previous batteries are described in previous reports. Since the battery stack replacement in November 2020, the Redflow battery has not experienced any operational issues.

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.

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

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 7. The data suggests a SOH of 93% after ~800 cycles[3].

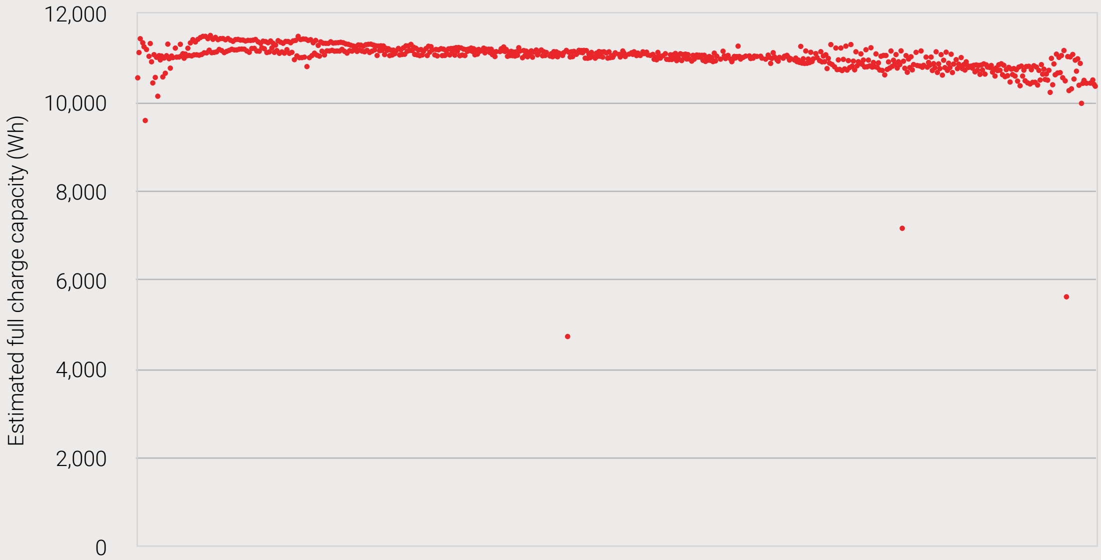

Figure 7: Estimated full charge capacity per cycle by the Redflow battery pack

[3] Starting from replacement of the battery stack in November 2020

4.6. Tesla Powerwall 2

Operational Issues

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

ITP have no direct control over the battery (as Tesla do not allow this level of control of their products) but rely on Tesla to implement the cycling schedule. This requires intermittent contact with Tesla as it appears that the control is only set for a finite period each time it is implemented.

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

The Tesla Powerwall 2 was experiencing small jumps in SOC at the end of the charge cycle as it recalculated from 92% to 100%. ITP observed that these jumps stopped occurring from November 2021. Since then, the energy discharged from the battery, and therefore the implied capacity, have increased. ITP thinks this may be due to a firmware upgrade and has reached out to Tesla for comment but has not yet received a response.

Capacity Fade

The energy discharged per cycle is depicted in Figure 8. The data suggests a SOH of ~79% after ~2,520 cycles.

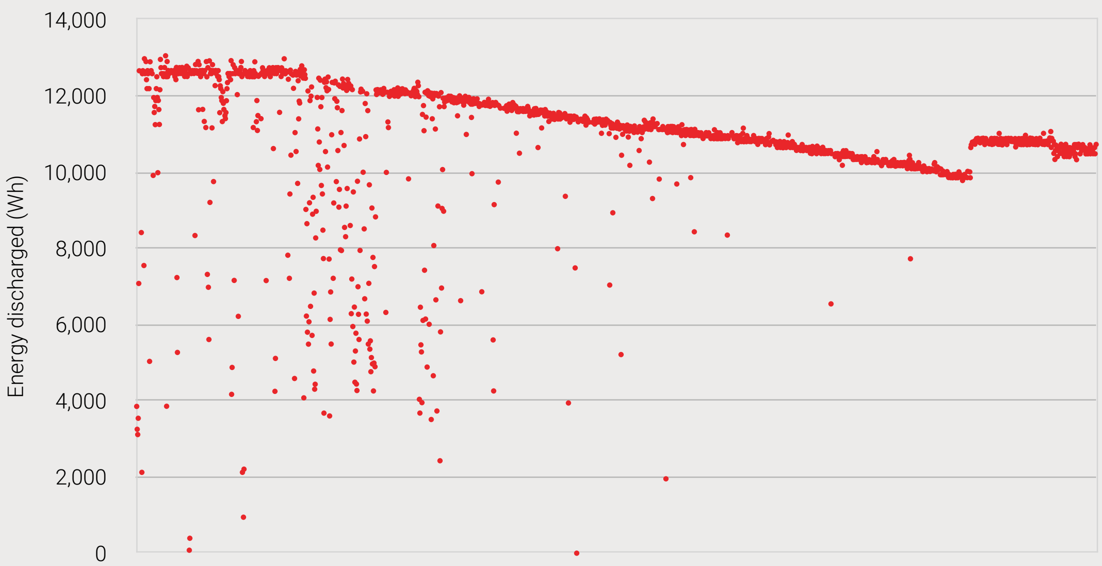

Figure 8: Energy discharged per cycle by the Tesla Powerwall 2 battery pack

[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 3 batteries, and gives an update on progress overall.

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. After the inverter firmware issues discussed in the previous report were resolved, the battery has been cycling reliably.

A firmware update was performed on the battery in October 2021 which appears to have increased the amount of energy being discharged from the battery. The resulting calculated increase in capacity is apparent in Figure 9.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 9. The data suggests that the SOH has improved as compared to the initial cycles (i.e. a SOH of 105%) after ~1,180 cycles. This is a likely result of the increase in capacity after the firmware update mentioned above.

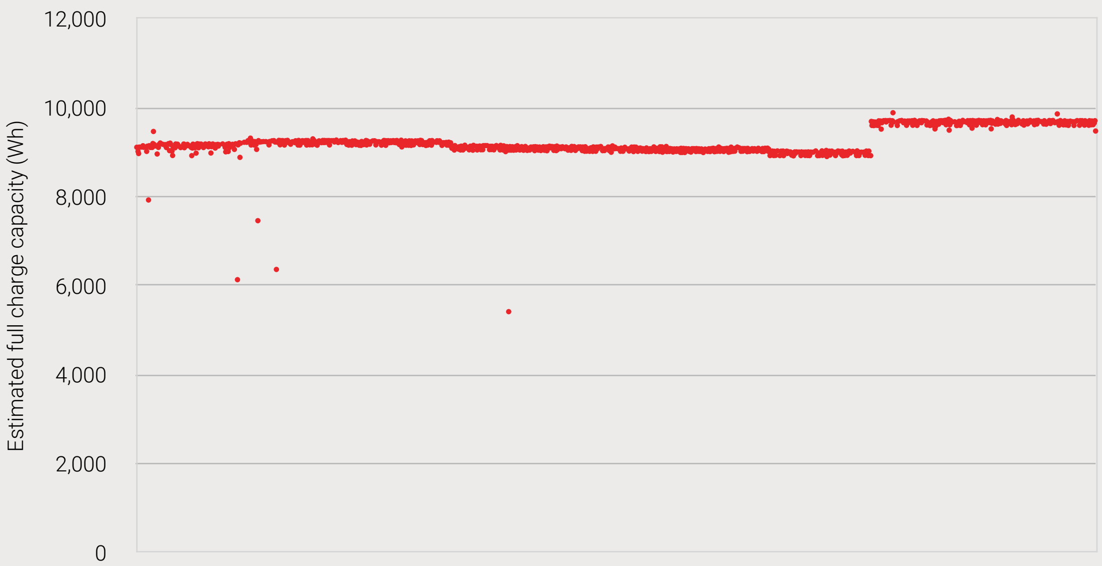

Figure 9: Estimated full charge capacity per cycle by the BYD HVM battery pack

5.2. Deep Cycle Systems (DCS) PV 10.0

Operational Issues

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

The DCS battery is cycled between minimum and maximum battery voltage limits (as per DCS advice), as well as a minimum inverter SOC (to avoid inverter shutdown), meaning that the end of the discharge cycle is determined by whichever of the minimum battery voltage or inverter SOC is reached first. When discharging the battery at a C3 rate, the battery voltage and inverter-estimated SOC were dropping to their cut-off levels well before the expected energy was discharged. To maximise the energy discharged per cycle while maintaining three cycles per day, ITP reduced the charge/discharge rate as well as the rest time between cycles. The slower discharge rate allows more energy to be discharged each cycle before the cut-off limits are reached; however, the 'full' capacity of the battery is still not discharged through this cycling regime.

Recently, ITP noticed a rapid decline in the battery capacity and reached out to DCS. They have requested the battery to be sent back to their factory in South-East Queensland for analysis.

Capacity Fade

The energy discharged per cycle is depicted in Figure 10. The data suggests a SOH of ~57% after ~1,100 cycles.

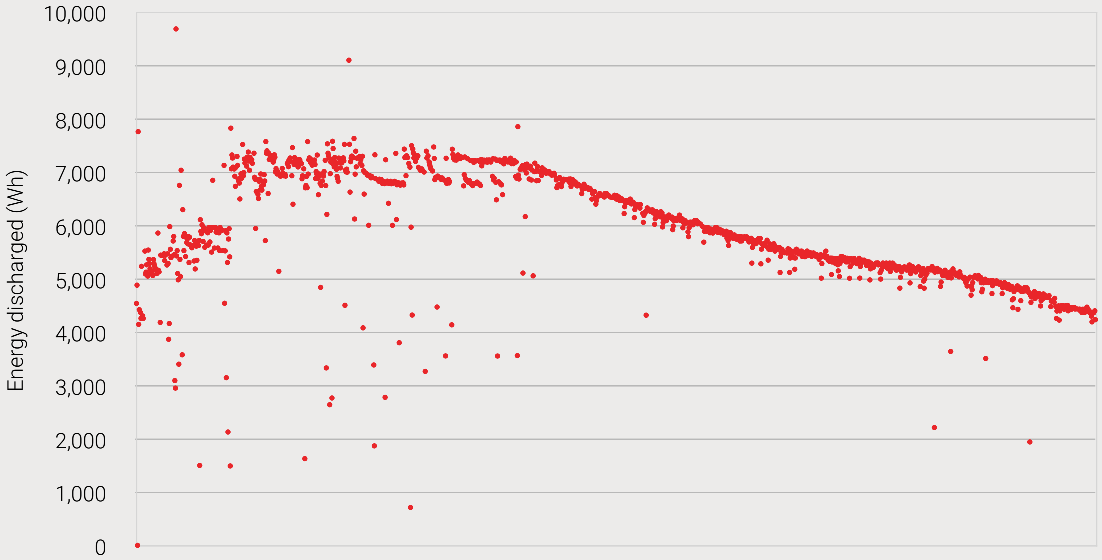

Figure 10: Energy discharged per cycle by the DCS battery pack

5.3. FIMER REACT 2

Operational Issues

ITP did not experience any operational issues with the FIMER REACT 2 battery until March 2022, when a decline in energy discharged from the battery was observed.

ITP reached out to FIMER, who has found that the SOC of one of the two REACT 2 units has been dropping below 5%, triggering the BMS/inverter to stop the discharge. FIMER expect that the system should continue discharging as the two battery modules should act independently and are conducting lab tests to investigate why the discharge is being interrupted.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 11. The data suggests a SOH of 86% after ~1,740 cycles.

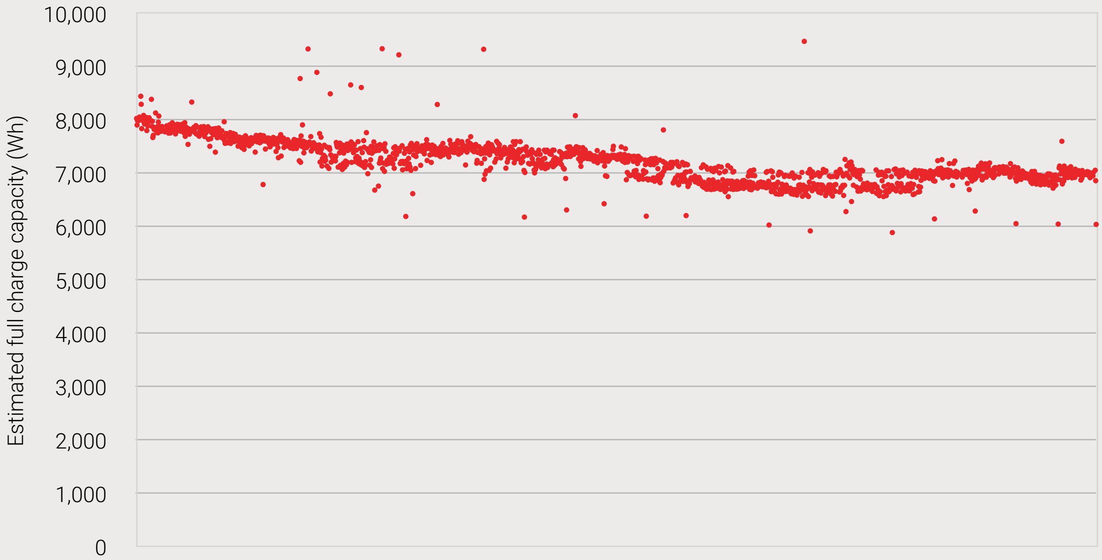

Figure 11: Estimated full charge capacity per cycle by the FIMER battery pack

5.4. FZSoNick

Operational Issues

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

FZSoNick previously 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. In December 2021, FZSoNick updated their advice and removed the requirement of regular full discharges, while still requiring a prolonged charge full charge every seven days. This means that the FZSoNick battery accumulates cycles at a slower rate than other batteries in the trial, although at an increased rate compared to before December 2021.

In January 2022, ITP noticed that the maximum SOC being reached by the battery had reduced from 100% to 80%. This was raised with FZSoNick, and a firmware upgrade in February 2022 rectified this issue, and the battery has been cycling normally since then.

Capacity Fade

The full discharge capacity implied by each partial cycle is depicted in Figure 12. The data suggests a SOH of 94% after ~880 cycles.

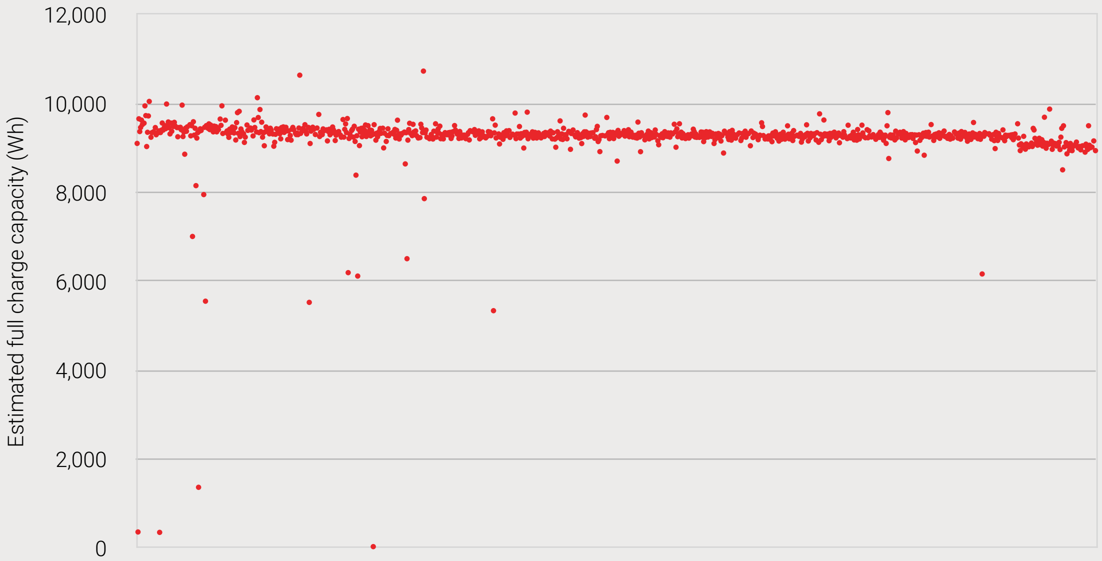

Figure 12: Estimated full charge capacity per cycle by the FZSoNick battery pack

5.5. PowerPlus Energy LiFe Premium

Operational Issues

The PowerPlus batteries in the trial are connected to an SMA Sunny Island inverter. Although each battery has a BMS, the BMS does not communicate with the inverter. The battery warranty is dependent on the battery not being cycled below 20% SOC but SOC is not reported by the BMS and hence the inverter is responsible for estimating SOC based on configurable parameters, and its own measurements (e.g. voltage, temperature, Coulombs etc.).

The inverter does not appear able to accurately estimate the SOC of the PowerPlus battery, as SOC jumps at the end of discharge cycles and 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 setpoint.

ITP found that when cycling at C3 (i.e. 3-hr) 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 PowerPlus battery also requires a 100% recharge every 7 to 14 days to keep the external SOC counter accurate.

Capacity Fade

The energy discharged per cycle is depicted in Figure 13. Some capacity fade is apparent (~95% SOH) after ~1,030 cycles and each cycle can be seen to be delivering much less energy than the nameplate capacity. This is likely a result of the issues described above.

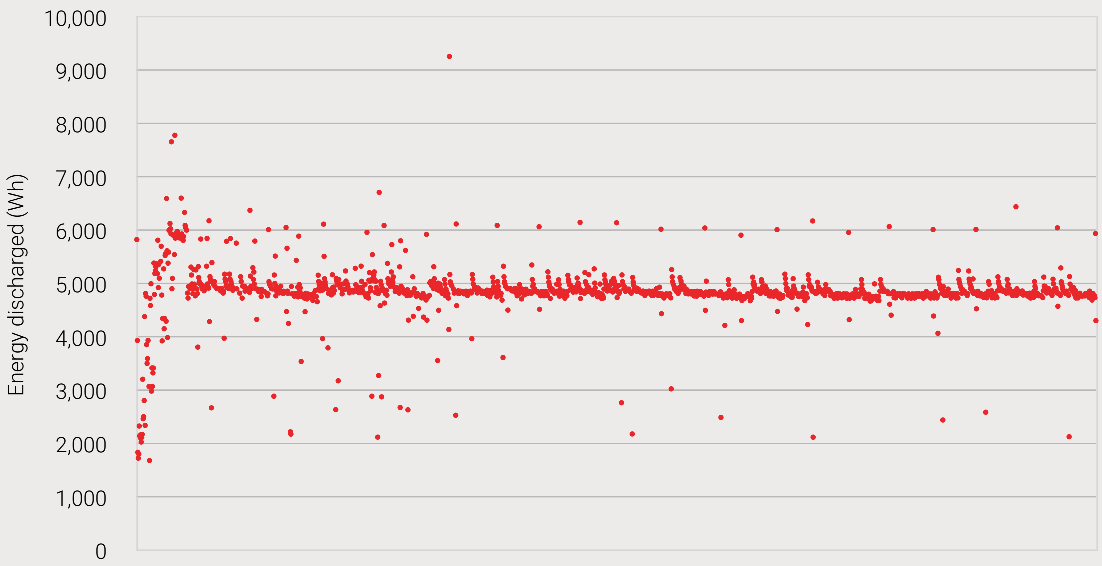

Figure 13: Energy discharged per cycle by the Powerplus battery pack

5.6. SolaX Triple Power

Operational Issues

The SolaX battery was replaced in July 2021 after an issue with the battery modules (described in the previous report). The battery has been cycling reliably without any issues since the replacement.

Capacity Fade

The energy discharged per cycle is depicted in Figure 14. The data suggests very minor capacity fade (i.e. a SOH of 98%) after ~600 cycles.

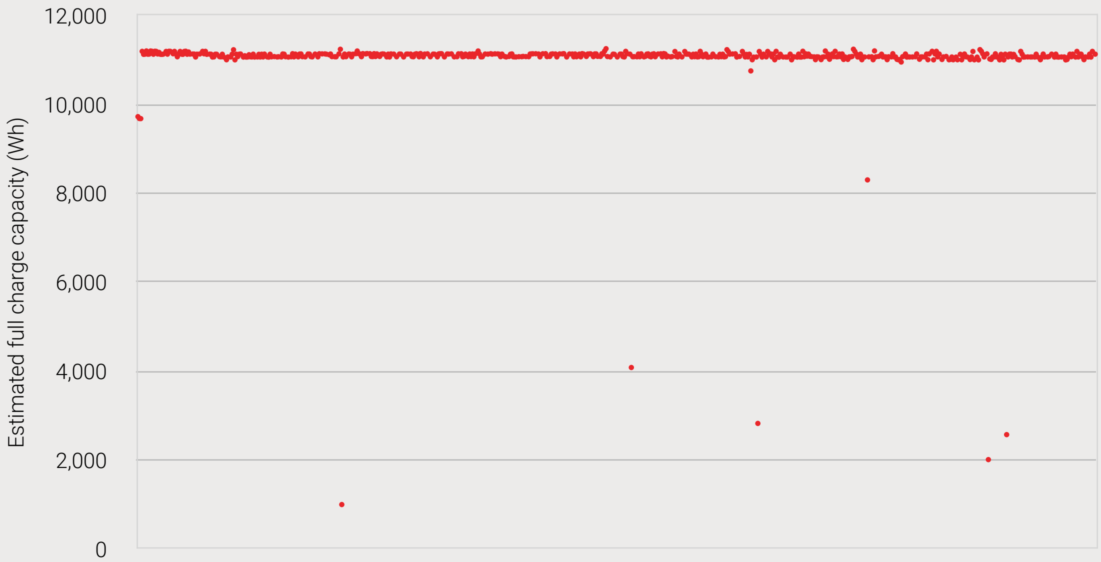

Figure 14: Energy discharged per cycle by the SolaX battery pack

5.7. sonnenBatterie

Operational Issues

Following some issues establishing control of the battery during commissioning, ITP did not experience any operational issues with the sonnenBatterie until March 2021, when accelerated decline in energy and SOC discharged per cycle was observed.

ITP reached out to sonnen regarding the issue in April 2021, but they were unable to diagnose the issue remotely. A representative from their technical team visited the lab in June 2021 to conduct on-site diagnostics and replaced a faulty module in the battery. Sonnen's investigation found that one of the cells was not able to manage its voltage properly, which caused the entire module to shut down earlier when discharging.

Sonnen has been remotely monitoring the performance of the refurbished battery and reached out to ITP again in July 2021. Sonnen noted that the battery performance was still not up to their quality standards and would like to visit the site again to conduct further diagnostics. After the COVID-19 lockdown restrictions ended, sonnen found another battery module with voltage imbalance, which was replaced in December 2021 and all four battery modules were recalibrated. Given that two of the four modules have been replaced, for this analysis ITP has reset the number of cycles completed by the sonnenBatterie.

Capacity Fade

The energy discharged per cycle is depicted in Figure 15. No capacity fade is apparent after ~180 cycles since the module replacement was done.

Figure 15: Energy discharged per cycle per cycle by the sonnen battery pack

5.8. Zenaji Aeon

Operational Issues

The Zenaji batteries are connected to an SMA Sunny Island inverter. Although each unit has a BMS, the BMS does not communicate with the inverter. Therefore, the inverter is responsible for estimating SOC based on configurable parameters, 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 exceed 85%, and the end of each discharge cycle is limited by the inverter SOC setpoint (to avoid shutdown) rather than the minimum voltage setpoint.

This behaviour has made it difficult to cycle the batteries according to the test methodology (i.e. ~3 x 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.

Capacity Fade

The energy discharged per cycle is depicted in Figure 16. Owing to the issues described above, the trend in capacity fade is unclear after ~700 cycles. Each cycle can be seen to be delivering much less energy than the nameplate capacity. This is likely a result of the issues described above.

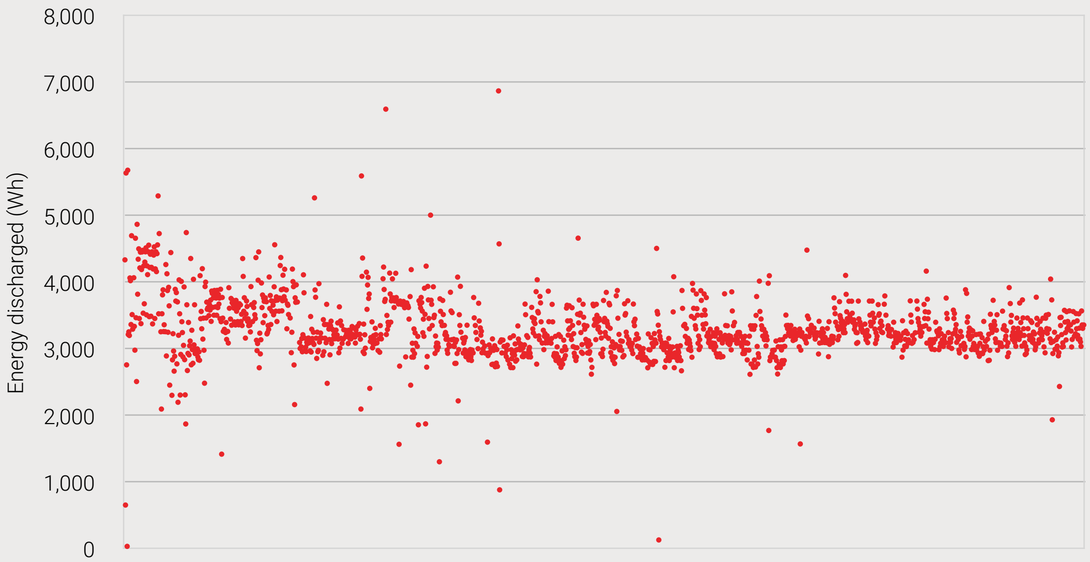

Figure 16: Energy discharged per cycle by the Zenaji battery pack

6. PERFORMANCE COMPARISON

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

Throughout the trial, ITP has observed erratic SOC estimation resulting in significant variability in the energy discharged each cycle. As such, this report provides data and analysis based on both the energy discharged during the monthly capacity tests (below), as well as on the energy discharged each "cycle" over the course of the trial (see Sections 3, 4 and 5 above). Both data sets should be considered before drawing conclusions.

6.1. Phase 1 Capacity Test Results

Figure 17 shows the estimated state of health (SOH) against cycles completed for each Phase 1 battery pack still cycling (i.e. only the Sony). SOH is estimated by dividing the energy delivered during each capacity test by the energy delivered in the first capacity test. (Energy delivered in the first capacity test might be lower or higher than the nominal capacity of the battery).

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

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

Sony Fortelion

Based on a linear regression between estimated SOH and cycles completed (Figure 17), the Sony Fortelion pack is on track for 60% SOH at ~7,390 cycles. As above, however, a linear extrapolation may not be appropriate.

6.2. Phase 2 Capacity Test Results

Figure 18 shows the estimated state of health (SOH) against cycles completed for each Phase 2 battery pack still cycling. SOH is estimated by dividing the energy delivered during each capacity test by the energy delivered in the first capacity test. (Energy delivered in the first capacity test might be lower or higher than the nominal capacity of the battery). No line of best fit has been included for batteries with less than 500 cycles, or where it is difficult to establish a meaningful trend.

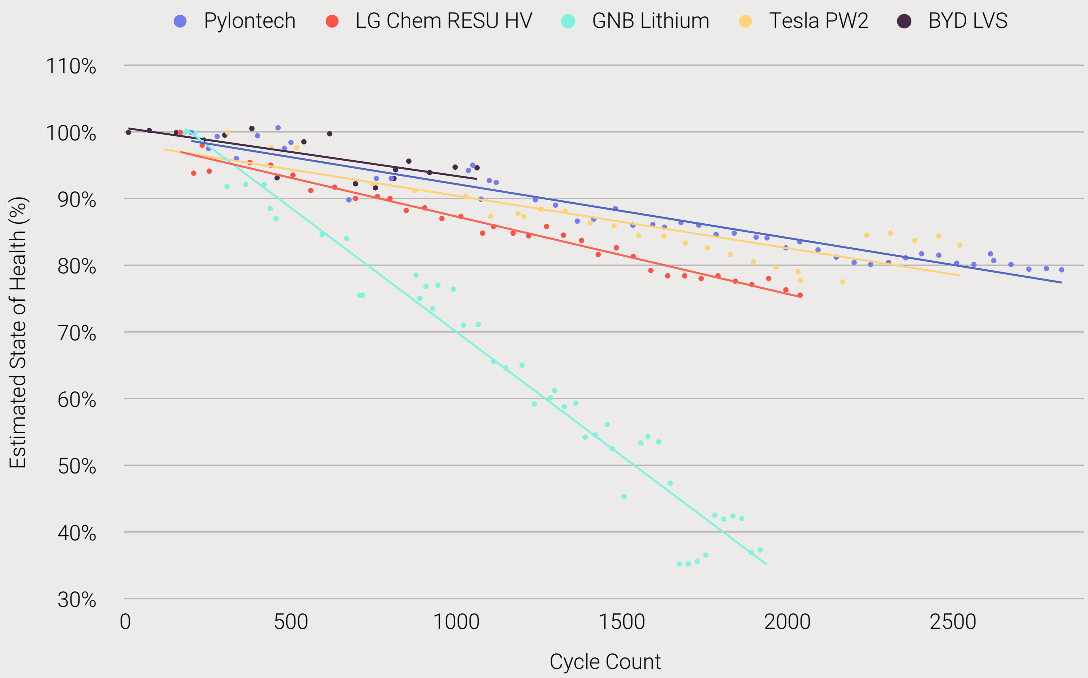

Figure 18: Capacity fade of Phase 2 battery packs based on monthly capacity tests

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

BYD LVS

Based on a linear regression between estimated SOH and cycles completed (Figure 18), the BYD LVS battery is on track for 60% SOH at ~5,640 cycles. As above, however, a linear extrapolation may not be appropriate.

GNB Lithium

Based on a linear regression between estimated SOH and cycles completed (Figure 18), the GNB Lithium reached 60% SOH at ~1,270 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 18), the LG Chem RESU HV is on track for 60% SOH at ~3,360 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 18), the Pylontech US2000B is on track for 60% SOH at ~4,995 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 18), the Tesla Powerwall 2 is on track for 60% SOH at ~4,885 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

Figure 19 shows the estimated state of health (SOH) against cycles completed for each Phase 3 battery pack. SOH is estimated by dividing the energy delivered during each capacity test by the energy delivered in the first capacity test. (Energy delivered in the first capacity test might be lower or higher than the nominal capacity of the battery).

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

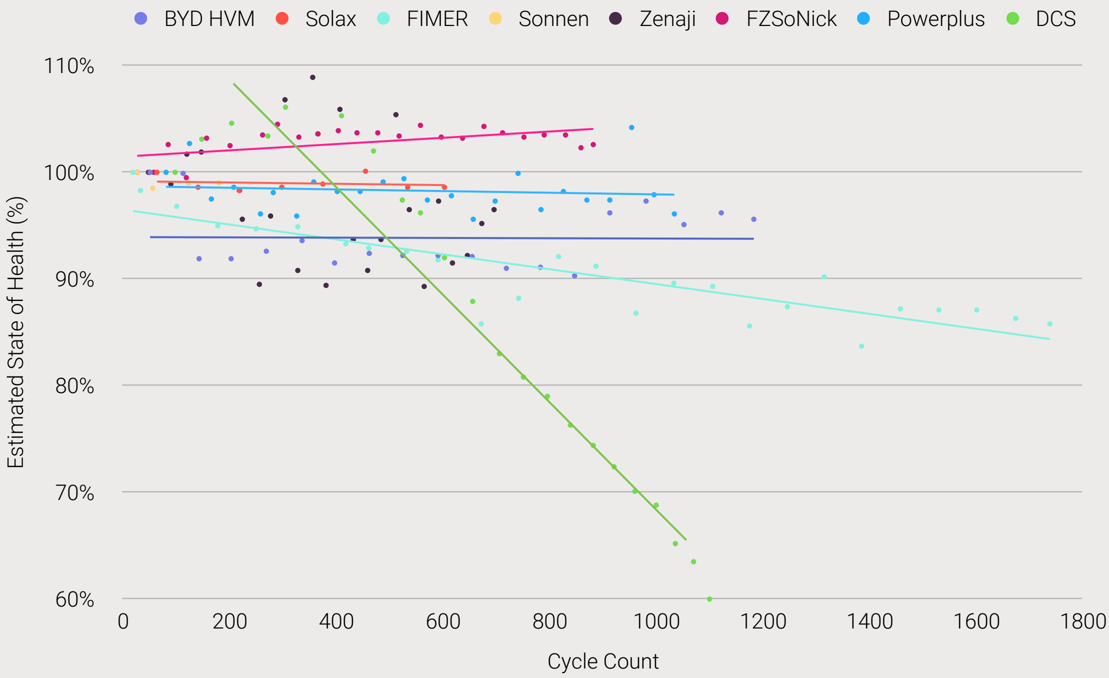

Figure 19: Capacity fade of Phase 3 battery packs based on monthly capacity tests

BYD B-Box HVM

The battery has completed approximately 1180 cycles, however, a linear extrapolation for estimating cycles at 60% SOH is not appropriate as a recent firmware update appears to have increased the amount of energy being discharged and the estimated SOH of the battery (Figure 19).

DCS PV 10.0

Based on the linear regression between estimated SOH and cycles completed (Figure 19), the DCS PV 10 is on track for 60% SOH at ~1,195 cycles. As above, however, a linear extrapolation may not be appropriate, and it is worth noting that the depth of discharge, charging and discharge rates are low for this battery.

FIMER REACT 2

Based on the linear regression between estimated SOH and cycles completed (Figure 19), the FIMER REACT 2 is on track for 60% SOH at ~5,225 cycles. As above, however, a linear extrapolation may not be appropriate.

FZSoNicK

The battery has completed approximately 880 cycles, however, a linear extrapolation for estimating cycles at 60% SOH is not appropriate as the capacity of this battery appears to have increased with cycles completed thus far.

PowerPlus Energy LiFe Premium

The battery has completed approximately 1,035 cycles, however, a linear extrapolation for estimating cycles at 60% SOH is not appropriate as the capacity of this battery doesn't seem to have decreased with cycles completed thus far. It is also worth noting that the depth of discharge, charging and discharge rates are low for this battery.

SolaX Triple Power

The battery has completed approximately 600 cycles, however, a linear extrapolation for estimating cycles at 60% SOH is not appropriate as the capacity of this battery appears to have increased with cycles completed thus far.

Zenaji Aeon

The battery has completed approximately 700 cycles, however, a linear extrapolation for estimating cycles at 60% SOH is not appropriate as the battery capacity has not followed a linear trend to date.

6.4. Round-Trip Efficiency

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

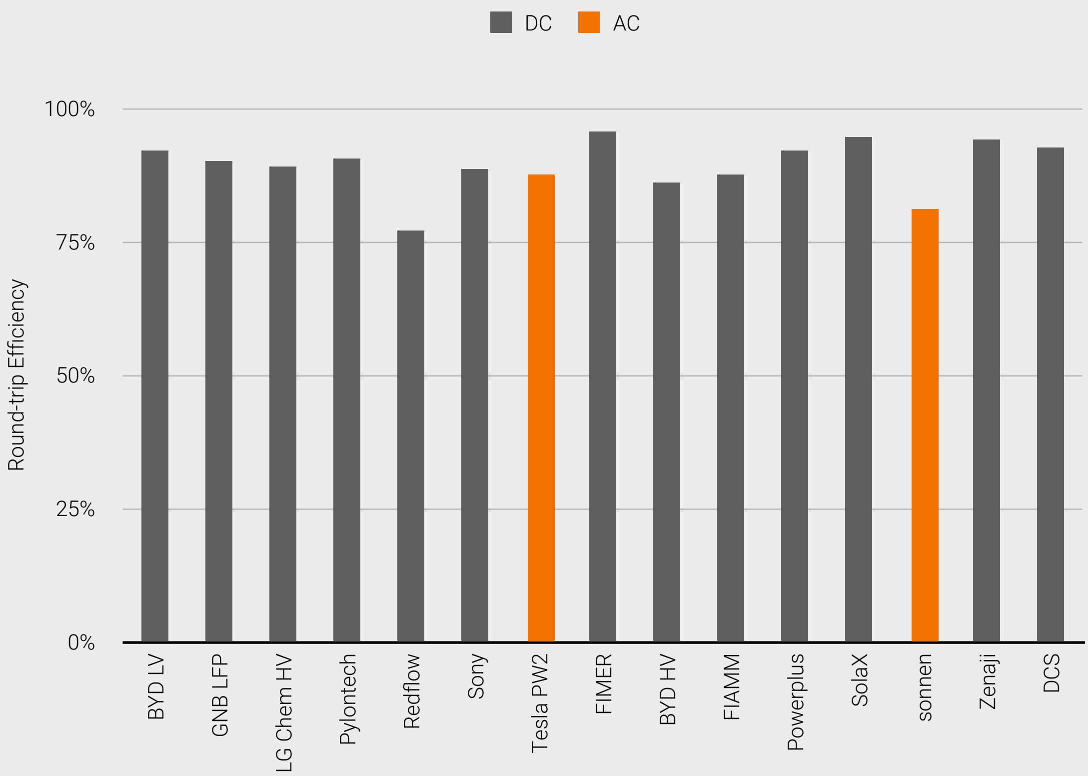

Figure 20: Lifetime round-trip efficiency for each battery pack

7. MARKET DEVELOPMENT

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

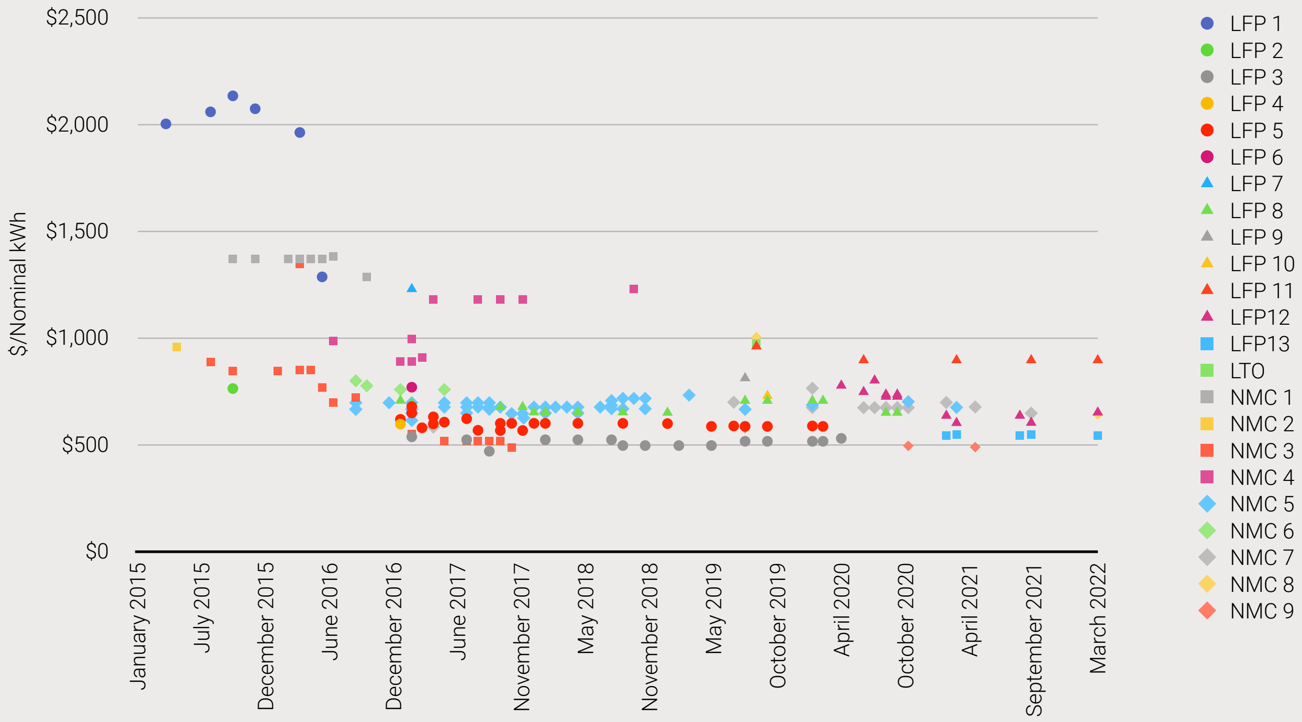

Figure 21: Wholesale prices for lithium-ion battery products installed in the Battery Test Centre

Globally, significant additional lithium-ion battery production capacity is under development as both the EV and stationary storage markets expand. However, ITP has observed an increasing price trend for utility-scale storage products in recent months owing to increases in raw material costs, global component shortages, and increased shipping costs. This cost increase is not yet apparent in the price data above, but ITP is aware that the price of a Tesla Powerwall 2 has increased significantly. In the medium-term, supply should catch up with demand, and further reductions in lithium-ion materials and battery prices are expected.

8. LESSONS LEARNED

Having been in operation for six 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.

The lessons learnt throughout the trial are described in the following sections.

8.1. Battery Trial Design

- Inverter compatibility was a key criterion for inclusion, as the trial aimed to minimise the number of inverter models and therefore differences in testing set-up between batteries. Unfortunately, at the time of the lab design, information on inverter compatibility from battery manufacturers was often ambiguous or misrepresented, leading to integration and commissioning delays.
- The accelerated cycling methodology was designed to enable analysis of battery performance over a shorter timescale than would be possible in a typical installation. However, this did result in the batteries being worked harder (although still within manufacturer specifications) than would normally be the case in solar-storage applications. This led to de-rating and failures that might not normally arise, particularly related to heat management.
- This cycling regime was also more suitable for certain technologies; specifically, lithium technologies proved to be better suited to the accelerated cycling regime than lead-acid technology. The lead-acid battery (not including the advanced lead-acid chemistry) was therefore at an inherent disadvantage in the trial.
- With regards to the design of the testing facility, a fireproof enclosure was required for batteries installed in a Class 9 building. This added cost and complexity to the project.
- Monitoring and control of the systems was highly challenging, for multiple reasons. These included:
  - A lack of consistent protocols for inverter communications and control
  - The need to control multiple inverters types including, in some cases, integrated inverters in 'all-in-one' systems
  - Due to the difference in the monitoring and control systems of each inverter, ITP had to develop bespoke monitoring and control systems. As additional batteries and inverters were added to the trial over time, the requirements of this system also increased in complexity and ITP ended up designing and implementing multiple iterations which took significant time.
  - The need to develop cycling parameters for batteries which would fit the cycling methodology while ensuring the batteries did not operate outside of manufacturer operating requirements. This was especially difficult for batteries which did not have direct communications from the BMS to the inverter.

8.2. Procurement, Construction, Installation and Commissioning

- Delays in battery availability and delivery were common, particularly for products that were just entering the Australian market.
- The shelf life of batteries had to be considered while ordering; some battery warranties were even dependent on the date of manufacture as opposed to the date of installation or purchase.

- When the products did arrive, they sometimes did not include all the necessary instructions or even components. This made installation even more difficult for electricians who were, at the time, unfamiliar with lithium-ion battery products. At the time of Phase 1 and Phase 2 installation, manufacturer or installation support was often non-existent or difficult to access. This has improved with maturation of the market.
- Communications was the most difficult aspect of commissioning for most of the products installed. This was due to a number of factors, including incomplete product integration between batteries and inverters, and installers' lack of familiarity with battery and inverter communications. Registration and product-specific monitoring options varied widely between products and has also developed significantly since the time of Phase 1, Phase 2 and Phase 3 installation. Some products in later phases required online registration in order for the warranty to be valid.
- At the time of Phase 1 installation, both the distribution network and electrical installation regulatory service were generally unfamiliar with battery installations and did not have a standard approach. Regulatory requirements are now clearer with release of AS/NZS 5139 in November 2019. The standard specifies the requirements for general installation and safety requirements for battery energy storage systems (BESSs).
- The commissioning time required for control and monitoring systems was longer than expected, due to the complexity discussed above. This difficulty should not be underestimated in future projects.

8.3. Ongoing Operation

- The amount of time required for managing maintenance issues during ongoing operation was significantly underestimated. As discussed above, it is possible that the demanding cycling regime may have contributed to more issues and/or failures than might be generally expected. However, even with this taken into account, the failure rate far exceeded expectations. The reactive and unpredictable nature of the maintenance callouts, combined with the (off-site) location of the testing facility, resulted in more time spent on troubleshooting maintenance than was planned.
- The level of support received from manufacturers varied widely. Some were very engaged and willing to assist while others were dismissive or inaccessible. It is possible that the status of these particular installations as a tested product with public exposure may have influenced some manufacturers' approach to support, although to what extent is unclear. Residential homeowners may not, for example, always receive the same level of service.
- In many cases issues with battery performance were first noticed by ITP and raised with the manufacturer, rather than the other way around. While it is expected that commercial installations might be similarly closely monitored, residential homeowners may not necessarily keep such a close eye on their systems. It is conceivable that problems arising with residential installations could go unnoticed for significant periods, particularly if the issue is not one resulting in absolute failure.
- For this particular application, data shows that lithium-ion products can out-perform conventional lead-acid battery packs in terms of round-trip efficiency and capacity retention, but faults and premature failures are currently more common. Comparisons of capacity retention between lithium-ion technology and other new emerging technologies (Zinc-Bromine Flow and Sodium Nickel Chloride) have not been possible as these batteries have not completed enough cycles in the trial, or have had many replacements or refurbishments since being installed.
- Some of the new batteries installed under Phase 3 had no communications between the BMS and inverter. This approach relies on the inverter to estimate charge acceptance and SOC. ITP has encountered some difficulty in commissioning these batteries and in cycling them according to the testing methodology, resulting in lower depth of discharge, lower charging and discharge rates, and slower accumulation of cycles.
- Some faults are difficult to diagnose remotely. In these cases, a local (Australia-based) technical support team is important in resolving issues in a timely manner, including replacement where required.

8.4. Market Development

- 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. ITP experienced many integration issues between batteries and inverters during the commissioning of all the three testing phases. A single integrated product, or compatibility only between products from the same manufacturer, removes the requirement for manufacturers to undertake R&D, testing, and maintenance with external partners. It also provides a single point of accountability for users who experience system problems.

- More high-voltage battery inverters and battery packs are now available. High-voltage battery products are generally simpler to install, due to smaller cables being required. Higher-voltage inverters are generally more efficient and have higher power density, meaning cheaper equipment and easier/cheaper installation.

- Many manufacturers now ensure that battery products, and their compatibility with specific inverter models, are tested before market release. Manufacturers are now moving towards requiring batteries to be directly connected to the internet and available for external monitoring, which allows them to remotely diagnose faults.

9. CONCLUSION

With testing ending in March 2022, this is the final Public Report relating to this project. As testing is complete, ITP will be undertaking the following:

- Investigation of options to decommission or dispose of the batteries under test. ITP has previously explored options for battery recycling, but would prefer that the batteries continue to provide value for knowledge-sharing purposes. Previous batteries have been donated to the CIT's electrical training program and ITP will explore whether similar options are again available.

- Investigation of options to decommission the battery testing facility at the CIT. This was a purpose-built room for testing. Again, ITP will prioritise options that allow the facility to continue to provide value, in conjunction with CIT.

- Update of the project website to indicate that testing is no longer ongoing, and the removal of live testing results.

The project's aims included:

- Independent verification of battery performance (capacity retention and round-trip efficiency) against manufacturers' claims

- Insights on the evolution of the battery industry based on battery commissioning and operation experiences

- Commentary on price changes of lithium-ion batteries

- Discussion of lessons learned throughout the project, relating to design, procurement, product maturity, and maintenance

The Battery Test Centre started with eight batteries under test for three years. The expansion of testing to over 26 batteries over six years has allowed this project to add greatly to public knowledge and awareness of battery performance. This is detailed in all our public reports, particularly the Lessons Learned sections, and is expanded on below.

Manufacturers

Most battery manufacturers with products in the Australian market are aware of the Battery Test Centre project. During procurement, almost all manufacturers (or distributors) approached were supportive of the project and receptive to their product being involved in the trial. Any reluctance tended to be around how well testing results translated to performance in real-life applications. Some manufacturers who hoped to be included did not have suitable products available within the required timeframe. More broadly, ITP received many expressions of interest from manufacturers over the course of the trial, not just for inclusion in public testing and reporting, but also seeking private testing services. This indicates an understanding from manufacturers of the value of testing to consumers, but possibly also a gap in the market for these services.

During operation, ITP found most manufacturers to be responsive to requests for support. It is noted that, due to the public nature of the installation, manufacturers would have a strong incentive to provide support and that this may not necessarily translate to other installations. However, the project was still able to provide valuable insights on the accessibility of support;.e.g. whether the manufacturer has local support in Australia.

Some manufacturers withdrew their product partway through testing, due to subsequent dissatisfaction with the testing methodology or implementation. Although the inability to continue testing these products has been a loss to the project, it has underlined the importance of manufacturers providing clear operating guidelines and documentation.

Throughout the trial, several manufacturers (or suppliers) have noted to ITP that they have received questions or comments about their products directly from consumers with regard to testing results. ITP believes that this has resulted in an increased accountability from manufacturers on information and performance claims for their products.

ITP has also received enquiries from installers who have found the detail in commissioning experiences helpful. This is likely to have resulted in further pressure on manufacturers to provide the required knowledge and support to installers, and increased the quality of installations.

Consumers

The level of public interest in the results of the battery trial exceeded original expectations and resulted in two further phases of testing, each with additional batteries. The original trial focussed on the comparison between lithium ion technologies and the 'conventional' lead acid technology. At that time, six lithium ion batteries were selected for testing because it was difficult to find even six commercially available products for residential / small commercial applications. As the trial progressed, and the number of available products increased, so did interest in the trial and its results from consumers.

Residential consumers, in particular, have found value in the independent nature of the testing and the public availability of results. The extent of public interest in the website, the main knowledge-sharing tool, is expanded on in Appendix A. ITP also regularly receives direct enquiries about performance of the batteries under test. While the small sample size means that the project should not be used to compare performance of specific products, it has provided valuable insight into the state of the technology and market as a whole. This has provided consumers with a better understanding of the landscape, making them better equipped to make decisions with regards to chemistry, brands, and products.

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[4] was established as the key mechanism for this Knowledge Sharing. In parallel, ITP undertook various other knowledge sharing activities including article publication, conference presentations, webinars, and lab tours throughout the period of the project. COVID -19 restrictions affected Knowledge Sharing activities in this reporting period, however the following knowledge sharing activities were undertaken:

- ITP was a speaker at pv magazine's virtual Insight on Quality event in October 2021, where the lessons learned from testing were shared with the public.
- ITP hosted representatives from the Embassy of Sweden and Business Sweden (Asia-Pacific) for a lab tour in April 2022 and shared our knowledge and expertise in lithium-ion storage technology with them.

The primary knowledge sharing tool, the Battery Test Centre website, allows the public to view live and historical test results and background information about battery technologies. 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 356,485 page views with an average of 2:09 minutes spent per page overall and 3:51 minutes spent on the reports page.

[4] batterytestcentre.com.au

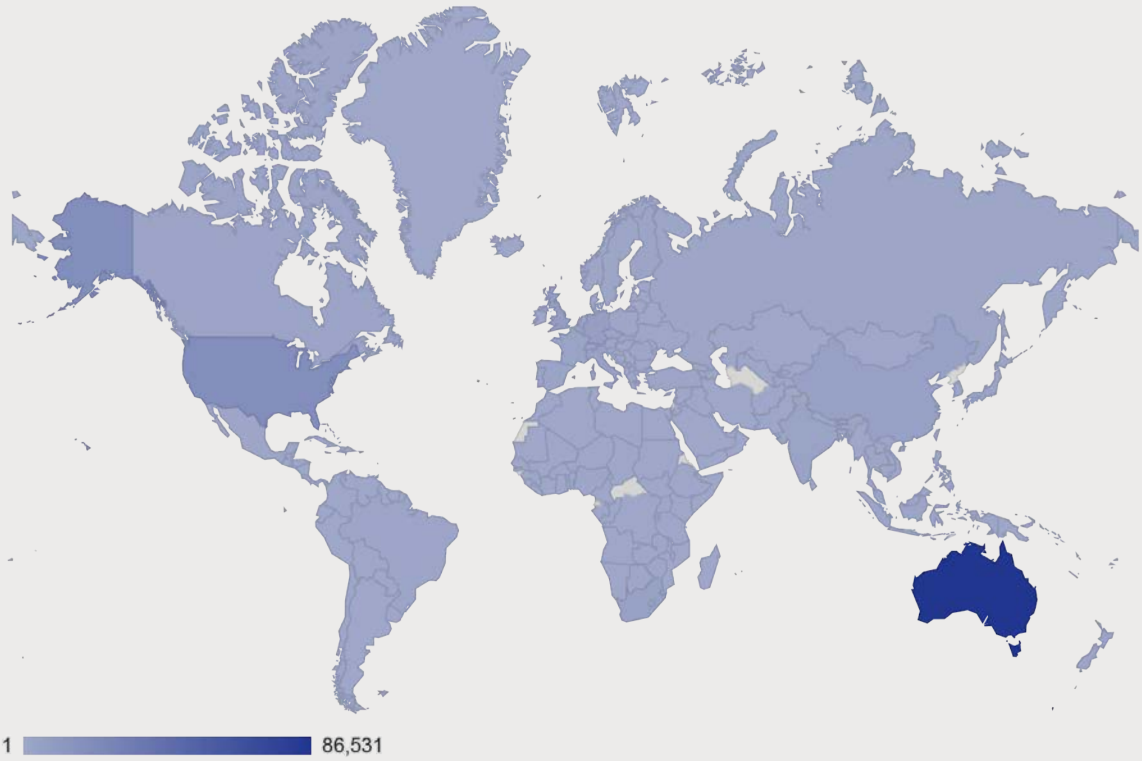

Figure 22: Number of sessions by country

The data from the website shows that the key audience is Australia, with Australian IP addresses accounting for 86,531 sessions (44.9%). 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 19,548 sessions from the United States, 6,891 from the United Kingdom and Germany not far behind on 6,486. It is interesting to note, however, that the content has been accessed from right across the globe.

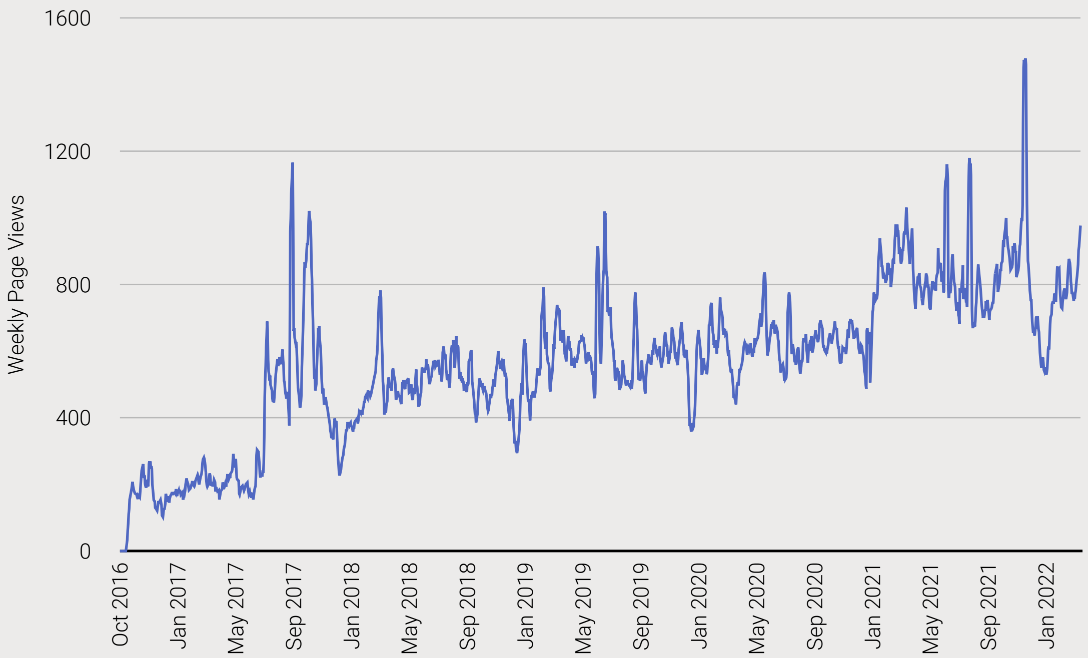

Figure 23: Weekly active users

Figure 23 above shows the number of weekly active users that have accessed the website and there is a clear rise between the Phase 1 figures at around 250 weekly users, to the launch of Phase 2 in August of 2017 when the weekly averages nearly doubled to around 500 active weekly users. The peaks coincided with media articles that were distributed on those dates. Since then the number of users has been on a gradual upwards trajectory, with an increase noted after the release of Report 6 and associated media articles in June 2019. Around April 2020 there was a small decline in viewers, likely due to the focus on COVID-19 related news at that time. In the long term, interest in the site has remained reasonably constant with the number of weekly users hovering around an average of 600. But interest in the website has been spiking again starting from 2021 with the no. of weekly users going up to 800. Some peaks of 1,100 weekly users were seen in June and July 2021, which coincided with online articles being circulated on those dates, as well as a lab visit which was conducted for the IEEE ACT branch. The biggest peak of around 1,460 weekly users was seen between October and November 2021 shortly after the release of the previous project report.

There is a good spread of views across the website, particularly the technology and results pages; the top five most viewed pages after the homepage (19%) are the reports page (14%), the batteries page (10%), Pylontech US2000B (7%), LG Chem RESU (5%) and the background page on lithium-ion technology (4%).

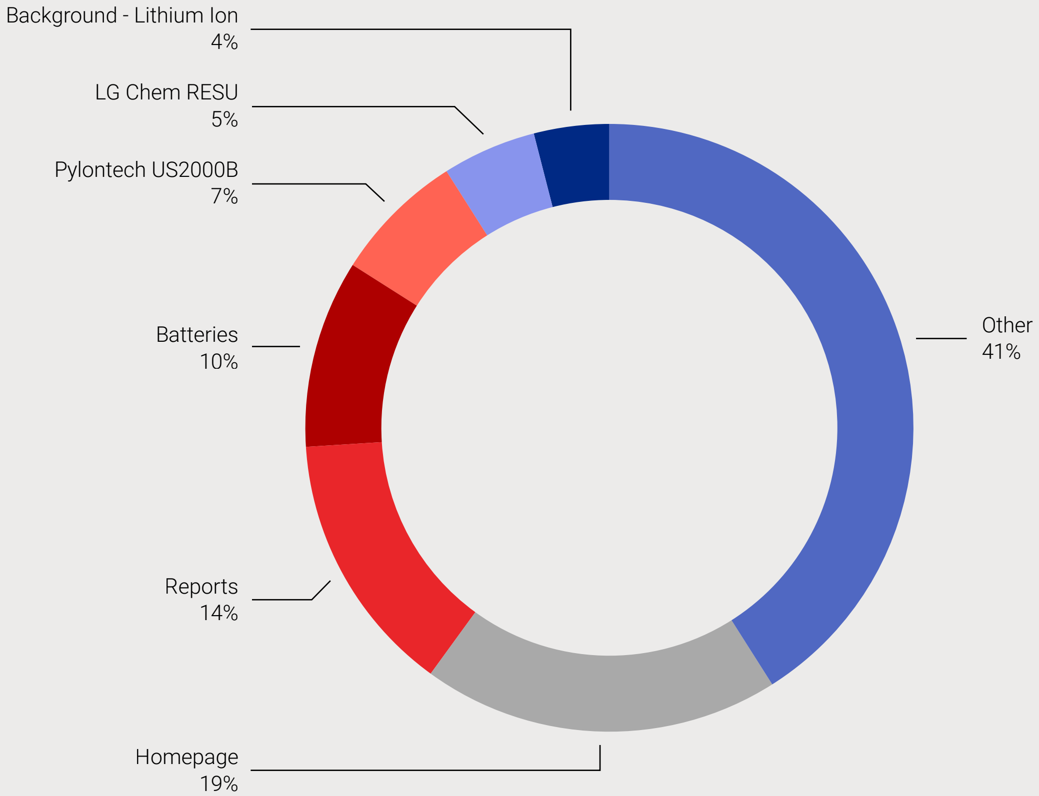

Figure 24: Breakdown of the 356,485 page views

Appendix B: Testing Procedure

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

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

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

Temperature Profile

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

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

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

Table 2: Daily high and low ambient temperatures throughout the year

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

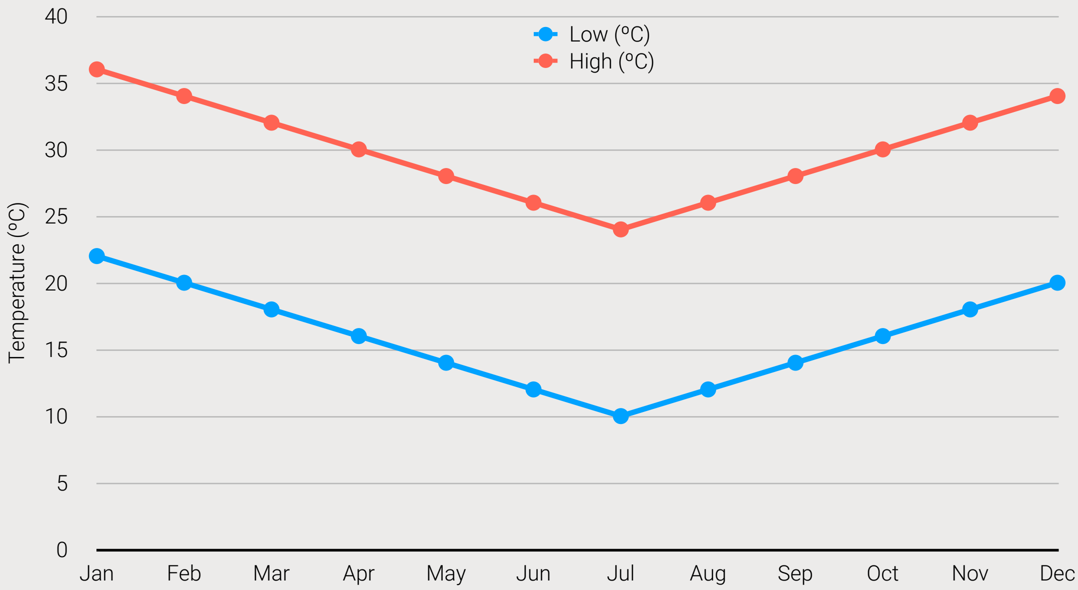

Figure 1: Daily hot and cold cycle temperatures throughout the year

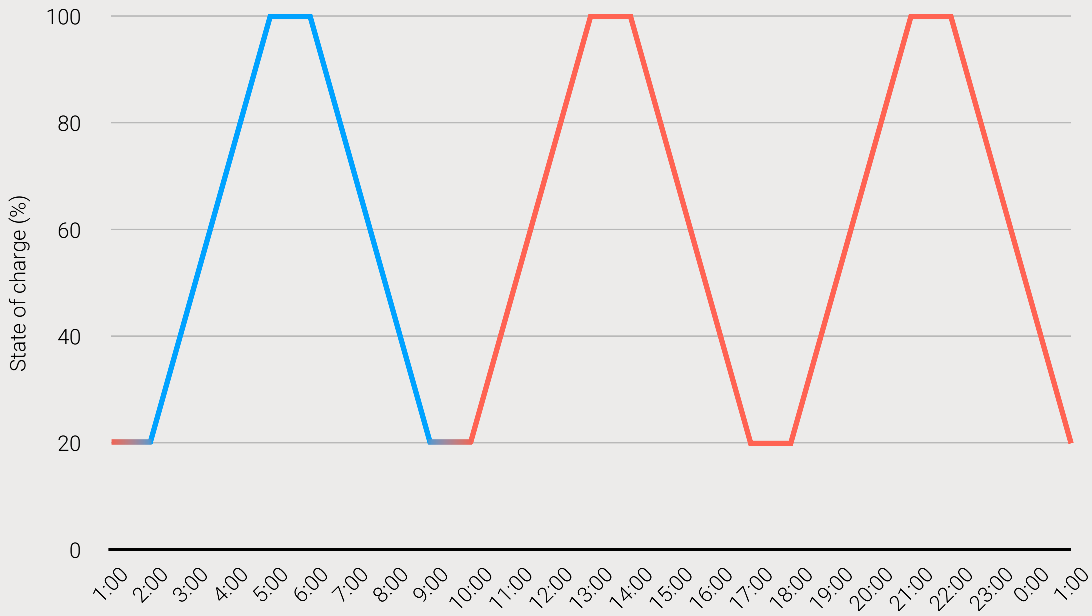

Figure 2: Summer temperature regime and charge regime

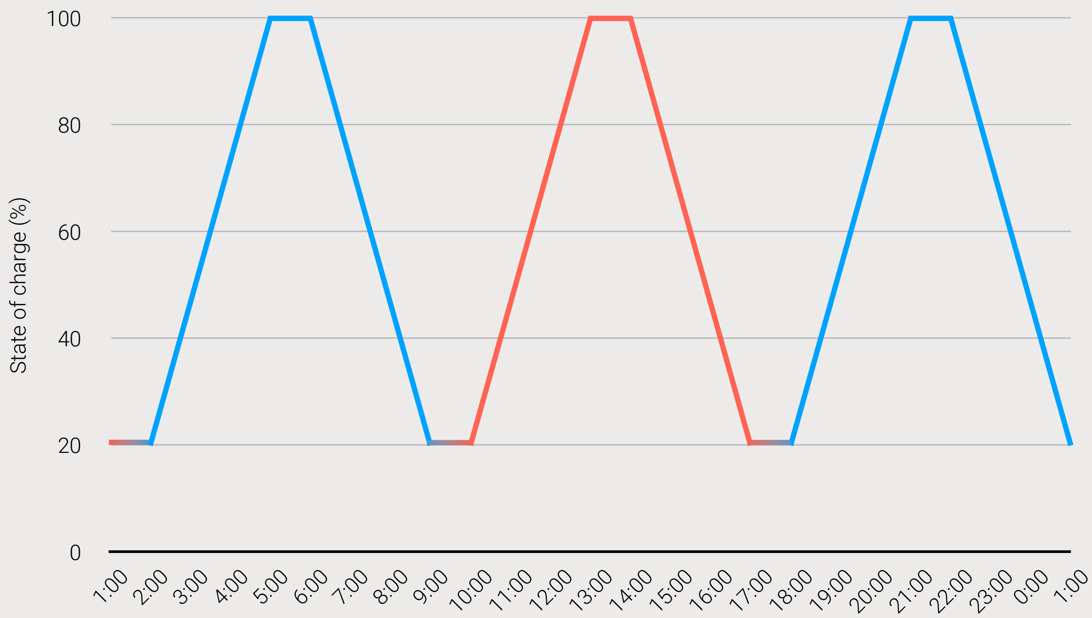

Figure 3: Winter temperature regime and charge regime

Appendix C: Previous Report Summary

Report 1
September 2016

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

The report described conventional lead-acid and lithium-ion technologies, the process of battery selection, and the testing procedure. The implementation process from procurement through installation to commissioning was also described for the eight Phase 1 batteries listed in Table 3 below.

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

Table 3: Phase 1 battery packs

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

Report 2
March 2017

Capacity tests were conducted in each of the six months between September 2016 and February 2017, and the results were published in Public Report 2.

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

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

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

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

Report 3
November 2017

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

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

Table 4: Phase 2 battery packs

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

In terms of Phase 1 pack performance, one Ecoult cell failure was reported and general SOC estimation issues with the

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

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

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

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 5: Phase 3 battery packs

Report 9
September 2020

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

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

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

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

Report 10
March 2021

Report 10 included analysis and commentary on two batteries from Phase 1 (Sony and Samsung), six batteries from

Phase 2 (BYD LV, GNB Lithium, LG Chem HV, Pylontech, Redflow, and Tesla Powerwall 2) and eight batteries from Phase 3 (BYD HV, DCS, FIMER, FZSoNick, PowerPlus, SolaX, and sonnen).

The Sony battery pack from Phase 1 had continued to operate reliably, alongside the Pylontech and GNB Lithium battery packs from Phase 2. Both the Sony and Pylontech batteries were also showing excellent capacity retention after a high number of cycles. Phase 3 batteries had completed less than 1000 cycles until then.

ITP concluded testing for the Samsung battery, which was requiring frequent intervention to enable cycling towards the end of its testing period. Overall, the battery was very reliable and had completed more cycles than most of the other batteries in the test centre.

The Redflow battery had to have its battery stack replaced. Previously, four replacements were done due to contaminated electrolyte and electrolyte leaks.

While capacity retention has varied significantly between battery packs, round-trip efficiency has not varied to the same degree. ITP has observed DC round-trip efficiency values as high as 95% for some lithium-ion battery packs, and as low as 78% for Redflow's zinc bromine battery.

Report 11
September 2021

Report 11 included analysis and commentary on one battery from Phase 1 (Sony), six batteries from Phase 2 (BYD LV, GNB Lithium, LG Chem HV, Pylontech, Redflow, and Tesla Powerwall 2) and eight batteries from Phase 3 (BYD HV, DCS, FIMER, FZSoNick, PowerPlus, SolaX, and sonnen).

The Sony battery pack from Phase 1 continued to operate reliably, alongside the Pylontech and GNB Lithium battery packs from Phase 2. Both the Sony and Pylontech batteries were also showing excellent capacity retention after a high number of cycles. Most Phase 3 batteries had completed less than 1000 cycles at the time of report publication. The FIMER REACT2 from Phase 3, which had retained over 85% of its initial capacity after nearly 1300 cycles, and FZSoNicK battery showed minimal capacity fade but its lower discharge rate meant that it hadn't completed as many cycles as other batteries installed in the same phase.

An accelerated decline in energy and SOC discharged per cycle was observed for the sonnen battery, which was caused by voltage mismatch in one of its modules. Sonnen replaced the faulty module but was not satisfied with the battery performance and hence continued to monitor the battery performance.The SolaX battery was replaced after both its modules were found to be faulty, and the replacement battery has been cycling reliably since then.

While capacity retention varied significantly between battery packs, round-trip efficiency was not varied to the same degree. ITP observed DC round-trip efficiency values as high as 95% for some lithium-ion battery packs, and as low as 78% for Redflow's zinc bromine battery.

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