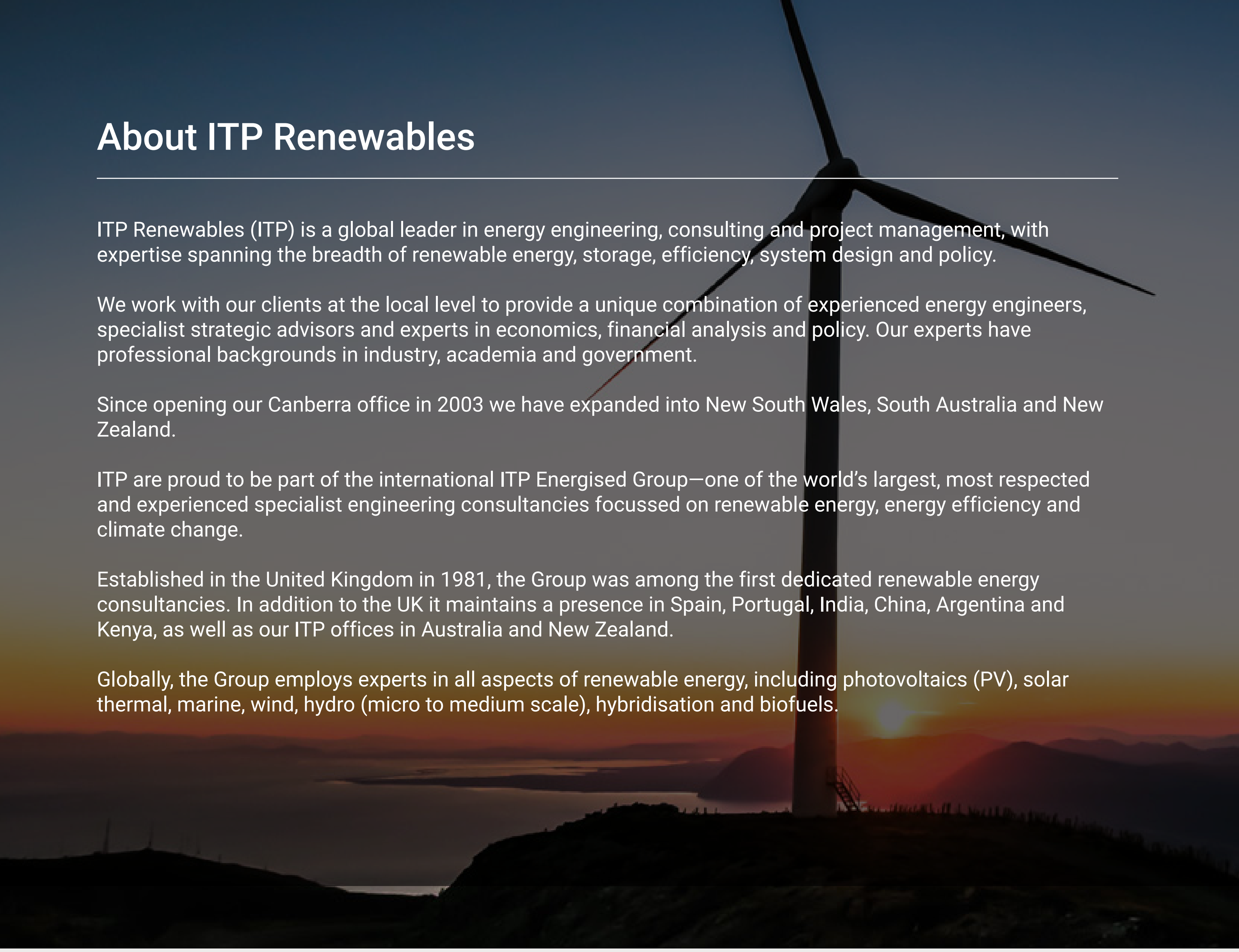
Public Report 7
Lithium-Ion Battery Testing

ENGINEERING | STRATEGY | ANALYTICS | CONSTRUCTION

September 2019



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 to include an additional eight lithium-ion packs, a zinc bromide flow battery, and an aqueous hybrid ion battery bank.

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

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

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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 (nominal) battery capacity is charged/discharged (ie. a C10 rate indicates a charge/discharge rate at which a full charge/discharge takes 10 hours. A 2C rate indicates a charge/discharge rate at which a full charge/discharge takes only 0.5 hours)
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 seventh public six-monthly report.

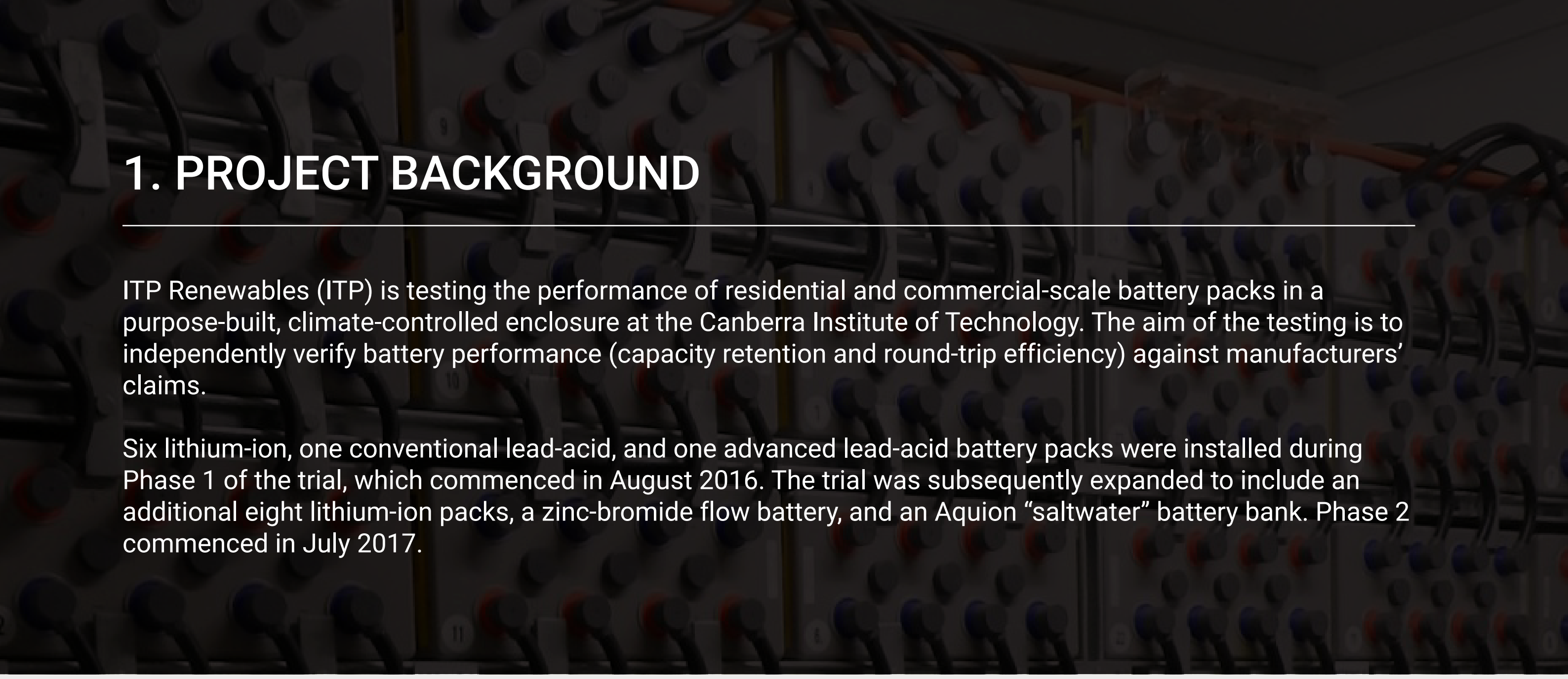
While some battery packs have experienced faults and/or failed prematurely, the Sony, Samsung, Tesla Powerwall 1 (Phase 1), BYD, Pylontech, and GNB Lithium (Phase 2) battery packs have generally demonstrated high reliability, with minimal issues encountered throughout the testing period.

Linear extrapolation of capacity fade to date suggests cycle life varies significantly between products. The Sony, Samsung (Phase 1), and Pylontech (Phase 2) battery packs continue to demonstrate good capacity retention over a large number of cycles. Following replacements, the current Tesla Powerwall 2 and Redflow ZCell (Phase 2) are also demonstrating excellent capacity retention thus far, though the number of cycles completed to date is low.

Variability in round-trip efficiency is lower, 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 high raw material prices. Nevertheless, most analysts believe that manufacturers are substituting away from high cost inputs, and that the large amount of production capacity currently under construction will put downward pressure on prices in the medium-term. ITP's opinion is that price reductions are required for mass-market uptake, alongside improvements in products, interfaces, and technical support.

A third phase of battery testing has recently been announced and will comprise another eight battery packs, including a lithium-titanate battery and a sodium-nickel battery. These will replace eight batteries from Phases 1 and 2 which have either completed the original testing period or 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.

A Phase 3 has recently been announced and will comprise another eight battery packs, including a lithium-titanate (LTO) battery and a sodium-nickel battery. The batteries to be installed under Phase 3 are listed below:

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

The new batteries will replace eight Phase 1 and Phase 2 batteries to be removed from testing. Batteries still being cycled from Phase 1 and Phase 2 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)

Cycling of Phase 3 batteries is scheduled to begin before the release of the next Public Report.

This is the seventh public report outlining the progress and results of the trial thus far. A summary of the six previous reports is provided below. Complete reports are accessible on the Battery Test Centre website at **www.batterytestcentre.com.au/reports/**.

1.1. Report 1 — September 2016

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

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

Table 1. Phase 1 Battery Packs

Product	Country of Origin	Chemistry	Total Installed Capacity (kWh)
CALB CA100	China	Lithium Iron Phosphate	10.24
Ecoult UltraFlex	USA	Lead Acid Carbon	14.8 (C8)
GNB Sonnenschein	Germany	Lead Acid	14.4 (C100)
Kokam Storaxe	Korea	Nickel Manganese Cobalt	8.3
LG Chem RESU 1	Korea	Nickel Manganese Cobalt	9.6
Samsung AIO	Korea	Nickel Manganese Cobalt	10.8
Sony Fortelion	Japan	Lithium Iron Phosphate	9.6
Tesla Powerwall 1	USA	Nickel Manganese Cobalt	6.4

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.

1.2. 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.

1.3. Report 3 — November 2017

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

Table 2. Phase 2 Battery Packs

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

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

In terms of Phase 1 pack performance, one Ecoult cell failure 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.

1.4. Report 4 — March 2018

Report 4 was published in March 2018. It outlined the preliminary testing results and general issues encountered with both Phase 1 and Phase 2 batteries. This report provided particular detail on the ongoing commissioning challenges with the Tesla Powerwall 2 and Aquion 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.

1.5. Report 5 — September 2018

With testing of both Phase 1 and 2 batteries well under way by the time Report 5 was published, 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.

1.6. 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.

2. Battery Operation Overview

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

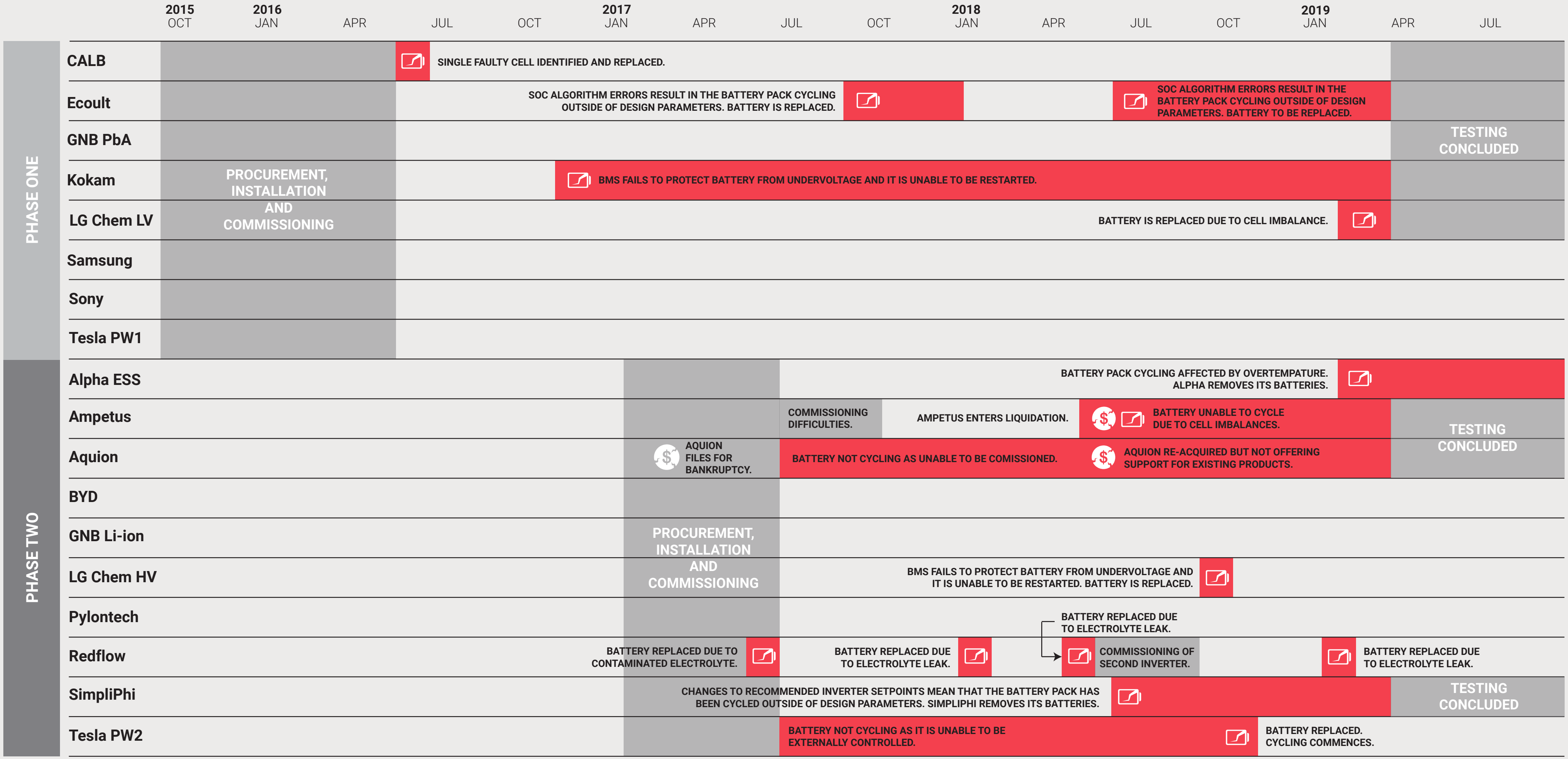


Figure 1: Overview of battery operation

3. PHASE 1 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 AIO10.8

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.

Capacity Fade
The average energy discharged each cycle (Figure 2) can be seen to have decreased over time, with increasing variance between cycles also evident. The data suggests a SOH of ~79% after ~2,190 cycles.

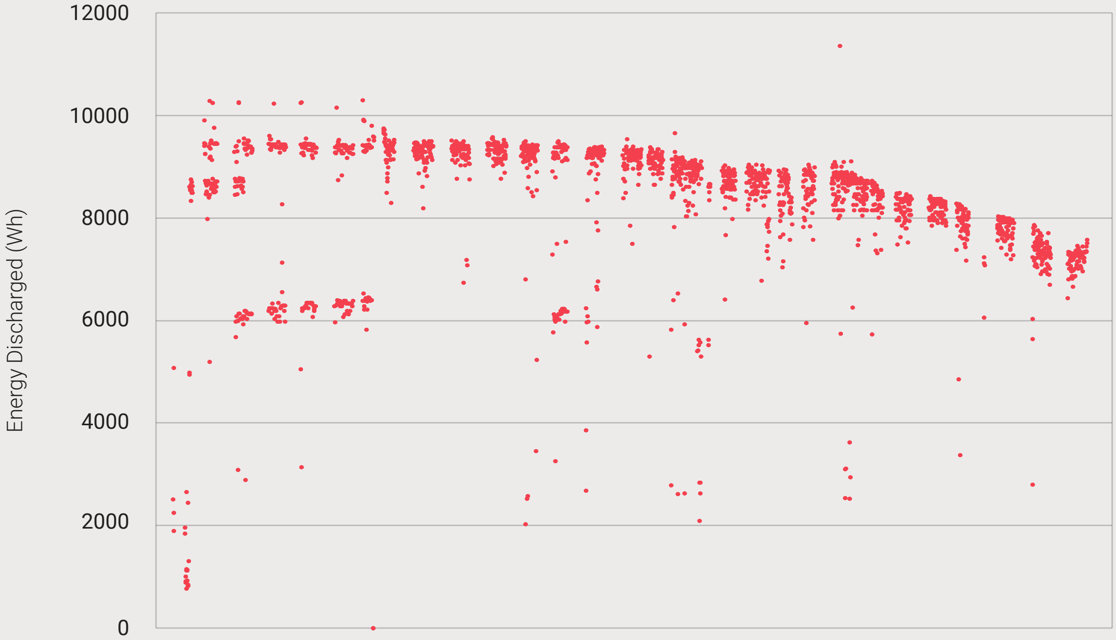


Figure 2. Energy discharged per cycle by the Samsung battery pack

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 average energy discharged each cycle (Figure 3) can be seen to have generally decreased over time, with greater variance between cycles also evident. The data suggests a SOH of ~83% after ~2,100 cycles.

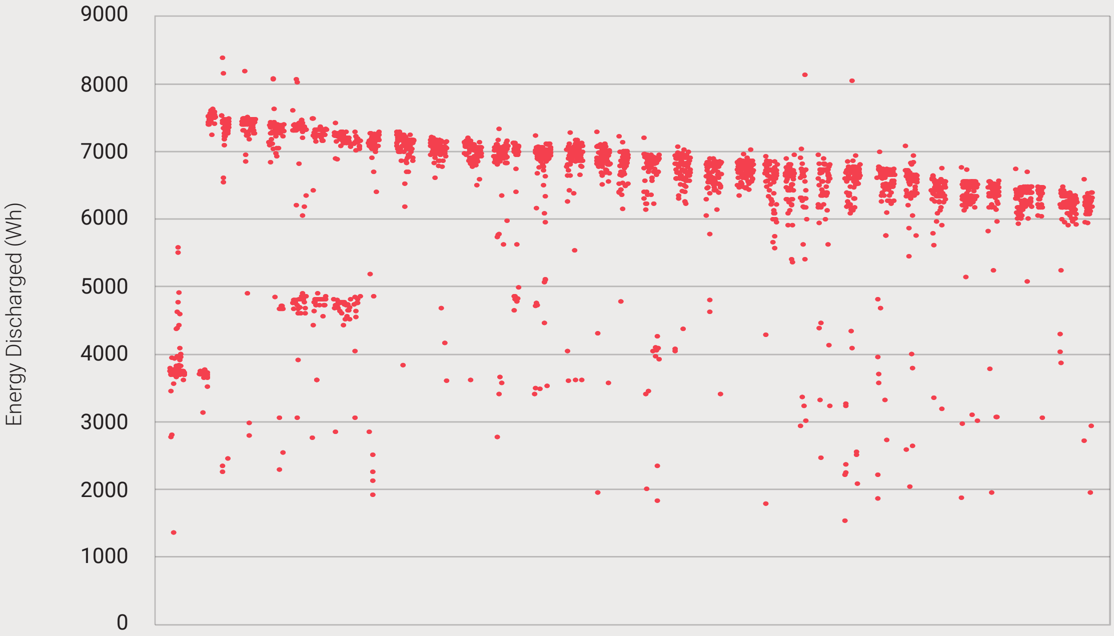


Figure 3. Energy discharged per cycle by the Sony battery pack

3.3 Tesla Powerwall

Operational Issues
At the beginning of the trial (Phase 1), Tesla's Powerwall 1 was only compatible with a Solar Edge inverter. All other Phase 1 packs, excluding the Samsung, were compatible with the market-leading SMA Sunny Island inverter, which the control system had been designed to control.

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

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

Capacity Fade
The average energy discharged each cycle (Figure 4) can be seen to have generally decreased over time. The data suggests a SOH of ~64% after ~2,190 cycles.

Figure 4. Energy discharged 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. Alpha ESS M48100

Operational Issues
During the 2018/19 summer temperature regime, ITP observed that the Alpha battery pack was constraining the charge and discharge rate below the rate requested by the test centre's control system. Alpha stated that this behaviour is abnormal, and collected the battery pack for analysis in March 2019. In August 2019 Alpha contacted ITP to say that the battery had experienced over-temperature alarms, and stated that they would not be continuing in the battery trial.

No further data is available since publication of the last report and as a result no analysis is included here.

4.2. BYD B-Box

Operational Issues
ITP has not experienced any operational issues with the BYD battery pack. However, BYD performed a firmware update on the BMU in June, and again in August. The BMU was also replaced at that time as it was unable to accept the firmware update.

Capacity Fade
The energy discharged per cycle is shown in Figure 5. The data suggests a SOH of ~64% after ~1,740 cycles, with capacity fade appearing to accelerate and then decelerate. The deceleration may be the result of the firmware/BMU upgrade.

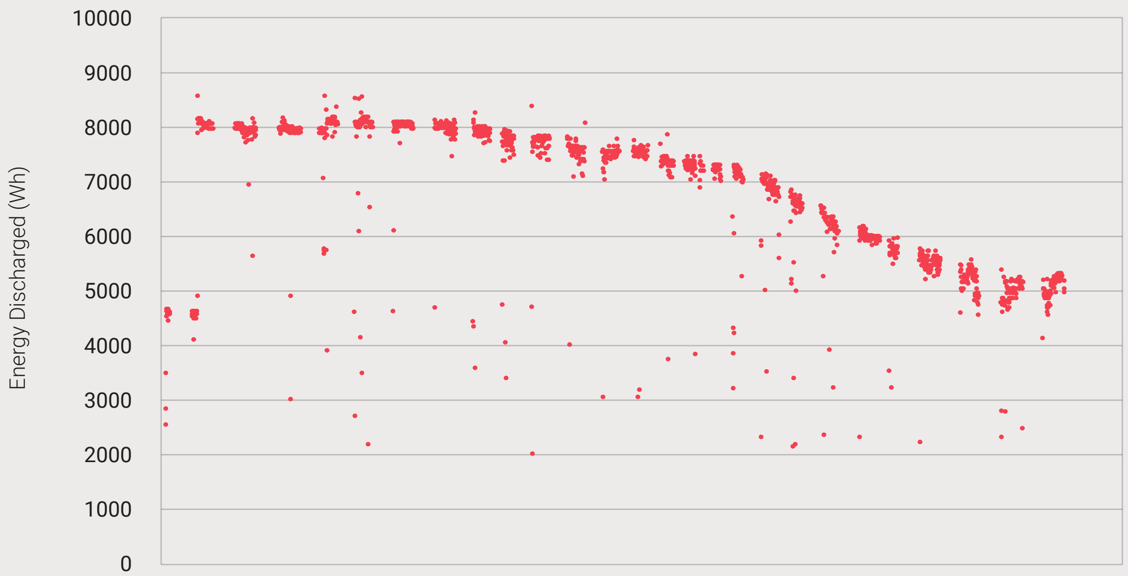


Figure 5. Energy discharged per cycle by the BYD battery pack

4.3. 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 energy discharged per cycle is shown in Figure 6. The data suggests a SOH of ~65% after ~1,190 cycles. It is notable that some cycles show capacity has been retained far above the average capacity delivered each cycle. This suggests the capacity is still available but that some kind of fault is rendering it unavailable for most of the time. Nevertheless, GNB have advised that no fault is apparent.

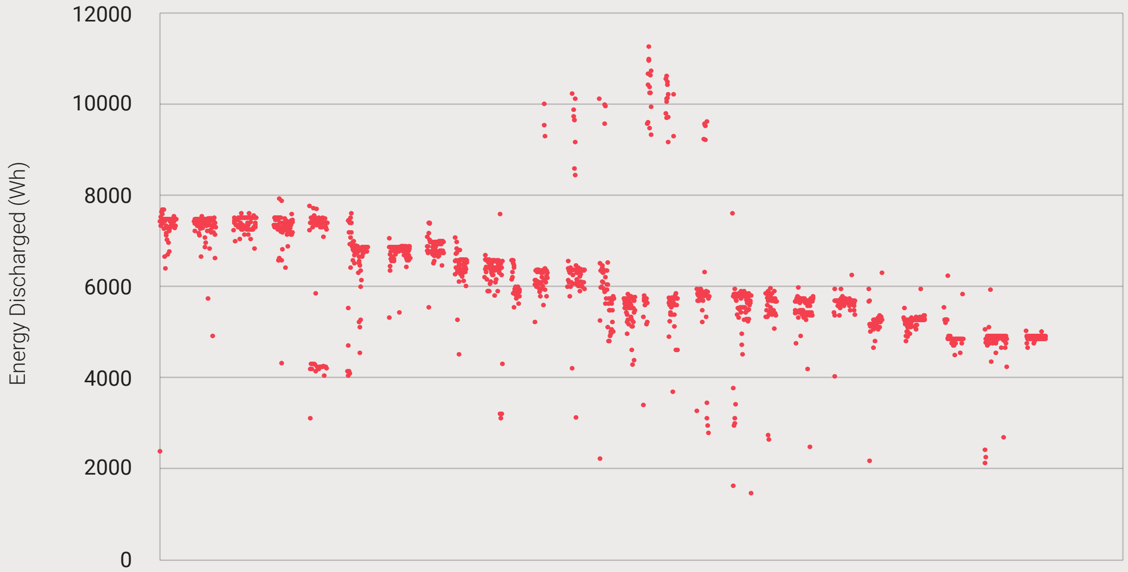


Figure 6. Energy discharged per cycle by the GNB LFP battery pack

4.4. LG Chem RESU HV

Operational Issues
In October 2018, the LG Chem RESU HV battery pack in the trial was replaced by LG Chem, as the previous unit experienced swelling of the battery cells and undervoltage after a period of disconnection. LG Chem has advised that the deep self-discharge is due to the internal DC-DC converter staying on and consuming energy from the battery. Since publication of the last report, LG Chem has developed an improved battery model which prevents deep self-discharge with a switch between the DC-DC converter and the battery cells. LG Chem offered a replacement unit to ITP; however, ITP has chosen to retain its current battery in order to continue testing. LG Chem has advised that it will be replacing units which experience undervoltage problems.

Capacity Fade
The energy discharged per cycle is shown in Figure 7. The data suggests a SOH of ~90% after ~620 cycles.

Figure 7. Energy discharged per cycle by the LG Chem RESU HV battery pack

4.5. Pylontech US2000B

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

Capacity Fade
The energy discharged per cycle is shown in Figure 8. The data suggests a SOH of ~86% after ~1,470 cycles.

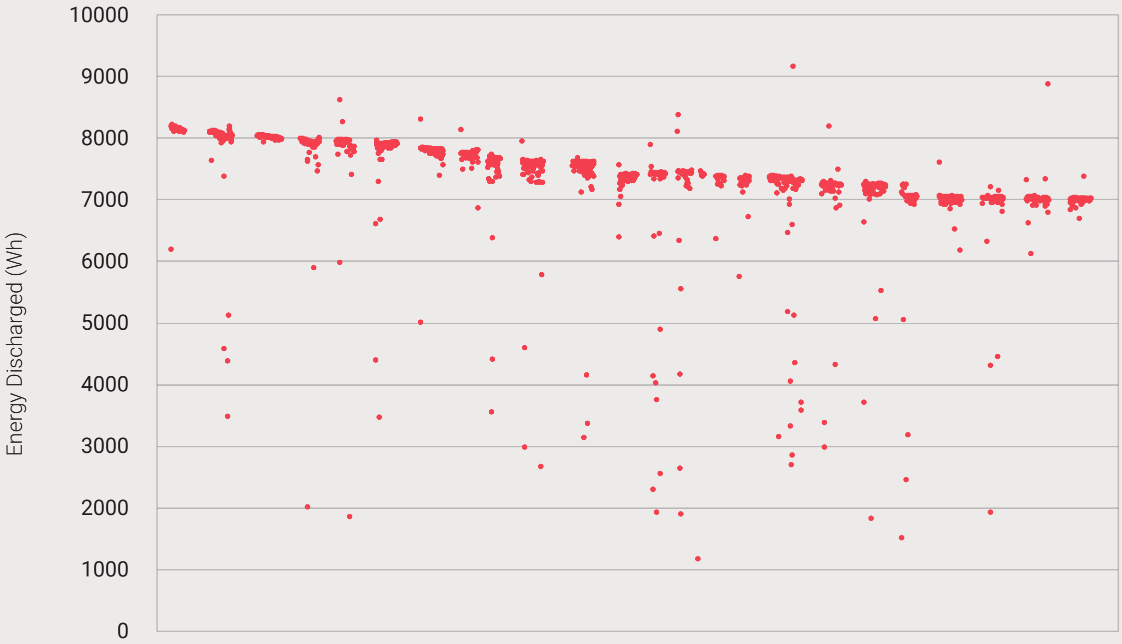


Figure 8. Energy discharged per cycle by the Pylontech battery pack

4.6. Redflow ZCell

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

Redflow attributed the leak to a step in their manufacturing process in which the electrolyte tank was washed with a particular soap after manufacture, causing brittleness in the plastic and therefore increased risk of cracks. This apparently only affected a specific batch of products.
The previous leaks were attributed to micro-cracking of the electrolyte tank that occurred during road transport. The problem identified was that the electrolyte trays were not sufficiently supported on the sides to withstand the weight of the electrolyte. Redflow state that they have since modified their transport techniques and believe this problem will be avoided in the future.

Since then, the Redflow battery has not experienced any problems, and has been cycling well. Redflow staff visited the test centre in September 2019 to check the pH of the electrolyte, and reported that it was satisfactory.

The Redflow battery also 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 energy discharged per cycle is shown in Figure 9. The data suggests a SOH of 100% after ~370 cycles.

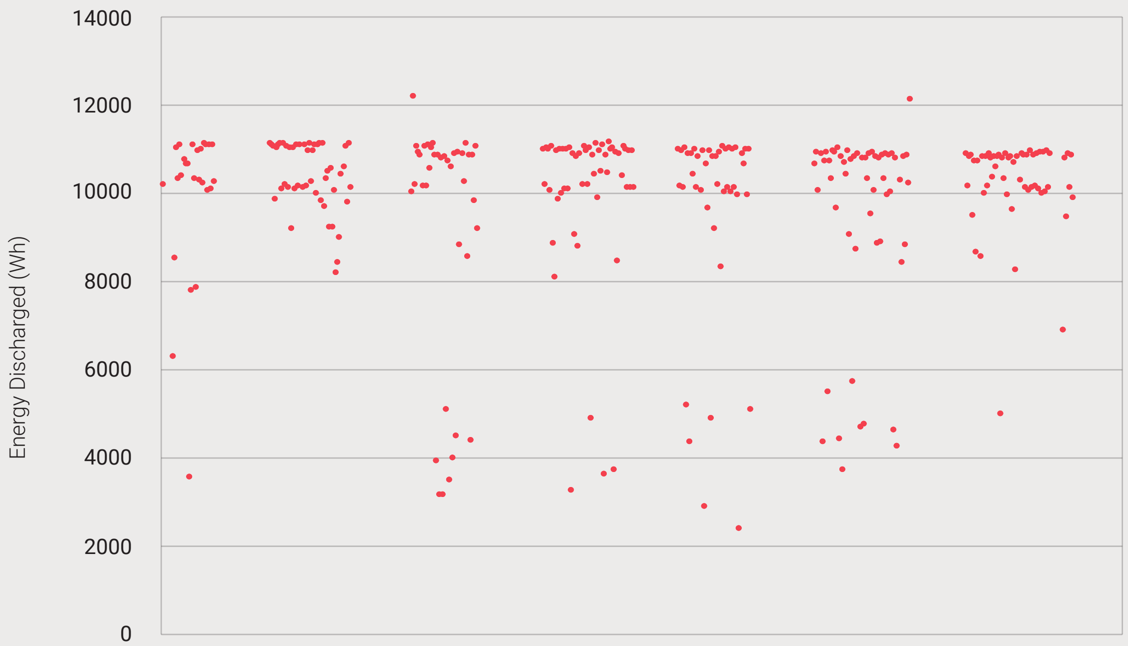


Figure 9. Energy discharged per cycle by the Redflow battery pack

4.7. 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 were subsequently replaced by Tesla. Cycling of the replacement Powerwall 2 commenced in late November.

ITP still have no direct control over the battery (as Tesla do not allow this level of control of their products), but rely on Tesla to implement the cycling schedule. This has generally worked well; however, in June 2019 ITP noted that the discharge power appeared to be fluctuating, and that as a result the battery wasn't always reaching the minimum SOC every cycle. Tesla has stated that the Powerwall 2 inverter is turning off due to overvoltage (as required by Australian Standards). This may be a result of the Battery Test Centre electrical connection being re-located due to electrical works at the CIT. The issue appears to have abated in recent months.

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[1] data used by ITP in monitoring and analysis is obtained from this API.

Capacity Fade
The energy discharged per cycle is shown in Figure 10. The data suggests a SOH of ~96% after ~640 cycles.

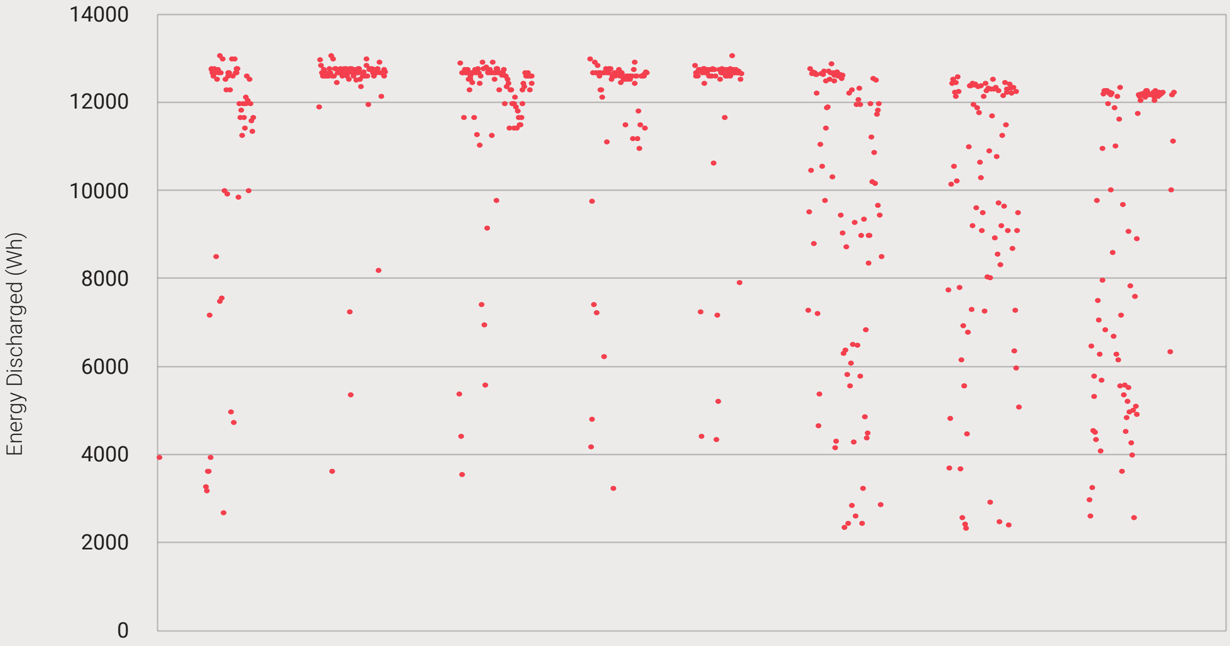


Figure 10. Energy discharged per cycle by the Tesla Powerwall 2 battery pack

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[1] mikesgear.com/2017/12/07/monitoring-teslas-powerwall2-on-pvoutput-org/

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 11 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.

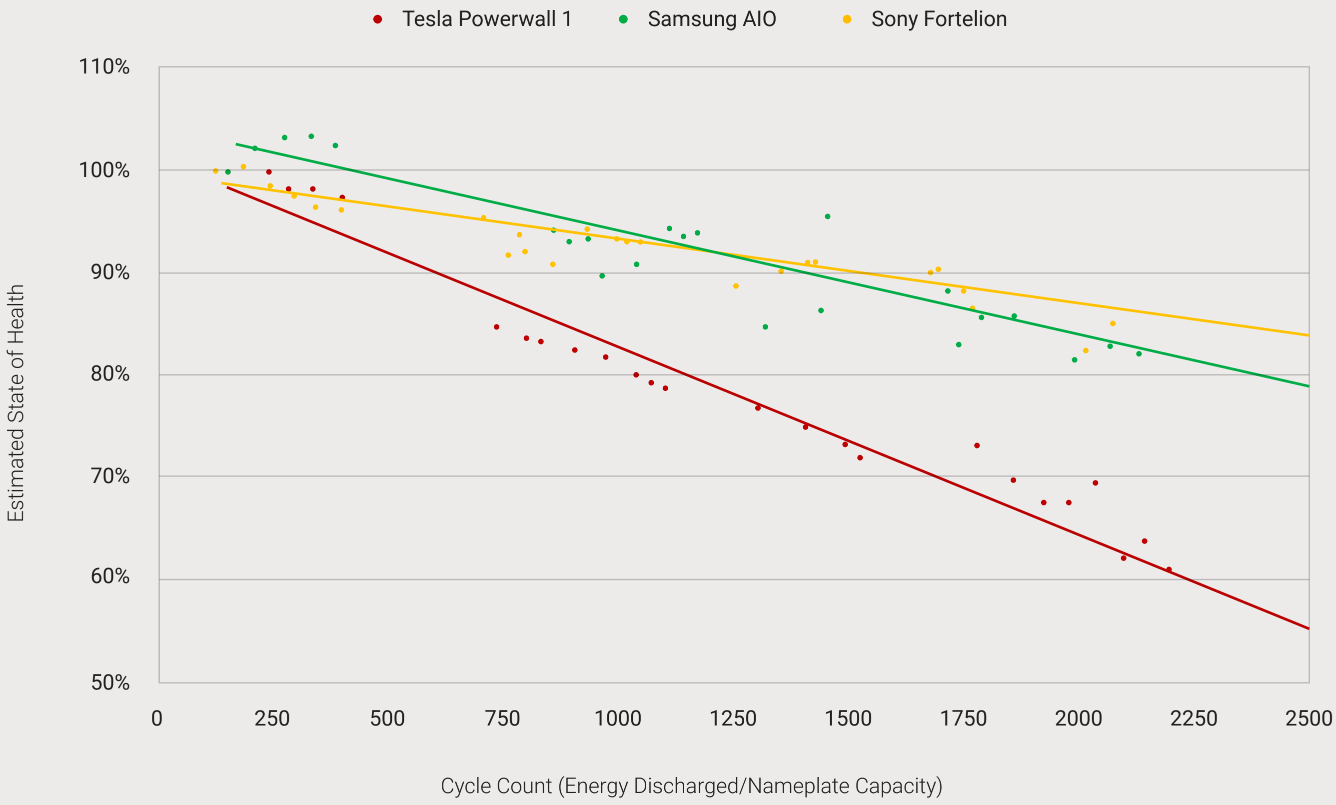


Figure 11. Capacity fade of Phase 1 battery packs based on monthly capacity tests

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 a good fit to the capacity test data collected thus far, extrapolating linearly into the future may not be appropriate.

Samsung AIO10.8

The most recent capacity test suggests a SOH of 82%, broadly in agreement with the 79% SOH estimated from cycle data (described in Section 3.1).

Based on the linear regression between estimated SOH and cycles completed (Figure 11), the Samsung AIO pack is on track for 60% SOH at ~3,770 cycles. As above, however, the cycle data suggests some non-linearity which may invalidate this extrapolation.

Sony Fortelion

The most recent capacity test suggests a SOH of 85%, broadly in agreement with the 83% SOH estimated from cycle data (described in Section 3.2).

Based on a linear regression between estimated SOH and cycles completed (Figure 11), the Sony Fortelion pack is on track for 60% SOH at ~5,640 cycles. As above, however, a linear extrapolation may not be appropriate.

Tesla Powerwall 1

The most recent capacity test suggests a SOH of 61%, broadly in agreement with the 64% SOH estimated from cycle data (described in Section 3.3).

Based on a linear regression between estimated SOH and cycle count (Figure 11), the Tesla Powerwall 1 is on track for 60% SOH at ~2,310 cycles. As above, however, the cycle data suggests some non-linearity which may invalidate this extrapolation.

5.2. Phase 2 Capacity Test Results

Figure 12 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.

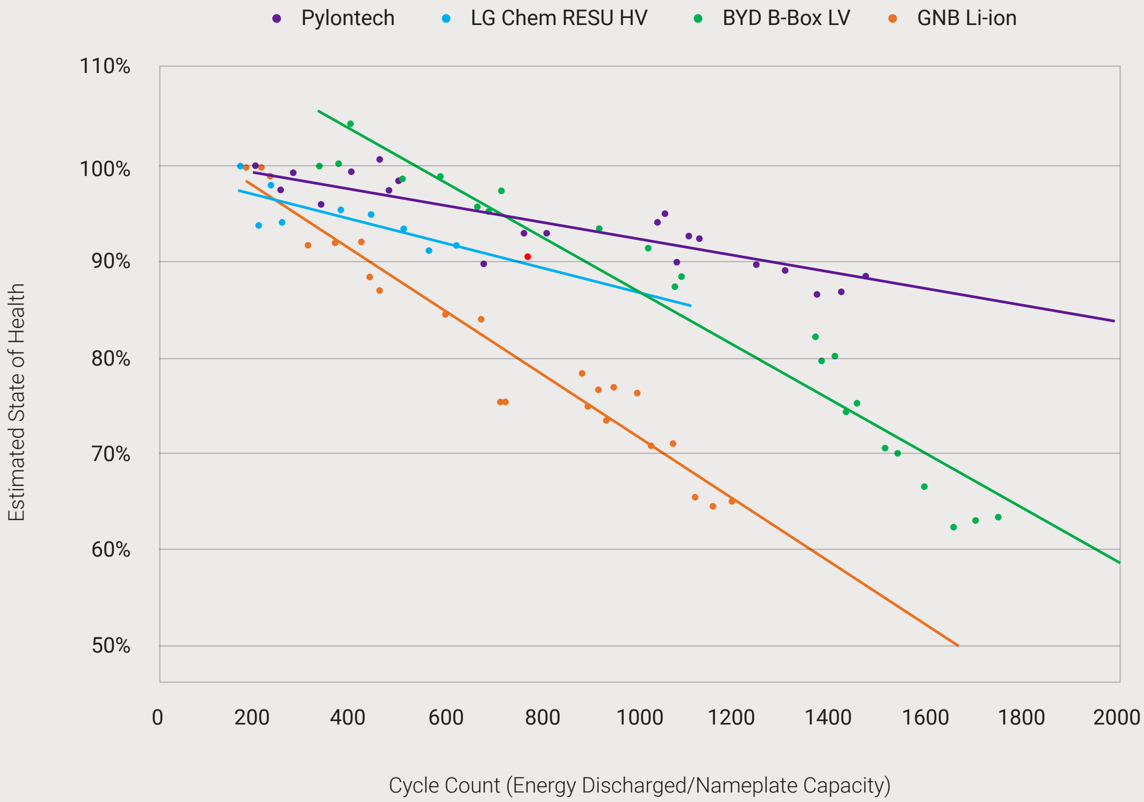


Figure 12. Capacity fade of Phase 2 battery packs based on monthly capacity tests

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

BYD B-Box

The most recent capacity test suggests a SOH of 64%, in agreement with the 64% SOH estimated from cycle data (described in Section 4.2). Based on the linear regression between estimated SOH and cycles completed (Figure 12), the BYD B-Box is on track for 60% SOH at ~1,960 cycles. As above, however, the data suggests some non-linearity which may invalidate this extrapolation.

GNB Lithium

The most recent capacity test suggests a SOH of 65%, in agreement with the 65% SOH estimated from cycle data (described in Section 4.3).

Based on the linear regression between estimated SOH and cycles completed (Figure 12), the GNB Lithium is on track for 60% SOH at ~1,360 cycles. As above, however, the data suggests some non-linearity which may invalidate this extrapolation.

It should be noted that the previous report assumed a higher nameplate capacity when determining the cycle count at each capacity test. As a result, a lower rate of capacity fade appears in this report. The previous assumption was that the nameplate capacity was as per the brochures/manuals provided to ITP by the supplier at the time of purchase. In this report, the nameplate capacity has been assumed as per the actual nameplate on the battery, which aligns better with the specifications provided by diagnostic reports produced by the in-built BMS.

LG Chem RESU HV

The most recent capacity test suggests a SOH of 91%, broadly in agreement with the 90% SOH estimated from cycle data (described in Section 4.4).

Based on the linear regression between estimated SOH and cycles completed (Figure 12), the LG Chem RESU HV is on track for 60% SOH at ~3,080 cycles. As above, however, a linear extrapolation may not be appropriate.

Pylontech US2000B

The most recent capacity test suggests a SOH of 89%, broadly in agreement with the 86% SOH estimated from cycle data (described in Section 4.5).

Based on the linear regression between estimated SOH and cycles completed (Figure 12), the Pylontech US2000B is on track for 60% SOH at ~4,460 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. Though few cycles have been completed to date, from the cycling data shown in Figure 9, no capacity fade is apparent.

Tesla Powerwall 2

The Tesla Powerwall 2 cycling regime is implemented by Tesla, based on requests from ITP. However, capacity tests for the Tesla Powerwall 2 have suffered from the overvoltage issue mentioned in Section 4.7, resulting in intermittent cycling. From the cycling data shown in Figure 10, only a small amount of capacity fade is evident thus far.

5.3. Round-Trip Efficiency

The lifetime round-trip efficiency results are shown for each battery in Figure 13. 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.

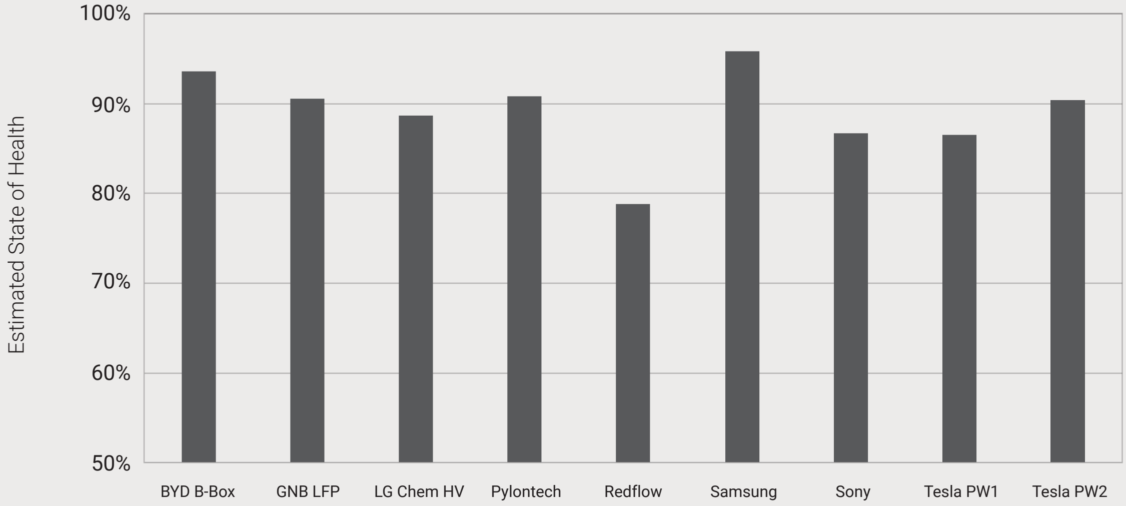
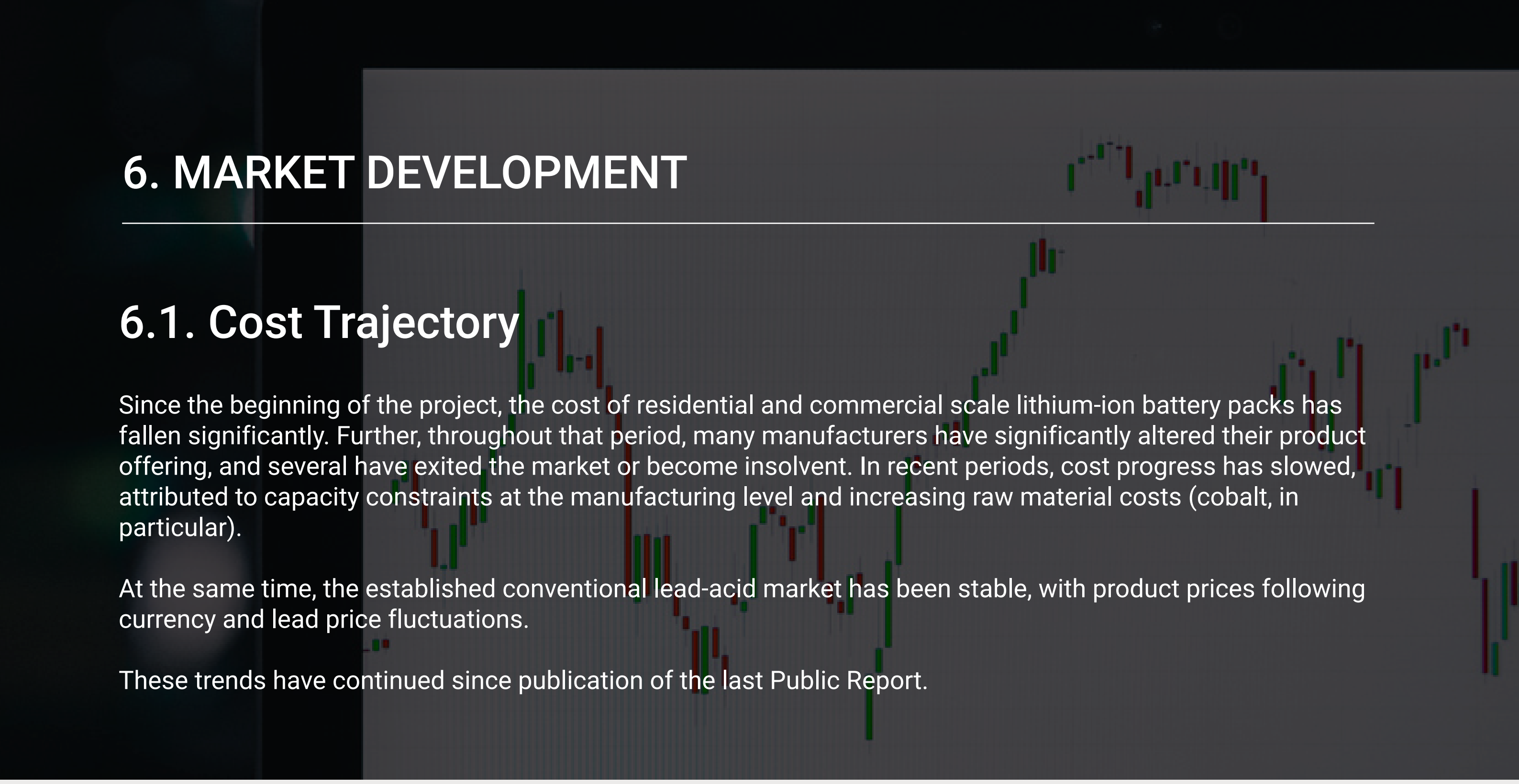


Figure 13. Lifetime round-trip efficiency for each battery pack

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



6. MARKET DEVELOPMENT

6.1. 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 and increasing raw material costs (cobalt, in particular).

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

These trends have continued since publication of the last Public Report.

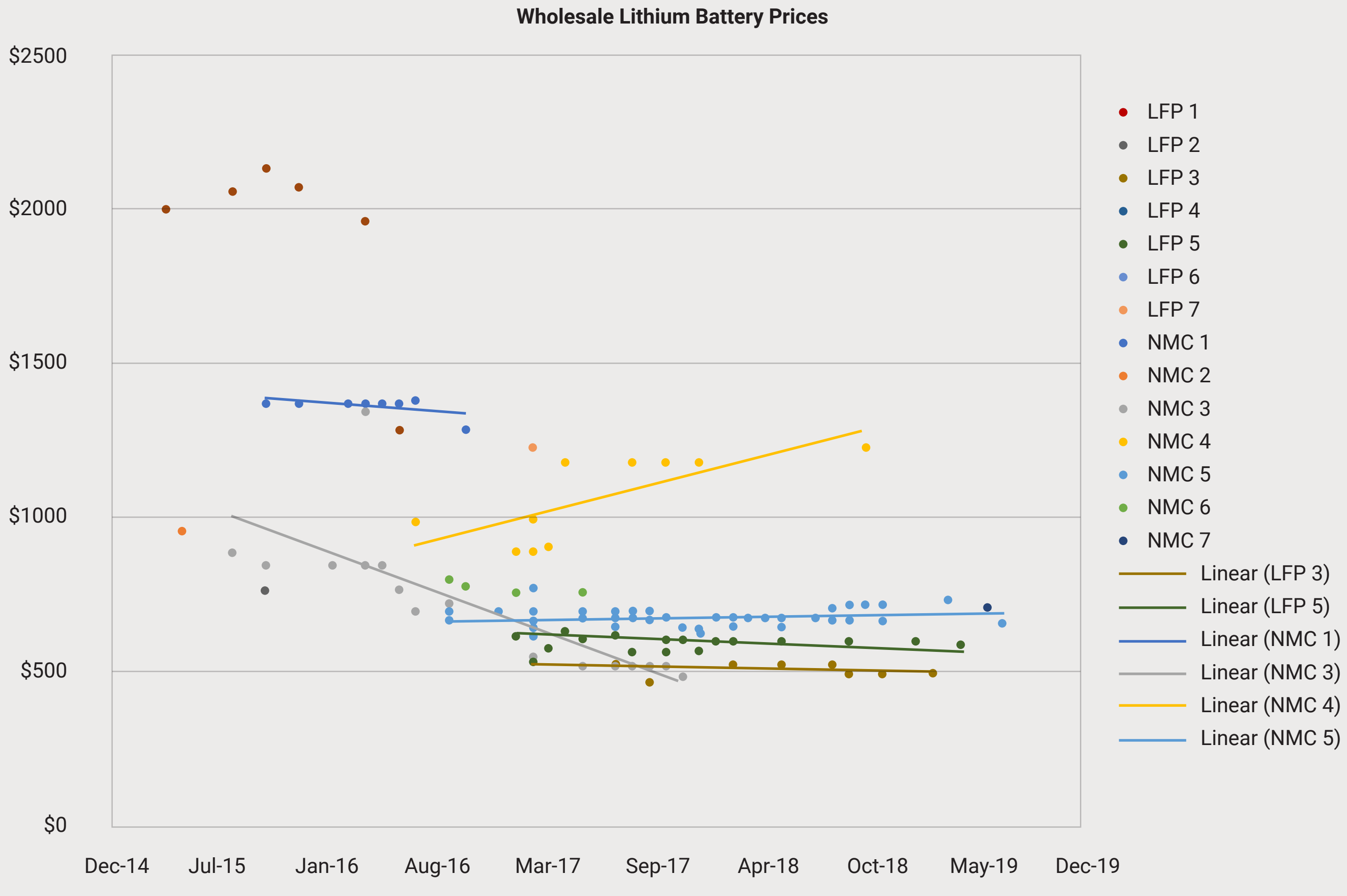
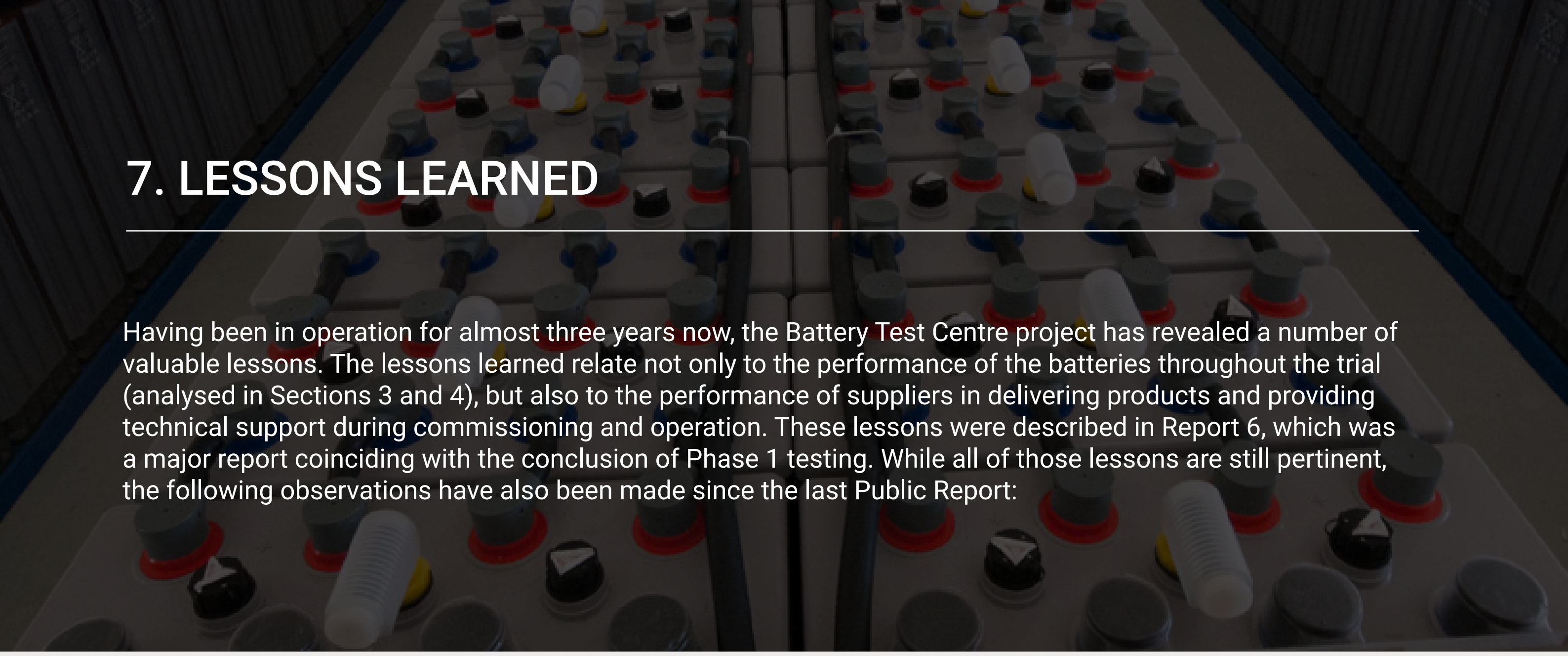


Figure 14: Wholesale prices for lithium-ion battery products installed in the Battery Test Centre

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

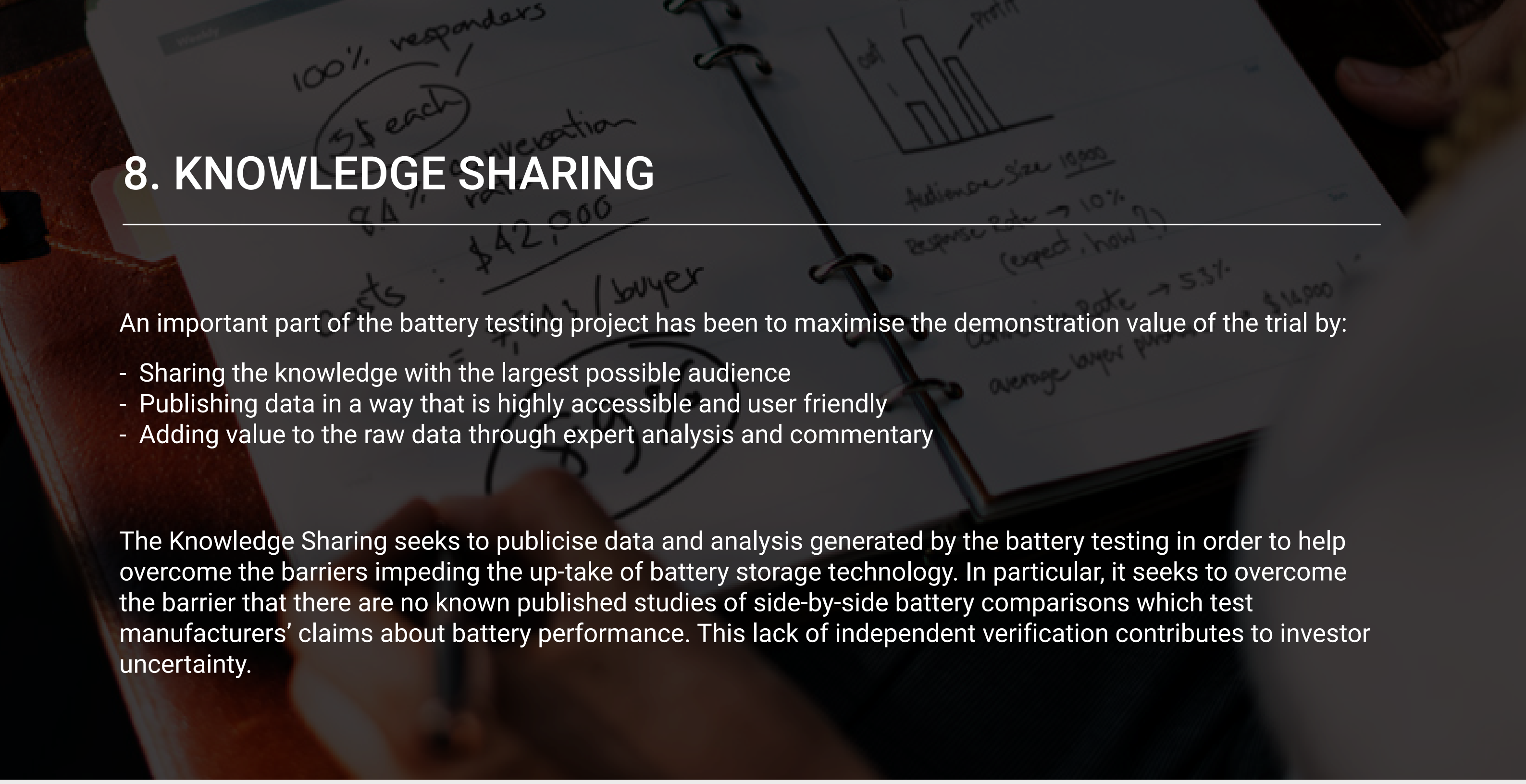


7. LESSONS LEARNED

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 (analysed in Sections 3 and 4), but also to the performance of suppliers in delivering products and providing technical support during commissioning and operation. These lessons were described in Report 6, which was a major report coinciding with the conclusion of Phase 1 testing. While all of those lessons are still pertinent, the following observations have also been made since the last Public Report:

- 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 Phases 1 and 2. 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.



8. 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[2] 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 167,150 page views with an average of 2:03 minutes spent per page overall and 3:53 minutes spent on the reports page.

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[2] batterytestcentre.com.au

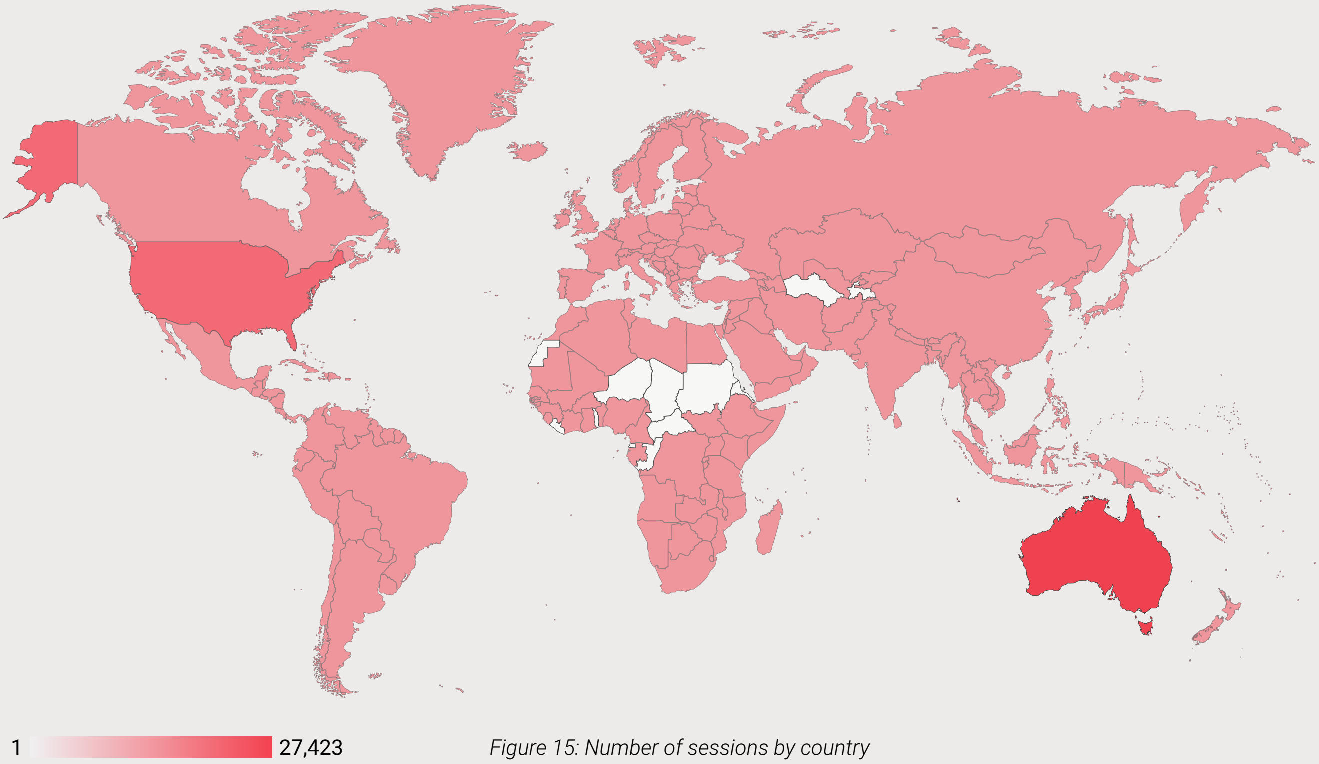


Figure 15: Number of sessions by country

The data from the website shows that the key audience is Australia, with Australian IP addresses accounting for 41,267 sessions (50%). 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 9,501 sessions from the United States, 2,755 from the United Kingdom and Germany not far behind on 2,727. It is interesting to note, however, that the content has been accessed from right across the globe.

Figure 16: Weekly active users

Figure 16 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 500.

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 results page (12%), LG Chem RESU (9%), the reports page (9%), Pylontech US2000B (6%) and the background page on lithium-ion technology (4%).

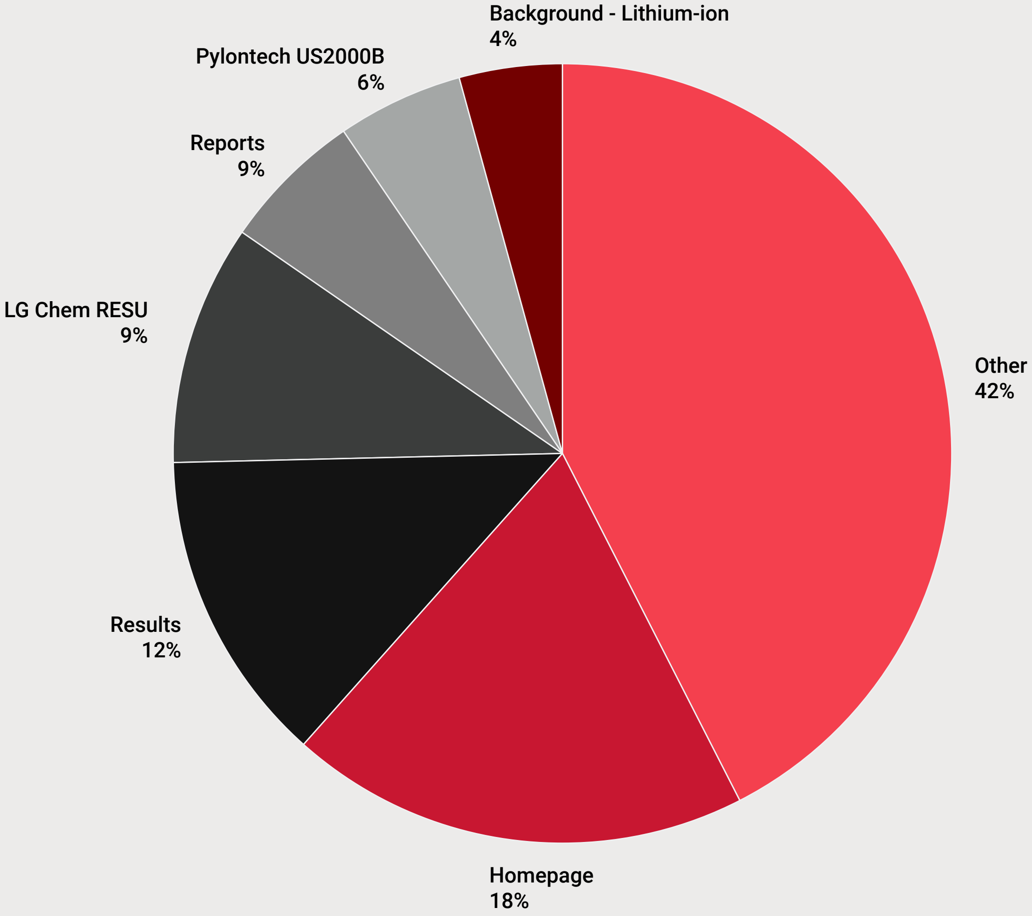
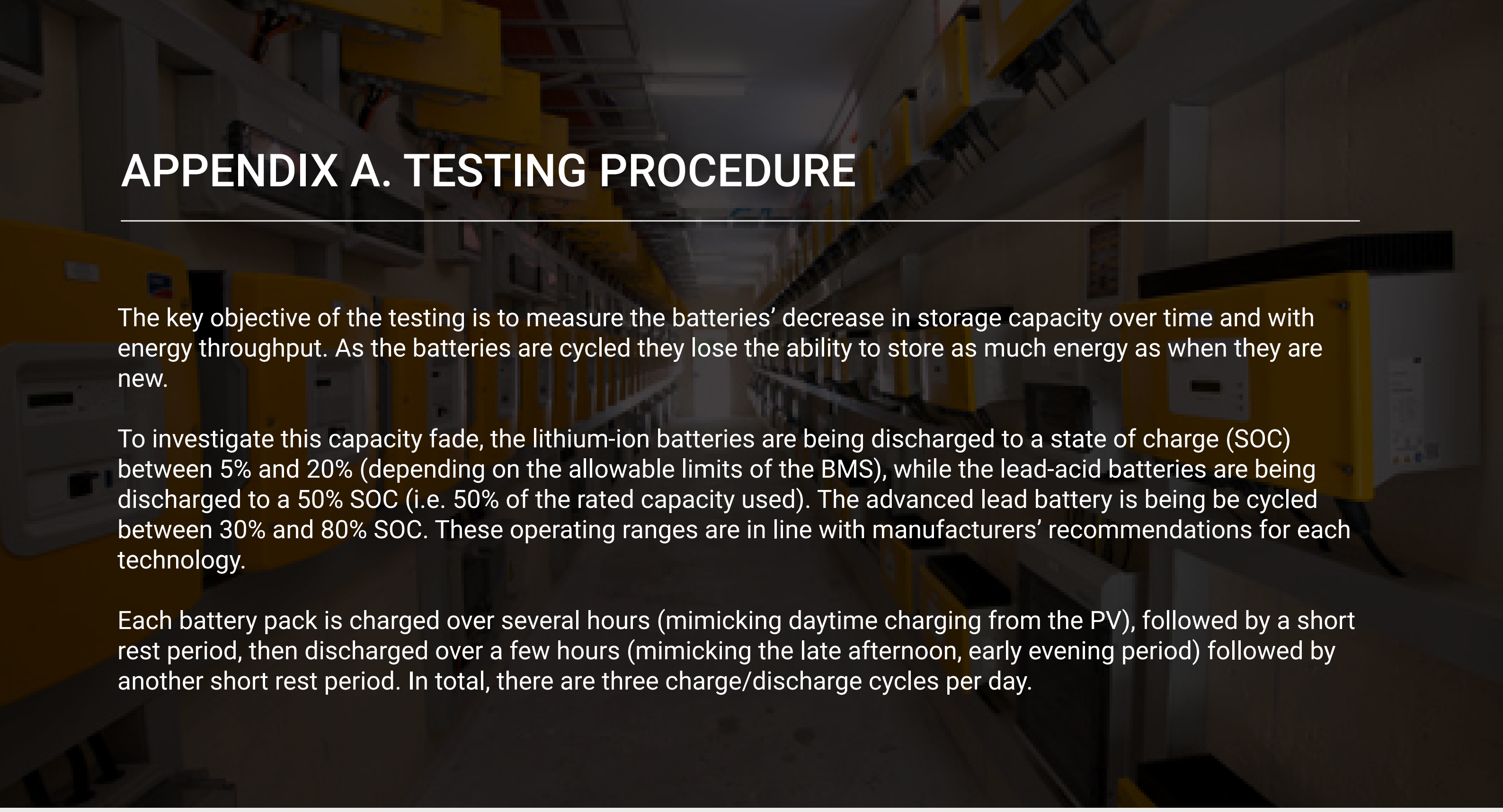


Figure 17: Breakdown of the 167,150 page views



APPENDIX A. TESTING PROCEDURE

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

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

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

Temperature Profile

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

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

Table 3: Daily high and low ambient temperatures throughout the year

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

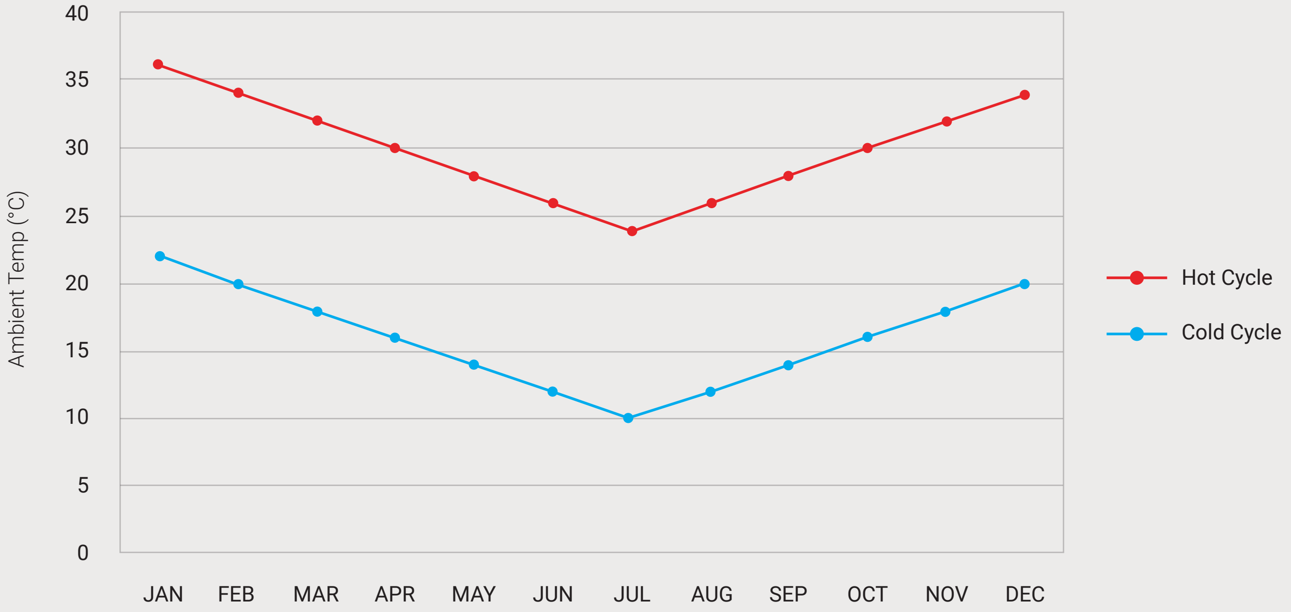


Figure 18: Daily hot and cold cycle temperatures throughout the year

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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.

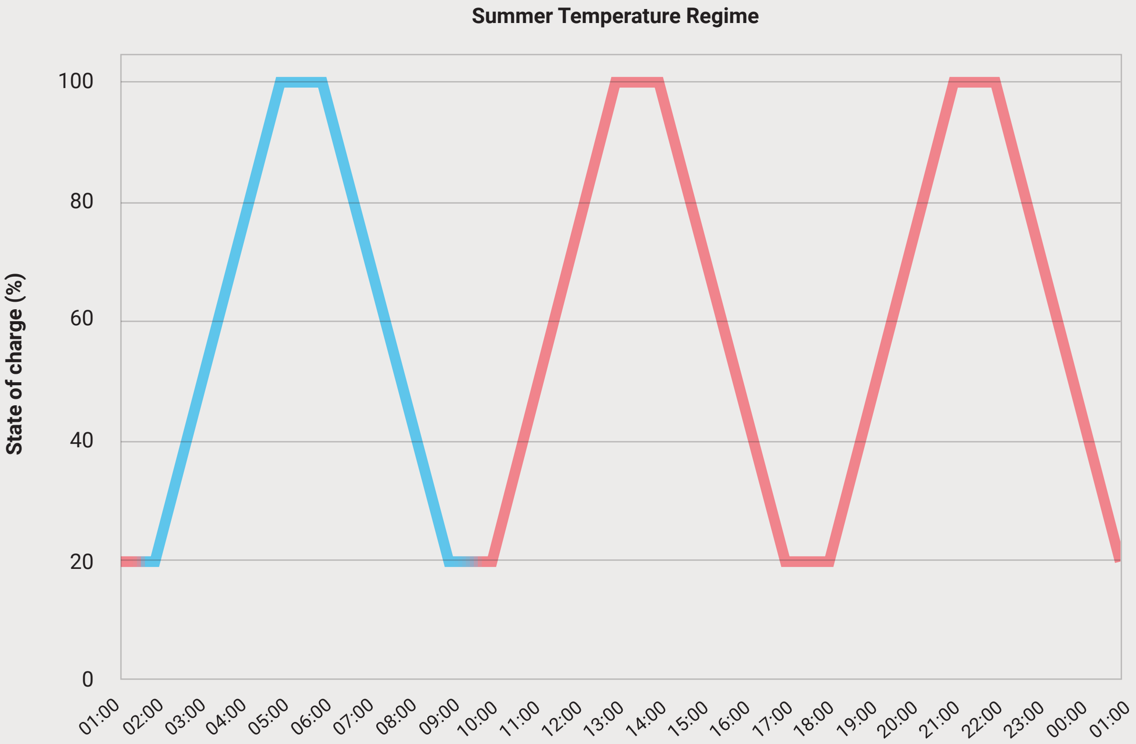

Figure 19: Summer temperature regime and charge regime

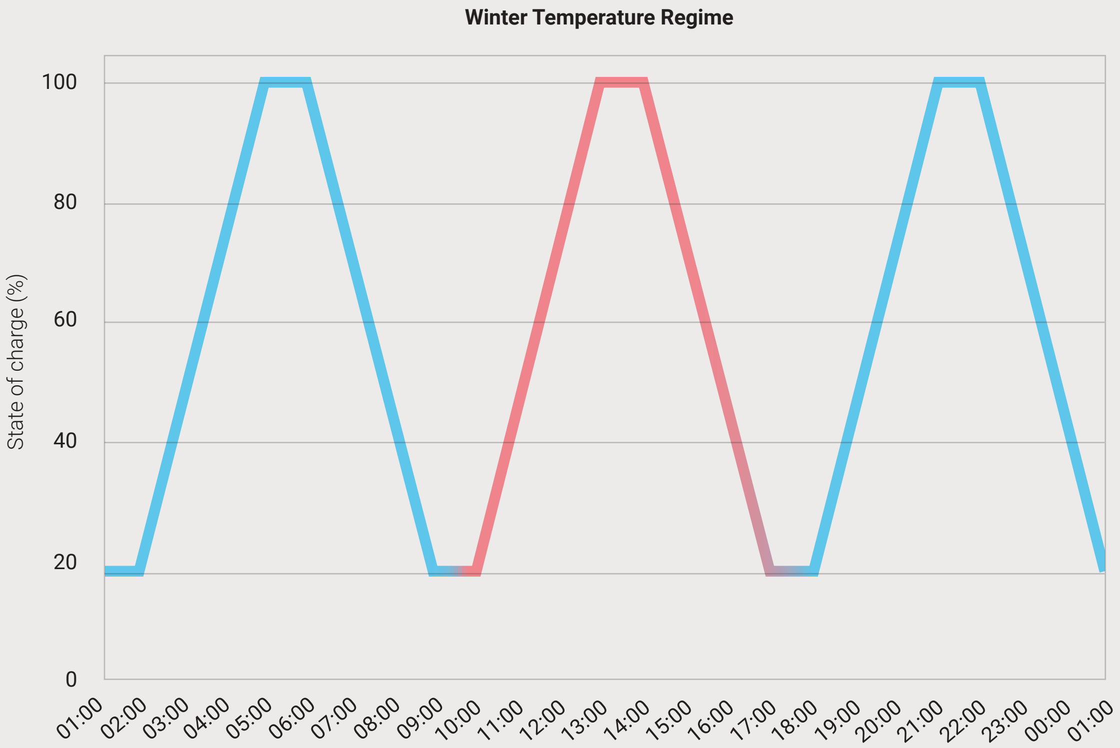

Figure 20: Winter temperature regime and charge regime

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

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