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ARENA

Australian Government
Australian Renewable Energy Agency

BATTERY TEST CENTRE
REPORT 4

March 2018

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 an $870,000 grant from the Australian Renewable Energy Agency, 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 Aquion “saltwater” battery bank.

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

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

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Document prepared by:

ITP Renewables
Level 1, Suite 1,
19 -23 Moore St, Turner, ACT, 2612, Australia

PO Box 6127, O’Connor, ACT, 2602, Australia
Tel. +61 2 6257 3511
Fax. +61 2 6257 3611
E-mail : info@itpau.com.au
http://www.itpau.com.au

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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 which use and electrolyte composed of a lithium-slat dissolved in an organic solvent)
LMO	Lithium Manganese Oxide (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)
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) are testing the performance of residential or small commercial-scale battery packs in a purpose-built climate-controlled enclosure at the Canberra Institute of Technology.

The first part of the report provides a review of the project to date covering the three previous report summaries. Report 1 covered the installation of Phase 1 batteries, including six lithium-ion, one conventional lead-acid, and one advanced lead-acid battery packs. Report 2 covered initial findings in the Phase 1 data. Report 3 outlined the implementation of Phase 2 when the centre was expanded to include an additional eight lithium-ion packs, a zinc bromide flow battery, and a saltwater battery bank.

This report describes ongoing commissioning challenges with the Tesla Powerwall 2 and Aquion saltwater battery packs, the replacement of the Redflow and Ecoult packs, and upgrades to the Ampetus pack.

Ongoing erratic behaviour of the CALB lithium-ion and GNB lead-acid battery packs has been observed, but generally higher round-trip efficiency for lithium-ion technology over conventional lead-acid and zinc-bromide technologies has been demonstrated.

Capacity test results show characteristic capacity fade for all the Phase 1 battery packs (1,000+ cycles completed) still in operation. There is significant variability between packs, and the potential role of temperature effects in contributing to these results is discussed. Phase 2 battery packs (500+ cycles completed) show similar initial trends and variability in capacity fade. Long-term trends should be apparent in the next report.

The Battery Test Centre website is proving an effective means of knowledge sharing with page views of over 74,000, global reach and good interaction with the content.

Key lessons continue to be that manufacturer’s must comprehensively test their battery pack or battery management systems with the applicable inverter prior to dispatch.

1. PROJECT BACKGROUND

ITP Renewables (ITP) are testing the performance of residential or small commercial-scale battery packs in a purpose-built climate-controlled enclosure at the Canberra Institute of Technology. This is the fourth public report outlining the progress and results of the trial. A summary of the three previous reports are below but are accessible in the complete form on the Battery Test Centre Website[1].

Report 1 – September 2016

Report 1 was published September 2016 and outlined the background of the project. The intended audience of the trial included the Australian 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, the testing procedure including temperature profile, cycling profile, and 3-year timeline. The implementation process from procurement through installation to commissioning was also described for the eight batteries listed in the table below.

Phase 1 Batteries

Product	Country of Origin	Chemistry	Total Installed Capacity (kWh)
CALB	China	Lithium Iron Phosphate	10.24
Ecoult UltraFlex	USA	Lead acid carbon	14.8
Kokam Storaxe	Korea	Nickel Manganese Cobalt	8.3
LG Chem	Korea	Nickel Manganese Cobalt	9.6
Samsung	Korea	Nickel Manganese Cobalt	11.6
Sonnenschein	Germany	Lead acid	15.84
Sony Fortelion	Japan	Lithium Iron Phosphate	9.6
Tesla Powerwall	USA	Nickel Manganese Cobalt	6.4

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

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[1] http://batterytestcentre.com.au/reports/

Report 2 – March 2017

By the publication of Report 2 in March 2017 the battery cycling for Phase 1 batteries had been ongoing since August 2016. Capacity and efficiency tests were conducted in each of the six months between September 2016 and February 2017.

It was reported that since testing had commenced, the Kokam Storaxe battery pack had suffered irreversible damage due to improper low-voltage protection provided by the built-in Battery Management System (BMS). 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 BMS.

The main lessons recorded included that capacity fade was evident for some of the battery packs under test, as expected. However, for others, the trends were not yet discernible owing to the inherent variability in capacity testing results. In particular, this variability arises because of imprecision in the 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 was published in November 2017. It described the process of procuring and installing the 10 new Phase 2 battery packs listed in the table below, and outlined preliminary testing results and general observations or issues encountered with the Phase 1 batteries.

Phase 2 Batteries

Product	Country of Origin	Chemistry	Total Installed Capacity (kWh)
Alpha ESS	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	Lithium Iron Phosphate	13.6
LG Chem RESU HV	Korea	Nickel Manganese Cobalt	9.8
Pylontech	China	Lithium Iron Phosphate	9.6
Redflow Zcell	USA	Zinc-Bromide Flow	10
SimpliPhi	USA	Lithium Iron Phosphate	10.2
Telsa Powerwall 2	USA	Nickel Manganese Cobalt	13.2

The Phase 3 Report described how battery supply and installation issues continued to hamper the progress of the battery market as a whole, which had been characterised by instability with a number of manufacturers either exiting the market or substantially changing their product offerings. In particular, market leaders Tesla and LG Chem aggressively cut wholesale pricing, and introduced second generation battery packs. There was one EcoUlt Cell failure and SOC recalculation issues with the GNB lead acid.

Integration of battery packs with inverters continued to be problematic for battery products 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 capacity fade was continuing and that lithium ion batteries continued to demonstrate higher efficiency.

2. BATTERY PERFORMANCE

This section describes the operational challenges and performance of both Phase 1 and Phase 2 batteries over the last 6 months.

Operational Challenges

While most battery packs continue to perform without any specific issues, some have demonstrated challenges that affect operation, capacity fade testing, and efficiency testing. These issues are described below.

CALB

The CALB capacity test cycles continue to show that the BMS is regularly cutting off charge/discharge cycles before the maximum and minimum SOC setpoints are reached. In addition, charge delivery/acceptance (the ability of the battery to discharge or charge at a certain current) in the final third of both the charge and discharge cycles fluctuates significantly. It is expected that this is the result of either a weak/faulty cell, or poor cell management by the REC BMS managing the CALB pack. The CALB pack currently still operates acceptably, but the issues impact the variability and reliability of the capacity test data collected.

Ecoult UltraFlex

In September 2017 Ecoult removed some underperforming battery units from this test for analysis and identified that the BMS’ control system algorithm (specific to the test site) allowed some cells to stray beyond their normal cycling limit for extended periods, accelerating deterioration. Ecoult updated their control and replaced all batteries under warranty. Cycling of the new batteries commenced in January 2018.

GNB Sonnenschein Lead Acid

The previous report identified SOC recalculation issues with the lead acid battery and reduced capacity due to sulfation. Despite undergoing a series of equalisation charges to restore it to a serviceable condition, the lead-acid battery pack appears to remain sulphated or degraded as a result of the cycling. SOC estimation (conducted by the SMA inverter) frequently adjusts downwards (to ~20%) during discharge to trigger protection modes in the inverter to prevent further discharge. The inverter does this when the battery voltage reaches a minimum setpoint. The opposite is true during charging, where the SOC rapidly adjusts upwards.

If this is the result of sulfation, then this demonstrates the unsuitability of lead-acid batteries for frequent cycling applications due to their characteristic charge requirements. In particular, this impacts their long-term effectiveness in stationary storage for solar applications, where daily charge and discharge cycles are expected, that may not allow for a daily full charge.

Ampetus Super Lithium

During commissioning of the Ampetus SuperLithium in early October 2017, ITP observed that the Ampetus pack was constraining the charge rate below the setpoint of the test centre's control system. The manufacturer attributed this behaviour to communication issues between the BMS and the inverter. The battery pack was sent to the manufacturer's technician in Queensland for assessment and the issues were resolved with a firmware upgrade. The pack was subsequently returned to the test centre mid-November.

Aquion Saltwater Battery

Aquion's bankruptcy in early March 2017continues to leave ITP without support from Aquion for final commissioning of the batteries with the Victron inverter. ITP has set all parameters detailed in existing documentation but is still unable to complete commissioning the battery, at the time of writing.

Although Aquion was bought out in July 2017, it is not supporting existing products in any way, and all existing warranties are void. There is some hope that the company who bought out Aquion may provide support in the future but to date the data available from this inverter is not meaningful.

Redflow

The Redflow battery pack suffered an electrolyte leak and was replaced in February 2018. Redflow attribute the leak to micro-cracking that occurred during road transport. The identified problem was that the trays with the electrolyte were supported at the feet but not sufficiently on the sides to withstand the weight of the electrolyte. Redflow have since modified their transport techniques and believe this problem will be avoid in the future.

ITP have worked to incorporate the pack's maintenance cycles into their cycling regime, but its characteristic requirements fundamentally differ from the lithium-ion batteries.

Tesla Powerwall 2

The Tesla battery has been idle for most of this reporting period because the unit was unable to execute charge/discharge commands without time-of-use control functionality. This functionality was originally expected to be released with the product, pushed to November 2017 and then March 2018. ITP are currently testing control possibilities via the new Tesla Powerwall 2 (TP2) application programming interface (API). It is expected this will allow control and meaningful data collection in the near future.

Capacity Fade Analysis

Phase 1 Battery Packs

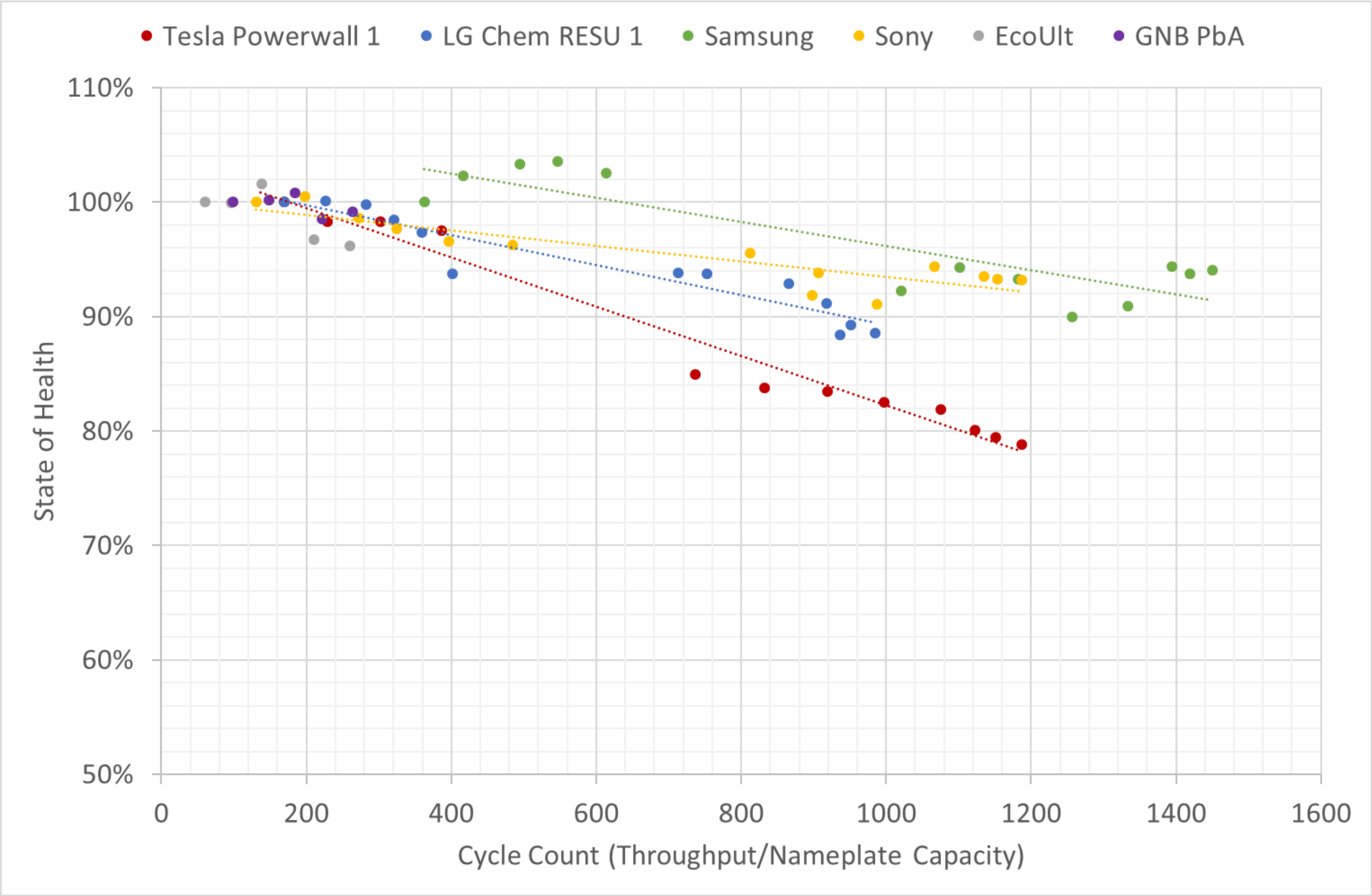

Figure 1. Capacity fade of Phase 1 battery packs

The above chart shows capacity fade for each of the Phase 1 battery packs over the life of the trial. All lithium-ion batteries have now achieved at least 1,000 equivalent full cycles. From the data available thus far, the following is apparent:

- The issues associated with state of charge estimation for the CALB battery continue to make capacity analysis difficult
- At this stage of the testing the capacity of the Sony and Samsung packs has degraded the least. SOH is over 90% after 1,200+ cycles
- The LG Chem RESU 1 shows slightly faster degradation, while the Tesla Powerwall 1 shows the fastest degradation rate, noting that:
  - the LG Chem pack has the highest energy density of all packs, and hence is disadvantaged in terms of its ability to dissipate heat generated during charge and discharge. In real world applications, the charge and discharge rates would typically be

less consistently high; meaning less heat build-up, lower battery cell temperatures, and likely slower capacity fade.

- the Tesla Powerwall 1 is charged and discharged at a faster rate than all other battery packs being tested. At the beginning of the trial, Tesla's Powerwall 1 was only compatible with a Solar Edge inverter. All other 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) while other batteries charge and discharge over ~3hrs. This means the Tesla has less time to dissipate heat, which may be causing higher battery cell temperatures leading to accelerated capacity fade. ITP is unable to analyse battery cell temperature data to confirm this hypothesis as the functionality is not provided by Tesla.

Phase 2 Battery Packs

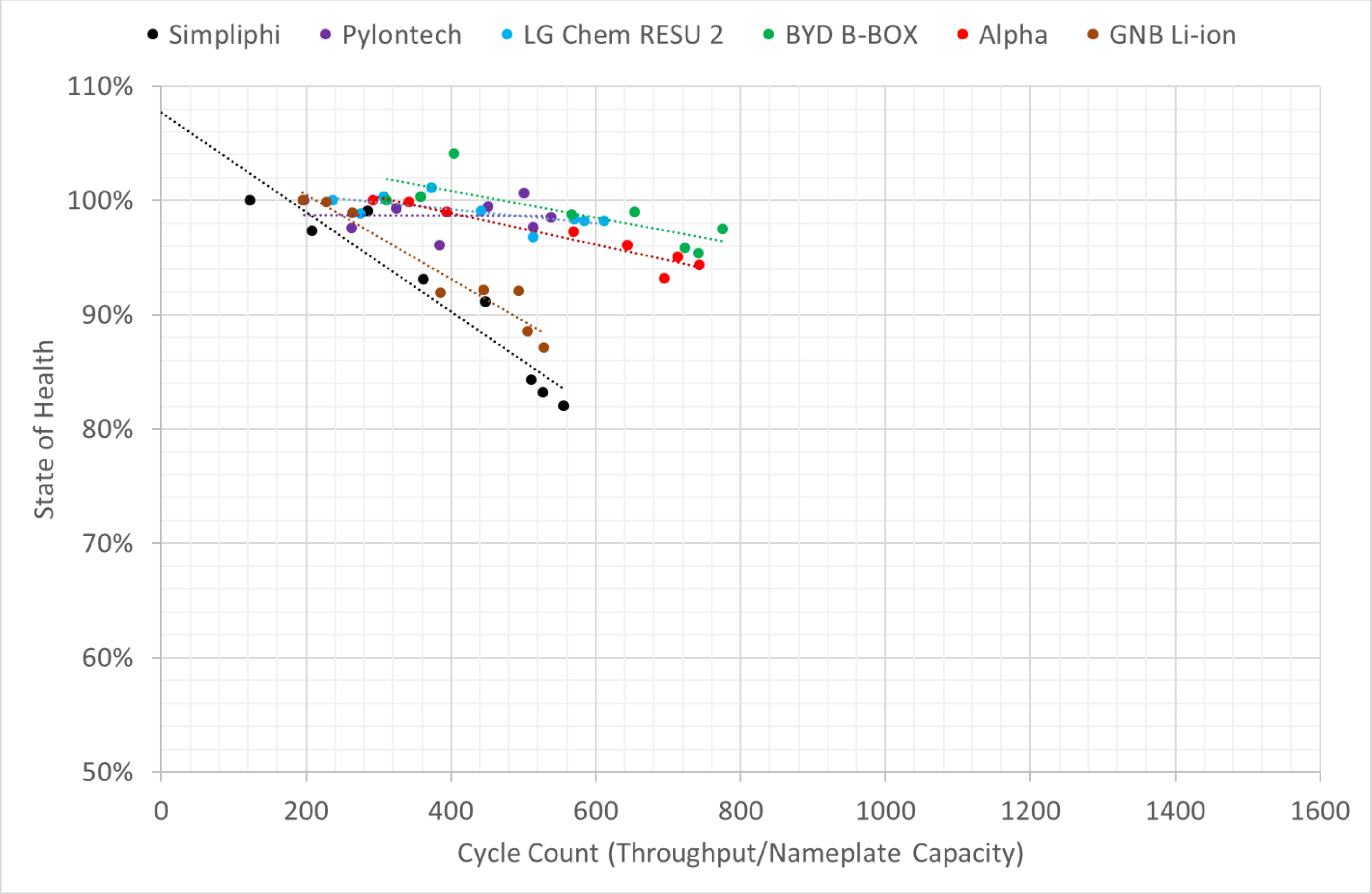

Figure 2. Capacity fade of Phase 2 battery packs

Owing to the later start date of the Phase 2 battery pack testing, fewer cycles have been completed than Phase 1 batteries. While some battery packs appear to demonstrate faster capacity fade than others, at this early stage it is difficult to be confident about any conclusions. Analysis to be provided in the next report should be instructive.

Efficiency Analysis

Efficiency data shows greater variance than capacity results (due to inconsistencies and inaccuracies with SOC estimation by BMS), but nevertheless it is possible to observe generally higher lithium-ion efficiency than lead-acid and zinc-bromide efficiency.

A trend of decreasing efficiency over time is also apparent in some batteries under test, but this may only become conclusive in subsequent analyses with more data points. In light of the variance in results, only average efficiency values derived from consistent results are depicted in Figure 3 below. Because of trend efficiency fade effecting some battery packs, the average shown has been taken from the first five results only.

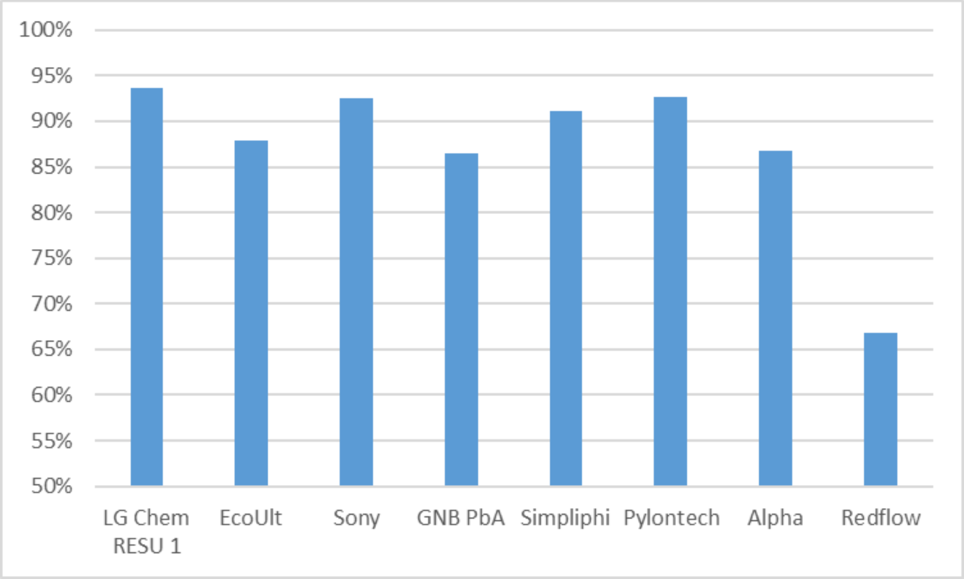

Figure 3. Apparent initial round-trip efficiency of various battery packs

2. LESSONS LEARNED

Many of the lessons learned from the first phase of the battery trial remain relevant for this second phase of the trial. Procurement of batteries and integration with inverters remain the most challenging aspects of installing these products. Proper BMS integration with lithium-ion battery management systems is crucial for commissioning and operation. When this has not been comprehensively established by the manufacturer prior to product dispatch, commissioning is typically unsuccessful, or else system capability is limited.

The data shows lithium-ion technology out-performing conventional lead-acid battery packs in terms of round-trip efficiency, despite lead-acid efficiency appearing higher than general expectations. The initial data suggests that efficiency of >85% can be expected for either Li-ion NMC or Li-ion LFP chemistries, and it is possible that a conclusive difference in efficiency will be apparent between the different Li-ion chemistries by the conclusion of the trial.

The advanced lead-acid battery pack (EcoUlt) outperforms the conventional lead-acid (GNB) in terms of round-trip efficiency in the data collected thus far. The ability of the advanced lead-acid to avoid the majority of the conventional lead-acid’s absorption charge phase is likely to be largely responsible for this result.

The widespread issues with consistent SOC estimation do not meaningfully impact battery pack operation but do introduce inconsistency and hence uncertainty to capacity testing results. For this reason it is particularly important to consider long-term trends above individual results.

The issues experienced by the lead acid battery (described above) highlight the shortcomings of the technology in high cycling and high charge/discharge rate applications. These shortcomings have typically been overcome by installing larger than required battery banks which increases transport and installation costs on top of the cost of additional batteries. The trial to date demonstrates that lithium batteries are better suited to high cycling and high charge/discharge rate applications and that higher efficiency can be expected.

3. 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 1: 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

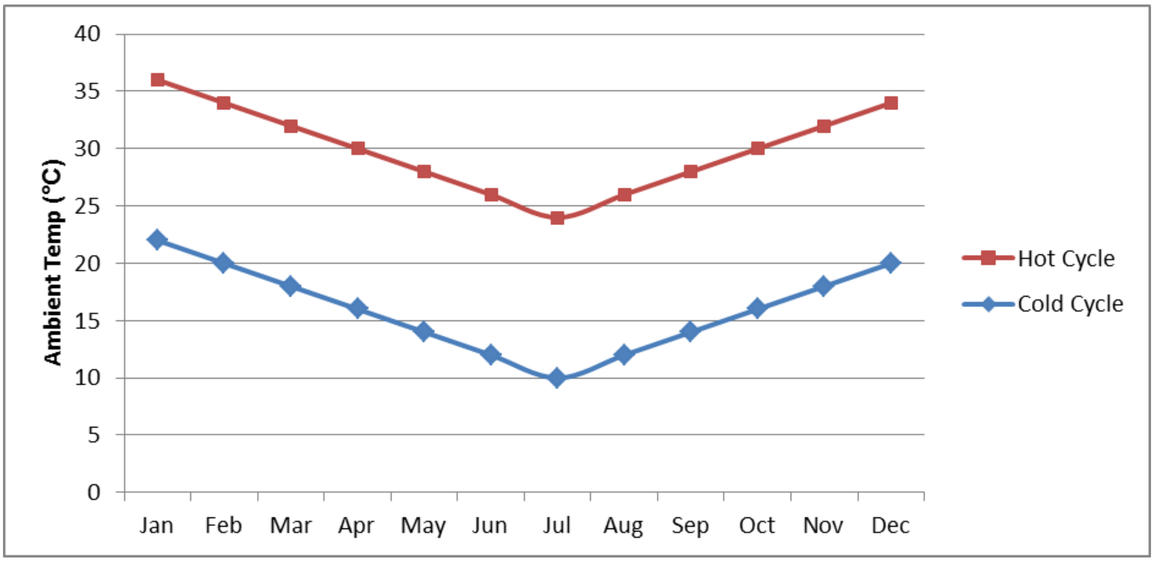

Figure 4: Daily hot and cold cycle temperatures throughout the year

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.

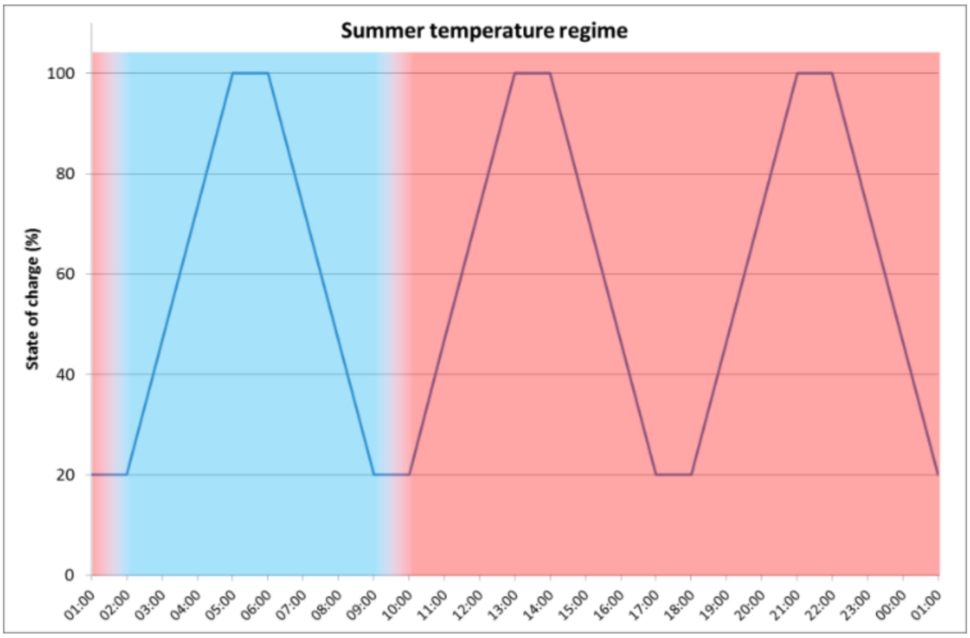

Figure 5: Summer temperature regime and charge regime

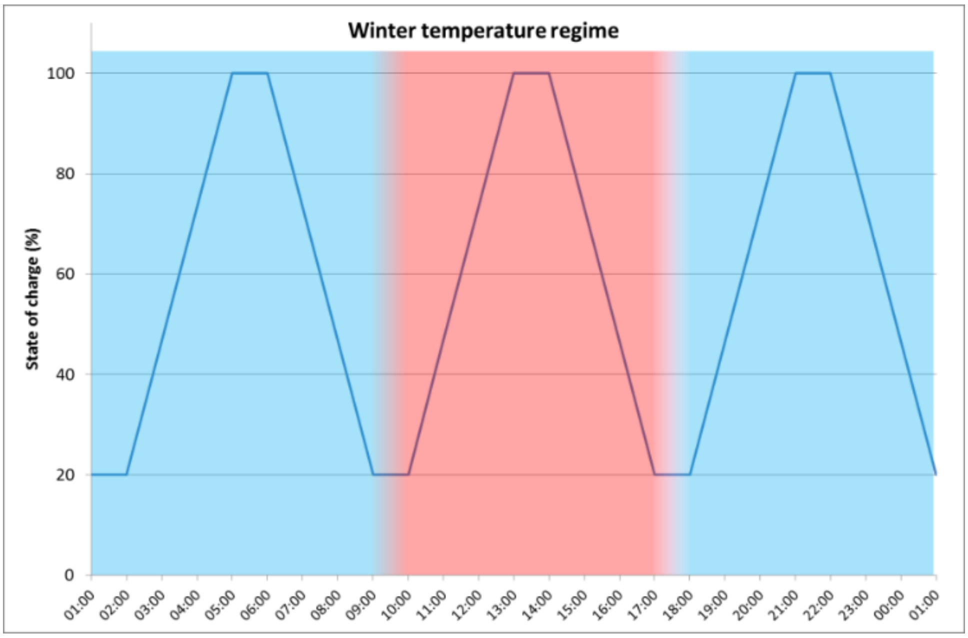

Figure 6: Winter temperature regime and charge regime

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.

4. 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 performance 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 manufactures' 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 the electricity generators, TNSP, 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 states of charge and a virtual reality component that replicates the battery test facility. To date the site has had over 74,000 page views with an average of 2:18 minutes spent per page and over 4 minutes spent on the reports page.

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[2] http://batterytestcentre.com.au/

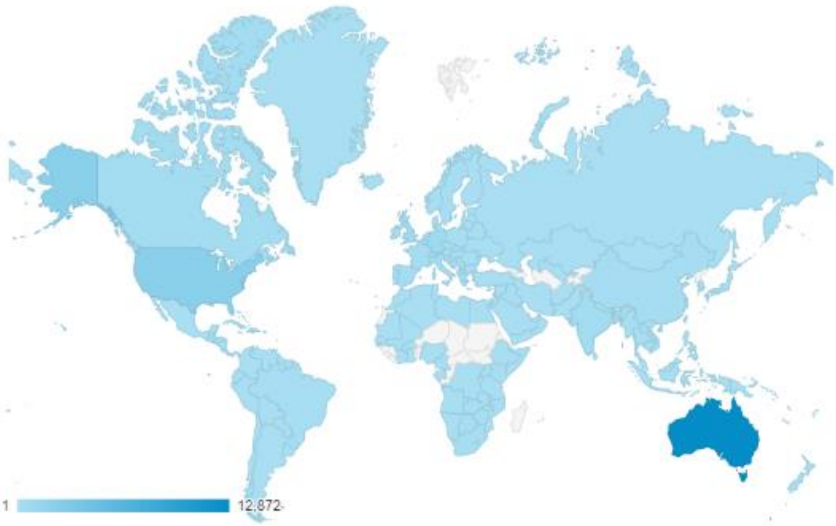

Figure 7: Number of sessions by country

The data from the website shows that the key audience is Australia, with Australian IP addresses accounting for over 12,870 sessions. 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 2,388 sessions from the United States, 749 from Germany and the United Kingdom not far behind on 708. It is interesting to note, however, that the content has been accessed from right across the globe.

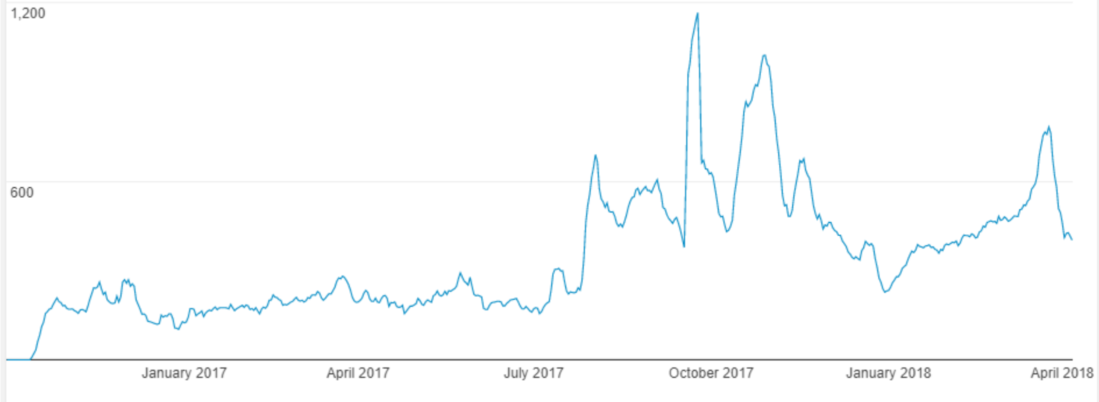

Figure 8: Weekly active users

Figure 8 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.

There is a good spread of views across the website, particularly the technology and results pages but the top five most viewed pages after the home page (20%) are the results page (15%), LG Chem RESU (10%), Tesla Powerwall (5%), the background page on lithium-Ion technology (5%) and the reports page (4%).

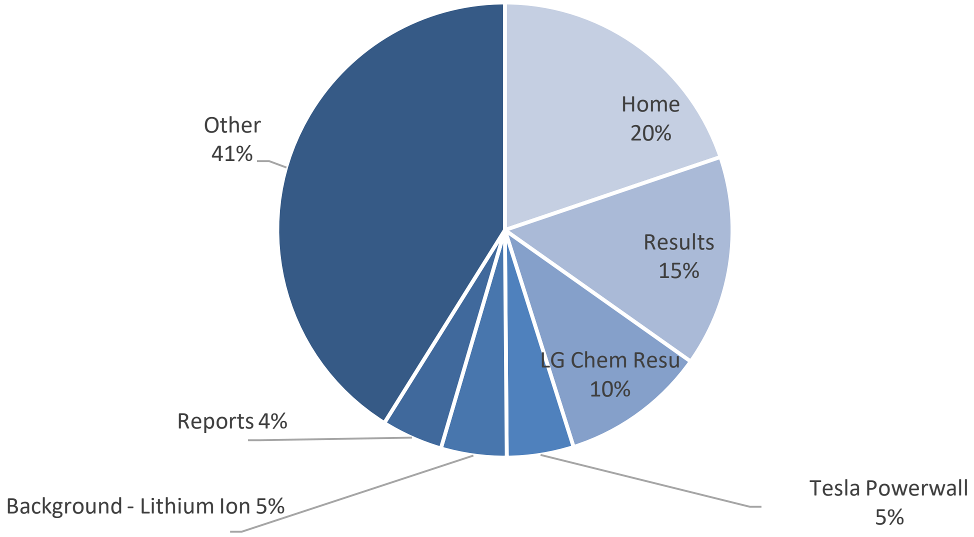

Figure 9: Breakdown of the 74,000 page views

IT Power **Renewable Energy Consulting**

Southern Cross House, 6/9 McKay St, Turner, ACT
PO Box 6127 O'Connor, ACT 2602
info@itpau.com.au

abn 42 107 351 673
p +61 (0) 2 6257 3511
f +61 (0) 2 6257 3611

itpau.com.au