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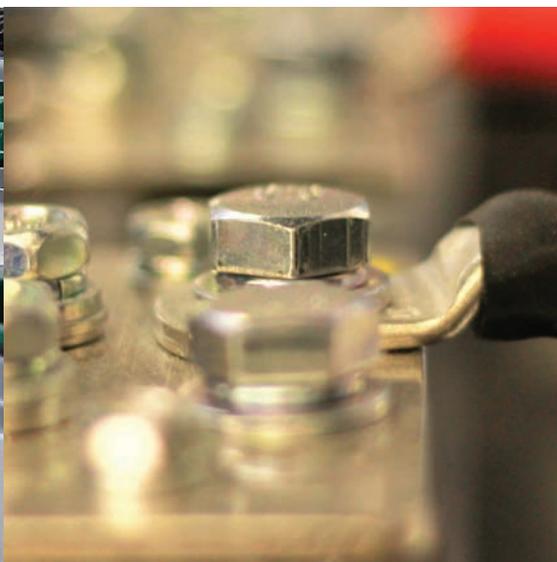


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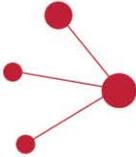
Australian Renewable
Energy Agency



BATTERY TEST CENTRE REPORT 2



March 2017



About 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.

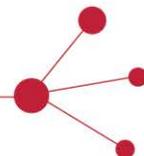
Established in the United Kingdom in 1981, the Group was among the first dedicated renewable energy consultancies. In addition to the UK it maintains a presence in Spain, Portugal, India, China, Argentina and Kenya, as well as our ITP offices in Australia and New Zealand.

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

The Lithium Ion Battery Test Centre program involves performance testing of six lithium-ion batteries, one lead acid battery and one advanced lead acid battery. The project is supported by a \$450,000 grant from the Australian Renewable Energy Agency (ARENA). This report provides analysis and discussion of testing data collected between September 2016 and February 2017.

At the time of writing ITP is in the process of adding a further ten batteries to the Battery Test Centre, supported by a second ARENA grant of \$420,000.



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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>

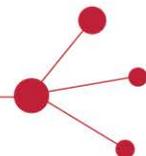
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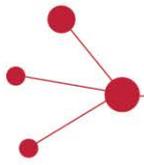
LIST OF ABBREVIATIONS

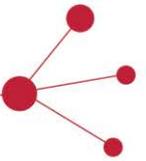
AC	Alternating Current
AIO	All-in-one (referring to a battery unit which is combined with a battery inverter and PV inverter)
ARENA	Australian Renewable Energy Agency
AUD	Australian Dollar
BESS	Battery Energy Storage System
BMS	Battery Management System
BOS	Balance of System
C(number)	“C Rate” (charge 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
EV	Electric vehicle
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 Standard Test Conditions
LFP	Lithium Iron Phosphate (a common li-ion battery chemistry)
Li-ion	Lithium ion (referring to the variety of battery technologies which use an electrolyte composed of a lithium-salt 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
PV	Photovoltaic
RE	Renewable Energy
SOC	State of Charge of a battery
UPS	Uninterruptable Power Supply
VRLA	Valve Regulated Lead Acid



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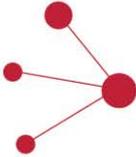
EXECUTIVE SUMMARY

ITP Renewables (ITP) are testing the performance of commercially available residential or small commercial scale lithium-ion batteries. The aim of the testing is to independently verify battery performance against manufacturers' claims. Specifically, ITP is investigating capacity fade, efficiency, and charge characteristics of six lithium-ion batteries, one conventional lead-acid battery, and one advanced lead-acid battery. They are tested in a purpose-built climate-controlled enclosure at the Canberra Institute of Technology.

Battery cycling has now been ongoing since August 2016, and will continue until end July 2020. Capacity and efficiency tests have been conducted in each of the six months between September 2016 and February 2017. At this early stage, capacity fade is evident for some of the battery packs under test, but for others, the long-term trend is difficult to discern, owing largely to the inherent variability of battery capacity between cycles.

Since testing has commenced, one of the lithium-ion battery packs has suffered irreversible damage due to improper low-voltage protection provided by the built-in Battery Management System (BMS). Another battery is functional but showing evidence of either a weak cell or poor battery management by the BMS.

While trends in capacity fade are expected to become clearer over the next six months of testing, already it can be seen that lithium-ion efficiency is generally higher than the conventional lead-acid pack.



1. PROJECT BACKGROUND

Purpose of Testing

Lead-acid (PbA) battery technologies have been used in energy storage applications for decades. In recent years, however, new technologies have appeared on the market, and the range of options for the storage of renewable energy and/or the provision of back-up power has increased significantly.

In particular, manufacturing of lithium-ion (Li-ion) battery cells for electric vehicles (EV's) has improved the cost and performance of Li-ion battery packs, and there is now increasing interest in using this technology in stationary applications. Nevertheless, energy system designers and end users have been reluctant to transition to this new technology, particularly in remote applications where reliability is critical. In part, this reluctance is due to a history of over-stated manufacturers' claims, which are often based on lab-based tests lacking independent verification.

The purpose of the battery performance testing is therefore to verify claims made by manufacturers about performance, integration, and installation of lithium-ion battery packs, and to disseminate the results to the public. To achieve this ITP is independently testing the performance of:

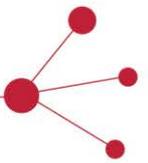
- Six different Li-ion battery packs;
- An 'advanced' PbA battery bank (lead acid with a carbon ultracapacitor); and
- A conventional gel VRLA (PbA) battery bank

The batteries are tested side by side in hot daytime and cool overnight temperatures, similar to what they would be expected to face in real-world conditions. The desired outcome is to better inform energy storage system investors, to facilitate further uptake of renewable energy.

Conventional Lead-Acid vs. Lithium-Ion Technologies

Conventional lead-acid batteries have been in operation for decades across many applications, and their performance and maintenance requirements are well understood. However, the technology has some limitations. For example, conventional lead-acid batteries can only be partially discharged when regularly cycled; require frequent full charges; have low energy density; and contain toxic heavy metals and corrosive acid.

Lithium-ion cells have been widely used in portable electronic devices since the 1990's, and in EV's for the past decade. Lithium-ion battery packs typically have a higher capital cost per unit of nominal storage capacity compared to lead-acid batteries, and require more complex battery protection systems to protect against both under- and over-discharging. Nevertheless, they have



a number of technical advantages, if demonstrated, should result in a lower levelised cost of energy (LCOE) in high-cycling applications when using li-ion storage over conventional lead-acid, despite the higher initial capital cost. A list of the key advantages claimed is as follows:

- Higher allowable depth of discharge (DoD) - lead-acid batteries should not be discharged by more than 30-50% (of the nominal capacity) daily if standard design lives of 5-10 years are to be achieved. Lithium-ion manufacturers' guidelines allow discharging of 80-95% for similar, if not longer design lives;
- Higher efficiency - a lead-acid battery is typically assumed to have a 75-80% round-trip efficiency, compared to ~95% claimed by lithium-ion battery manufacturers;
- Lower risk of gas explosions and reduced ventilation requirements – no gases are produced during normal operation of lithium-ion batteries. Lead-acid batteries, on the other hand, can produce explosive hydrogen gas during charging, and hence strict ventilation requirements are in place, which adds to system cost and complexity;
- Lighter and more compact - for the same energy/power capacity, a lithium-ion battery pack will weigh less and consume less space, also lowering balance of system (BOS) requirements such as cabling, and installation costs.

Conventional Lead-Acid vs. Advanced Lead-Acid Technology

An advanced lead-acid battery incorporates an ultracapacitor into a conventional lead-acid cell. This has the effect of reducing negative plate sulphation, which reduces the frequency of equalisation charges, and frees the battery from the necessity of the absorption charging phase, where efficiency and charge acceptance are lower and gassing is higher. The supposed result is increased overall efficiency, faster recharge times, reduced downtime, and increased safety.

The technology is currently in the demonstration phase, and hence costs, which are currently higher than for conventional lead-acid batteries, can be expected to decrease if production scales increase. As above, a lower LCOE may result in high-cycling applications when using advanced lead-acid storage over conventional lead-acid storage, despite the higher initial capital cost.

Project Summary

A battery test centre has been built at the Sustainable Skills Training Hub at the Canberra Institute of Technology and performance testing has commenced. In brief this involves:

- Cycling the batteries three times a day for three years to simulate nine years' worth of 'normal' daily cycling of the batteries (noting that while accelerated, this cycle rate is within manufacturers' specifications);
- Mimicking 'real world' conditions by cycling the temperature of the facility where the batteries will be installed; and,

- Publishing performance data, including the batteries' decrease in storage capacity over the three years of the trial, and documenting any integration challenges or issues that arise.

Our proposed Knowledge Sharing Plan aims to maximise the demonstration value of the trial by:

- Sharing the knowledge with the largest possible audience;
- Publishing trial data in an accessible and user-friendly manner; and
- Adding value to the raw data through expert analysis of the results.

If the trial successfully demonstrates that Li-ion and/or advanced lead-acid technology is superior in performance and cost-effective compared to traditional PbA batteries, then the outcome will be that:

- Those interested in grid-connected energy storage systems will be in a position to make more informed investment decisions;
- The cost of integrating high levels of renewable energy into mini-grids will decrease, and hence cheap but variable renewable energy generation (ie. solar PV and wind) will become more attractive.

Testing Procedure

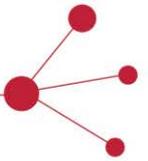
The key objective of the testing is to measure the batteries' decrease in storage capacity over time and with energy throughput. As the batteries are cycled they lose the ability to store as much energy as when they are new.

To investigate this *capacity fade*, the lithium-ion batteries are being discharged to a state of charge (SOC) between 5% and 10% (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 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

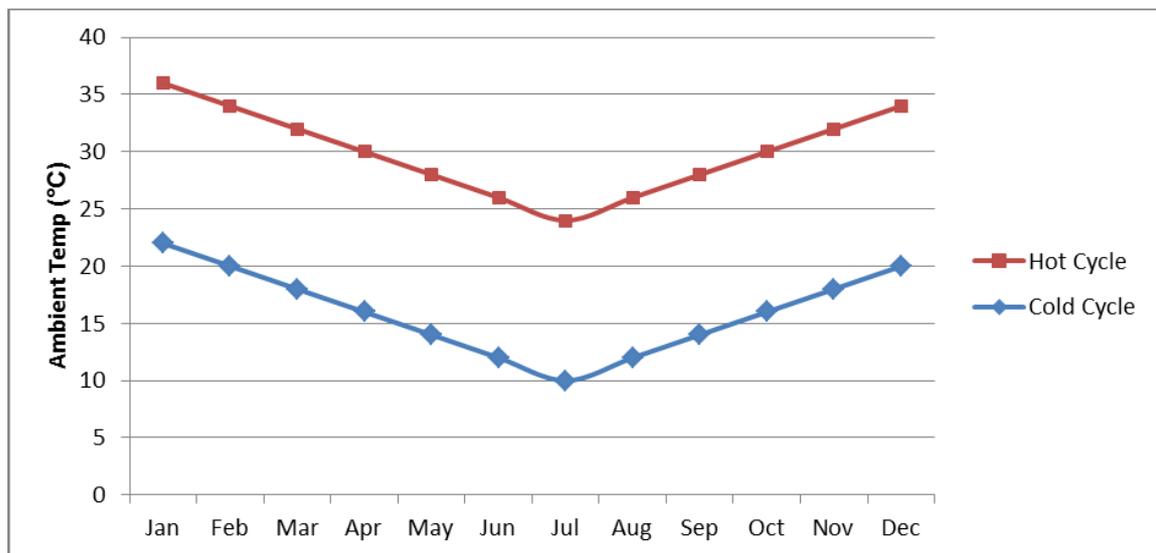


Figure 1: Daily hot and cold cycle temperatures throughout the year

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.

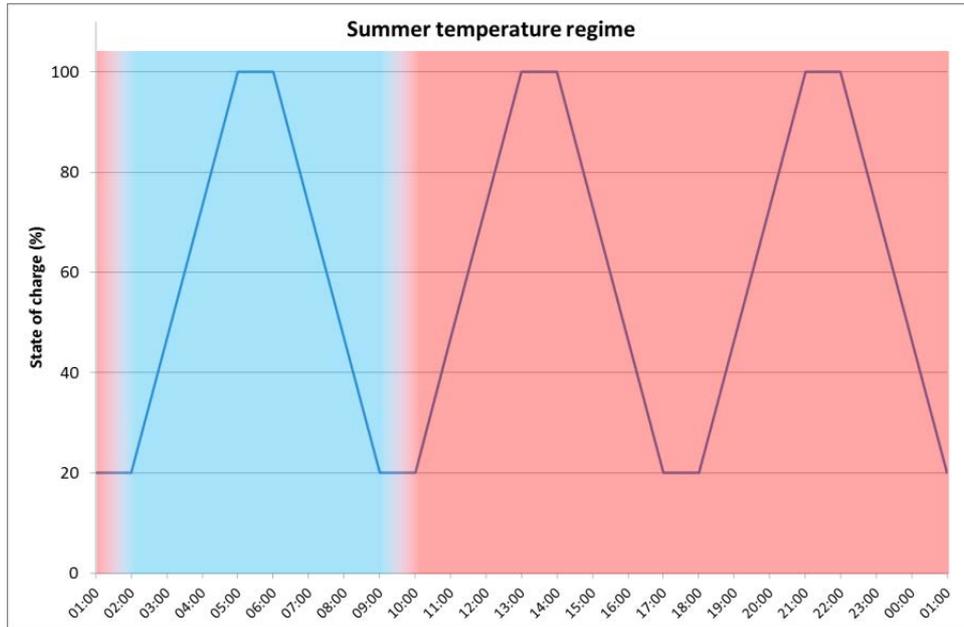


Figure 2: Summer temperature regime and charge regime

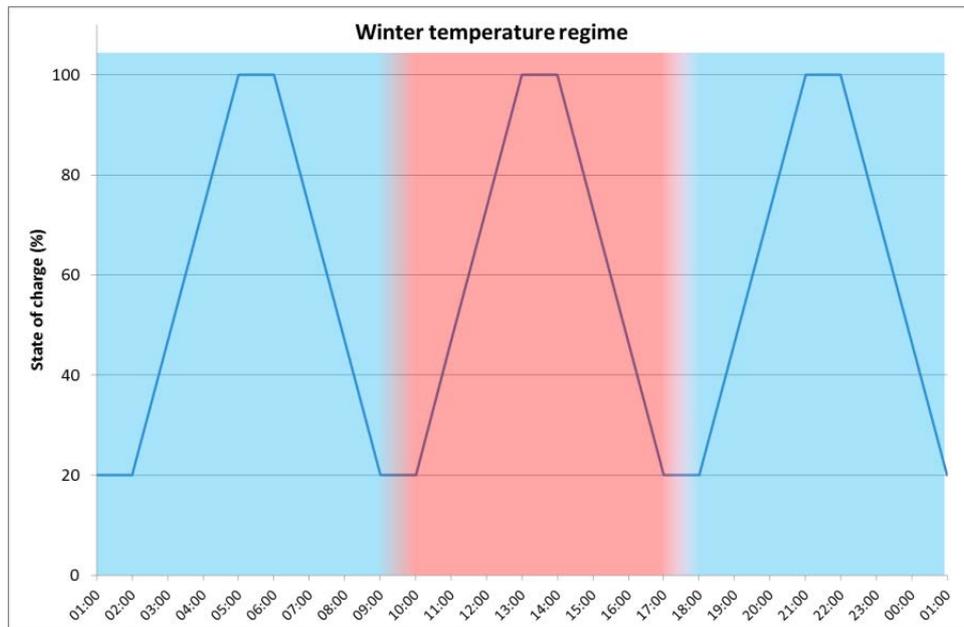
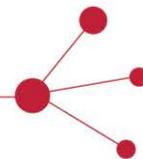


Figure 3: Winter temperature regime and charge regime

On the last day of each month, the batteries will 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, this will not make a statistically relevant difference to the results.



2. TESTING RESULTS

StoraXe Failure

In early November 2016, the StoraXe battery pack containing the Kokam battery cells and ADS-TEC BMS produced an error code indicating that the battery pack had entered a low voltage protection mode, whereby contacts on the BMS open to prevent the battery from further discharging.

ITP inspected the pack and measured a pack voltage of 44.6V. With no ability to manually close the contacts and allow the inverter to charge the battery pack, the manufacturer advised that the battery pack would have to be charged manually using a constant 50V_{DC} voltage source (max 20A current), until the charge current decayed to 5A. ITP was also advised that the cells would not discharge further, and the system could be left online to allow for remote diagnostics by the manufacturer.

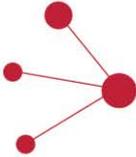
When ITP arrived to site to manually charge the pack the following week, the pack voltage had fallen from 44.6V to 6.8V. Once lithium-ion cells fall below their minimum voltage they cannot be recharged, and to do so risks a short-circuit occurring across battery electrodes. Hence, once this occurred, there was no possibility of reviving the battery pack. It appears that over the week, re-energising the BMS (to allow for remote diagnostics) drained the remaining energy from the cells, causing them to discharge into an under-voltage states. ITP are in discussions with Kokam and ADS-TEC about possible remedies/warranty claims etc.

Data Assessment

Accurate SOC estimation is crucial for operation of both lead-acid and lithium-ion batteries. In the latter case, over- or under-estimation of SOC can lead to battery failure as both over voltage and under voltage conditions can destroy battery cells.

When conducting capacity tests on integrated (ie. battery + BMS) lithium-ion battery packs, the capacity available is determined both by the electrochemistry of the cells, but also by the algorithms of the BMS. The BMS translates cell/pack voltage into a SOC estimate (based on any combination of temperature, current, nominal capacity, historical capacity, coulomb counting, etc.) to maximise the energy capacity available, while protecting against over/under voltage. Nevertheless, because the reported SOC is only an estimate, on any given capacity test the capacity available can vary, distorting the results.

ITP has found that SOC estimation appears stable and precise (ie. resolution of 1%) for the Samsung, LG Chem, and Sony battery packs, but not for the Tesla pack, nor for the CALB cells integrated with the REC BMS.



The Tesla Powerwall shows relatively low SOC resolution (ie. $\pm 3\%$) and, moreover, the SOC tends to drop significantly when the battery is loaded. It is normal for the voltage of a battery cell/ pack to fall when it is put under load, but the BMS should allow for this loading in their SOC estimation. From the data collected, it is unclear if the Powerwall is doing so. In any case, capacity and efficiency results are consistent and as expected, and ITP is confident that the Tesla data collected is representative.

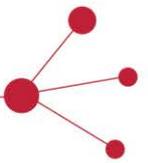
Capacity and efficiency data collected from the capacity tests of the EcoUlt advanced lead-acid battery pack are consistent between months except for results from December 2016. The December test cycle shows significantly higher efficiency and capacity than for any other month. Inspecting the test cycle more closely shows that the SOC adjusts upwards by $\sim 5\%$ during discharge. The resulting capacity and efficiency results for this month are outliers and have been excluded from the charts below. Data from the other months is consistent and as expected, and hence ITP is confident that the EcoUlt data provided below is representative. This is not the case for the CALB data collected. Analysing the capacity test cycles in detail shows the CALB pack 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 discharge and charge cycles can be seen to fluctuate 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.

CALB pack behaviour was also erratic during commissioning, and ITP identified a weak cell with low capacity and high internal resistance that had to be replaced under warranty. Following the replacement, pack behaviour returned to normal through August and September, but issues appear to have developed shortly after. The pack currently still operates acceptably, the issues described above impact the variability and reliability of the test cycle data collected, and for this reason the data has been excluded from the charts below.

No data is provided for the Tesla Powerwall in September due to the late arrival of the unit and subsequent issues limiting the charge/discharge rate. In October, no data is provided because the unit had entered a low voltage protection mode which ultimately required a technician to visit the site and force charge the battery. No data is provided for the GNB (conventional lead-acid) battery in September owing to issues integrating an equalisation charge into the cycling regime. This resulted in uncalibrated and hence inaccurate SOC estimation, meaning efficiency and capacity test results were not meaningful.

Generally, efficiency data shows greater variance than capacity results due to the compounding effect of SOC estimation inaccuracy on both the charge and discharge cycle.

The results derived from data collected from both the shunts at the battery pack, and from the inverters themselves are presented below.



Capacity Fade Analysis

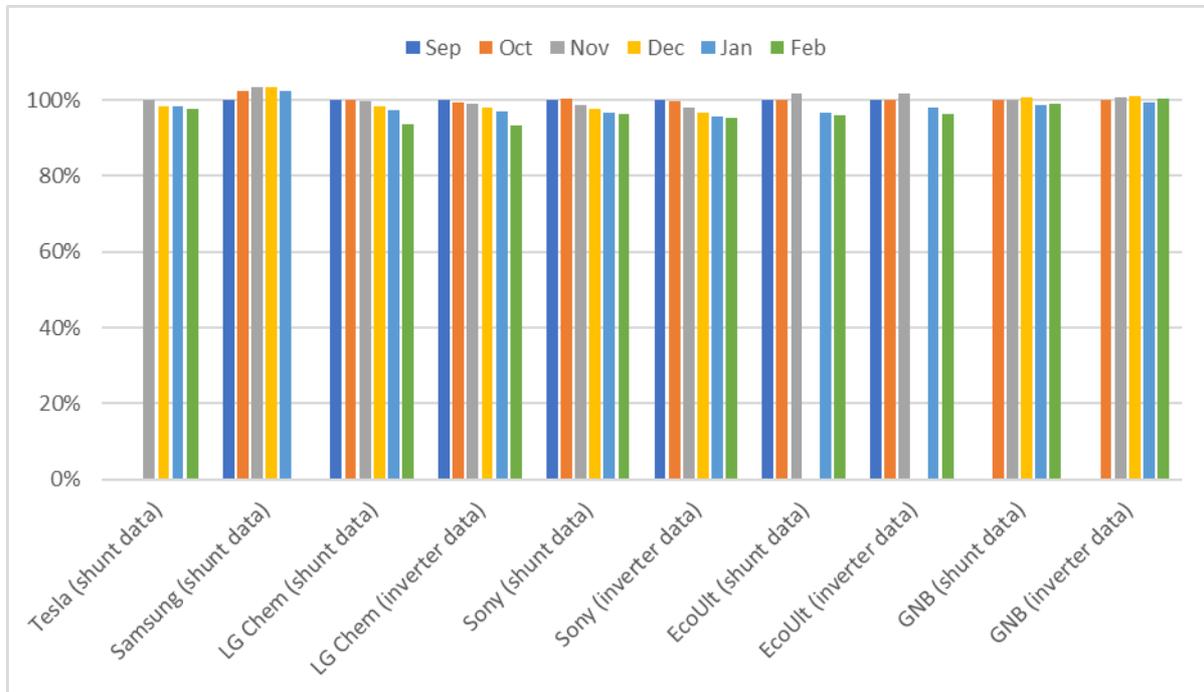


Figure 4. Measured discharge capacity relative to first-month measured discharge capacity

From the capacity test data collected thus far, the Tesla, Sony, and LG Chem packs (lithium-ion) demonstrate appreciable capacity fade (**Error! Reference source not found.**). The long-term trends for the Samsung (lithium-ion), EcoUlt (advanced lead-acid) and GNB (conventional lead-acid) packs are more difficult to discern.

In the case of the Samsung pack, capacity appears to increase initially, with the final month suggesting future capacity fade.

While no appreciable capacity fade is evident for the two lead-acid technologies, it should be noted that each has completed considerably less equivalent full cycles than the lithium-ion packs over the same period, owing to the narrower allowable depth-of-discharge window.

Capacity fade will be normalised against cycle count in subsequent reports, when longer-term trends are more apparent.

Efficiency Analysis

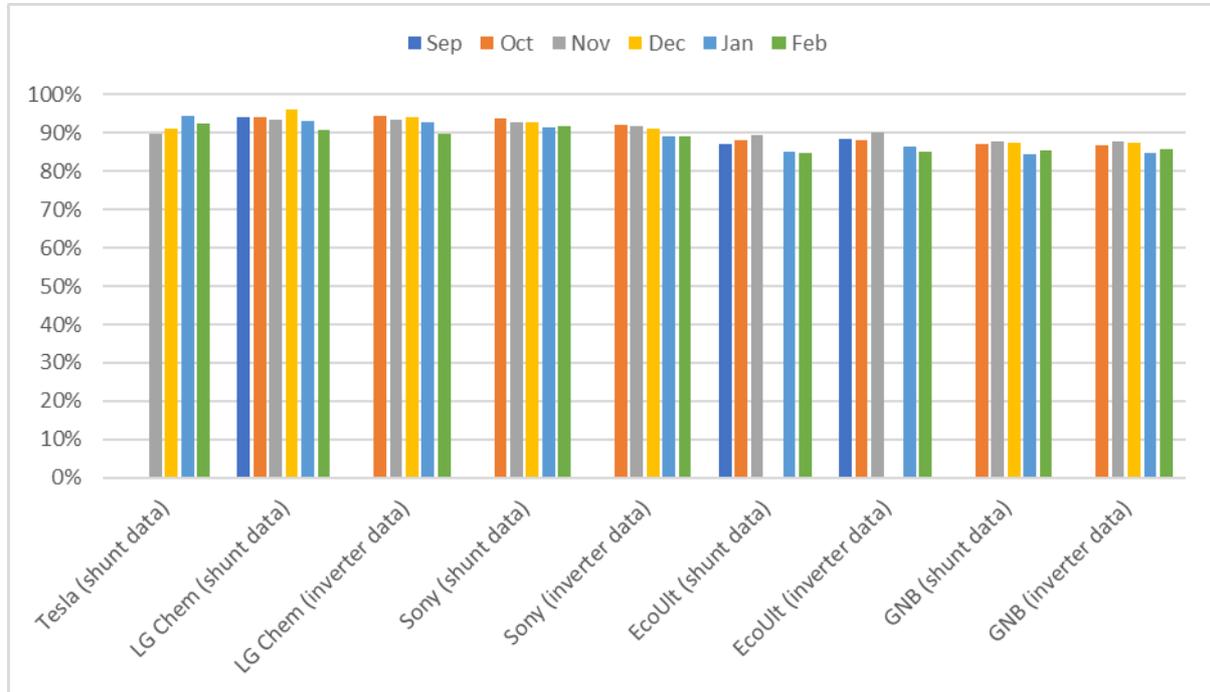
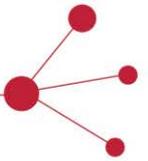


Figure 5. Measured discharge capacity relative to measured charge capacity

Thus far it is possible to observe generally higher lithium-ion efficiency than advanced lead-acid efficiency, and slightly higher advanced lead-acid efficiency than conventional lead-acid efficiency. Efficiency data for the Samsung pack requires further validation before publishing, and will be included in the next report.



Charge Acceptance Analysis

As per manufacturer recommendations, the traditional lead-acid battery (i.e. GNB VRLA gel) is operated between 50-100% SOC, while the advanced lead-acid (i.e. EcoUlt lead-carbon) is operated between 30-80% SOC. The state of charge and power input/output over a discharge and charge cycle for select batteries are shown in Figure 6 below.

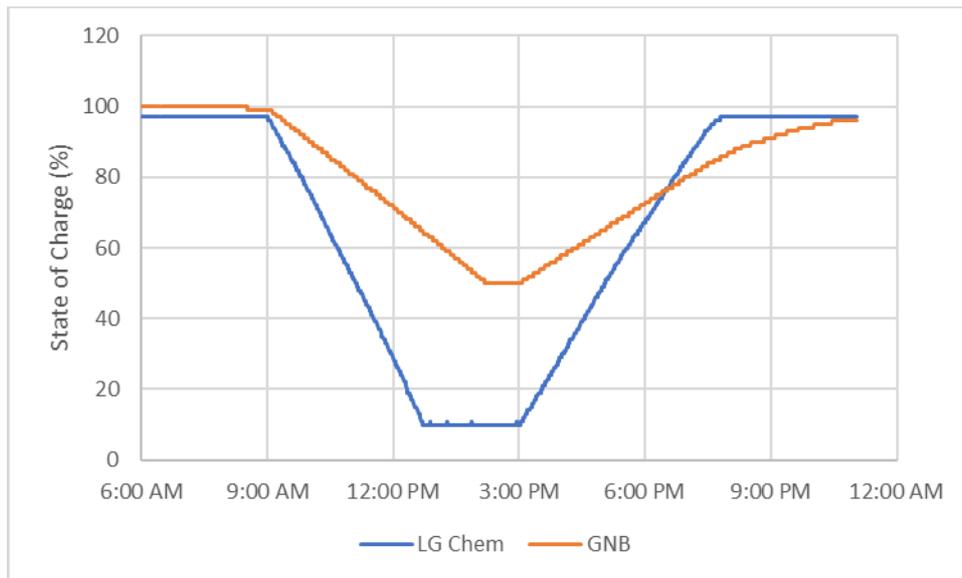


Figure 6. Battery pack SOC throughout a full discharge and charge

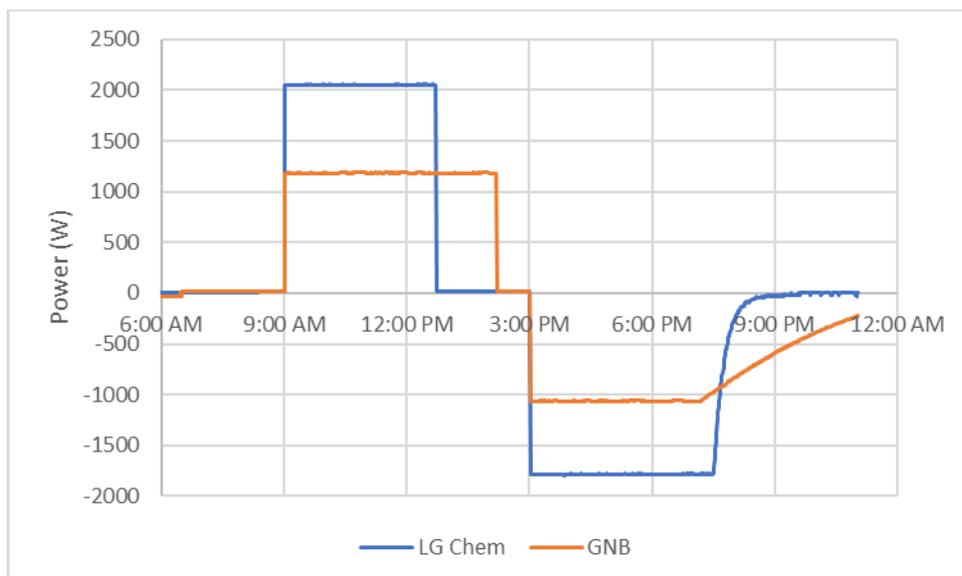
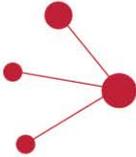


Figure 7. Battery power throughout a full discharge and charge

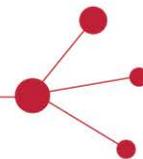
The curved sections of the SOC and power curves depict the “absorption charging” phase, where the maximum pack voltage setpoint has been reached and must thereafter be held constant for



the remainder of the charge cycle. The charge current decreases toward zero once this point is reached, meaning that the final absorption stage of the charge proceeds slower than the earlier “bulk” charging phase. In the case of conventional lead-acid batteries, a regular complete absorption charge is nevertheless crucial to avoid sulphation and ensure battery longevity, and a periodic “equalisation” charge is required to dissolve any sulphation that has occurred. The necessity of this charge takes the battery out of service, and also has an energy cost as the equalising charge is highly inefficient.

Lithium-ion batteries do not require a regular complete absorption charge, or an equalisation charge, though a full charge allows for cell balancing and potentially SOC calibration.

While the advanced lead-acid battery does require a periodic equalisation charge, the frequency of this charge is reduced compared to a conventional lead-acid battery, and regular complete absorption charges are not necessary.



3. LESSONS LEARNED

Capacity Fade

Capacity fade is evident for some of the battery packs under test, as expected. However, for others, the trends are not yet discernible owing to the inherent variability in capacity testing results. In particular, this variability arises because of imprecision in the SOC estimation conducted by the BMS of some packs. The real trends will become clearer as time goes on.

From the data collected thus far, capacity fade is noticeably highest for the battery with the highest average temperature (the LG Chem pack). High cell temperatures increase the rate of irreversible side reactions within cells. These reactions consume the “active” materials within the cells, reducing the available capacity.

The LG Chem battery has the highest energy density of all the packs under test, and has no fans or coolant loops to assist with heat dissipation. While lab temperatures reflect expected real world ambient temperatures, the cycling regime is necessarily much more aggressive. Hence, the battery pack is unable to dissipate the heat generated as quickly as the other packs under test. This causes the higher cell temperatures and likely explains the apparent capacity fade rate.

Efficiency

Despite the limited data, already it can be seen that lithium-ion out-performs both the advanced and traditional 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 >90% can be expected for either Li-ion NMC or Li-ion LFP chemistries, and it is possible that a 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.

Charge Acceptance

A shorter absorption charge phase for the lithium-ion and advanced lead-acid battery packs has been demonstrated. This results in faster charging overall, a key operational advantage over the traditional lead-acid battery.

4. MARKET PROGRESS

Since commissioning of the batteries in the test centre, the residential lithium-ion battery market has changed significantly. In particular, market leaders Tesla and LG Chem have aggressively cut wholesale battery pack pricing, as well as introducing second generation battery packs:

- LG Chem's second generation RESU is available in five models: 48V packs available in capacities of 3.3, 6.5, or 9.8kWh; and 400V packs available in 7.0 or 9.8kWh capacity. Two 48V packs can be paralleled to allow for additional energy capacity (although power capacity only increases to a maximum of 5kW). Compared to the first generation model, the new RESU offers higher energy density and greater ability to tailor the total energy capacity. The 400V version is also compatible with SMA's new grid-connected battery inverter, the Sunny Boy Storage, a significantly cheaper model than their off-grid Sunny Island inverter.
- Tesla's second generation Powerwall comes with an inbuilt battery inverter and increased energy capacity (13.5kWh, up from 6.4kWh). Energy density has improved significantly, while the cost of installation is expected to be far lower than for the first generation Powerwall, which was time-consuming and costly to install.

On the other hand, both Samsung and Sony have withdrawn their residential energy storage products from the Australian market. This is consistent with the rapid rate of change in the market.

The rapid fall in lithium-ion battery prices has been driven largely by Tesla's price-leading, which has opened up many new applications for lithium-ion storage and generally raised the profile of the technology. Production volumes have had to increase rapidly to meet this increased demand and, despite supply constraints on cobalt globally, continuing price decreases can be expected over the coming years.

As lead-acid batteries are an established technology, the price has remained stable for a number of years, with fluctuations linked primarily to the prevailing cost of commodity lead.



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

itpau.com.au

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