Comparison of lithium–ion battery cell technologies applied in regenerative braking system

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Abstract

This research presents the performance evaluation of four various type of top-of-the-line commercial and prototype lithium-ion energy storage technologies with an objective to find out the optimal cell technology which is suitable for the development of high power battery packs for regenerative braking system applied in next-generation demonstrator platform vehicles. The novel porotype lithium ion cell technology is developed using linear combined nanofibers and microfibers battery separators laden utilising wet nonwoven processes compared to the dry process laden multilayered porous film separators in commercial cell technologies. The performance comparison of all technologies has been conducted both at 'cell-level' and 'pack level' through the study of internal performance parameters such as capacity, resistance, self-discharge and battery temperature rise. This study also encompasses the differences in using external pack assembly and/or development parameters like the number of cells which are required to develop the pack, pack mass, pack volume and pack cost. Both the internal performance parameters and external pack assembly and development parameters have revealed that novel prototype cell technology is the most optimal technology amongst all four cell technologies for regenerative braking system which have been investigated during this research. The novelty of this work is the development of novel prototype cell technology and its performance comparison with commercially available cell technologies used in regenerative braking system of latest Hybrid /Electric Vehicles which is in-line with the global initiatives such as UK/EU transition to EVs, and UN sustainability goals. The significance of this work in terms of high-power pack development for regenerative braking of next generation vehicles is evident from various industrial applications. This work will influence decisions for both battery testing techniques and accurate battery comparison methods to automotive, locomotive, aerospace, battery manufacturers and wind turbine industries.

Keywords: Lithium ion batteries; High power cells; Performance comparison; Battery testing; Regenerative Braking System

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1. Introduction

Lithium ion battery manufacturers around the globe use various techniques to improve the performance of batteries in terms of power, energy, storage losses and extended useful temperature range [1]. This is achieved by either enhancing the quality of electrolyte additives, improving the materials chemistry of cell-electrodes and/or oxidation-reduction (redox) reactions [2-4]. Therefore, the performance of lithium ion batteries directly relates to their internal chemistry.

Latest lithium ion batteries age due to continuous cycling, high current operation and self-discharge when sat idle for longer durations [5, 6]. One key reason for aging is internal capacity loss and internal resistance increase [7]. In addition to above aging factor, another factor like pack assembly/development, greatly influences important performance parameters like life-time, cyclability, safety and – most of all – cost [8-15].

The project requirement was the development of high-power battery pack for regenerative braking system (RBS) intended to integrate with the next-generation demonstrator platform vehicle for our lead partner. In the past few years, a lot of research has been conducted in the failures analyses of materials used in electrochemical battery cells [16-37]. In this project, comparison of several competing lithium-based technologies at both cell and pack level was performed. This involved the comparison of four different types of top-of-the-line commercial and prototype lithium cells manufactured by world-leading battery manufacturers and then selecting the optimal cell technology for the development of the next-generation high power battery pack for RBS [38, 39]. The regenerative braking can improve energy usage efficiency and can also extend the driving distance of Hybrid /Electric Vehicles. This can improve the battery efficiency by 16-25%, depending on the speed and the motor size [40]. The power dissipated by the vehicles can be partially taken back for powering up for some of the utilities on board. Regenerative braking power generation could provide a remarkable power source for vehicles, but the amount of energy capture during braking considerably depends on the efficiency of lithium ion battery pack.

Comparison was conducted at both cell and pack level according to IEC 62660-1 standard test procedures and conditions to test bench mark performance characteristics of lithium-ion technology. The main performance parameters which characterise the lithium ion cell technology for their suitability in RBS involve internal parameters such as capacity, resistance, self-discharge and battery temperature rise which have been considered in this research [13, 41, 42]. In addition, the pack level comparison was also performed by first developing the packs using the respective cell technologies and then comparing their performance using various electrical tests. The performance of assembled packs significantly depends on external pack assembly/development parameters including series/parallel connections, number of cells used in assembly, weight, volume etc, which is the motive of performing pack level performance comparison in this research. The cost-effectiveness of the developed pack was also considered as a primary factor for selecting the optimised lithium ion cell technology.

RBS promises significant gains in town driving since 62.5% of energy is dissipated in the Metropolitan cycle due to frequent braking. If all brake energy could be regenerated with no loss in the regenerative system, fuel consumption would be improved by 33% [43, 44]. Alternative sources state that the addition of regenerative battery storage systems to motor vehicles can achieve theoretical fuel savings of up to 23% in a 1600 kg vehicle on a level road urban driving schedule [45, 46]. Therefore battery technology used in RBS should be very efficient in order to take large amount and rapid charge in a very short period. The novel prototype battery cell technology presented in this paper is capable of addressing these challenges.

This research has employed state-of-the-art techniques to develop a novel prototype pack. This newly developed prototype has major significance in essence that unlike the conventional battery, it is capable of taking a substantial charge (up to 50% of braking energy) very quickly when vehicle brakes are applied, in turn they can be charged at high currents (up to 600A per cell). This energy, which would have otherwise lost, is stored in the prototype pack and will be delivered back to the vehicle motors again, which will provide the energy to accelerate. Hence major energy recovery gains are to be made and will result in substantial cost savings and battery charging time. Such packs do not act as primary source of power; they only work in-combination with the other main energy source such as hydrogen fuel cells or Electric Vehicles batteries [47].

Therefore, the research goal was to compare the novel porotype cell technology with the commercially available cell technologies used in RBS to find the suitability of prototype cell technology for the high-power pack development, which is capable of taking huge charge in a very short period during regenerative braking of vehicles.

2. Test Procedures

2.1. Lithium ion Cells and Test Equipment

In this research a comparative performance analysis was conducted on three commercially available and one novel prototype high-power lithium ion cell technologies for sustainability in RBS. The three commercially available cell technologies are widely used in automotive sector for high power applications including RBS, while the prototype high power cell technology has been developed for RBS in super sports vehicles and is still in testing phase. In all four cell technologies, an insertion material coke-type carbon substance, graphite anode was used with Lithium cobalt oxides (LCO) as cathode material [48]. However, all these cells differ in the structure of the separator. The performance of lithium-ion batteries is greatly affected by structure of the separators [49]. The porotype cell presented in this paper used the wet process laden nonwoven nanofibers and microfibers separator [50, 51] while the commercially available cells used the dry process laden nanoporous multilayered separators [52, 53]. Many research articles have anlaysed that wet process laden non-woven mat separators perform better in high power batteries compered to dry process laden multilayered separators [54-56].

Following cell technologies based on separator types have been analysed in this research[1].

Commercially available cell technologies – utilise dry process multilayered porous film separators

- The 50Ah cells uses dry process laden multilayered polypropylene-based microporous separator [57],
- The 25Ah cells uses modified dry process laden multilayered polypropylene-based microporous separator [57],
- The 1.5Ah cells use a dry process laden multilayered microporous separator coated polypropylene (PP, Celgard 3501) and cellulose-based TF40-30 (NKK Nippon Kodoshi Corp., Japan) [58, 59]; and finally,

Prototype cell technology – utilise nonwoven processes mat separator

- The 4Ah cells utilises separator coated poly(viylidene fluoride) (PVDF) that apply novel nonwoven wet processes laden nanofiber technology and its precision stamping technologies [60]. This cell features a size and capacity comparable to that of above commercially cells and realises the same output density and durability as capacitors, which makes is a good candidate in the league of high power automotive cells.

[1] Due to commercial sensitivity and non-disclosure agreements (NDA), it is not possible to disclose the names of cell technology manufacturers.

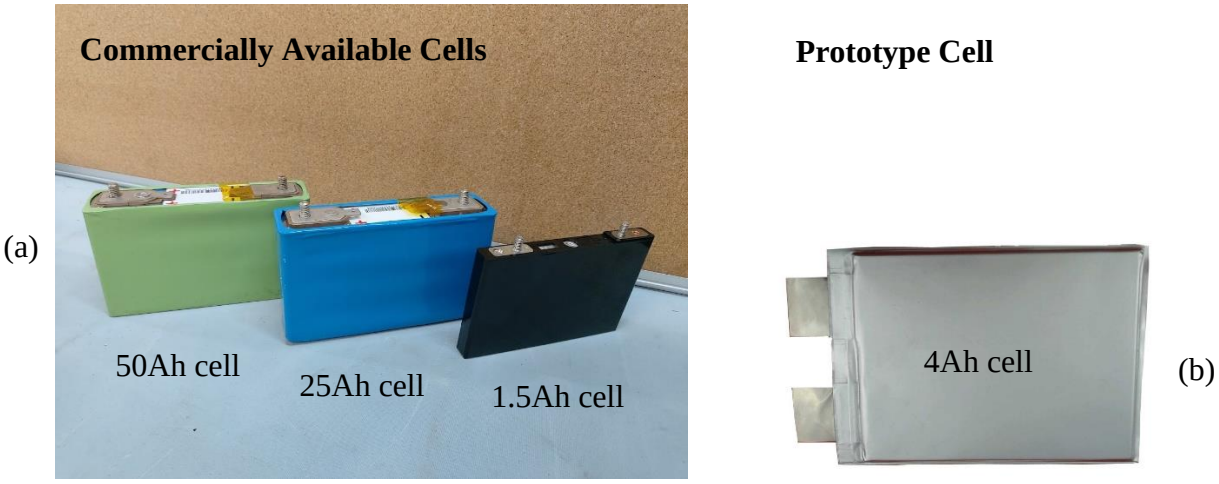


Figure 1. Commercially available cells Vs Prototype cell

Commercially available Vs Prototype cell technologies

In commercially available cell technologies, the stretched dry process laden multilayered porous film separators are thin, strong, and provide a good barrier between electrodes, but at the cost of having very high internal resistance and low ionic flow due to low porosity and high "dead space" that come from starting with a solid material and trying to impart porosity thereby resulting in cell power loss [61]. The prototype cell technology uses an alternative approach, where linear nanofibers and microfibers are combined in wet laid nonwoven processes to give separators that are strong and thin, but have higher porosity (60-70%) and so have much higher ionic flow. Fig. 2 shows SEM images of separators extracted from fresh cells, clearly showing the porosity differences between the dry process laden multilayered and nonwoven wet process laden separators from fresh cells.

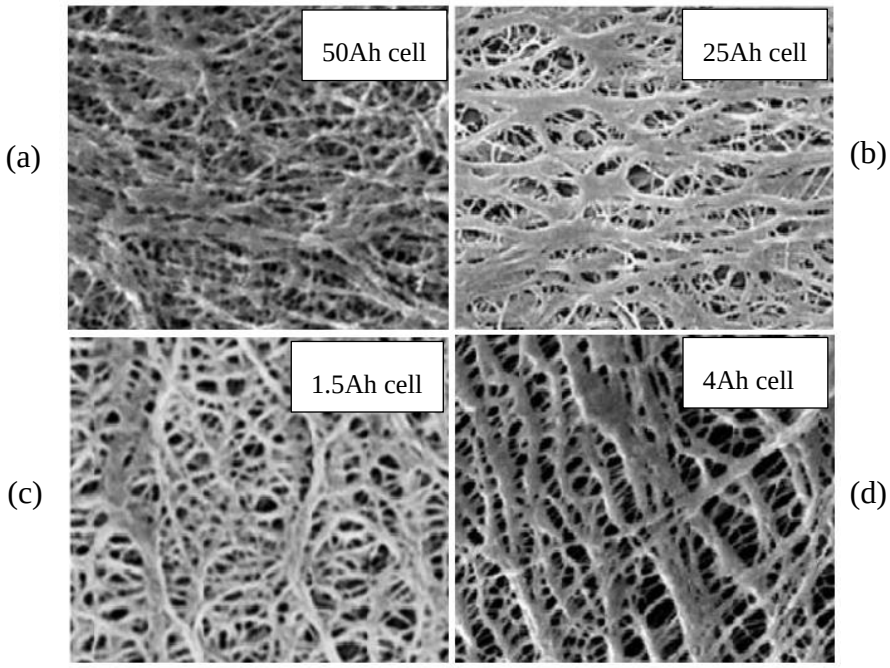


Figure 2. The schematic showing SEM images of separators extracted from fresh dry process laden commercially available (a) 50Ah cell (b) 25Ah cell (c) 1.5 Ah cell, and fresh nonwoven wet process laden novel prototype (d) 4 Ah cell.

The specifications of four cells are shown in Table 1. The focus of this research is on performance comparison of above cell technologies using electrical testing, check the suitability of prototype cell, and find the best technology for pack development for RBS application, however, the in-detailed manufacturing details of porotype cell can be found in ref [62].

Table 1. Tables of specifications for 50Ah, 25Ah, 1.5Ah and 4Ah cells

Cell Specification					
Cell Technology:		**50Ah**	**25Ah**	**1.5Ah**	**4Ah**
Cell Availability		Commercially Available Cells			Prototype Cell
Format:		Prismatic	Prismatic	Prismatic	Pouch
Type:		Power/Energy	Power	Power	Power
Cell Chemistry:		LCO	LCO	LCO	LCO
Rated Capacity:	C_0Ah	50	25	1.5	4
Maximum Charge Voltage:	V_{max} V	4.1	4.15	3.8	4.2
Minimum Discharge Voltage:	V_{min} V	2.75	2.75	2.2	2.7
Minimum Operating Temperature:	T_{min} ^oC	-20	-30	-30	25
Maximum Operating Temperature:	T_{max} ^oC	60	60	70	75
Maximum Rated Charging Current:	$I_{chrg,max}$ A	125	600	600	600
Maximum Rated Discharge Current:	$I_{dchrg,max}$ A	300	600	600	600
Weight:	Kg	1.65	1.65	0.32	0.27
Dimensions:	mm	171 x 44 x 111	171 x 44 x 111	180 x 10.9 x 126	160 x 6.4 x 257

From here onwards, we will refer to the cells by their respective Amp-hours (Ah) ratings for example, a cell with capacity of 50Ah will be referred as 50Ah cell.

2.1.1. Preparations for cell level testing

A Bitrode MCV EV/HEV battery cell tester (Bitrode Corporation, St. Louis, USA) [63] test bench was used for cells testing as shown in Fig. 3 (a). It provides eight channels with current and voltage ranges from 1 µA-2400 A and 0-18 V respectively with accuracy of ±0.1 % full-scale. The above cells were installed in environmental chamber as shown in Fig. 3 (b). The test conditions were controlled using VisualCN software (Fig. 3 (c)) which was also used to constantly monitor the performance, which was linked with Bitrode MCV EV/HEV battery cell tester. For cell level testing, no battery management system (BMS) was used, rather, current and voltage readings were directly taken from the terminal leads attached to cells terminal, and PT100 temperature sensors installed on terminal measured the cells temperature. These measurements were fed in to Bitrode which eventually controlled the charging/ discharging of cells, while keeping the cells within safe operating limits. For prismatic cells, clamping device was used to keep cells upright (Fig. 4 (a-c)) while for pouch cells, a specialised jig was set-up to safely assemble cells on to the jig before they were installed in chamber (Fig. 4 (d)).

Figure 3. The schematic showing (a) a Bitrode MCV EV/HEV battery cell tester (b) an environmental chamber for performing cell testing under controlled conditions (c) VisualCN software for controlling test conditions and constantly monitoring the performance of cells.

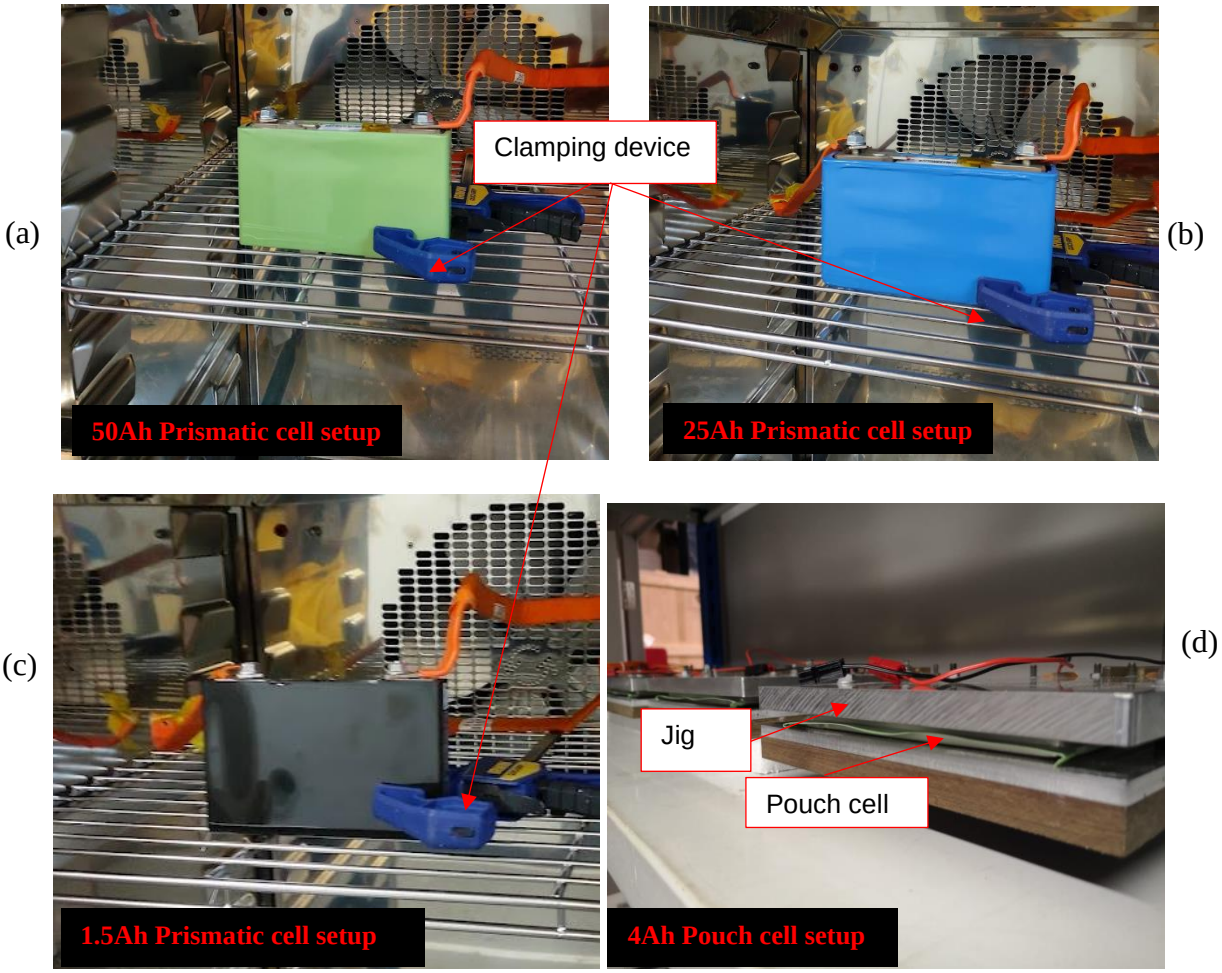


Figure 4. The schematics showing the installed (a) 1.5Ah prismatic cell and (b) 4Ah pouch cell on a specialised jig installed inside environmental chamber connected to Bitrode MCV EV/HEV battery cell tester for cell level testing.

2.1.2. Preparations for pack level testing

For pack level tests, the pack configuration of assembled packs from various cell technologies was based on the pack requirements from our project lead partner i.e. Pack capacity = 0.67kWh (=2.4MJ), $V_{min(pack)}$ = 70V, $V_{max(pack)}$ = 120V. To address these pack requirements, the pack configuration for 25Ah cell was set as 1p x 30s, for 4Ah cell as 2p x 30s, and for 1.5Ah cell as 4p x 30s. For illustration, 25Ah (1p x 30s), 1.5Ah (4p x 30s) and 4Ah (2p x 30s) 0.67KWh packs are shown in fig. 5.

In pack assembly, the stiffness of the prismatic cells is regarded as better compered to pouch cells, which is produced with the help of a flat winding, and then inserted into a solid housing. However with the pouch cell, the stiffness is not given by the pouch foil and must be supplemented with a frame when inserted into the pack casing. The cells are stored in a casing to provide them mechanical support. The pack casing is made of aluminium. Furthermore, the cells are connected on the tabs by busbars, made of aluiminum. For temperature, PT100 sensors are applied on to the tabs of cells. Unlike cell level testing, for pack level tests, each battery pack had its individual battery management system (REAP BMS) which was responsible for opening and closing of contactors during charging/discharging and looking after battery's overall safe performance including temperature, current and voltage levels. The pack performance during testing was constantly monitored by Bitrode MCV VisualCN software using controller area network (CAN) messages from BMS.

In this research, for thermal management, no cooling method was introduced in pack assembly, which is a part of our forth-coming study.

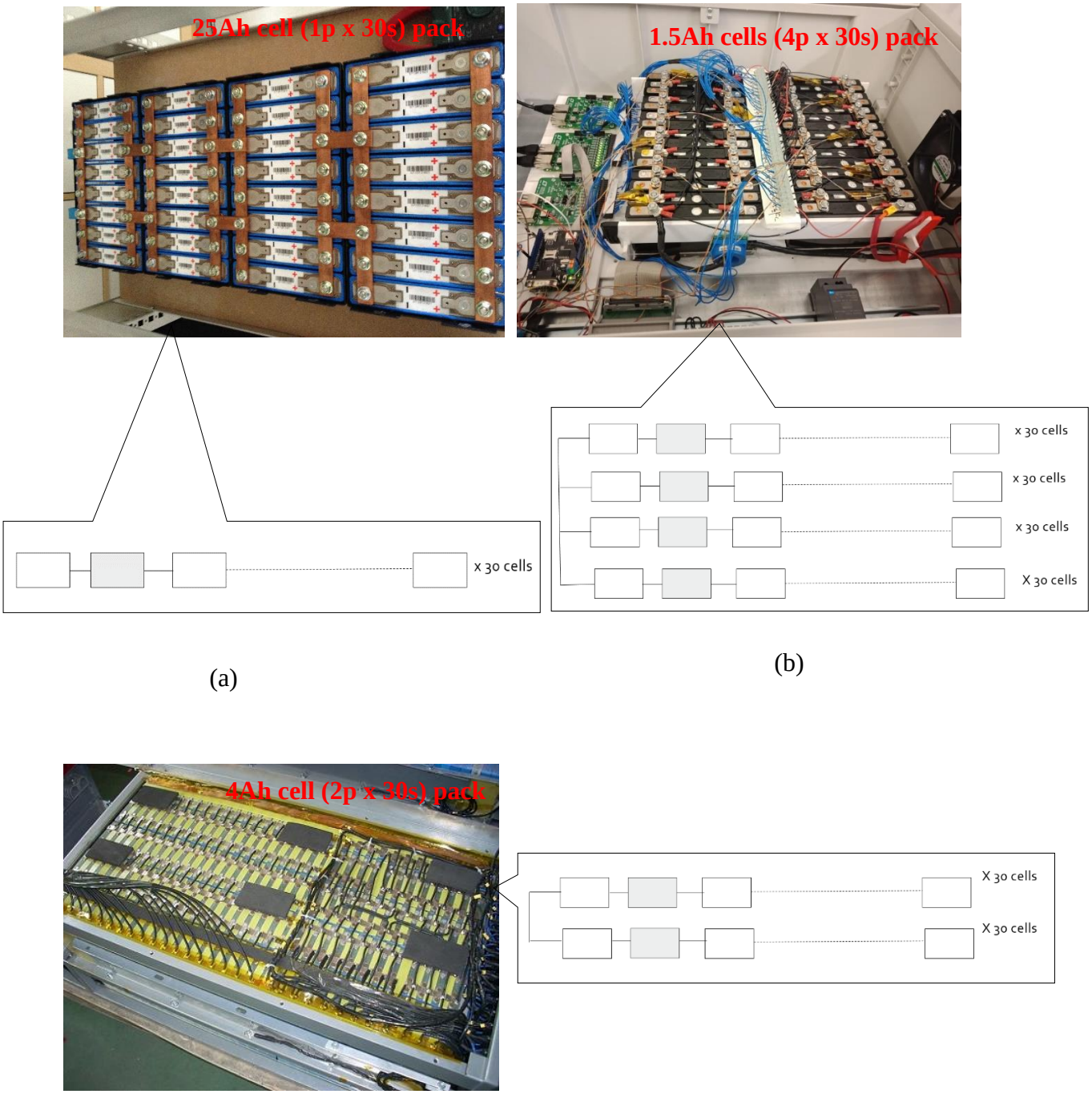


Figure 5. Schematics showing 0.67kWh packs assembled using (a) 25Ah cell (1p x 30s) (b) 1.5Ah cells (4p x 30s) and (c) 4Ah cells (2p x 30s) for pack level testing.

2.2. Test Methodology

In total, six types of tests were performed to compare the performance of four cell technologies. All these tests followed the international standard IEC 62660-1 procedures [64]. The C-rate/ current rating and temperatures

corresponding to each test is mentioned in Table 2. Furthermore, for repeatability, all six tests were repeated three times each to ensure the accuracy of results.

The hierarchy in which tests were performed is shown in Table 2. This table clearly indicates that Test 1 to 3 were performed at cell level while tests 4 to 6 were performed at pack level. The tests included cell level capacity retention, cell level High Power Pulse Characterisation (HPPC), cell level self-discharge test 3, pack level capacity retention test 4, pack level cyclic ageing test 5, and finally pack level real world drive cycles test 6.

Table 2. List of tests performed with their corresponding test conditions

		Type of Testing	**C-rates /Current**	**Temperature Set**
Cell Level Tests	**Test 1**	Cell Level Capacity Retention	1C, 4C, MaxC	25 ℃
	Test 2	Cell Level High Power Pulse Characterisation (HPPC)	100A constant discharge current	25 ℃
	Test 3	Cell Level Self-Discharge	-	25 ℃ and 45 ℃
Pack Level Tests	**Test 4**	Pack Level Capacity Retention	200A, 600A constant charge-discharge current	25 ℃
	Test 5	Pack Level Cyclic Ageing	50A constant continuous reference cycles	25 ℃
	Test 6	Pack Level Real World Drive Cycles	Continuous varying power as per drive cycle profile. Profiles max power during charging: 1800W Profiles max power during discharging: 2100W	25 ℃

The tests were performed in a fashion to sequentially filter the best cell technology suitable for high power applications. The horizontal filtration chart is shown in Fig. 6 illustrating the hierarchy in which cells were filtered out during testing. The chart explains the test hierarchy for filtration of cells.

It can be seen in Fig. 6 that test 1 was performed on all four cell technologies. The results from test 1 were compared to filter the cell technologies which can go for further testing. Three out of four cells were filtered for the next tests 2 and 3. The tests 2 and 3 were performed to compare the cell level performance of three respective filtered cells while the test 4 was performed to compare the pack level performance of three filtered cells. For pack level performance in test 4, three packs each 0.67KWh (packs energy calculations already discussed) were developed using three respective filtered cells. The reason for comparing pack level performance of three cell technologies in test 4 was to get the clarity on pack level performance of all three cell technologies before further filtration. After pack level performance test 4, two out of three cell technologies were filtered for further test 5. The test 5 revealed the best fit cell technology which was finally subjected to real world drive scenario in test 6.

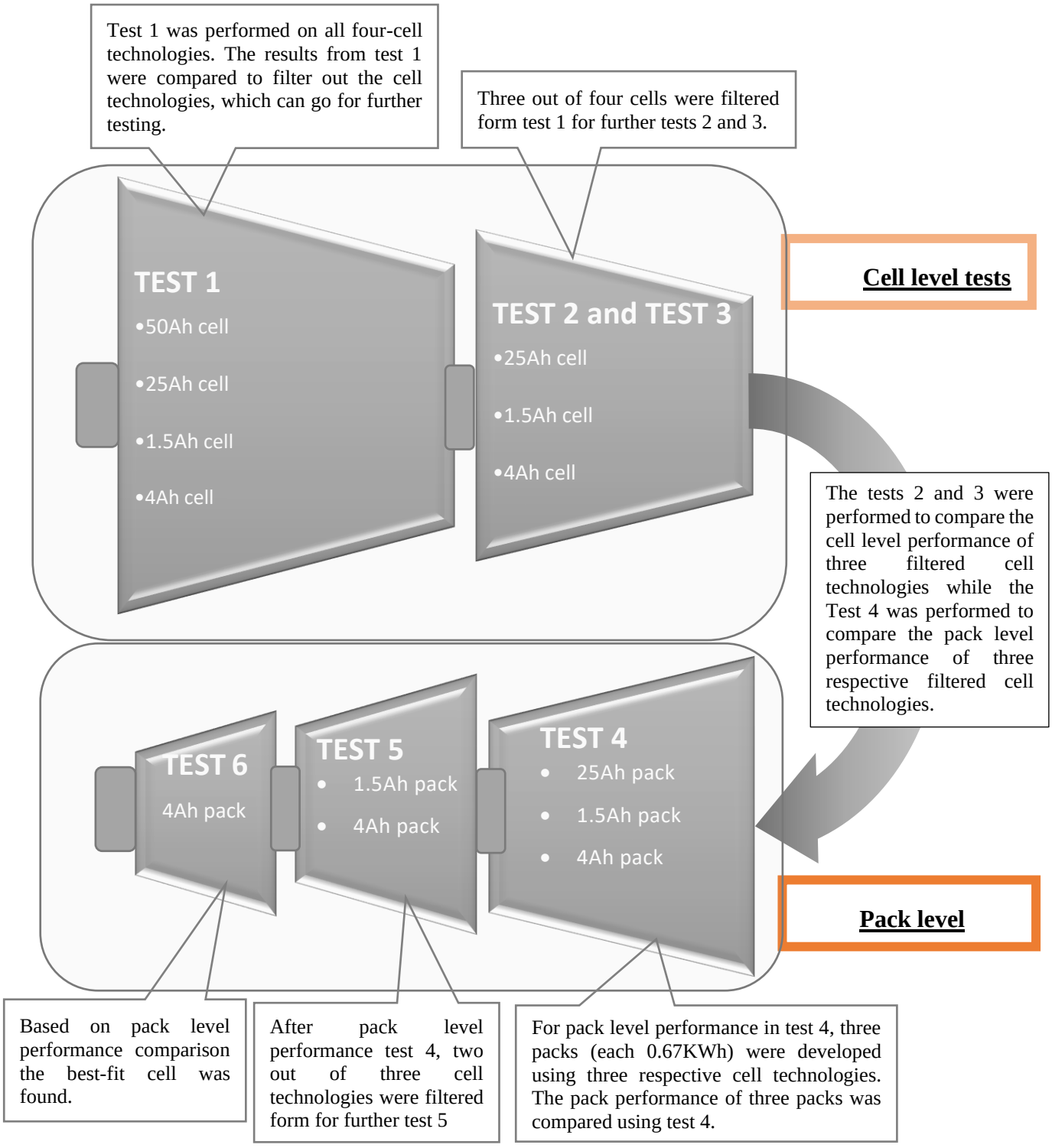


Figure 6. Horizontal filtration chart showing test procedure performed in a fashion to sequentially filter out the best cell technology suitable for high power applications.

2.2.1. Cell Level Tests

The cell level capacity retention test 1: was performed to determine an accurate and comparable capacity retained by cells at 25ºC when they were cycled for 5000 reference cycles at various C-rates i.e. 1C, 4C and MaxC [65]. Where one reference cycle indicates a complete chare-discharge cycle and MaxC indicates the maximum rated

charge $I_{chrg,max}$ and discharge $I_{dchrg,Max}$ currents of cells as mentioned in Table 1. Such that for various C-rates during charge cycle, the constant current charged the cells up to V_{max}, and maintained constant voltage of V_{max} until the current ramped down to 0.05 x Rated Capacity (in Ah). Likewise, during discharge cycle, the constant current discharged the cells to V_{min} and maintained constant V_{min} until the current ramped up to 0.05 x Rated Capacity. There was a rest time of 1 hour in between charge and discharge cycles to allow cells to return to electrochemical & thermal equilibrium condition. To observe rise in temperature of all four cell technologies as a function of reference cycles, a special constant current capacity test was designed with charge-discharge cycles at constant 100A current corresponding to reference cycles. The reason for constant current capacity test was to make a fair comparison between cells to address temperature rise. The cycles were repeated three times.

The cell level High Power Pulse Characterisation (HPPC) test 2: was performed to determine the internal DC resistance and dynamic power capability of cells at various SOC's (from 100% SOC to 20% SOC) at 25ºC. In HPPC test, single repetitions of profile separated by 20% SOC constant discharge segments, each followed by ½ hour rest period were performed [66]. The test initially started from 100% SOC and ended after completing the final profile at 20% SOC, and final ½ hour rest. The pulse tests was designed to estimate the DC internal resistance of the cells at a given temperature and SOC.

The cell level self-discharge test 3: was performed at 25ºC and 45ºC to validate the capacity loss of cells independent of charge-discharge cycling i.e. under long term storage condition [67]. Before going to storage conditions, the candidate cells were fully charged to 100% SOC at 1C. The cells were then stored in an open-circuit condition for 3 months in pre-conditioned environmental chambers to 25ºC and 45ºC. The voltage and temperature values during storage time were continuously logged to dataTaker DT85 smart data logger equipment [68] with sampling rate of 3 minutes/sample. All measurement devices except data logger were disconnected from the cells during this period to reduce parasitic losses.

2.2.2. Pack Level Tests

The pack level capacity retention test 4: was performed on 0.67KWh packs in which pack level capacity performance comparison of cell technologies was simulated for two constant current scenarios: i.e. at 200A and 600A. The pack capacity retention was demonstrated in terms of the ability of pack to retain stored energy at above-mentioned two current levels. The reason for selecting 200A and 600A currents being that in hybrid electric vehicle's regenerative braking system, the 200A relates to energy captured in pack under normal braking while 600A relates to energy captured under extreme braking for example when going downhill. The pack level test followed the standard capacity test procedure with charge-discharge cycles and 1-hour rest in between both cycles.

The pack level cyclic ageing test 5: was performed to determine cells capacity loss, temperature rise and internal DC resistance increase over repeated standardised cycles until the criteria for end of life was reached; namely a capacity loss of 20% and/or a resistance rise of 100% [69]. The charge-discharge cycle was conducted at 4C and repeated for 6000 reference cycles at 25ºC without rest between charge and discharge. Internal DC resistance of cells was calculated using capacity loss, voltage drop and OCV [70].

The pack level real-world drive cycle test 6: was performed to validate the performance of candidate cell technologies against a real-world drive cycle profile, specific to the intended application for example in-city charge-discharge automotive cycle [71]. The profile was pack power in Watts and was repeated 3 times continuously. This test was specially designed to analyse the rise in temperature of packs subjected to continuous real-world profile.

For all tests, the raw data from Bitrode was logged in excel format and further analysis was performed using MATLAB program to extract and plot the required useful information.

3. Results and Discussion

3.1. Test 1 - The cell level capacity retention

Fig. 7 shows that the charge data capacity loss is significantly dependent on the charge rate. At high constant-current C-rates, the capacity loss was considerably higher than for low C-rates. The loss in cells capacity during charging phase of total 5000 reference cycles showed that as the current for respective cell technology was increased from 1C to MaxC there was significant loss of capacity for all cell technologies. Where values for MaxC current during charging and discharging for all four cell technologies is shown in Table 1 across maximum rated

charging current $I_{chrg,max}$, and maximum rated discharging current $I_{dchrg,max}$ respectively. The maximum loss in capacity was observed for 50Ah cell (95%) followed by 25Ah (92%), 4Ah (85%) and 1.5Ah (44%) cells.

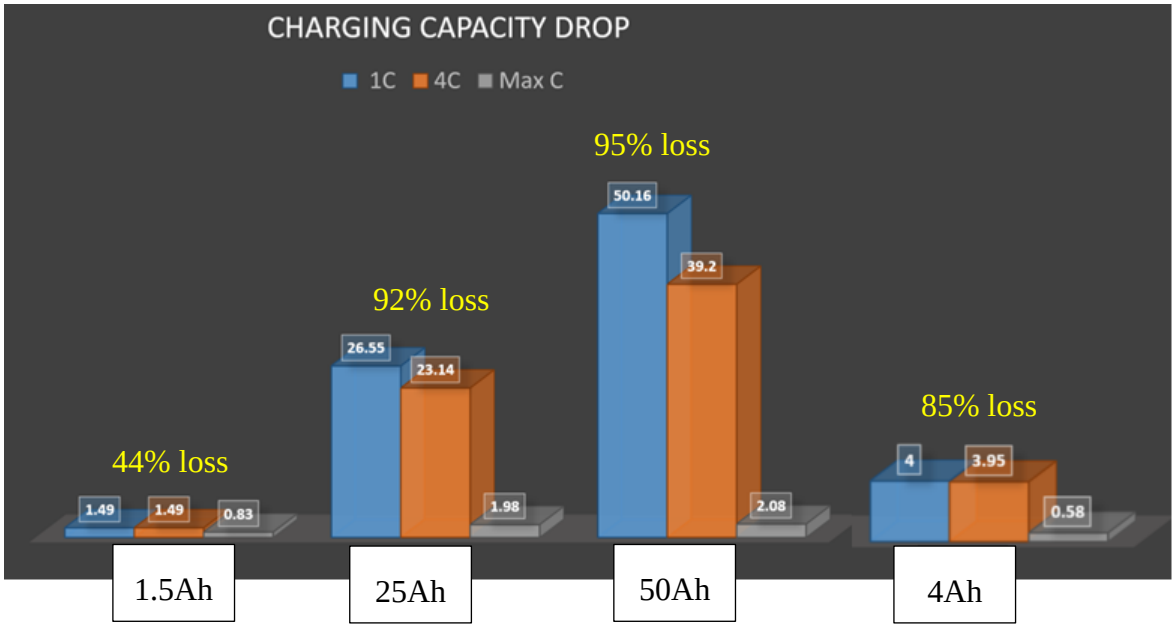


Fig. 7. The loss in capacity at 1C, 4C and MaxC for various cells during charging phase

Likewise during the discharging phase, the maximum loss in capacity was observed for 50Ah cell (90%) followed by 25Ah (90%), 4Ah (79%) and 1.5Ah (40%) cells as shown in fig.8.

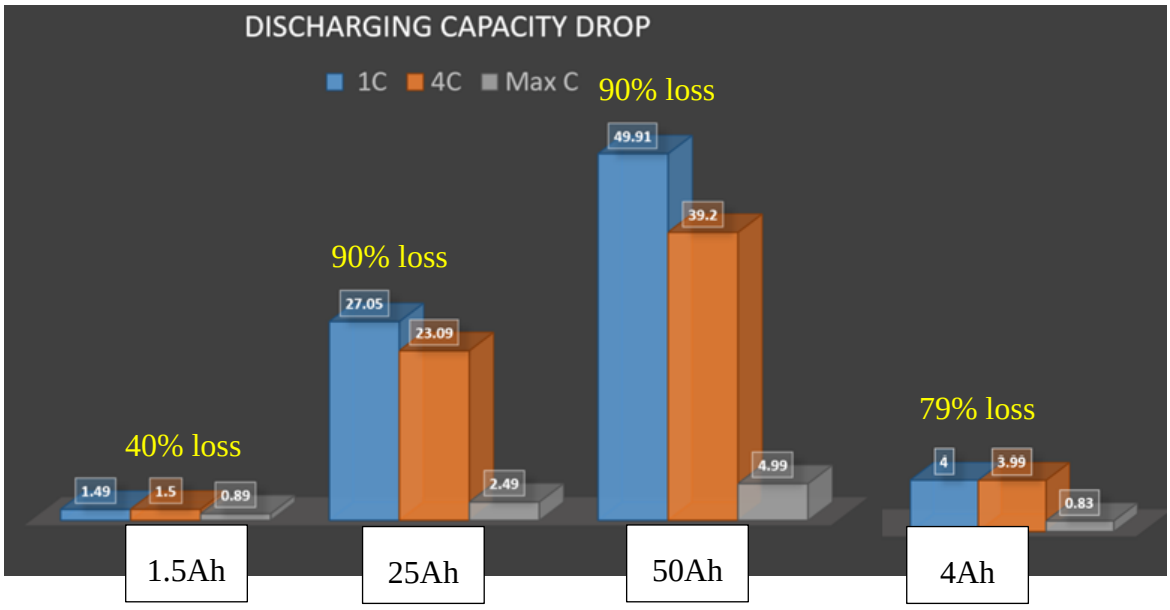


Fig. 8. The loss in capacity at 1C, 4C and MaxC for various cells during discharging phase

The capacity retention test also showed decline in specific energy for all cell technologies as a function of specific power when C-rate was increased from 1C to MaxC as shown in fig. 9. The following graph shows specific energy vs specific power trends at various C-rates (1C, 4C and MaxC) during discharge phase. The graph shows that for 50Ah cell when C-rate was increased from 1C to MaxC, the trend exhibited sharpest dip in specific energy compared to other cells. It is well-known that specific energy (Wh/Kg) is a function of cell capacity (Ah), cell voltage (V) and per unit mass (Kg) [72]. As from fig.7 and 8, it is evident that for both charge and discharge

phases, maximum capacity loss was observed for 50Ah cell. This large capacity loss of 50Ah cell also resulted in sharp dip of specific energy trend in fig. 9 due to the reason that specific energy is a function of capacity, as discussed above. Likewise, the sharpness of dips for trends decreased in following order i.e. 25Ah, 4Ah and 1.5Ah cells respectively such that, the trend for 1.5Ah cell was almost a horizontal line. This horizontal line is an indication that 1.5Ah cell brilliantly retains specific energy with increasing C-rate, possibly due to advanced Lithium ion Capacitor technology. However, overall, in terms of high power delivery, which is also the research question of this project, 4Ah cell proved much better compared to other three technologies.

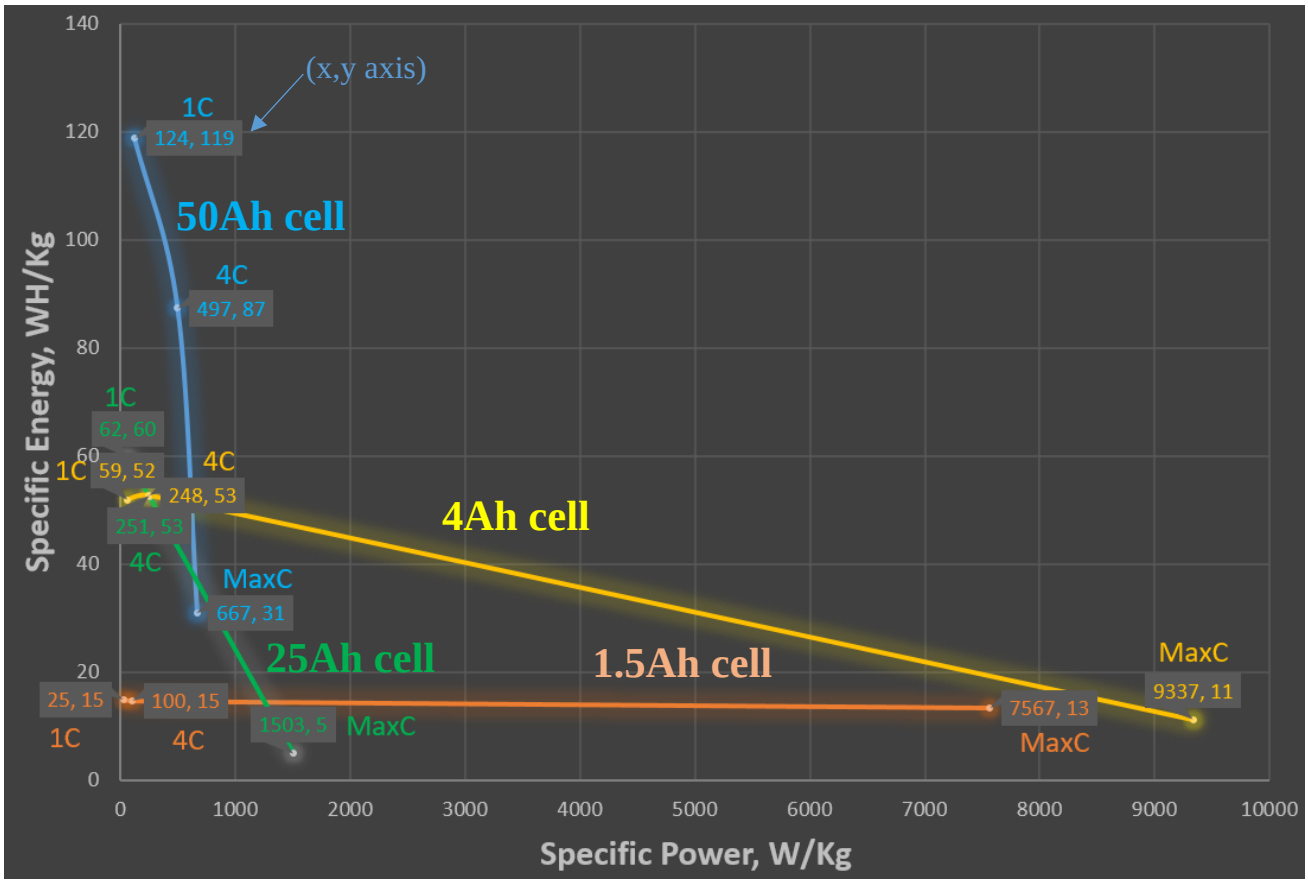


Fig. 9. Specific energy vs specific power for 50Ah, 25Ah, 4Ah and 1.5Ah cell at various C-rates during discharge phase: 1C, 4C and MaxC

For more clarity, the bubble plot in fig. 10 showed the maximum power delivery performance of cell technologies at MaxC. The plot shows an interesting observation, that although 4Ah cell delivered highest power, but the downside with this technology is that it was not able to retain specific energy at MaxC unlike 1.5Ah cell. Likewise, 25Ah cell performance was not the best in terms of power delivery, but still better compared to 50Ah cell.

Fig. 10. Specific energy vs specific power for 50Ah, 25H, 1.5Ah and 4Ah at MaxC only during discharge phase.

Constant current capacity retention test at 100A was performed to address the rise in temperature for all four cell technologies as a function of 5000 reference cycles as shown in fig. 11. The results showed that the highest rise in temperature was observed for 50Ah cell followed by 25Ah, 1.5Ah and 4Ah cells. Such large temperature rise of 50Ah cell can accelerate the degradation of cell especially when subjected to applications with high current ratings.

Therefore, the cell level capacity retention test 1 concluded that 50Ah cell technology did not prove to be a good choice for high power applications and was not taken forward for further testing in this research.

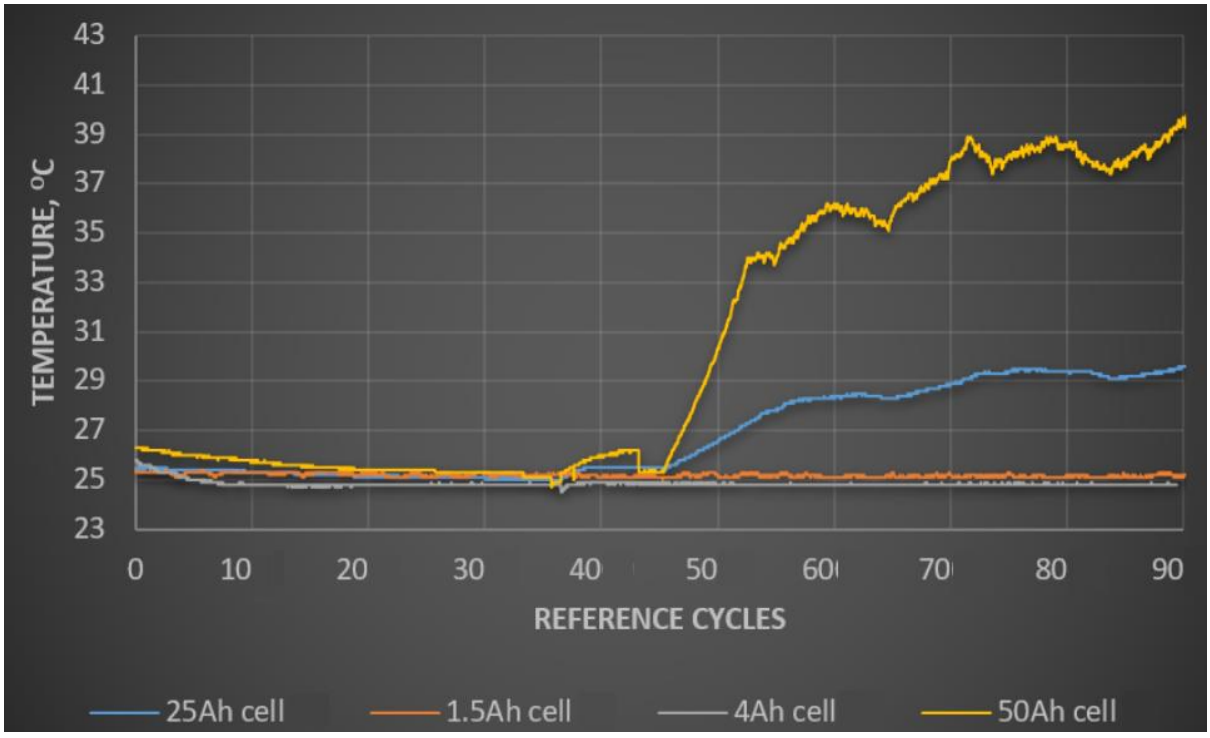


Fig. 11. Temperature as a function of reference cycles for 50Ah, 25H, 1.5Ah and 4Ah at constant current 100A.

3.2. Test – 2 The cell level High Power Pulse Characterisation (HPPC)

Fig. 12 shows the trends for internal DC resistance of three cell technologies (25Ah, 4Ah and 1.5Ah) from 100% to 20% SOC. For fair comparison, HPPC test was performed at constant discharge segments of 10A for all cell technologies. Overall performance in terms of internal DC resistance showed that highest resistance was observed for 25Ah cell followed by 1.5Ah and 4Ah cells. High internal DC resistance results in restricted current, voltage drops on load and cells heats up while cells with low internal DC resistance deliver high current on demand [73].

Another important observation was that at two extreme SOC's i.e. at 20% and at 100%, the 25Ah and 4Ah cells showed the largest resistance. However, unlike 25Ah and 4Ah cells, the 1.5Ah cell showed opposite behavior i.e. it had lowest resistance at two extreme SOC's. This distinct behavior of 1.5Ah compliments the results from [74, 75]. In general, lower number of available Li sites in the cathode as the cell approaches either extremes of SOC in lithium ion technology such as 25Ah and 4Ah cells, the resistance in the low SOC region is higher and internal DC resistance at high SOC also increases [76, 77]. In contrast, Lithium ion Capacitor i.e. 1.5Ah cell tends to show low resistance at both extremes of SOC probably because of internal chemistry of these cells, which also resembles the internal DC resistance trends of super-capacitors as a function SOC [78].

Therefore, the HPPC test 2 concluded that 25Ah cell technology did not perform well due to high internal DC resistance. Before filtering any technology, some other tests were performed on all three cell technologies to further investigate their performance.

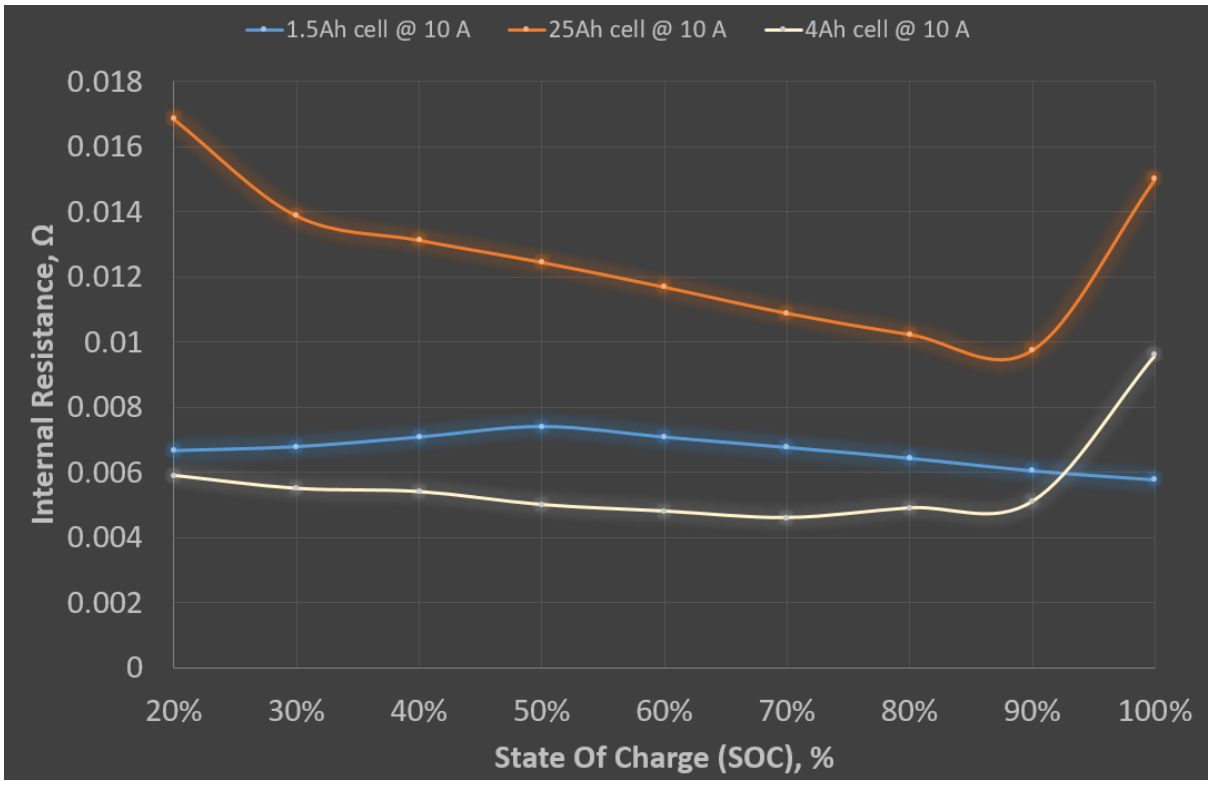


Fig. 12. Comparison of internal DC resistance of 25Ah, 4Ah and 1.5Ah cells by using HPPC test

3.3. Test 3 – Cell Level Self-Discharge

Self-discharge test at 45°C was performed for almost 3 months on all three cell technologies i.e. 25Ah, 4Ah and 1.5Ah cells as shown in fig.13. The most interesting result was found for 4Ah cell which showed that at the end of first month the cell discharged by 87% of its initial voltage, well below the minimum voltage (V_{min} = 2.7V), showing that the cell failed completely. The test was repeated for second month with a fresh cell. This cell again showed the similar behavior and discharged by 75% of its initial voltage i.e. it failed completely. To confirm this

abnormal behavior, the test was repeated for third month with fresh cell, which showed almost the same discharge behavior as the previous two. This severe drop in voltage for 4Ah cell shows that this cell might not be good choice for applications which stay non-operational for long durations at higher temperatures like 45ºC. The other two cells i.e. 1.5Ah and 25Ah discharged by 12% and 34% respectively. The 25Ah cell almost reached to its minimum voltage (V_{min} = 2.75V) at the end of third month.

Self-discharge test at 25 ℃ was performed for 3 consecutive month as shown in fig. 14. It was seen that the total drop in voltage for 4Ah, 1.5Ah and 25Ah cells during this period was 11%, 3% and 5% respectively. This showed that 4Ah cell performed much better at 25ºC compared to 45ºC, as this cell did not fail at 25ºC. In addition, the performance of other cells was much better compared to their performance at 45ºC. Overall comparison of self-discharge test for all three cells showed that 1.5Ah cell performed better compared to other two cell technologies as the voltage drop for 1.5Ah cell from initial voltage was only 12% and 3% at 45ºC and 25ºC respectively.

It was difficult at this stage to filter any cell technology, although 4Ah cell did not perform well in terms of self-discharge; however, its performance in terms of power and energy delivery was far better compared to other two cell technologies. Therefore, some other tests were performed for further comparison.

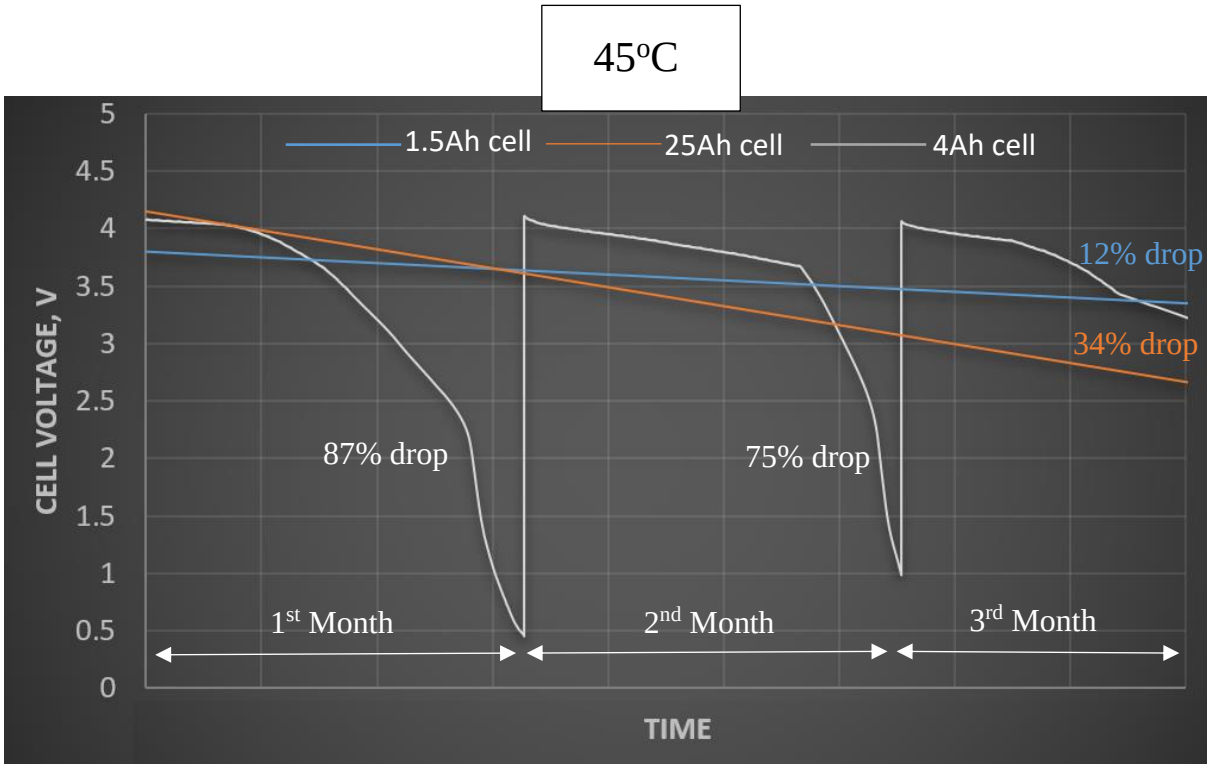


Figure 13. Self-discharge test of 4Ah, 1.5Ah and 25Ah cells at 45ºC for three consecutive months.

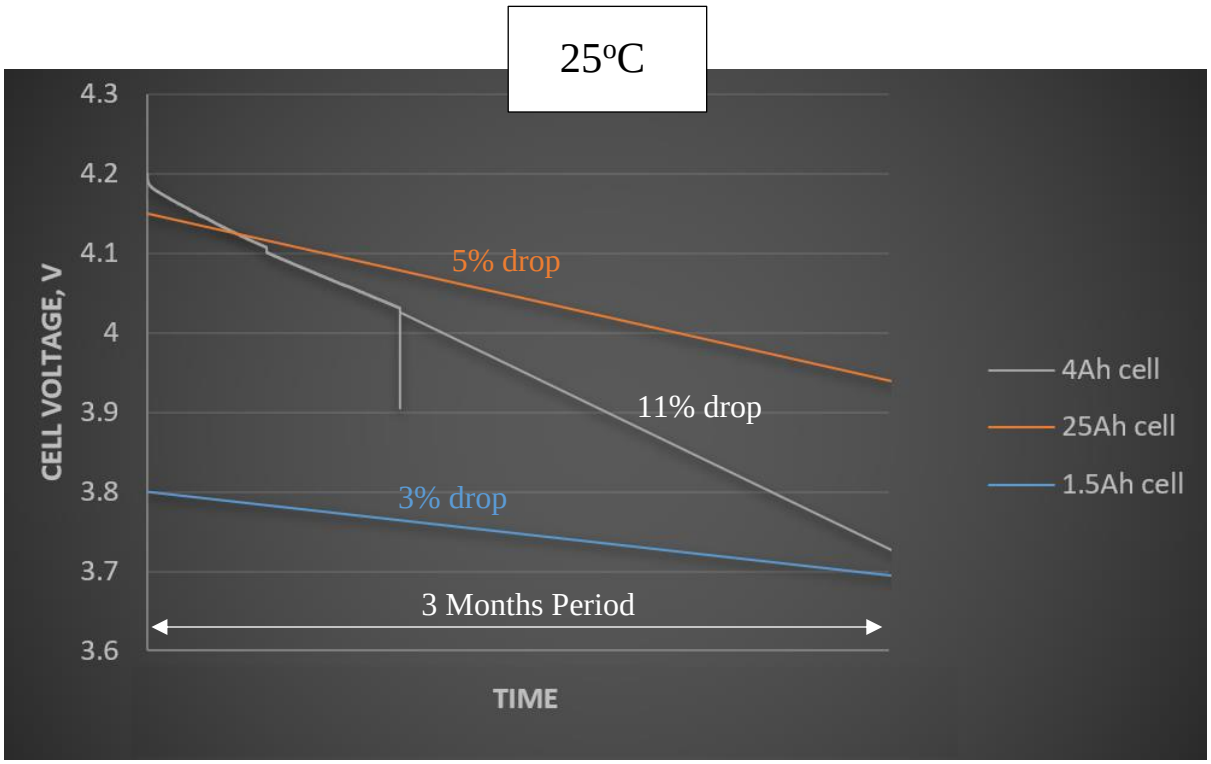


Figure 14. Self-discharge test of 4Ah, 1.5Ah and 25Ah cells at 25ºC for three consecutive months.

3.4. Test 4 – Pack Level Capacity Retention

From here onwards, further comparative tests were performed at pack level. The pack level capacity retention test was performed on all three cell technologies based on the test specifications discussed in test procedures section. The pack capacity retention was demonstrated in terms of the ability of pack to retain the stored energy at two current levels i.e. 200A and 600A as shown in fig. 15. The minimum loss in pack capacity was observed for the pack that was made of 4Ah cells (referred as for P-4Ah pack) followed by P-1.5Ah and P-25Ah packs. It is noteworthy, that at 600A, the minimum loss in capacity was observed for 4Ah cell at pack level compared to its capacity loss at cell level (discussed in cell level capacity test section 3.1). The reason is that the configuration of 4Ah cells in a pack (2p x 30s) allow 4Ah cells to operate at only 75C compared to 150C at cell level.

Likewise, another observation from fig. 16 is that at 600A, the P-1.5Ah pack offered a high capacity loss compared to P-4Ah pack, while interestingly opposite behavior was observed for both at the cell level (discussed in section 3.1), where 1.5Ah cell offered a low capacity loss compared to 4Ah cell. The reason is that 1.5 Ah cells at pack level (4p x 30s) operate at 80C compared to 75C for 4Ah cells at pack level (2p x 30s). Therefore, the comparison of P-1.5Ah pack with P-4Ah pack at 600A showed that the P-4Ah pack outperformed P-1.5Ah pack in terms of capacity retention.

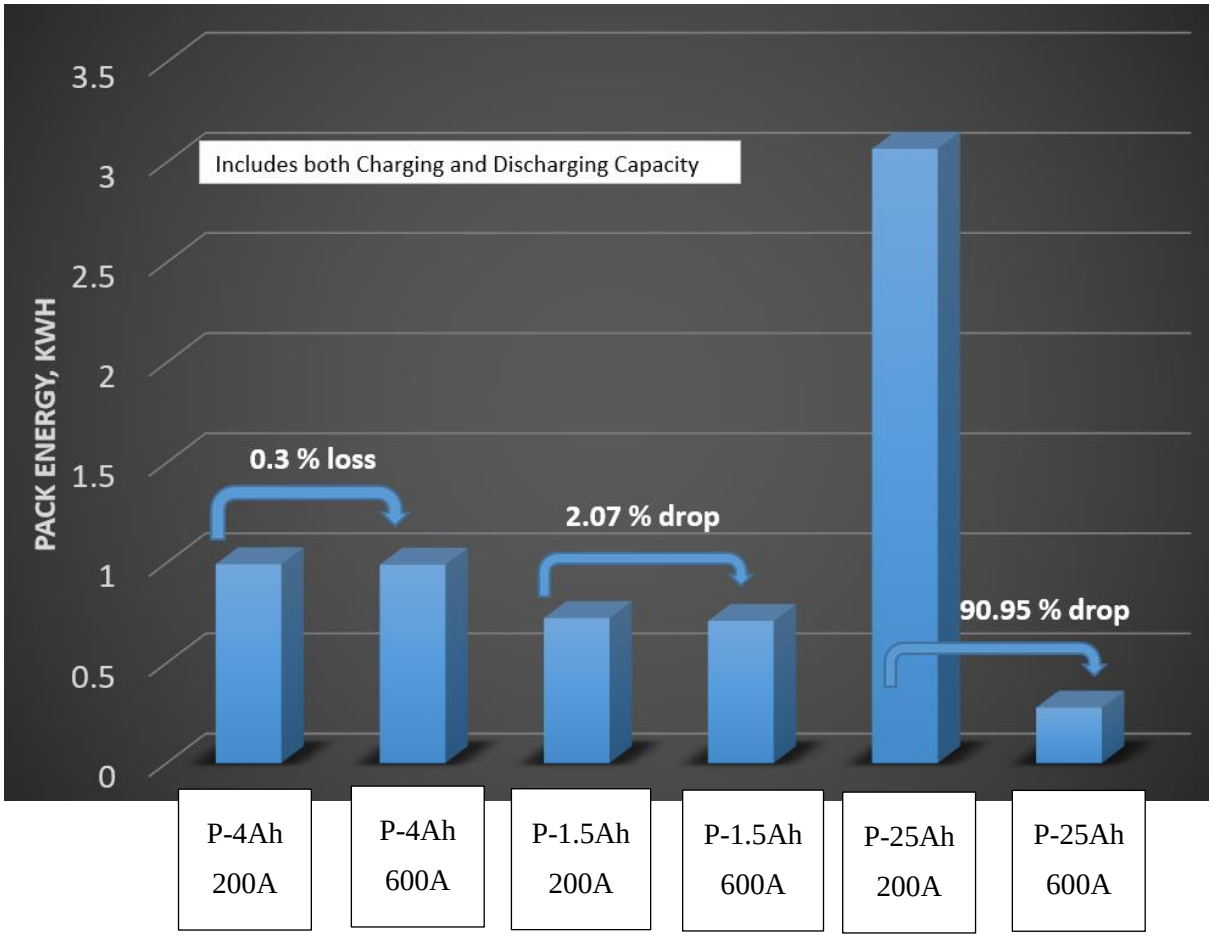


Figure 15. Pack level comparison for the loss in pack capacity from 200A to 600A

As shown in fig. 10, it was observed that P-4Ah pack performed well in terms of both energy and power at both 200A and 600A followed by P-1.5Ah pack. Comparatively, P-25Ah pack performed very well only in terms of energy at 200A (with corresponding power almost same as of other packs) but at 600A the energy of P-25Ah pack dropped even below the minimum pack requirement (highlighted as yellow area in fig. 10) i.e. 15KW and 2.4MJ. Our project lead partner provided the minimum pack requirement. Therefore, P-25Ah pack did not prove to be a good choice for high power applications, because at high current (600A), the energy loss was significant making it unsuitable to be used as an energy storage system during extreme braking.

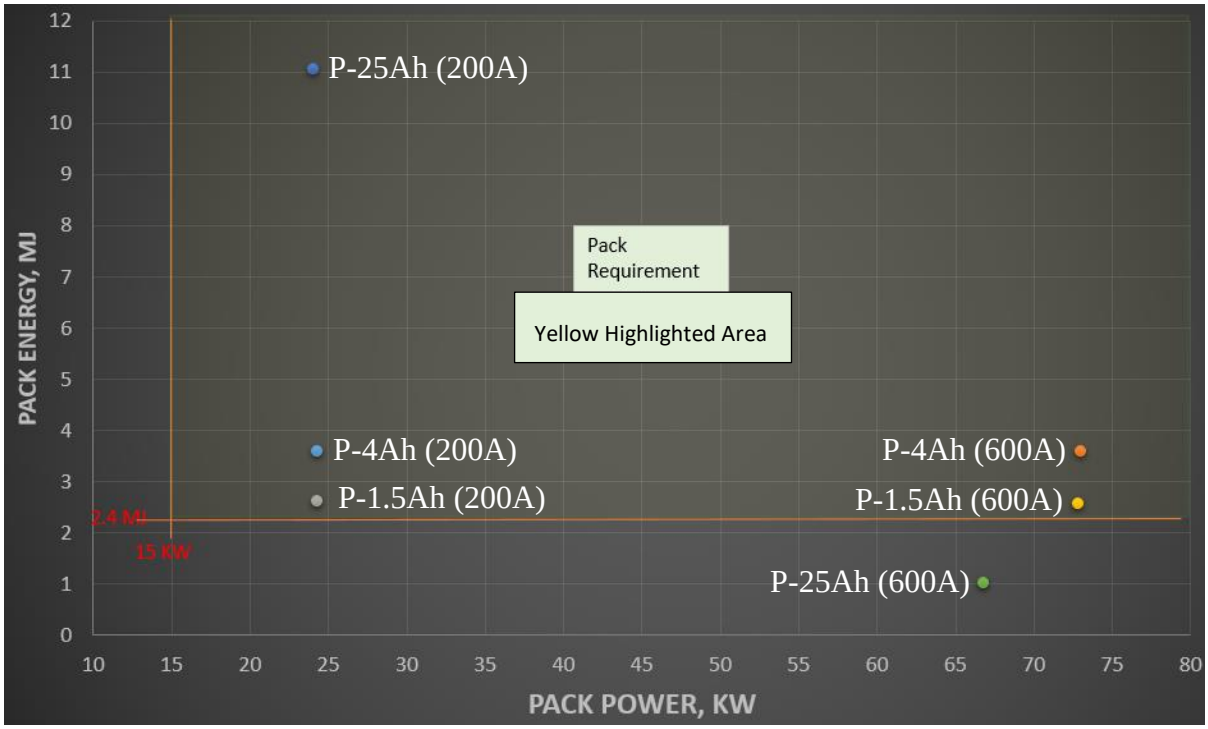


Figure 16. Pack level comparison of P-25Ah, P-4Ah and P-1.5Ah packs at 200A and 600A.

Furthermore, in fig. 17, P-4Ah and P-1.5Ah packs showed good voltage retention during 1 hour rest period between charge-discharge cycles and the voltage drop was not significant. Also for both packs, 200A and 600A currents accounted for almost the same level of voltage drop during rest showing that these packs were able to maintain voltage even for higher currents. However, P-25Ah pack showed significant drop in voltage when subjected to 600A, showing that P-25 totally failed to retain voltage at higher currents.

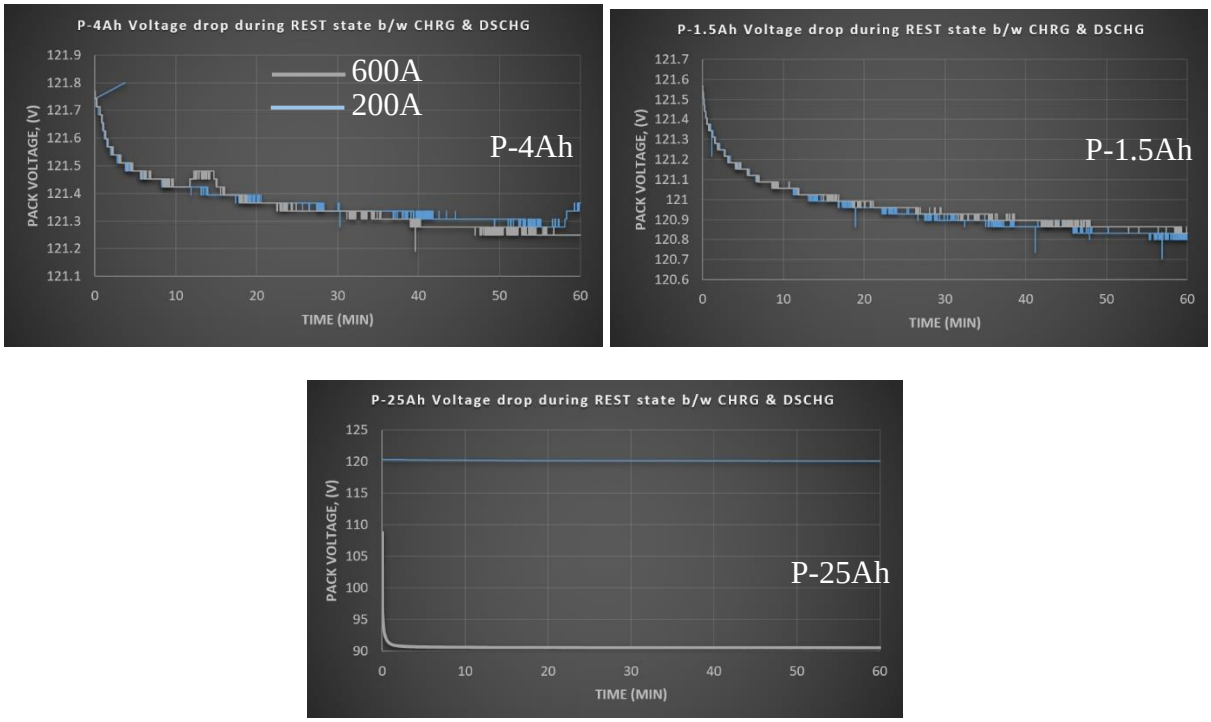


Figure 17. Comparison of voltage drop during rest period for P-4Ah, P1.5Ah and P-25Ah packs at 200A and 600A.

As, power delivery is of main concern in this research. Therefore, above tests concluded that 25Ah cell technology did not prove to be a good choice for high power applications due to pack capacity loss and pack voltage drop at

high current and high internal DC resistance. The 25Ah cell technology was not taken forward for further testing in this research.

However, applications where self-discharge is of main concern, than 25Ah cell technology can be taken in to consideration as its self-discharge performance is good compared to other two cell technologies.

The 4Ah and 1.5Ah cell technologies, based on their good capacity and voltage retention, pack power delivery and internal DC resistance performances were taken for further tests.

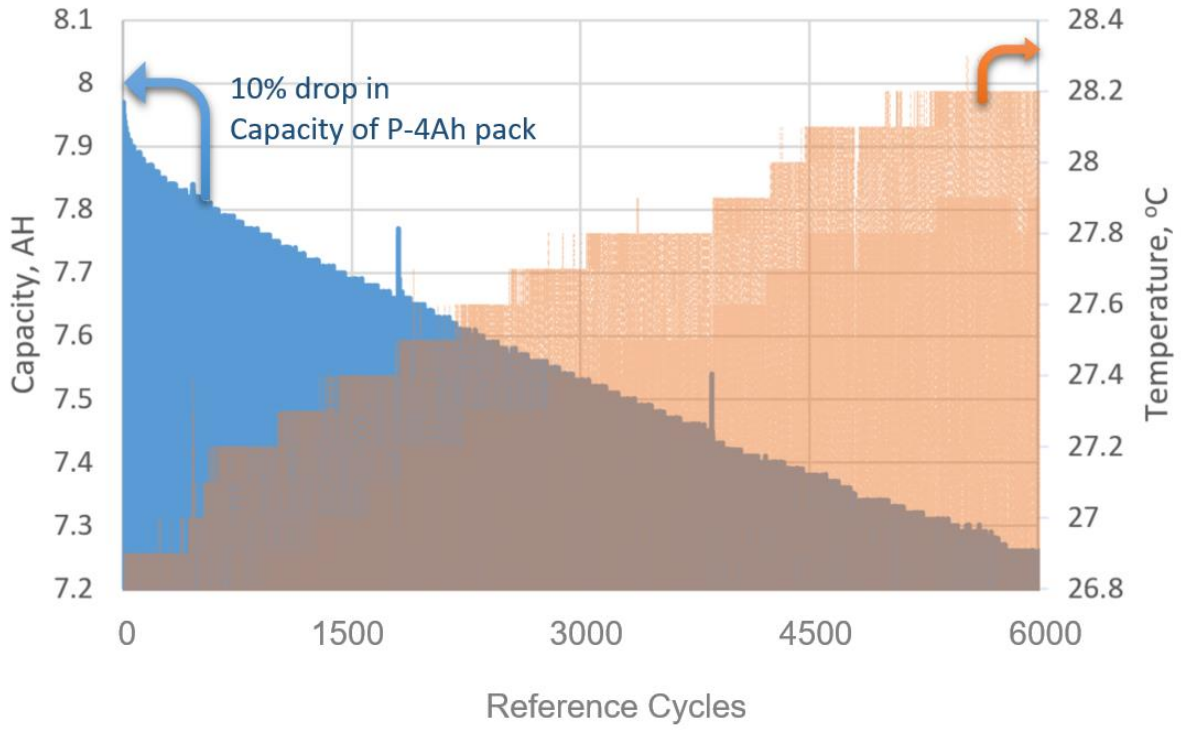
3.5. Test 5 – Pack Level Cyclic Ageing

Fig. 18(a) and 18(b) show capacity fade and cell temperature rise of P-4Ah and P-1.5Ah packs respectively when subjected to 6000 continuous reference cycles at 25°C and at 50A without rest. The initial capacity of both packs was ~ 8Ah. It can be seen that P-4Ah pack lost 10% of its initial capacity at the end of 6000 cycles with the rise in temperature from 25 to 28°C. Compared to P-4Ah, the P-1.5Ah lost only 7% of its initial capacity with the rise in temperature from 25 to 27°C.

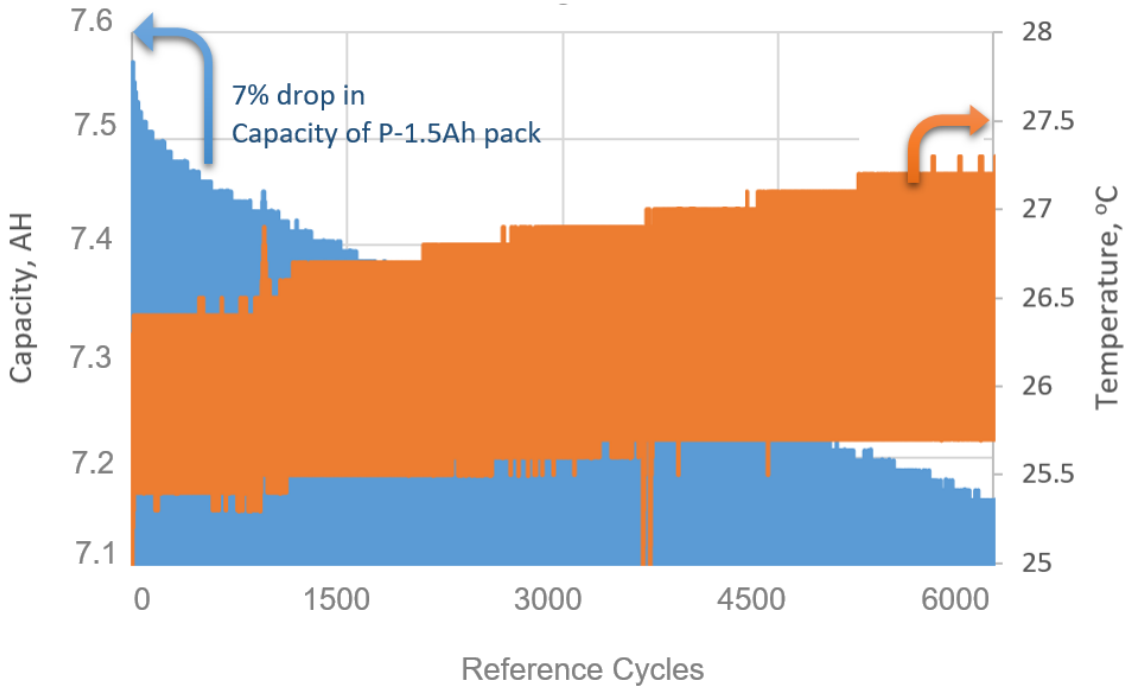
Continuous cycling also resulted in the internal DC resistance rise for P-4Ah and P-1.5Ah packs as shown in fig. 19. A 2% and 1% rise in internal DC resistance was observed for P-4Ah and P-1.5Ah packs respectively. It is interesting to note that although overall internal DC resistance for P-1.5Ah is high compared to P-4Ah pack but the rise in its initial resistance is only 1% which is low compared to 2% rise for P-4Ah pack. The reason for overall high internal DC resistance of P-1.5Ah pack can be attributed to the internal chemistry of 1.5Ah cell however, the low rise in resistance can be related to low capacity drop during cycling which is only 7% drop of its initial capacity. According to ref [79], the cyclic ageing capacity loss is due to the loss in active lithium which also results in increased internal DC resistance and rise in temperature of pack.

Pack level capacity test showed that P-4Ah pack is better than P-1.5Ah pack in terms of capacity retention and voltage retention at high C-rates and pack power delivery however contrarily, when it comes to cyclic ageing P-1.5Ah pack is better than P-4Ah pack because cyclic capacity drop of P-1.5Ah is low compared to P-4Ah.

As both technologies have pros and cons, therefore, it is difficult to filter at this stage, and another test was performed to find best fit.



(a)



(b)

Fig. 18. Drop in capacity of (a) P-4Ah cell and (b) P-1.5Ah cell and rise in corresponding temperature during 6000 continuous reference cycles

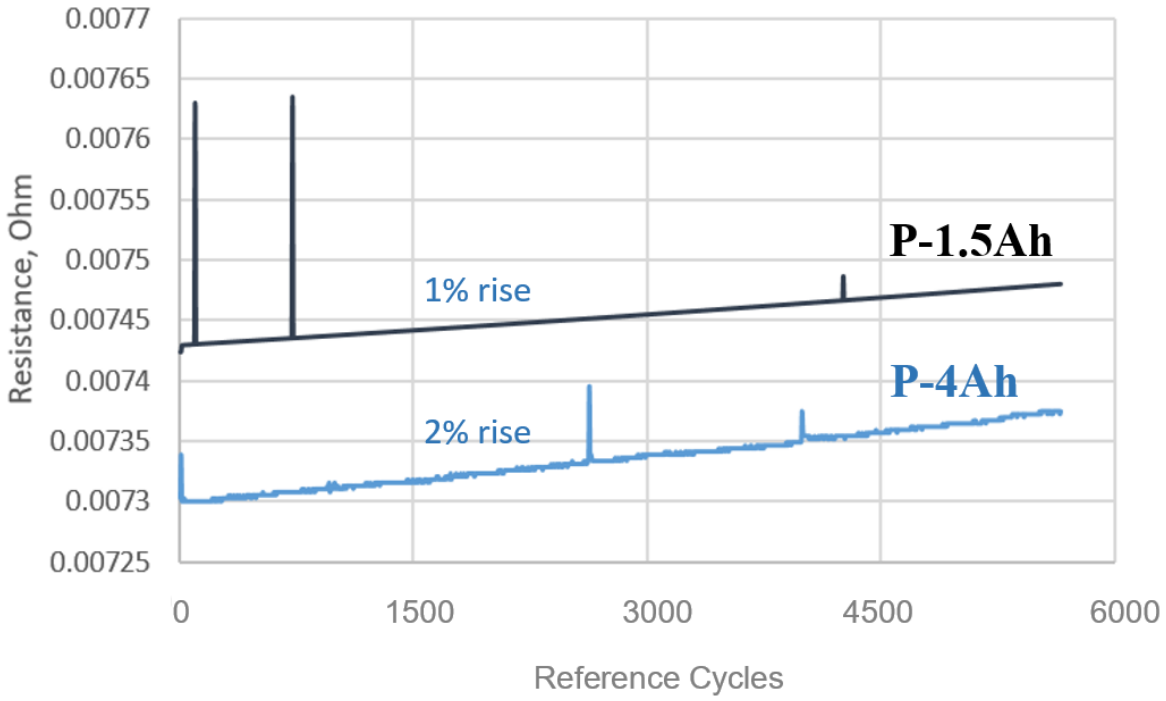


Fig. 19. Increase in internal DC resistance of P-4Ah and P-1.5Ah cell during 6000 continuous reference cycles at 25ºC and at 50A.

3.6. Test 6 – Pack Level Real World Drive Cycles

The temperature profiles for both packs i.e. P-4Ah and P-1.5Ah corresponding to the drive cycle pack power profile (in Watts) for 3 continuous cycles is shown in fig. 20. Maximum power as per drive cycle profile was 1800W during charging and 2100W during discharging. The temperature profiles corresponding to power profiles showed that during this continuous in/out program, the temperature of P-4Ah and P-1.5Ah packs reached to a maximum value of 39°C and 30°C respectively and then stabilised with 2 to 5% variation. The overall temperature of P-4Ah pack stayed higher throughout profile compared to P-1.5Ah pack.

In previous section 3.5, the pack level cyclic ageing test showed the drop in temperature rise of P-4Ah was higher compared to P-1.5Ah during 6000 continuous cycles. Similar results were again observed in drive cycle test, where temperature rise of P-4Ah pack was higher compared to P-1.5Ah pack.

This shows that temperature performance of P-1.5 pack is better compared to P-4Ah pack.

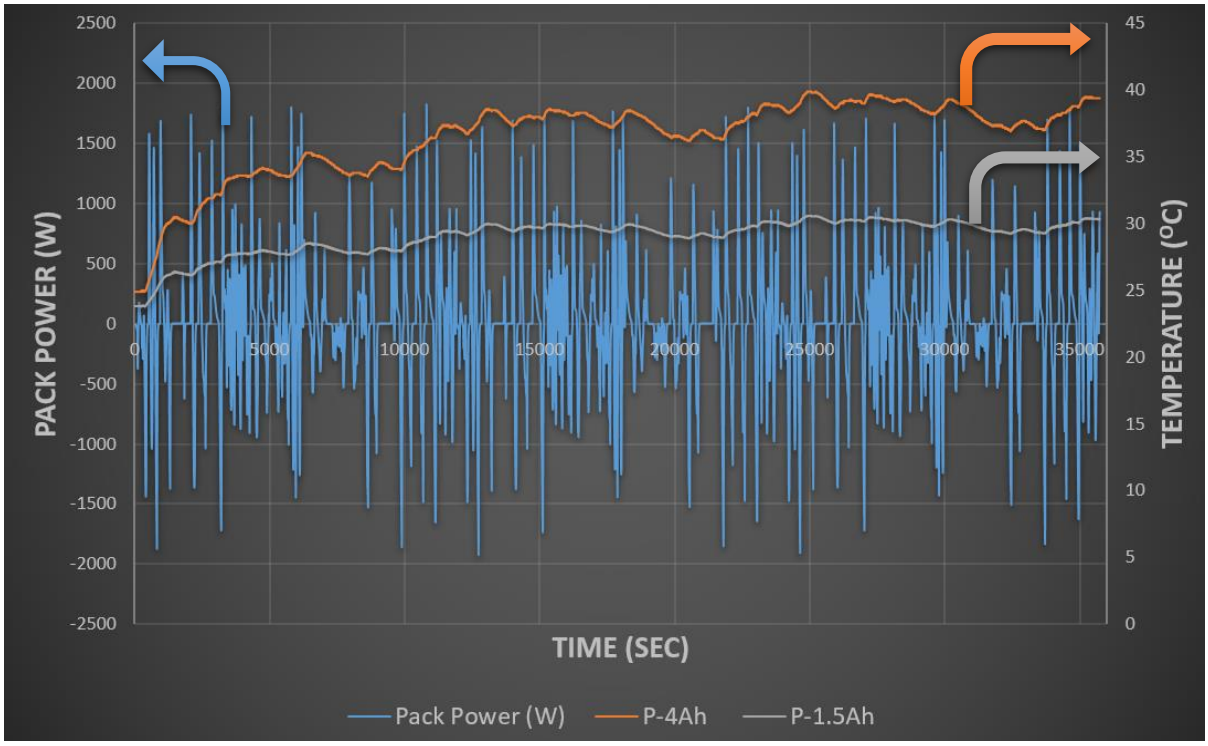


Figure 20. Real world drive cycle result showing temperature profiles (in °C) of P-4Ah and P-1.5Ah corresponding to Pack Power profile (in W) as a function of time (in sec).

4. Abstract Level Comparison – Concluding Table

Table 3 shows the abstract level comparison of all four cell technologies with various colors used for grading their performances compiling all above results.

In addition to testing, other important pack development/assembly parameters were are also considered for example, (i) cost per cell, (ii) number of cells required to develop a pack, (iii) pack cost, (iv) pack mass and (v) pack volume. In all these five parameters, 4Ah cell technology outperformed (shown in green) except in one parameter i.e. the required number of cells for developing a pack. However, the required number of cells to develop a pack becomes 'not-so-important', if the resulting developed pack has low development cost, small mass and small volume.

Further, 4Ah cell technology outperformed in most of the tests (for example, pack power, pack capacity retention from 200 to 600A, cell internal resistance etc.), as evident from most green boxes compared to other cell technologies. The only lowest test performance by 4Ah cell technology was the self-discharge (shown in red).

Therefore, 4Ah cell technology due to high self-discharge rate will not be suitable for applications with long storage requirement.

In this research, power delivery as well as pack development parameters were of key interest. Self-discharge was of supplementary interest here in. Based on this interest, 4Ah cell technology, after comprehensive comparison was graded as “The Best” technology for high power applications amongst all four. The other cell technologies were graded as: 1.5Ah is better than 25Ah is better than 50Ah cell technology.

Therefore, as per research goal, it was established that amongst all four technologies 4Ah cell technology is most suitable for the development of high power pack, which can be charged at high currents meaning that the pack is capable of taking huge charge in a very short amount of time during regenerative braking of vehicles.

Table 3. Concluding table showing the abstract level comparison of 50Ah, 25Ah, 1.5Ah and 4Ah cells.

Cells Type	Cell Specific Power @MaxC	Cell Capacity loss from 1C to MaxC	Per cell cost	Cells required for making a Pack	Pack Cost*	Pack Mass*	Pack Volume*	Pack Power @600A	Pack Capacity loss from 200A to 600A	HPPC-Cell Internal Resistance @50% SOC	Cell Self-Discharge (in 3 months)		Pack Capacity loss after 6000 cycles	Pack Resistance after 6000 cycles	Temperature rise during Drive Cycle test
											25ºC	45ºC			
50Ah cell	667Wh/Kg	95%	£200	30 Cells (1P x 30S)	£6000	50Kg / 1.65Kg per cell	21L	50Ah cell was not taken forward for these tests due to lowest cell power and cell capacity performance at MaxC							
25Ah cell	1503Wh/Kg	92%	£200	30 Cells (1P x 30S)	£6000	50Kg / 1.65Kg per cell	21L	1MJ	90%	12milliohm	5%	34%	25Ah cell was not taken forward for these tests due to lowest pack power, pack capacity and internal resistance performance		
1.5Ah cell	7567Wh/Kg	44%	£68	120 Cells (4P x 30S)	£8160	39Kg / 0.32 Kg per cell	27L	2.6MJ	2.0%	8milliohm	3%	12%	7%	7.5milliohm	30ºC
4Ah cell	9337Wh/Kg	85%	£50	60 Cells (2P x 30S)	£2900	16Kg / 0.27 Kg per cell	19L	3.6MJ	0.3%	5milliohm	11%	87%	10%	7.3milliohm	39ºC

= Lowest performance

= Low-Mid performance

= Mid-High performance

= Best performance

* Calculations based only on number of cells making a pack. These does not include thermal management, pack casing and electronics components

5. Conclusions

Comparison of four different types of top-of-the-line commercial and prototype lithium cells (4Ah, 1.5Ah, 25Ah and 50Ah cells) was performed to find the optimal cell technology which is suitable for the development of the next-generation high power battery pack for regenerative braking system. The research has characterised both the internal performance parameters like capacity, resistance, self-discharge and battery temperature rise and external pack assembly/development parameters which are, the number of cells required to develop the pack, pack mass, pack volume and pack cost.

Following conclusions are drawn:

- Both the internal performance parameters and external pack assembly/development parameters showed that novel prototype 4Ah cell technology was the optimal technology amongst all four cell technologies. All cell technologies were tested in depth and subjected to real world drive cycles, producing very accurate data and results that were used to select the next-generation of cell technology for platform vehicle's prototype battery pack used in regenerative braking system.
- The prototype 4Ah cell technology uses a novel approach of membrane fabrication, where linear nanofibers and microfibers are combined in wet laid nonwoven processes to produce separator membranes. These membranes are strong and thin, but have higher porosity (60-70%) and so have much higher ionic flow compared to membranes of commercial cell technologies used in regenerative braking system.
- The results also showed that the prototype 4Ah cell due to use of new separator technology features a size and capacity comparable to that of other commercially cells and realises the same output density and durability as capacitors, which makes is a good candidate in the league of high power automotive cells.

6. Acknowledgement

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