New Battery Technology for Remote PV Applications: A Brief Performance Analysis

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[This report contains sensitive information which is bounded by confidentiality and non-disclosure agreement. The Client wishes to keep this report confidential for an initial minimum period of two (2) years starting from the date of submission.]
Declaration

The work in this dissertation is wholly my own, except for where I have indicated and duly acknowledged.

Keng-Mun Low
Abstract

Lead-acid batteries have always been the dominant choice of technology when it comes to energy storage in remote area power supply (RAPS) systems. This is because it is the cheapest and the most developed battery technology in the market. Now, a new battery technology, the sodium-ion battery, has emerged as a rival. The sodium-ion battery is claimed to offer many benefits over the lead-acid battery, such as: longer cycle life, greater depth-of-discharge, suitability for high temperature operations, suitability for partial state-of-charge (PSoC) operations, is completely recyclable and can be manufactured cheaply. A local Australian company has taken interest in this battery technology for use in their RAPS systems, and has approached Murdoch University with a battery test proposal to verify such claims. These battery testing activities form the basis of this Masters dissertation.

The test methodology employed in this project is meant to give the Client a basic idea of how the prototype sodium-ion battery behaves, and to evaluate its suitability for RAPS systems. The tests conducted can be categorised into characterisation tests and load simulation tests.

The characterisation tests revealed several interesting findings: the battery has a non-flat discharge curve, has a high self-discharge rate, and has high internal series resistance.

The load simulation tests so far demonstrate that the prototype sodium-ion battery has low energy efficiency at high currents, and the preliminary results indicate that its performance is not quite on par with the lead-acid battery. A lithium-ion battery included in the test for comparison shows a far superior performance. Further tests are still required on this Na-ion battery to see if it can meet its claimed specifications, and to further differentiate it from the lead-acid battery. Doing so will allow proper economic analysis on whether it will be a suitable replacement for lead-acid batteries.
Acknowledgements

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<th>Definition</th>
</tr>
</thead>
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<tr>
<td>BMS</td>
<td>Battery management system (for Li-ion)</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DoD</td>
<td>Depth of discharge</td>
</tr>
<tr>
<td>D.M.M.</td>
<td>Digital multimeter</td>
</tr>
<tr>
<td>EE</td>
<td>Energy efficiency</td>
</tr>
<tr>
<td>GPIB</td>
<td>General Purpose Interface Bus (an IEEE-488 specification)</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>Na-ion</td>
<td>Sodium-ion</td>
</tr>
<tr>
<td>PSoC</td>
<td>Partial state-of-charge</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RAPS</td>
<td>Remote area power supply</td>
</tr>
<tr>
<td>SAS</td>
<td>Solar array simulator</td>
</tr>
<tr>
<td>SoC</td>
<td>State of charge</td>
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<tr>
<td>UPS</td>
<td>Uninterruptable power supply</td>
</tr>
<tr>
<td>VPC</td>
<td>Volt per cell</td>
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1. Introduction

An Australian company that specialises in renewable energy projects, Optimal Power Solutions Pty. Ltd., has approached Murdoch University with a project on battery testing. Optimal Power Solutions (the “Client”) plans to apply a new battery technology (sodium-ion or Na-ion in short) into their PV-based remote area power supply (RAPS) systems, and require a series of tests to be carried out to verify the manufacturer’s claims on its performance. This dissertation details the test activities that have been carried out and gives a brief analysis on the battery’s performance.

1.1 Objectives

The end objectives of this project are to:

- Assist the Client in understanding the characteristics of this new battery technology, and to evaluate its suitability for RAPS applications. This includes comparing this new battery technology with existing options, specifically lead-acid and lithium-ion batteries.

- Revive the dormant battery test system (BaSyTec) that resides in the former RISE Laboratory (now Engineering & Energy Lab) at Murdoch University.

1.2 Scope

The work carried out in this project is largely catered to the requirements set out by the Client. As such, the tests conducted in this project do not strictly adhere to established battery test standards, such as those outlined in AS 4086.1-1993 (Standards Australia 1993, 9). Ideally, the Client would like to have a comprehensive understanding of this new battery
technology, but given the time constraints imposed by the Client’s own business requirements as well as this Masters dissertation, some tests had to be omitted. The tests conducted in this project are also only meant to give *ballpark* results – results sufficient for the Client to use in their analyses and modelling, but not necessarily highly accurate. Again, this is due to the time constraints given by the Client, as well as the equipment constraints in Engineering & Energy Lab (i.e. a working temperature-controlled bath for the batteries). It should also be noted that the term “test” used in this dissertation is more inclined towards *observing* the new battery’s characteristics/performance, rather than determining if it meets certain requirements set out in established battery test standards. As such, the test results are presented as is without any conclusive pass/fail criteria applied.

It should also be noted that further tests are still being carried out at the time this dissertation is written. These tests are being done on the latest prototype battery sample provided by the Client (B1 prototype). The results presented and discussed in this dissertation will be confined to only the first two prototype batteries (B0 and B0V), as the data available for the latest prototype is still very limited.

### 1.3 Methodology

Two approaches were employed in this dissertation process, namely through experimentation and through literature research. In line with the project objectives, the experimentation process was designed to characterise the Na-ion battery and to evaluate its performance under a simulated load. Several battery prototypes were provided by the Client for this purpose. Along with the Na-ion battery, two lead-acid batteries (from different manufacturers) and a Li-ion battery were also included in some of the tests for comparison of performance. The literature review supplements the experimentation process in the following areas:
• Comparison of established test methodologies.

• Analysis methods for the collected data.

• Comparison of lead-acid and Li-ion battery characteristics.

The sections that ensue will be presented in the following manner. Firstly, some background will be given on how this project came about. Then, the test systems as well as the analysis methodology used for this project will be explained. Before heading on to the core of this dissertation, a list of the battery test samples used along with their given details will be presented to set the stage. Then, the tests that were conducted (characterisation test and load simulation test) together with the analysis of the results will be discussed. The final section will summarise all the results, present a comparison between the battery technologies tested and form an unbiased opinion on this new battery technology, before concluding the report.
2. Background and Context

2.1 Energy storage – a critical component of RAPS systems

RAPS systems are stand-alone power generation systems used in locations situated too far-off from the main electricity grid to be connected economically. Depending on the local conditions (e.g. geographical factors and load demand), the RAPS system can be supported by:

- Diesel generators only.
- A hybrid system - diesel generators used in conjunction with renewable energy systems (e.g. a solar array, a wind turbine or a small hydro system).
- Renewable energy systems only.

Regardless of the type of energy resources used, most RAPS systems share one important component – the energy storage system. The energy storage system serves a multitude of purposes (Butler, Cole, and Taylor 1999, 1), such as providing frequency regulation, spinning reserve as well as addressing the short and long-term intermittency of renewable energy resources.

Among the various energy storage technologies, e.g. flywheel, compressed air and water pumping, the electrochemical battery is the most common option for RAPS applications (Patrick T. 2006, 84). To be more specific, “batteries” in RAPS applications have always been largely synonymous with lead-acid batteries (Baker 2008, 4369–4370; Patrick T. 2006, 84; Wagner 2007, 1). The reason for this will be briefly explained in Section 2.2. The wide usage of lead-acid batteries in RAPS systems highlights the criticality of energy storage system from another perspective – its effect on the overall cost of the system. In the analysis done by Sauer et al. (1997) on the cost ratio of lead-acid batteries to a PV system, it was
found that even though the battery component is cheap relative to the installation cost (one-eighth of it), it makes up one-third of the system's lifetime cost due to the frequent replacements required. These figures assume a lifetime of twenty-four (24) years for the PV component and four years for the lead-acid battery. Considering the fact that the cost of PV is dropping rapidly over time (Bazilian et al. 2012), and that the lead-acid battery technology has already reached price maturity (Schoenung and Hassenzahl 2003, 33), the economic impact of batteries on RAPS systems will become even more apparent in the future.

In short, it can be seen that batteries influence not only how a RAPS system functions, but also how economical the overall system becomes. These are the two main drivers on why the Client has taken interest in this new Na-ion battery technology and brought them to Murdoch University for testing. The following sections will give some insights into the battery technologies that have been put to the test in this project.

### 2.2 The Incumbent: Lead-acid Battery

As mentioned earlier, lead-acid battery has been the predominant technology used in energy storage for RAPS systems. This is unsurprising as the lead-acid battery technology has been around for more than a century (Dell and Rand 2001, 100). What this really means is that this technology has seen many improvements over its lifetime, i.e. the development of Planté-type batteries, pasted-plate batteries, flooded batteries, VRLA (valve-regulated lead-acid) batteries, gel batteries and AGM (absorptive glass micro-fibre) batteries. The level of maturity this technology has reached is the reason for its wide-spread use and availability at a low cost – i.e. factors that make it attractive for RAPS applications (Wagner 2007, 498; Baker 2008, 4369–4370).
Nevertheless, lead-acid batteries still have several drawbacks despite their popularity. The first is that the lifetime of lead-acid batteries can be severely affected by deep discharges and high operating temperatures (Salkind, Cannone, and Trumbure 2002, 23.79). The following discusses this in detail.

- **Effect of deep discharge on battery life**

  Lead-acid batteries in general cannot be deeply discharged or left in a partial state-of-charge (PSoC) state for long periods of time. Doing so can potentially shorten its life due to problems such as sulfation and corrosion of electrodes which lead to irreversible loss of capacity (Garche, Jossen, and Döring 1997, 202, 211; Ruetschi 2004, 40). This can become an issue for lead-acid batteries in PV-based RAPS systems as the solar charging time is limited, and the solar resource can be poor for long periods of time. Thus, in practice, lead-acid batteries are usually cut off from the load and get charged by a diesel generator before they become too deeply discharged. This helps to prolong their life, but reduces the number of days of autonomy for the battery. According to the Client’s experience with lead-acid batteries in RAPS systems, the depth of discharge (DoD) is normally not more than 50%. Even though lead-acid battery manufacturers have since introduced “deep-cycle” batteries (claimed DoD of up to 80%), this higher figure merely represents the extreme limit of the battery – users are often advised to keep the DoD lower (at about 50%) to get more satisfactory lifetimes (Northern Arizona Wind & Sun n.d.). In order to satisfy this 50% DoD constraint, lead-acid batteries are normally sized with a capacity larger than the load they are required to meet – this basically means trading unused or wasted battery capacity for longer battery life.
Effect of high operating temperature on battery life

A common failure mode for lead-acid batteries is the corrosion of the battery plates, and this corrosion increases with temperature (Salkind, Cannone, and Trumbure 2002). This phenomenon is related to the Arrhenius Law, which states that for most chemical reactions at room temperature, the reaction rate doubles for every increase of 10°C. Hence, the lifetime of lead-acid batteries are usually halved with every increase of 10 °C (Tsujikawa and Matsushima 2007, 101).

Apart from that, lead-acid batteries have inherently low energy density. The theoretical maximum energy density of lead-acid batteries is 176Wh/kg, but in practice only 15% to 25% of this value (26.4Wh/kg to 44Wh/kg) is achievable (Newell, Patankar, and Edwards 2009, 1). This means that the larger the storage requirement is, the heavier the lead-acid batteries will be. Nonetheless, this is seldom an issue for stationary RAPS applications where more priority is placed on volumetric energy density (Wagner 2007, 498). The only foreseeable problem is the cost of transporting heavy batteries to remote locations.

From the environmental perspective, lead-acid batteries use toxic lead and corrosive acid in their construction. However, these components can be recycled or disposed of safely. The recycling of used lead can be up to 95% efficient (Armand and Tarascon 2008, 656) while the sulphuric acid can be neutralised prior to disposal or chemically treated into useful manufacturing components (Battery Council International 2010). However, this process of recycling is questionable in remote areas.
2.3 The Pinnacle? : Lithium-ion Battery

Although lithium-ion (or Li-ion for short) batteries are more recently developed compared to the lead-acid battery technology, it is nevertheless an established technology, particularly in the portable electronics industry (Armand and Tarascon 2008, 656). In fact, some would say that the Li-ion technology is “…likely to represent the pinnacle of cell development in terms of specific energy density” (Baker 2008, 4372). The following briefly examines the Li-ion technology and how it is suited for PV RAPS applications.

Lithium, in its elemental form, has a very low atomic mass (the lightest metal) and is highly reactive (high electrode potential) (Dell and Rand 2001, 143). These two properties enable Li-ion batteries with high energy density (normally greater than 100Wh/kg) to be built. Compared to lead-acid batteries of the same capacity, Li-ion batteries can be made smaller and lighter. Nonetheless, as highlighted in the previous sub-section, the lighter weight is only advantageous during the transport of the batteries to the remote location – once the batteries are in place, the importance of storage capacity outweighs the size of the batteries.

Other features that make Li-ion batteries attractive for PV RAPS applications are (based on Ehrlich 2002, 35.2; Dell and Rand 2001, 150):

- **Long cycle life**: Li-ion batteries normally last more than 1000 cycles at a DoD of greater than 50%, although this is also subjected to other operating conditions, i.e. ambient temperature and discharge rate.

- **High coulombic and energy efficiency**: These are important factors in PV RAPS systems. If the battery is to be solely charged by the PV array (no diesel operation), a high charge acceptance (high coulombic efficiency) will enable the battery to be quickly and easily charged with the limited solar hours. A battery with high energy efficiency requires less generation capacity (to overcome the losses), and this allows
for more rigid battery sizing, which translates to better economics for the overall system.

- **Broad temperature range**: Li-ion batteries can typically operate safely in the temperature range of -20°C to 60°C.

- **Absence of memory effect**: The partial discharging and recharging of the battery will not induce “capacity memory effect” as normally seen in nickel-cadmium batteries.

Looking at how the Li-ion features can easily match the requirements for PV RAPS systems, one would then wonder why its use is close to non-existent in RAPS applications. The reason for this is simply cost – Li-ion batteries, at its current stage of development, are still too expensive compared to lead-acid batteries. The Li-ion and lead-acid battery purchased by the Client for this project paints a clear picture for comparison: a 12V 40Ah Li-ion battery costs $277, while a 12V 100Ah lead-acid battery costs $310. Comparing the costs in terms of $/kWh, the Li-ion battery costs $577/kWh and the lead-acid battery costs $258/kWh – the Li-ion battery is more than twice as energy expensive as the lead-acid battery.

In addition to that, Li-ion batteries can be easily damaged (due to thermal runaway) when overcharged (Ehrlich 2002, 35.2). Hence, systems that use Li-ion batteries normally require a “battery management system” or BMS – a system that prevents overcharging by monitoring the individual cell voltage and controlling the flow of charge to them (MeVay 2011; Ehrlich 2002, 35.3). From the perspective of a RAPS system, this BMS incurs not only additional cost but also some additional complexity to the overall system.

### 2.4 The Newcomer: Sodium-ion Battery

Sodium-based battery technologies have been in existence for about three decades. The two most developed technologies, referred to as sodium-beta batteries, are sodium/sulphur and
sodium/nickel-chloride (Braithwaite and Auxer 2002, 40.1). According to Braithwaite and Auxer (2002, 40.2), the sodium/sulphur battery offers the following advantages:

- Potentially lower cost compared to other advanced batteries.
- High cycle life.
- High energy and good power density.
- High energy efficiency.

These benefits are also assumed to be captured by the sodium/nickel-chloride battery technology as it is an improvement over the sodium/sulphur battery technology. However, these sodium-beta batteries are high temperature batteries which operate in the range of 270°C to 350°C – which means they are impractical for RAPS applications.

This project focuses on a new kind of sodium-based battery, known as the sodium-ion (Na-ion) battery developed by Aquion Energy (Whitacre et al. 2012). Unlike the sodium-beta batteries, the Na-ion battery operates at ambient temperature. Its electrolyte is water-based and uses a chemical mix consisting of abundantly-found materials such as sodium and manganese (Whitacre et al. 2012). Aquion Energy claims that this new Na-ion technology offers the following benefits (Aquion Energy 2012; Whitacre et al. 2012):

- High DoD and long cycle life – greater than 5000 cycles at 100% DoD is expected (based on prototype results).
- High temperature operation – up to 60°C without loss of capacity.
- No detrimental effects in PSoC operation mode.
- High energy efficiency – 100% coulombic efficiency and 70% - 90% round trip efficiency (for operating current of less than 5A).
- Low cost – expected to cost less than $400/kWh during mass production phase.
- Safe – non-toxic materials are used and the battery is 100% recyclable.

Table 1 summarises and compares the main characteristics of these three batteries.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Lead-acid</th>
<th>Li-ion</th>
<th>Na-ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle life</td>
<td>1000 – 2000 cycles</td>
<td>~3000 cycles</td>
<td>&gt;5000 cycles*</td>
</tr>
<tr>
<td>Typical depth of discharge</td>
<td>50%</td>
<td>60%</td>
<td>Up to 100% with no expected damage</td>
</tr>
<tr>
<td>Temperature operation range</td>
<td>&lt;45°C</td>
<td>-20°C to 60°C</td>
<td>Up to 60°C</td>
</tr>
<tr>
<td>Typical energy efficiency</td>
<td>75% - 80%</td>
<td>&gt;90%</td>
<td>75% - 90%*</td>
</tr>
<tr>
<td>Cost</td>
<td>~$300/kWh</td>
<td>~$600/kWh</td>
<td>$400/kWh*</td>
</tr>
</tbody>
</table>

*Expected values

Table 1: Comparison of battery characteristics

Indeed, such claims make the Na-ion battery an attractive alternative to lead-acid batteries in RAPS applications. Long cycle life, high DoD and its ability to function at high temperatures are desirable characteristics for RAPS batteries operating in harsh environments. This dissertation will attempt to evaluate some of these claims.
3. The Test Systems

One of the objectives of this project is to create an opportunity to revive the abandoned BaSyTec system located in the Engineering & Energy Lab. This system has in the past been used to test various battery technologies, but the knowledge and capability to operate the system has since vanished with the departure of staff and the lack of documentation. Getting this system up and running again will be invaluable to this project as it is a very capable battery test system – i.e. from performing simple charge/discharge tests to running complex load simulations; automatic monitoring and logging test parameters such as voltage, current, temperature and Ah-counting; and most importantly, it can test up to four batteries independently.

However, given the urgency of the Client to get the project running, a “makeshift” test system had to be first set up. This makeshift system, referred to as the “LabView system”, was designed to run simple charge and discharge tests while work was done in parallel to get the BaSyTec system up. The following explains the two test systems that were used in this project, and pictures of the test systems can be seen in Appendix A.

3.1 LabView System

The LabView-based test system was put together using the equipment available in the Engineering & Energy Lab. The main components of this system are:

- A desktop PC with a GPIB card and LabView 8 installed.
- A Prodigit 3311D (60V, 60A, 300W) DC electronic load.
- A dataTaker DT50 data logger.
- Two Protek 506 digital multimeters.

**Figure 1** illustrates the interconnectivity of the LabView system. In this system, the PC with LabView 8 installed acts as the main controller. Communication between the PC with the DC electronic load and SAS is established via the GPIB interface, while the DT50 data logger is connected via a RS232 (serial) interface. The following details the functions of each of the main components:

i. **Desktop PC**
   A simple LabView program that this author has written (**Figure 2**) serves as the main interface to control and monitor the test parameters – i.e. setting the charge and discharge currents, monitoring of the battery terminal voltage, and counting the charge and discharge duration.

ii. **DC electronic load**
   The DC electronic load, as its name suggests, is used to simulate a constant load (constant current draw) on the battery.

iii. **SAS**
   The solar array simulator is used to charge the battery. It can automatically switch between two charging modes – constant current charging or constant voltage charging.

iv. **Data logger**
   The DT50 data logger is used to log the test parameters (voltage, current and temperature). As the data logger analogue input supports up to 2.5V, a voltage divider circuit is used to step down the input voltage signal. A shunt resistor is also placed in series with the battery for current measurement. The parameters to
log have to be set using the dataTaker DeLogger program, which is also used to download the logged data.

v. **Digital multimeters**

The digital multimeters (D.M.M) included in the setup is meant for quick monitoring of the battery voltage and current, as well as to verify the accuracy of the logged data.

---

*Figure 1: LabView system setup*
3.2 BaSyTec System

In contrast to the makeshift LabView system, the BaSyTec system is a comprehensive battery test system which offers much more flexibility. The setup of the BaSyTec system is as follows:

- A desktop PC with BaSyTec software installed.
- Two BaSyTec modules – each module has two test channels.
- RS232 (serial) cables.

A quick guide to using the BaSyTec system can be found in Appendix C.

3.3 Data Filtering

Though laborious, the task of data filtering is necessary to transform the myriad of test system outputs into useable data. For the LabView test system, the raw data obtained from
the DT50 data logger comes in a .csv (comma-separated values) format. Such files can be easily manipulated using a spreadsheet program, such as OpenOffice Calc and Microsoft Office Excel. The latter program was used in this project. The BaSyTec system makes this process easier by having the option to directly export data into an .xls (MS Excel) file.

As with any data processing tasks, the first step is to validate the collected raw data. The data validation technique used in this project is relatively simple – a plot of the logged parameters (i.e. voltage and current) against the associated timestamp will reveal any potentially erroneous values. This is possible because these parameters have a well-defined range and trend. This validation technique has helped to identify a “quirk” in the BaSyTec system – the system sometimes produces “data spikes” when the program moves from one instruction step to another, as illustrated in Figure 3. Such erroneous data was deleted from record.

![Data logger data](image)

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<td>18.44192016</td>
<td>14.43192723</td>
</tr>
<tr>
<td>271</td>
<td>11.32004667</td>
<td>0.016687778</td>
<td>7</td>
<td>15.19992764</td>
<td>7.993054036</td>
</tr>
</tbody>
</table>

*Figure 3: Erroneous data in BaSyTec system.*

After validating the data, some further manipulations are done to derive or include some other additional data. For example:
- For the characterisation tests, the timestamps are converted to cumulative hours to reflect a change of battery status (i.e. voltage) with respect to the time elapsed.

- The data from initial characterisation test performed using the LabView system did not have an Ah counter. This was manually done by integrating the discharged current over the total discharge time.

- For the load simulation tests, the timestamps are converted to hours of the day to match the load profile used.

- PV output and load values are added to the load simulation test record to allow for graphical comparison.

Further details on these manipulated or derived data can be seen from the data files included with this dissertation.
4. The Test Samples

Table 2 lists the batteries that were used in this project. The Na-ion prototype battery samples were provided by Aquion Energy (via the Client). The Na-ion B0V prototype is an improvement over the B0 prototype with some refinements in its chemistry as well as the addition of relief valves on the cells. Aquion Energy did not disclose what changes were made to the B0V battery chemistry. The other batteries (Trojan and Sonnenschein lead-acid batteries, and Winston Li-ion battery) were included in some of the tests for comparison of performance. These batteries were purchased by the Client solely for this project.
<table>
<thead>
<tr>
<th>Rated characteristics</th>
<th>Aquion Energy</th>
<th>Trojan</th>
<th>Sonnenschein</th>
<th>Winston Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery type</td>
<td>Na-ion</td>
<td>Na-ion</td>
<td>Lead-acid (Flooded deep cycle)</td>
<td>Lead-acid (Gel tubular)</td>
</tr>
<tr>
<td>Model number</td>
<td>B0</td>
<td>B0V</td>
<td>SCS150</td>
<td>A602 (4OPzV 240)</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>13V</td>
<td>13V</td>
<td>12V</td>
<td>2V</td>
</tr>
<tr>
<td>Voltage range</td>
<td>3.2V – 16V</td>
<td>3.2V – 16V</td>
<td>10.5V – 15.5V</td>
<td>1.9V – 2.2V</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>24 Ah (C₂₀)</td>
<td>Unknown*</td>
<td>100 (C₂₀)</td>
<td>240 Ah (C₁₀₀)</td>
</tr>
<tr>
<td>Cells per stack (1 string)</td>
<td>8</td>
<td>8</td>
<td>n/a</td>
<td>1</td>
</tr>
<tr>
<td>Temperature range</td>
<td>0°C to 60°C (expected)</td>
<td>-20°C to 45°C</td>
<td>10°C to 45°C</td>
<td>-45°C to 85°C</td>
</tr>
<tr>
<td>Cycle life</td>
<td>&gt;5000 cycles at 100% DoD (expected)</td>
<td>n/a</td>
<td>&gt;3000 cycles at 60% DoD (C₁₀)</td>
<td>&gt;3000 cycles at 80% DoD (3-10 years)</td>
</tr>
<tr>
<td>Sample acquired on</td>
<td>Early March 2012</td>
<td>Mid June 2012</td>
<td>Mid June 2012</td>
<td>Early September</td>
</tr>
<tr>
<td>Number of samples</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*No data was given for the B0V capacity.

Table 2: List of battery samples.
5. Characterisation Tests

5.1 Objective

The objective of the characterisation tests is to gain some basic understanding of the underlying characteristics of the Na-ion battery. The other batteries (lead-acid and Li-ion) were excluded from these characterisation tests (except for self-discharge test) as their attributes are quite well understood from the literature. These first series of tests are designed to evaluate the following battery properties:

- The charge and discharge characteristics of the battery.
- The Ah capacity of the battery under different discharge rates.
- The charge retention capability of the battery.

Knowledge of the above battery characteristics is required in performing analyses such as:

- Sizing of the battery for the intended PV RAPS system.
- Matching the battery voltage characteristics to other system components (i.e. inverter).
- Estimating the cost of the battery ($/kWh).

5.2 Test Methodology

Battery test procedures such as those given in AS 4086.1-1993 (Standards Australia 1993, 9) and PVRS 5A (PV GAP 2003, 14) typically require quite a sizable number of battery samples to produce the desired test results. This normally ranges from 5 to 9 battery samples, depending on the tests to be carried out. Nevertheless, this criterion could not be adhered to in this project as the number of battery samples provided was very limited. Of the
seven B0 batteries given, four were used in the Client’s own inverter test – leaving only three for other tests. At a later stage, only one B0V battery sample was given. Consequently, the same few battery samples were used for all the tests intended in this project, including the load simulation test described in the next section. This is not the ideal method in evaluating the full performance of the batteries as some degradation may occur after each of the tests, but, to reiterate, the Client merely aimed for ballpark figures.

Prior to beginning the characterisation tests, the Client requested that the Na-ion batteries be put through a short conditioning cycle to “break-in” the batteries. According to the Client, this is a normal practice in maximising the performance of new batteries, particularly lead-acid batteries. The conditioning procedure generally is performed by first charging the battery at 5A (constant current charge followed by constant voltage charge) until its maximum rated voltage is reached. Then, the battery is discharged at a constant 5A until its final voltage (minimum rated voltage) is reached. This cycle is repeated for five consecutive times.

5.2.1 Charge/Discharge Test

The charge and discharge test was carried out with the following procedure:

- The battery is fully charged prior to beginning the test.

- The battery is then discharged at a constant current until the final voltage is reached. The discharge current is set to the range of 1A to 10A.

- The battery is then allowed to be in a state of rest (no charge or discharge) for 1 minute. This is to observe any occurrence of voltage recovery on the battery.

- The battery is then recharged at the same discharge current (constant current charge followed by constant voltage charge) until the estimated fully-charged voltage is reached.
• Finally, the battery is put into a rest state for 1 minute before the test is deemed complete.

The final voltage defined for the B0 and B0V prototype is 3.2V per battery or 0.4V per cell. The estimated fully charged voltage is 15V or 1.88V per cell. The tests were carried out in ambient (room) temperature conditions as a temperature-controlled bath was not in working order. The data from the tests (voltage, current and temperature) were recorded every minute.

5.2.2 Self-Discharge Test

Generally, a self-discharge test (or charge retention test) is performed by simply leaving the fully-charged battery in an open circuit state over a period of time. The guideline under AS 4086.1-1993 (Standards Australia 1993, 14) requires that the battery should be left in such a state for 92 days at (35 ± 2)°C, while the guideline under PVRS 5A (PV GAP 2003, 19) states that this should be done for 60 days at (25 ± 5)°C. After this 60 or 92 days, the battery should be put through a capacity test to determine its remaining capacity. Nevertheless, due to time constraints, this test was only carried out for approximately 11 days at ambient temperature for the Na-ion B0V battery. The Trojan lead-acid and Winston Li-ion batteries were also included in the test for comparison. The terminal voltage of each battery was recorded every 10 minutes via the BaSyTec “sense terminals”. No capacity test was carried out, again due to time constraints, but the result shown in Section 5.3.3 shows that this was not necessary.
5.3 Results & Analysis

5.3.1 Voltage Characteristic

Figure 4: Na-ion (B0/B0V) voltage characteristics.

Figure 4 shows the ‘battery terminal voltage versus time elapsed’ plots of the Na-ion battery (B0 prototype) during charge and discharge. The B0V battery shows a similar voltage pattern (refer to Appendix B). From the curves, it can be seen that the battery terminal voltage drops almost linearly with time. Since the discharge current is constant in these cases, the voltage drop is almost proportional to the discharged capacity. This voltage characteristic is quite different in comparison to lead-acid and Li-ion batteries. Figure 5 and Figure 6 illustrate the relatively flat discharge curves for the lead-acid and Li-ion batteries respectively. These figures show that the cell voltage for lead-acid and Li-ion batteries typically does not vary by
more than 0.5V during discharge. The Na-ion, on the other hand, shows quite a substantial voltage swing – about 1.4V per cell (or 11.2V per battery).

**Figure 5**: Typical discharge curves for a SLI lead-acid battery.
(Source: Figure 25.17, Salkind, Cannone, and Trumbure 2002, 23.38)

**Figure 6**: Typical discharge curves for polymer Li-ion battery.
(Source: Figure 35.90, Ehrlich 2002, 35.77)
In the context of using this Na-ion battery in PV RAPS systems, this large voltage swing may place additional design considerations on the inverter. In the Client’s inverter compatibility test with this Na-ion battery (four B0 batteries connected in series), it was found that 0.7V will be the minimum acceptable cell voltage for the inverter to operate correctly. Below this value, the sine wave output of the inverter suffers “voltage clipping” because the DC input voltage is too low. Figure 7 (a) shows voltage clipping on the inverter output waveform when the battery voltage is 21V (0.66VPC). Figure 7 (b) shows the undistorted waveform when the battery voltage is 37V (1.16VPC). Thus, it becomes clear that the inverter specifications can impose a restriction on the maximum performance of the Na-ion battery due to this voltage swing. This has traditionally not been a design problem to consider as lead-acid batteries normally maintain a fairly stable discharge voltage of 2V per cell.

![Figure 7: (a) Inverter output waveform with “voltage clipping”; (b) Undistorted output waveform. (Courtesy of Len Wright)](image)

One possible advantage of this large voltage swing is that it can be used as a gauge for the battery’s state of charge (SoC). Battery SoC determination via open circuit voltage is generally not used for lead-acid and Li-ion batteries because the small voltage drop of the battery can make estimations inaccurate. It is within this context that, perhaps, the large
voltage swing of the Na-ion battery can be advantageous. Further studies and experimentations are required to verify this possibility.

Analysing the discharge curve more closely as shown in Figure 8, there appears to be quite a significant voltage step change during the application and removal of the discharge current. This is not caused by voltage drops in the cabling as the current-carrying wires and “voltage sense” wires are separate. Table 3 lists the calculated DC resistance at the start of discharge and immediately after the removal of discharge. This resistance is calculated by dividing the step change voltage by the discharge current.

![Figure 8: Effect of internal series resistance.](image)

Based on Table 3, it appears that the Na-ion battery has quite high internal series resistance. The calculated average is approximately 0.6Ω or 600mΩ. In comparison, Li-ion and lead-acid batteries have typical internal resistance values in the region of tens of mΩ (Dell and Rand 2001). One disadvantage of high internal series resistance is that it will severely limit the available capacity of the battery at high discharge currents because the battery will quickly reach its final voltage. The other disadvantage is that it will reduce the overall energy efficiency of the battery as there will be power losses (across the resistance) during charging and discharging.
### Table 3: Calculated internal DC resistance values for B0 and B0V.

<table>
<thead>
<tr>
<th>Test current (A)</th>
<th>B0</th>
<th>B0V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DC resistance at start of discharge (Ω)</td>
<td>DC resistance at end of discharge (Ω)</td>
</tr>
<tr>
<td>1</td>
<td>1.450</td>
<td>1.045</td>
</tr>
<tr>
<td>1.2</td>
<td>1.315</td>
<td>0.635</td>
</tr>
<tr>
<td>2</td>
<td>0.692</td>
<td>0.516</td>
</tr>
<tr>
<td>3</td>
<td>0.701</td>
<td>0.516</td>
</tr>
<tr>
<td>4</td>
<td>0.698</td>
<td>0.521</td>
</tr>
<tr>
<td>5</td>
<td>0.687</td>
<td>0.529</td>
</tr>
<tr>
<td>6</td>
<td>0.622</td>
<td>0.564</td>
</tr>
<tr>
<td>7</td>
<td>0.646</td>
<td>0.557</td>
</tr>
<tr>
<td>8</td>
<td>0.639</td>
<td>0.546</td>
</tr>
<tr>
<td>9</td>
<td>0.663</td>
<td>0.558</td>
</tr>
<tr>
<td>10</td>
<td>0.589</td>
<td>0.543</td>
</tr>
</tbody>
</table>

#### 5.3.2 Capacity Characteristic

The capacity test for the B0 Na-ion battery was initially performed using the LabView system as the BaSyTec system was yet to be operational. This test was then repeated on the same B0 sample using the BaSyTec system for comparison. **Table 4** and **Figure 9** summarises the test results obtained for the B0 and B0V battery samples. **Figure 10** and **Figure 11** shows the volt per cell (VPC) versus the watt-hours (Wh) discharged.

The main observations that can be drawn from **Table 4** and **Figure 9** are:

- There is an obvious variation in battery capacity between the test performed using the LabView system and the BaSyTec system.
- The variation in capacity between the B0V and B0 battery is quite significant.
<table>
<thead>
<tr>
<th>Discharge current (A)</th>
<th>B0 (LabView)</th>
<th>B0 (BaSyTec)</th>
<th>B0V (BaSyTec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.8</td>
<td>28.80</td>
<td>23.9</td>
</tr>
<tr>
<td>1 (retest)</td>
<td>23.3</td>
<td>18.58</td>
<td>-</td>
</tr>
<tr>
<td>1.2</td>
<td>27.0</td>
<td>22.00(^1)</td>
<td>21.5</td>
</tr>
<tr>
<td>2</td>
<td>21.1</td>
<td>26.50</td>
<td>19.0</td>
</tr>
<tr>
<td>3</td>
<td>17.7</td>
<td>27.70</td>
<td>16.9</td>
</tr>
<tr>
<td>4</td>
<td>14.9</td>
<td>30.19</td>
<td>15.4</td>
</tr>
<tr>
<td>5</td>
<td>11.3</td>
<td>23.98</td>
<td>14.1</td>
</tr>
<tr>
<td>6</td>
<td>9.9</td>
<td>27.19</td>
<td>11.3</td>
</tr>
<tr>
<td>7</td>
<td>8.9</td>
<td>28.08</td>
<td>10.6</td>
</tr>
<tr>
<td>8</td>
<td>8.6</td>
<td>30.43</td>
<td>10.1</td>
</tr>
<tr>
<td>9</td>
<td>7.3</td>
<td>28.31</td>
<td>9.3</td>
</tr>
<tr>
<td>10</td>
<td>6.4</td>
<td>26.56</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Table 4: B0 & B0V capacity tests.

\(^1\): No temperature data recorded. Average temperature was inferred from other tests done within the same time region.

\(^2\): The discharge test at 10A was omitted to make way for other more urgent tests.

**no data:** No temperature data recorded, and no values could be inferred from other tests.

---

**Figure 9:** B0 & B0V Ah capacity at different discharge rates.
The following discusses these two observations.

I. **Capacity variation between the LabView and BaSyTec test systems**

The first intuition as to why the battery capacity varies between the two test systems is that the tests were conducted in different ambient temperature conditions. In general, battery capacity increases with temperature and decreases as the
temperature drops. The first battery capacity test using the LabView system was carried out in the summer-autumn period, while the second test using the BaSyTec system was carried out in the winter period. To verify that this was indeed the cause, a retest using the LabView system was done during the winter months. As seen in Table 4, the retest at 1A discharge produces quite a similar result with what was obtained from the BaSyTec system. The possibility of a reduction in the battery’s capacity due to repeated usage has also been ruled out – comparing the results at the higher discharge currents shows no reduction, but instead an increment, in capacity.

To take this verification further, the discharge curves produced by the two systems were compared more closely. In order to do this, the curves from the two sets of results had to be first normalised. The method of normalisation used here is based on that described by Pascoe and Anbuky (2004, 1518). This normalisation process, which produces what is known as the “unified discharge characteristic”, was developed by the said authors to estimate the discharge reserve time of VRLA batteries. The discharge reserve time in this context refers to the amount of time the battery can fully support the load before the battery becomes depleted of charge. This process involves calculating two set of parameters – the normalised discharge time ($t_u$) and the normalised discharge voltage ($V_u$). The normalised discharge time is calculated by simply dividing each time period with the total discharge period $t_u = t/t_T$.

The normalised discharge voltage is calculated using the following equation:

$$V_u(t_u) = \frac{[V(t) - V_{\text{end}}]}{[V_P - V_{\text{end}}]}$$

where $V_{\text{end}}$ is the end voltage or the final voltage.

$V_P$ is the “plateau voltage” of the start of discharge voltage.
Plotting $V_u$ against $t_u$ will produce the “unified” discharge curve. One advantage of this normalisation method is that it can suppress, to a certain extent, the effects of other conditions affecting the discharge curve, i.e. the discharge type, discharge rate, ambient temperature, final voltage, as well as the initial SoC. **Figure 12** shows the comparison between the normalised discharge curves of the LabView and BaSyTec systems.

**Figure 12: Comparison of normalised discharge curves.**
Figure 12 shows that for the lower discharge currents, there is a close match between the normalised discharge curves obtained from the LabView and BaSyTec system. However, it can be seen that as the discharge current increases, the two normalised curves begin to diverge slightly. The normalised plots for the BaSyTec results are consistently more linear than the LabView results. The exact reason for this disparity is unknown. Nevertheless, this difference in results at higher discharge currents is not significant as the Client is only interested in the low discharge current/high capacity region. The repeat of the discharge tests using the BaSyTec system has provided some verification and confidence that the data from the initial tests are useable.

II. Capacity variation between the B0V and B0 battery samples

As shown in Figure 9, 10 and 11, the capacity of the B0V battery is significantly more than the B0 prototype, even though they were tested at approximately the same ambient temperature. Aquion Energy stated that there were some chemistry refinements in the B0V, in addition to the new relief valves. No information was given on its nominal capacity, but discharge data in Table 4 gives a rough estimate of about 35Ah at the C20 rate.

5.3.3 Self-Discharge Characteristic

Figure 13 shows the self-discharge between the Na-ion (B0V prototype), Trojan lead-acid and Winston Li-ion batteries over 260 hours. Analysing this graph qualitatively, it can be seen that the Na-ion battery has a rather high self-discharge rate (or low charge retention capability) compared to the lead-acid and Li-ion batteries. Based on the manufacturers' data sheets, the lead-acid battery has a self-discharge of between 5% to 15% per month, while
the Li-ion battery is claimed to lose only 3% of its charge per month. Nevertheless, given that this Na-ion battery is intended to be operated continuously (see Section 6), this self-discharge is not likely to become an issue. The worst scenario would be that the battery requires a “top-up” charge after a certain period to make up for the self-discharge losses. This finding was nonetheless raised to Aquion Energy via the Client, and the response received was that this characteristic was not observed in their latest prototype (B1). Figure 14 shows the relatively flat (little self-discharge) open circuit voltage of the B1 Na-ion battery. The claimed self-discharge rate for this B1 prototype is 2% per month.

![Self-discharge comparison (260 hours)](image)

*Figure 13: Self-discharge comparison between Na-ion, lead-acid and Li-ion.*
5.3.4 Other observations

**Battery bulging and leakage**

One of the early observations of the B0 prototype Na-ion battery is that some cells tend to bulge horizontally (see Figure 15). The bulging came with the battery brand new, before any tests were performed. Subsequent test activities on the B0 battery did not show any obvious signs of further bulging or shrinking, but some of the cells did leak some electrolyte through the terminals (see Figure 16). The leakages were observed on both bulging and non-bulging cells. Later on, some inactive (untested) B0 batteries were also found to be leaking electrolyte.

Aquion Energy was aware of this issue, and clarified that the leakages will not affect the battery’s performance. The leakage and bulging were attributed to the lack of a relief valve.
on the cells, and the swelling of cells might have occurred during shipment in an unpressurised flight. The subsequent B0V (B0 battery with valve) sample sent by Aquion Energy showed no signs of bulging. The cell terminals were also sealed to prevent electrolyte from leaking (see Figure 17).

![Figure 15: Bulging of cells on the B0 Na-ion battery.](image)

Figure 15: Bulging of cells on the B0 Na-ion battery.

![Figure 16: Electrolyte leakage through battery terminals on the B0 Na-ion battery.](image)

Figure 16: Electrolyte leakage through battery terminals on the B0 Na-ion battery.
Figure 17: B0V Na-ion battery with relief valve and sealant on the terminals.

Relatively large footprint

Figure 18 (a) and (b) compares the relative size of the B0/B0V Na-ion battery with the Trojan lead-acid and the Winston Li-ion battery, respectively. The nominal capacity of the B0/B0V Na-ion, lead-acid and Li-ion batteries are 24Ah, 150Ah and 40Ah respectively.

Figure 18: (a) Size comparison of B0/B0V Na-ion and Trojan SCS150; (b) Size comparison of B0/B0V Na-ion and Winston WB-LP12V40AHA.
In terms of Ah capacity, the B0/B0V Na-ion battery occupies a much larger footprint compared to the lead-acid and Li-ion batteries. A simple qualitative footprint estimate can be done based on Figure 18 (b). In this figure, the B0/B0V battery is about twice the size of the Li-ion battery, but has about 1.5 times less capacity than the Li-ion battery (24Ah vs. 40Ah). This means that to have the same capacity as the Li-ion battery, the B0/B0V battery will be 3 times physically larger. But then again, Aquion Energy stated that the size of the battery is not their primary design goal; the cost and effectiveness of the battery is of more importance. This is mainly because the battery’s physical size is seldom a concern in stationary applications.
6. Load Simulation Tests

6.1 Objective

The objective of the load simulation test is to observe the battery’s performance under typical real-world loads. Such a test is necessary because, according to Harrington and Hund (1995), standard battery operating parameters given by manufacturers often do not fulfil the requirements of batteries used in PV systems. These parameters are traditionally derived from test procedures designed for motive power and UPS applications, in which the charge and discharge scenarios are predictable. Using such parameters directly in the design of PV systems may result in the batteries performing below expectations (e.g., lower capacity and lower cycle life) (Harrington and Hund 1995). While the literature recognises the limitations of this traditional battery test methodology, a formal or standard test procedure to determine a battery’s performance in PV-base RAPS applications has yet to be established. Hence, the test procedures used in this load simulation test was designed based on the Client’s own experience with battery systems. This load simulation test is designed with the expectation of painting a clearer picture of the battery’s performance – by exposing the battery to a typical real-world load profile, which consists of many random micro charge-discharge cycles. With such information, the optimal battery size for that typical load scenario can be determined, which in turn can be used to calculate the overall economics of the intended PV RAPS system.

In this load simulation test, the Client wants to consider a PV-Diesel hybrid RAPS system with a high solar fraction. All the solar energy collected in the battery will be used to meet the daily load demands, with the diesel generator supporting any shortfalls. The Client’s logic behind this is that such a system would be the most economical given the rising cost of diesel fuel and decreasing cost of PV modules. For such a system, the summer period (with
ample solar radiation) will impose the most demanding operating conditions on the battery – the battery will experience long discharge durations and be in prolonged periods of PSoC (partial state of charge). This summer condition will form the basis of this load simulation test as it will help to determine the battery’s maximum performance. This scenario, in which the battery supports 16 hours of load (the PV array will meet the remaining 8 hours of load while recharging the battery) and the diesel generator does not operate (zero-diesel), is denoted as the ZD16.

The batteries used for this test are the Na-ion B0 and B0V prototype, the lead-acid (Trojan and Sonnenschein) batteries and Li-ion battery. The test methodology explained in the next section deals mainly with the Na-ion battery, but the general concept was applied to all other batteries as well for consistency.

6.2 Test Methodology

The load/resource profile given by the Client was derived from one of their existing site installations. This typical 1-day profile is made up of load and PV output data in 1 minute resolution. Figure 19 shows the given load/resource profile.

The PV output in the given profile was then modified to reflect higher solar contributions, as shown in Figure 20. This profile was made by replacing the first half of the PV output curve with a duplicate (mirror image) of the second half. The load data remains unchanged.
This load simulation test methodology can be divided into two stages. The first stage is to scale the load/resource profile to match the battery’s capacity – so that the battery will be at the same state of charge (for a particular time instant) in every cycle. This is denoted as the “stable” cycle. When a stable cycle is achieved, the second stage is to tweak the profile so
that an “optimal balance” between the battery’s energy efficiency (EE) and its depth of discharge (DoD) can be determined. The Client's supposition is that the EE of this Na-ion battery will not be a fixed value (or a fixed battery characteristic) due to the downward sloping discharge curve, as seen in Section 5.3.1. The belief here is that varying the DoD will also vary the battery’s EE accordingly. Achieving this stable cycle as well as the optimal balance point of EE and DoD represents the first goal of this simulation test. The outcome of this first goal will be:

- Determining the optimum performance (EE and DoD) of the battery under the given load/resource profile.
- Determining the optimum ratio between the battery size and the PV array size (because these are the only two parameters that will be adjusted in the load/resource profile to achieve the desired stable cycle).

Upon achieving this first goal, the next step would be to put the battery through a long-term cycling test (approximately 6 months) to observe any detrimental effects (i.e. reduction in capacity, EE and etc.). The long-term cycling will also give an estimate to the battery’s cycle life under such a load scenario. These parameters will allow a proper evaluation of the economics of the battery.

Achieving that very first goal has been quite a challenge in this project, as much as it has been time consuming. Still, this aspect is understandable as the specifications of this Na-ion battery differs from other battery technologies. As will be described shortly, most of the work done to achieve this stable cycle and optimal balance point was carried out through trial-and-error. In fact, these two sub-objectives (cycle stability and optimal performance determination) were actually carried out in parallel as a means to save time. Admittedly, the approach used in this load simulation test has been rather unstructured, and it is attributed to
the lack of experience in conducting such tests. Nonetheless, the work documented in this report should form a good foundation for future tests of similar nature.

The repeated scaling of the profile and observation of the results eventually led to a better understanding of the important parameters that will affect the battery’s performance. The following describes the general concepts used in the simulation tests.

The “power profile”

As seen in Section 5.3.1, the discharge curve of the Na-ion battery is quite different from lead-acid batteries used in standard RAPS systems – the Na-ion battery voltage swing is quite significant as the battery gets discharged. Based on this characteristic, it was decided that perhaps a “power profile” would be suitable for these simulation tests. In typical load simulation tests, a constant voltage profile and varying currents will be used to simulate the load. In this “power profile”, the net power flow into and out of the battery (in watts) is used as the varying parameter. The voltage and current flows for these simulation tests are all done in DC form (without any inverter between the battery and the BaSyTec system).

Scaling the profile & general test approach

The profiles used for these tests must first be scaled to match the battery capacity. The scaling of the power profile is done by applying a scaling factor on the load and PV output data given in the original load/resource profile. An increment of the load scaling factor equates to increasing the battery size and a decrement of the load scaling factor equates to reducing the battery size. The same applies to the PV array size for the PV scaling factor.
The scaling of the load and PV is done based on several parameters such as the DoD, EE, and average discharge current during non-solar hours. The importance of these parameters was initially not well understood, but was then gradually taken into account as the simulation tests progressed, as described in Section 6.3. A critical point to note here is that these parameters are used to scale the load and the PV, and hence these parameters are initially derived based on assumptions and not measurements (as there are no measurements to begin with). The general approach to the load simulation test is as follows:

i. Assumptions are first made to derive the parameters. For example, the battery is first specified to operate at 60% DoD at an assumed nominal capacity of 24Ah. Then, it is also assumed (or rather, expected) that the battery will operate at a 70% EE. These parameters are then used to scale the load and PV for the simulation profile (the method of derivation for these parameters will be explained shortly).

ii. The battery is then simulated using this profile for several cycles, and how the battery responds is observed (i.e. how the voltage and current changes).

iii. The initial assumptions are then modified (or tweaked) based on the observations.

iv. Go back to step (i) to repeat the process until a stable cycle and optimal performance point is achieved.

Thus, it can be seen that this load simulation test is in essence an iterative process. Table 5 briefly explains how the parameters are derived:
<table>
<thead>
<tr>
<th>#</th>
<th>Parameter</th>
<th>Method of derivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DoD</td>
<td>Total Ah discharged / Nominal rated capacity in Ah OR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Wh discharged / Nominal rated capacity in Wh</td>
</tr>
<tr>
<td>2</td>
<td>Average discharge current (during non-solar hours)</td>
<td>(Nominal rated capacity in Ah x DoD) / 16 hours</td>
</tr>
<tr>
<td>3</td>
<td>Energy efficiency (EE)</td>
<td>Wh-out / Wh-in</td>
</tr>
</tbody>
</table>

Table 5: Derivation of scaling parameters.

The DoD will always be a specified value at the start of the test. This value is incorporated into the simulation profile by first assuming a nominal capacity for the battery (i.e. the rated capacity), for example 24Ah. Then, the battery is assumed to operate at an average nominal voltage, for example 8V. This nominal voltage will be lower than the Na-ion battery’s rated voltage (12V) because the battery voltage drops as it is discharged. The assumed nominal capacity for the battery is then 24Ah x 8V = 192Wh. Assuming that the DoD is specified to be 60%, then the total Wh to be extracted or discharged from the battery will be 0.6 x 192Wh = 115.2Wh. This 115.2Wh figure is then assigned to the simulation profile (by scaling the load) as the net energy to be extracted from the battery in each cycle.

The assumed average discharge current is calculated by multiplying the earlier assumed nominal battery capacity with the specified DoD, and then dividing this by 16 hours (the non-solar hours). Using the previous values, the average discharge current is (24Ah x 0.6) / 16 hrs = 0.9A. The measured average discharge current is then derived from the actual simulation result for comparison.

The EE parameter will also be a specified value at the start of the test. For example, an EE of 70% is specified. Using the previous values, this means that the total energy required to be put back into the battery will be 115.2Wh / 0.7 = 164.6Wh. This is the theoretical amount of energy that is required to get the battery into a fully-charged state before the next
simulation cycle begins. This 164.6Wh figure is then assigned to the simulation profile (by scaling the PV) as the net energy input energy.

As stated before, all these parameters will be continuously modified in each new simulation profile (or each new iteration) based on how the battery responds to it – with the ultimate goal of reaching cycle stability and determining the optimal point of EE and DoD.

6.3 Results & Analysis

The following sections explain the results obtained for the Na-ion, lead-acid and Li-ion batteries. The detailed data for each test can be viewed from the data files included with this dissertation. Do take note that in the title of most of the graphs given in this section, a percentage value can be seen for EE and DoD. These numbers represent the assumed or predetermined values incorporated into the load profile for the respective tests, not the measured values. It is an indication of what test parameters were used for that test. When a “stable cycle” is achieved, the actual measured values will be equal to these assumed values.

6.3.1 Na-ion Battery

Table 6 (in page 52) summarises all the simulation iterations (labelled as profile #) that were performed on the Na-ion battery. The following describes the results of these tests, as well as the evolving methods used to conduct the tests, in a chronological order.

The first scaled profile (profile A) used was designed to discharge the Na-ion battery (B0 prototype) at approximately 1.5A during the 16 hours of non-solar hours. The value 1.5A was derived as follows:

\[
\text{Average discharge current expected} = \frac{\text{Nominal rated capacity} \times \text{DoD}}{16 \text{ hours}}
\]
= (24Ah x 100%)/16hr

= 1.5A

A DoD of about 100% was expected from the battery with this profile, and the net energy flow into the battery was set to 34Wh – translating to an expected EE of close to 100%. This profile was designed as such just to see how the battery would respond, as not much is known about the battery under such a test scenario. Figure 21 shows the result of this test. From the graph, it can be seen that the battery voltage “collapsed” to a very low value (1.17V) in the middle of the second cycle (each cycle starts at 12:00AM). As understood in Section 5.3.1, the battery’s voltage drops as its capacity decreases. The low voltage in this plot indicated that the battery was depleted of charge in the second cycle.
In the second iteration (profile B), the load was arbitrarily reduced by 20% while the PV output remained unchanged. Figure 22 shows the result of this simulation. The result shows that although the battery wasn’t completely discharged this time, the minimum voltage (the “trough”) seemed to be dropping over time (Figure 23). This indicated that the battery was losing its charge in each successive cycle, and will eventually experience another voltage collapse. The reason for this occurrence was due to an imbalance between the load and the PV input. In other words, the assumed or predetermined EE and DoD is not suitable for the battery. This test also suggested that the minimum voltage can be used as an indication of the “stability” of the cycle. The 60% DoD seen in the figure is calculated based on the actual Ah discharged per cycle, divided by the nominal capacity of 24Ah.
Subsequent iterations involved adjusting the load and PV scaling factors up and down to get a stable cycle. One profile which came quite close to a stable cycle was profile D. The result is shown in Figure 24. In this iteration, the PV output was increased by 50% compared to the base case (profile A), while the load remained unchanged. The minimum voltage was quite stable (7.59V and 7.58V for the last two cycles, respectively – see Figure 25). It should be noted that the first cycle of these tests are not considered in the analysis as the battery has yet to “settle down” into an equilibrium state.

Nevertheless, as shown in Figure 24, this profile allows the Na-ion battery to operate at a “comfortable” low EE of 57.5% and DoD of 67%. This EE figure was not satisfactory because typical lead-acid batteries can have EE of 75% to 80%. Furthermore, the Na-ion battery is claimed to be able to operate up to 100% DoD without any negative effects. In any case, subsequent simulation tests moved on to the newly arrived B0V prototype.
Based on the tests carried out in Section 5.3.2, it was established that the B0V prototype has a higher capacity than the B0 prototype. Hence, subsequent load simulation tests were carried out with this in mind. In the first three iterations (profile E, F and G), various combinations of assumed EE and DoD were made to achieve a stable cycle, but none came close (the voltage collapsed in two of the simulations). It was then observed that in all these simulations, the peak charge current was relatively high (above 4A). The deduction from this is that the battery has low coulombic efficiency (and hence low energy efficiency) at high
charge currents. The design of the newer profiles ensured that the peak charge current does not exceed 4A (this is done mainly through trial and error – by scaling the load and PV, and observing the peak charge current).

In the last two simulation results included in this report (profile H and I), much of the effort was spent on trying to find an optimum balance between the EE and DoD. More specifically, the Client aimed for an EE of at least 80%. Figure 26 and Figure 27 show the results for profile H and I respectively. In both cases, the minimum voltage was still dropping in each successive cycle.

![Figure 26: Simulation result for Na-ion profile H.](image-url)
Further tests are still being carried out on this B0V battery at the time of writing this report (as requested by the Client), but the preliminary conclusions that can be made for this Na-ion battery based on the B0 and B0V load simulation results are:

- Achieving an EE of 80% seems unlikely for a DoD of greater than 50%.

- The charge current will be the main limiting factor of the battery's performance. A high charge current will reduce the battery's “effective capacity” as the battery appears to have low coulombic efficiency at such currents. An in-depth charge efficiency test is required to verify this.

*Figure 27: Simulation result for Na-ion profile I.*
<table>
<thead>
<tr>
<th>Battery</th>
<th>Profile #</th>
<th>EE*</th>
<th>DoD*</th>
<th>Average discharge current**</th>
<th>Peak charge current**</th>
<th>Comments</th>
</tr>
</thead>
</table>
| B0 (nom Ah = 24) | A        | 100% | 65.9% | 1.26A                       | 2.30A                | Preliminary test. Load scaled so that average discharge is about 1.5A, PV scaled so that net charge is close to 0 (100% EE)  
> Voltage collapsed (dropped to 1.17V) in the middle of 2nd cycle due to insufficient charge |
|               | B        | 74.0% | 60.0% | 0.95A                       | 2.80A                | Reduced load of profile A by 20%. PV remains the same.  
> Minimum voltage of each succeeding cycle drops over time - a sign of insufficient charge |
|               | C        | 79.0% | 69.5% | 1.36A                       | 3.12A                | Modify profile A: PV+25%, load unchanged.  
> Voltage collapsed in middle of 2nd cycle. |
|               | D        | 57.5% | 67.0% | 1.08A                       | 3.50A                | Modify profile A: PV+50%, load unchanged.  
> Minimum voltage of each succeeding cycle is fairly stable. |
| B0V (nom Ah = 35) | E        | 60.7% | 54.0% | 1.36A                       | 4.55A                | Characterisation test determined that this battery has more capacity than B0 prototype. A higher nominal capacity (35Ah) is assumed.  
Modify profile A: PV+100%, load+40%.  
> Test was stopped prematurely to increase expected battery efficiency. |
|               | F        | 72.0% | 82.0% | 2.25A                       | 4.91A                | Modify profile A: PV+98%, load+57%.  
> Voltage collapsed in middle of 2nd cycle. |
|               | G        | 80.0% | n/a   | 2.36A                       | 6.19A                | Modify profile A: PV+56%, load+34%.  
> Voltage collapsed in the first cycle, likely because battery not fully charge from previous test. |
|               | H        | 79.5% | 43.0% | 1.03A                       | 3.21A                | Modify profile A: PV+8%, load-8%.  
> Minimum voltage of each succeeding cycle drops over time - a sign of insufficient charge |
|               | I        | 83.5% | 55.5% | 1.31A                       | 3.98A                | Modify profile A: PV+25%, load+10%.  
> Minimum voltage of each succeeding cycle drops over time - a sign of insufficient charge |

*assumed/predetermined value  
**measured value

Table 6: Na-ion load simulation test summary.
6.3.2 Li-ion Battery

The same test methodology was applied to the LiFeYPO$_4$ Li-ion battery. Figure 28 shows the stable cycle that was obtained. In this result, an EE of about 99.5% and a DoD of about 54.5% were achieved. The DoD in the Li-ion load simulation tests were limited to around 60% as per the manufacturer's recommendation.

![Figure 28: Stable cycle for Li-ion load simulation test.](image)

A point to note in the load simulation test for the Li-ion battery is that the power profile used has a "shifted" time scale compared to the one used in the Na-ion tests. In this profile, each cycle starts at 6:30PM, which is the time the evening loads begin. This was done so that the battery is sufficiently discharged before being charged during the solar hours. Earlier attempts to start the cycle at 12:00AM resulted in the Li-ion battery being only partially discharged, and the battery voltage was pushed beyond 16V during the solar charging hours – a non-permissible situation as doing so would damage the battery. This is basically a
workaround for the BaSyTec system as it cannot limit the charging voltage (at least during load simulation) like a BMS would.

6.3.3 Lead-acid Battery

Table 7 lists four profiles that were used in the Trojan flooded lead-acid load simulation test. Of these four profiles, judging from the minimum voltage in each cycle, the first profile (profile A) showed the most stable result. Figure 29 shows the stable cycle that was obtained. As requested by the Client, tests are still being carried out at the time this report is written to find a more optimised balance of EE and DoD. A rough guess is that the optimal point will be in the region of 70% EE and 50% DoD.

<table>
<thead>
<tr>
<th>Profile</th>
<th>EE</th>
<th>DoD</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>75%</td>
<td>40.5%</td>
<td>Stable cycle.</td>
</tr>
<tr>
<td>B</td>
<td>80%</td>
<td>47%</td>
<td>Fairly stable cycle, minimum voltage slightly dropping over time.</td>
</tr>
<tr>
<td>C</td>
<td>85%</td>
<td>47%</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>90%</td>
<td>47%</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Trojan lead-acid load simulation test summary.

![Figure 29: Stable cycle for Trojan lead-acid load simulation test.](image)
The stable result for the Sonnenschein gel tubular lead-acid battery simulation test is shown in Figure 30. Similar to the Trojan lead-acid battery, several combinations of EE and DoD were applied to the tests for the Sonnenschein battery (refer to Table 8). The third profile (profile C) gave the most stable result.

<table>
<thead>
<tr>
<th>Profile</th>
<th>EE</th>
<th>DoD</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>80%</td>
<td>48%</td>
<td>Fairly stable cycle, minimum voltage slightly dropping over time.</td>
</tr>
<tr>
<td>B</td>
<td>85%</td>
<td>48%</td>
<td>Stable cycle.</td>
</tr>
<tr>
<td>C</td>
<td>75%</td>
<td>48%</td>
<td>Stable cycle.</td>
</tr>
</tbody>
</table>

*Table 8: Sonnenschein lead-acid load simulation test summary.*

A point to note in the graph illustrated in Figure 30 is that the charge currents are relatively high compared to the tests on other batteries. The reason for this is that the Sonnenschein battery used in this test has a terminal voltage of only 2V, and a capacity of about 200Ah. To match the power given in the test profile, a lower voltage will be balanced by a higher current.

*Figure 30: Stable cycle for Sonnenschein lead-acid simulation test.*
7. Summary of Results & Further Discussions

Table 9 (in page 58) summarises the overall test results and compares the Na-ion battery to the lead-acid and Li-ion batteries.

Based on performance alone and ignoring the cost of the batteries, the Li-ion proves to be the superior option. The salient point of the Li-ion battery is that it has excellent energy efficiency and can be charged at high C-rates – important characteristics that allow the battery to be fully charged in limited solar hours. The size of the PV array can also be made smaller as there are less charge inefficiencies to overcome in the battery, helping to lower the overall cost of the RAPS system. Nonetheless, these advantages may still be outweighed by its rather prohibitive cost.

The Na-ion, on the other hand, has yet to live up to its claimed performance. Based on the load simulation tests, its performance is quite similar to that of lead-acid batteries. To know if it is a worthwhile replacement for lead-acid batteries, the following claims still need to be verified through further studies:

- If its lifetime can last up to 5000 cycles.
- If it can operate at high temperatures (claimed up to 60°C) without any detrimental effects.
- If it can operate in PSoC mode without any detrimental effects.
- If its cost can undercut the price of lead-acid batteries (typically $300/kWh)

Satisfying the first two claims will heavily bias the decision towards the Na-ion battery as those are the key weaknesses of the lead-acid battery. The price factor will be quite meaningless should these other claims not be met. In fact, its relatively large footprint (higher transport cost) and non-flat discharge characteristic (more design considerations for the
inverter) may make it even less attractive. Of course, it should be borne in mind that the results presented in this dissertation are based on the early prototypes of the Na-ion battery. Future improvements of this new battery technology may or may not change the circumstances.
<table>
<thead>
<tr>
<th>Observations</th>
<th>Na-ion</th>
<th>Lead-acid (flooded and gel)</th>
<th>Li-ion (LiFeYPO4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage during discharge</td>
<td>• Voltage drops almost linearly with</td>
<td>• Voltage remains fairly</td>
<td>• Voltage remains fairly</td>
</tr>
<tr>
<td></td>
<td>discharged capacity.</td>
<td>constant throughout</td>
<td>constant throughout discharge,</td>
</tr>
<tr>
<td></td>
<td>• Large voltage swing - requires further</td>
<td>discharge, but with</td>
<td>with significant drop towards</td>
</tr>
<tr>
<td></td>
<td>design considerations in the inverter.</td>
<td>significant drop towards</td>
<td>charge depletion.</td>
</tr>
<tr>
<td>Internal series resistance</td>
<td>• Calculated to be approximately 600 mΩ</td>
<td>• Typically in the order of</td>
<td>• Typically in the order of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tens of mΩ.</td>
<td>tens of mΩ.</td>
</tr>
<tr>
<td>Self-discharge</td>
<td>• Early prototypes show high self-discharge.</td>
<td>• Typical self-discharge is</td>
<td>• Typical self-discharge is less</td>
</tr>
<tr>
<td></td>
<td></td>
<td>less than 15% per month.</td>
<td>than 5% per month.</td>
</tr>
<tr>
<td>Observed performance from</td>
<td>• Stable cycle (80 prototype) achieved at</td>
<td>• Stable cycle achieved at</td>
<td>• Stable cycle achieved at</td>
</tr>
<tr>
<td>the load simulation test</td>
<td>EE: 57.5% DoD: 67%</td>
<td>(average): EE: 75% DoD: 50%</td>
<td>EE: 99.5% DoD: 54.5%</td>
</tr>
<tr>
<td></td>
<td>• Battery shows low coulombic efficiency at</td>
<td>• In line with expectations.</td>
<td>• In line with expectations.</td>
</tr>
<tr>
<td></td>
<td>high charge currents.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Better EE figures are expected from</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>further tests.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other observations</td>
<td>• Battery requires relief valves to</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>prevent swelling caused by pressure build</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>up.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Sealing of terminals required to prevent</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>electrolyte leakage.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Size of battery is relatively large</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>compared to lead-acid and Li-ion batteries.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 9: Summary and comparison of test results.*
8. Conclusion

This project was set out with the following two main objectives:

- To revive the dormant battery test system (known as the BaSyTec) that resides in the former RISE Laboratory (now Engineering & Energy Lab) at Murdoch University.

- To assist the Client in understanding and evaluating the suitability of this new battery technology, the Na-ion battery, in PV-based RAPS applications.

The first objective has been successfully met, with the BaSyTec system now capable of running all four channels at once. A short user guide has also been written by the author to enable a continued operation of this system. In the process of getting the BaSyTec system up and running, a relatively simple “makeshift” test system was also developed to fill in the gap. A comparison of results between these two systems showed that the earlier results obtained from the “makeshift” test system is generally useable (refer to Section 5.3.2 for details). The BaSyTec system has been used for all other tests thereafter as it is a much more capable and flexible test system.

The second objective has also been largely met, though the Client has requested this project to be extended to enable more tests to be conducted, out of their own interests. To examine the suitability of this Na-ion battery for PV-based RAPS applications, two categories of tests were conducted, namely the characterisation test and the load simulation test. The characterisation tests revealed several interesting findings for this Na-ion battery (or at least for the prototypes given):

- The discharge voltage of the battery is non-flat, unlike conventional batteries such as lead-acid and Li-ion. The almost-linear voltage drop with respect to discharged capacity may impose additional design considerations for the inverter system. On the
other hand, this voltage drop may provide an easy way to determine the battery’s state of charge.

- The battery (specifically the B0V) showed high self-discharge in comparison to the lead-acid and Li-ion batteries. However, this may not likely be a problem if the battery is continuously cycled. A similar test by Aquion Energy on its latest prototype (B1) demonstrated that this problem is not present.

- The batteries showed relatively high internal series resistance (about 600mΩ), in comparison to tens of mΩ in lead-acid and Li-ion batteries. The likely implication of this is that the battery’s capacity will be severely limited at high discharge currents.

The aim of the load simulation test is to evaluate the battery’s performance under real-world usage. Two lead-acid batteries (flooded and gel tubular type) and a Li-ion battery were included in the tests for comparison. A sample load profile was used for the tests, and the results are as follows:

- Determining the Na-ion battery’s optimum balance between EE and DoD has been quite a challenge. The preliminary results appear to indicate that this battery will not have an EE of greater than 80% for a DoD of greater than 50%.

- The Li-ion battery achieved an EE of 99.5% at a DoD of 54.5%.

- The lead-acid batteries, on average, achieved an EE of 70% at a DoD of about 50%.

Further analysis of the results established that the Na-ion battery’s performance under this given load profile is limited by its low coulombic efficiency at high charge currents. In this aspect, the Li-ion battery offers superior performance over the Na-ion and lead-acid batteries.
The load simulation test was also found to be quite a difficult task, and this is mainly due to the lack of experience in conducting such tests. This is further complicated by the downward sloping discharge curve of the Na-ion battery, which makes determining the battery’s energy efficiency more difficult. Nevertheless, the groundwork laid out in this report should make future tests of similar nature a little easier.

Overall, this short-term testing on the prototype Na-ion battery shows that its performance is not quite on par with the lead-acid batteries. Nevertheless, further tests are still required to see if the battery can really meet its claimed specifications. Apart from that, long-term tests and studies are also required on other aspects of this battery technology, i.e. its claimed lifetime of greater than 5000 cycles, its ability to operate at high temperatures (up to 60ºC) and at PSoC without any negative effects, and if it can be manufactured at a lower cost than lead-acid batteries. Only then can it be decided if the Na-ion will be a worthwhile replacement for the incumbent lead-acid batteries.
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Appendix A – Photos of Test Activities

Test setup for the LabView test system (PC not shown).

DT50 data logger used in the LabView test system setup.
Test setup for the BaSyTec system.

Sonnenschein A602 solar battery
Appendix B – Additional Graphs

(Na-ion (B0V) voltage characteristics.

Comparison between Na-ion (B0) 1A discharge using LabView system and BaSyTec system (non-normalised curve).
Appendix C – A Quick Guide to Using BaSyTec

Introduction

The BaSyTec system is an integrated battery test system which can perform tests and log data simultaneously. This document seeks to provide a “quick-and-dirty” guide to new users wanting to operate the BaSyTec system. For more details or advanced operations, kindly refer to the BaSyTec hardware and/or software manual.

Getting started

To get started, ensure the following is available:

- A 3-phase power supply for the BaSyTec system.
- A desktop PC connected to the BaSyTec system, with the BaSyTec software installed.
- RS232 (serial) cables. For desktop PCs with limited serial ports, a USB-to-RS232 converter can be used (the ATEN UC-232A converter is verified to be compatible).
- Test leads for connecting the test batteries to the BaSyTec system.

The Hardware

The BaSyTec system available at the (former) Engineering & Energy Lab is made up of two modules (which can be switched On and Off independently). Each module is made up of two test channels, giving the system a total of four test channels. Each test channel is rated at 18V/50A. The following diagram explains the terminals on a single channel:
## Out terminals
The output terminals are connected directly to the battery terminals. “+Out” to the positive battery terminal, “-Out” to the negative battery terminal.

## Sense terminals
The sense terminals are used for sensing the battery’s terminal voltage. The connection is similar to the “out” terminals. For accuracy, the sense terminals must be connected directly to the battery terminals (instead of sharing the same wire as the “out” terminals).

## Aux terminals
A special orange-coloured connector is used to connect the auxiliary terminals. These terminals can be used for other user-defined measurements, such as temperature or digital input.

### The Software

#### General user interface
On launching the BaSyTec software (basytec.exe), it will automatically check if the desktop PC serial ports are connected to the BaSyTec system. The user will be prompted with an error message if it is not done so. Simply clicking “OK” will allow you to proceed.
Next, the user will be prompted to enter a password. Leave the password field blank and click “Ok” to proceed, or “Cancel” to exit the program. The following shows the main screen when the program is loaded, known as the “Database of tests”.

The important buttons to remember:

[1] – Database of tests: Shows the list of tests that have been run or is currently running. This is the default screen on launching the program.

[2] – Battery database: Use this section to define the parameters for a new test battery, if it is not already an existing battery in the database.
Online measurement table: This window will allow the user to monitor the tests that are currently running (i.e. monitor voltage, current, temperature, Ah and etc.).

To switch between windows, click on “Window” in the toolbar and select the appropriate entry.

Creating a new test plan

A test plan is list of program steps that defines how your test runs. To create a new test plan, select File->New. The following shows the new test plan editor window:

Notice that some texts are in German. To change it to English, select Extra->Language->English->OK. This may have to be performed every time the test plan window is opened – a minor bug in the BaSyTec program.

The commonly used fields/columns in the test plan editor are described as follows:

<table>
<thead>
<tr>
<th>Command</th>
<th>What to do in the program step, e.g. charge, discharge, pause, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Command-dependent parameter, e.g. charge at 1A, pause for 10s, etc.</td>
</tr>
<tr>
<td>Termination</td>
<td>Criteria to exit the command step, e.g. t=10s; go to next step when timer counts 10s.</td>
</tr>
</tbody>
</table>
How the data defined in the “Registration-Format” should be recorded for this particular step. For example:

$t=10s$; record data every 10 seconds.

$U=1V$; record data every time the voltage increments by 1V.

| Registration | How the data defined in the “Registration-Format” should be recorded for this particular step. For example: $t=10s$; record data every 10 seconds. $U=1V$; record data every time the voltage increments by 1V. |
| Comment | A field to enter comments – does not affect how the program runs. |
| Label | Defines a name for a particular step, can be left blank. |
| Action | The default action is to go to next program line. The program can jump to a defined “Label” by using the “Goto” command. This action will be executed when the Termination criteria is met. |

To select the settings for each of these fields, double click on the selected cell. Remember to click on “Use” to make the settings effective. Clicking on “Ok” will not do anything other than to close the dialog box. The test plan can be edited during “run” mode, but will only take effect after it has been stopped and re-run. The following table lists the “commands” that can be used.
<table>
<thead>
<tr>
<th>Command</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>I, U, P</td>
<td>Charge with the parameters of the parameter field</td>
</tr>
<tr>
<td>Discharge</td>
<td>I, U, P</td>
<td>Discharge with the parameters of the parameter field</td>
</tr>
<tr>
<td>Pause</td>
<td>---</td>
<td>Open circuit, OCV relays is open, current =0</td>
</tr>
<tr>
<td>Ramp-i</td>
<td>I1: Start value Slope: slope I2: limitation</td>
<td>Current ramp with limitation</td>
</tr>
<tr>
<td>Ramp-u</td>
<td>U1: Start value Slope: Slope U2: Limitation</td>
<td>Voltage ramp with limitation</td>
</tr>
<tr>
<td>Set</td>
<td>Ah-Set, W-Set, t-Set, Ah-Ch-Set, Ah-Dis-Set, Wh-Ch-Set, Wh-Dis-Set</td>
<td>Setting of counters and timers</td>
</tr>
<tr>
<td>Set-Temp</td>
<td>T: Temperature H: Humidity</td>
<td>Set of the control parameters (temperature and humidity) of a connected climate chamber</td>
</tr>
<tr>
<td>Table</td>
<td>file: Name of data file t: column of time I: column of current U: column of voltage P: column of power repeat: Repeat table timeformat: Format of time</td>
<td>Use a ascii data table as load profile</td>
</tr>
<tr>
<td>Calculate</td>
<td>free definable</td>
<td>on-line calculation of equations</td>
</tr>
<tr>
<td>Cycle-Start</td>
<td>-----</td>
<td>Begin of loop</td>
</tr>
<tr>
<td>Cycle-End</td>
<td>Anzahl, Count</td>
<td>End of loop</td>
</tr>
<tr>
<td>@...........</td>
<td>different</td>
<td>Subroutine</td>
</tr>
<tr>
<td>Result</td>
<td>State</td>
<td>Store special marked data sets</td>
</tr>
<tr>
<td>Extern*</td>
<td>-----</td>
<td>Connect battery with external load/charger</td>
</tr>
</tbody>
</table>
**Running a test**

To run a test, ensure the following is ready:

- The battery is connected to one of the BaSyTec channels.
- A test plan is ready.
- The battery is already defined in the battery database.

Steps to run a test:

1. Click File-&gt;Open and select the appropriate test plan (a file with .pln extension).

2. The test plan window will open. Ensure the column “Registration” is defined for the associated command (e.g. t = 1 min) for data logging to work.

3. Click on the “Registration-Format” button to select the parameters to be logged (e.g. T1 [temperature], Wh-Charge, Wh-Discharge, etc.).

4. Save the settings for this test plan.

5. Click on the blue “play” button to begin the test.

6. A window will pop-up to prompt the user to select the correct test channel and battery type.
7. Ensure the correct test channel is selected (check the label on the test channel the battery is connected to). S1 CH00 refers to module 0, channel 1; S1 CH01 refers to module 1, channel 1. Then, select the correct battery from the list. Enter a test name and some comments for the test if desired.

8. Clicking “Ok” will begin the test. The “online measurement table” window will be automatically opened to show the running test.

9. To pause the test, click the yellow “pause” button. Clicking on the red “stop” button will terminate the test, which cannot be resumed.

Running a load simulation test from a file

The steps required to run a load simulation test from a file is the same as above. The only difference is that the “Table” command must be used. To load the load profile into the test plan, double-click parameter and a dialog box will pop-up. Click “open folder” in the “Data source” field to locate the directory the file is stored, and select the file. If the file is successfully located, the first 10 data lines of the file will be displayed. To really check if the data file is loaded into the test plan, close the dialog box and reopen it. If there is an error reading the data file, a “No data file” error message will be displayed in the dialog box. Each column must be assigned with the correct “value”. If the first column in the data file is Time, then make sure the “Time” is associated with 1. If the second column in the data file is Power, then check “power” and associate it with 2. The default time scale is in seconds – if the data file is made up of 1-minute resolution data, enter 60 into “Factor”.

Some other issues to take note:
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- The load profile data file should be in tab delimited form with a .txt or .prn extension. Such a file can be easily made using MS Excel (File->Save As->Tab delimited (*.txt)).

- As a dated program, the BaSyTec requires a strict naming convention to function correctly.
  - Name the files without spaces, e.g. "load_1.txt" instead of "load 1.txt"
  - Put the load files into the simplest directory possible, e.g. “c:\basytec_load” instead of “c:\user files\basytec_load”. Again, the directory name should not contain any spaces – use underscore instead.
**Downloading data**

The “data table” can be accessed from either the “Database of tests” or from the “Online table”. In “Database of tests”, right-click on the test name and select “data table”. In “Online table”, click on the “data table” button. The following shows the “data table” screen.

In this screen, the user plot a graph based on the data collected (the default plot is voltage vs. time). The X and Y parameters can be changed by selecting the entries in the X/Y Field Name drop-down list. The data can be exported in two forms; as a comma or tab delimited text file or as an MS Excel file. The latter is preferred as it allows direct data manipulation using MS Excel. To export the data as a text file, click on the “Export” button. To get the data in .xls format, click on the “Excel” button.