



RedFlow White Paper

Field Application Experience of Zinc-Bromide Flow Batteries in a Smart Grid

Rising electricity demand and the intermittency of renewable energy sources have contributed to the development of Smart Grid technologies, including energy storage. This study investigates the use of zinc-bromide module (ZBM) batteries in an Australian Smart Grid trial, and how this type of energy storage can be used to address several new and challenging issues facing electricity utilities, such as grid instability, reliability and growing peak demand. As part of this trial, sixty ZBM-based energy storage systems (ESS) were installed at residential dwellings and operated under utility control. The financial case for implementing such projects on a wider scale was also investigated. It was concluded that ZBMs themselves are reliable and highly effective in a range of Smart Grid applications.

1 INTRODUCTION

INCREASING electricity usage, international environmental concerns and their associated technical challenges have necessitated significant changes to the existing electricity infrastructure in many countries. Further advances in technology, especially in the communications sector, have also enabled additional monitoring of the electricity network. Two-way communications coupled with two-way power flows from new types of embedded generation have contributed to a revolution away from the traditional power grid. This is known as a Smart Grid, which “integrates and enhances other necessary elements including traditional upgrades and new grid technologies with renewable generation, storage, increased consumer participation, sensors, communications and computational ability” [1]. Energy storage plays an important role in Smart Grids to achieve improved efficiency, reliability, sustainability and economic viability [2].

This paper provides an overview of zinc-bromide battery module (ZBM)-based energy storage supplied by RedFlow Limited (RedFlow) and installed as part of the Smart Grid, Smart Cities (SGSC) trial in Australia. It investigates the effect of ZBM-based energy storage on the reduction of peak demand, improvements in reliability and power quality, peak price events, and scalability to megawatt (MW)-sized systems.

This paper will begin with Section 2 as a background to the ZBM technology designed and used by RedFlow, as well as a brief summary of the SGSC trial. Section 3 then outlines the methodology used in analysis, before Section 4 presents the results from the study of data, including an investigation of the business case for this type of residential energy storage system. Following this, Section 5 provides an overview of the top-level lessons learnt and further direction for research into using energy storage in Smart Grid applications. Section 6 will then highlight the major conclusions drawn from the study presented in this paper.

2 BACKGROUND

2.1 ZBM Technology

There are many types of energy storage in a wide variety of applications. This paper will primarily address ZBMs manufactured by RedFlow. The ZBM is a 5 kilowatt (kW)/10 kilowatt-hour (kWh) battery module. The components of RedFlow's ZBM are shown below in Figure 1.

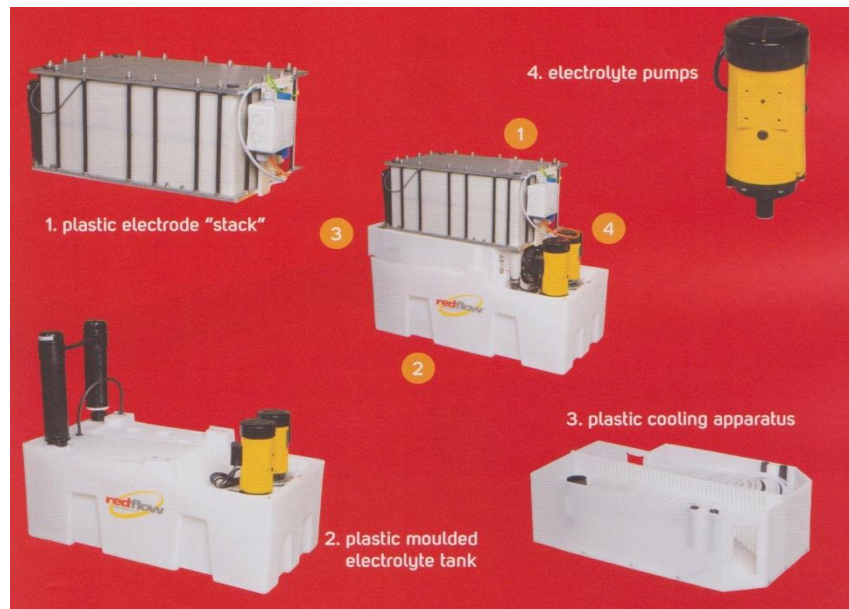


FIGURE 1: The components of a ZB battery [3]

The operation and chemical reactions of the ZBM flow battery differ significantly from conventional battery technologies, such as lead acid batteries. The ZBM stores electricity by electroplating zinc onto its plastic electrodes and then reverses this process during its discharge cycle. The flow of electrolyte, which contains additional zinc ions, between the stacks and tanks during charging and discharging is facilitated by a set of two pumps. Coupled with charging and discharging in a ZBM's regular cycle is the 'strip' period. This is required regularly for healthy operation of a ZBM, and involves stripping the stacks of all zinc. The ZBM has the ability to operate to 100% depth of discharge on a daily basis without reducing its lifetime. Furthermore, as a primarily plastic product with no rare earth metals, the ZBM has the potential to provide very low-cost energy storage when produced in large volumes.

RedFlow's ZBMs require power electronics and other integration equipment to operate as a grid-connected energy storage system (ESS). RedFlow produces a small number of technology demonstrator ESS that are all based on its ZBM flow battery technology. The R510 ESS was used in this study trial. It contains one ZBM, a battery management system, remote terminal unit (RTU), inverter and 3G modem that enables remote communications and control of the ESS by the electricity utility. All components are housed in a metal enclosure.

2.2 SGSC Trial

This study uses the SGSC trial as the basis for an analysis of the use of energy storage in Smart Grids. The SGSC trial is currently taking place in eastern New South Wales, Australia (see Figure 2). In its entirety, it will involve at least 30,000 households over three years.

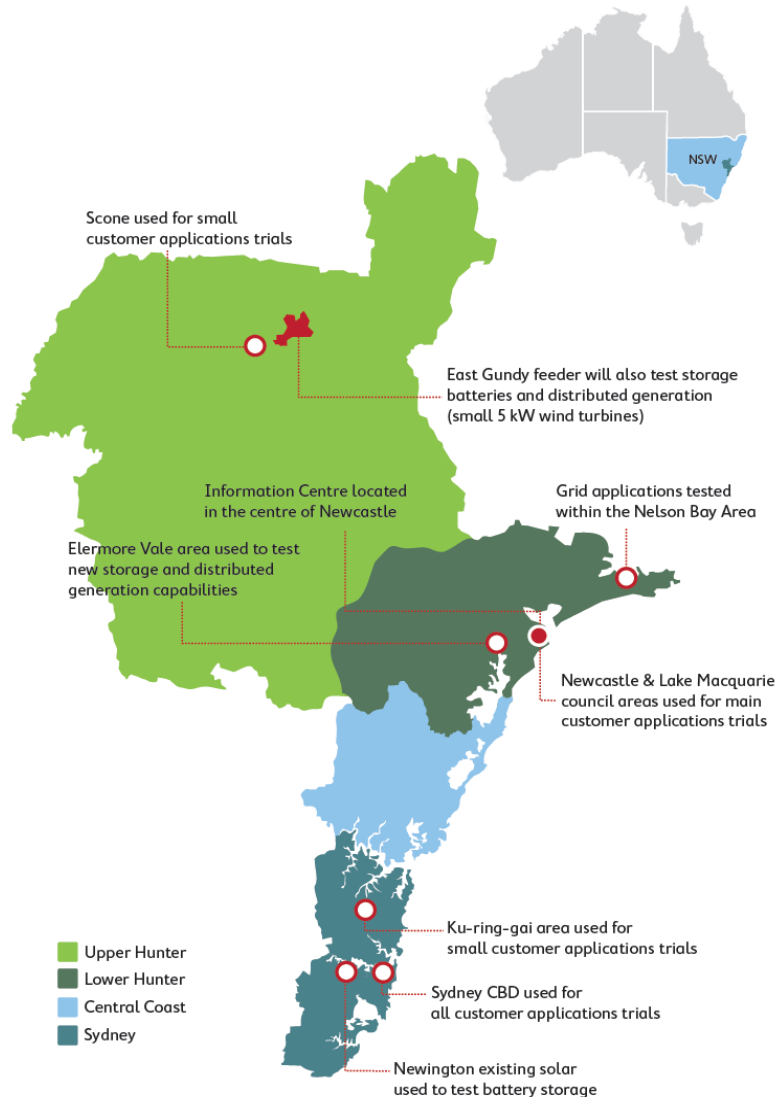


FIGURE 2: The various locations of different elements of the SGSC trial [4]

The SGSC trial is designed to test nine key hypotheses about Smart Grid operation, one of which is solely concerned with investigating the use of energy storage. In particular, there are seven potential benefits of energy storage to be tested:

- Reduction in peak demand
- Improvement in network reliability/voltage/power factor/power quality
- Energy supply during peak price events
- Minimisation of customers' energy bills
- Combined benefit between consumer, retail and network sectors
- Investigation of large capacity (~1MVA) storage
- Intermittent generation support

As part of the energy storage trial, RedFlow has installed 60 of their R510 ESS (5kW, 10kWh) (see Figure 3), each at different residential dwellings. The first 40 ESS are located in Newcastle, Australia and began operation in February 2012. These were followed by a further 20 ESS in Scone, Australia, which began operation in May 2012. During the trial, the RedFlow systems have addressed all of the seven potential benefits of energy storage in some way.



FIGURE 3: Two R510 ESS being installed in Newcastle

3 METHODOLOGY

There were many steps taken for data-gathering and analysis in this study. This included monitoring, optimizing systems and extensive analysis of raw data. Data was primarily collected from two sources. Firstly, each ESS collects operational and diagnostic data through the use of their RTU, which is regularly logged and sent to the utility's server via a 3G communications link. RedFlow's proprietary software, the HOST, is used to log the data, control the operation of the R510s, and provide diagnostic capabilities. However, in this project, access is only available via the utility for reasons of customer privacy. Secondly, the utility has monitoring equipment on their own infrastructure that sends information such as grid voltage and power levels at certain feeders. This information is sent to the utility through 3G communications links and manual readings of meters on site.

Monthly compilation and analysis of data for operational systems allowed a broad overview of the performance and reliability of the ESS. The utility has also been monitoring and controlling other Smart Grid devices, such as hot water systems, electric vehicles, air-conditioning units and distributed generation.

4 RESULTS AND ANALYSIS

The results obtained from the SGSC trial involving the RedFlow R510 ESS are presented in this section. It will cover four of the seven aforementioned potential benefits of energy storage being tested during the trial, in the areas of peak demand reduction, improvements in network reliability and power quality, peak price events and scalability to MW-sized systems. The business case for the R510 is also addressed.

4.1 Peak Demand Reduction

Results from analysis of feeder data in one area of Newcastle show that RedFlow's ESS can be used to effectively reduce peaks in demand seen by the grid during traditional evening peak periods.

An indication of the average 24-hour demand on the 11kV feeder supplying the area of Newcastle where forty R510 ESS are installed is shown in Figure 4, where the average and highest demand day are shown. The average has been taken over a six month period from July to December 2012. As can be seen, the average load shows expected peaks in the morning and evening, with higher than expected load during the night. This is partly due to the use of automated hot water systems in this area that charge during this traditional off-peak time.

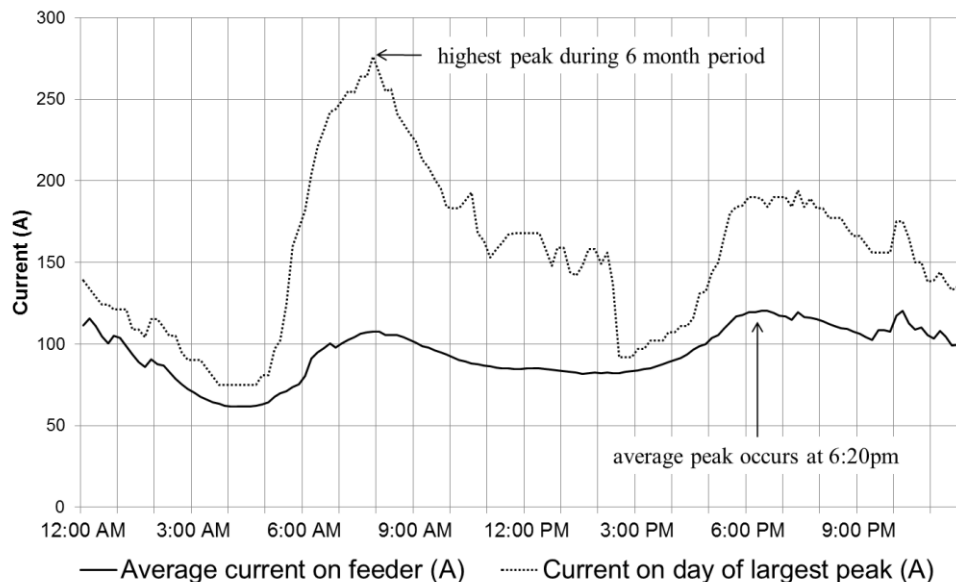


FIGURE 4: The average and peak demand seen on the 11kV feeder supplying the trial area in Newcastle

The daily peak reduction capability of the R510 ESS is shown in Figure 5.

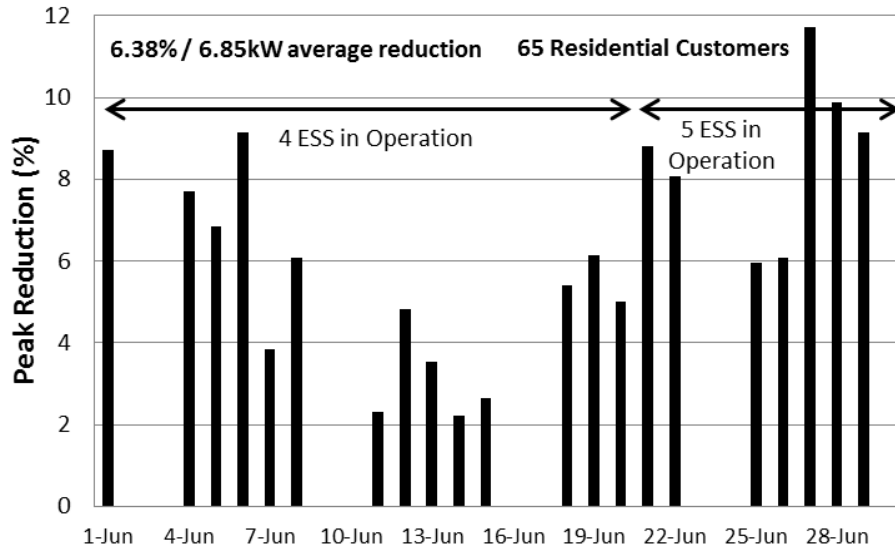


FIGURE 5: The reduction in peak demand from the use of RedFlow energy storage seen in one area of Newcastle in June 2012

As seen in Figure 5, with four ESS in operation at a ratio of about one 5kW/10kWh ESS for every sixteen residential customers, the average reduction in peak demand seen by a low voltage distributor in the winter month of June was 5.31%. In the latter part of June with five R510s connected to this distributor at a ratio of about one ESS for every thirteen residential customers, the average reduction in peak demand was 8.52%. A ratio of one ESS for every five residential customers could thus reduce the peak by an average of 15-20%.

Furthermore, the ESS in this part of Newcastle have shown that when peaks of load and peaks of energy storage discharge occur at the same time, the reduction in peak demand can be over 10%, as seen below in Figure 6.

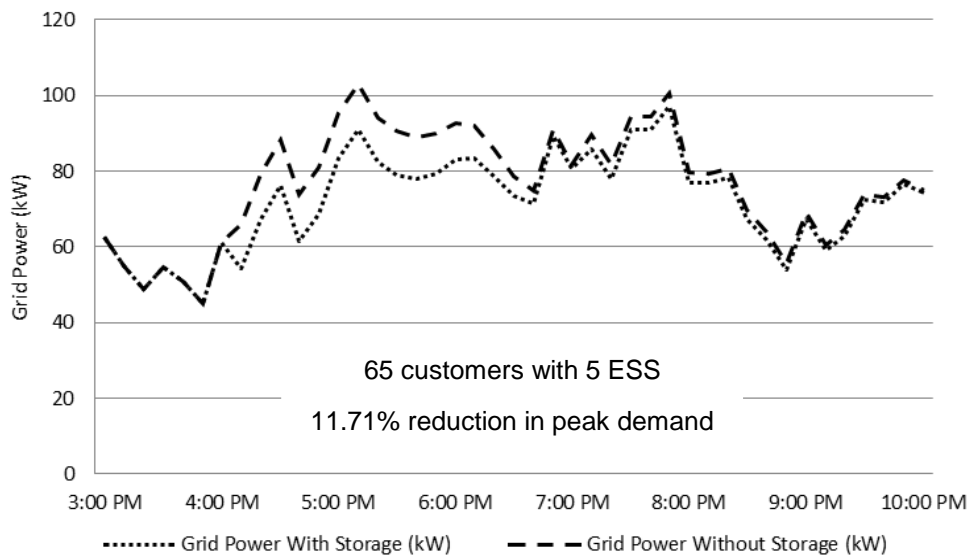


FIGURE 6: A day of high reduction in peak demand from the use of RedFlow energy storage seen in one area of Newcastle in June 2012

In the more rural area of Scone, the use of energy storage during the winter month of June at a ratio of approximately one ESS for every one residential customer has shown that a high penetration of energy storage in one area can significantly reduce the peak load seen by the grid. As can be seen in Figure 7, a significant trough replaced the peak during traditional peak periods.

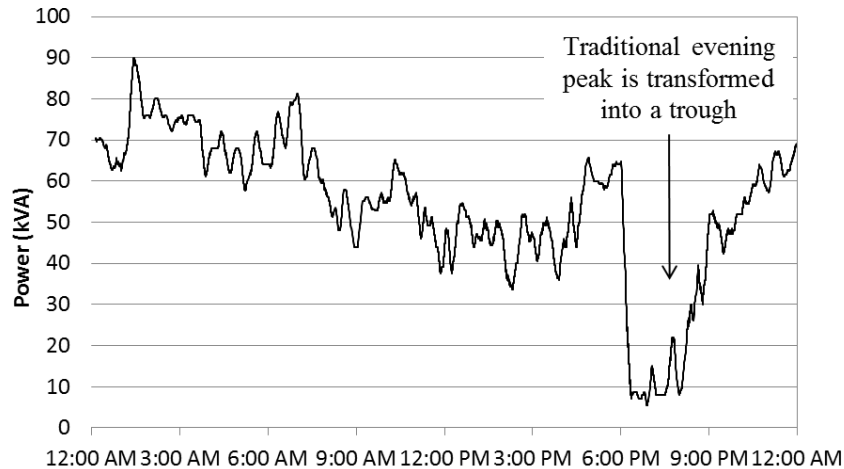


FIGURE 7: The average demand seen on the grid at Scone in June 2012, where a trough can be clearly seen to replace the traditional evening peak

4.2 Network Reliability and Power Quality

4.2.1 Voltage Support

Further to peak demand management, the R510s in this trial were also used to investigate the use of energy storage in supporting grid voltage in a residential kilowatt-scale Smart Grid application. While the ESS in Newcastle were installed in suburban areas with relatively reliable electricity, the R510s showed the capability of zinc-bromide flow batteries in voltage support. This is shown in Figure 8 below, where it should be noted that grid voltages were only recorded during times of R510 operation, and were recorded as 0V at all other times.

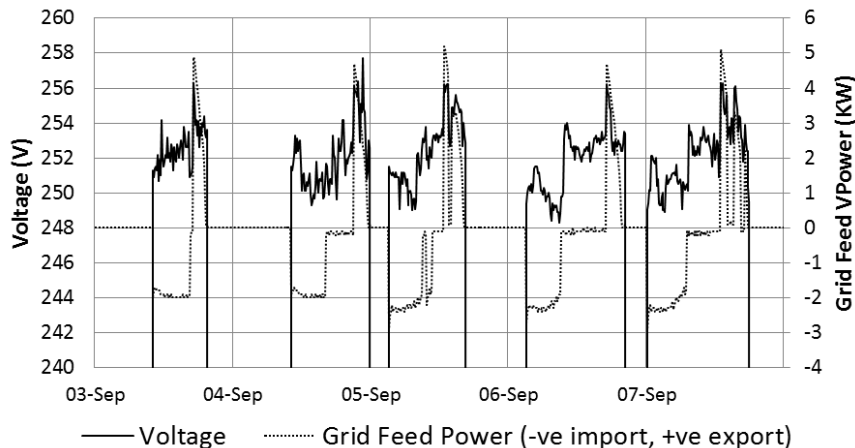


FIGURE 8: Voltage support capability of R510s in Newcastle in September 2012

It can be seen from Figure 8 that the grid voltage rose when the R510s discharged, or exported into the grid during peak demand periods. Furthermore, the last three days shown in Figure 8 in particular, represent the ways that energy storage can also be used to reduce grid voltage by importing, or charging from the grid during the day. This coincides with times of higher solar penetration, which has been seen to raise grid voltages. The R510s installed in Scone show similar behaviour, as shown in Figure 9.

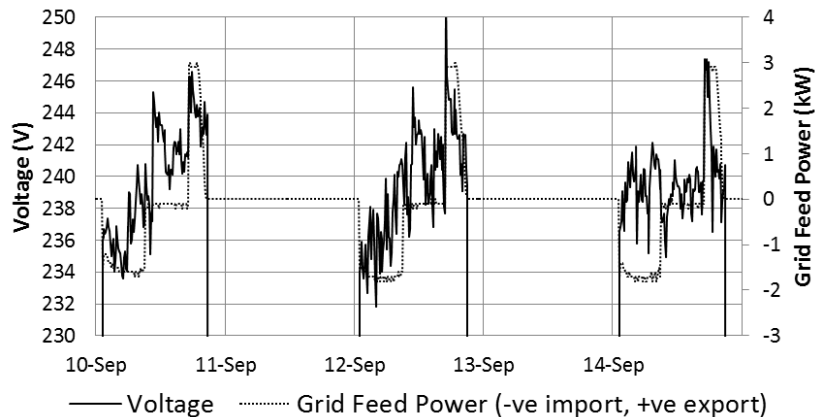


FIGURE 9: Voltage support capability of R510s in Scone in September 2012

As such, energy storage can be used to manage the voltage rise associated with distributed generation, as well as with the sags associated with peak demand periods.

4.2.2 Reactive Power Control

The reactive power dispatch capabilities of the inverters in the R510 ESS have also been tested using a simultaneous test using some of the systems installed in Newcastle. As can be seen in Figure 10, the usual reactive power consumption seen on this feeder is transformed into reactive power supply during times of dispatch. This test used pre-determined periods of dispatch, and extra trials are required to test any kind of capability that reacts to real-time reactive power on the grid. Regardless, this test has shown that this kind of ESS can be used to support assets such as Static Var Compensators (SVC) in improving power factor and smoothing voltage fluctuations.

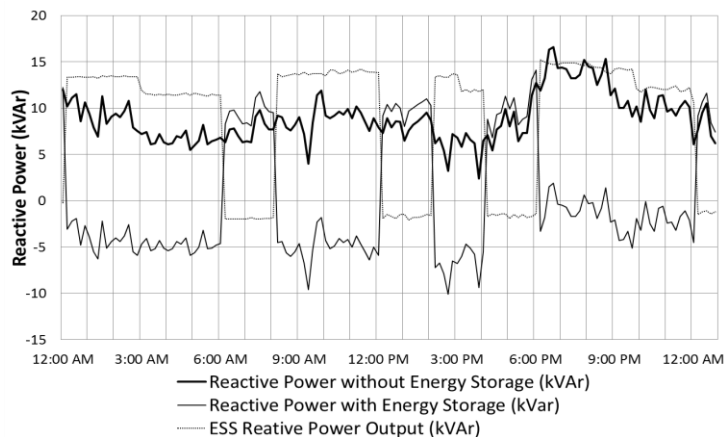


FIGURE 10: Reactive power dispatch capabilities of R510s in Newcastle in November 2012

4.2.3 Reliability of R510 ESS

The R510 ESS were installed in the SGSC Trial as technology demonstrators, not commercial systems. As such, RedFlow has engaged with ongoing maintenance of operational issues experienced throughout the trial thus far, which has significantly contributed to the learnings gained from the trial. On average, 76.88% of the R510s have been operational from the date of each system's installation to mid-December 2012 (a period of at least 6 months for each system). However, the reliability of RedFlow's ZBM batteries themselves has been much higher, at an average availability of 93.63% over the same period. Therefore, this shows that RedFlow's core technology is strong, and has performed well in the Smart Grid application. In order to increase the reliability of the ESS, work would most efficiently be allocated in improving the system integration of ZBMs into ESS. This is reflected in the direction that companies such as RedFlow are taking in their turn towards a 'system integrator' approach. This involves interested third-party companies that take on the work required to integrate DC batteries (such as the ZBM) into AC ESS. These companies have far more expertise in system integration, and are far better placed to meet the extensive requirements of utilities.

4.3 Peak Price Events

Some preliminary tests using RedFlow's R510 ESS to reduce demand on the network during forecast peak price events have been performed. This involved pre-programming the R510 ESS in Newcastle to discharge during the scheduled peak price period at 4pm on the test day. However, in reality, the peak actually occurred ten minutes early, thereby meaning that the peak was 'missed' by the energy storage. As such, it was found that longer duration energy storage is useful for reducing the peak during peak price events, to allow for flexibility between forecast and actual peak times. While the R510s could have been programmed to discharge over a longer period like four hours, this would have resulted in lower discharge rates, and as such, the effect of energy storage on the peak event would have been less pronounced. Another solution would be to install a higher penetration of energy storage into the trial area. Alternatively, a more elegant solution involves "real-time" control of ESS, where ESS react dynamically to grid characteristics such as power or voltage and charge or discharge accordingly. While RedFlow has demonstrated this capability with one R510 ESS in another related Smart Grid trial, this requires extra infrastructure that was not implemented as part of the SGSC trial.

4.4 Scalability of RedFlow ESS

RedFlow have already made significant progress in developing their kW-sized R510 ESS into scaled-up, modular larger systems. In early July 2012, RedFlow installed and commissioned a 90kW, 240kWh M90 ESS into the field at the University of Queensland in Brisbane, Australia (see Figure 11), operating to support a solar PV array.



FIGURE 11: The M90 (bottom right) installed next to a 340kW-peak solar array at the University of Queensland

The M90 is comprised of 24 of RedFlow’s ZBMs with power electronics including 18 5kW inverters, all housed in one 20-foot shipping container. The system is located next to the 340kW-peak solar PV array that it is supporting. Thus far, the M90 has operated in a number of applications, including renewables shifting and peak demand shaving, as well as early trials of renewables firming. A similar system, the M120 that is rated at 120kW, 360kWh, will be installed and commissioned at the University of Queensland in 2013 in a different application. Instead of operating next to a solar array to support its output as the M90 does, the M120 will be situated in the basement of a new building to support the building’s load and own distributed generation.

However, this size of ESS represents the upper limit of systems relying on the types of low voltage topologies used in the M90 and M120. As such, in 2013, RedFlow will continue its research on the development of an energy storage system that operates at higher DC voltages, allowing for the use of megawatt-scale inverters. There is industry recognition that this is a necessity for grid-connection in distribution networks.

4.5 R510 Business Case

The value of energy storage varies depending on the parties involved and application it is used in. Broadly speaking, there are three main value streams for a residential ESS like the R510. These are outlined in the following sub-sections.

4.5.1 Electricity Bill Savings for End Customers

The value of energy storage to end customers is primarily through reductions in their electricity bills. This is most effectively done on a Time of Use (TOU) tariff structure, where they are charged at a variable rate depending on the time of day that they consume electricity: it is most expensive during traditional evening peak times and least expensive during traditional times of low demand. The utility’s TOU tariff structure from mid-2012 is shown in Table I below [5].

TABLE 1: The Utility’s Time of Use tariff structure [5]

Applicable Charges	Times of Day	Price (Goods and Services Tax inclusive)
Peak Consumption	Monday to Friday 2pm – 8pm	\$0.52547/kWh
Shoulder Consumption	Monday to Friday 7am – 2pm, 8pm – 10pm Saturday, Sunday, Public Holidays 7am – 10pm	\$0.2134/kWh
Off-Peak Consumption	All Other Times	\$0.1309/kWh
Daily Supply Charge	All Days	\$0.8217/day

From Table 1, the savings to the end customer at the Smart Home can be estimated, shown in Table 2 below. Data from the Newcastle R510s was used to calculate the average daily import and export by the ESS. The inefficiencies of the R510 have already been taken into account when calculating the total costs and savings.

TABLE 2: Savings to the end customer with an R510 [5]

	Electricity Price Tariff (\$)	Average Daily Energy Imported/Exported by ESS (kWh)	Total Cost for Month (\$)	Total Cost for Year (\$)
Off-Peak Import	0.119	11.55	42.22	\$494.61
Peak Export	0.4777	6.72	96.25	\$1155.01
Total Saving			\$55.03	\$660.40

Therefore, if an R510 were operated every weekday, the total monthly saving in electricity bills alone would be \$55.03, which equates to a saving of \$660.40 each year. This uses the TOU tariffs detailed in Table 1 above. As such, for 5 years of operation, the value of an R510 to the end customer in electricity bill savings alone would be \$3300. For 10 years, the value would be \$6600.

4.5.2 Transmission and Distribution Investment Deferral for Utilities

In addition, utility access to ESS can provide many other benefits, such as peak shaving that defers the need for infrastructure upgrades. The following table shows estimates from the Electric Power Research Institute (EPRI) [6] for the value of energy storage in transmission and distribution investment deferral to utilities over the lifetime of the energy storage (see Table 3).

TABLE 3: Value of energy storage in investment deferral to utilities [6]

Benefit	Present Value for 10kWh R510 (\$)	Present Value for 5kW R510 (\$)
Distribution Investment Deferral	1570	1490
Transmission Investment Deferral	4140	5370
Total	5710	6860

Therefore, for a 5kW, 10kWh R510 ESS, the target distribution deferral savings would be approximately \$1500 over its life. Furthermore, if R510 ESS were installed on a large scale throughout the transmission network, additional savings in transmission deferral would be between about \$4000 and \$5000 over the R510's life. This gives a total benefit of approximately \$6000 over the lifetime of an R510.

4.5.3 Supporting Renewable Generation for End Customers and Utilities

The last value stream of energy storage supports renewable generation. Current utility responses to over-penetration of distributed renewable generation usually results in simply disconnecting units from the grid until loads increase or generation decreases. Instead, energy storage is beneficial for end customers since it can store energy generated by renewable sources (such as rooftop PV panels) and discharge it during times when the residential load is greater, or when feed-in tariffs are higher (both usually during traditional peak periods). This is also beneficial to utilities, who also wish to shift renewable generation to peak periods. This supports overloaded infrastructure during peak consumption periods and lowers high voltages and other side

effects of high renewables penetration during peak generation periods (such as the middle of the day in areas with high rooftop PV penetration). Table IV below shows estimates from EPRI [6] for the value of energy storage in renewable energy integration and voltage and reactive power support to utilities over the lifetime of the energy storage.

TABLE 4: Value of energy storage in renewable integration and support to utilities [6]

Benefit	Present Value for 10kWh R510 (\$)	Present Value for 5kW R510 (\$)
Renewable Energy Integration	1040	1490
Voltage and Reactive Power Support	130	205
Total	1170	1695

Therefore, for a 5kW, 10kWh R510 ESS, the target renewable energy integration savings would be approximately \$1200 over its life, with a further \$170 saved due to voltage and reactive power support. This gives a total benefit of approximately \$1400 over the lifetime of an R510.

4.5.4 Total Value Benefit of R510 ESS

The total benefit from these three value streams for 5 years of operation is therefore approximately \$10 700. For 10 years of operation, the value of an R510 would be \$14 000. It should be noted that the customer benefits in electricity bill savings does not take into account inflation or other similar variables. Therefore, in order for the R510 to be a viable product in the commercial market, its total capital and operational costs must be under \$10 000 to be attractive for joint utility and end customer investment. This corresponds to a total capital cost of less than \$2000/kW and \$1000/kWh for an ESS with power electronics installed in the field.

However, it is also important to note that the value of energy storage depends on which stakeholder has control over its operation. For customers, financial returns on energy storage come almost exclusively through reductions in their electricity bills. This is of most benefit to end consumers when they are operating on a TOU tariff structure.

In Australia, the distribution and retail sides of utilities are separated to encourage competition. As such, the real value of energy storage to transmission and distribution utilities comes from the reduction in peak demand seen on the highest-use days of the year. This leads to the ability to defer infrastructure upgrade investments. A secondary benefit of energy storage to transmission and distribution utilities is improved power quality in areas around the energy storage.

Conversely, for retailers, the value of energy storage is most pronounced when operating at times when it is most expensive to buy electricity from generators. This may not correspond to times of highest electricity cost on TOU tariffs, or at times of peak demand seen by the grid. As such, energy storage can serve multiple uses for different stakeholders, which may or may not be complementary. However, the multi-hour discharge capability of zinc-bromide batteries makes it suitable for all of the value streams mentioned above.

There are also other benefits to installing an ESS like the R510. A single-unit trial that is related to the SGSC Trial has shown how an R510 operated in conjunction with a residential load, an electric vehicle (EV) and distributed generation. It has been shown that the R510, with minor modifications to its hardware and RTU

firmware, is capable of dynamically reacting to the load and generation, to maintain a programmed operation with the grid. For example, Figure 12 below shows that on this sample day, the R510 reacts dynamically to the solar output, fuel cell output and load consumption from the hours of 7am to 9pm. In doing so, it is supporting the EV load until the ZBM is fully discharged, which also defers any load seen by the grid until after the traditional peak period. At almost 3kW, the EV load is significant and in large numbers, would cause significant impact on the grid without energy storage or reliable and sufficient embedded generation (for example, a higher output fuel cell).

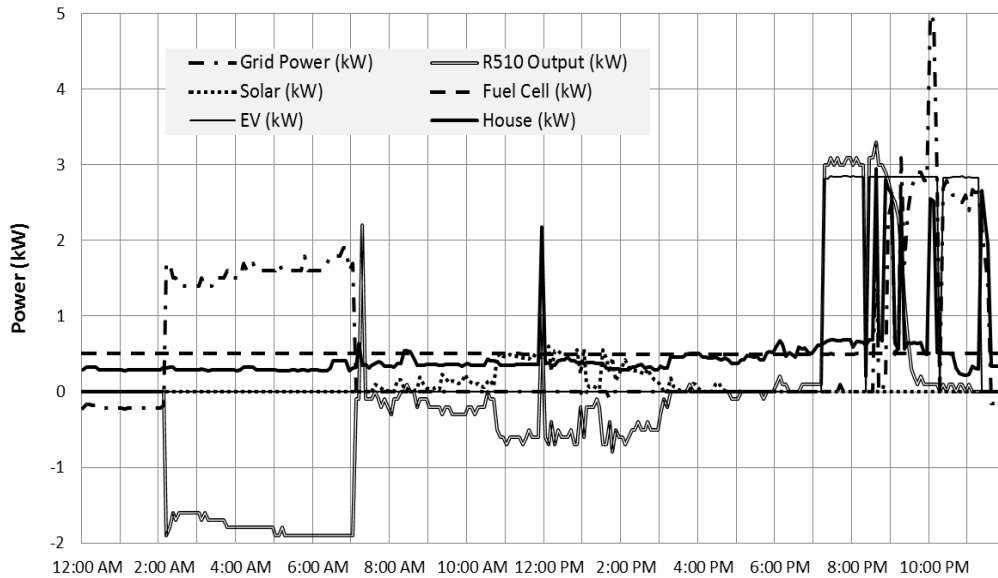


FIGURE 12: A graph showing the dynamic capabilities of the R510 ESS

5 LESSONS LEARNT

5.1 Success of ZBM Technology in Smart Grid Applications

The performance of R510 ESS based on RedFlow's ZBM technology has shown that significant issues facing utilities, such as rising peak demand and network stability can be addressed using zinc-bromide flow battery energy storage. A distribution of 10kWh of energy storage for every one customer has shown that traditional demand peaks can be transformed into troughs. While this level of penetration may not be economically viable, a distribution of 10kWh of energy storage for thirteen customers has been shown to reduce peaks by an average of over 8%, a level at which expensive traditional infrastructure upgrades can be deferred.

Furthermore, the use of R510s in the voltage support application has shown that energy storage can reverse the voltage rise associated with high penetrations of intermittent renewables and distributed generation at predictable times of day, for example the middle of the day for rooftop solar PV panels. Additionally, energy storage can be used in much the same way to reverse the voltage sags associated with traditional peak demand periods. This effectively means that upgrades or new installations of infrastructure such as SVCs and other reactive power control equipment can be deferred.

5.2 Reliability of Core ZBM technology

The investigation of R510 reliability has shown that RedFlow's core ZBM technology is a great deal more reliable than the surrounding power electronics and Balance of System (BoS) in each ESS. As such, the reliability, as well as the cost of R510s would be greatly improved with extra development on these parts of the ESS. These parts are not RedFlow's core area of competence and are instead an area for system integrator involvement.

It should also be noted that the distributed approach to deploying ESS significantly increases the availability of the total capacity of energy storage installed. That is, a failure on one R510 ESS has no influence on other R510s, allowing the rest of the installed capacity to operate as normal, as has been shown in the SGSC trial. However, if a failure occurs with a larger community-sized ESS, the entire ESS becomes unavailable for operation and thus requires faster maintenance to be carried out to achieve a similar level of availability.

5.3 Business Case for R510 ESS

The value of energy storage, both to utilities and to end electricity consumers has been found to be just over \$10 000 for a lifetime of 5 years. As such, the cost of an R510, which is currently sold in very small numbers to system integrators for approximately \$35 000, must be reduced significantly to become attractive for wide scale use. However, the rising cost of electricity, the increase in intermittent renewables penetration, as well as the potential for very low cost production of ZBMs and ESS in high volumes, will all contribute to the significant reduction in costs for zinc-bromide-based energy storage in this application in the future.

5.4 International Deployment Opportunities

This trial has been conducted in areas of suburban and more rural parts of grid-connected Australian residential areas in fairly temperate climates. In order to deploy these types of ESS to other areas of the world, several key developments are required. First, power electronics must be converted for any areas that do not operate at Australia's 240V or 50 Hertz type of electricity supply. Second, grid-connection guidelines differ between countries so while the R510 ESS pass the AS4777 Australian Standard for Grid Connection of Energy Systems, this may not be the case in other countries. Third, this trial was performed in an area that has a relatively strong grid, like much of the rest of Australia. Areas with weaker grids and more frequent outages would improve the case for energy storage as a back-up option to crucial loads. It should be noted that these developments only require changes to the surrounding power electronics and BoS, and not to the actual ZBM battery module itself.

6 CONCLUSIONS

From analysis undertaken so far in the first ten months of the SGSC trial, it has been found that RedFlow R510 ESS are effective in reducing peak demand seen by the grid, supporting voltage fluctuations, and can be scaled-up to larger, modular ESS. However, in order to maximise the commercial potential of ZBMs in Smart Grids, there is a need to include installers and system integrators in future projects to reduce system integration costs, improve system reliability and move towards fully commercial kilowatt-scale residential energy storage systems.

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