An Assessment of the State of the Zinc-Bromine Battery Development Effort

at RedFlow Limited, Brisbane, Queensland, Australia
by Garth P. Corey

Energy Storage Systems Engineer

Introduction

Background to this Report

This report was commissioned by RedFlow Limited for inclusion in its prospectus to be dated on or about 29th October 2010. It covers a technical review of RedFlow's zinc-bromine battery module (ZBM). I began an in-depth study of the RedFlow zinc-bromine flow battery development effort in early July, 2010. In early September, 2010, I initiated a visit to RedFlow in Brisbane, Queensland, Australia, to perform an on-site assessment of the state of the development effort for an advanced zinc-bromine technology flow battery. Over a 4-day period, I was provided with detailed information on the early development effort, current progress toward commercialism, and future plans for full deployment of a truly innovative and quickly maturing version of a utility scale battery using zinc-bromine flow technology. My key findings on the RedFlow development activities related to the zinc-bromine flow battery technology are as follows:

Key Observations

- All aspects observed in the development and deployment effort for the RedFlow ZBM battery building block are far superior to other zinc-bromine battery development efforts that I have personally observed.
- The RedFlow approach to the engineering, development, and deployment of a fully operational zinc-bromine flow battery system is fully viable. Historically, the only successful deployments of energy storage technologies for commercial applications have involved the development of turnkey systems, those developments in which all aspects of the system from component selection and design to full system integration, including field support, were fully implemented. RedFlow has developed a fully functional, well engineered, turnkey system, based on the ZBM battery building block that exhibits those qualities.
- The research and development team has successfully and innovatively solved all fundamental engineering and development challenges encountered. In my opinion, these challenges currently remain unresolved by other groups in their attempt to develop and deploy a fully functional zinc-bromine technology flow battery.
- The basic ZBM building block module has been matured to the point that it is now in the final stage of development refinements that will quickly lead to a fully commercialized product; product is currently fully operational in field applications.
- A management and engineering team is in place that exhibits all the qualities necessary to the successful deployment of an advanced battery technology.

- RedFlow has demonstrated that it can successfully work with electricity utility customers to develop and install fully functional, grid-connected energy storage systems based around its zinc-bromine battery module.
- Future plans include a well conceived development of a manufacturing capability that will lead to the successful commercialization and deployment of its new and existing energy storage systems, all based on its proven ZBM building block technology.

Author Biography

Garth P. Corey currently consults on energy storage projects worldwide. He was formally a Principal Member of the Technical Staff, Sandia National Laboratories, had project management responsibilities with the Energy Infrastructure and Distributed Energy Resources Department. Sandia National Labs is a US Department of Energy research facility and is the lead national laboratory for energy storage research and development activities sponsored by the US Government. Most of his Sandia career was dedicated to advising engineers involved in the integration of various energy storage technologies with the balance of plant needed for a successful operational energy storage system.

During his more than 15 years at Sandia, he was involved in high technology energy storage R&D projects. He has managed projects that span the utility scale energy storage arena that includes flywheels and ultra capacitor systems, sodium sulfur, nickel cadmium, lead-acid, (including advanced lead-acid technologies), lithium ion batteries, and several flow battery technologies. Much of his time was dedicated to assisting Sandia Renewable Power engineers in the proper integration of batteries in off-grid and grid-tied photovoltaic systems.

He is a member of the Institute of Electrical and Electronics Engineers Power and Energy Society and active with the Power and Energy Society Stationary Battery Committee. In addition to continuing his association with Sandia as a consultant, with responsibilities related to electric energy storage system development, he is active in a consulting role to industry in the evaluation of emerging energy storage technologies for distributed energy and storage applications on the national grid.

Purpose

The purpose of this report is to present the details of the assessment that I made at the RedFlow facilities concerning the development and planned deployment of turnkey, fully operational energy storage systems based on the RedFlow ZBM battery building block, an advanced zinc-bromine flow battery system.

Background

Zinc-bromine Technology Overview

A general definition of the zinc-bromine electrochemical process can be found at the Electricity Storage Association (ESS) website (www.electricitystorage.org) as follows:

> *In each cell of a zinc-bromine battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane.*
>
> *During discharge, Zn and Br combine into zinc bromide, generating 1.8 volts across each cell. This will increase the Zn2+ and Br- ion density in both electrolyte tanks. During charge, metallic zinc will be deposited (plated) as a thin film on one side of the carbon-plastic composite electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents (organic amines) to make thick bromine oil that sinks down to the bottom of the electrolytic tank. It is allowed to mix with the rest of the electrolyte during discharge. The net efficiency of this battery is about 75%.*

The fact that electrical energy is stored in the flow battery electrolyte provides many benefits that are not available in traditional batteries. Unlike lead-acid and most other battery technologies, the zinc-bromine battery uses electrodes that cannot and do not take part in the electrochemical reactions but merely serve as substrates for the reactions. Because of this process, there is no material deterioration resulting from continuous cycling activity and flow batteries routinely deliver more 100% discharge cycles than other battery technologies, during their operational lifetimes.

Flow battery technology is of high interest to energy storage systems users in that the flow battery eliminates the limitation of traditional battery systems associated with the decoupling of the power and energy components of the system. In a traditional energy storage system, once a power/energy requirement is satisfied by the installed energy storage system, a load variation that results in an increase in stored energy or power requirements necessitates major modifications to the existing energy storage system. If more energy is needed in a traditional energy storage system, multiple parallel strings that are equivalent to the power requirement must be added. In contrast, if more energy is needed in a flow battery system, only the capacity of the electrolyte needs to be increased. If more power is needed in a traditional battery system, a change in battery string size is necessary; whereas, in a flow battery system, only additional cells are needed to be connected in series in the flow battery electrolyte system to realize an increase in power for the system. Consequently, changes in power/energy requirements can be more economically implemented in flow battery systems than in traditional battery systems.

Prior attempts to develop zinc-bromine batteries

Although there have been many attempts by previous developers to develop and deploy zinc-bromine battery systems in recent years, as of this date there has not been a successful demonstration of a fully operational and fully functional zinc-bromine flow battery in a power utility application except for the RedFlow demonstration systems currently fielded.

Many of the technical and physical challenges involved the proper management and control of the electrolyte as it moves into and through the cell and throughout the flow path have not yet been overcome by previous developers. Failure to develop a successful design was primarily due to the application of poor engineering decisions in the design and integration of the components necessary to manage the electrolyte, both in plumbing and cell design, as well as in materials selection and controls application. A fundamental understanding of the operation and management requirements of a flow battery system was also severely lacking by the early zinc-bromine flow battery developers.

Barriers to deployment of the technology

One of the primary barriers to the deployment of flow battery systems has been the reluctance of the utilities to allow the interconnection of untried/unproven storage devices on the utility grid. Much of this reluctance is based on the early failures of flow battery systems that were introduced before they were fully ready to perform a successful demonstration. The rush to bring these poorly designed and untried flow battery systems to market has contributed heavily to this reluctance.

Another barrier to the wide deployment of flow battery systems is the issue of bringing large quantities of potentially dangerous liquid electrolytes to locations that could expose the public to these chemicals in the event of a spill. The public perception of the danger in having bromine chemicals nearby is somewhat widespread. This “not-in-my-backyard” issue has been a major stumbling block in the deployment of large flow battery systems.

The RedFlow Approach

Improvement of the fundamental technology

During my assessment, I found that RedFlow has a solid grasp on how to manage the zinc-bromine flow battery technology through a full understanding of the process requirements in charging and discharging a flow battery and applying sound engineering practices to the design of the basic system. Good understanding of the materials and plumbing issues surrounding the management of a zinc-bromine electrolyte has reduced the potential for leaks and spills to nearly non-existent.

Strengths of the RedFlow approach

One of the most obvious strengths I noted during my assessment is the solid engineering approach applied to ensuring that design and performance issues were resolved through the assignment of priorities such that development progress shortcuts were avoided. The RedFlow development started with a reasonably small and manageable turnkey unit at 5 kW, 10 KWh as the primary building block, and then went on to ensure that all functionality was managed at that power/level.

This development strategy is fully responsible for RedFlow’s capability to take its technology to full commercialism. This approach is a unique characteristic of previously successful energy storage commercialism efforts which indicates that RedFlow has taken the correct path for a successful commercialization effort.

The RedFlow use of independent research entities such as Rise (Research Institute for Sustainable Energy, Murdoch University) to test and report on the functionality and reliability of the ZBM products developed to date indicates their confidence in the operation of the fully integrated zinc-bromine flow battery system. To my knowledge, no other zinc-bromine flow battery system developer has had a successful demonstration of its system by an independent test organization.

Innovative developments

Many engineering challenges in flow battery design were solved with innovative solutions by the RedFlow engineering team. Although this is not a complete list of the innovations implemented in the ZBM basic block design, in my opinion, these are the most important solutions which have led to the successful development of a viable flow battery system Significant innovations are:

- Proper management of the flow pattern and flow path within each cell [Patent Application Reference #1 and #2 below]. See Photo 1.
- Unique cell design to optimize plating and de-plating of zinc during charging and discharging operations. [Patent Application Reference #1 and #2 below]. See Photo 1 which shows the physical layout of a RedFlow ZBM cell, the basic component of all flow batteries.
- Significant reduction in the number of discrete tube connections throughout the battery electrolyte management system. [Patent Application Reference #1 and #2 below].

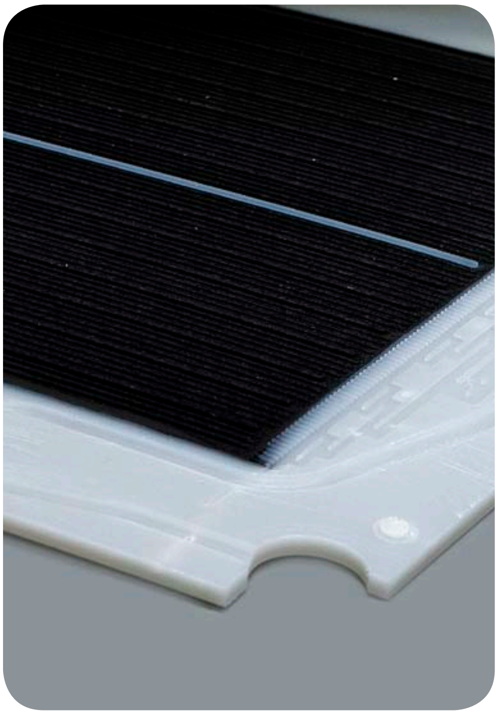


Photo 1. Unique cell design

- Efficient and reliable spill reduction and containment strategy. [Patent Application Reference #5 below].
- Minimization of the number of welds needed to seal the cell stack. [Patent Application Reference #2 below].
- Design of the cell separator as a single integral unit rather than molding it to a plastic housing for better cell integrity. [Patent Application Reference #6 below].
- Design of the flow path within the cell to minimize the pile-up of zinc during charging which could require significant effort to remove the zinc through a stripping activity. [Patent Application Reference #1 and #2 below]. See Photo 1. Note the unique header where flow is divided systematically among all the channels in the cell. This design solves a serious problem that has plagued all preceding zinc-bromine designs.
- Approach to the minimization of efficiency losses due to circulating currents in the electrolyte. [Patent Application Reference #1 below]. See Photo 1. The unique loop limits circulating currents by extending the length and impedence of the electrolyte path.
- Complete understanding of how to manage the electrolyte viscosity changes during charge and discharge operations. [Patent Application Reference #4 and #5 below].
- Method to control electrolyte temperature to an optimal point without active external cooling. [Patent Reference #5 below].
- Selection and integration of a low cost, efficient and reliable pump for anolyte and catholyte electrolyte movement. [Patent Application Reference #5 below].
- Elimination of a third pump to manage the control of bromine complex in the electrolyte reservoir. [Patent Application Reference #4 below].
- Proper management of pressure differential between the anolyte and catholyte within the cell to minimize uncontrolled electrolyte cross contamination. [Patent Application Reference #1 and #2 below].
- Approach to discrete managing of bromine complex during charge and discharge functions to result in more efficient operations. [Patent Application Reference #4 and #5 below].
- Fully effective system controller integrated with bi-directional data management system.

Technologies covered by current patent applications as referenced in the preceding section:

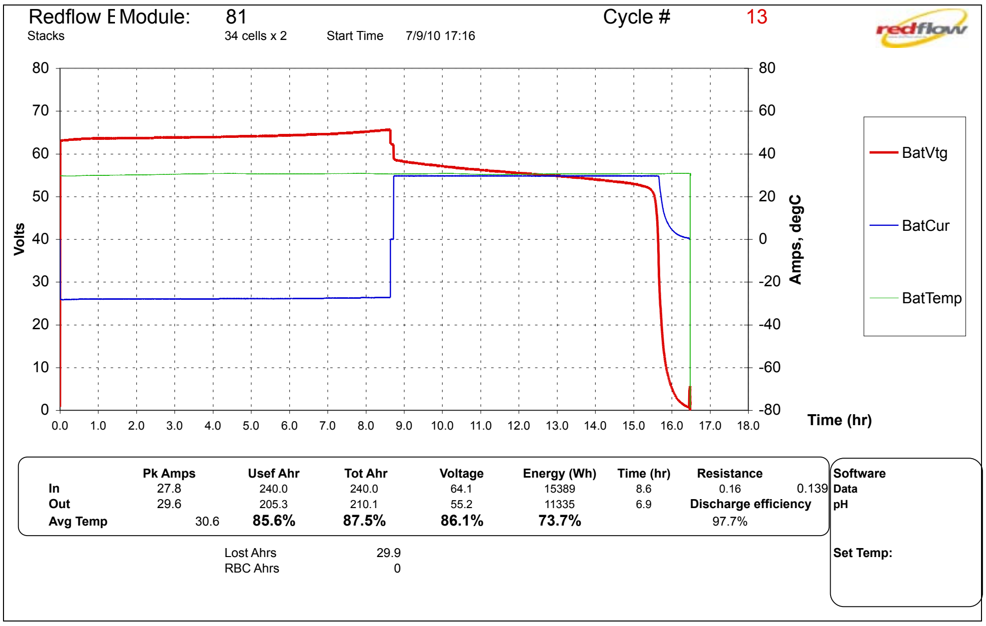
1. A cell stack for a flowing electrolyte battery – official patent application number 2008232296.
2. An integral battery cell stack manifold – PCT/AU2009/001078.
3. A recombinator for a flowing electrolyte battery – official patent application number 2009905192.
4. A bromine complex valve – official patent application number 2009905358.
5. A battery reservoir system – official patent application number 2009906174. See Photo 2 which shows the Company’s “tank within a tank”, a unique design with the outer container holding the zinc-based electrolyte while the inner container holds the bromine complex electrolyte isolating the bromine complex from the outside by two separate walls.
6. A battery cell stack separator – official patent application number2010900299.

Photo 2. Battery reservoir system

Life Cycle/Performance Testing

RedFlow has been very diligent and thorough in its testing program and has willingly shared its testing experiences with me. Although battery cycling is a very time consuming and long term activity, RedFlow has taken an aggressive approach in order to test and evaluate their technology.

Figure 1 shows a typical discharge curve. Note the high number, 81, of the module indicating that there have been many modules preceding this particular one. Also important is that this is cycle 13 indicating that cycle testing is just in the early stages for this module.



	Pk Amps	Usef Ahr	Tot Ahr	Voltage	Energy (Wh)	Time (hr)	Resistance	
In	27.8	240.0	240.0	64.1	15389	8.6	0.16	0.139
Out	29.6	205.3	210.1	55.2	11335	6.9	**Discharge efficiency**	
Avg Temp	30.6	**85.6%**	**87.5%**	**86.1%**	**73.7%**		97.7%	

Lost Ahrs	29.9
RBC Ahrs	0

Software
Data
pH

Set Temp:

Figure 1. Typical RedFlow zinc-bromine module discharge curve

The first 8 hours show the module on charge with a very stable constant current and steadily increasing voltage, the slight rise indicating the battery is indeed charging. Immediately following the completion of the charge, a constant current discharge is initiated. Following a 6 ½ hour discharge at a 30 amp rate, during which the battery temperature remained unchanged indicating a very stable electrochemistry, a stripping event is noted which returns each cell component to a known end-of-discharge condition. The fact that the stripping activity was successful is indicated by examining the open circuit voltage, which is zero, showing that there is virtually no zinc remaining in the cell. The module is again ready to begin another cycle. Note in the table below the trace the energy efficiency of 73.7%, which is an excellent rating for this electrochemistry. I reviewed many plots of other cycle tests, some of which were well beyond 300 cycles, and noted very little variance between the plots indicating that the RedFlow module is very stable over multiple cycles indicating that the currently targeted cycle life of the cell of 1,500 cycles is definitely achievable.

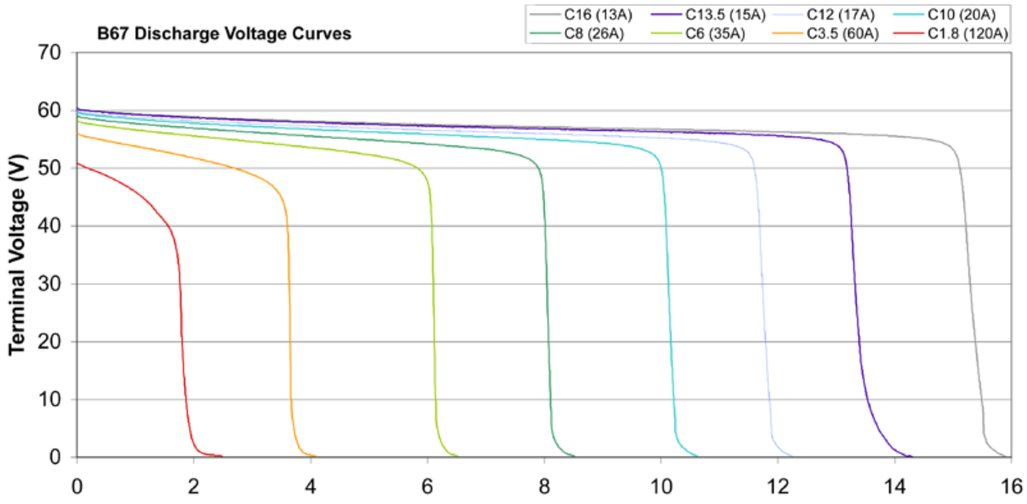


Figure 2. RedFlow zinc-bromine module showing range of discharge currents over multiple 100% discharge cycles

The RedFlow ZBM is designed to operate over a wide range of power settings. Figure 2 shows the performance of the module over a wide range of currents representative of the anticipated applications that will be served by this technology. Of primary interest is the behavior of the voltages throughout the test periods. The monotonic nature of the declining voltages for each of the traces indicates that the module reacts predictably and is well behaved over a range of currents. Each of the tests shown are complete 100% depth-of-discharge constant current cycles as shown by the voltage going to zero at the end of the discharge. All of these cycles were produced using a single test module number 67 discharged over the current ranges noted.

Figure 3 shows the stability of the RedFlow ZBM module for battery 67 shown in Figure 2. Of major importance is the actual performance of the battery against a theoretical Pukert prediction curve for module number 67. As noted in the figure, the battery performed exactly as predicted by the Pukert calculation. This indicates a very repeatable process that is not dependent on the rate that current is taken from the module. Most other energy storage technologies are rate sensitive and would exhibit a very broad range of variance when tested in this way, another very strong indicator of one of the strengths of this ZBM technology.

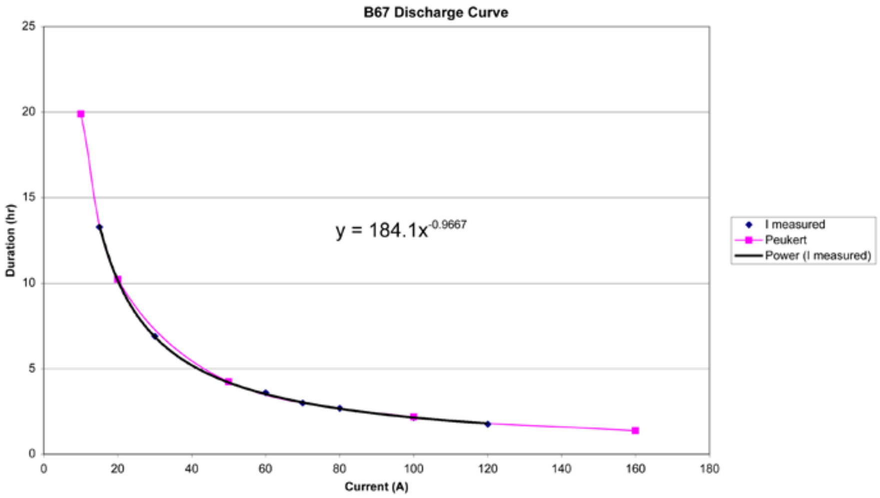


Figure 3. RedFlow zinc-bromine module Pukert curves for a range of discharge currents over multiple 100% discharge cycles

I was provided a copy of the Rise (Research Institute for Sustainable Energy) report completed in April 2010 which tested a RedFlow Gen 2.70 module. An excerpt of the summary of battery performance during testing as reported by rise is taken from their report as follows:

> *The zinc-bromine Module received from RedFlow Pty. Ltd was tested as specified by the client. All the key performance tests on the battery were conducted successfully from 23-Feb-2010 to 20-Mar-2010.*
>
> *The battery performance during all the tests was satisfactory and matched the expected outcomes. For all the battery capacity measurement tests, the battery measured capacity (in Ah as well as kWh) was consistent with the nominal capacity. When the battery was charged up to 150 Ah it delivered 7.1 kWh to the load and at 200 Ah charge it delivered 9.4 kWh to the load. In terms of the power delivery capability, the battery successfully supplied 5.0 kW power for the intended duration.*

From the results obtained during this testing, it can be concluded that the overall battery performance for various tests was highly satisfactory.

I also completed a thorough review of the testing provided by Rise. The Rise independent testing confirms the claims made by RedFlow that their technology is indeed ready for commercial applications and it will deliver as promised.

I was also afforded an opportunity to observe the remote data being constantly generated by RedFlow units deployed in the field and was extremely pleased to see that all units were under constant monitoring. The monitoring system is bi-directional in that commands and operational parameters can be communicated to each operational unit in the field and data can be collected from the field operation. This is significant in that RedFlow has the capability to assess potential problems before they become serious, a great benefit indeed to RedFlow customers.

Photo 3 shows the testing terminal for units undergoing factory testing at the RedFlow facility. The amount and intensity of the testing, which is a continuous activity at RedFlow, was very reassuring. It indicates that it is of high importance that RedFlow considers testing of great value both in the early development activities as well in their intent for product improvement. Photo 4 shows several units undergoing 24/7 testing to learn as much as possible about the potential failure mechanisms of the system and to prove the system capable of uninterrupted daily cycling without loss of service. The testing program conducted by RedFlow including pre-shipping testing and preparation for deployment to the field is indeed remarkable.

Photo 3. Testing terminal

Photo 4. Units in test bay

Hardware Currently Being Sold

The keep-it-simple approach executed by RedFlow is easily realized when viewing the basic ZBM module, filled with electrolyte, shown in Photo 5. This design is very clean and uncluttered.

Photo 5. Basic RedFlow ZBM module

Photo 6. Plastic electrode plates for basic RedFlow ZBM module

The battery stack component shown in Photo 6 shows how clean and solid the stack of cells, shown on the right, are assembled and ultimately mounted on the top of the electrolyte tank. What is immediately obvious is the total lack of plumbing, which in my experience has been the major inhibitor to bringing any functional flow battery to full commercialization. All electrolyte flow is managed by design. Pumps, seen on the right end of the module, remove the electrolyte from each of the tanks and deliver it directly into the cell manifolds, bypassing a fractional amount of electrolyte to the cooling system where air is blown over cooling tubes, which is the only part of the system that might be referred to as plumbing. Although not seen in the photo, the cooling system is well designed to provide the appropriate amount of cooling using only ambient air passing over the cooling tubes. However, in the event a system is to be installed in a very hot environment, a method of actively cooling the system with chilled air is designed into the system. A significant amount of field testing has led RedFlow to this very clean design for the cooling system.

Photos 7 and 8 are completely assembled systems ready for delivery.

Hardware Currently Being Sold

Photo 7. Fully assembled RedFlow ZBM-based energy storage system

Photo 8. RedFlow storage systems in RedFlow assembly facility.

Hardware In Final Development

While at the RedFlow facilities, I was made aware of RedFlow's intent to enter the utility scale energy storage market with the RedFlow 200kVA/400kWh unit as shown in Photo 9.

Photo 9. RedFlow 200kW System

With the introduction of this technology, RedFlow is ready to join the ranks of utility scale battery suppliers. In my opinion, based on the development path taken by RedFlow, I believe this system will be very successful in competing with all other technologies in this power and energy range.

Potential for deployment of the RedFlow technology

In my opinion, the RedFlow ZBM technology is ready for deployment in a broad range of applications, some of which are listed below. This is a partial listing of applications specified in a document recently published by Sandia National Laboratories titled "Electric Utility Transmission and Distribution Upgrade Deferral Benefits from Modular Electricity Storage" which defines the benefits that the energy storage user can expect in order to be cost effective with the introduction of energy storage in their operations. The RedFlow technology can currently address all of these applications on a relatively small scale primarily in the domestic and community scale areas. With the introduction of the RedFlow 200kW system, RedFlow will be strategically positioned to support all of these applications on a grid scale level.

- Transmission and distribution upgrade deferral
- Wholesale Electric Energy Time-shift ("Buy Low – Sell High")
- Electric Supply Capacity
- Electric Supply Reserve Capacity
- Reduce Transmission Congestion
- Voltage Support (Reactive Power)
- On-Site Power Quality
- Electricity Service Reliability
- Retail Time-of-Use Energy Cost Reduction
- Renewable Energy Time-Shift
- Demand Management and Curtailable Loads

Appropriateness of the Technology in the Selected Market

I was given a thorough tour of the RedFlow production plant where all the products currently available were described in detail along with the applications they were targeting for future deployment. I was very impressed with the fact that RedFlow is taking a very deliberate path in focusing on applications that are ideal for the energy storage systems they have developed. Many emerging energy technologies have not successfully commercialised because the developers neglected to identify the appropriate target for their technology. RedFlow fully understands where their customers reside and are totally focused on reaching that market before expanding to other potential markets.

The only battery technologies that are currently in the market place are Sodium Sulfur (“NaS”) and lead-acid based and only one developer in each of these technologies has taken the RedFlow approach of delivering a turnkey device specifically targeting a single application for which the system is specifically designed to support. All others are still in testing and final development. The only fully commercialized, utility scale battery system currently being deployed is NGK Insulators Limited’s (NGK) NaS large scale battery that operates at a nominal temperature of 300 to 350 degrees Celsius, which greatly limits the potential wide deployment of the NaS battery technology. In addition, the difficulty in manufacturing the NaS battery is severely limiting NGK’s ability to meet existing orders in a reasonable amount of time. RedFlow will not be experiencing this limitation as planning is in place to ramp up the production rate of the ZBM modules to meet future demands. Additionally, the complexity of the NaS system far surpasses the keep-it-simple approach by RedFlow, again giving RedFlow a distinct advantage over other energy storage technologies. Other flow batteries are far behind RedFlow in their approach to full commercialization. None of them have reached the state of maturity that the RedFlow ZBM flow battery currently exhibits.

Cost Comparisons to Existing Energy Storage Systems

RedFlow is targeting to market the ZBM turnkey systems at an initial price range of $2,000/kW to $2,500/kW, which is very competitive to all existing energy storage solutions. The following table summarizes current turnkey price points.

Turnkey Energy Storage System Costs

Technology	Current Cost $/kW	Target KWh
Advanced Pb Acid	1500	4
Flow (current technology)	2600	8
Flow (developing technology)	2500	1200
Flywheels	2000	0.25
Li Ion	3800	4
NaS	3200	7
NiCd	2400	4
Pb Acid	1200	4

Many of these prices are for one-of-a-kind systems and many are still in development. Only NiCd and Pb Acid are widely deployed but are not held in high esteem by the potential market as their reputations have been substantially tarnished. This has been due to poor system design and integration, and improper battery management which have led to early failures and short cycle lives. RedFlow has overcome these potential problems by consistently paying attention to integration and battery management issues and not relying on external system integrators that have typically allowed system abuse which leads to early failures. Their approach to the "no customer maintainable parts inside" will keep much of this abuse at bay.

Conclusions

In my opinion, RedFlow Limited has developed a very innovative and functional zinc-bromine flow battery that is nicely positioned to make a major impact on the current energy storage system market. RedFlow has avoided many of the errors I have noted in other startup companies involved in bringing new, advanced technologies to market. RedFlow has chosen a proven path to success. They have not outpaced their engineering capabilities but have taken a deliberate, conservative approach to bringing a specific product to a specific market. In my experience, only the few successful recent entries into the energy storage market have chosen this path to development. RedFlow has a well conceived plan to capture its initial market by developing a modern and effective plant in which to manufacture their successful ZBM product. Results to date in their sales and field experiences give solid credibility to their approach. They have a great advantage to being first to their chosen market with a viable and proven energy storage product. RedFlow is also looking to the future where they intend to expand their research and development activities in order to enter currently attractive utility-scale markets for reliable energy storage devices. In my opinion, RedFlow is in an extremely strong position for the emerging energy storage market.

This report has been prepared for inclusion in a prospectus to be issued by RedFlow Limited to be dated on or about 29 October 2010.

Other than as set out in this prospectus, Garth Corey and related entities do not have at the date of this report, and have not had within the previous two years, any shareholding in or other pecuniary interests or relationship with RedFlow Limited (and its associated entities) that could reasonably be regarded as capable of affecting his ability to provide an unbiased opinion in relation to the matters contained in this report.

Garth Corey has no involvement with, or interest in the outcome of the proposed initial public offer and ASX listing of RedFlow Limited (Transaction), other than the preparation of this report.

Garth Corey will receive a fee based on commercial rates and reimbursement of outlays for the preparation of this report. This fee is not contingent on the outcome of the Transaction. Garth Corey will receive no other benefit for the preparation of this report.

Consent to the inclusion of this report in the prospectus in the form and context in which it appears has been given. At the date of this report consent has not been withdrawn.