An Investigation Into Energy Storage Technologies For the University of British Columbia's New Student Union Building

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AN INVESTIGATION INTO ENERGY STORAGE TECHNOLOGIES FOR THE UNIVERSITY OF BRITISH COLUMBIA'S NEW STUDENT UNION BUILDING

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ABSTRACT

"An Investigation into Energy Storage Technologies for the University of British Columbia's New Student Union Building"

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This report investigates the potential of flywheel energy storage (FES) and vanadium reduction-oxidation flow batteries (VRB) as methods of storing renewable energy generated at the new student union building (SUB). One of the long term design goals of the new SUB is that the building will be able to generate enough energy through the use of photovoltaic cells to supply its annual energy demand. In order to assess the feasibility of the implementation of FES and VRB technologies in the new SUB, the assessment for each technology has been broken down into three parts: economic, social and environmental impacts.

After assessing the two energy storage technologies, this report recommends that energy conservation coupled with a relatively small amount of VRB installed storage is the most effective means of having the new SUB meet its goal of energy self sufficiency. In order for the SUB to meet its goal of "Net Zero Consumption" the planned renewable energy capacity would need to be drastically increased. VRB technology is a suitable candidate for storing energy because of its ease of scalability, relatively constant round trip efficiency, long life and small footprint. In addition, the technology has a relatively small impact on the environment and would help justify the increased renewable energy capacity by storing surplus energy to be used at later times to allow the renewable system meet peak energy demand.

TABLE OF CONTENTS

ABSTRACT.. ii
LIST OF ILLUSTRATIONS iv
GLOSSARY.. v
LIST OF ABBREVIATIONS vi
1.0 INTRODUCTION.. 1
2.0 The NEW STUDENT UNION BUILDING 2
    2.1 Generation Supply Projections.. 2
    2.2 Load Demand Projections... 4
3.0 FLYWHEEL ENERGY STORAGE... 8
    3.1 BACKGROUND AND HISTORY OF TECHNOLOGY........... 8
    3.2 ECONOMICAL FEASIBILITY ANALYSIS.......................... 10
    3.3 SOCIAL IMPLICATIONS.. 10
    3.4 ENVIRONMENTAL IMPACT...11
4.0 VANADIUM REDOX FLOW BATTERY STORAGE 12
    4.1 BACKGROUND AND HISTORY OF TECHNOLOGY......... 12
    4.2 ECONOMICAL FEASIBILITY ANALYSIS.......................... 14
    4.3 SOCIAL IMPLICATIONS.. 14
    4.4 ENVIRONMENTAL IMPACT.. 15
5.0 COMPARISON OF ENERGY STORAGE TECHNOLOGIES 17
6.0 CONCLUSION AND RECOMMENDATIONS............................... 19
REFERENCES 20
APPENDIX: FIGURE SOURCES 21

LIST OF ILLUSTRATIONS

Figure 1: Average Daily Sunlight Duration And Bright Sunshine..................3

Figure 2: Average Daily Energy and Power...4

Figure 3: Degree-Days For Vancouver Over The Course Of 30 Years............5

Figure 4: Breakdown of Average Daily Energy Consumption..........................6

Figure 5: Average Daily Energy Production to Consumption Ratio...............7

Figure 6: Schematic Drawing Of A Typical Modern Day Flywheel...............8

Figure 7: Beacon Power Flywheel Unit and Cutaway View Rendering.........9

Figure 8: Cost of Flywheel Energy Storage..10

Figure 9: Basic VRB System Schematic...12

Figure 10: VRB Half Cell And Overall Chemical Reactions...........................13

Figure 11: Cost of Vanadium Redox Battery Storage..14

Table 1: Breakdown of Annual Energy Consumption and Generation............2

Table 2: Monthly Weather Statistics..5

Table 3: Material Prosperities for Flywheels..11

Table 4: Life-Cycle Energy Use and CO_2 Production.......................................16

Table 5: Comparison of FES and VRB Technologies.......................................17

GLOSSARY

Angular velocity:	The speed at which an object rotates around an axis.
Building integrated photovoltaic:	Photovoltaic materials used to replace conventional building materials (ie. Skylights and roof)
Catastrophic Failure:	Total failure in which the system is unable to recover. In the case of FES, this leads to the destruction of the unit and damage to the surrounding area.
Degree-Days:	A measurement of heating or cooling.
Kilo-Watt:	Unit of Power, 1kW = 1000W
Kilo-Watt hour:	Unit of energy, 1kWh = 3.6M joules
Load:	Anything that takes electricity to work.
Load smoothing:	To shift the consumption of energy so that it is more uniform.
Moment of Inertia:	The tendency of a body to resist angular acceleration.
Net-Zero Energy Consumption:	Electricity consumption when over the duration of a year the total amount of energy consumed from the grid has at least been generated, effectively nullifying the grid power consumption.
Peak shaving:	Using stored energy to supply any excess energy demand that exceeds base load.
Production to consumption ratio:	The percentage of the building's energy demand met by its renewable energy generation.
Proton exchange membrane:	A semi-permeable membrane that conducts protons while being impermeable to gases such as hydrogen and oxygen.
Ramp up:	The process of moving from basically no generation to rated generation.
Reduction-Oxidation:	Chemical reactions in which the number of electrons (oxidation number) is either increased or decreased (as opposed to forming new molecule).
Round Trip Efficiency:	The overall efficiency of a system from the time raw AC is converted to chemical/mechanical energy to the time the chemical/mechanical energy is converted back to AC power.
Total bright hours of sunshine:	Sunshine that is intense enough to generate to use for power generation. This threshold is 100W/m^2
Vanadium:	A Common metal widely distributed in nature.
Photovoltaic Cell:	A silicon based device that generates a current when light is shone on it.

LIST OF ABBREVIATIONS

SUB	Student Union Building
LEED	Leadership in Energy and Environmental Design
THBS	Total Hours of Bright Sunshine
FES	Flywheel Energy Storage
BIVP	Building integrated photovoltaic
VRB	Vanadium Reduction-Oxidation Battery
PEM	Proton Exchange Membrane
VO5	Vanadium Pent-oxide
PVC	Polyvinyl Chloride
SO4	Sulfuric Acid
DHW	Domestic Hot Water

1.0 INTRODUCTION

The construction of a new, environmentally sustainable Student Union Building (SUB) was approved by the students of UBC in a referendum vote last year. Current designs of the new SUB building incorporate the use of photovoltaic cells* as a renewable energy source. Unfortunately, this kind of energy source is intermittent in nature. In order to improve reliability of the photovoltaic system and to help the SUB achieve net-zero energy consumption*, an energy storage system may be used to store excess energy when there is an energy surplus and then supply stored energy to the SUB when there is an energy deficit. This will reduce the amount of energy that the SUB requires from the distributed power grid since generated energy can be used over a longer period of time (as opposed to instantaneously) which will also help justify the cost of the expensive photovoltaic cells.

This report looks at two technologies as potential storage technologies to be used in the new SUB: flywheel energy storage (FES) and vanadium reduction-oxidation* flow batteries (VRB). Each technology will be assessed according to their economical, environmental and social impacts. Published papers and commercial websites focused on the two technologies will be examined as well as a document supplied by the new SUB's design team (HBBH+BH and associates) regarding the renewable energy and building load* profile. The main section of the report include: The New Student Union Building, Flywheel Energy Storage and Vanadium Redox Flow Battery Storage.

*this term as well as all subsequent terms can be found in the glossary p. V

2.0 THE NEW STUDENT UNION BUILDING

UBC's long-term goal for the new SUB building is to produce enough renewable energy to achieve net-zero energy consumption. In the short term, UBC is aiming build the new SUB so that it will be the most sustainable student union building in the world and to achieve LEED Platinum status In order to achieve LEED certification, a minimum of 25% of the energy consumed by the SUB must be sourced from renewable energy generated within the foot-print of the building. Current, designs plan to implement solar panel arrays to produce this renewable energy [1]. In order to improve the reliability of the solar array as an energy source, an energy storage system may be installed. An energy storage system would store surplus energy during times of low energy demand and high energy generation for use during subsequent periods of low energy generation and high energy demand. Sections 2.1 and 2.2 estimate the frequency and duration of the surplus energy periods in order to determine whether installing an energy storage is a feasible as well as to roughly estimate how much storage may be required for the SUB.

2.1 Generation Supply Projections

Table 1 is a summary of the annual energy consumption/generation of the various components of the new SUB building based on energy consumption and production projections supplied by HBBH+BH Associated Architects [1].

Table 1: Breakdown of Annual Energy Consumption and Generation

Load Component	(MWh)	Generator Component	(MWh)
Lighting	290	**Solar Cell Array**	320
Plug Load	486		
Space Heating	253		
Space Cooling	253		
Pumps	260		
Fans	155		
DHW	400		
Total :	**1864**		**320**

At the annual level, it is clear that the energy produced from solar panels (320MWh) is much less than the energy consumed (1864MWh) However, if this data is separated into periods of days or hours, instances when supply is greater than demand do exist. Since things like weather, day light hours and student traffic vary throughout the year, energy consumption and power generation vary during different times of year and a surplus of power may occur.

It was assumed that solar power generation is proportional to the amount of bright sunshine in a year. Given that the solar panels are estimated to generate 320 MWh annually and that they generate power during times of bright sunshine, it is reasonable to distribute the annual generation over the months of the year based on the total hours bright sunshine* (THBS) in a given month. *Figure 1* displays the average monthly sunlight and THBS based on historical data of the Vancouver area.

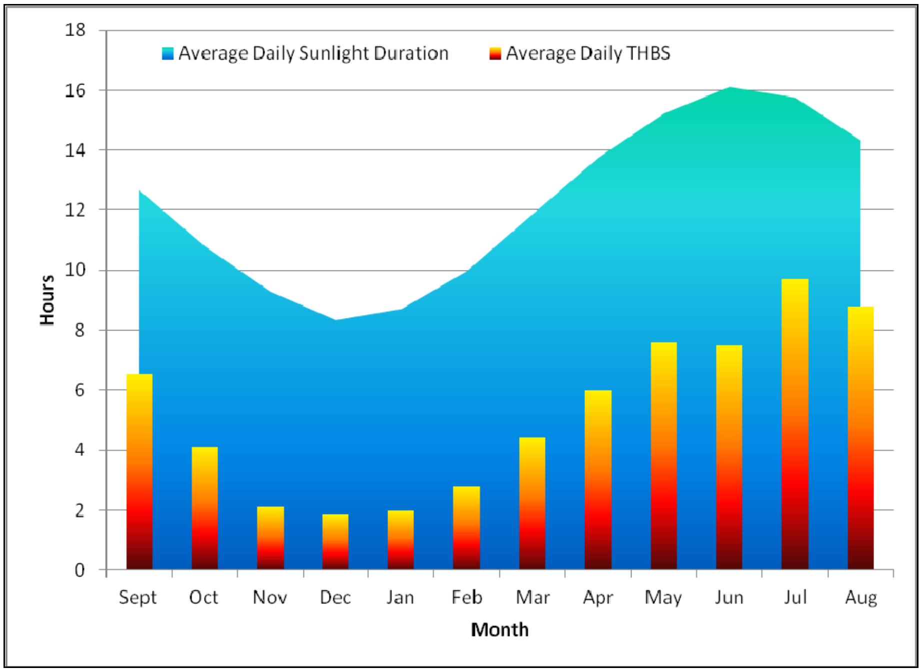


Figure 1: Average Daily Sunlight Duration and Bright Sunshine

The weighted daily energy generated was calculating by multiplying the annual energy generation by the proportion of the hours of daily sunlight divided by the annual amount of sunlight.

Figure 2 displays the estimated monthly power generation. This was calculated by adding the daily weighted average of power generation over each month. It can be observed that the power generated from month to month can vary by a large amount. Energy production can be as low as 306 kWh in December to as high as 1610 kWh in July.

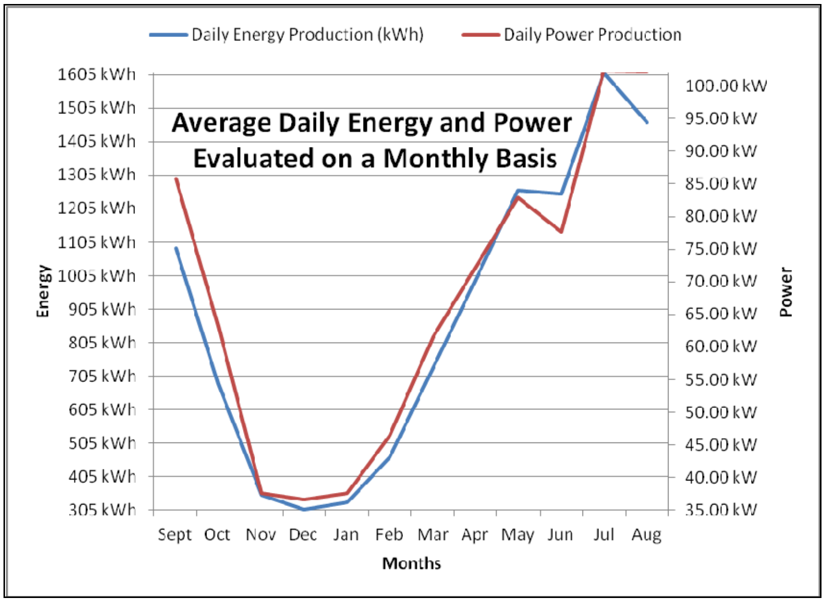


Figure 2: Average Daily Energy and Power

2.2 Load Demand Projections

Similar to the generation supply projections, approximations were made to determine the monthly distribution of energy consumption. *Table 2* contains the monthly heating degree-days, cooling degree-days and total hours of bright sunshine. Based on historical weather data, monthly energy consumption was estimated for lighting, space heating and cooling [2].

Table 2: Monthly Weather Statistics []

Month	Total hours bright sunshine	Above 18 °C (cooling Degree days)	Below 18 °C (heating Degree days)
Sept	199	3	85
Oct	125	0	215
Nov	64	0	330
Dec	56	0	408
Jan	60	0	413
Feb	85	0	344
Mar	134	0	326
Apr	182	0	242
May	231	1	151
Jun	229	8	70
Jul	295	28	26
Aug	268	32	21

THBS (refer to *table 1*) was used to calculate the amount of lighting energy would be required per month. It is assumed that there is an inverse relationship between THBS and total lighting energy required. In other words, less sunshine results in more energy being used for lighting the building.

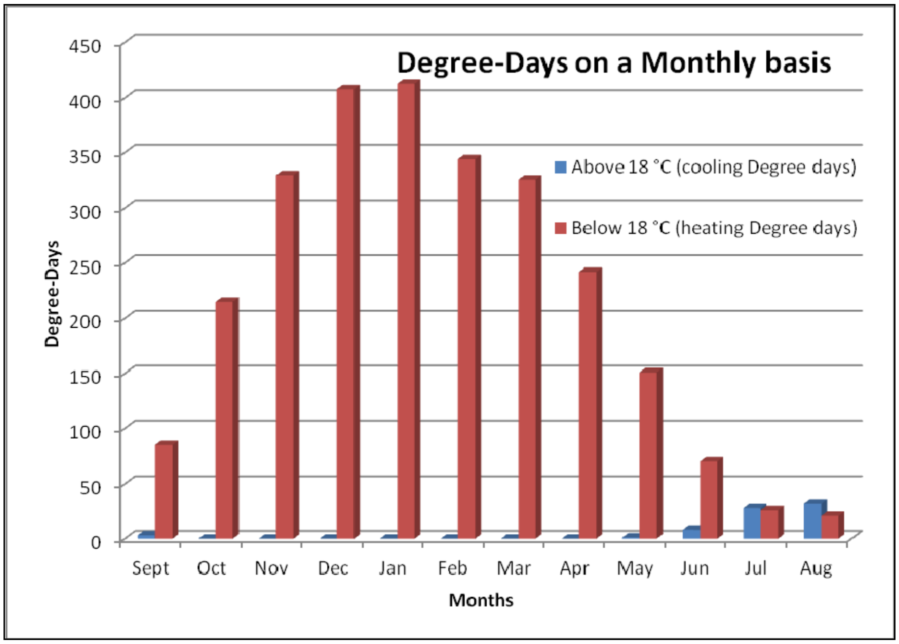


Figure 3: Degree-Days For Vancouver Over The Course Of 30 Years

Degree-days* were useful in determining the monthly distribution of energy consumed in heating and cooling the building. The remaining portion of energy consumed (pumps, plug load, fan and DHW) was estimated based on a weighted average of expected daily traffic. It is estimated that 8,500 people use the SUB in some manner on a daily basis during the two terms of the winter session. During the summer session, human traffic is expected to be reduced by about one-third of the winter session. Approximations resulted in the projection are combined and summarized in *figure 4*.

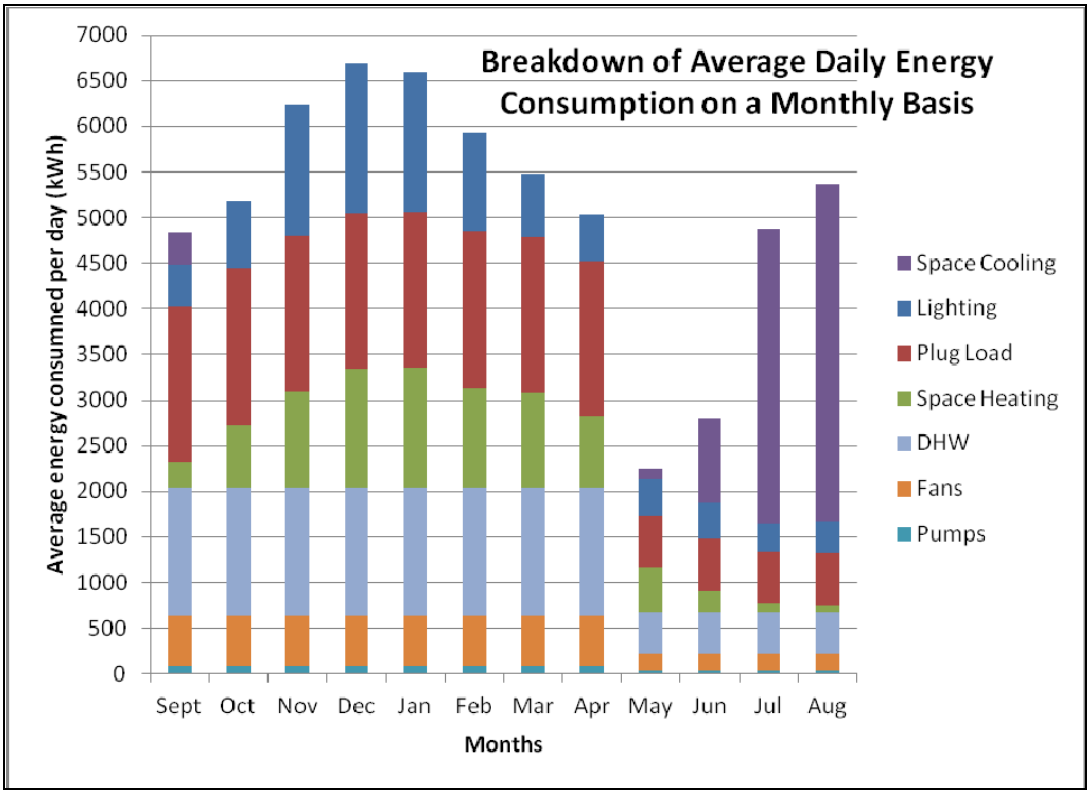


Figure 4: Breakdown of Average Daily Energy Consumption

According to this *figure 4*, the average daily consumption is highest in December (6690 kWh) and the lowest in May (2244 kWh.) It is worth noting that energy consumption in the summer months is not as low as one may expect. This is due to the incredible amounts of energy required to cool the building.

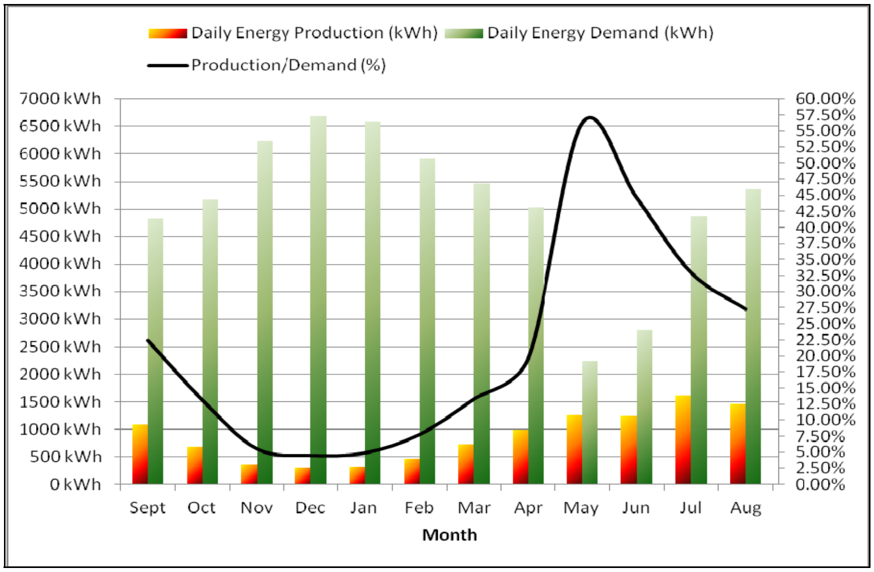


Figure 5: Average Daily Energy Production to Consumption Ratio*

Figure 5 compares the average daily energy production with the average daily energy consumption. When comparing the average daily production and consumption of energy, it can be observed that even on a daily level, there is never an energy surplus. On average, the highest production to consumption ratio occurs in May (56.2%) and the lowest occurs in December (4.6 %.) It is also worth mentioning that for one-third of the year (November, December, January and February), the production to consumption ratio is less than 8%. In order to start generating a surplus on the daily scope (long-term storage), the annual energy generated by solar panels would have to be increased to a minimum of 570MWh (a 78% increase over the current projection). Despite this drastic increase in energy production, for one-quarter of the year the production to consumption ratio would still be a single digit percentage. Based on an average hourly power load of ~200kW (refer to Appendix for average daily load) an energy storage system of 150kW, 150kWh rating will be used in the following two sections of the report. This size system would have the capacity to power 75% of the load for an hour which is thought to be reasonable for the relatively small amount of surplus generation expected to be available for storage.

3.0 FLYWHEEL ENERGY STORAGE

Flywheels are mechanical devices that store rotational energy by rotating a mass at high velocity (refer to *figure 6)*. Kinetic energy is generated via the inertia and speed of the rotating mass (which is driven by the motor) and is stored as rotational energy. Energy is removed from the system by using the rotation of the flywheel to either spin a motor or power a generator, or simply by the reserve process of charging the flywheel system.

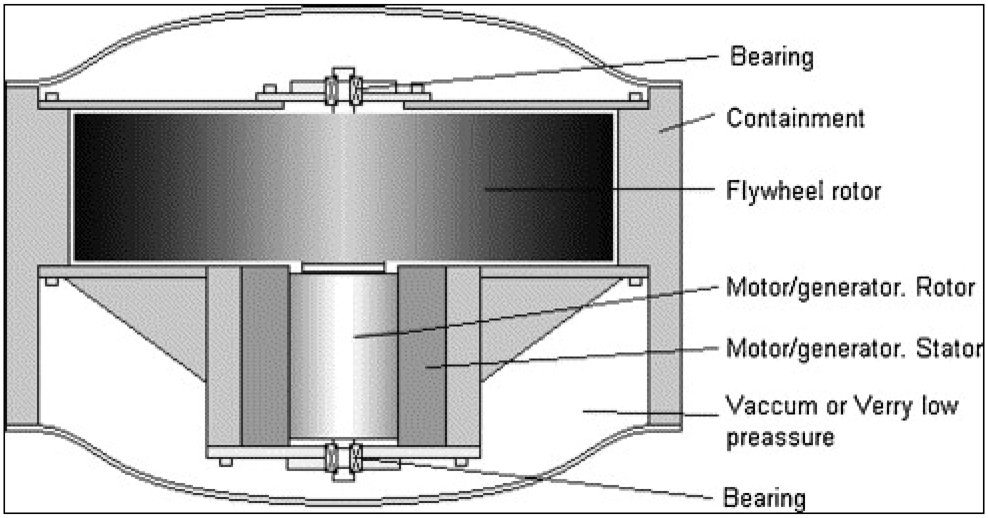


Figure 6: Schematic Drawing of a Typical Modern Day Flywheel [3].

3.1 BACKGROUND AND HISTORY OF TECHNOLOGY

Flywheels have existed and been used for the past two centuries. Their initial purpose was to smooth out mechanic systems by adding mass, thus momentum to the system. Flywheels were not considered as a means to store energy until the 1960's and 1970's when NASA began research into the their use for space missions [3,4].

In modern systems, the flywheel is housed inside a vacuum to reduce energy loss due to drag and is suspended by either steel or magnetic bearings to reduce contact friction. In addition, the vacuum chambers and magnetic bearing also reduce wear on parts (since there is less friction stress on the components) leading to reduced maintenance on the systems. [3] The two governing principles in how much energy a flywheel can store are the moment of inertia* and angular velocity* of the flywheel. The simplest way to increase the power of a flywheel is increase its speed; however the inertial loads generated can overcome the tensile strength of the material used to construct the flywheel, leading to catastrophic failure* [3]. In order to prevent overstressing flywheel units,, researcher have experimented with both the shape of the flywheel and the material used in order to achieve high velocities safely. In new systems, composite material which perform well under high tensile loads are used.

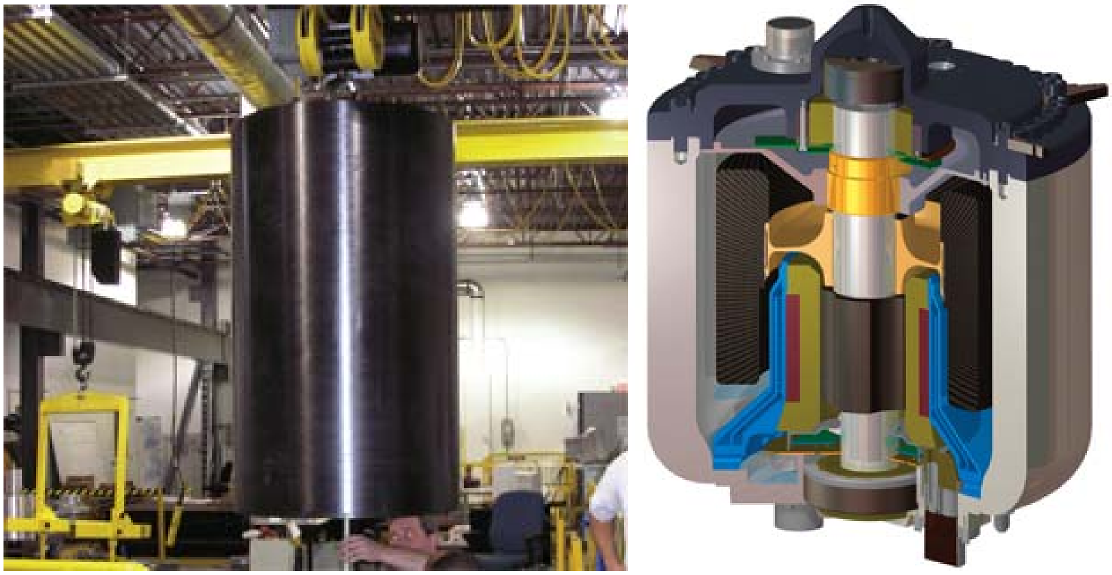


Figure 7: Beacon Power Flywheel Unit and Cutaway View Rendering

Flywheel Energy Storage (FES) systems have been used in number of different applications from smoothing power output of intermittent energy generation sources (such as wind turbines) to extending load supply times for renewable energy generation. In 2001, a FES system was used in conjunction with a building integrated photovoltaic* (BIVP) in Hong Kong to increase the load supply time from 9 am – 3 pm to 8am – 6pm [3]. Beacon Power, Massachusetts USA, currently has two flywheel units used for voltage stability installed in the United States – one in Amsterdam, NY and the other in

San Ramon, CA. *Figure 7* is a photo of one of Beacon Power's flywheels next a 3D cut away view of a FES system [5]. In both systems, flywheels are used to either absorb or release energy according to the current frequency of the system. These systems consist of seven flywheels with 30kWh of collective energy storage. This is enough energy to supply a 5kW load for six hours. [5]

3.2 ECONOMICAL FEASIBILITY ANALYSIS

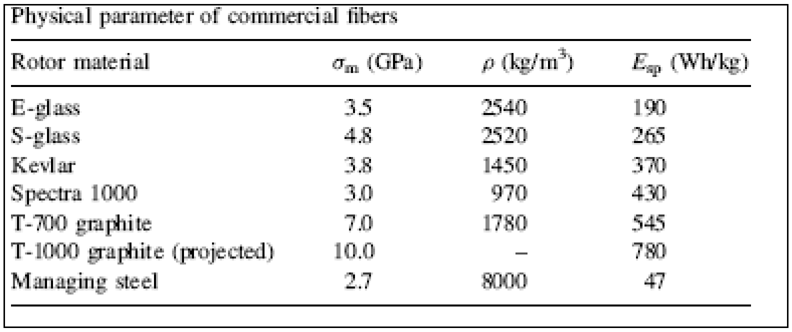
Currently, FES systems are still quite high at about $700 to $800 per kWh and approximately $200 to $500 per kW [6,7]. In the foreseeable future, however, the cost of FES systems will decrease as the price of expensive materials needed for high efficiency, high energy density units decreases. One of the key selling features of FES systems is the high round trip efficiency of the units. A typical FES system, of about five kWh, has a round trip efficiency* of greater than 90% [8]. This is a much higher efficiency than most other systems such as hydrogen fuel cells which have a round trip efficiency as low as 40% [9]. *Figure 8* shows a rough calculation for the cost of a FES system for the new SUB. It is estimate that a 150kW, 150kWh VRB unit will have an initial capital cost of approximately $165,000 with negligible maintenance and disposal costs.

Capital Cost = \$750 x (kW rating) + \$350 x (kWh rating)

Figure 8: Cost of Flywheel Energy Storage [6]

3.3 SOCIAL IMPLICATIONS

FES systems have very little social implications. FES systems require a small amount physical space due to the high energy densities that can be achieved. *Figure 9* summaries the energy densities (E_{sp}) that can be achieved in FES system depending on the material used for the flywheel.



Physical parameter of commercial fibers

Rotor material	σ_m (GPa)	ρ (kg/m^3)	E_{sp} (Wh/kg)
E-glass	3.5	2540	190
S-glass	4.8	2520	265
Kevlar	3.8	1450	370
Spectra 1000	3.0	970	430
T-700 graphite	7.0	1780	545
T-1000 graphite (projected)	10.0	–	780
Managing steel	2.7	8000	47

Table 3: Material Prosperities for Flywheels [4]

The main social implication of a FES system is safety. Due to the nature of rotating a mass at high velocity the tensile strength the flywheel material can be overcome leading to failure. Such a failure could be catastrophic* so researchers and developers have optimized the shape of flywheels and materials used to construct them. σ_m in *figure 9* represents the tensile strength of material used in flywheels, this is much higher than that of A36 Steel (structural steel) which has a σ_m of 0.4GPa [10] meaning that they can handle much higher rotational velocities and stress than regular building materials. In addition to using specialized flywheel materials, vacuum chambers are lined with thick steel and are usually located underground away from people in order to increase the safety of flywheel systems Storing these system underground has the added benefit of reducing the usable space taken up by the storage/leveling system.

3.4 ENVIRONMENTAL IMPACT

FES systems do not directly produce any emissions while in use. However, during the production of steel for the vacuum chamber and the production of materials need for constructing the flywheel and the generator/motor, CO_2 and other emissions are produced. The materials used in flywheel construction (such as copper, steel, and composite fibers) can all be sourced in North American, reducing the need for international shipment and thereby lowering the carbon footprint of the system.

4.0 VANADIUM REDOX FLOW BATTERY STORAGE

Vanadium reduction-oxidation* flow battery storage (VRB) is a chemical energy storage system that stores power in the form of two electrolytic* solutions of vanadium oxide and vanadium ions. Flow batteries differ from traditional batteries in that they require at least two pumps to transport the charged electrolytic solutions across a proton exchange membrane* (PEM) in order to generate electricity. *Figure 10* outlines the basic components of a VRB system.

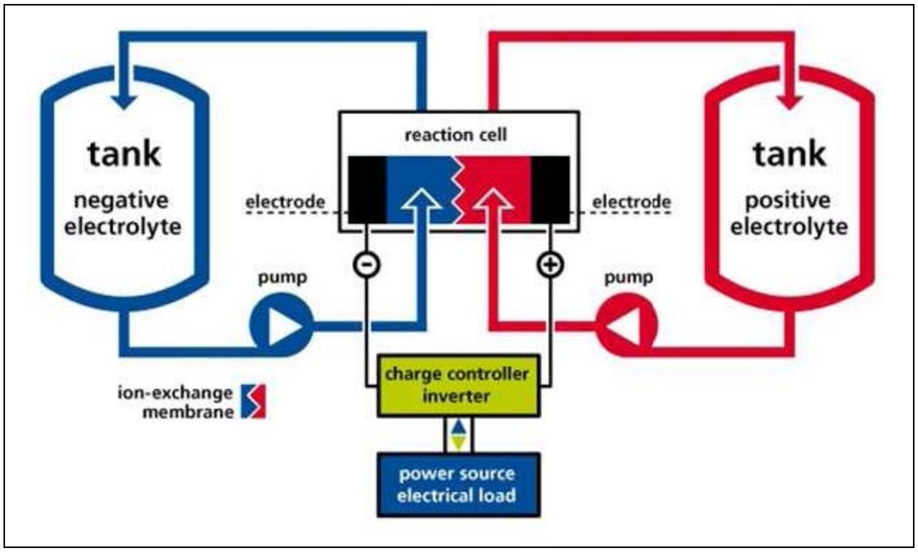


Figure 9: Basic VRB System Schematic [11]

4.1 BACKGROUND AND HISTORY OF TECHNOLOGY

Figure 11 expresses the two half cell equations as well as the overall chemical reaction for the cell. Since the battery only requires the use of one basic electrolyte (in different oxidation states), irreversible cross contamination (like in other flow battery technologies such as Zinc-Bromine) is impossible.

Negative Half Cell: $V^{3+} + e^{-} \leftrightarrow V^{2+}$

Positive Half Cell: $VO^{2+} + H_2O \leftrightarrow VO_2{}^{+} + 2H^{+} + e^{-}$

Overall Cell: $V^{3+} + VO^{2+} + H_2O \leftrightarrow V^{2+} + VO_2{}^{+} + 2H^{+}$

Figure 10: VRB Half Cell and Overall Chemical Reactions [11]

VRB technology was first developed in the 1980s and was patent protected until the early 2000s. Since the patent expired, more and more companies have been entering the VRB market, marketing the batteries to be used for uninterrupted power supply, peak shaving* and load smoothing* devices for telecom, off-grid applications and renewable power generation. There have been numerous instances of VRBs being used to level the generation of intermittent renewable energy sources such as wind and solar. Examples include: 0.2MW, 0.9MWh unit in King Island Australia, 4MW, 6MWh unit in Sapporo Japan and 0.25MW, 2MWh unit in Castle Valley, Utah. [12]

Since batteries are an array of cells configured in parallel and series, VRB batteries can be scaled quite easily to supply rated power from kilowatts to megawatts. Capacity of the battery is directly proportional to the amount of charged electrolytic solution available so by adding additional storage tanks, the energy capacity of these systems can range from kilowatts to megawatts. The current energy density of VRBs are in the range of 20-30Wh/L[13]. A 150kWh unit would require about 6000L of solution which would have a foot print of two square metres (if three metres in height) – easily fitting in any space in the SUB. The current AC round trip efficiency of VRB batteries is around 45% which is very competitive with other storage technologies. In addition, because there is virtually no discharge during storage, this technology is suited well for long term power storage.

4.2 ECONOMICAL FEASIBILTY ANALYSIS

The majority of the life-cycle costs of a VRB system are contained within the upfront cost to purchase and install the system. *Figure 12* calculates a very rough estimate on the cost of a unit based on rated power and energy capacity. It is estimate that a 150kW, 150kWh VRB unit will have an initial capital cost of approximately $182,000.

$$\boxed{\text{Capital Cost} = \$1{,}100 \text{ x (kW rating)} + \$110 \text{ x (kWh rating)}}$$

Figure 11: Cost of Vanadium Redox Battery Storage (adapted from Tables 3 & 4 [14])

Regular maintenance on the VRB is minimal – consisting of visual inspections of VRB piping, HVAC and pumps every six months and bolt torque checked every year [13]. The pump bearings and O-rings may need replacement in five year intervals. The cell stacks are the limiting component of the life of the VRB system – estimated to last approximately 10-15 years. The stacks can be refurbished by replacing the PEM which wears with time. Replacement of the PEM in the stacks is estimated to be about 11% of the initial capital cost (~$20,000) [13]. If pumps and cell stacks are maintained and refurbished as necessary, a VRB has an expected life of easily more than 20 years. Disposal and recycling costs associated with the unit are also minimal since the electrolytic solution can be virtually reused indefinitely. For the Tanks, piping and cell stacks, standard commercial processes to dispose and recycle are available.

4.3 SOCIAL IMPLICATIONS

The majority of the material and chemicals used in the manufacturing of these batteries will be produced or sourced in North America where human rights and health are seldom violated. Vanadium pent-oxide (VO_5) (which is used to make the electrolyte solution) may originate from a region where ethnical practices may be suspect, however it would be very difficult to trace its origins since VO_5 is a widely traded commodity in North

America (where it is primarily used in strengthening steel).

Since VRBs do not contain any heavy metals [11] and are designed to be fully closed systems, the batteries will not have any health implications on the student population of UBC. However, due to the nature of the product (dealing with large amounts of power and energy) a VRB system would best be isolated from the student population so the effectiveness of using a VRB storage system to demonstrate energy storage technology is quite small. However, a VRB system (similar to any reliable energy storage system) would have an indirect positive impact on the local student population by allowing intermittent, renewable energy sources such as wind and solar be a viable option for power generation. Most renewable generation (wind, solar, tidal, run of river hydro) ramp up* and down quite quickly and generally do not match power load demand. A battery would be able to store surplus energy and then release it on demand – making the system a slightly more reliable and reducing the need to switch back and forth between renewable and grid power during times of intermittent generation.

4.4 ENVIRONMENTAL IMPACT

VRBs are much more environmentally friendly than other battery energy storage technologies [11]. VRB systems have a fairly low toxicity since they do not require heavy metals in their construction such as nickel, cadmium, lead or zinc. Heavy metals are generally toxic and will harm the surrounding environment if concentrations become large enough. However, similar to lead acid batteries, VRBs require sulfuric acid (SO_4) to form the vanadium solutions. Concentration of SO_4 in VRB batteries is approximately the same as that of lead-acid battery [13]. However, unlike lead-acid batteries, once the aqueous solution of vanadium ions is created it can virtually be used indefinitely [14] so there is minimal environmental impact on the environment once the solutions are produced. Sulfuric acid is one of the largest manufactured chemicals in the US and in the world and is readily available for construction of VRB units. The storage tanks and piping are usually made with fiberglass or polyvinyl chloride (PVC) as they are very common materials and can withstand the acidic environment.

The most energy intensive components of the VRB system are the initial process of extraction to vanadium solutions and the production of the cell stacks. Vanadium is commonly found around the world in a variety of ores (bauxite, vandinite, camotite) and carbon containing deposits (shale, coal, crude oil) [13], however needs to be refined before being used. The power stack is the most complicated component of the VRB system containing parts that require specialized and energy intensive production techniques (such as the proton exchange membrane). *Table 3* summarizes an estimate of the embodied energy and carbon dioxide used and produced for a 150kWh unit.

Table 4: Life-Cycle Energy Use and CO_2 Production [15]

Component	**GJ/MWh**	**Tons CO2/MWh**	**GJ/150kWh**	**Tons CO2/150kWh**
Electrolyte materials and manufacturing	453	32.0	67.95	4.8
Power Stack materials and manufacturing	986	70.7	147.9	10.605
PCS	236	16.8	35.4	2.52
Balance of plant	435	30.9	65.25	4.635
Transportation	79	6.2	11.85	0.93
Decommissioning and recycling	64	4.7	9.6	0.705
Total	2253	161.3	**338 GJ**	**24.195 Tons CO2**

Based *on table 3,* the energy required and CO_2 produced for a 150kWh VRB unit is in the range of 340GJ and 24 tons CO_2. Based on an 11MWh annual energy consumption [16] and 11,450 pounds CO_2 annual production from passenger vehicles [17], the construction of the VRB requires almost enough power to supply nine homes and produces enough CO_2 to run five cars for a year.

5.0 COMPARISON OF ENERGY STORAGE TECHNOLGIES

After assessing the economic, environmental and social impacts of FES and VRB technologies, the costs and social/environmental implications ofeach technology are very similar. *Table 4* summarizes some of the key differences of the two technologies.

Table 5: Comparison of FES and VRB Technologies

	FES	VRB
Energy Density	50-190Wh/kg	20-30Wh/L
Short term round Trip Efficiency	90%	45%
Long term round trip efficiency	~0%*	~45%**
Up front Capital Costs for (150kW, 150kWh unit)	$165,000	$185,000
Scalability	Requires additional units	Easily implemented retrofits available

*Since the flywheel is constantly fighting some form of friction, most of the energy in a flywheel will be consumed in anything over a dozen hours

**As long as the electrolytic solutions remain in storage tanks they will not discharge

Since one of the SUB's goals is to achieve net-zero power consumption, the renewable energy sources are expected to be added after the building is first constructed. It is important that the technology is easily scalable, does not take up too large a space, can store energy for durations of days (instead of hours) and reasonability priced.

Energy density of FES is much higher than that of VRB, however the actual space required to house the two systems would be quite similar. Both systems require a dedicated basement or room to be housed as a safety precaution (and neither is too large that it would not fit in a reasonably sized storage space). Flywheels do excel in short term round trip efficiencies, however if the energy is ever to be stored for periods longer than a few hours that efficiency decays to below that of VRB and eventually approaches 0% if enough time passes. Up front capital costs are similar, VRB has a larger maintenance cost due to cell refurbishment, however this is offsetting by the ease of increasing energy storage capacity (which would be required if the SUB were to become self sufficient in its energy production). In a FES system, additional flywheel units would be required to increase the energy capacity and to increase the power capacity the flywheels would need to rotate even faster – requiring more expensive materials in the system. VRB systems can easily increase energy capacity by retrofitting the unit with additional storage tanks and electrolyte. Power capacity can be increased by retrofitting VRB systems with additional PEM cells.

6.0 CONCLUSION AND RECOMMENDATIONS

This report investigated two potential solutions for energy storage in the new SUB - flywheel energy storage and vanadium redox flow batteries. Initial analysis of the new SUB designs determined the amount of power and energy that would be required as well as the amount of power and energy that could potentially be produced using a solar panel array. Annual energy consumption is estimated to be 1864 MWh with a potential production of 320 MWh. Despite the net energy deficit energy storage will still be needed for the SUB to achieve LEED Platinum certification and for additional future generation capacity. A triple bottom line assessment of both FES and VRB systems with special attention to the scalability and practicality of each system was performed. This report's findings conclude that that both FES and VRB systems are ideal for use in load leveling/power quality applications such as that of the new SUB. Each technology has a relatively small environmental footprint and an indirect positive social impact by encouraging the use of renewable power supplies. However, the length of energy storage is quite short FES systems, on the scale of a few minutes to a few hours. Conversely, VRB systems can stored on the scale of hours to days.

Due to the short energy storage time for FES systems and difficulty in scaling the units (additional units must be installed if there is an increased need for energy storage) a VRB system would be recommended for meeting the storage requirements for the SUB. In addition, further research into reducing the building's energy load (with focus on effective heating, cooling and domestic hot water) as well as the possible increase of renewable generation capacity is needed. If surplus energy is not available for storage for a reasonable proportion of the year, an energy storage system is not a worthwhile investment.

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APPENDIX: Figure Sources

Table A: Average Daily Energy and Power

Month	Daily Energy Production (kWh)	Daily Power Production
Sept	1086 kWh	85.77 kW
Oct	682 kWh	63.21 kW
Nov	349 kWh	37.62 kW
Dec	306 kWh	36.67 kW
Jan	327 kWh	37.60 kW
Feb	464 kWh	46.50 kW
Mar	731 kWh	61.60 kW
Apr	993 kWh	72.25 kW
May	1261 kWh	82.86 kW
Jun	1250 kWh	77.61 kW
Jul	1610 kWh	102.26 kW
Aug	1462 kWh	102.15 kW

Table B: Breakdown of Average Daily Energy Consumption

Month	Lighting (kWh)	Plug Load (kWh)	Space Heating (kWh)	Space Cooling (kWh)	Pumps (kWh)	Fans (kWh)	DHW (kWh)	Daily Energy Demand (kWh)
Sept	462.0	1711.9	268.7243	346.5753	91.58513	545.9883	1409.002	4836
Oct	735.4	1711.9	679.7145	0	91.58513	545.9883	1409.002	5174
Nov	1436.4	1711.9	1043.283	0	91.58513	545.9883	1409.002	6238
Dec	1641.6	1711.9	1289.877	0	91.58513	545.9883	1409.002	6690
Jan	1532.2	1711.9	1305.684	0	91.58513	545.9883	1409.002	6596
Feb	1081.5	1711.9	1087.543	0	91.58513	545.9883	1409.002	5928
Mar	686.0	1711.9	1030.637	0	91.58513	545.9883	1409.002	5475
Apr	505.1	1711.9	765.074	0	91.58513	545.9883	1409.002	5029
May	398.0	570.6	477.3809	115.5251	30.52838	181.9961	469.6673	2244
Jun	401.4	570.6	221.3024	924.2009	30.52838	181.9961	469.6673	2800
Jul	311.6	570.6	82.19803	3234.703	30.52838	181.9961	469.6673	4881
Aug	343.0	570.6	66.39072	3696.804	30.52838	181.9961	469.6673	5359
Average	794.5	1331.5	693.2	693.2	71.2	424.7	1095.9	**5104.1**

Table C: Average Daily Energy Production to Consumption Ratio and Average Daily Power Usage

Month	Daily Energy Production (kWh)	Daily Energy Demand (kWh)	Production/Demand (%)	Daily Power (kW)
Sept	1086	4836	22.5%	201
Oct	682	5174	13.2%	216
Nov	349	6238	5.6%	260
Dec	306	6690	4.6%	279
Jan	327	6596	5.0%	275
Feb	464	5928	7.8%	247
Mar	731	5475	13.4%	228
Apr	993	5029	19.7%	210
May	1261	2244	56.2%	93
Jun	1250	2800	44.6%	117
Jul	1610	4881	33.0%	203
Aug	1462	5359	27.3%	223
			Average Daily Power (kW)	213