UBC Social Ecological Economic Development Studies (SEEDS) Student Report

An Investigation into Sustainable Energy Storage Systems for Buildings

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ABSTRACT

This report documents the research that has been done on the use of Energy Storage Systems (ESS). To ensure the reliability of the alternative energy source for the new SUB, ESS needs to be incorporated in the energy system to store electricity at off-peak periods and release the energy at peak time. Three storage techniques are presented in the report, including the most traditional batteries, and two promising techniques— the flywheel system, and the superconducting magnetic energy system. Operation and implementation of every energy storage method is covered. In addition, each technique's advantages and disadvantages are analyzed, and triple-bottom line analyses are made. Although battery is very reliable and has an energy density of about 80kwh/kg, it has a cost of over $1/kwh, and it is non-environmentally friendly; the flywheel is both reliable and efficient; the superconducting magnetic energy system is 97% efficient and reliable, still it is not cost-effective at small scale. Based on the cost, social and environmental impacts, the flywheel energy storage system is recommended for the new SUB.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage System
COE	Cost of Energy
DC	Direct Current
ESS	Energy Storage System
HOMER	Hybrid Optimization Model for Electric Renewables
NiCd	Nickel Cadmium
NiMH	Nickel-Metal Hydride
SMES	Superconducting Magnetic Energy Storage
SUB	Student Union Building
UBC	University of British Columbia

GLOSSARY

HOMER	A modeling software for analyzing hybrid power systems.
Power Factor	A ratio of the efficiency of an energy system in terms of real power to apparent power. An ideal power factor has a value of one.
Reactive Load	A load without an ideal power factor, causing extra stress to a supply system and resulting in higher costs.
Superconductor	Materials that have zero electrical resistance when held below a particular characteristic temperature.

1.0 INTRODUCTION

The University of British Columbia (UBC) is in the midst of planning a new Student Union Building (SUB), projected for completion by September 2014. Part of the planning process includes looking at energy storage systems for use in conjunction with renewable energy sources. The three tenets used to evaluate these systems is part of a triple bottom line assessment, which includes looking at the environmental, economic, and social impacts of each technology. The university hopes that energy storage, along with many other tenets of the new SUB, will result in a LEED Platinum certification.

Energy storage is a relatively young concept in the context of buildings. The most traditional energy storage system is the battery, and as batteries and fellow technologies have been developed, their use along with renewable energy sources has grown exponentially, particularly as sustainable development becomes an increasingly important issue. Many new energy storage technologies have emerged in the past half-century, including flywheel-based storage, hydro pump storage, superconducting magnetic, along with the development of new types of batteries commonly found in various markets. This report will look at battery systems as well as flywheel-based and superconducting magnetic energy storage. If satisfactory to the triple bottom line assessment, any of these technologies stands as a candidate for energy storage in the new Student Union Building at UBC.

2.0 BATTERY ENERGY STORAGE SYSTEMS

Batteries have been widely used in our daily life, ranging from the six cell lithium ion battery that powers mobile phones to the rechargeable nickel-metal hydride cells (NiMH) that power digital cameras. Additionally, the Battery Energy Storage System (BESS) is becoming more and more important in integrating renewable energy sources to electricity networks [1]. It has been recognized with the benefits such as technology being mature, ensuring the reliability and greater use of the renewable energy sources, and providing security and power continuity. Moreover, BESS can be easily added to the current power station to provide temporary backup power, and may reduce the cost for the consumers because electricity can be purchased at off-peak periods, stored in the BESS and used in the peak time [1]. Consequently, BESS is promising in integrating the renewable energy source with the current electricity network.

2.1 ANALYSIS OF BATTERIES

With so many types of batteries available, there are many benefits and drawbacks to each one. For this report, three common types of batteries: Lead-Acid, Nickel-Metal Hydride Cell, and Lithium Ion, will be discussed and compared.

2.1.1 Lead-Acid Battery

Invented in 1869, Lead-Acid battery is one of the oldest batteries and has been universally used for automobile starter motors and backup power supply at computer centers. For this type of battery, energy is converted between electrical energy and chemical energy, and it can be recharged after use. Combined with power conditioning system and controlling circuit, Lead-Acid batteries can form a BESS [2]. The advantages of Lead-Acid Battery are low cost, reliability, tolerance to overcharging. The shortcomings are limited life-cycle (only 300-500 charge cycles), low energy density, and use of non-environmentally friendly chemicals [1].

2.1.2 Nickel-Metal Hydride Cell

A hydrogen-absorbing alloy is used as a negative electrode and nickel oxyhydroxide is used as the positive electrode in the nickel-metal hydride cell (NiMH). It is mostly used in hybrid electric vehicles. It overshadows the Lead-Acid battery as it gives a higher energy density (about 80 kWh/kg), a low discharge rate, available in various sizes and weight, and a longer lifespan. While it costs more than the Lead-Acid battery, it is more environmentally friendly.

2.1.3 Lithium Ion Battery

In a Lithium-Ion Battery, lithium ions move from the positive electrode during charging and move from the negative electrode to the positive electrode when discharge. Lithium-ion batteries have been in wide use in consumer electronics such as computers, mobile phones, and digital cameras. While there is constant research conducted in order to improve it, Lithium-ion has already shown its superiority due to its high energy-to-weight ratios, small charge loss, and lack of memory effect, which is advantageous as there is no need to totally discharge the battery before charging it again. Still, they are disadvantageous in being vulnerable to high temperature, a relatively high cost, and a diminishing capacity the more it is charged and discharged [1].

2.1.4 Characteristic Comparisons

[1] developed a Simulink model to compare the peak voltage and maximum powers of different batteries. The result is shown in Table 1 below.

Table 1: Simulink Modeling Results

Battery Type	**Characteristics**				
	Nominal Voltage (V)	***Nominal Discharge Current (A)***	***Time to reach Nominal Voltage (s)***	***Peak Measured Voltage (V)***	***Max. Power (W)***
Pb-Acid	12	20	6800	13.5	306.5
NiCd	12	18	4500	13.7	307
NiMH	12	20	3700	14.1	314
Li-ion	10.8	43	4000	11.7	270

(N. Garimella and N. Nair, “Assessment of Battery Energy Storage Systems for Small-Scale Renewable Energy Integration”, Sept. TENCON 2009- 2009 IEEE Region 10 Conference. pp 1-6)

It can be seen that NiCd and NiMH batteries give the highest peak measured voltage and the maximum power supply.

2.2 TRIPLE BOTTOM LINE ASSESSMENT

As part of the evaluation of each storage system, below is a triple bottom line analysis for all three proposed battery types.

2.2.1 Economic Assessment of Different Battery Types

[1] also used the National Renewable Energy Laboratory software HOMER to build a model to assess the economic cost of those batteries. In this model, the direct current generated by the photovoltaic system is stored by the battery and discharged through the converter to become alternating current (see Figure 1). In this case, the resulting electric energy is to meet the primary load with a 1.6kW peak.

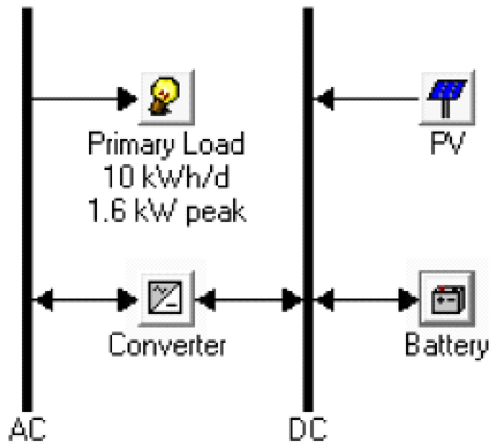

Figure 1: HOMER Photovoltaic Model
(N. Garimella and N. Nair, "Assessment of Battery Energy Storage Systems for Small-Scale Renewable Energy Integration", Sept. TENCON 2009- 2009 IEEE Region 10 Conference. pp 1-6)

The optimized results are shown in Table 2 below. The Lead-Acid battery offers the lowest Cost of Energy (COE) and the lowest initial cost. However, it has the highest operating cost due to its short life cycle. Although Lithium Ion batteries give the lowest operating cost, they have the highest initial cost and consequently the highest COE. NiMH is therefore placed in the middle.

Table 2: HOMER Modeling Results on Economic Costs

Factors	Battery Type			
	Lead-Acid	*NiCd*	*NiMH*	*Li-ion*
PV (kW)	4	3	3	4
No. of Batteries	20	24	24	20
Converter (kW)	1.3	2	2	1.3
Initial Capital ($)	31,814	42,267	39,987	54,654
Operating Cost ($/Year)	1,137	991	1,001	772
COE ($/kWh)	1.13	1.36	1.31	1.62

(N. Garimella and N. Nair, "Assessment of Battery Energy Storage Systems for Small-Scale Renewable Energy Integration", Sept. TENCON 2009- 2009 IEEE Region 10 Conference. pp 1-6)

2.2.2 Environmental Impacts

Even though the Lead-Acid battery seems economically desirable, it is non-environmentally friendly. For example, while lead-recycling is a mature industry, every year about 40,000 metric tons of lead, most from lead-acid batteries, ends up in landfill, which is harmful to the environment. As UBC is a leading university in sustainability research and practice, the New Student Union Building (SUB) is an unlikely candidate to adopt Lead-Acid batteries for energy storage.

Both NiMH and Lithium-Ion batteries have comparatively small environmental impacts. In fact, Lithium-Ion is not listed as an environmental hazard by the US government. For NiMH, the environmental impacts (see Table 3) as found by [3] show that about 70% of human health damage, 50% of ecosystem quality damage, and 65% of resources damages by the use of NiMH can be traced back to production. Table 3 also shows that by recycling, there is 20% less damage because of the reuse of some materials. Consequently, recycling of batteries is strongly recommended.

Table 3: Comparison of Batteries Using Eco Indicator 1999 Methodology

Battery type	NiCd		NiMH		Alkaline
End of life scenario	Landfilled	Recycled	Landfilled	Recycled	Landfilled
Damage to human health DALY	6.14 E-6	6.42 E-6	5.03 E-6	5.26 E-6	482 E-6
Ecosystem quality PDF*m^{2}Yr	0.23	0.24	0.20	0.21	19.4
Resources MJ surplus	5.71	4.40	5.40	4.23	427

(David Parsons, "The Environmental Impact of Disposable Versus Re-Chargable Batteries for Consumer Use", the International Journal of Life Cycle Assessment 12 (3), 2007, pp 197-203).

2.2.3 Social Assessment

Materials used in batteries, such as lead, nickel, lithium, have adverse human health impacts. If those batteries end up in landfill instead of being recycled, the metal component may not only damage the environment, but also pollute underground water, possibly posing harmful effects on human health. [3] found that about 70% of human health damage by the use of NiMH can be traced back to the production. Additionally, the high voltage of batteries used in the new SUB Energy Storage System poses a threat to humans if caution is not exercised.

2.3 RECOMMENDATION ON BATTERIES

Although Lithium-Ion can give an energy density of 120-130 Wh/kg, it is seen that due to its relatively high cost, Lithium-Ion battery is not desirable for any energy storage system that has a capacity of larger than 30kWh [4]. Considering the high energy storage capacity requirement, it is not recommended for the SUB project. As a result, Nickel-Metal Hydride batteries seem promising and satisfactory for the SUB energy storage system as long as the batteries are properly recycled. Without a high initial or operating cost, the overall cost of energy is relatively low. Additionally, NiMH can give an energy density as high as 80Wh/kg. In summary, NiMH can be used to form a Battery Energy Storage System, offering the benefits such as ensuring the reliability and greater use of the renewable energy sources, providing security and power continuity, and potentially reducing the electricity cost [1,5].

3.0 FLYWHEEL ENERGY STORAGE

One of the most efficient and environmental friendly energy storage systems is the flywheel. The flywheel can be used at the micro scale and at the macro scale which makes it very useful for certain applications.

3.1 OPERATION AND IMPLEMENTATION

Flywheel energy storage systems take in electrical energy and store it in the form of mechanical energy that is used when needed. A flywheel is an electromechanical energy storage system in which the energy is stored in the kinetic energy of a rotating mass. The main concept behind flywheel storage is the storage of energy within the angular momentum of the flywheel itself. The rotor itself contains a motor/generator that converts energy between mechanical and electrical energy and vice versa. The rotor can be made from steel or composite, however both have the same general mechanics and usefulness. In both cases the rotor operates in a vacuum and spins on a bearing to lower friction levels and increase efficiency [6]. Steel rotor flywheels depend on mass to store the energy while composite flywheels rely mostly on speed. Both will store energy due to their momentum since momentum is dependent on mass and speed (as momentum transfer equals mass times speed). During charging, electric current flows through the motor which increases the speed of rotation thus increasing total energy of the system [6] (see Figure 2). During discharge, the generator produces current flow out of the system by using the mechanical energy in the flywheel. Connecting two or more flywheels in parallel provides more power [7]. The flywheel is used for a wide variety of energy storage due to its advantages in reliability, long-life, cost, and its fast response [8]. High speed fly wheels are used mainly in embedded applications such as satellites, and that is due to their reduced mass making them light enough to apply to small devices [8].

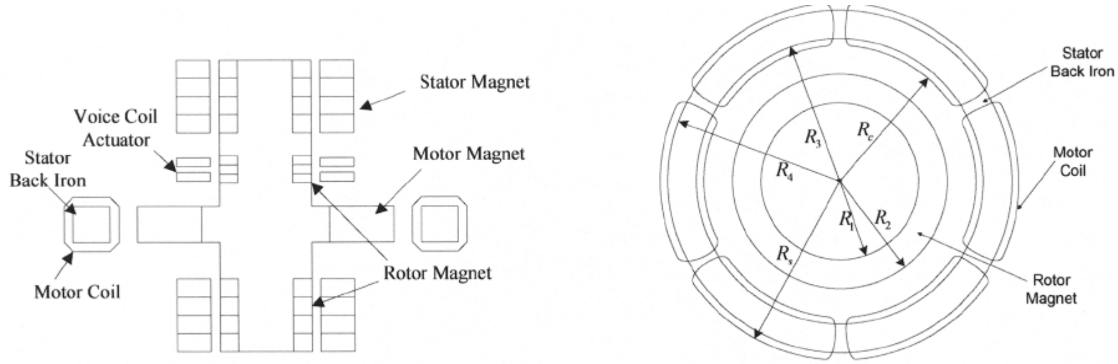

Figure 2: Schematic Diagram for Micro Flywheel Energy Storage System

(S.Y.Yoo, H.C.Lee and M.D.Noh, "Optimal Design of Micro Flywheel Energy Storage System", in Automation and Systems 2008, pg. 492-497)

3.2 ANALYSIS OF FLYWHEEL ENERGY STORAGE SYSTEM

Before deciding if the flywheel energy storage system is the most effective system for the new SUB, evaluation of the technology is necessary.

3.2.1 Benefits

Because the flywheel stores energy in a mechanical fashion, it is completely environmentally friendly. Also, it is one of the most efficient energy storage systems with close to 90% power transfer. Physically, the rotor is spun in a frictionless vacuum and therefore theoretically there is no power loss. However, some energy is lost in the form of sound and heat. The placement of more than one flywheel in parallel results in greater energy storage which is needed for some applications.

3.2.2 Drawbacks

The flywheel energy storage system has very few drawbacks. The flywheel would need to occupy a certain amount of space and has to have a designated room or rooms for multiple rotors. There was little information on spacing and flywheel size ratios as this is a new but growing technology. A possible drawback is the spacing needed to occupy these flywheels plus the room conditions (e.g. noise reduction) would mean higher construction costs.

3.3 TRIPLE BOTTOM LINE ASSESSMENT

While evaluating flywheel energy storage system it is important to look at the impact it has economically, environmentally, and socially. Upon doing that we can decide which energy storage system would be the most reasonable for the new SUB.

3.3.1 Economic Assessment

The cost to store 1kWh of energy in a flywheel energy storage system is approximately $700/kWh for a demand of 100MWh. At the micro scale, it is much cheaper as the material cost and construction cost to maintain macro flywheels diminish. As the new SUB would need a more macro-oriented flywheel, the costs would be great. However, as one of the longest lasting energy storage systems on the market, their lifetime compensates for initial cost. For a 0.25MWh demand, the total capital cost is between 750,000 and 2,000,000 dollars which is much larger than the demand of 100MWh. This implies that the greater the demand the cheaper per MWh will be. For the new SUB, it is safe to assume that the demand will be fairly below industry average which implies that the cost per MWh will be fairly expensive.

3.3.2 Environmental Assessment

The flywheel energy system suffers power losses only in the form of heat and sound and even those are very minimal. This high efficiency implies that the flywheel energy storage system is environmentally friendly. Also the material used to construct the flywheels is purely of steel and composites which is also environmental friendly. Chemical combustion is involved in a lot of energy storage systems (i.e. batteries), which can pollute the environment and waste resources. Flywheels are purely mechanical based and not chemical based in any way.

3.3.3 Social Assessment

Unfortunately, not much research has been done on the social aspect because it is very hard to find how energy storage systems can affect socially. However, it is known that flywheel energy storage systems have been used at macro and micro scale which would indicate that it had not had a negative social impact. This energy system should be placed in a good size room which should be out of public reach due to the high electrical potential associated with such systems.

4.0 SUPERCONDUCTING MAGNETIC ENERGY STORAGE

One of the more radical and recent approaches to energy storage has been superconducting magnetic energy storage (SMES). Although not widely used, SMES presents a large amount of promise and offers an opportunity for innovation that could lead to widespread future implementation.

4.1 OPERATION AND IMPLEMENTATION

Superconducting magnetic energy storage systems store energy using magnetic fields generated by currents in a cryogenically frozen superconductive coil. The coil is contained within a vessel containing liquid helium, typically kept at 1.8 Kelvin for high current density. As the current runs through the coil, heat is generated which is then absorbed by the liquid helium and extracted by a refrigerator (see Figure 3). Simultaneously, the coil generates a magnetic field that stores electric potential for later use. When power demands increase, a controller within the system tells a firing system to change the direction of an electrical converter, which is both an AC to DC rectifier and DC to AC inverter, so that the system can be either charged during times of low power demand or discharged for use when power demands are high.

As the SMES coils will run currents on the order of 100kA, a transformer is required to bring the current down to acceptable levels. The nature of the system means it is seen as a reactive load to the AC system to which it is connected. This necessitates use of a compensation system that eliminates the reactive load. Once the outgoing current has been properly inverted and cleared of a reactive element, it leaves for an AC system that can be accessed via standard 120V outlets.

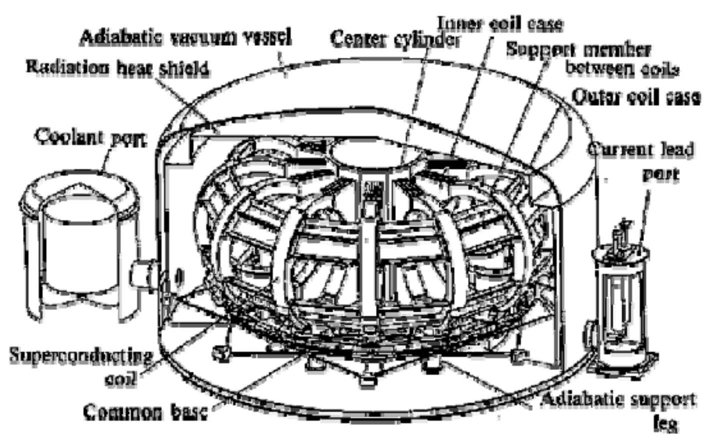

Figure 3: Basic structure of an SMES unit

(Imperial College London, "Superconducting Magnetic Energy Storage")

4.2 ANALYSIS OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE

SMES, like all technologies, yields a variety of benefits as well as drawbacks that must be carefully taken into account before choosing an energy storage system.

4.2.1 Benefits

Because SMES does not convert electricity to other forms of energy such as chemical or mechanical (as in battery- and flywheel-based), it is perhaps the most efficient form of energy storage available, with efficiency typically around 97%, in contrast to around 70% for various chemical and mechanical systems [11]. The superconductive coil itself is theoretically 100% efficient, but there are small heat losses from the transformer and converter. SMES also includes a decreasing cost as storage capacity increases [11], meaning there is greater cost incentive to build larger systems and thus serve a greater populace. A secondary but nonetheless important additional benefit of SMES is that power can temporarily continue to be delivered to a system that has experienced a power outage due to a blown transformer, downed power line, or other failure [14], granting emergency lighting and power capability.

4.2.2 Drawbacks

SMES, however, has a host of issues, not the least of which is the space required to house the system, which becomes particularly large as power needs increase due to the relatively low energy density of magnetic fields [10]. This increases construction and manufacturing costs considerably, so while the overall cost per kilowatt-hour will decrease, the raw costs of producing a larger system increase as well [11].

In the case of larger systems meant for dealing with larger power loads, the system will also suffer large parasitic losses from the transformer and converter despite the high efficiency rate of the overall system [10]. This is undesirable but also minimized through use of SMES as opposed to other storage systems, which will often suffer similar losses.

4.3 TRIPLE BOTTOM LINE ASSESSMENT

In evaluating SMES it is important to look at the impact it has economically, environmentally, and socially. Within each of these constructs SMES poses different advantages and disadvantages which must be carefully taken into account before choosing a system.

4.3.1 Economic Assessment

SMES has not seen widespread use particularly because of impracticality on small scales; construction costs remain high no matter the scale, but at larger power needs the cost per kilowatt-hour decreases dramatically, approximately $800/KWh for a 100MWh demand as opposed to approximately $175/KWh for a 10000MWh demand [11]. On a large scale, SMES is a very promising technology ready to be embraced by utilities. However, given the scale of the New Student Union Building Project, it is fair to assume there will be much smaller power demands, meaning higher costs per kilowatt-hour.

The use of a reactive load compensation device also means potential savings on additional utilities fees caused by highly reactive loads. BC Hydro, as a relevant example, adds between two- and eighty-percent to bills for businesses and users that have highly reactive loads. In the context of a building with high energy needs such as the new Student Union Building, this could lead to unsustainable costs.

Another huge issue is that of high temperature superconductors, which are up to ten times as expensive as traditional super conductors. As these prices decline with more research and development, SMES will become more financially viable in smaller scales [13]. However, it will take many more years before these prices are achievable.

4.3.2 Environmental Assessment

Given the efficiency of SMES, there is very little net energy loss, meaning SMES is the most environmentally friendly storage system available today. This is a particular benefit at night, when energy goes largely unused and slowly burns off in the resistance of copper wires. With a highly efficient SMES system, this energy is stored indefinitely to be used instantaneously at any given time. The end result is that SMES is extremely environmentally friendly, suffering much smaller losses than other storage systems or systems with no energy storage at all. This is caused by the superconductive material which has virtually zero electrical resistance.

4.3.3 Social Assessment

Unfortunately, not much research has been done on the health impact of SMES systems on humans. Given that SMES has been used fairly often in the past with no demonstrative side effects, it is safe to assume that it would not pose a problem in the context of the new Student Union Building. SMES systems are also typically shielded to mitigate the effects of the generated magnetic field. The other primary concern is a liquid helium leak which, with proper isolation and keeping in mind the generally harmless nature of helium, would not present a problem [11].

5.0 CONCLUSION AND RECOMMENDATION

Based on the triple bottom line assessment of these three energy storage systems our team recommends further investigation into the flywheel energy storage system. Batteries, while the most common, are better for very small operations and carry a heavy cost in addition to posing the greatest environmental risk. SMES suffers from the same issue of cost despite being perhaps the most impressive technology; although a full cost analysis was not possible for SMES, it is safe to assume given the primary application for utility companies that it is unsuitable at this scale. Flywheel storage offers the best of both worlds, with the lowest cost as well as a high efficiency not far from that of SMES. With this technology, energy harvested from renewable sources can be stored for a relatively long period of time and at a fairly cheap cost. Energy storage for renewable sources will greatly boost the university mission of becoming a world leader in sustainability and serve as an indicator of the innovation and dedication used to get there.

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