An Investigation into Energy Storage for Use with Renewable Energy Generation in the New SUB

Joel Beales, Jason Serwa, Andrea Slade

University of British Columbia

APSC261

November 30, 2010

APSC 261

An Investigation into Energy Storage for Use with Renewable Energy Generation in the New SUB

Team Members and Roles:
Joel Beales – Battery Assessment
Jason Serwa – Hydro Storage Assessment
Andrea Slade- Flywheel Assessment

Submitted To: Dr. P.D. Mills
Submission Date: Nov. 30, 2010

Abstract

Renewable energy is a key component in the new SUB project. The project vision, set out by the AMS to guide the project to completion, states one of the specific sustainability targets to meet LEED Platinum certification includes “design for a potential improvement of energy performance over time, to net zero energy use if possible” (SUB Vision). The largest challenge in implementing successful renewable energy systems is the storage and then redistribution of this energy.

The scope of this report is to carry out a triple bottom line assessment, including social, environmental and economic aspects, of energy storage methods for the new SUB. Three technologies are investigated, which include pumped hydro, flywheel, and battery storage. Both negative and positive impacts are addressed in order to determine the most viable option. Criteria to base to negative and positive impacts include successful implementation of the technology elsewhere, cost effectiveness, energy density, reliance on non-renewable resources, social consequences involved in the materials, and can function feasibly with renewable energy methods while demonstrating energy storage to the public. To compare the technologies, it is assumed the SUB is operating as net-positive energy and a baseline value is used to reflect this.

Taking all factors into consideration, batteries are concluded to be the most viable energy storage option for the new SUB project. What it lacks in demonstrating sustainable energy practices to the public is more than redeemed in the overall cost savings, high energy storage capacity per volume and weight, as well as the highly effective recycling programs that limit the negative impacts to the environment.

Table of Contents

Contents

List of Illustrations

1.0 Introduction

In order for there to be successful implementation of renewable energy generation in the new SUB, a method for storing the generated energy must be developed. There are many options for storing energy available that have been implemented commercially or independently by companies and researchers. However, many of the methods available pose a negative impact on the environment, or social consequences that make the options less feasible for an application such as the new SUB, where those negative impacts are to be minimized. The three applications of energy storage that were assessed are lead acid batteries, pumped hydro, and flywheels.

Lead acid batteries store chemical energy by using of lead, lead (IV) oxide and sulphuric acid.

A flywheel is a rotating mass that stores rotational kinetic energy that can be converted to other forms of energy. A flywheel consists of a large rotating mass connected to a shaft supported by precision bearings.

Pumped hydro storage (PHS) utilizes hydraulic potential energy to store electrical energy. The system is comprised of an upper and lower reservoir, connected through a piping network that travels through a turbine to harness the electrical energy

A triple bottom line assessment was done for lead acid batteries, a flywheel, and pumped hydro using the following criteria:

1. The technology has seen successfully used in other buildings
2. Are cost effective (MJ/$)
3. Are energy dense (MJ/kg)
4. Has potential for demonstrating energy storage to the public
5. Reliance on non-renewable resources
6. Energy required for production
7. Social consequences involved with manufacturing or shipping of materials

8. Can function with feasible options for renewable energy generation in the SUB like wind, energy harvesting/scavenging, solar photovoltaic or solar thermal.

The option with the lowest environmental and social consequence was recommended to be the most feasible.

2.0 Assessment of Pumped Hydro Storage

Introduction

Pumped hydro storage (PHS) utilizes hydraulic potential energy to store electrical energy (Deane et al , pp.1294). The system is comprised of an upper and lower reservoir, connected through a piping network that travels through a turbine to harness the electrical energy as shown in the figure below.

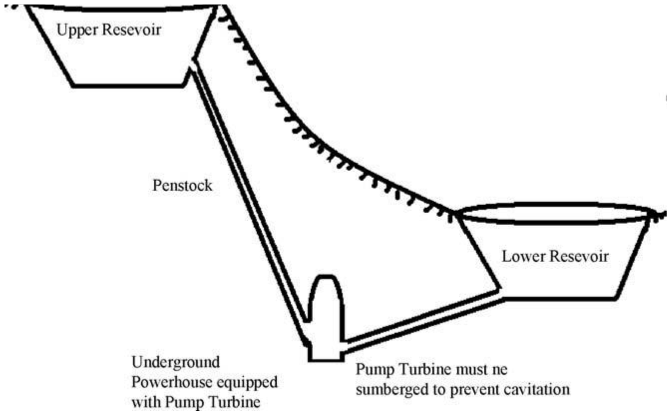

Figure 1- Pumped Hydro Storage System (image source: Deane et al)

The principle is that, when energy demands are low, the excess electricity is used to pump water from the lower reservoir to the upper reservoir. When demand is high, water flows from the upper reservoir to recapture the stored energy (Ilbrahim et al). A PHS system typically has a power conversion efficiency of 65 to 80 percent depending on the system component characteristics.

Successful Uses:

PHS has not been implemented on any single building or small scale application. It is more reserved to large scale projects, such as towns or communities, where mountainous terrain is utilized for creating the head required to run the turbines and stored by constructing a reservoir at the top.

Cost Effectiveness (MJ/$)

To determine the cost effectiveness, a system is considered in which all components of a PHS are included. This system includes a water tower for the upper reservoir, a swimming pool like structure for the lower reservoir, and the piping and turbine to connect the 2 reservoirs. The rough cost estimates are as follows;

- Water Tower: ~ $0.5 – $1.0 Million
- Lower Reservoir: ~ $75,000
- Pipe/ Turbine: ~ $10,000
- Total capital costs = $835,000 (approx.)

Based on the initial assumption that 150 kWh (540 MJ) of energy must be stored,

Cost effectiveness: 540MJ / $835000 = 0.00065 MJ /$

Maintenance demands for this system would be low relative to capital costs. The only component requiring any sort of care is the turbine which will run for decades, but needs to be overhauled every several years.

Energy Density (MJ/kg)

To calculate the energy density, the following formula was used: $P = \eta * \rho * g * h * \dot{q}$

- P = Power
- η = turbine efficiency (assume 0.85)
- ρ - Density of water (1000 kg/m^3)
- g- Acceleration of gravity (9.81 m/s^2)
- h – Head (55 ft required = 16.75m)
- q – Flow rate (0.107 m^3/s) from 10 h discharge to meet 150kWh

Power = 15000 (J/s) or Watts

However, this only demonstrates half of the efficiency looses as the water still needs to be pumped to the upper reservoir. Assuming the same conditions for pumping,

The available power will simply be 15000 * (0.85) = 12750 Watts

12750 (J/s) * 1 /0.107(s/m^3) * 1/1000 (m^3/kg) = 119.16 J/kg

Energy density: 119.16 J/kg = 0.000119 MJ/kg

Potential To Demonstrate Energy Storage To The Public

The implementation of this technology would demonstrate energy storage to the public as nearly the entire system would be visible. The lower reservoir could be an appealing water feature and the water tower could become a landmark for UBC. In addition, the water level of each reservoir would be constantly rising and falling demonstrating the dynamics of the system.

Reliance on Non-Renewable resources

Once operational, this technology has little to no reliance on non-renewable resources as it uses the gravitational potential energy of water, a highly concentrated renewable energy source (Ilbrahim et al). However, to construct this system will require some reliance on non-renewable resources. Firstly will be the diesel fuel consumed by the heavy machinery to excavate the site. Secondly will be the materials required including the concrete or lining for the reservoir, the steel in the water tower, and most of the components that make up the water turbine/ pump. Also, the piping required to connect the reservoirs would most likely be a type of plastic which is heavily reliant on non-renewable resources.

Social consequences

The major social consequences associated with this system arise mainly from the mining of the raw materials needed for the building materials such as the limestone, clay, sand and gravel for concrete, and the iron ore used in steel manufacturing. The mining of these natural resources poses huge environmental degradation to the local ecosystem around the mines. Tailing piles from these mines leech acidic water, also known as acid rock drainage, to the surrounding streams whose effects can be seen kilometres downstream.

Another social consequence involved is associated with the PVC piping required to connect the different components of the system. The manufacturing of PVC creates an unavoidable by-product dioxin. There is no ‘threshold’ does for dioxin, meaning that even the most minute exposure can cause health risks, and is thought to be the most toxic human-made chemical (Goettlich).   Dioxin is so incredibly toxic that it is hard to justify the continued manufacturing of PVC and its use as an appropriate building material.

Feasibility

Depending on the quantity of energy storage required, this type of energy storage may not be possible due to the sheer volume water required. Say we need to store 150 kWh and this is released over a 10 h timeframe (during the evening), power required = 150 kWh/10h = 15 kW as previously stated. This yields a flow rate of 0.107 m^3/s, which over 10 hours equates to a volume of 3852 m^3, or over 1000000 gallons. The volume of water required under the stated conditions makes this type of system highly unfeasible and is the reason why there are such high capital costs. It is understandable why this technology is usually reserved for large scale energy storage projects.

3.0 Flywheels

Introduction

A flywheel is a rotating mass that stores rotational kinetic energy that can be converted to other forms of energy. Most flywheel systems are designed to provide approximately 15 seconds of full load power (Walls et all) . Flywheels are beneficial in applications where there is frequent discharging and recharging, since frequent cycling is harmful to battery life. All of the energy stored in the flywheel is proportional to the rotational speed of the flywheel; therefore the energy stored quadruples as the rpm doubles.

$$K_{rotational} = \frac{1}{2} I \omega^2$$

Flywheels are a feasible solution to energy storage in the new student union building and should be investigated further in the triple bottom line assessment.

Flywheels typically see an average potential loss of 0.1 to 1% of its rated power on its own. In combination with a rectifier and inverter, electrical components which allow voltage and current control, up to 75% of the energy stored in the flywheel may be used. The higher the rpm, the greater the frictional losses associated with the bearings. Typical design life is approximately 20 years.

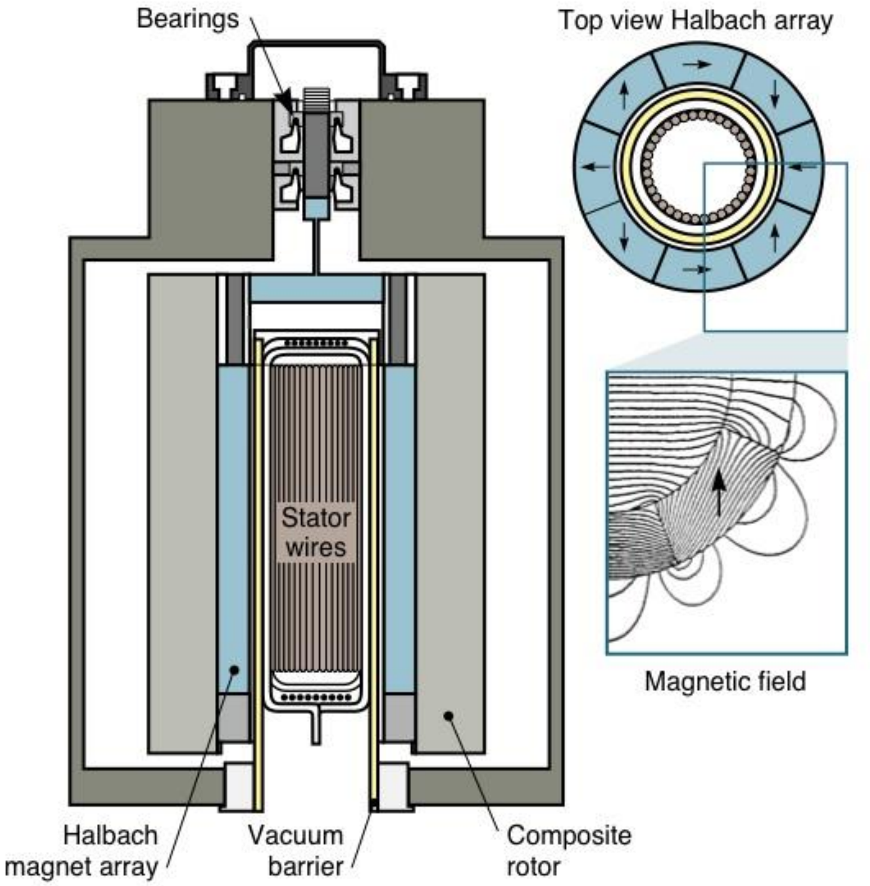

Figure 2 - Typical Flywheel System[1]

Successful Uses:

Flywheels have been successfully implemented in many uninterrupted power systems (UPS) providing short term back up. They have also been used in federal application by the Department of Defence, and at State Department of Veterans Affairs facilities. However, flywheels are not well documented of energy storage for renewable energy generation. This is an application that has not been successfully implemented.

---

[1] image source: http://myecoproject.org/2009/06/26/hawaiian-nonprofit-organization-to-utilize-llnl-energy-technologies-for-food-production/

Cost Effectiveness (MJ/$)

The following is a cost breakdown for the capital and total costs of the flywheel system. These values were obtained from Pacific Northwest National Laboratory. The values were calculated Based on the assumption: 150kWh = 540 MJ

- Purchase: $100-$300 / kWh
- Installation: $20-$40 / kWh
- Maintenance: a few $/kWh/year
- Service Contracts $5/kWh/year
- Bearing Replacements $5/kWh to $15/kWh,
- Vacuum Pump replacement: $5/kWh
- Stand-by Power Consumption: $5/kWh/year

If a system which has the capacity to supply 150kW, total capital cost (Purchase and installation cost) become:

Capital cost: $200/kWh*150kWh + $30/kWh*150kWh = $30300
Cost effectiveness: 540MJ / $30300 = 0.01782 MJ/$

Maintenance demands vary depending on the flywheel, but generally, the maintenance cost is lower than for a battery. Changing cabinet air filters and changing vacuum pump oils magnetic bearings typically have no significant maintenance cost.

Energy Density (MJ/kg)

In the application of flywheels in space, they are typically designed with a specific energy density of 0.15 MJ/kg (IEEE Explore). Flywheels typically have a much higher energy density than batteries, typically by a factor of 5 or 10 (PacificNorthwest National

Laboratory) which would make it approximately 0.882MJ/kg. This number was calculated based on the value for Lead Acid Battery and then multiplied by a factor of 7.

Potential To Demonstrate Energy Storage To The Public

A flywheel has potential to demonstrate energy storage to the public. Unlike a battery, which is a stationary an generic, a custom flywheel may be built with a transparent viewing window. When energy is to be stored, for example after a large gust of wind or on a hot day, people will see the flywheel begin to rotate. Since electricity is likely constantly being generated and depleted from the storage supply, people may see the change in rotational energy which may inspire them to conserve energy in order to keeps the flywheel rotating.

Reliance on Non-Renewable resources

Low-speed flywheels are usually made from steel, where high-speed flywheels are typically made from carbon or carbon and fiberglass composite materials. Both of these materials are non-renewable but can almost always be recycled and reused in other applications. Since 1990, Canadian steelmakers have increased the amount of scrap steel they recycle by 26 per cent (Chaurand et al)

Energy required for production

The energy required for production involve the manufacture, and possible shipping energy since the installation can generally be assembled relatively easily. Most of the flywheel systems would be shipped from places in the States, and in most cases would be shipped by the train. The manufacture of the flywheels would require large quantities of energy for the production of steel.

Social consequences

The significant social consequences occur in the mining and manufacture of the steels. In 2002, steelmakers in Ontario and Quebec consumed about four million tonnes of Canadian metallurgical coal, about seven per cent of Canadian consumption. They also imported coal from the U.S. (Centre for Energy). As coke is burned, tar and hot oven gases are created. This gas mixture contains carbon dioxide, carbon monoxide, water vapor, benzene, and other harmful emissions (Centre for Energy). The coal tar and oven gas are collected and transported to a by-products facility at the steelmaking plant. In steelmaking, greenhouse gases result from the chemical reaction that occurs in the blast furnace reaction between coke and iron ore (Centre for Energy)

Feasibility

A flywheel is a feasible approach to function with energy generation options.

Conclusion

Advantages (Information obtained from Pacific Northwest National Library)

The design life for a flywheel is typically about 20 years, while most batteries in UPS applications will only last 3 to 5 years.

Batteries must be kept within a narrow operating temperature range typical of space-conditioning requirements for people, while flywheels are tolerant of normal outdoor ambient temperature conditions.

Frequent cycling has little impact on flywheel life. In contrast, frequent cycling significantly reduces battery life.

Flywheel reliability is 5 to 10 times greater than a single battery string or about equal to two battery strings operating in parallel.

Flywheels are more compact, using only about 10 to 20% of the space required to provide the same power output from batteries.

Flywheels avoid battery safety issues associated with chemical release.

Flywheel maintenance is generally less frequent and less complicated than for batteries.

Disadvantages

Batteries typically have a large capital cost associated with installation and manufacture

Many greenhouse gasses and harmful emissions are released in the steelmaking process

4.0 Assessment of Lead Acid Batteries

Introduction

Batteries energy in the form of chemical potential energy. The first battery was invented over 200 years ago, but battery technology is far from dated. Many modern advances have been made to improve the performance of batteries.

The battery type that presents the most feasible solution for energy storage in the new SUB building is the lead-acid battery. This battery is most commonly known for being used as a car battery, but it is also the leader in chemical energy storage for use with technologies such as solar and wind power. Chemically, the lead acid battery is made up of lead, lead (IV) oxide and sulphuric acid. Though the use of these chemicals may make lead-acid batteries seem like a very unsustainable solution, the lead-acid battery recycling program is extremely successful and effective.

Successful Uses:

Lead-acid batteries have been in use for many years for purposes from use in cars to storing solar power. They are proven to be an affordable and effective means for storing energy.

Cost Effectiveness (MJ/$)

Initial capital costs for lead-acid batteries range are approximately $100 per kWh. These batteries require regular maintenance, but the majority of the maintenance cost would be labour which could be easily completed by a UBC employee. This maintenance cost would be very small. All the batteries used in the system would need to be replaced every 3-5 years.

If the system has the capacity to store 150kWh, the total capital cost of this storage system would be:

$100/kWh * 150kWh = $15 000

This leads to a cost effectiveness in mega joules per dollar of:

540 MJ/$15000 = 0.036 MJ/$

Energy Density (MJ/kg)

The energy density of a lead-acid battery is 0.126 MJ/kg. Though this density is far greater than pumped hydro storage, it is significantly less than the flywheel provides. However, lead-acid batteries are sufficiently energy dense to provide energy storage for the new SUB building without inhabiting too much space.

Potential To Demonstrate Energy Storage To The Public

This storage option offers nothing for demonstrating energy storage to the public. These batteries would likely be stored in a room out of site from any of the buildings guests.

Reliance on Non-Renewable resources

The main components of lead-acid batteries are lead, sulphuric acid, and plastic. Though our planet has a limited amount of lead, we do not need to consider lead to be a non-renewable resource because we can recycle it. In fact, the lead acid battery recycling program is one of the most successful recycling programs in the world. In the United States, 97% of the lead from batteries is recycled at the batteries end of life. The acid from batteries is neutralized producing water, and even the plastic is reused. This recycling program allows the manufacture of lead acid batteries to be a sustainable practice.

Social Consequences

Lead is a toxic substance and exposure to lead causes harmful effects to humans. Though the lead-acid battery program is extremely effective, 40,000 metric tons of lead find their way to a landfill every year. 70,000 metric tons are also released in the lead mining and manufacturing process. However, by recycling the batteries used in the new SUB properly, we would not be contributing to the 40,000 tons of lead per year added to landfills. We would still be contributing to lead released in manufacturing, but constant improvements in lead furnace and recycling plant designs are required for industry to keep up with emissions standards. Other social issues, such lead miners and workers in lead recycling plants in less developed countries having symptoms of lead poisoning, are discomforting. However, these are the result of lax or unenforced safety standards. We can avoid contributing to this kind of damage by purchasing our batteries from reputable companies.

Energy Required for Production

12,000 megajoules of energy are required to produce each lead-acid battery using all new materials. However, only 2600 megajoules of energy are required to produce a lead-acid battery using recycled materials. (Gaines et al)

Feasibility

Lead-acid batteries are the most commonly used energy storage option for small scale solar and wind energy storage. In fact, the United States Department of Energy suggests using lead-acid batteries for residential energy storage (U.S. Department of Energy). Though the new SUB is not a residence, it should produce similar energy levels. Lead-acid batteries have been commonly used with energy generation technologies in buildings for years and there is no doubt that they are a viable option for the new SUB.

3.0 – Conclusion and Recommendation

In this project, we looked at three different options for energy storage in the new SUB building: Pumped Hydro, Flywheels, and Lead-acid Batteries.

A pumped hydro system could be highly effective in demonstrating energy storage to the public, but it's lack of energy density and extremely high cost make it infeasible for a project like the new SUB building.

Flywheels are a much more viable option for energy storage for the new SUB. Flywheels had the top energy density of all three options and show potential for demonstrating energy storage to the public. However, flywheels have a high initial capital cost.

Lead-acid batteries could not be used to demonstrate energy storage options to the public. They are less energy dense than the flywheel, but within the acceptable range. Additionally, lead-acid batteries have a highly effective recycling program, limiting their harmful impacts on the environment. Batteries offer the lowest initial capital costs, at less than half the cost of a flywheel system.

Taking all factors into consideration, the Lead-acid battery is the superior energy storage option for the new Student Union Building at UBC. Lead-acid battery provides acceptable results for all assessment criteria and a far lower cost than both hydro and pumped storage. Though lead-acid batteries would not be used to demonstrate energy storage to the public, the effectiveness of batteries as a storage option outweighs this criteria.

References

R. Hebner, and J. Beno A Walls, "Flywheel Batteries Come Around Again," *IEEE Spectrum* , pp. 46-51, April 2002.

J. P. Deane, B. P. Gallachoir, and E. J. McKeogh, "Techno-economic review of existing and new pumped hydro energy storage plant," *Renewable & Sustainable Energy Reviews*, vol. 14, no. 4, pp. 1293-1302, 2010.

P. Goettlich. (2001, October) Mindfully.org | Mindfully Green. [Online]. http://www.mindfully.org/Plastic/Polyvinylchloride/PVC-Health-HazardPWG25oct01.htm

A. Ilinca, and J. Perron H. Ibrahim, "Energy storage systems - characteristics and comparisons," *Renewable and Sustainable Energy Reviews* , vol. 12, no. 5, pp. 1221–1250, June 2008.

Pacific Northwest National Laboratory, "Flywheel Energy Storage," US Department of Energy – Energy Efficiency and Renewable Energy, 2003.

N. Garimella and N. C. Nair, "Assessment of Battery Energy Storage Systems for Small-Scale Renewable Energy Integration," *Tencon 2009 - 2009 IEEE Region 10 Conference*, vol. 1, no. 4, pp. 194-199, 2009.

J. Rose, O. Proux, J. L. Hazemann, V. Briois, M. Salome, J. Susini, J. H. Ferrasse, D. Borschneck and J. Y. Bottero P. Chaurand, "Environmental Impact of Steel Slag reused as Aggregates in Road Manufacturing: Molecular Mechanisms of Chromium and Vanadium Release".

R. B. Schainker, "Executive Overview: Energy Storage Options For A Sustainable

Energy Future," *Power Engineering Society General Meeting, 2004. IEEE*, vol. 2309-2314.

U.S. Department of Energy. (2002, October) Battery Power for Your Residential Battery Power for Your Residential Solar Electric System. [Online]. http://www.nrel.gov/docs/fy02osti/31689.pdf

Linda Gaines and Singh Margaret. (1996) Impacts of EV Battery Production and Recycling. [Online]. http://www.transportation.anl.gov/pdfs/B/239.pdf