LCA: Batteries and Fuel Cells for Commercial Buildings in British Columbia

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An analysis of grid storage zinc bromide and hydrogen proton-exchange membrane technologies, emissions and costs in the context of the British Columbia electricity rates and usage.

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Section 1: Summary

A typical office building might consume 250 kWh at its peak hour. The existence of the ebb and flow of electricity demand is amplified when considering large areas such as cities, or even a 50,000 student university such as the University of British Columbia (UBC). Infrastructure and energy costs, in terms of emissions and dollars, are required to manage “peak”, resulting in excess capacity that still must be paid for during “off peak” hours.

Based on these complications, large scale stationary storage has recently become more attractive to better optimize existing infrastructure. This report reviewed this scenario in the context of a “model building” in British Columbia. This building was modeled after the UBC University Services Building, which is similar in electricity demand or load profile as that of commercial office buildings. A life cycle analysis for zinc bromide batteries and hydrogen fuel cells specified to meet this office building demand were completed. The results were scaled to determine what emissions, costs, and peak-demand “load shaving” could result from using these technologies in a fraction of the commercial buildings identified in the Vancouver Metropolitan Area, and for a fraction of the buildings at UBC.

Results were disappointing from a costs perspective, in that figures showed over $1.1B would need to be spent to reduce peak demand by 9%, or 795MW, for four hours, for Vancouver. For UBC, costs would be between $23MM (fuel cells) - $26MM (batteries) to reduce peak demand by 17.5 MW, or 37% of current load. This is in comparison to $260k to upgrade the existing 42 MVA transmission lines or ~$10MM to replace the lines with 62MVA lines, which at a 98% power factor would allow load to increase to 60MW, an increase of 13 MW from current 47 MW peak.

Emissions results were encouraging, but should be noted that emissions of either technology are strongly dependent on energy consumption and source during the “use” phase.

For further analysis, it is recommended that focus on the raw materials emissions and disposal energy/emissions processes be completed. It is recommended that vendor-specific data be obtained regarding materials in terms of emissions, energy, Net Present Value (NPV) and costs.

The analysis does not recommend implementation of either technology unless time-of-use electricity pricing is put in place.

Section 2: Context, Goal and Scope

Context

At a global level, large scale stationary (grid) energy storage technologies are becoming increasingly popular. Currently, power grids tend to use only 20 to 30 percent of its capacity because they need to be built to meet very high demand peaks. Storage can help lower these peaks, reducing capital requirements for transmission and distribution and making power cheaper to deliver[1].

The implementation of grid storage is becoming increasingly more attractive: grid infrastructure is unable to keep up with increased loads, replacing the aging infrastructure is proving to be very complex, and also because of grid storage's ability to "smooth" and optimize the power generation capabilities of renewable energy sources, particularly that of wind and solar. Hydrogen fuel cells have also been a popular option to meet the demand for energy. Popular technologies include hydrogen fuels for vehicles, as well as using hydrogen to produce the electricity needs of office parks and buildings.

At a local level, the University of British Columbia (UBC) exemplifies the struggles of using the current grid infrastructure to meet increasing demand. In 2010, UBC campus expansion increased the demand for electricity and caused existing transmission lines to operate at capacity during peak demand periods. Given the current transmission capacity and approximately 98% power factor, we estimate the transmission lines to have current capacity of ~ 47 MW (less in summer, more in winter). Peak demand was estimated to be between 36 to 47 MW. In order to meet the increased peak demand, the transmission capacity would need to be upgraded from the current 43 MVA to at the least 62 MVA with an estimated cost of $260k (+/- 30%). Above 62 MVA, UBC would need to upgrade its campus substations, with the cost roughly estimated at $10 million (2010).[2]

From both a macroscopic and local perspective, grid storage is becoming more attractive. However, from a cradle-to-grave perspective, the emissions and energy impact of widespread use of grid storage is unclear. Of the various types of grid storage available, this paper examines the life-cycle effects of two popular technologies: zinc-bromide flow batteries, and proton-exchange membrane (PEM) hydrogen fuel cells.

For this analysis, we chose to perform a life cycle analysis based on meeting the 4-hour, 250 kw electricity demand of a commercial office building. We determined the energy required and emissions output to operate either a zinc-bromide battery or hydrogen fuel cell. We then scaled these results for the hypothetical scenarios of 1) using the batteries for a given number of Vancouver commercial office

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[1] Rogers, Matt "Five technologies to watch", McKinsey Quarterly, January 2012

[2] Rampley, Greg "Evaluating Peak Demand Management Alternatives for the University of British Columbia", Aug, 2010, UBC Social Ecological Economic Development Studies (SEEDS) Student Report

buildings, and 2) comparison of using either batteries or fuel cell technology for 70 of the 400 identified buildings in UBC. A high-level cost analysis is also completed.

Section 3: LCA Scope and Parameters: Vancouver Area and Commercial Building Model

3.1 Assessment of Vancouver and UBC Impact

1. Vancouver Area

In the 2009 Vancouver Metropolitan Area, there were 100.8 million square meters of commercial-type floor space[3], of which 38.4 million square meters were for office space[4]. A 2000 count of commercial building types in Vancouver[5] indicated 6,893 medium-sized buildings between 465 – 929 m^2 in floor space, and 287 large buildings between 929 – 4,645 m^2 in floor space.

For the Vancouver Metropolitan Area, the following parameters were defined:

Available battery charge time: 4 hours. Average hourly electricity usage varied by season. Based on data obtain from BC Hydro, we determined that peak usage for the province was in winter time, of approximately 9,200 MWh. Since Vancouver uses the same electricity grid, it was determined that charging time for our models should be limited to the hours between midnight and four a.m.; which was the only timeframe consistently and significantly below peak demand.

Figures: Total Average Hourly Consumption, **Province of British Columbia**, 2007-2011 by Season

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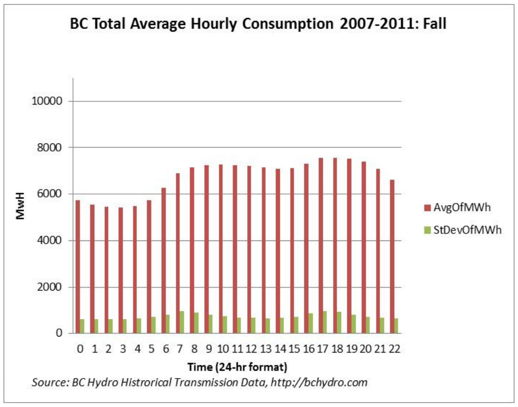
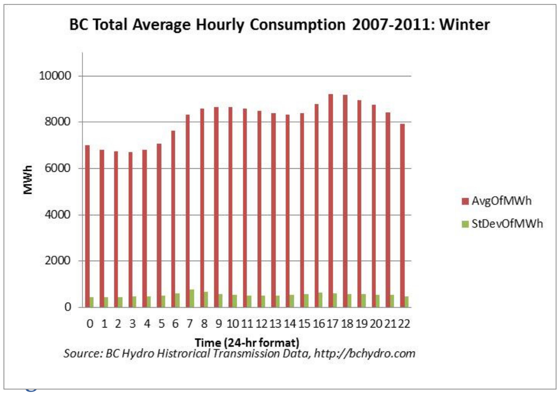
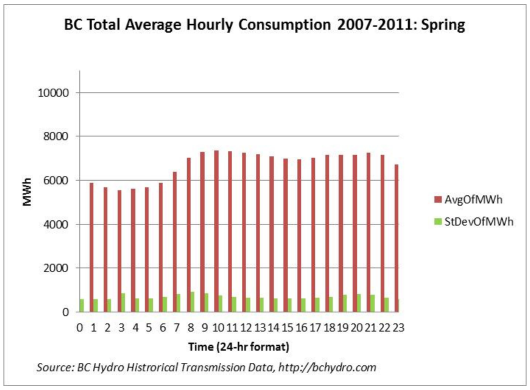
[3] http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/com_bct_3_e_4.cfm?attr=0

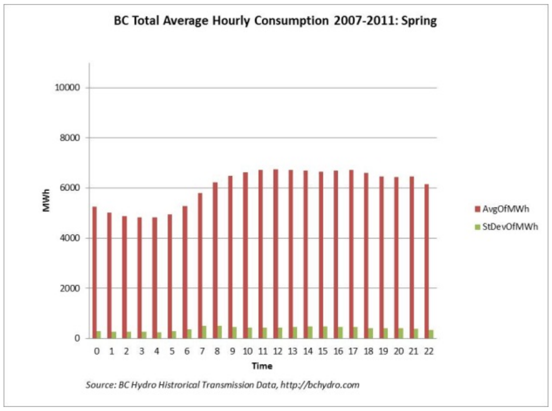
[4] http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/com_bct_12_e_4.cfm?attr=0

[5] Appendix C, http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/CIBEUS_ENG.pdf









- Number of office buildings in Vancouver: 287 large commercial buildings (between 929 – 4,645+ m^2 ; 10,000 – 50,000 ft^2 floor space) and 6,893 medium-sized buildings (465 – 929 m^2 ; 5,000 to 10,000 ft^2 in floor space).

> The Commercial Sector is loosely defined by utilities to include electrical energy used in service-providing facilities and equipment of businesses; federal, state, and local governments; and other private and public organizations. The Commercial Sector is defined as non-manufacturing business establishments, including hotels, restaurants, wholesale businesses, retail stores, warehouses, storage facilities, and health, social and educational institutions. For our studies, data from the 2000 Commercial & Institutional Building Energy Use (CIBEUS Detailed Statistical Report), published by the Office of Energy Efficiency (OEE) of Natural Resources Canada was used to estimate the number of commercial buildings that would be categorized as part of the commercial sector and commercial sector energy demand.

2. *UBC Model Building: University Services Building*

UBC has a total land area of 402 hectares, of which there are 326 hectares available for campus land use. There are approximately 1.4 million m^2 of campus-related floor space concentrated into a footprint of 57 hectares. 95 hectares of land is foreseen to accommodate future campus facility growth.[6] There are

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[6] The University of British Columbia, Vancouver Campus Plan Part 2 (June 2010), obtained from http://www.planning.ubc.ca

currently (2012) over 400 buildings on campus[7], of which 70 have electricity-consumption tracked by Pulse Energy. In 2010, peak demand was estimated to be at 47 MW.

The University Services Building was completed in 1992 and houses Building Operations, Campus Mail, Centre for Teaching and Learning Technology, and Project Services. It will soon be home to a daycare as well. This 2-floor building consists of a low double height volume with 2-storey office space. Its facing is metal wall panel, except for bricks which are applied to the base of the facades to the West Mall and Agronomy Road. It includes 9,225 m^2 of floor space.

This building was chosen as the model primarily because it is similar in floor space to a large commercial building, with a similar usage (and thus energy consumption) profile as that of a typical office building. Hourly electricity consumption was obtained from the Sustainability Office for the years 2009 – 2011. Interestingly, seasonality had a lesser impact on energy consumption variability. That is, hourly energy consumption did not vary as much for the same hour between seasons. On further discussion with a manager of the Sustainability Office, it was proposed that this is due to implemented building improvements.

Based on the BC Hydro total daily demand curve, we decided to limit the usage of the alternative technologies to 4 hours per day, or 1,460 hours per year. The battery functional unit was modeled such that it could only charge between the hours of midnight and 4 a.m., when province-wide demand was significantly below peak.

Challenges to growth

Both from a regional and UBC perspective, challenges to growth arise due to constraints in meeting increased electricity demand. For the province, peak power generation is almost equal to the projected peak demand, while existing infrastructure is underutilized. For UBC, as noted in the introduction, transmission lines are at near capacity and would require an estimated $10MM (2010 dollars) to upgrade past 62 MVA.

Figures: **Model building (USB)** average hourly electricity consumption, by season, Jan. 2009 – Sept, 2012

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[7] http://ubc.pulseenergy.com/

Figure 3

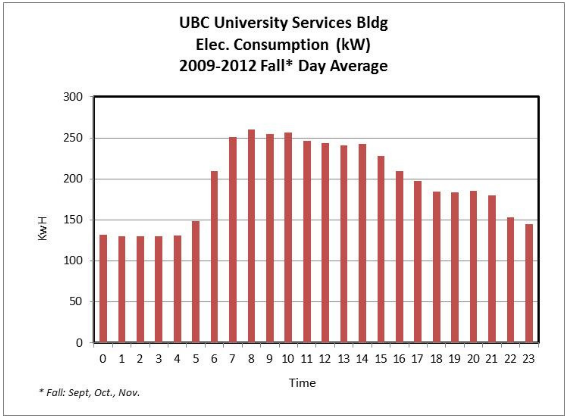


Figure 4

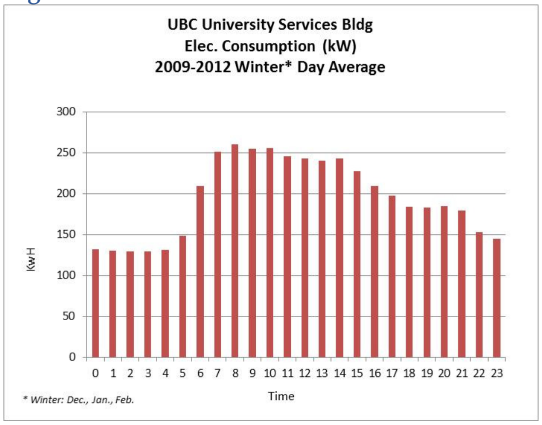


Figure 5

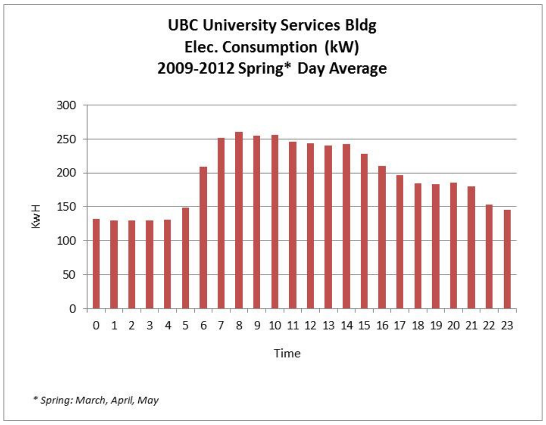
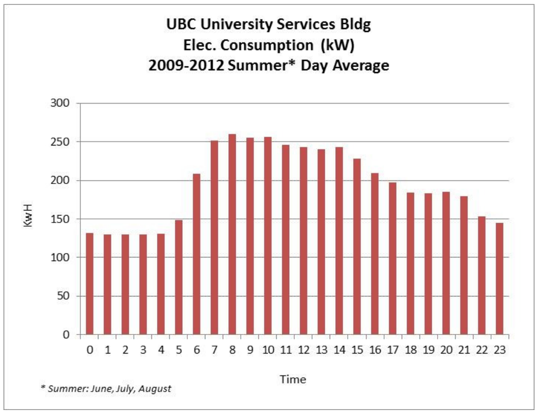


Figure 6



3.2 Grid Scale Stationary Storage: What is the Vancouver / UBC potential?

Could stationary storage help reduce peak demand in Vancouver? Could they be used in the UBC campus? How much space would the storage take up? How much would it cost? What would the life-cycle emissions and energy costs be like?

From the model building LCA, three scenarios were developed to provide theoretical answers to these questions.

- Scenario 1: Install batteries in all 287 large and ~42% of the 6,893 medium sized commercial buildings in the Vancouver Metropolitan Area for a total of 3,180 buildings
- Scenario 2: UBC: Install batteries at 70 buildings to reduce UBC peak load (47 MW)
- Scenario 3: UBC: Install fuel cells at 70 buildings to reduce UBC peak load (47 MW)

All buildings are modeled with the parameters given below. That is, the model building was scaled up by the required number of buildings for each scenario (3,180 and 70 buildings respectively). For scenarios 2 & 3, 70 buildings were chosen because these are the buildings that are already fitted with smart meters linked to Pulse Energy diagnostics. It is assumed it would be easier to install the batteries at these buildings, and that these buildings would also have sufficient demand to warrant the installations. Also, because the hydrogen fuel cell functional unit generates 250 kW per hour, it was decided that 250 kW (for 4 hours of peak demand use) would be the uniform benchmark requirement for the model building.

Scenario Parameters

Given the proposed scenarios, and the results of the life cycle analysis for batteries and fuel cells, the following parameters were used for one model building.

Specifications	**Battery**	**UOM / comment**	**Fuel Cell**	**UOM / comment**
Functional Unit (FU)	50	kWh per module	250	kWh per Functional Unit
Lifetime	20	Years	20	Years
Hours of use / discharge per day	4	4rs use, 4 hrs to recharge	4	Hrs use
Power requirements:	250	kW for 4 hrs use per day	250	kW for 4 hrs use per day
Capacity reqm't	1000	KWh	250	kW
Footprint per FU (m^3 area, l x w x h)	1.83 x 0.67 x 2.44	Battery + container	12 x 2.5 x 3	Tank + modules
			.415(pi) x 2.11	Storage, per cylinder, (diameter x length) 4.89kg H2 capacity
Unit costs	$1,200	per kW (vendor correspondence)	$1,300	per kW [8]

Requirements to service one building:

Specification	**Battery Unit**	**UoM / comment**	**Fuel Cell Unit**	**UoM / comment**
Number of functional units;	20	modules @ 50 kWh ea	1	Functional unit
Actual footprint for one bldg: **Note: Parking spot = 2.5 m x 4 m (in m, l x w x h)**	40	m^2 or ~ 4 parking lots	12 x 2.5 x 3	per functional unit (4 -5 parking lots)
			10.5 x 8.3	Storage: 48 cylinders, 5 stacks of 8-10 per stack : 2.1 x 1.66 x 1.66 m (lwh) per stack

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[8] Lipman, T. E., Edwards, J. L., & Kammen, D. M. (2002). PWP-092 Economic Implications of Net Metering for Stationary and Motor Vehicle Fuel Cell Systems in California Economic Implications of Net Metering for Stationary and Motor Vehicle Fuel Cell Systems.

Use: # hours available for recharging	4	hrs	N/A	Need to refill tanks 3x per week

Emissions and Costs, for 1 model building

MFG: Emissions	Battery	Metric	Fuel Cell	Metric / Comment
Global warming potential	224.09	kg CO2 eq.	21,042	kg CO2 eq.
Acidification	133.159	kg H+ mols. Eq.	5,016	kg H+ mols. Eq.
Ozone depletion	2.7E-11	kg CFC-11 eq.	1.904E-08	kg CFC-11 eq.
Smog formation	51.27	kg O3 eq.	801	kg O3 eq.
USE: Emissions				
Global warming potential	444.74	kg CO2 eq.	29,184	kg CO2 eq.
Acidification	60.536	kg H+ mols. Eq.	9,615	kg H+ mols. Eq.
Ozone depletion	4.32E-10	kg CFC-11 eq.	3.71E-09	kg CFC-11 eq.
Smog formation	23.84	kg O3 eq.	2,267	kg O3 eq.
COSTS (lifetime):				
Est. capital cost	$300,000	20 modules	$331,000	$6,000 - $13,500 installation, $1,300 per kW (See table below below)
Estimated operations cost	20%	of installed cost	$8,340	See table below below

Additional specifications for fuel cell, for 1 model building:

Fuel Cell Specifications	**Units**	**Unit of Measure & comments**
Hours of operation - annual	1,460	Hrs per year
lifetime	29,200	Hrs
Estimated $ cost, fuel	$35,000	lifetime, see next table
Estimated total $ cost maintenance	$584,000	lifetime, see next table
Fuel Transport distance	24	Km (from North Vancouver sodium chlorate plant to UBC[9])
Fuel Transport weight	4.750	Metric tonnes or ~ 5.23 tons (~ 50 cylinders or 12.5 kh of H_2); classified as a Heavy light-duty truck (HLDT, 6,000 lbs GVWR)
Storage cylinder capacity	4.89	Kg H_2 per cylinder
Storage cylinder capacity	95	Kg per cylinder
Storage capacity	12	Hrs use (3 days)
Storage	48	Cylinders

Hydrogen Fuel & Maintenance Use Phase Costs		
Est # hrs lifetime use	1,460	
Fuel consumption per hr	16	kg H_2 per hr
Estimated fuel consumption (lifetime)	23,360	kg H_2 for 1,460 hours usage
Cost of hydrogen gas	**$2**	**per kg based on US Dept. of Energy target cost**
Maintenance – Fuel Cell Enclosure	$8,340	for lifetime use (1,460 yrs per year) (derived $2,500 for a battery used for 8,760 hours per year [10])

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[9] "B.C. projects benefit environment, bottom line" (2007), Canadian Broadcasting Corporation, retrieved from http://www.cbc.ca/news/background/energy/hydrogen.html

Maintenance – Fuel Cell refurbishment	.1488 * (cost per kW)	for 4-hr use, 20 year lifetime, (derived from[0.93 * (cost per kW)] for a battery used as 24-hr use, 15 year lifetime)

Scenario 1 All-battery, 3,180 GVA buildings results:

Scenario 1 Results	Unit	Metric / Comment
# of buildings	3,180	buildings
Total # of modules:	63,600	modules @ 50kWh each
Lifetime	20	years (Lifetime of equipment if used to generate 250 kW for 4 hours)
Total footprint	31,800	m^2 or 12,720parking lots (1 lot = 1.8 x 4 m^2)
Storage /discharge capacity req'd per bldg.	3,180,000	kWh (total for 4 hours discharge)
Total storage /discharge capacity	3,180	MWh For 3,180 buildings
Reduction in peak demand	795	MW per hour
Peak hourly demand	9,200	MW
Peak hourly demand – Total storage	8,405	MW
% reduction in transmission load	9%	
Costs (lifetime)		
Estimated $ cost one-time	$954.00 MM	
Estimated $ cost maintenance	$190.80 MM	
Total $ Lifetime cost:	$1,144.80 MM	

Emissions (lifetime)	Manufacture	Use	**Total Lifetime**
Global warming potential (kg CO2 eq.)	14,252,124	28,285,464	**42,537,588**
Acidification (kg H+ mols. Eq.)	8,468,912	3,850,090	**12,319,002**
Ozone depletion (kg CFC-11 eq.)	1.7172E-06	2.74752E-05	**2.92E-05**
Smog formation (kg O3 eq.)	3,260,772	1,516,224	**4,776,996**

Scenario 1 Commentary

It costs $1.1B for a 9% reduction in peak load / demand (795 MW) using zinc-bromide batteries. You will also need to find 3-4 parking lots' worth of space near each building where this solution is installed.

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[10] Lipman, T. E., Edwards, J. L., & Kammen, D. M. (2002). PWP-092 Economic Implications of Net Metering for Stationary and Motor Vehicle Fuel Cell Systems in California Economic Implications of Net Metering for Stationary and Motor Vehicle Fuel Cell Systems.

Scenario 2 UBC: Install batteries @ 70 buildings to reduce UBC peak load (47 MW)

Scenario parameters	Unit	Metric / comment
# of buildings	70	buildings
Total # of modules:	1400	modules @ 50kWh each
Lifetime	20	years (Lifetime of equipment if used to generate 250 kW for 4 hours)
Total footprint	2,016	m^2 or 280 parking lots (1 lot = 1.8 x 4 m2)
Total storage /discharge capacity	70	MWh For 70 buildings
Reduction in peak demand	17.5	MW per peak hour (4 hours of peak)
Current UBC peak hourly demand	47	MW
"NEW" peak demand	29.5	MW Peak hourly demand – Total storage
Current transmission line capacity	43	MW (98% of 43 MVA), **above "NEW"**
% reduction in transmission load	37%	
Costs (lifetime)		
Estimated $ cost one-time	$21,000,000	
Estimated $ cost maintenance	$4,200,000	
Total $ Lifetime cost:	**$25,200,000**	Compared to $260k to upgrade the transmission lines for similar capacity (+10.5MW)

Emissions (lifetime)	Manufacture	Use	Total Lifetime
Global warming potential (kg CO2 eq.)	313,726	622,636	**936,362**
Acidification (kg H+ mols. Eq.)	186,423	84,750	**271,173**
Ozone depletion (kg CFC-11 eq.)	3.78E-08	6.048E-07	**6.43E-07**
Smog formation (kg O3 eq.)	71,778	33,376	**105,154**

Scenario 2 Commentary

A preliminary analysis of the battery specifications indicate there is sufficient time to charge the batteries during off-peak hours. This assumption should be reviewed if further analysis is completed.

Scenario 3 UBC: Install fuel cells to reduce UBC peak load (47 MW)

Scenario parameters	Unit	Metric / comment
# of buildings	70	buildings
Lifetime	20	years (Lifetime of equipment if used to generate 250 kW for 4 hours)
Total footprint	4,032	m^2 or 560 parking lots (1 lot = 1.8 x 4 m2)
Total electricity generated	17.5	MWh For 70 buildings
Reduction in peak demand	17.5	MW per peak hour (4 hours of peak)
Current UBC peak hourly demand	47	MW
"NEW" peak demand	29.5	MW
Current transmission line capacity	43	MW (98% of 43 MVA)
% reduction in transmission load	37%	

Costs (lifetime)		
Estimated $ cost one-time	$23,170,000	
Estimated $ cost maintenance	$583,800	
Estimated $ cost, fuel (lifetime)	$35,040	
Total $ Lifetime cost:	**$23,788,840**	Compared to $260k to upgrade the transmission lines for similar capacity (+10.5MW)

Emissions (lifetime)	Manufacture	Use	Total Lifetime
Global warming potential (kg CO2 eq.)	1,472,974	2,042,898	**3,515,871**
Acidification (kg H+ mols. Eq.)	351,153	673,050	**1,024,203**
Ozone depletion (kg CFC-11 eq.)	1.33E-06	2.60E-07	**1.59E-06**
Smog formation (kg O3 eq.)	56,055	158,690	**214,745**

Scenario 3 Commentary

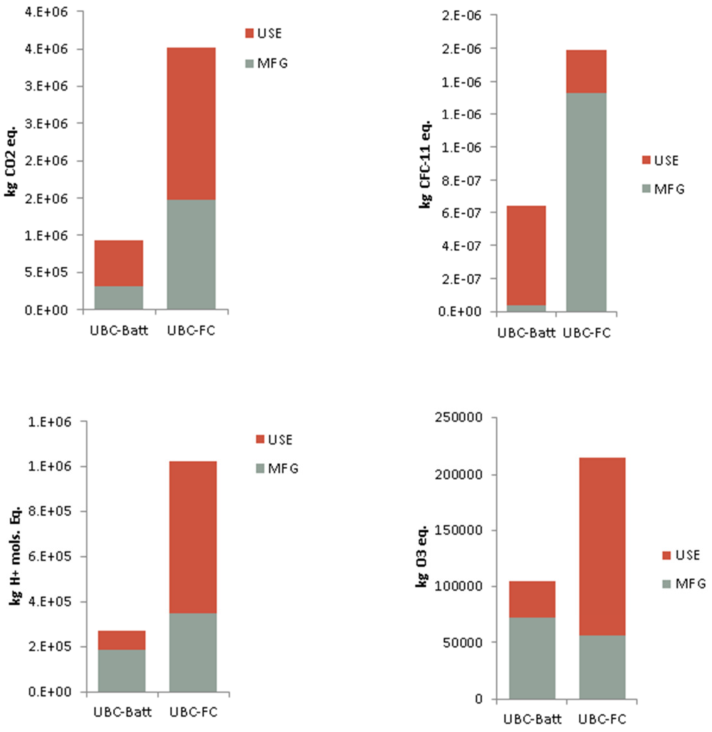
Total footprint of hydrogen fuel cell scenario is twice as large as that of the batteries, primarily due to the storage required. Also note that the storage costs are not included. Additional costs for storage would have to be accounted for.

Scenario 2 and 3 Comparisons

Emissions (lifetime)	Batteries Scenario	Fuel Cells Scenario
Global warming potential (kg CO2 eq.)	1,918,140	3,515,871
Acidification (kg H+ mols. Eq.)	404,802	1,024,203
Ozone depletion (kg CFC-11 eq.)	1.62E-06	1.59E-06
Smog formation (kg O3 eq.)	157,780	214,745

	29.5 MW "New Peak"		~60 MW "New Peak"	>60 MW "New Peak"
Costs (lifetime)	**Batteries**	**Fuel Cells**	**Upgrade to 62 MVA**	**>62 MVA upgrade**
Estimated $ cost one-time,	$21,000,000	$23,170,000	$260,000	$10,000,000
Estimated $ cost maintenance	$4,200,000	$618,840		
Total $ Lifetime cost:	**$25,200,000**	**$23,788,840**		

Figure 7: Graphical comparison of batteries and fuel cell lifetime emissions to service 70 UBC buildings (56 MWh per day)



Based on the comparisons, batteries are less harmful when considering environmental effects. However, because there are no revenues, both technologies are very expensive when compared only to transmission infrastructure upgrades. It is important to note that differences in how space footprints, costs and emissions scale up in reality for both technologies (i.e. marginal vs. linear) may cause differences in actual vs. theoretical comparisons.

3.3 Conclusions and Recommendations

Conclusions

Based on the theoretical "mass installations" scenarios, the emissions for the use of zinc bromine batteries or hydrogen fuel cells seem reasonable. However, based on the need to avoid increased infrastructure costs alone, it seems that the costs are not justifiable. For the 3,180 buildings Metropolitan Vancouver Area scenario, a 9% , 795 MW (per peak hour demand) solution costs more than $1.1 B and for the 70 building UBC scenario, a 37% 17.5 MW peak hour demand reduction costs ~ $23 - $25 MM, depending on technology. The UBC scenario cost seems to fulfill the same need / service as paying $260k in infrastructure upgrades.

What incentives are there to pursue either technology? (Time of use pricing, net metering, but NPV still minimal)

It may seem from a cost perspective that neither technology is viable. <u>**But**</u>, this is because of the current flat-rate electricity pricing in effect in BC. When **time-of-use pricing** and **net metering** technologies and policies are put into place, large scale storage become more attractive.

Net Present Value calculations however, show sensitivity to discount rates and the number of hours that the peak rate is charged. Note that capital costs for batteries are noted at $1200 per kW and $1300 per kW for fuel cells.

Est. NPV for 17.5 MW @ 6% discount rate (20-yr lifetime)	**Batteries**	**Fuel Cells**
NPV @ 5 c/kwH peak-base diff, 4 hrs energy sold @ peak	-$9,780,994	-$5,909,412
NPV @ 5 c/kwH peak-base diff, 5 hrs energy sold @ peak	-$631,969	**$3,239,613**
NPV @ 6 c/kwH peak-base diff, 4 hrs energy sold @ peak	-$6,528,007	-$2,656,426
NPV @ 6 c/kwH peak-base diff, 5 hrs energy sold @ peak	**$4,450,823**	**$8,322,405**

Recommendations

Overall, it is recommended that neither technology be pursued for Vancouver or UBC until time-of-use pricing is put in place for the BC electric grid. This situation is not too improbable, as many other electricity markets in North America (such as Ontario and California) are already implementing this pricing scheme.

Should UBC consider either fuel cells or batteries in further detail, it is recommended that a vendor Request for Information (RFI) is developed which takes into consideration the specific cost-estimating components, and requests for additional material such as a NPV analysis over the UBC-specific lifetime of the product(s) and vendor-specific data on lifetime emissions.

For hydrogen fuel cells, UBC may consider a pilot test as part of a larger opportunity to expand the existing "hydrogen highway" to include stationary hydrogen fuel cell usage as part of the infrastructure.

For a Vancouver-wide implementation, it is critical that policy planners, municipal governments, and BC Hydro begin to develop a framework both for the <u>financial</u> (ex. ownership or leasing options, space considerations) and <u>regulatory</u> (both economic and energy policies) <u>foundations</u> that are enablers of distributed storage and generation. Hydroelectric power is finite. To enable clean energy growth will require alternate technologies and policies, and stationary storage and fuel cells can be a large part of British Columbia's clean energy future.

Section 4: LCA: Zinc Bromide Battery Model

Zinc Bromide Background

There are many commercially available energy storage systems on the market today. Compressed air, super capacitors, pumped hydro and battery energy storage (BESS) are just a few of the options. Battery Energy Storage systems are attractive options for residential and commercial buildings due to their comparatively small space requirements and their ability to scale up or down according to user specifications.[11]

Historically, BESS were limited to lead acid batteries. Their low energy densities, high maintenance requirements and short lifetime[12] made them unattractive for most non-transport related applications. The recent development of flow batteries has led to a renaissance in the world of BESS and a reevaluation of the potential applications. A flow battery is one that utilizes standard electrochemical reactions to produce electricity but goes one step further than traditional structures by circulating anolyte and catholyte solutions separately through the cell stacks. In the case of a zinc bromide flow battery, a common and commercially available technology, this yields an even deposition of zinc on the anode and allows for the easy removal of complexed bromine contributing to an extended lifetime. Furthermore, the removal of reaction products from electrode active sites prevents self-discharge increases the depth of discharge.[13]

The EnerStore Module is a commercially available zinc bromide battery manufactured and sold by ZBB Energy Corporation, a company based in Menomonee Wisconsin. It is is a semi turn-key installation. The EnerStore Module was selected as the BESS technology for this report. Several other technologies, including lithium ion, vanadium redox, and nickel sodium batteries were considered as possible alternatives for the EnerStore system. In the opinion of the authors, the EnerStore system proved to be the most attractive technology in context of this analysis when energy density, scalability, footprint, ease of installation and company policy were taken into account.

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[11] Denholm, P., & Kulcinski, G. L. (2004). Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Conversion and Management*, 45(13-14), 2153–2172. doi:10.1016/j.enconman.2003.10.014

[12] Denholm, P., & Kulcinski, G. L. (2004). Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Conversion and Management*, 45(13-14), 2153–2172. doi:10.1016/j.enconman.2003.10.014

[13] Mathews, J.F. Lex, P. J. (1992). Recent Developments in Zinc/Bromine Battery Technology.

1. Goal of Study

The purpose of this study was to conduct a high level life cycle analysis on the ZBB's EnerStore module in order to obtain an overview of the system's environment impacts. Furthermore, this study served as the foundation for an economic feasibility analysis discussed later in this report.

2. Data Collection

Data collection is a fundamental aspect of any LCA. Unfortunately it is also the area most fraught with uncertainty. For this analysis a tiered decision process was used to determine the where and how the data was collected. As this analysis was based on a commercially available product, manufacturer specifications were the first choice for data collection. If all data required was available through the manufacturers' website, data sheets, or through communication between the authors and the company, no other source would have been consulted. If manufacturer data was not available, assumptions were made and data was extrapolated based on the information that had been provided. Factors relevant to the LCA but not directly connected to the EnerStore module, i.e. emissions and GWPs were calculated via the Gabi Database. Manufacturing energies and requirements were determined through journal and review articles on BESSs.

3. Functional Unit, Time Parameters and System Boundaries

Functional Unit:

A main focus of this report is to compare a BESS and a fuel cell system for the same end use. Though this is the foundation of the final economic analysis, it does not provide a suitable functional unit for individual BESS and fuel cell system LCAs. For this reason a functional unit will be defined and utilized in the individual LCAs and a different functional unit will be defined and used in the final analysis.

For this LCA the functional unit is defined as:

One EnerStore Module, with an energy storage capacity of 50 kWh, a maximum discharge rate of 25 kW an operating voltage of 400V and a lifetime of 5000 charge/discharge cycles.

Time Scale

This LCA was based on an operating lifetime of approximately 5000 charge and discharge cycles. It is estimated that 5000 cycles when cycled roughly 5 times a week translates into 20 years of use. This assumes a constant demand every week. It does not incorporate periods of low usage for example during the holidays. After 2500 cycles, approximately 10 years according to company data, the cell stacks and pumps should be replaced. The rest of the infrastructure, including the electrolyte, will remain functional at least until the following cell stack replacement. Besides cell stack and pump replacement no other significant maintenance is recommended.

System Boundaries

A very high level life cycle analysis was conducted on this BESS. A complete LCA accounting for all inputs, outputs, processes, and manufacturing stages was beyond of the scope of this report. The boundaries of this LCA are subsequently quite important as they serve to restrict the amount of detail needed by setting the scope. The boundaries are defined as follows.

Foreground System:

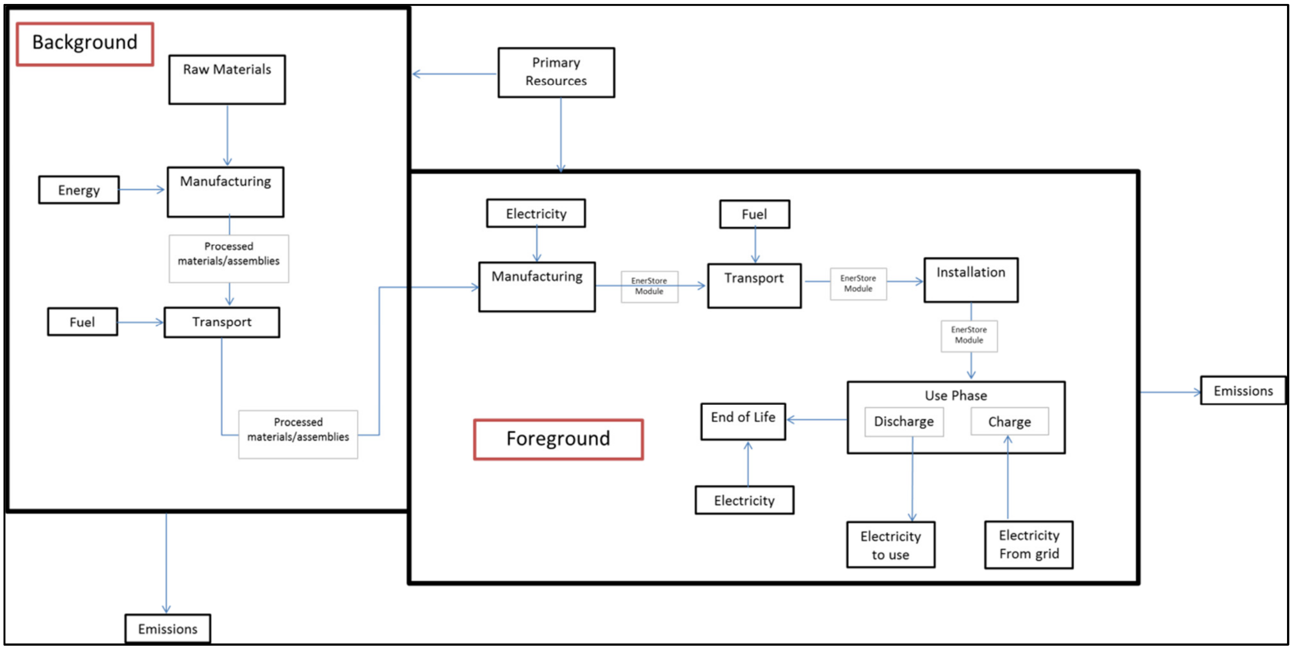
For this analysis the foreground system is comprised of:

- Assembly: The last stage of the manufacturing process wherein processed materials and assemblies are compiled to create the final EnerStore Module. This process occurs at ZBB Energy Corporation's North American headquarters in Menomonee Wisconsin.
- Transport: The transfer of the final EnerStore from Wisconsin to its final destination of Vancouver British Columbia. This process is carried out wholly by 34-40 tonne diesel trailer.
- Installation: Setting up the BESS on site, including grid connectivity and building integration.
- Use: The environmental and energy costs required for daily operation.
- End of Life: waste disposal and/or recycling of EnerStore components.

Background System:

For this analysis the background system is comprised of all the processes required to generate the processed materials and assemblies that form the inputs to the foreground system. The background system includes resource extraction, refinement, and the creation simple component parts see Figure 8. The background system was not included in the analysis.

Figure 8 Foreground and Background System



4. *Zinc Bromide Battery Model Properties (Data Inventory)*

Material Components

ZBB Energy Corporation EnerStore System is sold in modules of 50 kWh. Each module is encased in its own housing and can be used as a stand-alone product. Multiple batteries can be connected together to increase the storage capacity of the system achieving up to 2 MW of storage with one connection point. Each module comes equipped with 8 cell stacks, electrolyte storage containers, pumps, heat exchangers, and internal operating control systems see **Error! Reference source not found.**. Each module has an energy capacity of 50 kWh, maximum charge and discharge rate of 17 kW and 25 kW respectively see **Error! Reference source not found.** for full characteristics.

The following is a breakdown of major the components in an EnerStore Module:

Battery Stacks:

- Cell Stack Enclosures:
    - Quantity: 8enclosures
    - Materials: PVC
    - Dimensions: D 60cm x H 60cm x W 20cm
- Electrodes:
    - Quantity- 960 electrodes (anodes and cathodes)
    - Materials: Activated Carbon
    - Dimensions: D 50cm x H 50cm x W 0.056cm
- Separators:
    - Quantity: 480
    - Materials: Polyethylene
    - Dimensions: D 50cm x H 50cm x W 0.056cm

Electrolyte Storage Tanks:

- Quantity: 1 (separated into two equal sections)
- Materials: PVC
- Approximate dimensions: D 60cm x H 85cm x W 175cm

Electrolyte:

- Zinc Bromide Solution
- Volume: 630L
- Concentration Br and Zn: 2moles/L

Heat Exchanger:

- Standard ASME Space Saving Heat Exchanger
- Quantity: 1
- Material: Copper
- Dimensions: 53cm x 11 cm x 11cm

Pumps:

- Quantity: 2
- Materials: Iron
- Mass: 3.2kg each

Power Control System

- Quantity: 1
- Materials: 70% Silicon, 20% Copper, 10% Iron

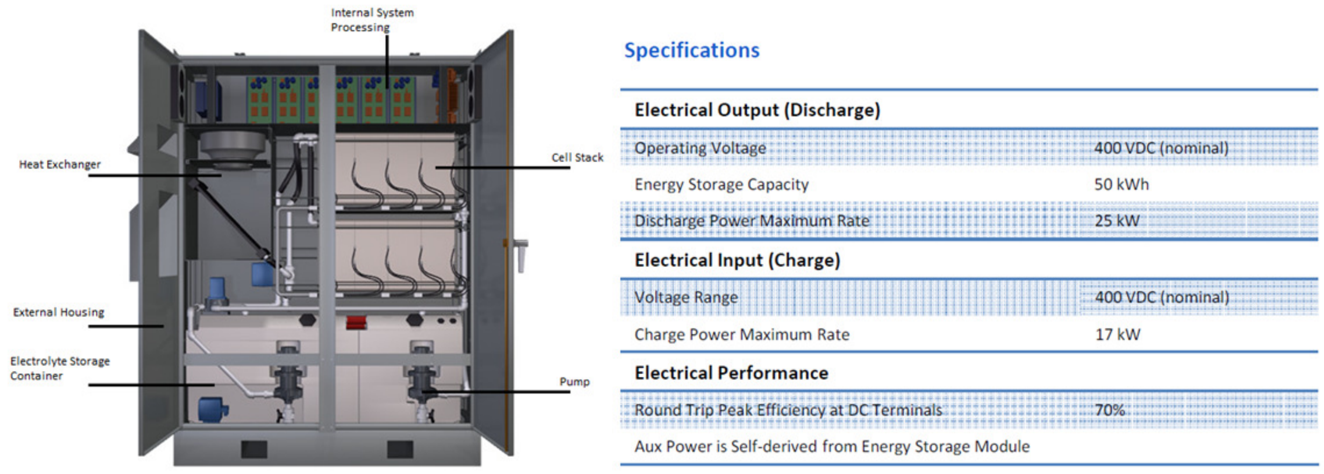
Spill Containment

- Quantity: 1
- Materials: Steel
- Dimensions: D 67cm x H 10 cm x W 183 cm x thickness 0.5cm (open top)

System Enclosure:

- Quantity: 1
- Materials: Steel
- Dimensions: D 67cm x H 244cm x W 183cm x Thickness 0.5cm

Figure 9: EnerStore Module Componentry and Electrical Characteristics



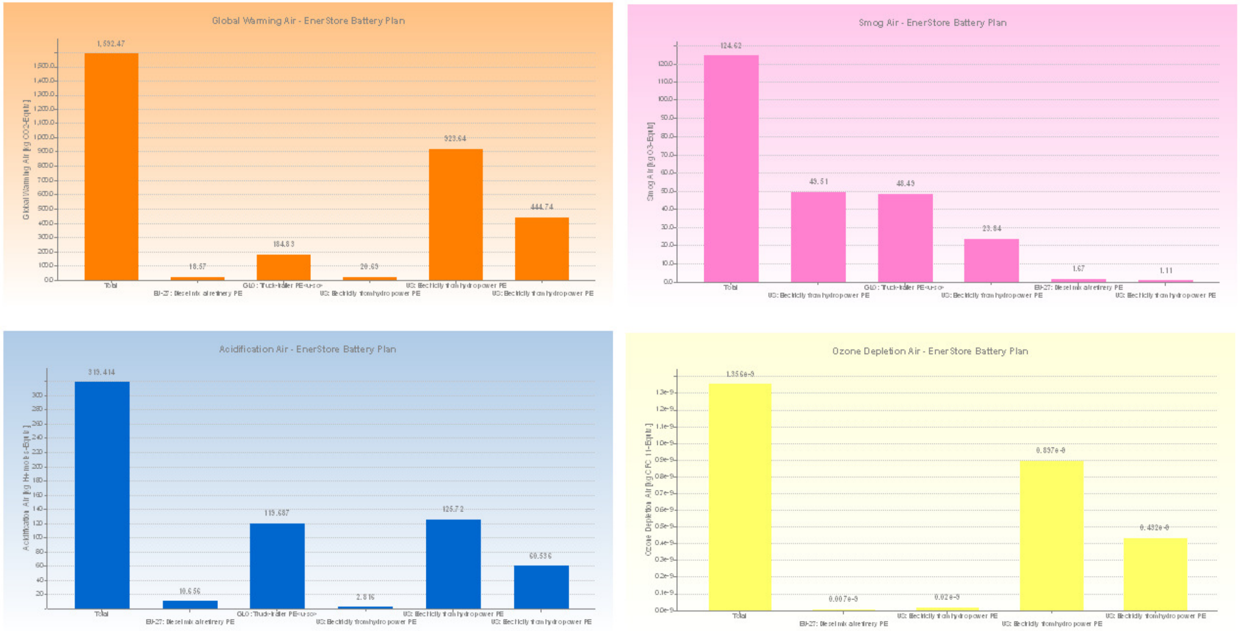
Specifications

Electrical Output (Discharge)	
Operating Voltage	400 VDC (nominal)
Energy Storage Capacity	50 kWh
Discharge Power Maximum Rate	25 kW
Electrical Input (Charge)	
Voltage Range	400 VDC (nominal)
Charge Power Maximum Rate	17 kW
Electrical Performance	
Round Trip Peak Efficiency at DC Terminals	70%
Aux Power is Self-derived from Energy Storage Module	

5. Results

The results of this study were generated from the Gabi LCA program. All results were calculated with respect to the entire 20 yr life cycle of an EnerStore Module.

Figure 10 Local and Global Environment Impacts of the EnerStore Module



6. Conclusions and Discussion

The results generated can be split into two major impacts categories, local and global affects. These effects are detailed in Figure 10. The total contribution to smog and acid rain are approximately 214 kg eq of O_3 and 319 kg H+ respectively. The total contribution to global warming is 1592 kg e CO_2 and the total contribution to ozone depletion is 1.35×10^{-9} kg e CFC-11. The impact of CFC-11 is so minimal that it will not be considered negligible going forward.

Each impact can be broken down into transport or electricity contributions. Transport is comprised of transport from the manufacturing center in Wisconsin and diesel required. Electricity is further broken down into manufacturing, use, and end of life phases. The most electricity is consumed in the end of life phase followed by the use phase and finally the manufacturing phase. This is clearly visible in the results, as the emissions, when broken down into individual categories mimic the trends in electricity consumption.

These numbers mean very little by themselves. To give a more complete picture of how the EnerStore Module affects the environment several comparisons were made, see Table 1, to other energy storage systems.

Table 1: Green House Gas Emissions of Various Energy Storage Devices[14]

Technology	GHG Emission during Lifetime (Tonnes CO2 eq/Gwh)	Lifetime	GHG Emission during Lifetime (Tonnes CO2 eq/Gwh) (60yrs)
ZBB Enerstore Module	6.4	20 years	19
Pumped Hydro Storage	5.6	60 years	6
Compressed Air Storage	292	40 years	438
Poly-Sulfide Bromide Battery	32.6	20 years	98
Vanadium Redox Battery	40.2	20 years	121

In order to ensure a fair comparison, the CO_2 eq emissions were normalized by the GWh outputs over the system's lifetime. As the lifetimes of each system varied slightly, a further normalization to a set time period was introduced as well.

The emissions/GWh of EnerStore Module is on the same order of magnitude as the two other flow battery systems over a lifetime of 20 yrs, suggesting that the calculations conducted in study are valid. Furthermore, the results from this study seem to compare favorably with literature values. Suggesting a significant reduction in GHG emissions is possible by using an EnerStore Module in place of a vanadium redox (VRB) or poly-sulfide bromide battery (PSB). Over a twenty year period approximately 26 or 34 tons of CO_2 can potentially be avoided by using a EnerStore Module instead of a PSB or VRB system. The data suggests though, that pumped hydro storage may be more environmentally friendly than the other technologies.

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[14] Denholm, P., & Kulcinski, G. L. (2004). Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Conversion and Management*, 45(13-14), 2153–2172. doi:10.1016/j.enconman.2003.10.014

However, these results are hugely dependent on the geographical placement of the system. The LCA conducted in this study was based on the fact that the module would be used in Vancouver, British Columbia where the electricity on the grid is predominantly hydroelectric. Hydroelectricity is one of the cleanest forms of electrical energy yielding small amounts of GHG emission when compared to typical coal or natural gas power generation facilities. It must be understood that BESS are highly dependent on the source of the electricity used for charging. They should be considered a redistribution of the electrical source never a generation facility themselves. The data presented in Table 1 for the energy storage systems, excluding the EnerStore Module, are values averaged over multiple systems, suggesting a wide range of electricity compositions. If PSB or VRB systems were analyzed for use in Vancouver, one would expect a reduction in GHG emissions per GWh.

7. Assumptions, Constraints and Next Steps

The major assumptions associated with this study stem from the simplification of the LCA model. Regarding the model the authors assumed that there was no recycling stream of reusable components into the main processing stream. Furthermore, it was assumed that the manufacturing process only "connected" preassembled components. Lastly, data found through literature review provided total energy requirements for the manufacturing and use phases. The percentages of energy from electricity and other sources was not mentioned and it was therefore assumed that all energy required was provided from electricity.

Going forward, more detail is required. The system boundaries should be expanded to include manufacturing of components and not solely assembling them. ZBB's recycling policy should be investigated and incorporated along with a typical breakdown of the energy required for manufacturing and recycling. Additionally, a sensitivity analysis should be conducted to determine the relationship between GHG emissions from the electricity mix used for charging and the GHG emissions of the module. This would strengthen the external validity of the LCA and allow the results to be applied to a range of geographic regions.

Section 5: LCA Scope and Parameters: Proton Exchange Membrane Fuel Cell Model

Background

Stationary fuel cells are fuel cells that are installed as the primary or auxiliary power for a home, business, or data center. These fuel cells provide clean, efficient, and reliable off-grid power to homes or businesses. Using fuel cells for a buildings power generation can reduce energy costs dramatically, with some facilities reducing costs by 20%-40%. In addition, due to the lack moving parts, stationary fuel cells require very little maintenance, while still providing continuous power for years.[15]

There are two kinds of stationary fuel cell, solid dioxide fuel cell and proton exchange membrane fuel cell. Compared with the former one, PEM fuel cell can operate under a relative low temperature, varying from 50℃-100℃. It is quiet, efficient and flexible. The only production of the reaction in PEM fuel cell is water, which means zero emission to environment.

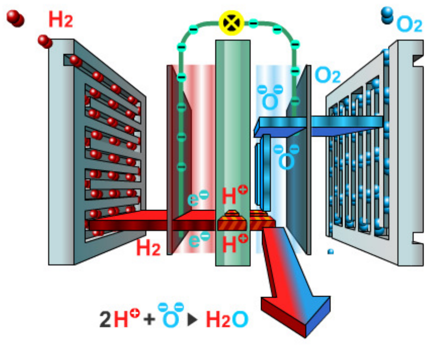

Figure 11 PEM fuel cell chemistry

A key component of a PEM fuel cell is the Membrane Electrolyte Assembly or MEA. The MEA consists of two electrodes, the anode and the cathode. These are porous carbon electrodes, which are each coated on one side with a low amount of platinum catalyst and separated by a proton exchange membrane (PEM). The PEM is the electrolyte in this assembly. It is a thin sheet that is only permeable for protons and water. It must allow hydrogen protons to pass through but prohibit the passage of electrons and gases.[16]

In a fuel cell, hydrogen gas flows to the anode. There, with the help of the catalyst, the molecules are broken down into protons (hydrogen ions) and electrons. The positively charged protons go through the porous membrane and migrate toward the cathode. The membrane blocks the electrons, which flow from the anode to the cathode of the adjacent cell. On a stack level, this flow can be used to power electric applications.[17]

The chemical reactions are:

$H2 \longrightarrow 2H++2e-$

$½O2+2H++2e- \longrightarrow H2O$

$H2+½O2 \longrightarrow H2O$

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[15] Fuel Cell & Hydrogen Energy Association. www.fchea.org

[16] Nedstack. www.nedstack.com/faq/about-pem-fuel-cells

[17] Nedstack. www.nedstack.com/faq/about-pem-fuel-cells

1. Goal and Scope

The purpose of this work is to do a life cycle assessment of stationary PEM fuel cell power system.

2. Function and functional unit

The primary function of the PEM fuel cell system is electricity production. Besides, it provides the option of heat recovery. The PEM fuel cell system can be operated as a heat and power system. It requires constant supply of hydrogen.

The project aims at modeling the life cycle of one PEM fuel cell power system. The functional unit is:

Type	**PEM (Proton Exchange Membrane) Fuel Cell Generator**	
Performance	Net Power	250kW
	Efficiency Output voltage	40% 420V AC
	Output frequency	50-60Hz
Physical Characteristics	Fuel Cell Module: Dimensions(H×W×L) Weight	2.9×2.4×9 meters <40,000 kg
	Electrical Module: Dimensions(H×W×L) Weight	2.9×2.4×6.3 meters 15,000 kg
Fuel	Hydrogen	>98%
	Fuel consumption	16kg/hr
Emission	Pollutants	Zero emissions
Lifetime		20yrs

Figure 12 Functional unit parameters

This fuel cell module is based on a similar Ballard fuel cell module.

3. System Boundary

Ideally a life cycle assessment should include all economic and environmental inputs and outputs. However, in practice it is impossible. Therefore, it is necessary to define the system boundary and indicate which process and materials are included in the LCA. In order to create a clear overview of the system boundary, it is analyzed in three parts: manufacturing phase, use phase and the end of life.

Manufacturing phase

An inventory table of manufacturing phase should include:

- The materials used for components and parts.
- The processes used for the product manufacturing.
- Overhead energy and other non-product materials.
- The emissions caused and waste generated by product manufacturing.[18]

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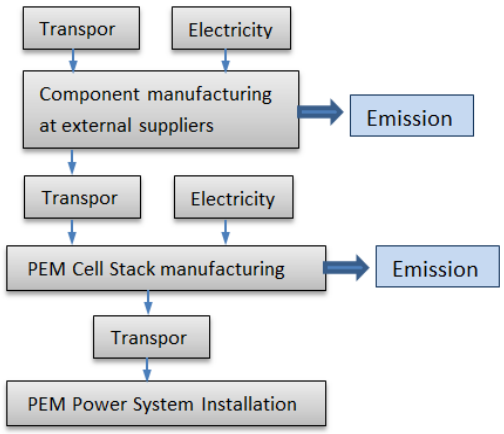
[18] Jaap van Pooijen.2006. A Life Cycle Assessment of the PureCell™ Stationary Fuel Cell



Except the fuel cell stack, all the other components are manufactured by external suppliers. However, it is hard to get this data from external suppliers. Therefore, it is assumed that all the components and fuel cell stack are all made in the fuel cell company. Then this cell stack is transported to the location to be installed.

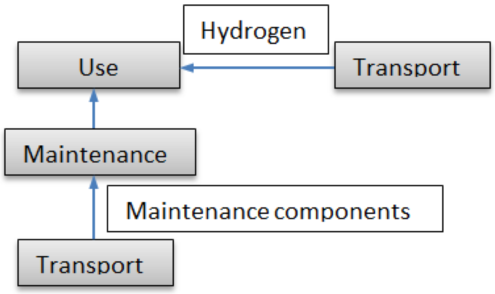
There should be emissions for each raw material. However, because of the limited database from GABI (education version), only transportation and electricity energy could be calculated.

Figure 13 Manufacturing Phase Flow

Use phase

An inventory table of the PEM fuel cell system should include:

- The hydrogen input for the PEM fuel cell lifetime
- The installation materials and processed for installing the PEM fuel cell system
- Components and parts that need to be replace during the PEM fuel cell system lifetime
- Waste generated by maintenance activities
- Transportation of, installation of, maintenance of, and waste disposal.[19]



However, for this analysis, only transportation of hydrogen, maintenance components, and installation materials data could be found, and only diesel and electricity energy analyzed.

Figure 14 Using Phase Flow

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[19] Jaap van Pooijen.2006. A Life Cycle Assessment of the PureCell™ Stationary Fuel Cell

End of life phase

An inventory table of the PEM fuel cell system end of life phase should include:

- The materials that recycled
- The materials that are going to landfill
- The materials that are going to another waste treatment [20]
- Transport of materials to waste treatment facility

Because there is no database for PEM fuel cell end of life phase, this part is not included in this LCA analysis.

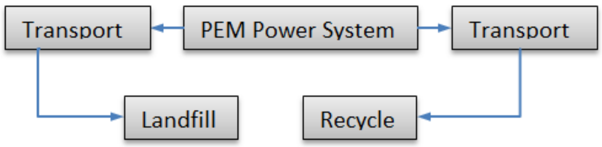

Figure 15 End of life Phase Flow

GABI System Boundary:

The main tool used for this work is GABI. This is the system boundary got from GABI. The heat generation part is not included in this LCA

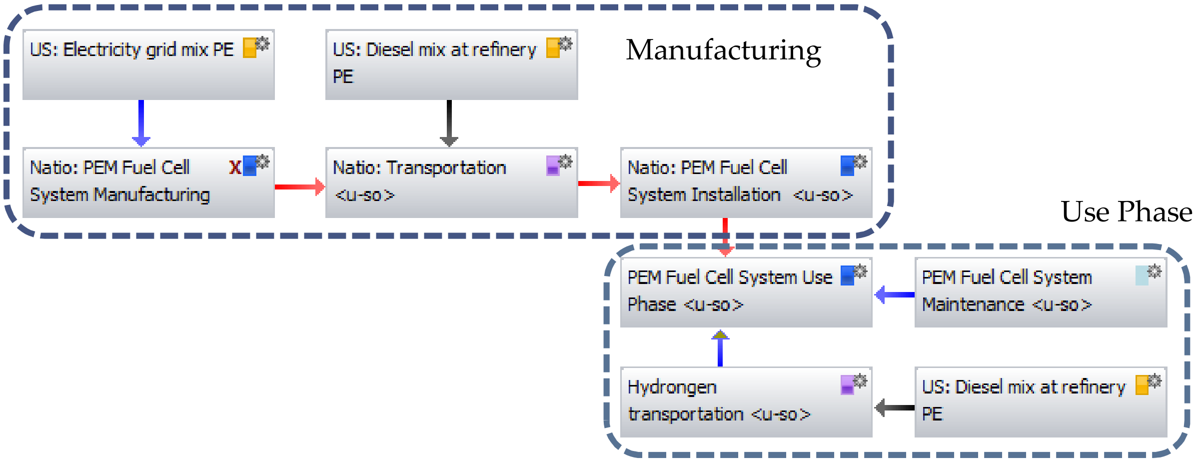

Figure 16 System Boundary

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[20] Jaap van Pooijen.2006. A Life Cycle Assessment of the PureCell™ Stationary Fuel Cell

4. Proton Exchange Membrane Fuel Cell Model Properties

A fuel cell stack is obviously the heart of a fuel cell system, however, without the supporting equipment the stack itself would not be very useful. The fuel cell system typically involves the following subsystems:

- Oxygen or air supply
- Hydrogen supply
- Water management
- Power conditioning
- Instrumentation and control[21]

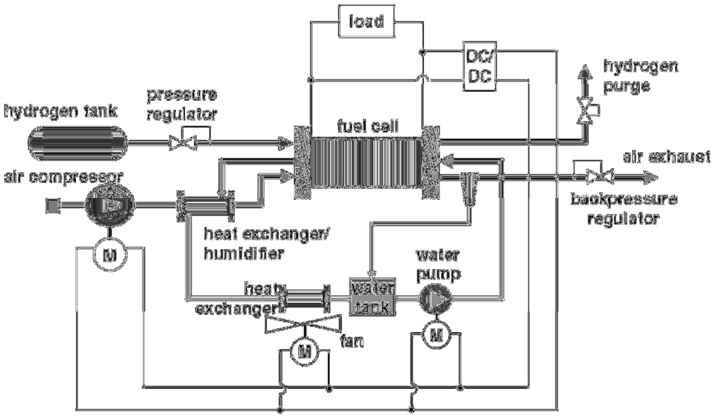

Figure 17 PEM Fuel Cell Properties

5. Data Inventory

Manufacturing Phase:

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[21] Frano Barbir. 2006. PEM Fuel Cell

Air Blower

The process air blower provides high capacity air flows to key components.

Processes	Amount	Unit
Rolling steel l	50	lb
Cold transforming steel	50	lb
Turning steel	50	lb
Cold transforming Al l	50	lb
Turning aluminum l	50	lb

Air valve subassembly

Processes	Amount	Unit
Injection molding	10	lb
Forging steel	95	lb

Cabinet ventilation fan

The cabinet ventilation fan blows air into the PEM fuel cell system.

Processes	Amount	Unit
Rolling steel l	250	lb
Cold transforming steel	250	lb
turning steel	250	lb

Cell stack shipping bracket

Processes	Amount	Unit
Cold transforming steel	120	lb
Electric welding steel	2	m

Condenser

The function of the condenser is to condense water vapor as a product of combustion upon exit from the reformer burner and from the cathode.

Processes	Amount	Unit
Rolling steel l	1350	lb
Cold transforming steel	1350	lb
Electric welding steel	10	m

Cell stack assembly

Stainless steel 304 2B llSl	637.5	lb
Steel cold rolled coil llSl	5302.5	lb
perfluorosulfonic acid	376.5	lb
PE granulate average B250	702	lb
Graphite	5676	lb
Copper ETH	111	lb
Glass fiber l	750	lb
Silicium carbide	2854.5	lb
Cold transforming steel	5940	lb
Electricity	99270	kWh

Electrical control system

The electrical control system provides complete control over the PEM fuel cell system power system.

Processes	Amount	Unit
Cold transforming steel	1000	lb
Electric welding steel 5	5	m
Copper wire	300	lb

Enclosure

Processes	Amount	Unit
Rolling steel l	3490	lb
Cold transforming steel	3490	lb

Frame

Processes	Amount	Unit
Cold transforming steel	3795	lb
Electric welding steel	10	m

Fuel compartment ventilation fan

Processes	Amount	Unit
Cold transforming steel	50	lb
Turning steel	50	lb

Harnesses and cables

Processes	Amount	Unit
Copper wire	100	lb
Extrusion I	85	lb

Integrated low-temperature shift converter

Processes	Amount	Unit
Rolling steel l	4712	lb
Cold transforming steel	4712	lb
Electric welding steel	5	m

Misc. small parts

Cold transforming steel	65	lb
Injection molding	35	lb

Power conditioning system

The PCS converts unregulated DC power into three phase utility grade power.

Cold transforming steel	3950	lb
Electric welding steel	5	m
Copper wire	1800	lb

Piping

Cold transforming steel	430	lb
Glass fiber l	200	lb

Reformer

Rolling steel	2615	lb
Electric welding steel	5	m
Cold transforming steel	2810	lb

Steam ejector

Stainless Steel	100	lb

Thermal management system

The TMS maintains a proper cell stack temperature.

Rolling steel	1050	lb
Cold transforming steel	2250	lb
Electric welding steel	5	m

Water treatment system

Cold transforming steel	200	lb
Electric welding steel	5	m

Using phase

PEM system installation

Materials	Amount	Unit
Cold transforming steel	738	lb
Propylene glycol	1428	lb
Activated carbon	180	lb
Concrete	23820	lb
Stainless steel	4560	kg
Water	2976	lb

Maintenance

Activated carbon	3600	lb

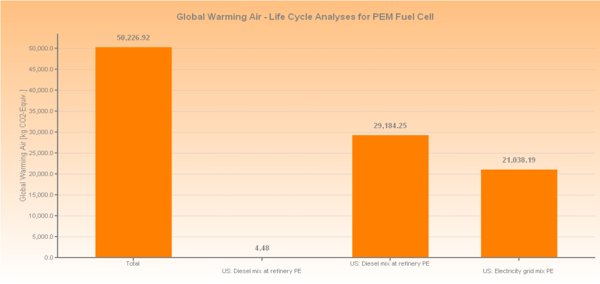
Hydrogen consumption and transportation

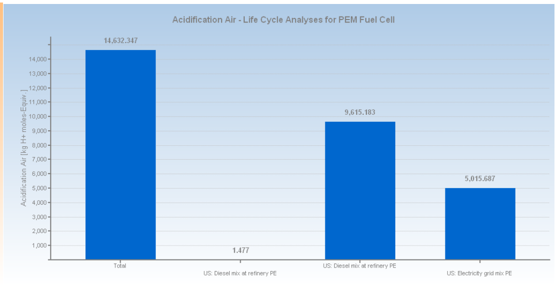
Materials	Amount	Unit
Hydrogen	467200	kg
Diesel	43610	kg

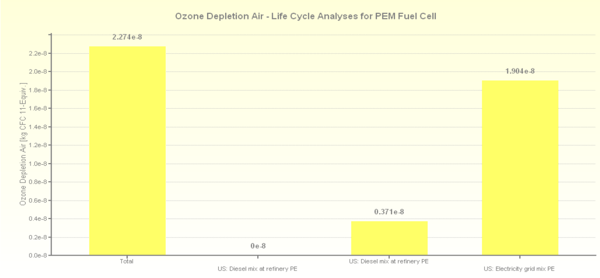
6. *Results*

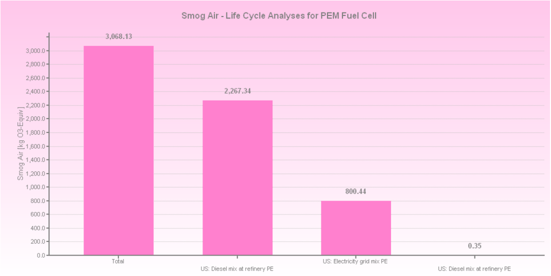
It is mentioned that only electricity and diesel are consumed in this analysis. Here is the result got from GABI, including global warming potential, acidification potential, smog formation potential and ozone layer depletion potential.

	Unit	Total	Manufacturing Phase	Use Phase
Global Warming Potential	kg CO2-Equiv	50476.23	21043.39	29432.84
Acidification Potential	kg SO2-Equiv	289.456	103.457	185.999
Smog Formation Potential	kg Ozone-Equiv	27.367	4.623	22.743
Ozone Layer Depletion Potential	kg R11-Equiv	0.0008575	0.0007326	0.0001248









7. Conclusion

According to the analysis, CO_2 emission is the main emission of the PEM fuel cell system. During its life time it produces 50476.23 kg CO_2, and produces 7.3GWh, which means its CO2 emission per kWh is 0.006915kg/kWh. In BC province, the total CO_2 emission for 2010 is 68.7 million tonnes[22], and 2% of this number produced by electricity generation, which is BC Hydro. And BC Hydro's electricity generation is 50392GWh[23], which means for BC Hydro the CO_2 emission per kWh is 0.0273kg/kWh. When comparing the two CO_2emission numbers, the PEM fuel cell system is of less environmental impact.

There are many assumptions in this study. If there is enough database and materials, the follow research should be included:

- Expand the boundary of the system. Raw materials energy consumption and emission should be included.
- The heat generator part of PEM fuel cell should be considered, because the heat water produced by it can provide the community usage and reduce the electricity used to heat water.
- To find the recycle information of PEM fuel cell. Add the end of life phase.
- Constant hydrogen consumption is a big problem for PEM fuel cell system. Therefore, further study for hydrogen storage should be considered.

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[22] BC Hydro. 2010. Load and Forecast

[23] Life Smart BC. http://www.livesmartbc.ca/learn/emissions.html