A Business Case for Solar to Electric Vehicle Charging Microgrids

April 2019

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1. Executive Summary

UBC has a challenge to lower the carbon footprint of its transportation fleet and align itself with the City of Vancouver goal of 100% energy from renewable sources by 2050 according to the "Renewable City Action Plan" (City of Vancouver, 2017). Ninety three percent of British Columbia energy is mandated to be derived from renewable sources by the BC Clean Energy Act (BC Laws - Clean Energy Act, 2010). To offset the nonrenewable component of BC electricity supply, the University of British Columbia is seeking to generate as much electricity as possible from renewable sources as possible and explore possibilities of reducing the carbon footprint of transportation at the University of British Columbia.

The Clean Connected and Safe Transportation Testbed (CCSTT) is a living laboratory project that will emulate critical links between energy, transportation, ICT, and urban design (Mérida, 2017). The Advanced Photovoltaic Laboratory is an exercise in building a parkade based microgrid that will connect a DC photovoltaic system to high voltage DC electric charging stations (Level 2 and 3), energy storage, supercapacitors and hydrogen electrolyzers, storage and refueling stations.

The potential of developing a 1MW solar facility on top of Thunderbird parkade was explored using solar canopies. 16 additional DC Level 2 and Level 3 EV chargers are planned to be added to the existing 8. A 100 kg/ day Hydrogen production storage and refueling station was sized for the projected based on projected needs from UBC. Major costs for the microgrid included capital expenditure, O&M costs, replacement costs and electricity costs. Revenue streams include energy offset from electricity generated from the PV plant, Low Carbon fuel standard credits from generation of a low carbon fuel like hydrogen, revenue from EV car charging and gasoline offset for fleet switch to electric vehicles.

A logic diagram was built to allocate flow of electricity through different components of the microgrid based on different usage scenarios through the year. This algorithm was then applied to a model that calculated hourly flow of electricity between the various components of the microgrid. The costs and revenue were mapped as yearly cash flows and the net present value was calculated over 40-year project life accounting for the various escalation life in EV usage and hydrogen vehicle adoption. Three models were then built based on the UBC electricity rates, City of Vancouver electricity rates and a city-based rooftop model without solar canopy infrastructure cost.

A sensitivity analysis was performed and optimizing the most critical components of the microgrid, positive net present values were achieved for all the models and reasonable payback periods. This is an indication that organizations with large fleets, parkades or commercial/industrial buildings should consider working with local governments and utilities to explore the options to build microgrids to support their operations, reduce their carbon footprint and be powered by renewable energy.

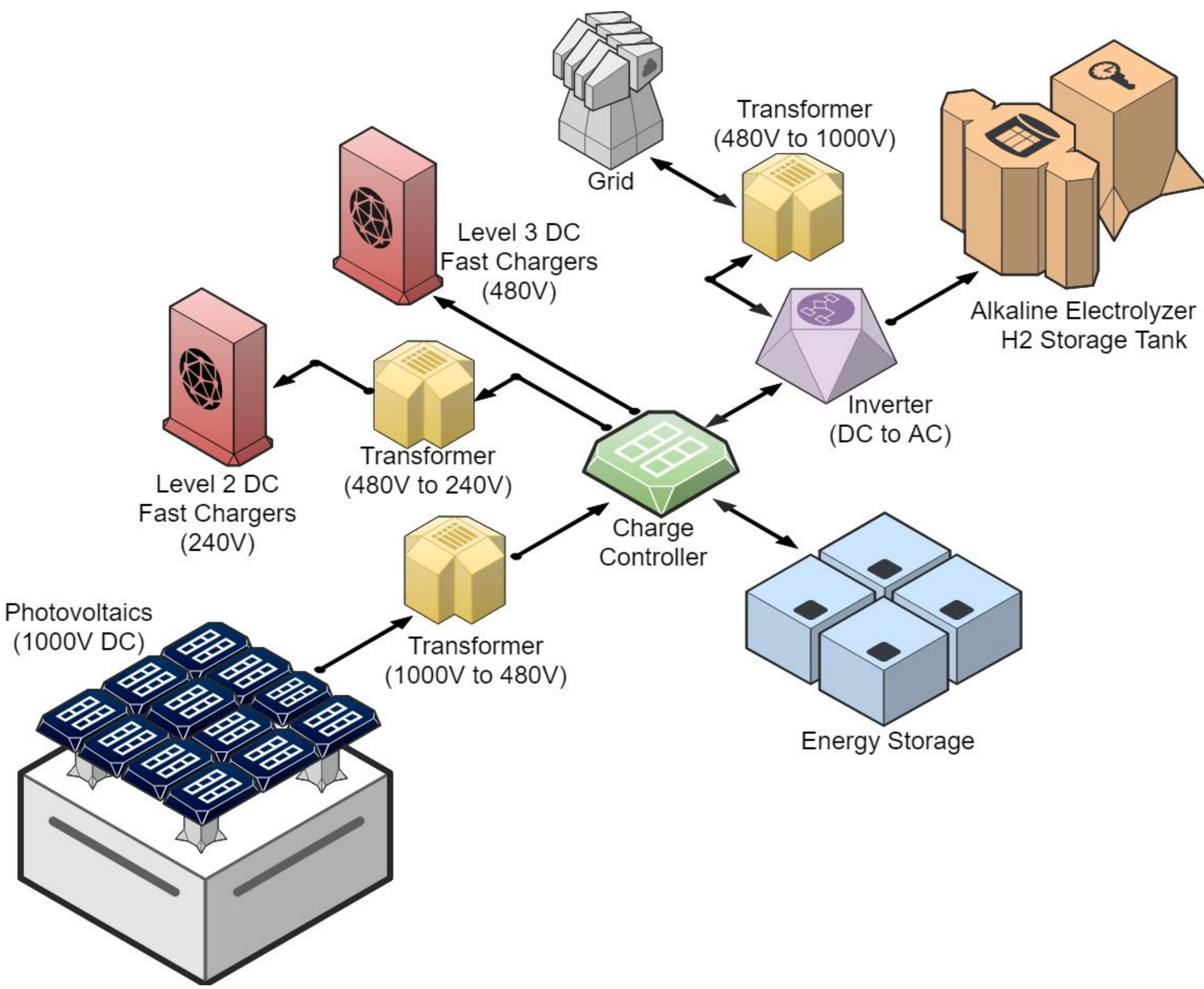

Figure 1 – Overview of the UBC CCSTT Microgrid

2. Background

The Clean Connected and Safe Transportation Testbed (CCSTT) is a city-scale, living laboratory that will emulate critical links between energy, transportation, ICT, and urban design. The Advanced Photovoltaic Laboratory is one of 5 components of the CCSTT, enabling the reconfigurable and optimized interaction of intermittent solar energy with smart grids and refueling infrastructure, and transportation assets, e.g., electrolyzers and electric vehicles (Mérida, 2017). This study is to explore the technical and financial models for the "Advanced PV Laboratory" component of the CCSTT lab looking at connecting renewable energy generation to hydrogen use in transportation.

Currently the production of energy from photovoltaic cells, energy storage, charging of electric vehicles and hydrogen production and refueling are widely regarded as the future of the transportation industry due to their low GHG emissions compared to the current fossil fuel-based system (Mérida, 2017). However, economically there are many challenges to building a viable business model that optimizes the use of all these components according to different usage scenarios, different times of the year, optimized for ideal size and where economic benefits like the low carbon fuel credits are used. If it can be shown that a financially viable business model can be built for one parkade in UBC, this model can serve as a blueprint for smart connected microgrids that include solar PV, storage, EV charging and hydrogen that can be implemented in other locations and help the transition towards a low carbon transportation future.

A literature review was performed exploring similar projects and analysis performed exploring the financial viability of different components of the microgrid. Examples of three relevant studies are:

- "Future cost and performance of water electrolysis: An expert elicitation study" (Schmidt, 2017)
    - Key findings: Current capital costs for electrolyzers are around €1000 and €2000 per kW installed. Capital costs by 2020 at current R&D funding and without production scale-up lie between 800 and 1300 € per kW installed.
- "Feasibility Study of a Solar Photovoltaic to Hydrogen Electrolyzer System at the Richmond Field Station" (Moore, 2015)
    - Key findings: Study considered pure solar vs. combination of solar + grid to power electrolyzers, and the pure solar scenario had significantly lower costs of operation after approximately 7 years operation. Combination case and business as usual case had significantly higher costs as time go on after this.

- "Power-to-gas for Decentralized Energy Systems: Development of an Energy Hub Model for Hydrogen Storage" (Murray, 2017)
    - Key findings: Power to hydrogen gas (P2G) is the storage type of choice when it comes to reducing emissions and maximizing utilization of installed renewables, however the technology comes at a very high cost.
    - With the high combined cost of electrolyzers, compressors, hydrogen storage, and fuel cells, the costs for P2G storage is economically challenging currently.
    - As the costs of these technologies drop in the future and as their efficiency improves, P2G could become a more cost-effective solution.

A site visit was conducted of the British Columbia Institute of Technology campus where a 250 KW Solar parkade is installed with added energy storage. Similarities between the proposed UBC microgrid and the installed facility were studied, and lessons learned incorporated into the models built for the project.

3. Scope & Objectives

The scope of this project is to explore the technical and financial feasibility of a solar microgrid onto an existing parkade on UBC's Vancouver campus. The models of the microgrid were optimized by performing a sensitivity analysis and iterating on component sizes, financial rates and technologies to be included.

Overarching goal:

- UBC is interested in reducing its carbon emissions and transitioning to a transportation fleet run by zero emissions vehicles. Building a microgrid that is financially viable that would power the fleet with either electricity or hydrogen would serve as a model for other installations and open the possibilities of expanding into new microgrids at UBC and beyond.

The following are the research objectives for the study:

- Model technical components of the Advanced PV Lab to match the design requirements for the CCSTT in appropriate software like HOMER, Simulink, or TRNSYS. Model predicted output of solar panels based on time of year, usage, etc. and provide flow chart for incoming energy.
- Prepare a detailed technical and financial analysis for the viability of the business case by iterating on the size of the variable components - e.g. size of the hydrogen production facility and EV storage size.
- To explore stand-alone business models outside of the CCSTT framework for future implementation by other entities, e.g. buildings owned by the City of Vancouver such as Industrial warehouse facilities.

4. Microgrid Components Description

The microgrid to be installed the Thunderbird parkade will consist of the components shown in Figure 2. The photovoltaic plant is connected via a transformer to energy storage, DC electric vehicle charging stations of various power ratings, an electrolyzer and hydrogen refueling facility and connection back to the electric grid.

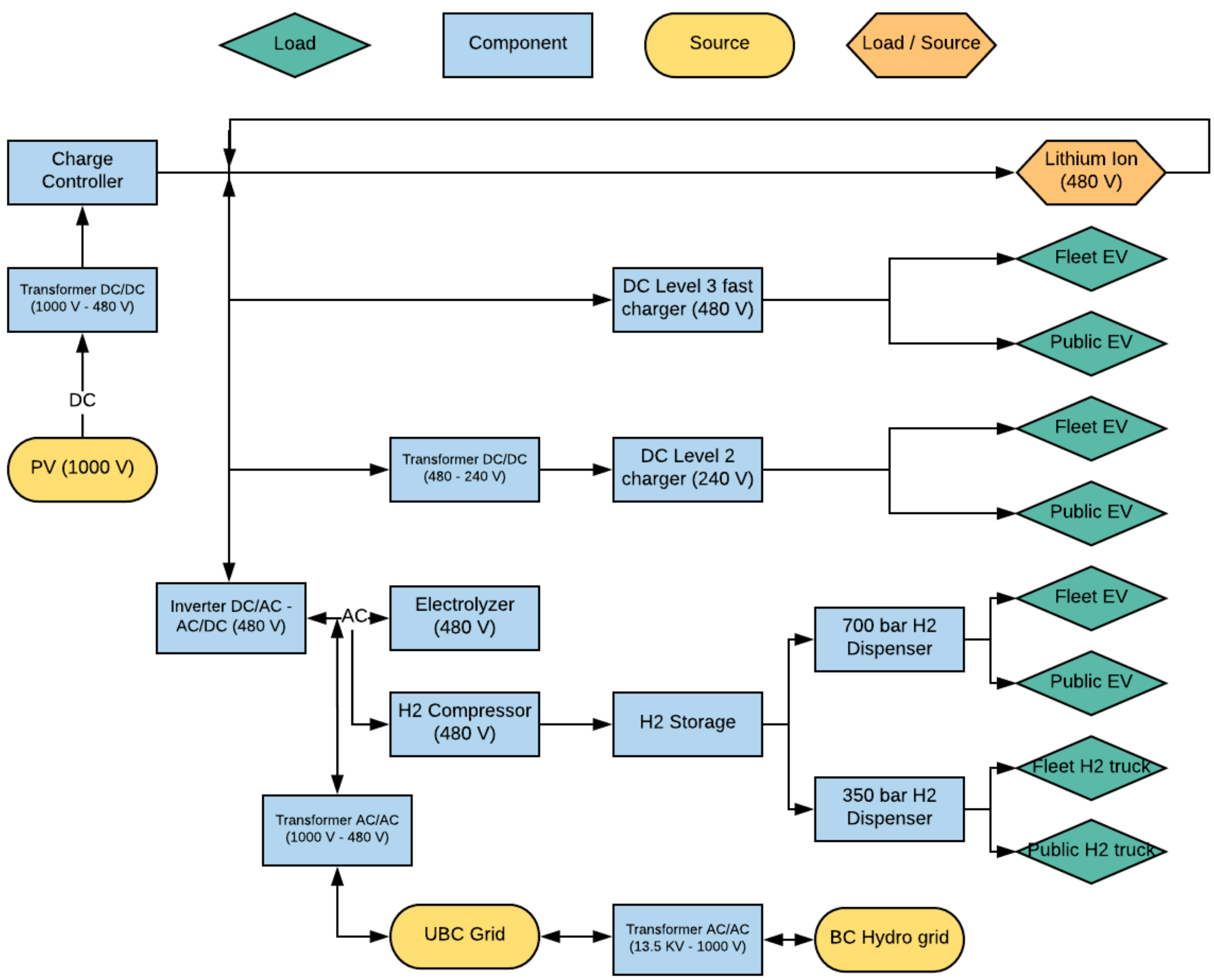

Figure 2 – Overview of the different components of the microgrid and the flow of electricity between components.

The detailed description of the various components and their sizing considerations are as follows:

4.1 Photovoltaic System, Canopy and Electrical Components

The area available on top of the Thunderbird facility and the solar potential has been evaluated by the UBC Rooftop Solar Potential Study (Nicoletti, 2018). With the available 10,253m^2 of area and size analysis by solar suppliers, it was estimated that a possible 1000kW photovoltaic facility can be built on canopies covering the cars on the top floor of the Thunderbird Parking Facility. After consultations with solar installers in the city, it was determined that 300W panels with efficiencies around 19% would offer the most value to the project.

Solar canopies that cover the parking spaces on the top floor serve both as a method to not lose valuable spots, but also to provide value for the cars parking on top by offering protection from t2he elements. After consultation with a solar and roofing installer, several design considerations must be accounted for while the canopies are designed. There is a ramp in the middle of the roof structure which must be accounted for in the steel beam support heights. The canopies have the constructed in a way that offers waterproofing. Lighting must be redesigned around the new structure. The backing panel design of the canopies have been envisioned to be made from glass to increase longevity and allow for light to come through the panels enabling users to visually see that the solar panels on top of the canopies.

The solar panels must be stepped down in voltage through a transformer to 480V and run through a charge controller into energy storage. This will also enable the electricity to be used by the Level 2 and 3 DC electric vehicle charging stations that are part of the microgrid. A 2-way inverter (DC/AC side) will allow the power to be used by the hydrogen electrolyzer, compressor and refueling station. If power is not available from the photovoltaic system and no energy storage is available, it will be drawn from the grid where the energy will be stepped down to a usable 480V through a transformer. The 2-way inverter (AC/DC side) will convert this electricity as needed to power the electric charging vehicles as needed.

4.2 Energy Storage

The system has a connection between the PV and energy storage consisting of a Li-ion battery pack. This arrangement will allow sustained energy storage over a long period of time through the batteries and can rapidly respond to acute energy demands over a short period of time, e.g. short-term load fluctuation. The Li-ion battery will provide energy in the unlikely event of grid electricity being temporarily cut-off from the parkade/campus. Finally, and potentially most significantly, energy storage can help with demand charge reduction, allowing peak shaving to occur and lowering energy demand from the grid during the most expensive peak periods, saving expenses in the long-term. The size of the energy storage components was iterated on for maximum net present value and can be seen in Figure 3. If the energy storage is maintained at 3MWh, the NPV improvement is found to be the highest. This value was chosen as the size of the energy storage component given the space limitations on campus to house a large energy storage facility and after consultation with BCIT on the size of their installed energy storage facility.

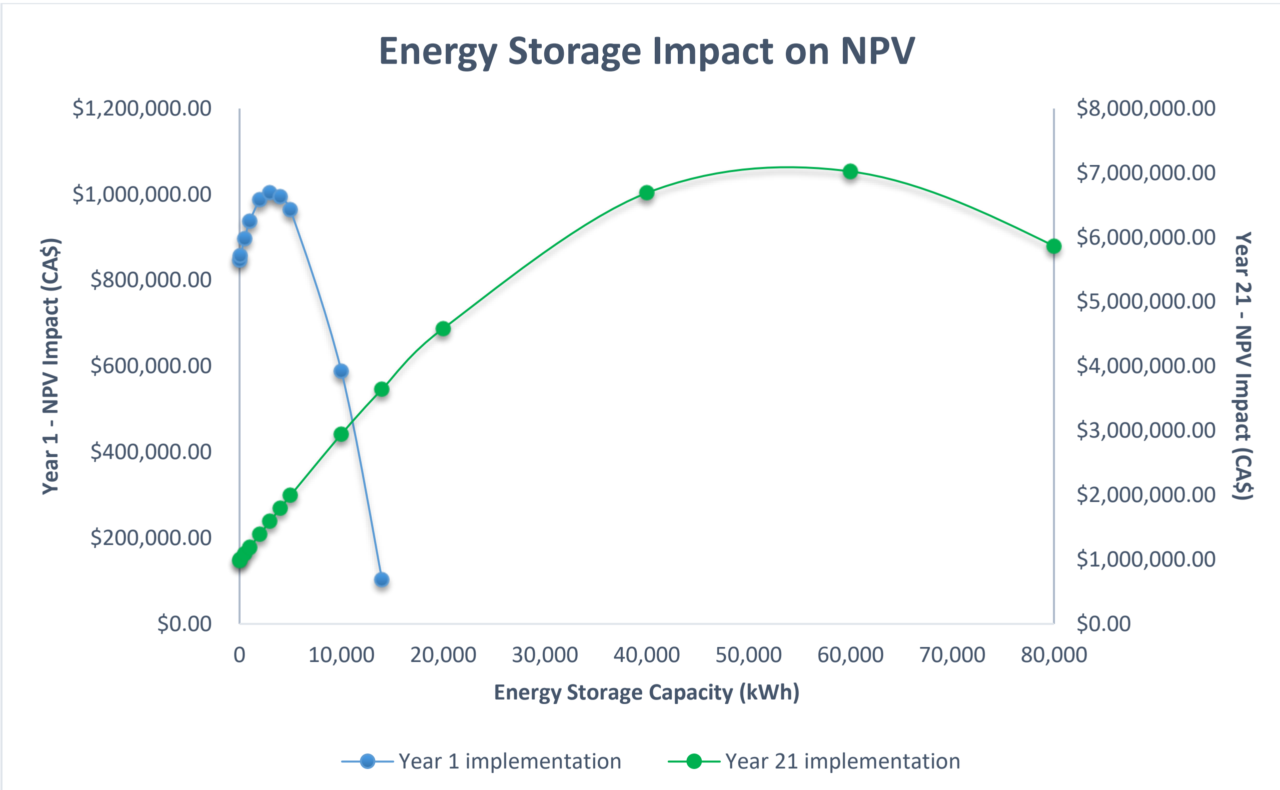

Figure 3 – Energy storage size variation with improvement in net present value.

4.3 EV Chargers

Currently, there are eight ChargePoint 7.2kW charging units in Thunderbird parkade. Two vehicles can be connected simultaneously per charger. To expand electric vehicle charging capacity, 16 additional charging units of various charging speeds will be added to the parkade. A mix was initially selected to allow gradual charging with standard Level 2 units (5-10kW) and well as fast DC charging Level 3 units (up to 156kW). The distribution of the 16 additional EV chargers to be added to the microgrid at project start is as follows:

- (6) ChargePoint Dual Port Pedestal CT4000 – 7.4kW
- (5) EV Box – 7.4kW
- (4) ChargePoint DC Fast Charger – 62.5kW
- (1) ChargePoint Express Plus Charger – 156.25kW

Electric vehicle batteries are charged by direct current (DC) whether the plug-in source is alternating current (AC) or DC. A charge controller in the vehicle converts AC to DC before it is fed to the battery. As such, supplying the battery directly with DC is more efficient as it avoids the conversion process. Further, DC chargers generally charger vehicles faster than AC chargers due to the large amounts of current possible in DC charging units (125A+). Currently, UBC's fleet consists of 27 Smart electric vehicles. Due to the significant emissions associated with transportation, the university aims to increase zero-emission vehicle adoption within the UBC fleet through a combination of electric and hydrogen powered vehicles.

4.4 Hydrogen Production, Storage and Refueling

The hydrogen component of the microgrid consists of an alkaline electrolyzer that has an initial output of 100 Kg a day. It is compressed and stored in tanks that supply a refueling system that is meant for public and fleet hydrogen car and truck charging. The Low carbon fuel standard provides hydrogen manufacturers with incentives for building infrastructure for low carbon fuels and for usage of the produced fuels. These credits can expect a revenue of approximately 164 CAD/credit that incentives the industry towards solving the infrastructure scaling challenges the sector faces until the program's projected close in 2040.

5. Data & Methodology

Various sources of data were used to define different components of the microgrid on Thunderbird Parkade. The solar PV generation potential was calculated through existing solar potential studies on UBC, RETScreen, Helioscope and HOMER software data.

Using existing data from installed EV chargers in Thunderbird parkade, the projected electrical load placed by adding 16 EV chargers to the parkade and the different usage patterns were estimated.

Bid documents from local suppliers were used to estimate the load placed by the hydrogen electrolyzer and hydrogen storage and refueling station.

A logic diagram and algorithm that describes the ideal distribution of power amongst the various components in the grid for different usage scenarios was established and can be seen in Figure 4.

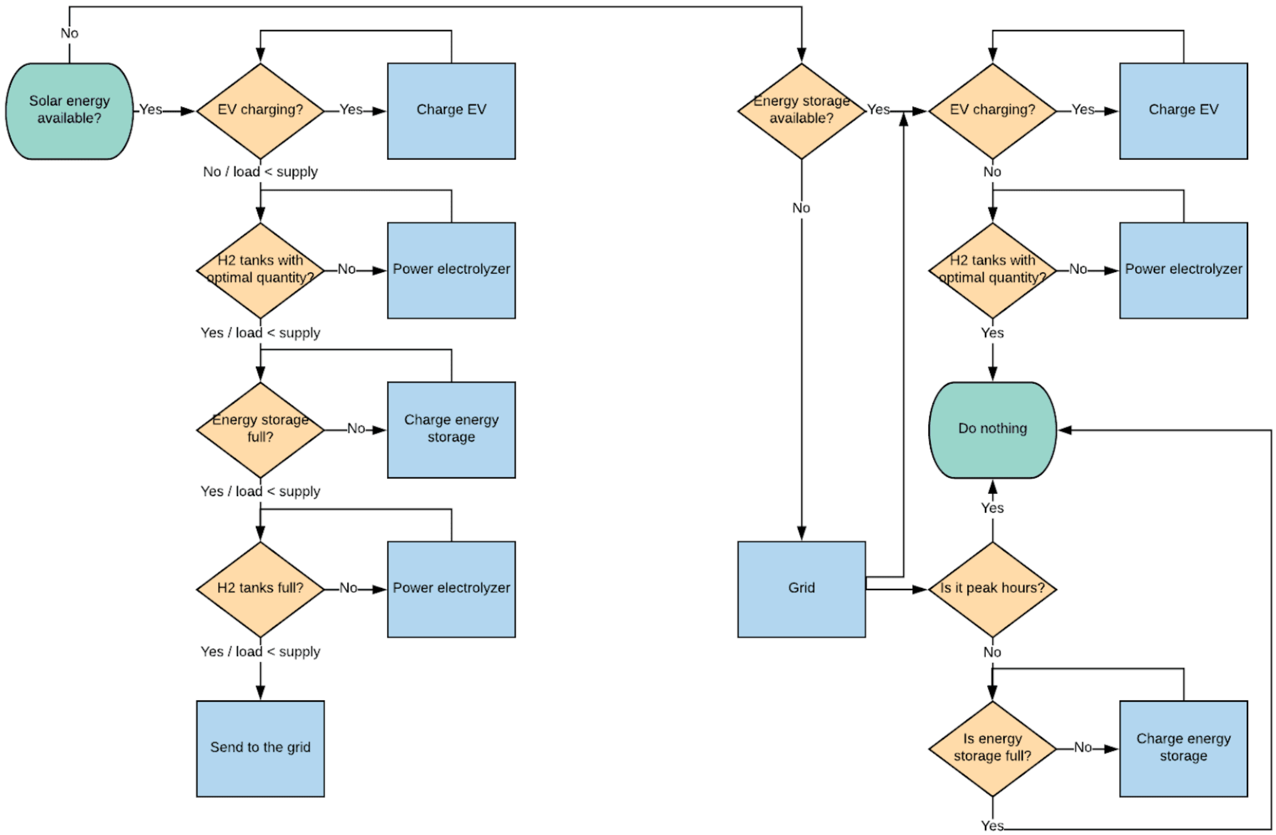

Figure 4 - Logic algorithm for flow of electricity between different components of microgrid.

The microgrid was modelled in excel since the internal logic within HOMER could not be manipulated to reflect the algorithm. A model with the hourly usage data and costs incurred for the project life was created and used to calculate the Net Present Value and Payback period for the project. Once the initial model yielded results, the model was iterated on for component size until a positive net present value is reached. This model was then replicated for the City of Vancouver. The key differences between the City of Vancouver model and the UBC optimized model are that the electricity rate of sell back to the city is calculated based on the BC Hydro standing offer program and that there is no fleet charging. A third model was created with no canopies and where the solar modules are placed on top of a commercial/industrial roof structure.

The following data sources were relied upon for data:

- RETScreen, Helioscope and HOMER software database for solar PV potential data and generation potential.
- José Jimenez from UBC Operations for electric vehicle usage data from Thunderbird parkade.

- UBC Rooftop Solar potential studies campus buildings.
- Supplier data on hydrogen electrolyzers and refueling station capabilities and energy storage specifications.
- IRENA - International Renewable Energy Agency data on average capital cost for various components of the microgrid.
- BC Hydro for cost of electricity and average escalation rates.
- Statistics Canada for inflation rates.
- SkySpark data for UBC electricity usage in buildings.

5.1 Assumptions Made for Model

To make safe assumptions for the initial UBC model, an intensive research had to be made to create the model as accurate as possible. Is important to note that the assumptions presented below were made for the UBC initial model. Following models were results of optimizing and adapting the initial model. When referring to "peak times", this is assumed to be between 8:00am and 5:00pm on a weekday. During this time, the electric vehicle chargers will be utilized by public vehicles entering the parkade. All other times are considered off-peak, during which time the EV chargers will be utilized by the UBC fleet of electric vehicles.

For more information about the sources of data, refer to Table 1 in the Appendices.

5.1.1 Logic Process Flow

A charge controller will determine the priority of electricity flow within the system. The priority will be to feed directly to the EV charging units if there is demand. Next, the hydrogen electrolyzer and compressor will be run until a minimal amount of hydrogen is present in the tanks (~55%). After this hydrogen threshold is reached, the lithium-ion battery and supercapacitors will be charged until they are full. Upon completing this, electricity will flow back to the electrolyzer until the hydrogen tanks are full. If the hydrogen tanks are full, electricity will then be fed into the UBC grid for use around the campus as it is not required in the microgrid system.

If solar energy is not available for the photovoltaics, EV charging demand can be fulfilled by the energy storage or directly from the grid if the batteries are depleted. If no EV charging demand is present and the hydrogen tanks are not at their minimal quantity, the electrolyzer can operate directly from the energy storage or directly from the grid. The energy storage will be charged by the grid if electricity costs are optimal, e.g. during low demand periods such as overnight.

If none of these conditions are applicable, the system will do nothing – see Figure 4.

5.1.2 Usage Scenarios

Thunderbird Parkade was determined to be the second-best location and the best parkade for Roof Solar potential (Nicoletti, 2018). Solar potential is not expected to vary each year and variation through the year is available through the hourly data collected from HOMER and validated through RETScreen. Solar suppliers use a conservative average of 1,100 kWh / kW installed / year of generation available and exact numbers are derived from hourly data. Solar generation potential including loss due to canopy was estimated by a solar supplier and a model was built to verify the PV potential on the roof using Helioscope.

5.1.3 Electric Vehicle Charging Stations

Based on the empirical data of EV charger usage in Thunderbird Parkade from September 2017 to August-end 2018, a usage for the following academic year was modeled.

The UBC initial model will be starting with 24 EV charging stations (18 x 7.4 kW, 5 x 62.5 kW and 1 x 125 kW). Charging stations will be added into the parkade every time public demand reaches 90% of utilization during the busiest day in the year.

Based on data from Fleet Carma, the EV growth rate is expected to grow @ 27.5% per annum in 2019 leveling off to 5% in 2043. At this year, charging stations will reach the maximum assumed utilization of 30% of the parking spots at Thunderbird (510 chargers maximum), and it was assumed EV growth rate will not increase any further for the period analyzed in this study.

During weekday peak periods (8am to 5pm), it is assumed that only public vehicles will be charged at the parkade. For more information, refer to Table 2 in the Appendices.

5.1.4 Fuel Cell Vehicle

It is estimated that the average hydrogen-powered vehicle will require 5 kg of hydrogen to fully recharge. It was also modeled that at least one hydrogen-powered truck would be added to the university fleet, which consumes 40kg of hydrogen during a full charge.

The initial model is not considering any public demand from Fuel Cell Vehicles (FCV) in 2019 and will consider 1 FCV refueling once a week starting 2020. Public demand will grow 60% the next year, and the growth is normalized, settling at 5% in 2048.

It is assumed that the Low Carbon Fuel Standard (LCFS) will provide between 5,000 to 10,000 credits after the hydrogen fueling station is built. Then, a continuous stream of credits as hydrogen is generated and refueled at the station.

Currently, the LCFS by British Columbia are only written to last up to 2030, in the model is assumed that they will remain until 2030 and decrease gradually to 0 in 2040. It is also assumed that the cost per credit will remain constant throughout the life of the project. Initial model will start with a capacity to produce 100 kg of Hydrogen per day, upgrading its capacity to 500 kg per day after 20 years.

For more information refer to Table 3 in the Appendices.

5.1.5 Fleet

Starting with 22 EV, the fleet will add 5 every year, until reaching the limit of 200. It is assumed that fleet will charge during off-peak hours (5pm to 8am next day). Although vehicles will have fully charged well before 8am, the session is scheduled to allow the morning crew to collect the vehicles as soon as the morning shift starts.

The UBC fleet will also start with 15 FCV and 1 Hydrogen Truck, refueling once a week, distributed randomly throughout the week. The fleet will grow up to 200 FCV and 2 Hydrogen Trucks.

For more information refer to Table 2 and Table 3 in the Appendices.

5.1.6 Energy Storage

As the average electric vehicle in the market has a battery size of approximately 20kWh, a battery capacity of 100kWh was chosen to allow at least 5 vehicles to be fully charged in the event of a power outage.

Lithium-ion battery degradation is dependent on several variables, such as battery temperature, average battery percentage at charging and discharging points, the rate of use, etc. For this model, it was assumed that a charging scenario of 100% battery being drained to 25% during a charging cycle at 21°C. It is estimated that the battery will have approximately 70% charging capacity after 10 years and will continue to deteriorate at a linear rate, reaching 40% of original capacity by the 20th year (Xu, 2016)

For more information refer to Table 2 in the Appendices.

5.1.7 Capital Costs

The following Capital Costs were estimated (for more information refer to Table 4 in the Appendices):

- **PV**: Industry standard for Solar installations including panels and labor is between C$2-4/Watt (IRENA, 2018). After consultation with solar suppliers in Vancouver, a value of C$3.5/Watt was estimated.
- **Solar Canopies**: The capital cost was estimated to be 2.2 million CAD after consultation with multiple solar installers. It is assumed the solar canopies will be constructed to cover an area capable of generating a minimum of 1MW solar generation.
- **Electrical Components**: The 2-way inverter and charge controller capital cost of 460,000 CAD is based on estimates from local solar suppliers. Two step-down transformers have been similarly estimated to cost around 60,000 CAD.
- **Energy Storage**: Estimated at approximately 20,000 CAD for a 100kWh size unit (IRENA, 2017).
- **EV stations**: Sourced from quotes from local major suppliers: EV Box and ChargePoint. Numbers vary between 14,000 (for Level 2 chargers) - 100,000 (for Level 3 chargers) CAD each.
- **Hydrogen Electrolyzer**: Estimated at 420,000 CAD for a 100 kg per day capacity with an installation factor of 1.12.
- **Hydrogen Refueling Station**: Capital and installation costs for the compressor, tanks and refueling station were assumed from bids received from Linde, a local supplier.
- A **BC Hydro Interconnection Study** assumed to be 300,000 CAD based on historical interconnection study costs for the UBC biomass facility of similar size.

5.1.8 Operations & Maintenance Costs

It is assumed the solar panels will not require cleaning given that rain showers are predicted to be sufficient to clean the panels as they are used. This assumption was validated after consultation with another solar microgrid in BCIT's Burnaby campus.

EV charging stations will not be maintained, as they will be replaced every 10 years.

Hydrogen electrolyzers, compressor, and dispensing stations will require annual maintenance based on usage (1.2 CAD/kg refueled).

For more information refer to Table 5 in the Appendices.

5.1.9 Replacement of Components

Inverters, transformers (with an upgrade), EV stations, hydrogen compressor, and dispenser will be replaced every 10 years.

The hydrogen electrolyzer, 5% of the solar panels, and all the batteries (at 40% their original capacity) will be replaced every 20 years.

Finally, hydrogen storage will be replaced after 30 years, with an upgrade according to production.

For more information refer to Table 5 in the Appendices.

5.1.10 Financial

The following financial assumptions were made for the model:

- Electricity rate in BC is expected to escalate at 3% per annum (BC Hydro, 2013). See Figure 17 in the Appendices.
- Thunderbird parkade step 1, step 2 thresholds and costs for electricity, and demand charge costs were obtained from UBC Operations and used in the model.
- The nominal discount rate at 5.75% and the inflation rate at 2% was also obtained from UBC Operations.
- The exchange rate at 1.3 CAD per 1 USD.

6. Results & Discussion

To assess the financial feasibility of this project, net present values were calculated using industry standard numbers for financial rates, allowing us to assess the financial feasibility over the 40-year project life. The baseline UBC model with no optimization yielded an NPV of -C$7.22 million (negative). As this was far from ideal, it was apparent that optimizations would be required. An NPV was then calculated for the optimized model, as well as for the City of Vancouver and warehouse models.

In addition, the energy split for the 40-year project life and carbon emissions avoided were calculated for the optimized UBC model.

6.1 Results

The baseline UBC model assumed a mix of level 2 and level 3 EV charging stations, and initial hydrogen production of 100kg/day. The hydrogen production was then upgraded to 500kg/day after the initial set of equipment reached end-of-life. Finally, a 100-kWh energy storage was implemented in this model, resulting in a negative NPV.

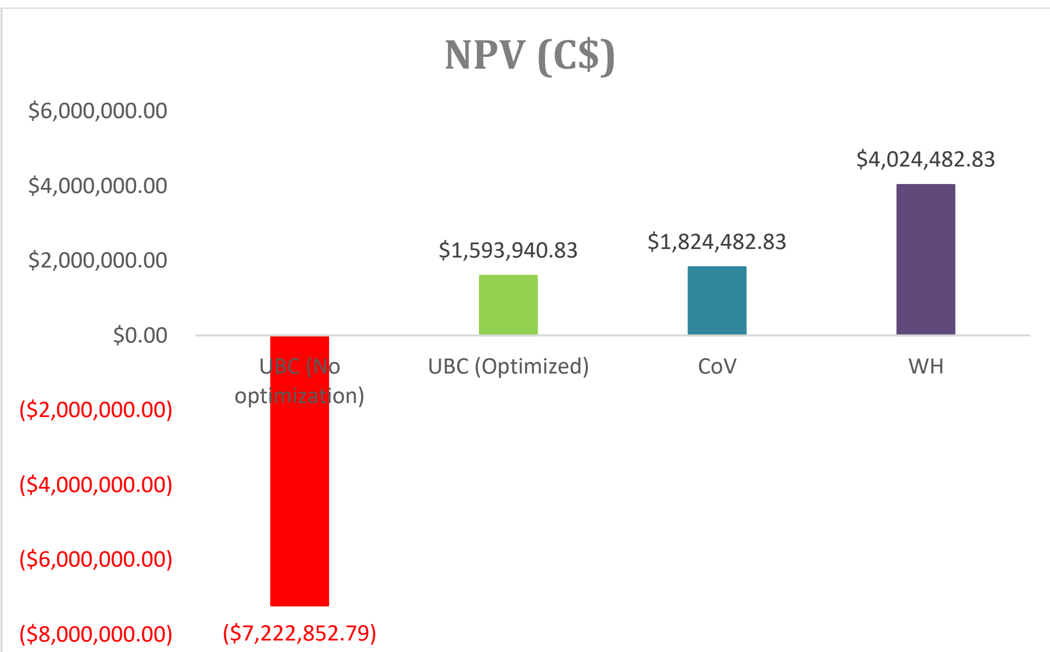

Figure 5 – Net present value (NPV) of the different models.

Based on the sensitivity analysis (see Table 6 in the Appendices), the optimized UBC model tweaked the mix of EV chargers by exclusively using level 2 chargers. These chargers had both a lower initial capital cost and were cheaper to install. In addition, they also reduced the peak load demand of the facility. In addition, it was deduced that an increase in hydrogen production capacity from 100kg/day to 500kg/day was not required, as the Hydrogen refueling station did not make financial sense. Finally, analysis was performed on energy storage capability and its effect on NPV. It was found that 3MWh of energy storage capacity improved the NPV through peak shaving (see Figure 6) - energy stored in the batteries can be utilized during peak consumption hours, reducing demand charges issued by the utility. The cumulative effect of these changes was that NPV increased to positive C$1.59 million.

For more information on the impacts of these optimizations, refer to

Table 7 in the Appendices.

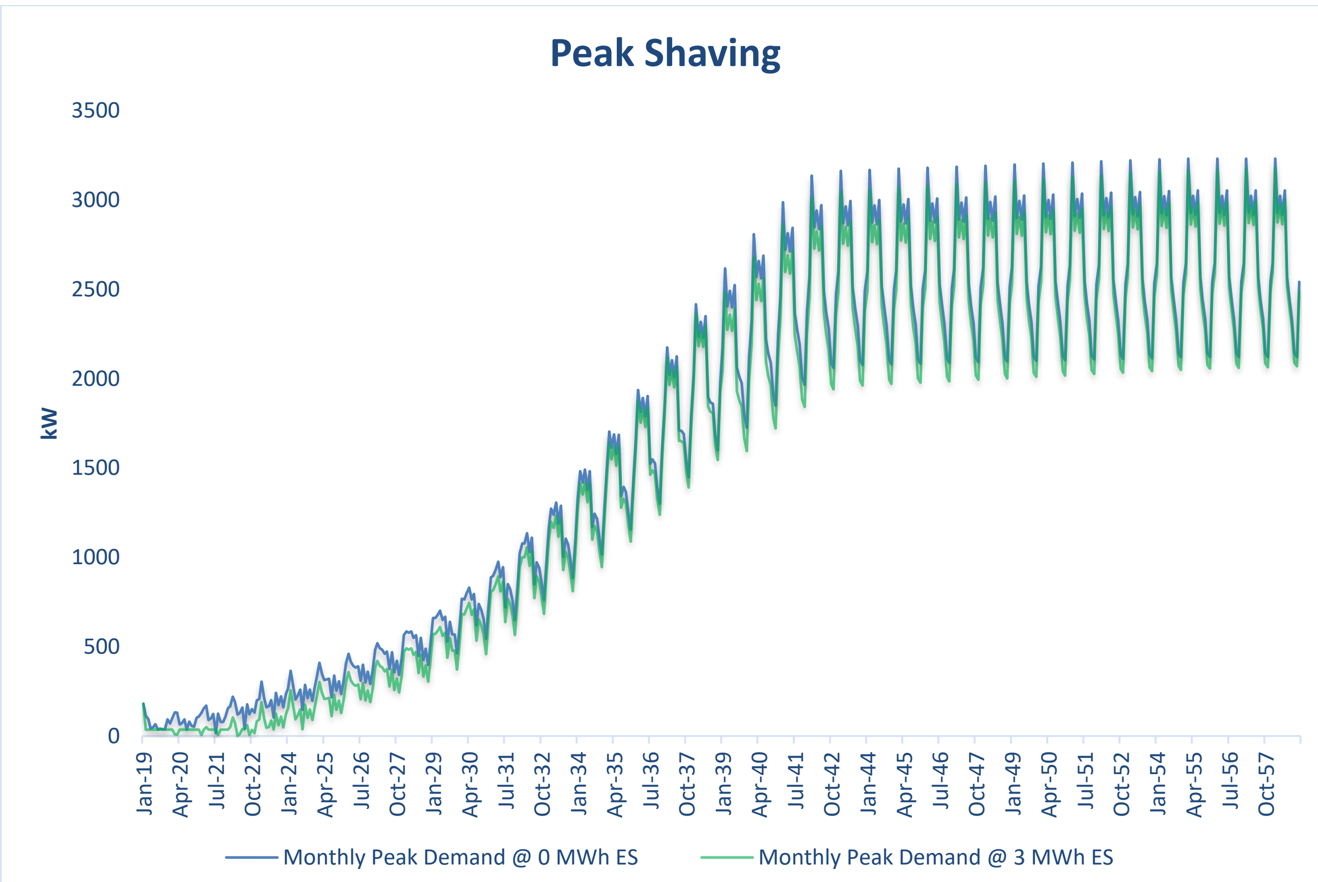

Figure 6 – Effect of energy storage on peak energy consumption over project life.

The third model analyzed assumed the same characteristics of the parkade, but in a public space such as a City of Vancouver building. A key difference is that this model will not be required to have a hydrogen refueling station as it does not make financial sense currently. This model does not consider any fleet and considers a different electricity rate from BC Hydro at C$ 0.12/kWh, and the parkade will be selling at C$ 0.10/kWh any extra electricity generated. The NPV resulted in positive C$1.82 million.

The last model analyzed was the warehouse model which will have a large amount of empty rooftop space for solar panels to be mounted. In addition to not requiring the hydrogen component, a big increase in NPV was obtained because the steel superstructure would not be required.

The cash flow analysis showed that the baseline UBC model without optimization did not break even during the 40-year project life. The optimized UBC model and the City of Vancouver model both broke even after 26 years, while the warehouse model broke even after 24 years.

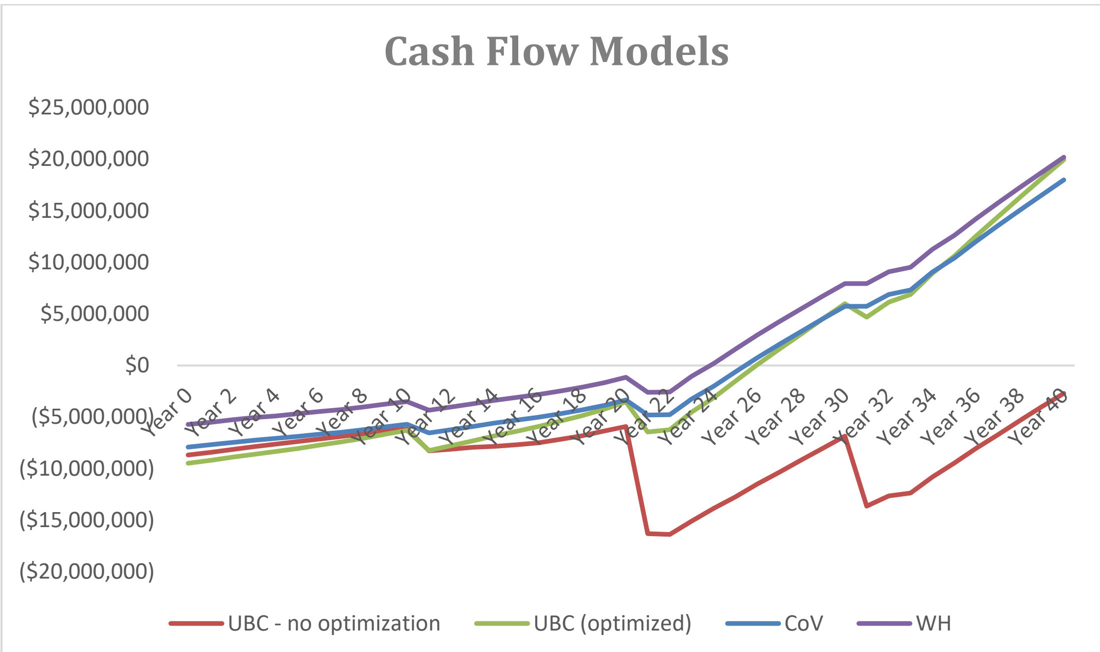

Figure 7 – Cash flow projections for the different models over 40-year project life.

UBC purchases electricity from BC Hydro at a special rate of C$0.071/kWh because the university maintains its own electricity grid. The university then "sells" electricity to various buildings around campus, such as Thunderbird Parkade, at nominal rates.

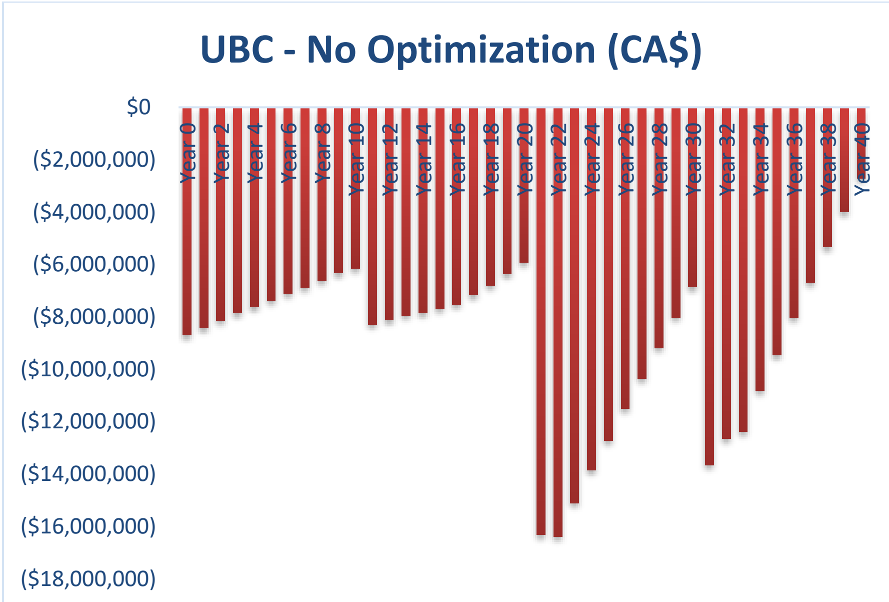

Figure 8 - Profit and loss projections for UBC model with no optimization.

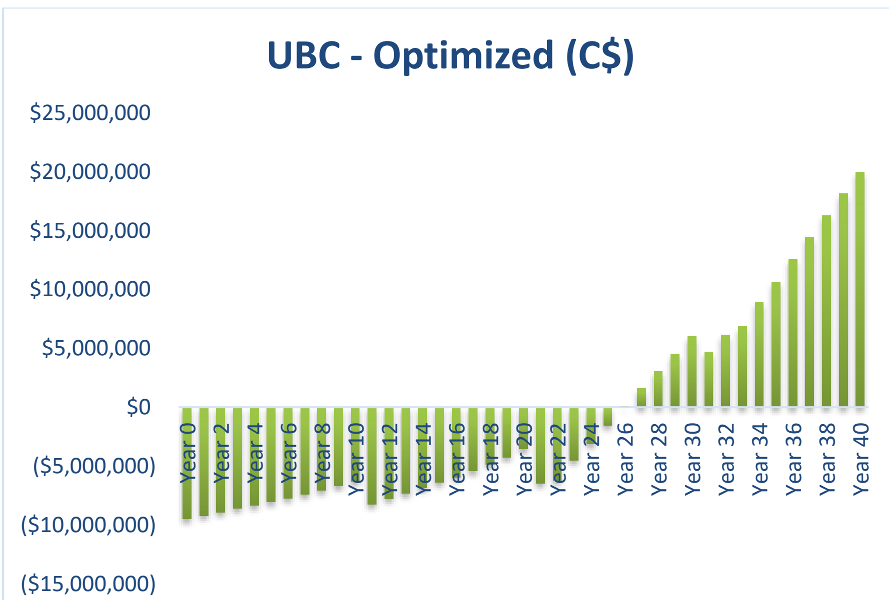

Figure 9 - Profit and loss projections for UBC model with optimizations.

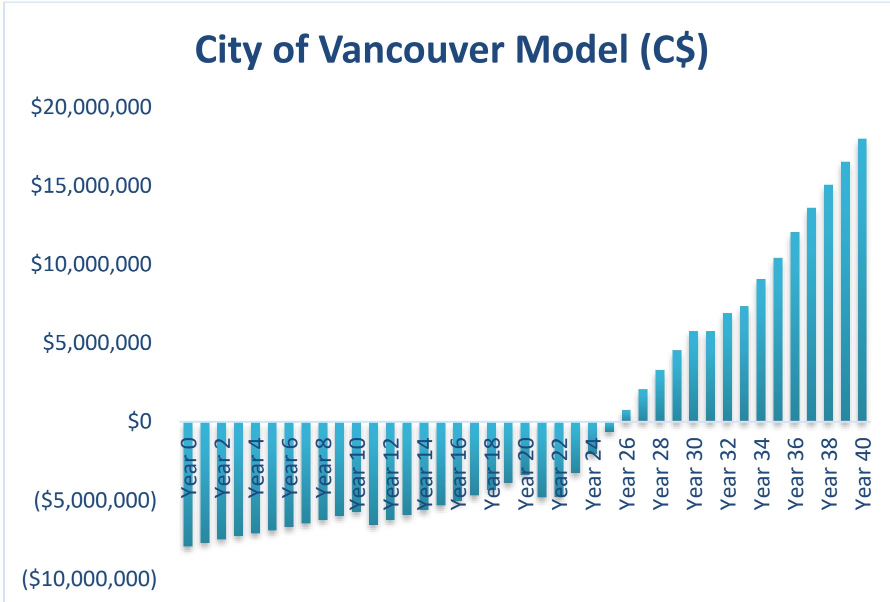

Figure 10 – Profit and loss projections for City of Vancouver model.

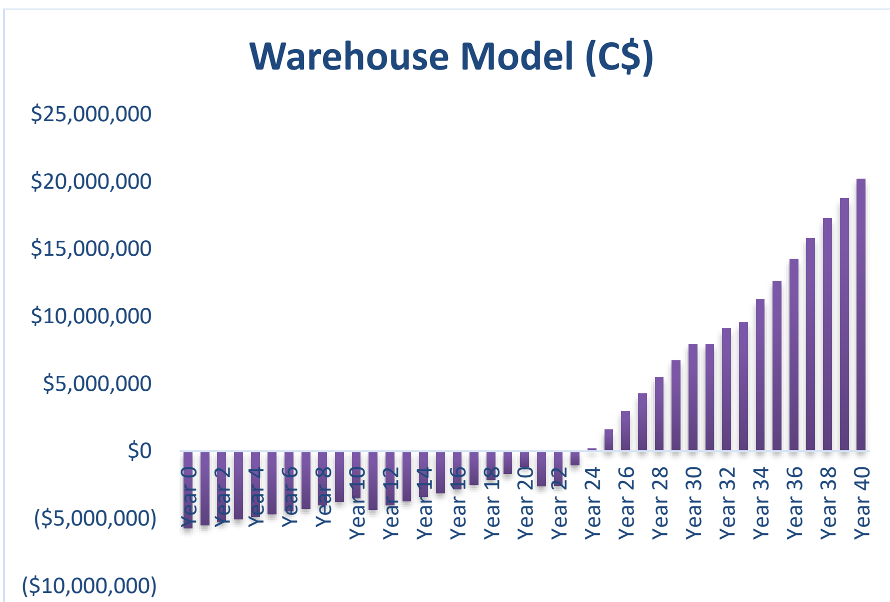

Figure 11 – Profit and loss projections for warehouse model.

The contribution from each source of costs and income is shown in the diagrams that follow:

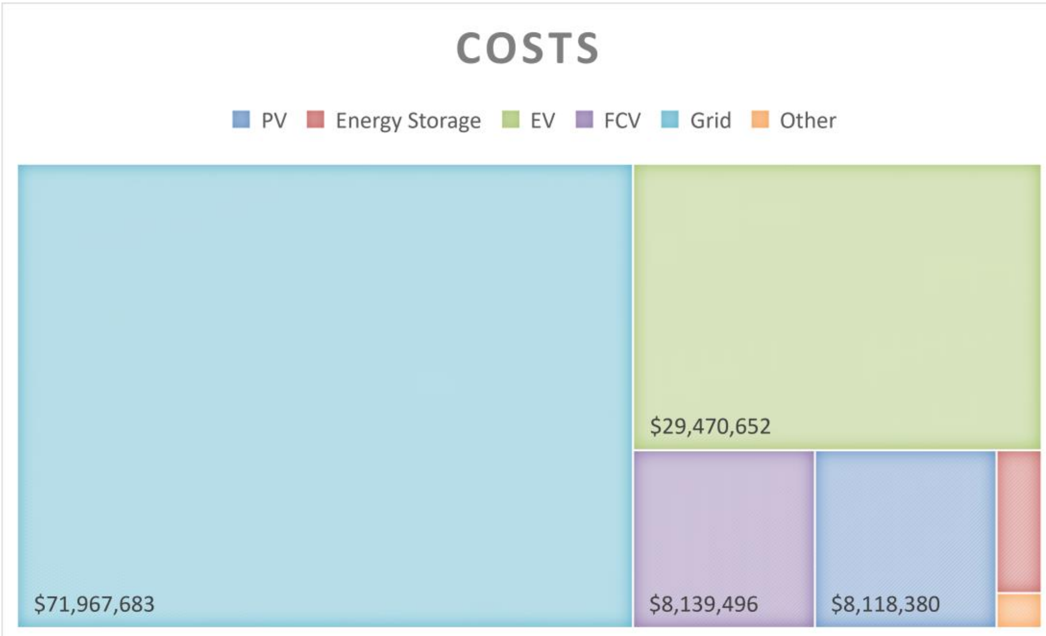

Figure 12 - Costs distribution over project life.

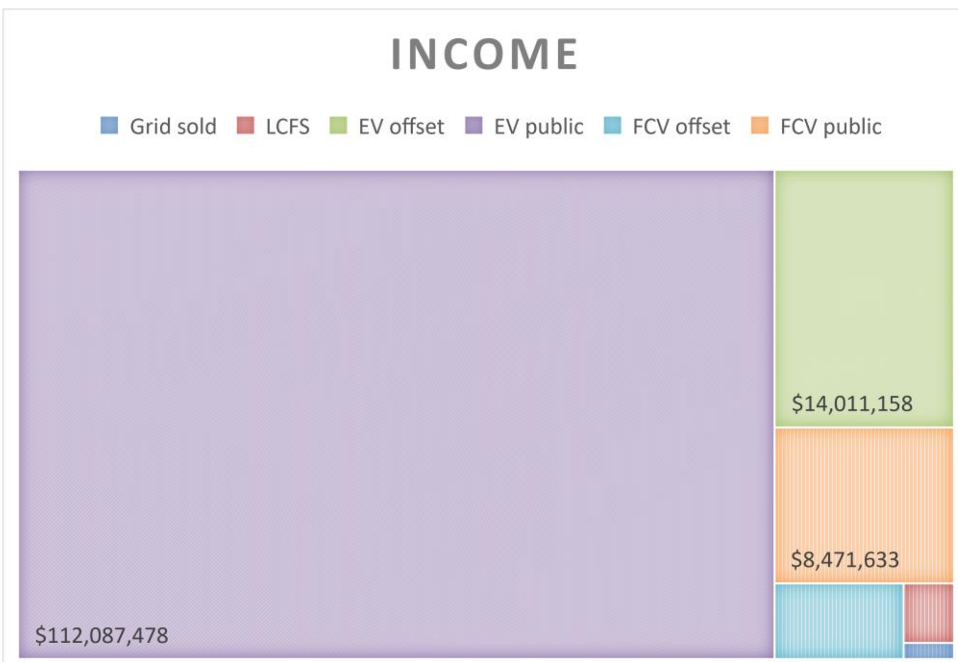

Figure 13 - Income distribution over project life.

Figure 14 and Figure 15 show the energy split for Year 1 and Year 40 respectively. Any value above the 0 line represents the supply, values presented below the 0 line represent a demand. In year 1, PV represents a big portion of the source. But as the year goes by, solar will remain while EV and FCV demand will grow. The extra load will be supplied from the grid, as presented in the Year 40 graph.

The same can be observed with the demand. In Year 1, with low demand from EVs and FCVs, energy will be sent mostly to the grid. But in Year 40 the electrolyzer will demand most of the energy.

For more information on the behavior of these components throughout the year, refer to Table 8 in the Appendices.

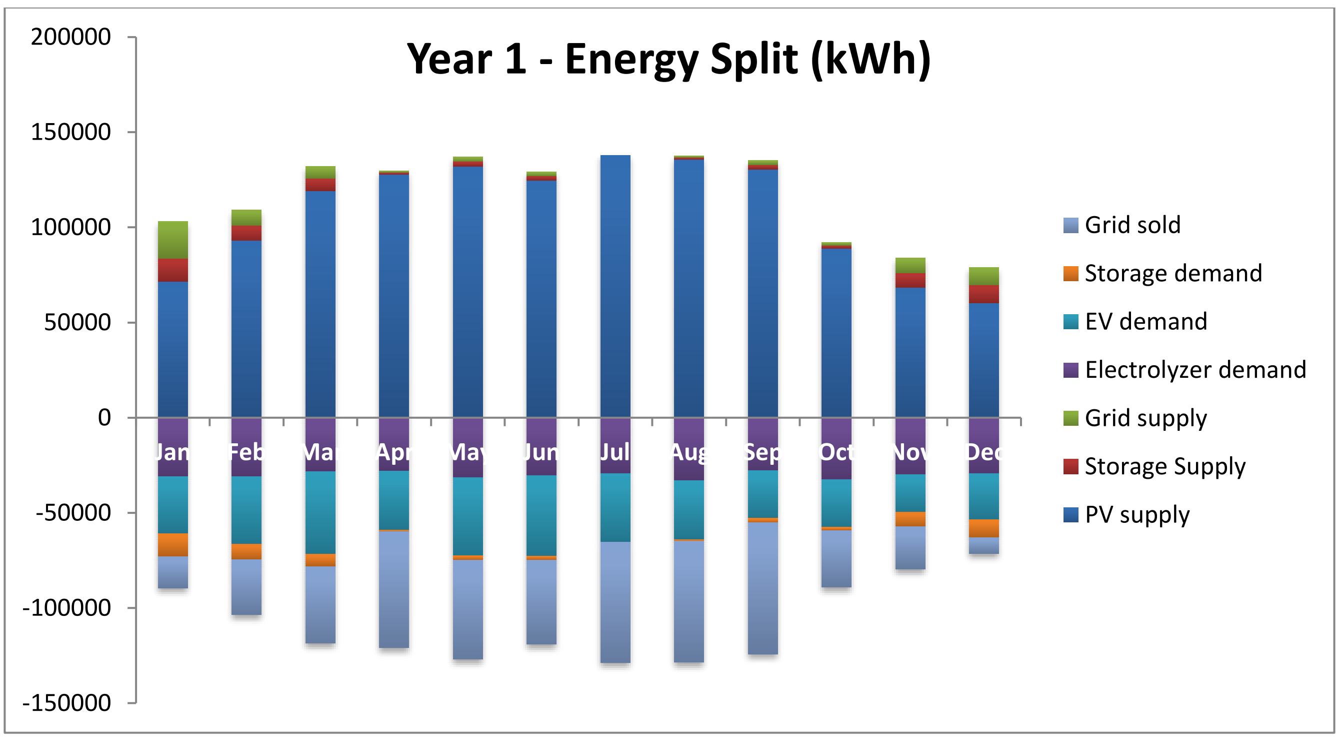

Figure 14 - Energy split by source and demand in Year 1.

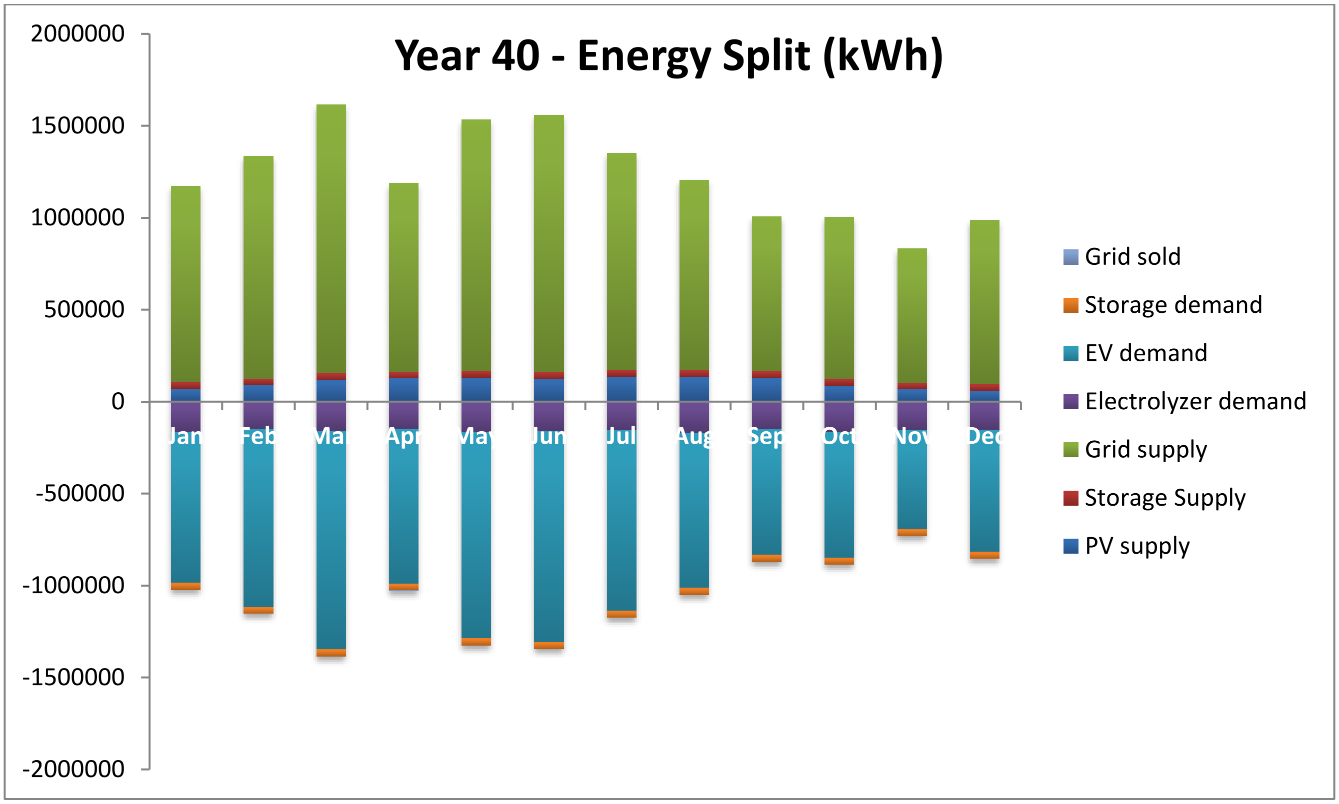

Figure 15 - Energy split by source and demand in Year 40.

The financial model, shown in Table 4 and Table 5 in the Appendices, takes into consideration the following costs:

- Capital costs for each of the components
- O&M costs for each of the components
- Replacement after lifetime of each of the components
- Feedstock costs (electricity and water)

The revenue streams that can be leveraged are:

- Grid offset revenue: Energy produced from PV that is not used in the system will be sent to another part of UBC. UBC will offset the BC Hydro energy cost.
- Low Carbon Fuel Standard (LCFS): UBC will receive credits from the BC government by providing a clean fuel for transportation. They will obtain credits for (1) Building the station, and (2) Per kilogram of Hydrogen refueled.

- Gasoline offset for FCVs and EVs fleet: The ZEVs Fleet will charge for free in the Thunderbird stations, thus offsetting the cost for refueling at a gas station.
- FCVs and EVs public: ZEVs not owned by UBC can charge at UBC at a predetermined rate.

Figure 16 summarizes the tons of CO_2 emissions that will be avoided from the supply of energy from the Thunderbird parkade to ZEVs.

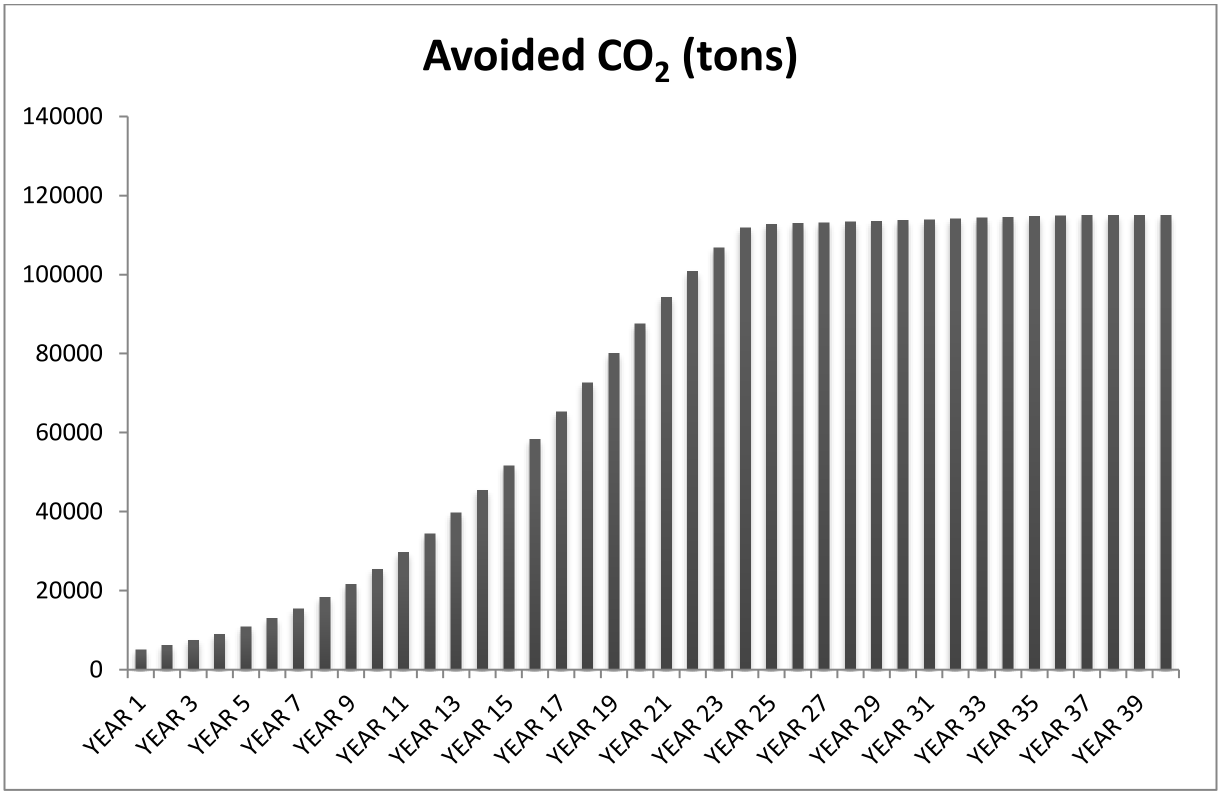

Figure 16 – Tons of CO2 avoided due to public and fleet zero-emission vehicles refueling at Thunderbird Parkade.

7. Conclusions & Significance of Work

Thunderbird parkade presents unused rooftop space that could be valuable for clean energy generation and a way to incentivize clean transportation. Thunderbird parkade would serve as a unique test ground for a microgrid that integrates PV with EV charging stations, hydrogen charging station and energy storage, while connected to the grid. Therefore, modelling and finding the optimal process and the optimal sizes and quantities to maximize Net Present Value is important to analyze the viability of the project.

After running the model with different scenarios, the following conclusions were made:

Modelling the project helped to understand that as the time of the project advances, the project will depend more on the grid for electricity (See Table 8 in the Appendices). This dependency on the grid makes the project sensitive to the cost of electricity. This is part of the reason there is a sizeable change in NPV from the optimized UBC model to the City of Vancouver model since the cost of selling electricity back to the grid is different.

Charging a fee for public electric vehicles represents more than half of the overall income. This opens up possibilities to leverage this revenue source but also uncertainty since the cost of EV charging in the free market has not been firmly established yet.

Although the optimized UBC model breaks even after 26 years, this is a similar break-even period compared to other solar projects in the Vancouver area (Vancouver Sun, 2017). There are 2 reasons that the breakeven point is after 26 years in Vancouver: (1) Relatively low solar potential, (2) Relatively low cost of electricity. However, given the project life of 40 years, this is still a sensible investment.

This analysis demonstrates that not only can a positive NPV be obtained, infrastructure can be built that will pay for itself with the expanding popularity of zero-emission vehicles. In addition, almost two million tons of CO_2 will be avoided from being emitted to the environment over the course of the project lifetime. This analysis can serve as a starting point for further analysis on the financial viability of microgrids, implementation of Low Carbon Fuel Credits and connecting renewable energy generation to transportation.

8. Recommendations

The analyses discussed in this report present data retrieved from different sources. To verify the accuracy of our model and to refine the uncertainties, here are the recommendations for future work:

1) Refine values for EV charging cost with local EV charging station owners and validate assumptions.
2) Consult with BC Hydro the validity of the Standing Offer program or its replacement and validate the sellback price of electricity for a microgrid in the city.
3) Evaluate the effects of the Low carbon fuel credits on the financial model if the policy was based on capacity produced rather than hydrogen used as in British Columbia.

9. References

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10. Appendices

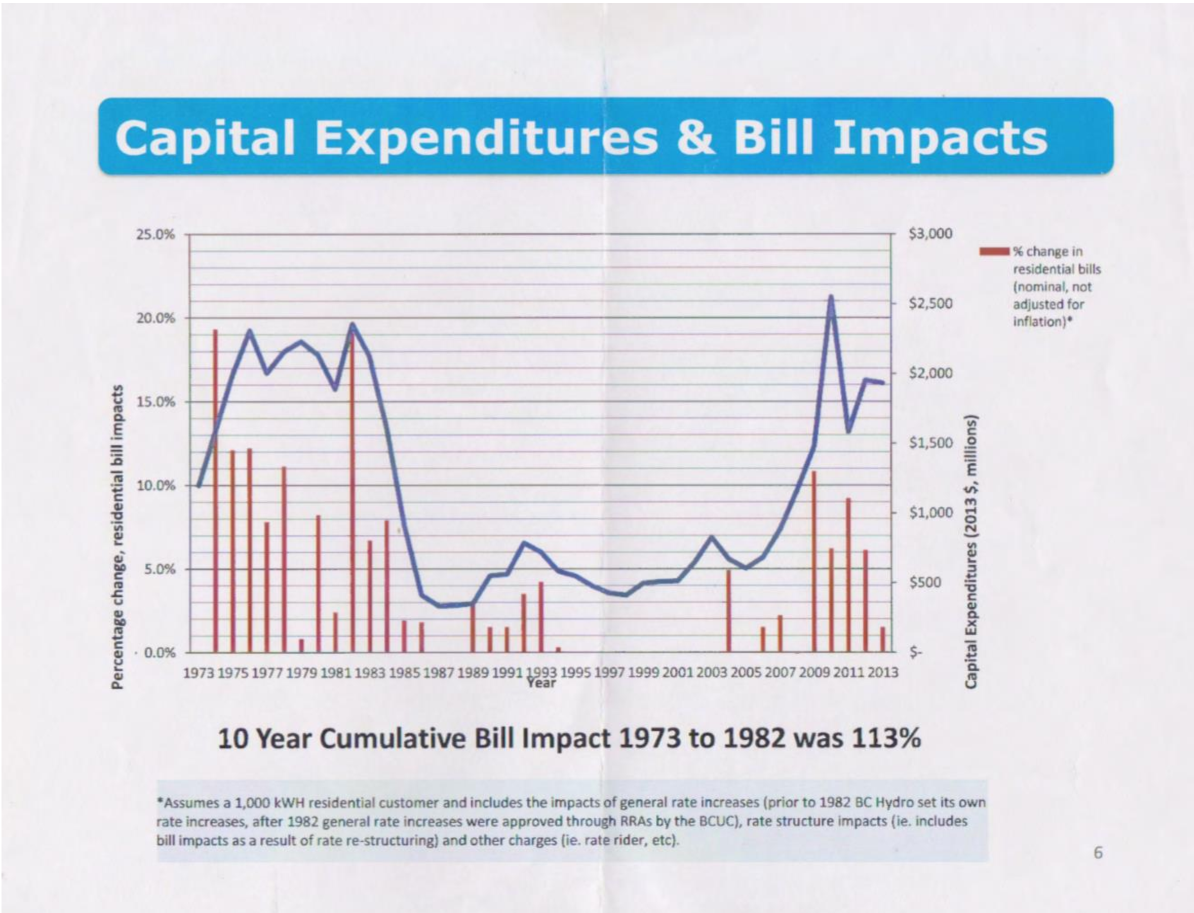

Figure 17 – Historical capital expenditures and bill impacts (BC Hydro, 2013)

Table 1 – List of sources for assumptions

Data	Value	Source
PV voltage	1 000 V	http://solarenergy.advanced-energy.com/upload/File/Application%20Notes/ENG-600vor1000V-260-02.pdf
PV capital cost	CA$ 3.8 /W inst.	SPCC research
ES output efficiency	99%	https://batteryuniversity.com/learn/article/comparing_the_battery_with_other_power_sources
ES capital cost	US$ 209 /kWh	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf
ES degradation rate	30% every 10 years	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf
EV efficiency	0.175 kWh / km	https://pushevs.com/2016/11/23/electric-cars-range-efficiency-comparison/
EV charging station lifetime	10 years	Charge point
EV 7.4 kW capital cost	CA$ 13 889 /unit	Charge point
EV 62.5 kW capital cost	CA$ 52 378 /unit	Charge point
EV 125 kW capital cost	CA$ 96 566 /unit	Charge point
Electrolyzer energy input	5.2 kWh/Nm3 H2	Hydrogenics
Compressor energy input	2.7 kWh/kg	H2 CSD technical status and costs (energy.gov)
Storage capital cost	US$ 242 500	H2 CSD technical status and costs (energy.gov)
Dispenser capital cost	US$ 200 500	H2 CSD technical status and costs (energy.gov)
100 kg electrolyzer capital cost	US$ 321 205	Current Forecourt Hydrogen Production from PEM Electrolysis (energy.gov)
H2 compression, storage & cooling unit	CA$ Disclosed	RFP
H2 CSD O&M costs	US$ 0.54 / kg	Electrolyzer O&M costs report
Electrolyzer O&M costs	US$ 0.4 / kg	Electrolyzer O&M costs report
H2 vehicle capacity	5 kg	https://www.toyota-europe.com/download/cms/euen/13096%20MIR_40_MAST_WEB_tcm-11-1150380.pdf
H2 truck capacity	40 kg	https://www.forbes.com/sites/markewing/2017/08/09/toyotas-hydrogen-fuel-cell-kenworth-can-revolutionize-heavy-transport/#13f99a776e48
H2 compressor lifetime	10 years	H2 CSD technical status and costs (energy.gov)
H2 storage lifetime	30 years	H2 CSD technical status and costs (energy.gov)
H2 dispenser lifetime	10 years	H2 CSD technical status and costs (energy.gov)
H2 electrolyzer lifetime	20 years	Electrolyzer O&M costs report
LCFS	0.0245 credits / kg	https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/pathway_assessment_2017.pdf
Cost of credit	CA$ 163.9 / credit	https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/pathway_assessment_2017.pdf
Electrolyzer voltage	3 x 480 V	Hydrogenics
Compressor voltage	480 V	RFP
Mileage gasoline vehicles	25 km / kg	https://www.forbes.com/sites/lauriewinkless/2016/06/01/are-hydrogen-fuel-cell-cars-becoming-normal/#894d77a683a0
Mileage H2 vehicles	100 km / kg	https://www.forbes.com/sites/lauriewinkless/2016/06/01/are-hydrogen-fuel-cell-cars-becoming-normal/#894d77a683a0
Price of gasoline	CA$ 1.51 / liter	https://www.expatistan.com/price/gas/vancouver
Gasoline escalation	Forecast	https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=1810000101#timeframe
H2 charging fee	CA$ 12.75 / kg	Shell charging station
Transformer & inverter efficiency	98%	http://pgembeddedsystems.com/securelogin/upload/project/IEEE/41/PG2013PE0026/Copy%20(4)%20of%20ok%20(2).pdf
Discount rate	6%	https://pdfs.semanticscholar.org/5638/1456a69973e99369f9079cb8f6bab9d25952.pdf
Inflation rate	2%	https://pdfs.semanticscholar.org/5638/1456a69973e99369f9079cb8f6bab9d25952.pdf
EV adoption rate year 1	27.50%	https://www.fleetcarma.com/electric-vehicle-sales-canada-2017/
EV charging fee year 1	CA$ 0.35 / kWh	https://pluginbc.ca/charging-stations/public-charging/
FCV adoption rate year 1	60%	https://www.statista.com/statistics/644545/global-sales-of-fuel-cell-vehicles/

Table 2 – Model data for electric vehicle infrastructure over 40-year project life

	EV					Other		
	General	Station	Public	Fleet		Grid		ES
	Escalation rate	EV stations (units)	EV charging fee (CAD/kWh)	EV Fleet (units)	EV gasoline fleet offset revenue (CAD/kWh)	Energy cost from grid (CAD/kWh)	Selling revenue to grid	Energy Storage Capacity (kWh)
Year 1		24	$ 0.35	22	0.47	0.119	0.119	100.00
Year 2	27.5%	24	$ 0.35	27	0.48	0.120	0.120	96.84
Year 3	26.5%	27	$ 0.36	32	0.49	0.121	0.121	93.68
Year 4	25.5%	34	$ 0.36	37	0.54	0.123	0.123	90.53
Year 5	24.5%	42	$ 0.36	42	0.52	0.124	0.124	87.37
Year 6	23.5%	51	$ 0.37	47	0.53	0.125	0.125	84.21
Year 7	22.5%	63	$ 0.37	52	0.54	0.126	0.126	81.05
Year 8	21.5%	76	$ 0.37	57	0.56	0.127	0.127	77.89
Year 9	20.5%	91	$ 0.38	62	0.57	0.129	0.129	74.74
Year 10	19.5%	110	$ 0.38	67	0.58	0.130	0.130	71.58
Year 11	18.5%	131	$ 0.39	72	0.59	0.131	0.131	68.42
Year 12	17.5%	155	$ 0.39	77	0.60	0.132	0.132	65.26
Year 13	16.5%	182	$ 0.39	82	0.62	0.134	0.134	62.11
Year 14	15.5%	212	$ 0.40	87	0.63	0.135	0.135	58.95
Year 15	14.5%	243	$ 0.40	92	0.64	0.136	0.136	55.79
Year 16	13.5%	277	$ 0.41	97	0.65	0.138	0.138	52.63
Year 17	12.5%	311	$ 0.41	102	0.66	0.139	0.139	49.47
Year 18	11.5%	346	$ 0.41	107	0.68	0.140	0.140	46.32
Year 19	10.5%	382	$ 0.42	112	0.69	0.142	0.142	43.16
Year 20	9.5%	419	$ 0.42	117	0.70	0.143	0.143	40.00
Year 21	8.5%	454	$ 0.43	122	0.71	0.145	0.145	100.00
Year 22	7.5%	510	$ 0.43	127	0.72	0.146	0.146	96.84
Year 23	6.5%	510	$ 0.43	132	0.74	0.147	0.147	93.68
Year 24	5.5%	510	$ 0.44	137	0.75	0.149	0.149	90.53
Year 25	5%	510	$ 0.44	142	0.76	0.150	0.150	87.37
Year 26	1%	510	$ 0.45	147	0.77	0.152	0.152	84.21
Year 27	0%	510	$ 0.45	152	0.78	0.153	0.153	81.05
Year 28	0%	510	$ 0.46	157	0.80	0.155	0.155	77.89
Year 29	0%	510	$ 0.46	162	0.81	0.156	0.156	74.74
Year 30	0%	510	$ 0.46	167	0.82	0.158	0.158	71.58
Year 31	0%	510	$ 0.47	172	0.83	0.159	0.159	68.42
Year 32	0%	510	$ 0.47	177	0.84	0.161	0.161	65.26
Year 33	0%	510	$ 0.48	182	0.86	0.163	0.163	62.11
Year 34	0%	510	$ 0.48	187	0.87	0.164	0.164	58.95
Year 35	0%	510	$ 0.49	192	0.88	0.166	0.166	55.79
Year 36	0%	510	$ 0.49	197	0.89	0.167	0.167	52.63
Year 37	0%	510	$ 0.50	200	0.90	0.169	0.169	49.47
Year 38	0%	510	$ 0.50	200	0.92	0.171	0.171	46.32
Year 39	0%	510	$ 0.51	200	0.93	0.172	0.172	43.16
Year 40	0%	510	$ 0.51	200	0.94	0.174	0.174	40.00

Table 3 – Model data for hydrogen components over 40-year project life

	FCV								
	General		Public		Fleet			Electrolyzer	
	FCV escalation rate	LCFS (credits / kg)	FCV public (units/week)	H2 charging fee (CAD / kg)	FCV fleet (units/week)	FC trucks fleet (units/week)	H2 gasoline fleet offset revenue (CAD/kg)	Electrolyzer capacity (kg/day)	Optimal quantity (kg)
Year 1		0.0245	0.0	12.8	15	1	8.20	100	55
Year 2		0.02448	1.0	12.8	15	1	8.40	100	55
Year 3	60.0%	0.02448	1.6	12.62	15	1	8.61	100	55
Year 4	55.0%	0.02448	2.5	12.62	15	1	9.46	100	55
Year 5	50.0%	0.02448	3.7	12.50	15	1	9.10	100	55
Year 6	45.0%	0.02448	5.4	12.50	15	1	9.31	100	55
Year 7	40.0%	0.02448	7.6	12.37	15	1	9.52	100	55
Year 8	35.0%	0.02448	10.2	12.37	15	1	9.73	100	60
Year 9	30.0%	0.02448	13.3	12.50	15	1	9.94	100	60
Year 10	25.0%	0.02448	16.6	12.50	15	1	10.15	100	60
Year 11	24.0%	0.02448	20.5	12.62	20	1	10.35	100	65
Year 12	23.0%	0.02448	25.3	12.62	20	1	10.56	100	65
Year 13	22.0%	0.02448	30.8	12.75	20	1	10.77	100	70
Year 14	21.0%	0.02225	37.3	12.75	20	1	10.98	100	70
Year 15	20.0%	0.02003	44.8	12.88	20	1	11.19	100	75
Year 16	19.0%	0.01780	53.3	12.88	20	1	11.40	100	80
Year 17	18.0%	0.01558	62.9	13.01	20	1	11.61	100	85
Year 18	17.0%	0.01335	73.5	13.01	20	1	11.82	100	90
Year 19	16.0%	0.01113	85.3	13.13	20	1	12.03	100	95
Year 20	15.0%	0.00890	98.1	13.13	20	1	12.24	100	100
Year 21	14.0%	0.00668	111.8	13.26	30	2	12.45	500	200
Year 22	13.0%	0.00445	126.4	13.26	40	2	12.66	500	200
Year 23	12.0%	0.00223	141.5	13.13	50	2	12.87	500	200
Year 24	11.0%	0.00000	157.1	13.13	60	2	13.08	500	200
Year 25	10.0%	0.00000	172.8	13.01	70	2	13.29	500	250
Year 26	9.0%	0.00000	188.4	13.01	80	2	13.50	500	250
Year 27	8.0%	0.00000	203.4	12.88	90	2	13.71	500	300
Year 28	7.0%	0.00000	217.7	12.88	100	2	13.92	500	300
Year 29	6.0%	0.00000	230.7	12.75	110	2	14.13	500	350
Year 30	5.0%	0.00000	242.3	12.75	120	2	14.34	500	350
Year 31	5.0%	0.00000	254.4	12.62	130	2	14.55	500	350
Year 32	5.0%	0.00000	267.1	12.62	140	2	14.76	500	400
Year 33	5.0%	0.00000	280.5	12.50	150	2	14.97	500	400
Year 34	5.0%	0.00000	294.5	12.50	160	2	15.18	500	450
Year 35	5.0%	0.00000	309.2	12.37	170	2	15.39	500	450
Year 36	5.0%	0.00000	324.7	12.37	180	2	15.60	500	450
Year 37	5.0%	0.00000	340.9	12.24	190	2	15.81	500	500
Year 38	5.0%	0.00000	357.9	12.24	200	2	16.02	500	500
Year 39	5.0%	0.00000	375.8	12.11	200	2	16.23	500	500
Year 40	5.0%	0.00000	394.6	12.11	200	2	16.44	500	500

Table 4 – Initial investments for microgrid components

Initial Investment (CA$)			
Solar	Superstructure	-$	2,200,000.00
	Solar Panels	-$	3,500,000.00
	Microgrid charge controller	-$	30,000.00
	Inverters	-$	433,000.00
	Transformers	-$	77,805.00
Energy storage	Batteries	-$	27,170.00
EV	Stations	-$	458,857.00
FCV	Electrolyzer	-$	417,566.50
	Electrolyzer Installation	-$	50,107.98
	Hydrogen Compression Storage & Cooling Unit	-$	977,255.76
	Storage	-$	315,250.00
	Dispenser	-$	260,650.00
	CSD Installation	-$	543,604.52
Indirect	Site Preparation	-$	50,000.00
	Engineering & Design	-$	50,000.00
	Interconnection study	-$	300,000.00

Table 5 – Operations and maintenance costs over 40-year project life

	O&M		Replacement								
	FCV		Solar			ES	EV	FCV			
	Electrolyzer	CSD station	Solar Panels	Inverters	Transformers	Batteries	Stations	Electrolyzer	Compressor	Storage	Dispenser
Year 1	-3,265	-4,198	0	0	0	0	0	0	0	0	0
Year 2	-3,407	-4,381	0	0	0	0	0	0	0	0	0
Year 3	-3,492	-4,490	0	0	0	0	0	0	0	0	0
Year 4	-3,617	-4,651	0	0	0	0	0	0	0	0	0
Year 5	-3,794	-4,878	0	0	0	0	0	0	0	0	0
Year 6	-4,032	-5,183	0	0	0	0	0	0	0	0	0
Year 7	-4,338	-5,578	0	0	0	0	0	0	0	0	0
Year 8	-4,714	-6,061	0	0	0	0	0	0	0	0	0
Year 9	-5,148	-6,619	0	0	0	0	0	0	0	0	0
Year 10	-5,619	-7,225	0	0	0	0	0	0	0	0	0
Year 11	-6,894	-8,864	0	-433,000	-101,147	0	-569,969	0	-977,256	0	-260,650
Year 12	-7,565	-9,727	0	0	0	0	0	0	0	0	0
Year 13	-8,355	-10,742	0	0	0	0	0	0	0	0	0
Year 14	-9,275	-11,925	0	0	0	0	-41,667	0	0	0	0
Year 15	-10,335	-13,288	0	0	0	0	-135,712	0	0	0	0
Year 16	-11,544	-14,842	0	0	0	0	-149,601	0	0	0	0
Year 17	-12,906	-16,593	0	0	0	0	-163,490	0	0	0	0
Year 18	-14,424	-18,546	0	0	0	0	-243,646	0	0	0	0
Year 19	-16,096	-20,695	0	0	0	0	-257,535	0	0	0	0
Year 20	-17,914	-23,033	0	0	0	0	-285,313	0	0	0	0
Year 21	-22,421	-28,827	-175,000	-433,000	-131,490	-27,170	-1,032,004	-2,087,833	-4,886,279	-1,261,000	-1,303,250
Year 22	-25,907	-33,309	0	0	0	0	-489,813	0	0	0	0
Year 23	-29,481	-37,904	0	0	0	0	-614,157	0	0	0	0
Year 24	-33,113	-42,574	0	0	0	0	-735,980	0	0	0	0
Year 25	-36,765	-47,269	0	0	0	0	-954,369	0	0	0	0
Year 26	-40,395	-51,936	0	0	0	0	-899,470	0	0	0	0
Year 27	-43,956	-56,514	0	0	0	0	-993,515	0	0	0	0
Year 28	-47,399	-60,941	0	0	0	0	-990,994	0	0	0	0
Year 29	-50,674	-65,153	0	0	0	0	-1,018,772	0	0	0	0
Year 30	-53,733	-69,086	0	0	0	0	-1,060,439	0	0	0	0
Year 31	-56,874	-73,124	0	-433,000	-170,938	0	-1,903,696	0	-4,886,279	-315,250	-1,303,250
Year 32	-60,101	-77,273	0	0	0	0	-1,251,050	0	0	0	0
Year 33	-63,419	-81,538	0	0	0	0	-2,007,765	0	0	0	0
Year 34	-66,831	-85,925	0	0	0	0	-735,980	0	0	0	0
Year 35	-70,343	-90,441	0	0	0	0	-954,369	0	0	0	0
Year 36	-73,959	-95,090	0	0	0	0	-899,470	0	0	0	0
Year 37	-77,686	-99,881	0	0	0	0	-993,515	0	0	0	0
Year 38	-81,527	-104,821	0	0	0	0	-990,994	0	0	0	0
Year 39	-84,070	-108,090	0	0	0	0	-1,018,772	0	0	0	0
Year 40	-86,741	-111,524	0	0	0	0	-1,060,439	0	0	0	0

Table 6 – Sensitivity analysis

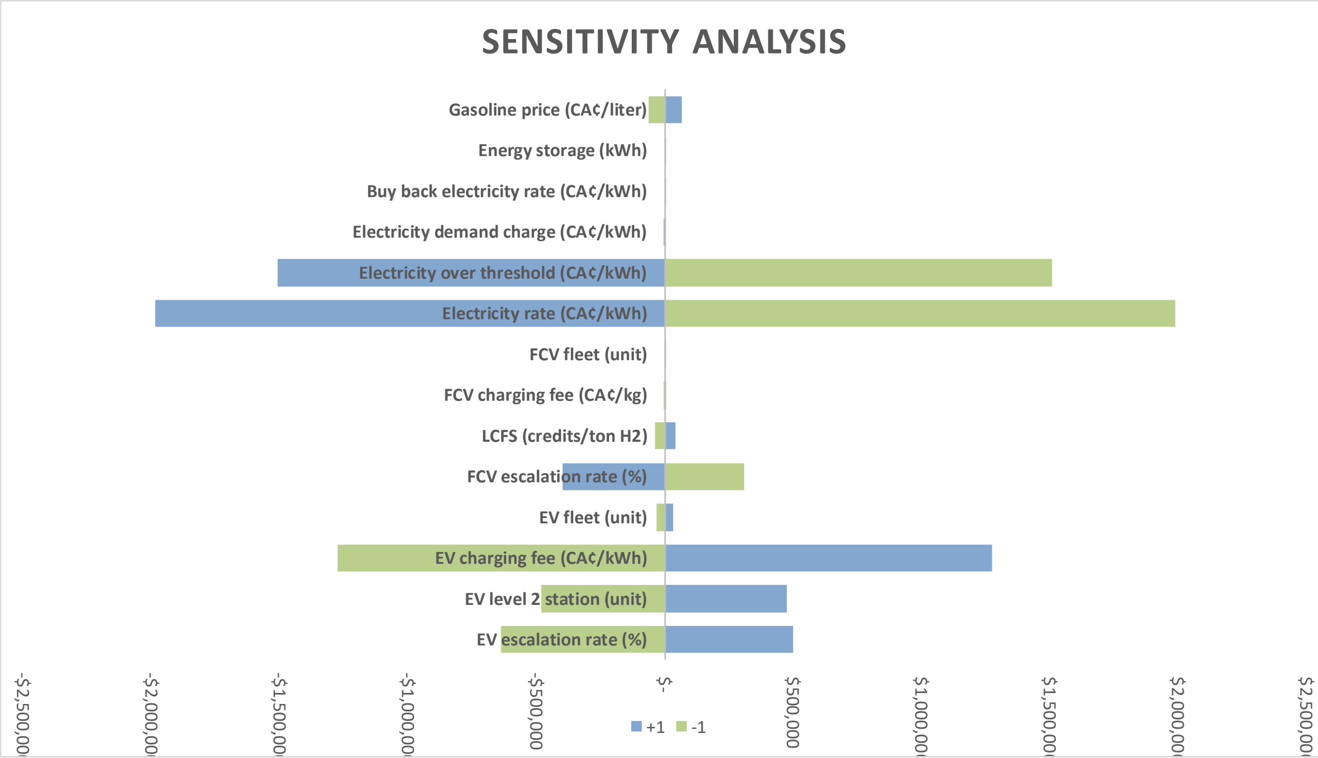

Table 7 – Optimization impact on NPV

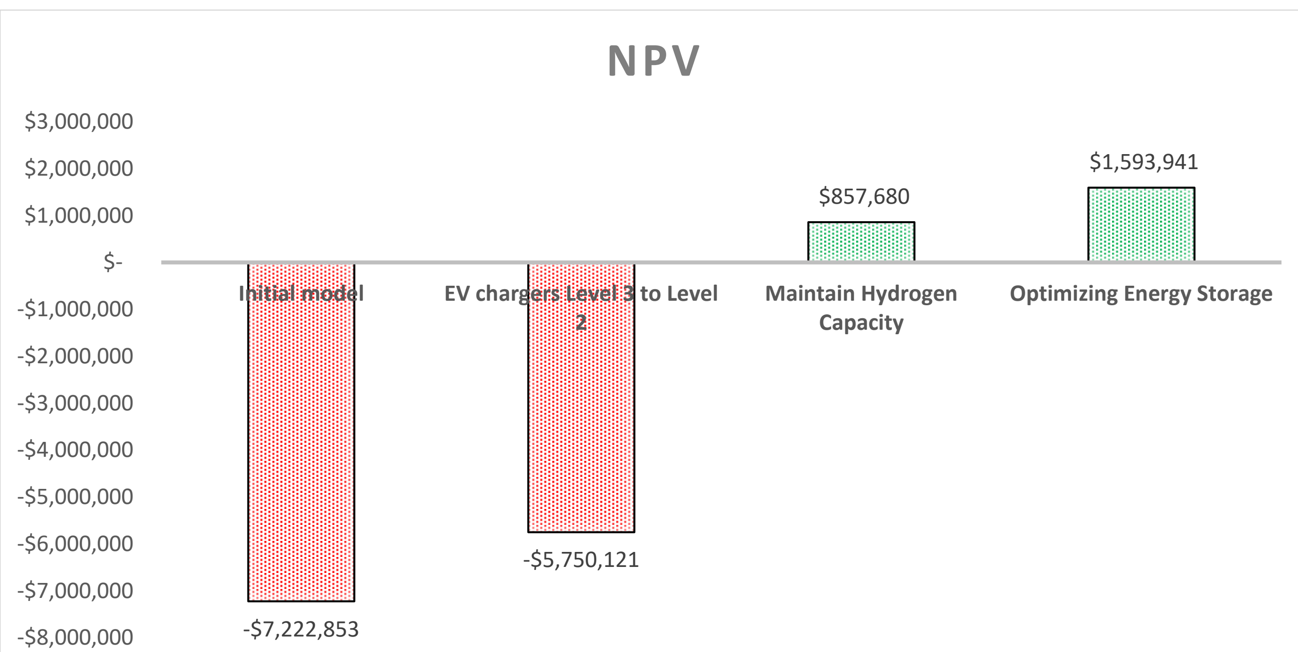

Table 8 – Demand and source of energy throughout the lifetime of the project