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SOLAR PHOTOVOLTAIC ELECTRICITY FOR SINGLE-FAMILY DETACHED HOUSEHOLDS: LIFE CYCLE THINKING-BASED ASSESSMENT

Piyaruwan Perera[1] , Kasun Hewage[2,5] , Shahria M. Alam[3], , Rehan Sadiq[4]
[1,2,3,4] School of Engineering, University of British Columbia (Okanagan Campus), Canada
[5] Kasun.Hewage@ubc.ca

Abstract: Electricity generation using solar photovoltaic (PV) can be considered as one of the key low-emission energy technologies that reduce building net operational level emissions compared to the fossil fuels-based energies. Small-scale grid-tie solar (PV) systems are being widely used in many parts of the world. These systems would be benefitted to the investors by reducing household level operational GHG emissions and securing low energy prices for long-term. Solar (PV)–based electricity generation in Canada can be improved immensely to achieve local emission targets while securing healthier energy rates for the consumers. However, there is a lack of knowledge on life cycle impacts of solar (PV)-based electricity generation in single-family detached households in Canadian regions with low-emission grid electricity. The objective of this study is to conduct an investigation to obtain the feasibility of small-scale solar (PV) systems for households in South British Columbia mountain climate region, Canada using life cycle thinking approach. The effect of domestic activities and transportation was used to identify the net energy use of the household throughout its entire life. The life cycle impact assessment and the life cycle cost assessment results were used to compare the impacts of different household alternatives. The results of this study showed that households with solar (PV) systems and electric transportation facilities indicated comparatively lower environmental impacts and higher long-term financial benefits. However, the upfront costs of households with solar systems are relatively high which may have adverse effects on the purchasing decisions. The short-term use of solar (PV) systems may result in higher cost and environmental impacts.

1 INTRODUCTION

Climate change, which is primarily caused by anthropogenic Greenhouse Gas (GHG) emissions, has gained extensive public attention as a key communal issue in the world. In 2015, the Canadian resident sector consumed approximately 17% of national energy and contributed to 14% of the national carbon footprint (NRCan 2016). The use of high-emission electricity and fossil fuels-based energy options for household activities are key causes that increase residential level GHG emissions. According to the literature, there is an immense global interest in studying the use of low-emission renewable technologies to reduce household level emissions (Karunathilake et al. 2016).

The solar photovoltaic (PV) technology that generates electricity using direct sunlight can be identified as the fastest growing renewable energy technology in the world (Branker, Pathak, and Pearce 2011). The annual growth rate of solar (PV) has shown approximately 40% from 2000 to 2010 decade due to the cleanliness and the sustainability nature of the primary energy source (Branker, Pathak, and Pearce 2011). In Canada, the GHG emissions and tariff of grid electricity changes with the location. Technically, the climate regions where the low-emission electricity available should have comparatively low household emissions provided that they use grid electricity as their individual energy source. However, in reality, a majority of the above households use Natural Gas as their primary space heating energy source and Gasoline as their primary transportation fuel due to the high tariff of the low-emission grid electricity. Solar (PV) technology creates a massive opportunity for Canadians to switch to low-emission electricity-based households with permanent electricity prices for the long-term. However, the implementation of solar (PV) systems for Canadian households is still in a juvenile state. At present, several programmes are being conducted by government institutions and utility providers to encourage the general public to purchase and consume solar (PV)-based electricity in order to reduce local environmental impacts and delay potential investment on new electricity generation and distribution infrastructure for growing communities. Despite the developing body of knowledge on this area of research, a real-time observation-based life cycle environmental and economic impacts of grid-tie solar (PV) systems for the single-family detached households (SFDHs) at regions which have low-emission grid-electricity have been overlooked.

This study is focusing on conducting an investigation to obtain the feasibility of small-scale solar (PV) systems for the households in South British Columbia Mountain (S-BC) climate region in Canada using life cycle thinking approach. A comprehensive literature review was conducted to identify key economic and environmental factors that have impacts on the use of domestic grid-tie solar (PV) systems. The effect of domestic activities and transportation was used to identify the net energy use of a household throughout its entire life. The actual data related to the above activities were obtained from Wilden Living Lab (WLL) at Okanagan, BC to conduct the life cycle impact assessment and the life cycle cost assessment. The cost data for small-scale solar (PV) systems were obtained from the local vendors and utility companies. The eco-efficiency assessment method was used to compare the impacts of different household alternatives. The results of this study can be used by building developers, policymakers, practitioners, government and private institutions to encourage the investments on solar (PV) grid-tie systems for new and existing households to reduce emissions and increase financial benefits in the long-run.

2 LITERATURE REVIEW

Over the past few years, solar(PV)-based energy generation for urban communities has become an important aspect to reduce the community-based emissions to the national inventory (Karunathilake et al. 2016). A comprehensive literature review revealed that there are several advantages of solar (PV) electricity generation for residential sector buildings. There are, 1) Enhance energy security in the domestic sector, 2) Fix the long-term electricity prices and by pass future changes of grid electricity tariff, 3)Support existing electricity grid and reduce the need of new grid infrastructure for growing communities, and 4)Reduce primary energy-based emission drastically by generating low-emission solar-based electricity (Karunathilake et al. 2016) (Perera, Kumar, and Rana 2018).

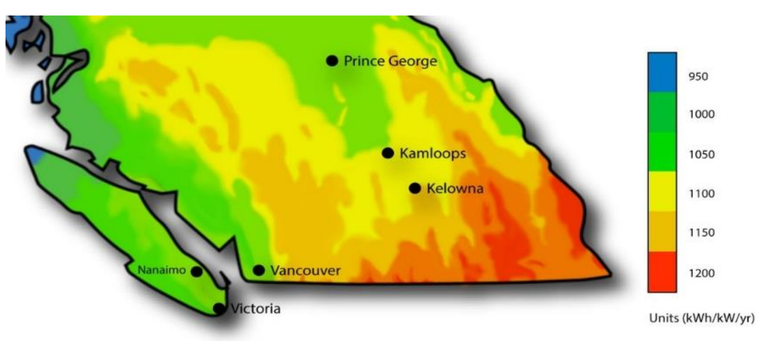

Figure 1: South British Columbia Mountains climate region solar energy map (energyhub.org 2017)

The efficiency of the solar (PV) electricity generation tends to be varied with the location due to solar densities of the area. Figure 1 shows the solar densities of S-BC climate region where the low-emission grid electricity is also available. According to energyhub.org, the solar (PV) electricity generation in S-BC is varying from 1004 kWh/kW/year (energyhub.org 2017) to1133 kWh/kW/year (Compass Renewable Energy Consulting Inc. 2015) (NRCan 2017).Over the last decade, electricity rates have increased on average by 5% per year (BC Hydro 2016). Given the need to maintain the current electricity infrastructure and the cost of new generation, electricity prices will continue to increase in the future too. Therefore, solar (PV) technology can be considered as a long-term solution to

avoid future electricity rate hypes. Furthermore, the solar (PV) capital cost (purchasing and installation cost) has decreased drastically within the last few years. According to Compass Renewable Energy Research Inc, the above costs of solar (PV) systems would be further decreased with a rate of 2.5% per year (Compass Renewable Energy Consulting Inc. 2015). There are few basic requirements that need to be fulfilled for Solar (PV) ready households, 1) Additional dead load required to mount solar (PV) system, South facing orientation would be the best orientation for maximum solar (PV)-based electricity generation, 3)15^0 to 56^0 roof pitches need to be maintained to minimize snow build up on the Solar (PV) array, and 4) The area would not be significantly shaded by surrounding buildings/mature trees at any time of the year.
There are numerous studies are being conducted to assess the building level implementation feasibility of solar (PV) systems in Canada and the rest of the world (Charron and Athienitis 2006) (Charron and Athienitis 2006) (Karunathilake et al. 2016). The implementation of renewable energy-based systems such as solar (PV) has a significant impact on location-based environmental, economic and social factors (Barrington-leigh and Ouliaris 2017) (Karunathilake et al. 2016). Therefore, it is important to assess the localized costs and environmental factors to develop an evident-based approach to find the feasibility of solar (PV) technology for micro-grid applications. As there are huge environmental benefits from electric vehicles in the regions with low-emission grid electricity, it is needed to investigate the aforementioned impacts of all the activities including domestic and transportation to reduce regional GHG impacts at the lowest possible cost (Perera et al. 2018). The life cycle-based thinking can provide long-term and short-term environmental and economic impacts of products and processes which can be compared using eco-efficiency analysis (Perera, Hewage, et al. 2017).

2.1 Eco-efficiency

The eco-efficiency concept is used to increase the value of product while reducing their environmental impacts (Huppes and Ishikawa 2007). Brattebo et al. (2005) introduced eco-efficiency method using life cycle-based thinking approach. Accordingly, eco-efficiency can be further described as the combined effect of environmental and economic cost and benefits of a particular product or product system through its entire life cycle (Brattebø 2005). Eq. 1 can be used to calculate the eco-efficiency ratio.

$$[1]\ \text{Eco} - \text{efficiency Ratio} = \frac{\text{LCC}}{\text{LCA}}$$

2.1.1 Life cycle assessment (LCA)

LCA have being used in decision making process to identify and evaluate the environmental performance of products or processes (Bianchini and Hewage 2012). According to USEPA (1995), LCA is a methodology to assess the potential emissions of a product or a process considering its entire life cycle, from cradle to grave. Figure 2 shows the LCA framework for a typical household.

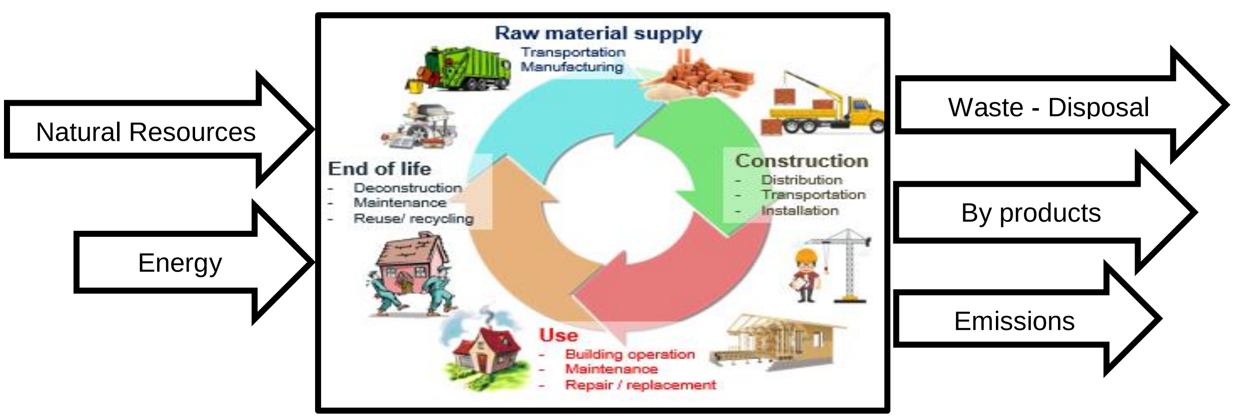

Figure 2: LCA framework

SimaPro database and the LCA software, Athena impact estimator and Building for Environmental and Economic Sustainability (BEES), are the commonly used software in North America to assess the life cycle impacts of a product or a process (Han and Srebric 2011) (Perera, Hewage, et al. 2017). The mid-point indicators such as global warming potential (GWP), stratospheric ozone depletion (SOD), acidification of land and water (ALW), eutrophication (EN), tropospheric ozone formation (TOF) and depletion of non-renewable energy resources (DNR) can be used in identifying potential environmental impacts (Yeheyis et al. 2013) (Ahamed et al. 2016) (Perera, Hewage, et al. 2017). Moreover, the BEES weight schemes can be used to aggregate the above environmental impacts and quantify an environmental score for each alternative (Cooper 2007) (Perera, Hewage, et al. 2017).

2.1.2 Life cycle cost (LCC)

LCC can be used to calculate the cost of ownership of an asset (Analysis 2006). This can be further defined as the external and internal cost related to a product in its total life span (Warren 1994). For an example, the LCC of a building asset consists of building construction cost and the net present worth of recurrence maintenance cost, operation cost, and end-of-life costs (Mirzadeh et al. 2013). According to literature, LCC can be calculated as per the Eq. 2 and the net present worth of future costs can be calculated as per Eq. 3 (Megan Davis 2005).

$$[2]\ \mathrm{LCC} = \mathrm{CI} + \mathrm{NPV}\,(\mathrm{operational}) - \mathrm{NPV}\,(\mathrm{end\_of\_life})$$

Where, *CI* - *Capital investment (Ex. Construction & manufacturing cost, labour, taxes etc.)*
NPV ($_{operational}$) - *Net present worth of operational cost through out its life cycle*
NPV ($_{end\_of\_life}$) - *Net present worth of end-of-life cost (Ex. Recycle cost, disposal cost etc.)*

$$[3]\ \mathrm{NPV}(\mathrm{i}, \mathrm{N}) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

Where: *NPV* - *Net present worth*; *i* - *Discount rate*
R_t - *Net cash flow*; *N* - *Study period*
t - *Time of the cash flow*

3 METHODOLOGY

The research methodology of this study is shown as Figure 3.

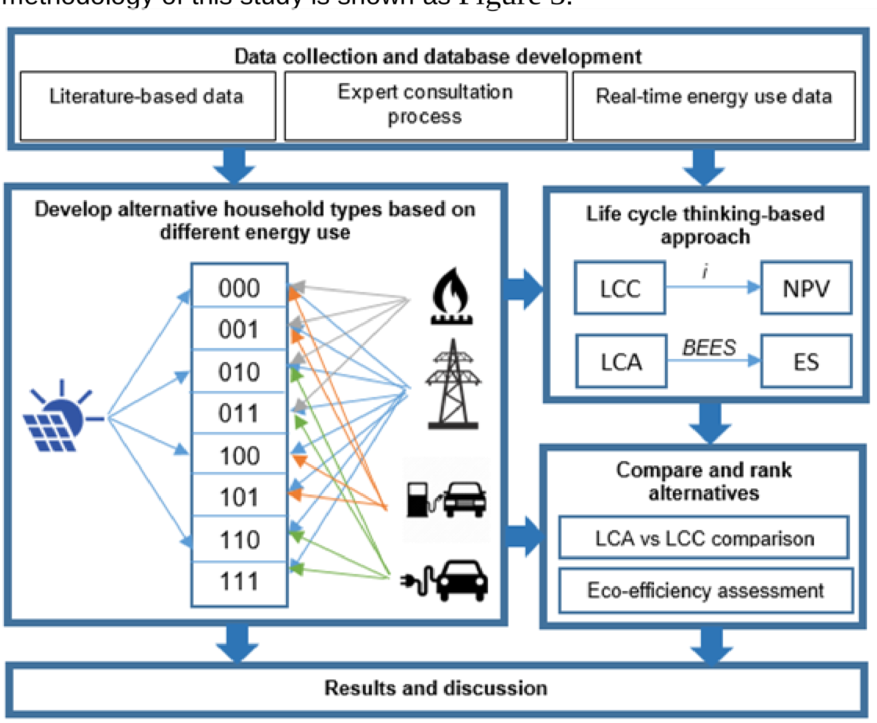

Figure 3: Research framework

The above methodology can be further explained as follows,

3.1 Data collection and database development

The literature-based data, data acquired from expert consultation and real-time monitoring data were collected and those were used to develop a database which can be used in future studies. Following are the key data collected from different sources,

- Literature-based data: Local environmental and economic factors were obtained from institutional reports and online resources published by local utility providers, solar (PV) system characteristics were obtained from the previous studies, Life cycle inventory and mid-point indicators were collected from SimaPro and Athena Impact Estimator databases
- Data acquired from Expert Consultation process: Local solar (PV) costs and other construction costs with installation data were collected from the local developers and vendors.
- Real-time monitoring data: Actual energy set-points, household energy consumption data, solar (PV) generation, and consumer behavioral data were collected from Wilden Living Labs.

3.2 Define alternative households considering different energy use

Typical household alternatives were identified considering the different sources of domestic energy and transportation energy. The selection of those alternatives can be shown in Figure 4.

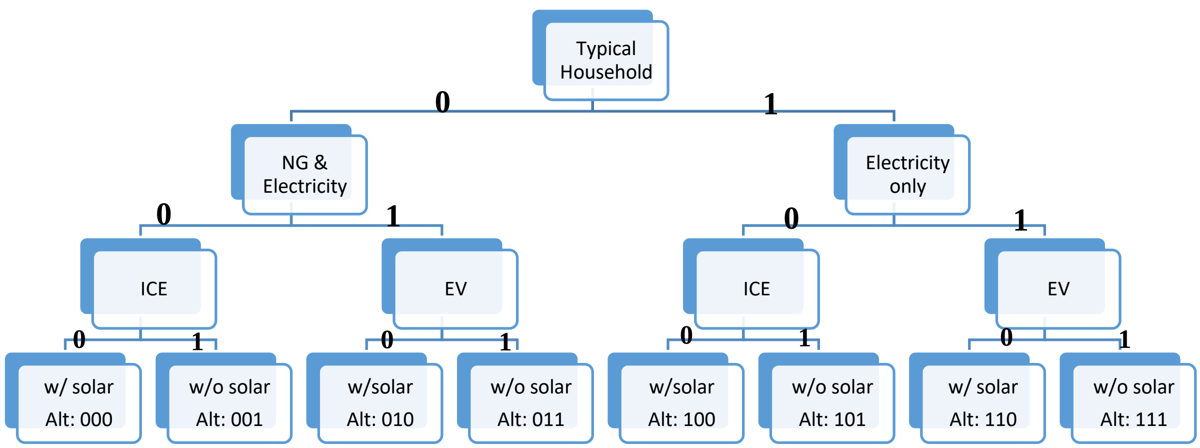

Figure 4 – Alternative households considered in this study

3.3 Phase1: Determine the life cycle cost and emissions of households

Quantification process of life cycle cost and emissions can be explained as follows.

Construction/manufacturing Emission Estmation: Building level environmental impacts were calculated using Athena Impact Estimator V5.2. The building envelope characteristics given in Appendix A and operational energy estimations (calculated in this study) were used for calculating the carbon footprint, human health impacts, global warming etc. Product stage, construction process stage, use stage, end-of-life stage and recycle/reuse stage (A to C) were considered in defining the system boundary for building LCA. The construction cost was obtained from the developer as per their databases.

The manufacturing emissions of electric vehicles (EVs), conventional gasoline-based vehicle (ICE), and solar (PV) systems were identified though high-impact peer-review journal. Those were added to the building level emissions and the total household emissions were calculated for alternative combinations. The cost of EV and ICE was obtained from on-line sources and the purchasing and installation cost of solar (PV) systems were obtained from local solar (PV) providers.

Operational Energy Estimation: A preliminary energy simulation was developed using HOT2000 V11.2 software which was developed by Natural Resources Canada. Temperatures settings, electricity consumption of appliances, occupancy levels, and hot water temperatures were calibrated in the above model based on the real-time data collected in the last year. Following are the parameters used to adjust the energy model and to identify actual-data-based operational energy consumption for this study.

- The front elevation of the SFDH is oriented to Northwest.
- Currently, the house is occupying by two adults and they are staying at the house for 50% of the day.
- The night time and day time heating temperature of the ground floor is 21^0C and the basement temperature is 20^0C.
- The appliances are high energy efficient appliances with energy star rating (stove, refrigerator, dish washer, clothes washer and dryer). According to the electricity-usage sensor data, the average per day electricity consumption is 9.26kWh.
- The average electricity consumption per day for the building lighting is 0.11kWh due to the use of energy efficient LED technology for lighting purposes.
- The domestic hot water temperature is being kept to 60^0C to comply with BC codes. Energy efficient (3.88 COP) 80 Gal, heat pump domestic water heater is used to provide hot water for the use of the occupancies.
- ACH @ 50Pa is identified as 0.9988 based on the blower door test conducted for above house and the blower door test observations were entered to the energy model to obtain an accurate results.

This study focused on a SFDH experimental model which was constructed in Okanagan, BC. The project was comprised of material testing, energy and cost simulation, monitoring and forecasting. The floor plan and the specifications of the particular SFDH is shown in Appendix A. Table 1 shows the differences of the two energy options for the above house. The above model was altered using the Table 1 data and the results were used as inputs to LCA model developed using Athena impact estimator V5.2.

Table 1: HVAC system for energy simulation

	Type / Fuel	Characteristics	Efficiency
House with Natural Gas and Electricity (Conventional)			
Space heating	Duel fuel (Natural Gas & electric) heating system	56000 BTU/hr, switching temperature 35^0F	EF - 92.1%
	Natural gas fireplace	2kW, 6824.28 BTU/hr	30% SS
Space cooling	Central split system, electric	14SEER, 10kW	COP 3
House with Electricity (Environmental-friendly)			
Space heating	Ground source heat pump operated using electricity	5 series (500A11) – Geothermal c/w ECM variable speed blower	COP 4
	Natural gas fireplace	2kW, 6824.28 BTU/hr	30% SS
Space cooling	Ground source heat pump operated using electricity	5 series (500A11) – Geothermal c/w ECM variable speed blower	COP 5.6

Moreover, the impact of the household transportation was considered in this study. 20,000km/year annual average distance per vehicle and 1.6 vehicles per household were assumed in a single household. The use of gasoline and electricity for household transportation was also calculated in this section. According to appendix A, the electricity consumption of electric vehicle (EV) was taken as 34kWh per 100km and the gasoline consumption of conventional-fuel vehicle was taken as 12.32km/liter (Perera, Hewage, and Sadiq 2017). According to the local solar (PV) industrial experts, the operational emissions of solar (PV) was identified as negligible. Therefore, there is no emissions were considered for the use phase of grid-tie solar (PV) systems for small-scale electricity generation.

The utility tariffs in BC were considered in calculating the operational cost of the household. The Canadian interest rates and local tariff increase rates were used while obtaining the net present worth (NPV) of the future operating costs. Eq. 2 and Eq. 3 were used to calculate NPVs. The building maintenance cost was calculated based on the life span of the building components and the vehicle maintenance cost was obtained from the available literature.

End-of-life emission/energy and cost estimation: End-of-life emissions of the household was calculated using Athena Impact Estimator. However the end-of-life of solar (PV) system and vehicle considered as negligible. The life cycle costs were collected from the available literature for the building and vehicles. The end-of-life cost and emissions of solar (PV) system was considered as negligible. The NPV of the end-of-life costs was obtained from Eq. 3.

3.4 Phase 2: Propose Solar (PV) system size to make households near net-zero grid electricity dependency

The operational electricity requirement of the alternative 000, 010, 100, and 110 was calculated using the calibrated energy simulation model and literature-based databases. The solar (PV) system sizes were obtained using following criteria,

1) Solar(PV)-based electricity required to be covered 50% - 75% of annual electricity consumption of the household
2) Solar (PV) system should be available to purchased from the local market (Commercially available)
3) The total area of the solar (PV) array should be limited by the productive Southern oriented roof area.

Accordingly, the system size was decided based on the data collected from the local solar (PV) vendors. The solar (PV) electricity production was calculated using Eq. 4.

[4] $$Solar\ (PV) - based\ electricity\ generation\ potential = \frac{PV\ potential}{Potential\ PV}$$

The solar (PV)-based electricity generation potential for the selected city was obtained from NRCan database. The details of the potential solar (PV) systems were obtained from the vendors and iterative process was used to select the most desirable solar (PV) option for the given alternative.

3.5 Phase 3 – Selecting the most desirable alternative for S-BC

The eco-efficiency approach was used to compare different alternatives based on their cost factors identified in LCC and the emission reductions identified in the LCA. BEES weights were used to aggregate different life cycle emissions and develop an environmental score (ES) for different household alternatives. Min-max normalization method was used to normalize impacts and costs. The normalized cost and impacts were entered in to eco-efficiency equation and the most desirable alternative were selected from the available alternatives.

4 RESULTS AND DISCUSSION

The household energy consumption for different alternatives are shown in Table 2 based on the data obtained from the real-time data monitoring system and literature-based databases. The operational data for solar (PV), grid electricity, natural gas, and gasoline were obtained accordingly. The real-time energy consumption data, literature data, and simulated data were used to develop operational energy requirement for alternative households.

Table 2: Operating energy requirement

Alternative Household ID	Household Operating Energy Assessment			
	Solar (PV) Electricity (kWh/year)	Grid Electricity (kWh/year)	Natural Gas (m^2/year)	Gasoline (l/year)
000	6,118.2 (~70%)	2,652.4 (~30%)	1,855.3	2,597.4
001	NA	8,770.6	1,855.3	2,597.4
010	12,236.4 (~62%)	7,414.2 (~38%)	1,855.3	NA
011	NA	19,650.6	1,855.3	NA
100	9,517.2 (~68%)	4519.8 (~32%)	NA	2,597.4

101	NA	14,037.0	NA	2,597.4
110	14,955.6 (~60%)	9,961.4 (~40%)	NA	NA
111	NA	24,917.0	NA	NA

The combined LCA emissions for Solar, vehicle and house can be shown as Table 3. The life cycle of the house was considered as 50 years, whereas the life cycle of the solar panel was considered as 25 years. In terms of transportation, operational emissions for 10 years were considered in this study. Athena Impact Estimator for building was used to simulate house and the operational energy quantities were entered to the model to obtain the A-D, LCA results for the household. LCA results for Solar (PV) 3KWp system was obtained from SimaPro database and TRACI 2.4 V 1.04/ US-Canadian 2008 method was used to obtain mid-point indicators. Accordingly, GWP, SOP, ALW, EN, TOF and DNR were derived as 8.05E+03kgCO_{2eq}, 1.28E-03kgCFC-11_{eq}, -6.00E+00kgSO_{2eq}, 6.4E+01kgN_{eq}, 4.81E+02kg$O3_{eq}$, and 7.40E+03MJ respectively. Moreover, LCA results for vehicle operating stage were obtained from the study conducted by Hawkins et al (2013) (Hawkins et al. 2012). The environmental impact score was calculated for the alternatives using BEES weights. According to Perera et al. (2017), the weightages for GWP, SOP, ALW, EN, TOF and DNR are 29.3, 2.1, 3.0, 6.2, 3.5 and 9.7 respectively (Perera, Hewage, et al. 2017).

Table 3: LCA results

Alternative Household ID	GWP	SOD	ALW	EN	TOF	DNR	Environmental Score using BEES
	kg$CO2_{eq}$	kgCFC-11_{eq}	kg$SO2_{eq}$	kgN_{eq}	kg$O3_{eq}$	MJ	
000	6.28E+05	3.56E-03	3.86E+03	2.72E+02	5.85E+04	9.68E+06	1.13E+08
001	6.83E+05	1.00E-03	3.94E+03	1.46E+02	5.81E+04	9.98E+06	1.17E+08
110	4.11E+05	2.42E-01	2.54E+03	3.42E+02	1.45E+04	5.39E+06	6.44E+07
011	5.20E+05	2.37E-01	2.68E+03	9.00E+01	1.38E+04	5.98E+06	7.33E+07
100	4.35E+05	4.84E-03	1.96E+03	3.17E+02	5.43E+04	5.90E+06	7.02E+07
101	5.20E+05	1.00E-03	2.08E+03	1.29E+02	5.39E+04	6.36E+06	7.71E+07
110	2.34E+05	2.45E-01	6.40E+02	4.52E+02	1.09E+04	1.65E+06	2.30E+07
111	3.57E+05	2.37E-01	8.32E+02	7.30E+01	9.55E+03	2.37E+06	3.35E+07

The utility tariff and cost data provided in Perera et al. (2018) and the capital cost data provided in Perera et al. (2017) were considered while calculating the net present worth (Perera et al. 2018) (Perera, Hewage, et al. 2017).

Table 4: LCC results

Alternative Household ID	Initial Capital Cost (CAD$/household @ 0^{th} year)	Household Total Energy Cost (CAD$/year)	Solar & vehicle replacement cost (CAD$/10year)	End-of-life (CAD$/household @ 50^{th} year)	Net present worth (NPV) (CAD$/household)
000	530,160	3,865	25,723	3,000	1,059,122
001	519,243	4,652	14,806	3,000	1,088,013
110	544,257	1,319	38,164	3,000	848,717
011	524,780	2,894	18,687	3,000	918,738
100	543,422	3,465	29,985	3,000	1,046,792
101	528,243	4,690	14,806	3,000	1,101,096
110	556,813	1,007	41,720	3,000	842,230
111	533,780	2,931	18,687	3,000	931,822

Domestic electricity rates – Base rate was considered as CAD$6/month, tier 1 rate was considered as CAD$ 0.0858/kWh up to 1350kwh, and CAD$ 0.1287/kWh for tier 2 consumption. Domestic natural gas rate was considered as CAD$ 12.06/month as the base rate and CAD$ 7.16/GJ based on the consumption.

The basic house was priced at CAD$498,098/house with some energy upgrades and the house which operated solely from grid electricity was priced at CAD$ 507,092/house. According to the local vendors, the prices of solar (PV) grid-tie systems were assumed as CAD$ 10,917 for 5.4kWp, CAD$ 19,477 for 10.8kWp, CAD$15,179 for 8.4kWp, and CAD$23,033 for 13.2kWp including purchasing, manufacturing and servicing up to 25 years. The end-of-life costs of solar (PV) systems were assumed as negligible. Accordingly, the detail LCC analysis is shown in Appendix B and the results of the aforementioned alternatives can be shown as Table 4. Annual average discount rates were assumed as 2% per annum and the utility tariff increase rate were assumed as 5% per annum.

The LCA and LCC results can be discussed using Table 3 and Table 4. Figure 5 shows the comparison of the LCA results and LCC results with the aforementioned alternative households.

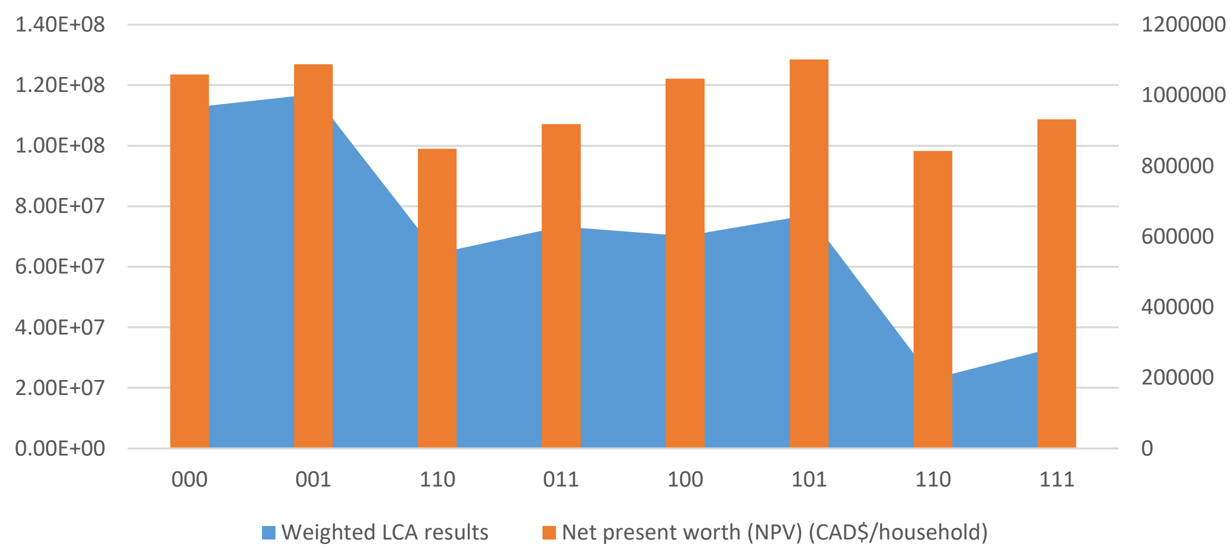

Figure 5: LCC and LCA results with the corresponding alternative

According to Figure 5, the households with solar (PV) systems (Ex: alternative 000, 110, 100, and 110) has comparatively low LCCs and low LCAs than the respective household without solar (PV) systems (Ex. Alternative 001, 011, 101, and 111). Moreover, it is clearly identify that the alternative 110 (Solar 13.4kWp system + EV + Electricity-based household w/o NG) has given the highest environmental benefits with lowest life cycle cost in the long-run.

A comprehensive literature review revealed that the upfront cost (capital cost) has the highest impact on the purchasing decision considering the perspective of the consumer. Therefore, an eco-efficiency-based analysis (Appendix C) was conducted to identify the best alternative which has considered LCA impacts and cradle to gate LCC costs of the households. According to the eco-efficiency ratings, the alternative 011 (Typical household with NG & electricity + EV + w/o solar) shows the highest purchasing potential due to the lower purchasing cost and better environmental performance. In short-term, the emissions per unit cost resultant from transportation seems to be significant than the emissions per unit cost from Natural Gas and solar (PV). The low-emission of grid electricity, the upfront cost of solar (PV) systems, and the upfront cost of domestic heating system with geo-source heat pump may cause to higher capital investment in the short-run. The LCA and LCC results of this analysis can be used to improve the grid-tie solar (PV)-based electricity generation in low emission grid communities. The LCA database developed in this research can be used in future studies and the same methodology can be easily applied to regions with high-emission grid electricity in Canada to identify the possibility of grid-tie solar (PV) systems for their households. The conclusions of the study will be important to building developers, potential building owners, practitioners, researchers, public and private institutes to select building systems according to their budget, expected household performances and to minimize the emissions.

As a limitation, the optimization of solar (PV) size and type has not been considered in this study. A criteria-based solar (PV) sizing has been conducted where there are some other practical limitations can be seen in the actual deployment. As future research, a renewable energy optimization model including solar (PV) will be developed and assessed using LCA and LCC analysis to provide more practical results to the industrial partners.

5 CONCLUSION

Renewable small-scale energy systems have gained extensive attention in the recent past due to high environmental and economic impacts of conventional energy sources. The Solar (PV) grid-tie systems can be considered as commercially viable small-scale low-emission electricity generation method which can be easily installed to new and existing buildings. However, the actual environmental and economic impacts of solar (PV) based electricity generation may vary with the local energy characteristics such as conventional energy costs, emissions, and consumer perspective.

This study has focused on identifying solar (PV) potential for household activities in Canadian regions with low-emission grid electricity. Different energy consumption in domestic and transportation activities were considered in defining different household alternatives. The cradle to grave LCC and LCA for the above alternatives were determined considering the environmental and economic impacts of in-situ electricity generation of solar (PV) systems. Accordingly to the analysis, solar (PV) systems indicated more cradle to gate emissions and negligible operating emissions. Therefore, solar (PV) is more desirable to reduce the life cycle impacts of household in the long-run. Households with solar (PV) systems show better financial performances in the long-run compared to the households without solar (PV) systems due to utility rate hikes in the future. The fossil-fuel-based emissions can be reduced using the households which depend solely on low-emission electricity. However, dependency on grid electricity without having solar (PV) indicated adverse economic impacts in the long-run. Investing solar (PV) in the short-run may increase the environmental and economic impacts due to cradle to gate impacts of solar (PV) systems. The findings of the above analysis would help local developers, contractors, planners, designers, and local institutions to access an evidence-based approach to develop policies, incentives, and procedures to improve solar (PV) systems in Canada.

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Appendices

Appendix A : Specification of Typical BC House

	LCA modelling spec.
Foundation footing	8” reinforced concrete
Basement slab	4” concrete
Below ground wall	ICF blocks, 8” reinforced concrete
Above ground wall	2”×6” wood studs @ 24” OC, 3/8” OSB sheeting, R20 insulation, ½” drywall
Interior wall	2”×4” wood studs, ½” drywall
Ground floor	Engineered I joist 11 7/8” @ 19.2” OC, ¾” plywood
Celling	R50 insulation, ½” drywall
Roof	Engineered trusses (wood), 1/2” OSB sheeting, Asphalt
Windows	Vinyl triple glazed windows c/w 366 lowE
Construction Cost (CAD)	462,592
End-of-life cost[1] (CAD) (Demolition)	3,000

Source: (Perera, Shahria, et al. 2017)

Appendix B : NPV Calculation

Alternative Household ID	Initial Capital Cost (CAD$/household @ zeroth year)	Household Total Energy Cost CAD$/year	Solar & vehicle replacement cost (CAD$/10year)	End-of-life (at 50th Year)	NPV energy cost (CAD$)	NPV replacement cost (CAD$)	NPV EOL cost (CAD$)	Net present worth (NPV) (CAD$/household)
000	530,160	3,865	25,723	3,000	420,004	107,843	1,115	1,059,122
001	519,243	4,652	14,806	3,000	505,582	62,074	1,115	1,088,013
110	544,257	1,319	38,164	3,000	143,344	160,002	1,115	848,717
011	524,780	2,894	18,687	3,000	314,499	78,345	1,115	918,738
100	543,422	3,465	29,985	3,000	376,545	125,711	1,115	1,046,792
101	528,243	4,690	14,806	3,000	509,665	62,074	1,115	1,101,096
110	556,813	1,007	41,720	3,000	109,393	174,910	1,115	842,230
111	533,780	2,931	18,687	3,000	318,582	78,345	1,115	931,822

Appendix C : Eco-efficiency Ratio Calculation

Alternative Household ID	Normalized LCC-NPV reduction	Normalized Environmental Impact reduction	Normalized capital cost	Eco efficiency ratio
000	0.03	0.04	0.02	1.82
001	0.00	0.00	0.00	NA
110	0.22	0.45	0.05	9.34
011	0.16	0.37	0.01	35.04
100	0.04	0.40	0.05	8.59
101	-0.01	0.34	0.02	19.67
110	0.23	0.80	0.07	11.11
111	0.14	0.71	0.03	25.51

[1]Based on the demolishing calculator given in http://www.buildingjournal.com/commercial-construction-estimating-demolition.html (The exchange factor is assumed as USD1:CAD1.28)