Proceedings of the 2nd International Conference on Advances in Energy Research and Applications (ICAERA'21)
~~Seoul, South Korea~~ Virtual Conference - November 24- 26, 2021
Paper No. 113
DOI: 10.11159/icaera21.113

Life Cycle Assessment of Using Solar Streetlights for Municipal Streetlighting

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Abstract -The lifecycle CO_2-Eq emissions of solar streetlighting for a subdivision development is analysed and compared with the emissions of grid connected streetlighting. Solar LED streetlighting is shown to offer the potential for the reduction of greenhouse gas emission over grid connected LED streetlighting in areas where the emissions associated with grid electricity generation are greater than ~80 gCO_2-Eq/kWh. In areas such as Alberta where fossil fuel energy sources provide almost 50% of the grid electricity generation, solar streetlighting can lead to a 92% decrease in emissions from streetlighting over a 30-year lifespan.

***Keywords*:** Carbon Footprint, Solar Streetlights, Sustainability, CO_2 Emissions.

1. Introduction

With the increasing need for sustainable development and energy savings, municipalities must examine all systems for increased efficiencies and reduced environmental impacts. Streetlighting is an example of a system that could benefit from improvements, with an estimated 281 TWh of electricity used globally for outdoor lighting [1]. LED streetlighting is already being implemented in various regions such as in Richmond Hill Ontario's outdoor lighting LED conversion project, where 13,000 outdoor lights are being switched to LEDs for energy savings. LED lights consume 50-60% less electricity and have a longer lifespan than traditional high pressure sodium (HPS) lights [2]. The Richmond Hill conversion project is expected to reduce CO_2 greenhouse gas emissions by 300 tonnes per year [2]. Solar powered streetlighting may present an opportunity to further cut costs and reduce the carbon footprint of a municipality. According to an analysis by the company Solar Grid Energy Inc, switching to solar powered streetlights can lead to a 40% upfront cost savings compared to traditional grid fed lights due to the reduction in trenching, cables, and installation infrastructure. Solar streetlights provide their own power by using a solar PV panel to generate electricity during the day and store it in a battery for use at night. Each streetlight is individually self supporting, eliminating the need to run buried power lines to each light. The battery is generally sized to provide two days of lighting to account for periods of low solar irradiance. In addition to cost and energy savings, solar streetlights can continue to operate during power outages due to independence from the grid. Solar streetlights have an advantage for remote areas where grid energy is unavailable; in contrast, this paper will explore the potential benefits of implementing solar streetlights into municipalities with readily available grid connections by conducting a life cycle assessment (LCA). This LCA study will compare the environmental impacts between using solar streetlighting and grid-connected streetlighting to power the streetlights included in Richmond Hill's outdoor lighting LED conversion project in a small subdivision in Richmond Hill, Ontario.

2. Scope

The scope of this study includes a new subdivision development in Richmond Hill, Ontario that utilizes grid connected LED streetlights. The functional unit will thus be road lighting for the entire development. The development has an area of approximately 0.16 km^2 and contains 134 streetlights. The study will compare CO_2-Eq emissions from grid connected LED streetlights with CO_2 emissions from solar powered LED lights for the same development. The grid connected streetlighting system will include the lifecycle emissions associated with the manufacturing of the cable and grid energy over the lifespan of the product. The solar powered system will include the life cycle emissions associated with the production of the solar cells and lithium-ion batteries. All other system components are assumed to be constant between both systems and will not be considered. For example, the transformers and the utility trench serve multiple purposes and are required with or without the streetlighting – thus the lifecycle costs for these processes will not be included in the scope of the study. The lifespan of the study is 30 years and it is assumed all general maintenance is the same for both systems. The CML 2001 human toxicity (20 years), acidification, and climate change (20 years) impact categories are evaluated.

3. Method

3.1 Cable Estimates

Using development plans provided by the Town of Richmond Hill the amount of cable required for the streetlighting was estimated. On average, 59 meters of cable is required per streetlight. This number includes the amount of cable required to run from the transformer to the first light, the spacing of each streetlight and the required cable to run up the height of the streetlight from the buried utility trench. The total length of wire required is 7.5 kms. The cable is listed as 2C-#6 AWG CU RWU90 1000V XLPEI, which was found to have a weight of 328 kg/km of wire and a copper content of 232 kg/km of wire. The cable is insulated using crosslinked polyethylene, which is assumed to make up the entirety of the mass difference between the wire and the copper mass. This leads to a total wire requirement of 2460 kg; 1740 kg of copper and 720 kg of polyethylene. LCA data for Primary copper; at Manufacturer was obtained from publicly available LCAcommons.gov and provided by Yang et al. [3]. The data set provides the amount of copper in terms of its monetary value, in USD, and thus the value of the mass of copper in the wire was also estimated in USD units; this was completed by looking up the price of copper per kg which was found to be 5.87 USD/kg Cu [4]. Similarly, LCA data for the polyethylene was obtained from the LCAcommons.gov and provided by the Plastics Division of the ACC; Cradle-to Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors [5].

3.2 Electricity Use

Each streetlight is 21 feet high, weighs 779 lbs, and uses a 75 W LED light, resulting in a total power consumption of 9.75 kWs for the development. Using data from the United States Naval Observatory's Daylight/Darkness Table, it was estimated that there is 4326 hours of darkness and 4434 hours of daylight per year in Toronto, Canada [6]. Using this number as the daylighting hours per year in Richmond Hill, it was estimated that the development uses 42,200 kWh of electricity annually for streetlighting.

3.3 Solar Cell Estimates

Environment Canada has published a comprehensive report about the lifecycle GHG emissions from multi-crystalline silicon photovoltaic (Si-PV) cells, providing a compilation of estimates from 5 different papers which averages to 35.25 gCO2-Eq/kWh [7]. Thus, in this report the lifecycle GHG emissions for multi-crystalline Si-PV solar cells is assumed to be 35.25 g CO2-Eq/kWh of electric energy generated. These values are comparable to other values in the literature. For example, Fthenakis et. al. [8] reported that the required energy needed for Si-PV systems is 2400 – 7600 MJ/m2 with greenhouse emissions in the range of 46-63 gCO2-Eq/kWh. Other reports estimate the GHG emissions from multi-crystalline Si-PV cells to be 40 gCO2-Eq/kWh over their 30 year lifespan [9] [10]. Additional pollution indicators were found to be 80 mg NO/kWh and 160 mg SO/kWh [7].

3.4 Lithium-ion Battery Estimates

The lifecycle impact of lithium-ion batteries was estimated using data found in various papers. Romare et. al. estimate the CO_2 emissions to be 150-200 kg$CO_{2\text{-Eq}}$/kWh of storage capacity [11] and verify the assumption of linear scaling of emissions per kWh capacity. Hao et. al. estimate the emissions to be 103 kg CO_2-Eq/kWh capacity [12] where as Ellingsen et. al. estimate the emissions to be 96.6 kgCO_2-Eq/kWh capacity [13]. Averaging out this data gives an emission of 120 kg CO_2-Eq/kWh capacity. Additional values for other impact categories are provided in Table 1.

Lithium-ion batteries degrade to 80% of their performance after 5000 cycles of operation [13], or 13.7 years of service. The use of the batteries can be extended past this point, and thus for the purposes of this study it will be assumed that the batteries must be replaced every 15 years. The lithium-ion batteries are assumed to be sized such that they will last 24 hours without any charge, and thus must be able to store 1.8 kWh. Note the assumption of full power and the exclusion of any additional features such as light dimming and light control which would reduce the required battery size or extend the amount of time the light can operate without being charged. Thus, the total required battery storage capacity for this case (referred to as case 1) for the development would be 241 kWh (134 streetlights multiplied by 1.8 kWh per streetlight). Two additional cases are considered to assess the sensitivity of the environmental impacts to the assumption of full lighting power without any dimming capabilities: Case 2, wherein dimming capabilities reduce the battery capacity required for each streetlight to 0.9 kWh with 120 gCO2-Eq/kWh of battery capacity, and Case 3, which is similar to Case 2 but with a more optimistic emissions estimate of 100 gCO2-Eq/kWh of battery capacity.

Table 1: Impacts associated with the production of lithium-ion batteries.
Data provided by [13] L. Ellingsen, B. G.Majeau-Bettez, A. Srivastava, L. Voloen and A. Stromman, "Life Cycle Assessment of Lithium-ion battery Vehicle Pack," *J. Ind. Ecol,* vol. 18, no. 1, pp. 113-124, 2014.

Fossil Fuel Depletion	49.5	kg Oil/kWh
Ozone Depletion	0.000011	kg CFC/kWh
Terrestrial Acidification	1.9	kg SO_2/kWh
Freshwater Toxicity	9.6	kg 1,4 DCB-Eq /kWh
human toxicity Potential	596	kg 1,4 DCB-Eq /kWh
Metal Depletion	154	kg FE-Eq /kWh

Deelat sells an 80-watt LED solar streetlight with a lithium-ion battery size of 1298 Wh (DEELAT Solar Streetlight – Motion Sensor-Multi-Function with Remote-8000 Lumens LED) [14]. Solar Grid Energy sells a 4000 Lumen solar streetlight with a listed lithium-ion battery capacity of 461 Wh (Product: IP-40) [15]. For a comparable 8000 Lumen light (double the brightness) the battery is assumed to be double the size; 922 Wh. These two products provide validation for the estimate of 900 Wh for the battery capacity in the solar streetlight.

In comparison, Deelat also sells a different version of the 80-watt LED solar streetlight that uses a 407 Wh lithium-ion battery, (DEELAT solar powered streetlight – 10000 Lumens LED – 21776409) [14]. It is speculated that this light is designed for applications where the light is able to operate on low power settings for the majority of its use. Dimming of streetlight systems has been implemented in large scale European systems with the expectation of reducing energy use by 30- 50% [16]. Marino [17] reported an estimated energy savings of 30% for streetlighting systems that use dimming control.

3.5 Electricity

Several different sources of electricity were examined. Ontario Grid electricity was found to emit 39 gCO2-Eq/kWh based on data from Ontario Power Generation [18]. Ontario has exceptionally low greenhouse gas emissions from electricity due to large amounts of hydro and nuclear power, however some provinces in the country emit as much as 790 gCO2-eq/kWh, with a national average of 140 gCO2-Eq /kWh [19]. The Canadian grid emissions were established by using the electricity generation split from Canada's Renewable Power Landscape 2017 [19] and linking the required process with providers in OpenLCA. Additionally, LCA databases for Electricity, at Grid, US 2010 [20], obtained from LCACommons.gov was used for comparison in the US.

3.6 High Pressure Sodium Streetlighting Comparison

Although this study is comparing LED grid connected streetlighting with LED solar streetlights, it is worth noting most streetlights use HPS lighting [2]. HPS lights use 40-50% more electricity than LED lights to produce the same amount of light [2]. A comparison case has been added to compare HPS lighting by increasing the calculated amount of electricity by 50% to represent the HPS grid connected lighting.

3.7 Software

OpenLCA was used to compile the various LCA databases and apply the CML 2001 impact assessment method.

4. Results

Error! Reference source not found. shows a summary of the results attained using OpenLCA software. A few different cases for the grid connected streetlights are presented which isolated impacts of the copper cabling, and shows the impact of various gCO2-Eq /kWh values from different grid electricity sources. Cases 1-3 are further broken down into contributing components in **Error! Reference source not found.**.

Table 2: CML 2001 impact category indicators

Case	Human Toxicity (HTP 20a) (kg 1,4-DCB-Eq)	Acidification Potential (general) (kg SO_2-Eq)	Climate Change (GWP 20a) (kg CO_2-Eq)
Grid connected streetlighting with electricity from the US Electrical Grid avg (no copper)	45,000	5,600	61,889
Grid connected streetlighting with electricity from US Electrical Grid avg	50,100	5,600	62,140
Grid connected streetlighting with electricity from Canadian Average (140 gCO_2-Eq /kWh)	5,180	92	177,000
Grid connected streetlighting with electricity from US Electrical Grid (60 gCO_2-Eq /kWh)	50,100	5,600	76,380
Case 1: Solar LED streetlighting (1800 Wh, 120 gCO_2-Eq/kWh)	226	1,160	102,440
Case 2: Solar LED streetlighting (900 Wh, 120 gCO_2-Eq/kWh)	182	706	73,500
Case 3: Solar LED streetlighting (900 Wh, 120 gCO_2-Eq/kWh)	182	706	68,700

Table 3: Detailed break-down of LED streetlight emissions for Cases 1, 2 and 3

Case 1 (worst case)	Amount (gCO_2-Eq/kWh)	%
Solar cells	44920	43.7 %
Li ion batteries	57840	56.3%
Total	102760	
Case 2 (Moderate Case)		
Solar cells	44920	60.8 %
Li ion batteries	28920	39.2 %
Total	73840	
Case 3 (Best case)		
Solar cells	44920	65.1 %
Li ion batteries	24100	34.9 %
Total	69020	

5. Discussion

From an environmental standpoint, based on the global warming indicator, the decision to use solar streetlights with battery storage or to use grid connected streetlighting comes down to the amount of CO2-Eq emitted while generating grid electricity compared to the CO2-Eq emissions associated with manufacturing the photovoltaic cells and batteries required for solar street lighting. For example, manufacturing the amount of copper cabling required would produce 8,700 kg CO2-Eq emissions, which represents 1% and 14.7% of the global warming potential impact when the streetlights are connected to the grid in the USA and Ontario, respectively. **Error! Reference source not found.** shows the results from the three different solar powered lighting cases considered (Case 1: the worst case, Case 2: a moderate case, and Case 3: the best case) and the lifecycle CO2-Eq emissions for the streetlights plotted as a function of the electric power generation emission factor (in units of gCO2-Eq/kWh). Markers for the emissions produced in each Canadian province are included and can be used to determine the advantages of implementing solar streetlights based on grid emissions.

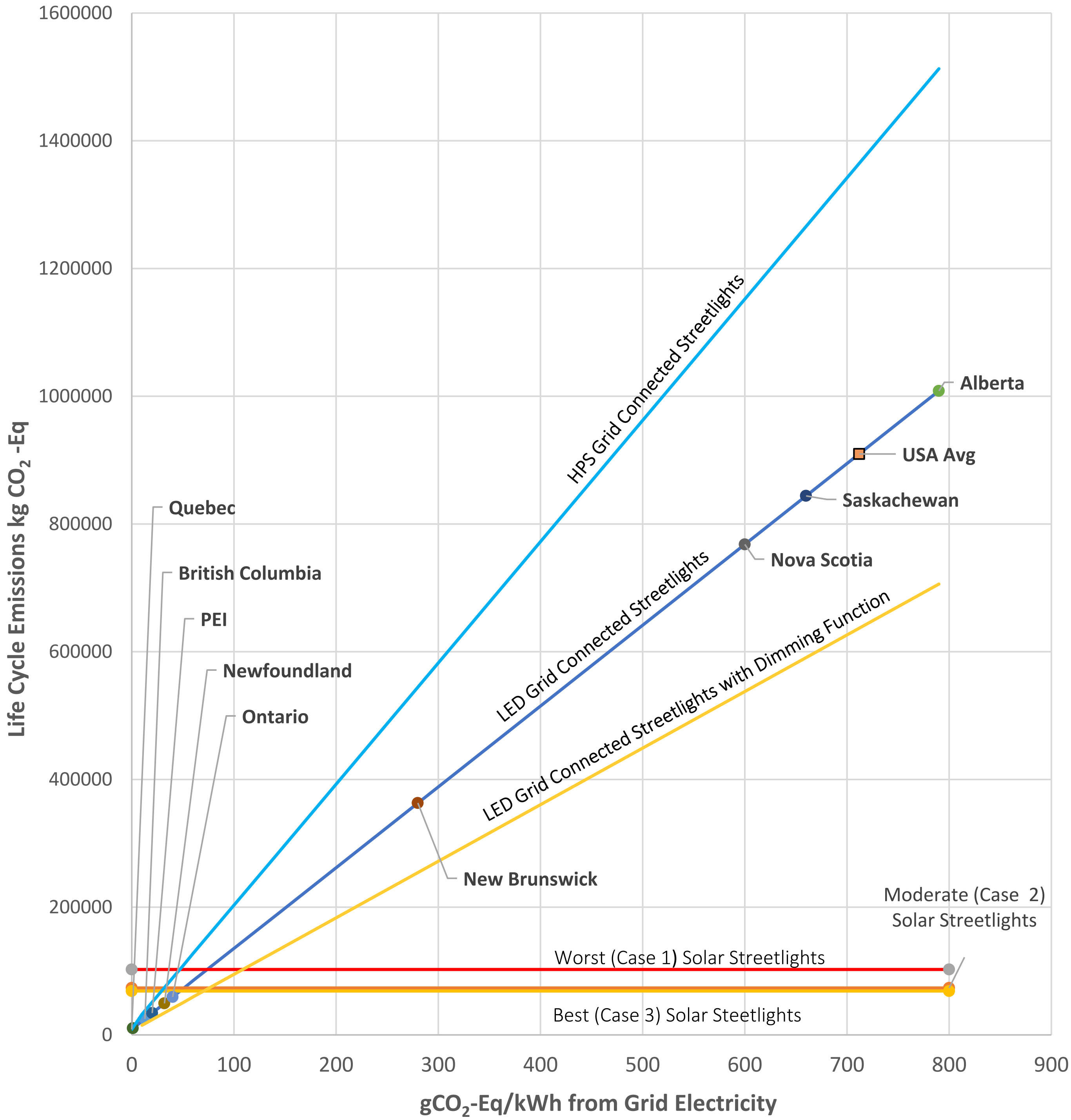

Fig 1: Emissions produced by streetlights over their lifespan with electricity sourced from different regions.
Source for CO_2 emissions per province from "Canada's Renewable Energy Landscape 2017. National Energy Board" [19]
note that the horizontal lines indicate the fixed CO_2-Eq emissions of the solar Streetlights. Error! Reference source not found.**

For the cases wherein the streetlights are assumed to have dimming capabilities (Cases 2 and 3), the results in Figure 1 show that using LED solar streetlights reduces CO_2-Eq emissions when generating grid electricity produces more than 80 gCO_2-Eq/kWh as compared to grid-connected LED lighting that uses light dimming strategies. Considering streetlights without dimming capabilities, for Case 1 (the worst-case scenario where no dimming is used, and 1800 W-h batteries are required for the solar streetlights) using LED solar streetlights reduces CO_2-Eq emissions when generating grid electricity produces more than ~75 gCO_2-Eq/kWh.

The results shown in Figure 1 reveal that the use of solar streetlights must be analysed on a case by case basis depending on the local grid electricity mix. In Ontario, due to the low CO_2 emissions associated with grid electricity generation, the use of solar streetlights is not recommended; However, they provide value to other provinces or countries with higher grid emissions – such as Alberta, USA, New Brunswick, Nova Scotia and Saskatchewan. Furthermore, it can also be seen in Figure 1 that the additional electrical needs of using HPS lighting causes an increase of between 40% (for low emitting electrical grids) to 50% (for high emitting electrical grids) in the amount of CO_2 emitted from the lighting system over its lifespan – thus switching to LED bulbs or to Solar LED Lighting are both beneficial as compared to HPS lighting. That is, in comparison to HPS lighting solar LED streetlights become a viable way to reduce CO_2 emissions in regions where electric grids produce more than 31, 33 and 50 gCO_2-Eq/kWh, for the best case (Case 3), moderate case (Case 2) and worst-case (Case 1) scenarios, respectively. **Error! Reference source not found.** shows that for the solar streetlights, the solar cells have a higher impact than the batteries for the best and moderate cases. Furthermore, additional analysis reveals that a 15% reduction in CO_2-Eq emissions from solar cell production results in a 6640 $kgCO_2$-Eq (9.6%) reduction whereas a 20% reduction in CO_2-Eq emissions from battery production results in a 4800 $kgCO_2$-Eq (6.5%) reduction in CO_2-Eq emissions. A 50% reduction in battery capacity (from 1800 kWh to 900 kWh) results in a 28,950 $kgCO_2$-Eq (28%) reduction.

For the grid connected streetlighting, the CO_2-Eq emissions associated with the copper cabling has minor impact on the overall results, accounting for 8689 kg (1%) of the CO_2-Eq emissions when using electricity from the US electrical grid and 14.6% of the emissions when using the Ontario grid. Improvements in solar cells and battery performance may further improve the case for solar streetlights by reducing the associated CO_2-Eq emissions from the manufacturing process. An alternative method to reduce greenhouse gas emissions related to streetlighting would be to improve the electrical grid supply by implementing renewable technologies – such as by building a dedicated solar array that feeds directly into the electrical grid in order to offset the electricity needs of the lighting system.

5.1 Notes on Study Accuracy

Due to limited availability and content of LCA databases, data was collected from various published works. Due to the rapid change in technology for both solar cells and lithium-ion batteries, more recent LCA data would improve the accuracy of the study. Transportation of components to build and install the cables, batteries and PV cells was generally excluded from the scope of the study. Calculations showed that the effect of transporting all 2.5 tons of copper wire over 1000 km by truck had less than a 0.1% effect on overall emissions, thus justifying its removal from the scope.

6. Conclusion

Solar streetlights can reduce emissions related to streetlighting by 92% when integrated into grids with high emissions such as in Alberta. The main factors found to influence of grid connected streetlighting was the amount of emissions produced per kWh of electricity generated. Implementation of solar streetlights for emission reduction purposes should be done on a case by case basis that examines the local electrical grid for the project. For solar streetlights, the main factors influencing the overall emissions are the amount of CO_2-Eq produced by manufacturing solar cells, followed by the required capacity of the battery storage and emissions related to the lithium-ion battery manufacturing. The cabling for grid connected streetlighting was shown to have minimal impact on the life cycle impacts of a streetlighting system.

Acknowledgements

The authors are grateful for support provided by the Natural Sciences and Engineering Council of Canada.

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