Life Cycle Assessment of Residential Buildings Considering Photovoltaic Systems

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Abstract

Nowadays, energy consumption in the building sector is considered one of the main contributors to increased carbon dioxide (CO2) emissions, which is having an enormous negative environmental impact worldwide. Correspondingly, rising CO2 emissions have become a global environmental issue. Life Cycle Assessments (LCAs) have been deployed for evaluation of the ecological impact of the building sector will be used to analyze and assess ecological effects. The primary objective of this research is to consider the different phases of life cycle energy and CO2 analysis of a PV system integrated residential building by designing geometry, spaces, and thermal zones in Sketch Up and simulating the building and calculating the energy load in EnergyPlus. For illustrative purposes, a single residential building in Toronto was simulated. Moreover, carbon emissions of the residential building were calculated through LCA and compared with the case of added PV systems. It was found that there would be a significant reduction in operating cost, energy cost, and CO2 emissions. However, the capital cost would increase by integrating PV systems, but it would be less significant considering a higher carbon tax in the future.

Keywords

Life Cycle Assessment, Photovoltaic Systems, Residential Buildings , Carbon dioxide (CO2) Emissions.

1. Introduction

Nowadays, energy consumption in the building sector is considered one of the main contributors to increased carbon dioxide (CO2) emissions, which is having an enormous negative environmental impact worldwide. Correspondingly, rising CO2 emissions have become a global environmental issue. Life Cycle Assessments (LCAs) have been deployed for evaluation of the ecological impact of the building sector will be used to analyze and assess ecological effects. As the architecture and construction industries increasingly accentuate sustainability, more holistic approaches are underway, which were developed to assess and reduce the environmental effects caused by buildings. Life cycle assessment (LCA) appears to be one of the most widely accepted methodologies being used during the design process to evaluate the environmental impact of construction (Bayer et al., 2010). However, Life cycle assessment, also known as Life cycle analysis, is a technique for assessing the environmental effects associated with all phases of the life of the project from the extraction of raw materials through processing, distribution, use, repair, maintenance, disposal and/or recycling. Designers use this process to help critique their products (Ragheb, 2011).LCA consists of four stages, which are 1. Definition of goals and scope, 2. Inventory analysis, 3. Impact analysis and 4. Interpretation and results (Bayer et al., 2010). In the first stage, the definition of goals and scope is defined as the aim and a limitation of the study documented and explains how and to whom the results are reported. It is essential to consider the function unit in this step, for example, CO2/ kg transported goods, CO2/m3 floor (Williams, 2009). Inventory analysis is the second stage which considers the data collection and data quality to quantify the input and output of products and energy; also, system boundaries and calculations are performed during this step (Bayer et al., 2010). The impact analysis presented in the third stage evaluates the potential environmental impacts, for example, resource depletion and the Global warming potential (Ragheb, 2011). Finally, the last scene is interpretation, assessment, and recommendation built on the results (Williams, 2009) .

The environmental life cycle assessment of an energy technology considers the impact analysis of all stages of production from ―cradle to grave,‖ that is, from fuel production to decommissioning . The manufacturing of PV system is not included in the current study, as the carbon footprint for PV manufacturing can be high. In the case of PV energy, the stages are simplified because no fuel needs to be prepared; no waste results from the conversion of sunlight into electricity and little maintenance are required during operation. The impacts are thus associated mainly with plant construction (raw materials, PV module and balance of system manufacturing, transportation, and plant manufacturing) and, to some extent, with decommissioning and recycling at the end of the PV system lifespan, which is typically 30 years (Vandeligt et al., 2012 & IEA, 2009). Many studies have worked on decreasing GHG emissions from the building segment by the adoption of two new building in Industrial Building System (IBS) structure categories. However, none of them considered the integration of LCA and Photovoltaic (PV) systems added to the Heating, Ventilation, and Air Conditioning (HVAC) systems and the impact on the load demand of the buildings. The primary objective of this research is to consider the different phases of life cycle assessment including carbon management of a PV system integrated residential building.

2. Energy Consumption

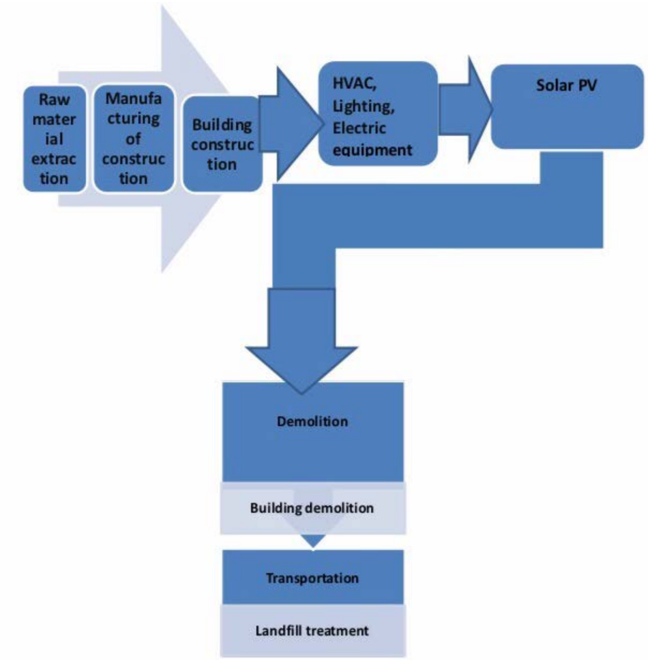
Kim et al. (2017) predicted that world energy consumption would grow 33% between 2010-2030 (Abdelaziz et al., 2011). In industrialized countries, total energy consumption in buildings represents about 20-40%. For example, in 2010 the United States consumed more than 40% of total primary energy in the building segment (DOE, 2011). With the growth of 82%, the major source of primary energy consumption is fossil fuels (EIA, 2011). These (non-renewable) energy resources are limited and also contribute significantly to CO2 emissions, which increased by more than 2% annually (DOE, 2011). In 2010, universal CO2 emissions surpassed more than 30 billion metric tons, with the U.S. contributing more than 4 billion metric tons (EIA, 2011). Due to increased energy consumption and inefficient use of energy, CO2 emissions continue to rise (Abdelaziz et al., 2011). Improving energy efficiency in complex buildings has significant potential to decrease energy consumption and related negative environmental impact. The related negative environmental impacts of greenhouse gas (GHG) emissions have been associated with global warming (Kessel, 2000) and the increased risk of natural disasters (Van Aalst, 2006). Energy efficiency in buildings has focused on improving energy consumption in air conditioning and lighting systems. More than 0.5% of energy consumption in buildings is due to Heating, Ventilation and Air Conditioning (HVAC) systems (Vali et al., 2009). More than 0.2% of total building energy is consumed by artificial lighting (Kozminski et al., 2006). HVAC and lighting systems have more than of 20% of potential energy savings. However, research thus has not provided energy-saving strategies for a complex manufacturing building. Therefore, this article focuses on the energy-saving technologies of the biotechnology manufacturing building such as laboratories and hospitals because this complex type of building requires health and safety regulations that consume far more energy consumption than a typical commercial building. The results identify that more than 13% of total energy cost savings resulting from energy-saving technologies. The savings were achieved by using high-efficiency HVAC equipment and advanced fluorescent lighting systems. When utilized to comparable types of buildings, the energy saving strategies considered will grow the economic and environmental benefits to homeowners. Also, the process energy consumes 67% of the building's total energy, almost double the energy consumed by air handling units (AHU), chillers, and lighting systems. Also, the annual energy savings estimate for air handling units, chillers, and lighting systems are 1,245,234 kilowatt hours (kWh); 869,202 kWh; and 1,122,165 kWh, respectively. The corresponding savings in dollars are \$161,880; \$112,996; and \$145,881, respectively. The AHU contributes to the highest annual saving in energy costs, followed by lighting and then chillers. Based on the US Environmental Protection Agency (EPA) carbon equivalent emission factor of 7×10-4 metric tons CO2/kWh (EPA, 2012), the annual estimate of CO2eq, or carbon dioxide equivalent, savings in metric tons for AHU, coolers, and lighting is 878.57 tons, 613.27 tons, and 791.74 tons, respectively. The annual estimate of total energy savings for the three systems is 3,236,601 kWh, or $ 420,758. The total annual saving in CO2 equivalent is 2283.58 metric tons. These energy savings reduce greenhouse gas emissions by 2,283.58 metric tons of carbon dioxide equivalent. Chel et al. (2017) pointed out that by developing more than 30% of the world's overall universal essential resources, the building sector is overgrowing. After the industrial area and agriculture, modern buildings have become the largest consumers of fossil energy. Within the framework of the sustainable environment program, there is an enhanced integration of renewable energy technologies installed with the building into several applications such as electricity generation, water heating, and heating/cooling (Feist et al., 2005). Sources put the amount of energy consumed in the building segment in Europe more than 40% of total energy consumption; about 0.66% of the amount as mentioned above is used in commercial buildings (Zografakis et al., 2000). Other sources claim that energy consumption in buildings in industrialization countries is responsible for 50 percent of CO2 emissions (Loveday et al., 2002& Yannas et al., 1994). In this article, the four main strategies for energy efficiency in a building are studied with their economic and environmental impacts. The first is associated with the previous design before the construction of passive solar building techniques adapted all over the world not only for passive heating/cooling but also for daylight buildings. The second strategy is to take advantage of low energy building materials. The third strategy considers the maintenance of operational energy using energy-saving equipment within the building. Finally, the building should benefit from integrated renewable hot water systems. Thus, the integration of passive solar features in buildings leads to a reduction in the energy consumption of buildings, thereby reducing carbon dioxide emissions and contributing to sustainable development. Another significant contribution to sustainability is the use of low internal energy and building materials available locally, to avoid the introduction of enormous energy requirement in the construction of the building, and thus reduce CO2 emissions. Therefore, as a viable alternative, the focus is on the promotion of renewable energy technologies to meet the energy demands of buildings. When the energy of the building is fully satisfied with renewable energy systems, it is known as high-efficiency green buildings or zero emissions. Total mitigation of CO2 emissions due to both heating and cooling energy saving potential capacity is identified as 5.2 metric ton per year (Arvind et al., 2009). The mitigation of carbon dioxide emissions was set at 58 metric tons due to the construction of a renovated mud house with an area of about 94 square meters compared to the reinforced concrete [RC] building house (Arvind et al., 2009). The carbon credits earned were set at $678 due to mitigation of CO2 emissions from mud house construction rather than RC structure building (Assuming 10 Euro/metric ton of CO2 reduction) (Arvind et al., 2009). Hence, the total building energy can be significantly reduced when using alternative energy systems included low energy building materials. Radwan et al. (2016) indicated that Egypt has significant energy production, but because of the substantial increase in domestic consumption and investment in the energy sector declined, Egypt became dependent on hydrocarbon imports. Egypt's dependency on hydrocarbon imports resulted in adverse impacts on the economic balance of trade and the national budget. Therefore, the Egyptian government is spurring energy-saving research. More than 55% of total energy in buildings is consumed by the air conditioning system (Fink, 2011, Aldossary et al., 2013). The future energy consumption of heating, ventilation and air conditioning (HVAC) will rise further due to increasing population growth, rapid expansion, and advocacy of new residential and commercial buildings and due to climate change and global warming. A hospital was selected in Alexandria, Egypt, as a case study because the hospital consumes a lot of energy because of 24 hour availability, medical equipment, and monitoring requirements for disease control and clean air requirements. In this study, an energy-efficient saving technology was developed to reduce energy consumption, which will provide specific methodologies and recommendations for energy-efficient operation. Improvements were made to the hospital to help both the hospital managers and designers begin the energy management program and create some "energy gains" to provide more energy saving for other purposes. The new system selected using the new cooling hospital loads was compared to the current system and a great deal of energy saving (7,068,178 kWh/year) was found. Also, the simulation showed potential annual electricity savings of 41% on the baseline scenario when applied the demand-controlled ventilation system (DCV) controls the amount of fresh outdoor air, based on the amount of CO2 in a building compared to the external door reading. DCV facilitates ventilation and improves indoor air quality while saving energy. Wang et al. (2017) concluded that the commercial and residential buildings had become the largest consumers of energy in all sectors, and energy efficient building has attracted increasing attention in recent years. Several studies indicate that occupancy detection is critical to enhancing energy efficiency in buildings because it is based on the idea of avoiding unnecessary waste while providing adequate service. In this paper, the proposed integration of an IBeacon enabled indoor positioning system (IPS) and a variable air ventilation system, \as well as the air conditioning system (HVAC) is to optimize the control system and provide high-resolution power detection occupancy for saving energy. The proposed system aims to harmonize thermal service with the spatial distribution of occupancy and redefine occupancy as a matrix of dynamic spatial occupancy distribution (DSOD). This paper proposes spatial occupancy measurement by linking large areas of indoor patches and zones, using a synthetic artificial neural network algorithm with specific characteristics to set the spatial IPS to signal patterns. After obtaining detailed spatial distribution, also developed a ventilation control mechanism based on the occupancy distribution. To verify the proposed control mechanism, compare it with other conventional controllers in the on-site experiment and by simulation using computational fluid dynamics (CFD). The results suggest that 20% of energy savings can be achieved when the proposed approach is implemented correctly.

3. Life Cycle Assessment

Hu et al. (2015) showed that the emission of greenhouse gases had become a common concern of the global societies. The building industry has caused a strain on the environment because of the emissions generated by the production of building materials and operation of the building system. Carbon emissions for residential buildings are calculated by a life cycle assessment (LCA). Impact factors, such as insulation thickness, air conditioning form and service life are analyzed. A typical energy-efficient residential building was chosen to calculate carbon emissions under several conditions. In this case, when the insulation thickness is 100mm, the carbon emission life cycle is minimal. In other words, each residential building has the optimum insulation thickness. As the building service is extended life, emissions will drop. As for air conditioning forms, the results appearance that residential buildings with split air conditioning have fewer carbon emissions than central air conditioning. Lotteau et al. (2017) indicated that in 2015, almost 55% of the population lived in world’s local areas (Habitat et al., 2016), and the sector is the hotspot for the environmental effects and source usage. For example, about 20% of the whole energy consumed worldwide is accounted for in the building segment (US El, 2014). The concluding energy consumption in developed countries accounts for about 42% in the building segment, almost 36% of greenhouse gas emissions and more than 50% of all removed material (European Commission, 2011). Analysis of the environmental effects of the constructed environment lectured through a diversity of methodologies depended on the gauge of study. At the building construction materials and the scale of individual buildings, life cycle assessment (LCA) is the accepted logical methodology for the quantitative evaluation of materials/buildings over their entire lifespan, taking into account upstream effects. LCA in the construction industry had been the topic of many studies. These reviews all point to the fact that case studies in the literature are difficult to compare because of their specificities such as resident regulations, building type, climate, cosiness requirements, and so on. Heating and cooling, and increasing the energy-sharing value of building materials in the context of low power buildings (Trigaux et al., 2014 & Lotteau et al. 2015). (Lotteau al., 2017) Propose a simplified model of assessment of the embodied power of buildings and embodied carbon concerning the urban planners' design levers. The model is based on the decomposition of buildings into functional elements to be sensitive to the shape of buildings. In detailed sensitivity analysis and contribution analysis, the model is conducted on two types of generic building forms to study influence meters binding to shape on the embodied power and carbon of the building. Sensitivity analysis shows that shape-related parameters (such as building size) have a more significant influence on energy and number of buildings per square meter than those for the elements themselves (such as wall thickness). Contribution analysis carbon proof of the relationship between the compactness factor, the CO2 embodied, and the building embodied.

4. Methodology

The methodology steps for this study are presented in the flowchart below.



Simulation Steps

Three steps presented in this study:

1. Design geometry, spaces, and thermal zones in Sketch Up The process of energy modeling begins with build geometry as Figures B1 and B2, space definition, and thermal zones. The Sketch Up software was used to model the building envelops. To create the envelope of the building, the Space Diagram tool was used to draw a floor plan. The surface matching tool was used to set boundary conditions after selecting the building envelope. The single thermostat used in a thermal zone where the thermal area represented an equal volume of air. It is important to note that the thermostat must be selected before running the EnergyPlus simulations with connected HVAC systems.
2. Simulate the building and calculate the energy load in EnergyPlus. After designing the geometry, space, and thermal zones in SketchUp, the Open Studio software was used to create the (IDF) file. To complete the building simulation and calculate the energy load, Energy Plus applied in three steps: the first step choose the IDF file as the input file and the second step choose the weather file for the building place. Finally, running to simulate the building to show the results select the text output file.
3. Calculate carbon emissions of the residential building through LCA and compare with the case of added PV systems, the carbon emissions of the residential building through LCA can be mathematically determined from the following: From the view of LCA, energy consumption in the life cycle of a single residential building can be mathematically represented.

EW ̈=∑ **Ei 5 *i*=1** (Gong & Song, 2015), where EW represents the life cycle energy consumption of a single residential building in Toronto and Ei represents the energy consumption of the building sectors during the phase i of the life cycle. CO2 "Ew ̈K (Gong & Song,' 2015) Where EW ̈is the building energy consumption from different phases of the life cycle building was calculated in EnergyPlus in the previous step. K is the carbon emission coefficient. After getting the results from the above equation will compare the results with the case of added PV systems.Scenario

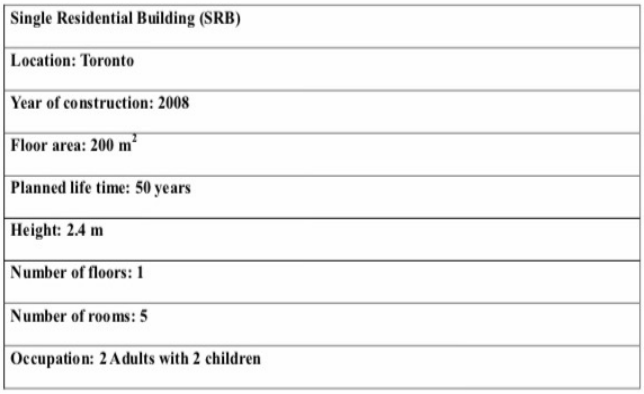
The four scenarios were used in this study.

1. Life Cycle Analysis of SRB: Business as Usual
2. Life Cycle Analysis of SRB Integrated with PV system (Low Efficiency)
3. Life Cycle Analysis of SRB Integrated with PV system (Medium Efficiency)
4. Life Cycle Analysis of SRB Integrated with PV system (High Efficiency)

CASESTUDY

Building Information

The single residential building located at Toronto used in his study.



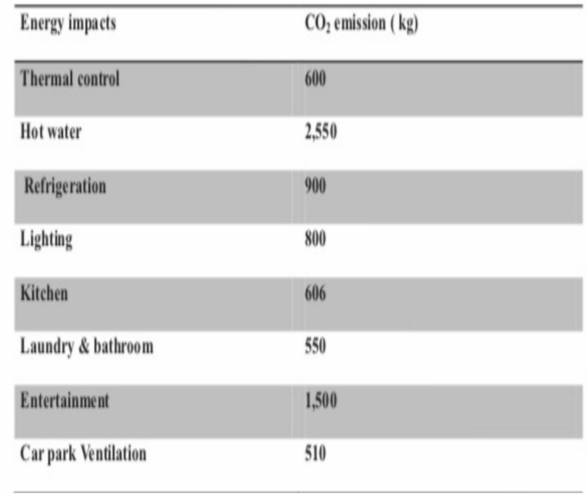
Single Residential Building (SRB)
Location: Toronto
Year of construction: 2008
Floor area: 200 m^2
Planned life time: 50 years
Height: 2.4 m
Number of floors: 1
Number of rooms: 5
Occupation: 2 Adults with 2 children

Table 1.Building Information

4. Results and Discussion

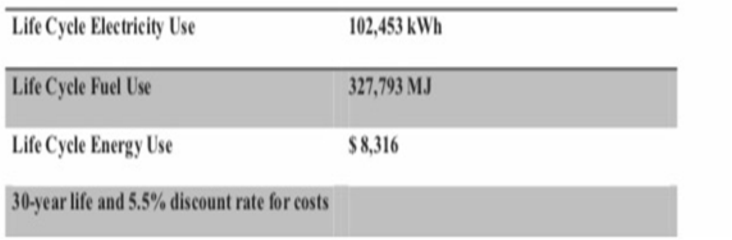
Weather Variables and Effects on Energy Consumption The energy consumption of a single residential building was affected by many weather variables. 1. Temperature: the changes in atmospheric temperature lead to using more or less HVAC. Also, using low or high energy convention and infiltration lead to using more or less electronic equipment through the building. 2. Humidity: the humidity in the atmosphere affected the energy consumption of building as well. It leads to using more or less HVAC and using low or high energy convention and infiltration lead to using more or less electronic equipment through the building. 3. Solar irradiance: the changes in radiant amount produced lead to more or less energy through the windows, where the windows are low or high radiation energy. These gains can affect HVAC and electronic equipment; in this case, the solar plan has to be concerned too. 4. Sunshine duration: the changes in sunlight produced an amount in specific time affected the energy consumption of the building as well. It leads more or less energy through the windows, where the windows are low or high radiation energy. These gains can affect the HVAC and electronic equipment; in this case, the solar plan has to be concerned too. 5. Sky conditions: when the sky is overcast with possibilities of rain, this can increase/decrease the energy when the use of internal lightning may be required. Also, the energy coming from solar energy plates can be significantly affected. 6. Precipitation: snow and rain lead to using more or less of HVAC and electronic equipment due to moisture on external surfaces is low or high power connection. Energy Consumption and CO2 Emissions. The second section in this study quantifies the energy consumption and CO2 emission by considering different sources of energy as pointed in the table below.

Table 2 : Energy Consumption and CO2 Emission by Considering Different Sources of Energy.
The results in this section show that the heat energy consumes about 18,800 Mcal of energy. This amount of energy consumption considered as the most significant amount of energy compared to other energy sources. On other hand, when using the propane as an energy source, the energy consumption was 10.8 kg. This amount represents the lowest value of energy consumption compared to other energy sources. Much energy consumption leads to increased CO2 emissions. Where the heat energy caused about 161,200 Kg of CO2, that represents the largest amount of CO2 emissions compared to other sources of energy. Besides, propane represents the lowest amount of CO2 emissions compared to other sources of energy around 1,248 Kg of CO2. However, the total results of CO2 emission for all energy sources of S RB was 338,674.3 Kg of CO2. Annual CO2 Emissions The third section in this study quantifies the annual CO2 emissions by considering the occupants and the energy impacts of some electronic equipment and some places of SRB as pointed in the table below.
Table 3. Annual CO2 Emission by Considering the Occupants.



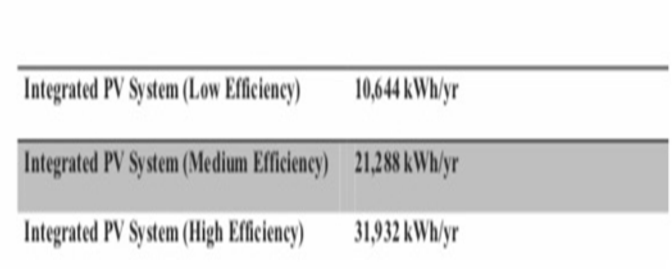
Energy impacts	CO_2 emission (kg)
Thermal control	600
Hot water	2,550
Refrigeration	900
Lighting	800
Kitchen	606
Laundry & bathroom	550
Entertainment	1,500
Car park Ventilation	510

The results in this section reveal that hot water uses a significant amount of electricity compared to other equipment in the building, and this leads to increasing carbon dioxide emissions that cause around 2,550 kg of CO2 emissions each year. Also, car park ventilation represents the lowest amount of CO2 emissions each year compared to other impact energy sources about 510 kg of CO2 emissions. The range of the rest of the impact source emission was between 550 - 1,500 kg of CO2 emission. Life Cycle Energy Analysis. The last section in this study quantifies life cycle energy analysis considering use and cost and life cycle renewable energy analysis as pointed in the tables below.
Table 4 : Life Cycle Energy Analysis (Use/Cost)



Life Cycle Electricity Use	102,453 kWh
Life Cycle Fuel Use	327,793 MJ
Life Cycle Energy Use	$ 8,316
30-year life and 5.5% discount rate for costs	

Table 5 : Life Cycle Renewable Energy Analysis



Integrated PV System (Low Efficiency)	10,644 kWh/yr
Integrated PV System (Medium Efficiency)	21,288 kWh/yr
Integrated PV System (High Efficiency)	31,932 kWh/yr

The results of the life cycle energy analysis considering the use and cost show that the electricity consumption was about 102,453 kWh, fuel consumption approximately 327,793 MJ, and their costs are significantly lower. The discount rate for costs was 5.5%. However, the results of life cycle renewable energy analysis using PV system shows that the amount of energy consumption of integrated PV system (Low Efficiency), (Medium Efficiency), (High Efficiency) was 10,644 kWh/yr, 21,288 kWh/yr, 31,932 kWh/yr respectively. As a result of these, there would be a significant reduction in operating cost, energy cost, and CO2 emissions. However, the capital cost would increase by integrating PV systems, but it would be less significant by a higher carbon tax in the future.

6. Conclusion

In this study, the different phases of life cycle energy and CO2 analysis of a PV system integrated residential building considered. We used the signal residential building located in Toronto in this study. EnergyPlus, SketchUp, and Open Studio were the software programs utilized for modeling the building. The benefit of this study is reduced energy consumption, higher energy efficiency and environmental benefits of CO2 emission reduction. The life cycle analysis is an effective method to reduce energy consumption and CO2 emissions. The results show that the energy consumption of the single residential building was affected by many weather variables. High and low temperature and humidity in the air affect HVAC system usage, which affects energy consumption and related CO2 emission levels. Besides, carbon dioxide emissions from space heating HVAC systems for a single residential building is higher than business as the usual electricity generation system. Moreover, hot water uses the largest amount of energy compared to other energy sources in SRB, which leads to increased carbon dioxide emissions. On other hand, propane water uses the lowest amount of energy compared to other energy sources in SRB, and it represents the smallest amount of CO2 emissions compared to other sources. In addition, the results quantify the annual CO2 emissions by considering the occupants, the energy impacts of specific electronic equipment and some places of SRB pointed that car park ventilation represents the lowest amount of CO2 emissions annually compared to other impact energy sources; hot water uses a significant amount of electricity compared to other equipment in the building, and this leads to increasing carbon dioxide emissions each year. Finally, the results of the life cycle energy analysis show that there would be a significant reduction in operating cost, energy cost, and CO2 emissions. However, the capital cost would increase by integrating PV systems, but it would be less significant than higher future carbon taxes.

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