

Life Cycle Assessment of Residential Buildings: A Case Study in Canada

Venkatesh Kumar, Kasun Hewage, Rehan Sadiq

Abstract—Residential buildings consume significant amounts of energy and produce large amount of emissions and waste. However, there is a substantial potential for energy savings in this sector which needs to be evaluated over the life cycle of residential buildings. Life Cycle Assessment (LCA) methodology has been employed to study the primary energy uses and associated environmental impacts of different phases (i.e., product, construction, use, end of life, and beyond building life) for residential buildings. Four different alternatives of residential buildings in Vancouver (BC, Canada) with a 50-year lifespan have been evaluated, including High Rise Apartment (HRA), Low Rise Apartment (LRA), Single family Attached House (SAH), and Single family Detached House (SDH). Life cycle performance of the buildings is evaluated for embodied energy, embodied environmental impacts, operational energy, operational environmental impacts, total life-cycle energy, and total life cycle environmental impacts. Estimation of operational energy and LCA are performed using DesignBuilder software and Athena Impact estimator software respectively.

The study results revealed that over the life span of the buildings, the relationship between the energy use and the environmental impacts are identical. LRA is found to be the best alternative in terms of embodied energy use and embodied environmental impacts; while, HRA showed the best life-cycle performance in terms of minimum energy use and environmental impacts. Sensitivity analysis has also been carried out to study the influence of building service lifespan over 50, 75, and 100 years on the relative significance of embodied energy and total life cycle energy. The life-cycle energy requirements for SDH are found to be a significant component among the four types of residential buildings. The overall disclose that the primary operations of these buildings accounts for 90% of the total life cycle energy which far outweighs minor differences in embodied effects between the buildings.

Keywords—Building simulation, environmental impacts, life cycle assessment, life cycle energy analysis, residential buildings.

I. INTRODUCTION

THE construction industry supports the human needs in growing urban environment, including provision of housing, water and food supply, health care facilities, efficient transport, and disposal of domestic waste. All these facilities, contribute significantly to resources and energy consumption, as well as to other environmental impacts, such as generation of wastewater, emissions and solid waste [1]. However, residential buildings being major shareholder of entire land use and serving largest number of consumers are the major

contributors to these issues. In the United States, building industry accounts for 39% of the total primary energy use, 38% of carbon equivalent emissions, and 40% of all raw material use annually; the statistics in Canada are almost the same [2]. Such consequences have led this industry to adapt the strategies for more efficient environmentally sustainable designs and construction techniques [3].

The environmental aspects are increasingly more significant in sustainability. Therefore, environmental assessment of building is a significant approach to attain the goal of sustainability. In general, Life-Cycle Assessment (LCA) technique is employed in building industry to quantify and evaluate the environmental aspects during its whole life time, which includes extraction of raw materials, construction, utilization, end of life, and beyond building life [4].

Many LCA studies have been conducted in building sector, various studies mainly focused on residential buildings. For example, [5] presented the method to calculate the energy use during the life cycle of a building and in the same year studied the life cycle of three single unit dwellings in Sweden. Reference [4] studied the LCA for three bedroom semidetached house in Scotland. This study is focused on five construction materials and their embodied energy, and associated Greenhouse gas (GHG) emissions. Reference [6] compared the high and low-density residential buildings in Toronto (ON, Canada) for their energy use and associated GHG emissions. Two functional units are selected for this study: living area (m²) and number of people in a house (per capita basis) and it is demonstrated that the choice of functional unit is vastly relevant for full understanding of urban density effects. The study found that, low-density suburban development consumes 2.0-2.5 times more energy and GHG intensive than High-density urban development on per capita basis. Reference [7] studied the two-storey single family residential building located in Vancouver, Canada. This study focused on construction materials, and manufacturing and operation phases of a building. This study also shows that operational phase contributes high environmental impacts.

Reference [8] proposed the 'emergy-based' LCA framework and compared the single-family and multi-family residential buildings in four Canadian provinces. Nevertheless, this study was not intended to select the better sustainable building; instead this study offered a sustainability assessment tool by providing quantitative and transparent results for informed decision-making. In conclusion, existing literature on the LCA of building focuses primarily on the energy use and greenhouse gas emissions of small to mid-size houses. However, neither the full life cycle (cradle to grave) nor full

Venkatesh Kumar is with the University of British Columbia, 3333 University way, Kelowna BC, Canada V1V 1V7 (corresponding author to provide phone: 250-899-6319; e-mail: venkat1601@gmail.com).

Kasun Hewage and Rehan Sadiq are with the University of British Columbia, 3333 University way, Kelowna BC, Canada V1V 1V7 (e-mail: Kasun.Hewage@ubc.ca, rehan.sadiq@ubc.ca).

range of impact categories that generally included in LCA is considered.

The purpose of this study is to contribute towards a better understanding of the full LCA impacts of residential buildings in Canada by focusing on the most common types of houses: Single family detached house (SDH), Single family attached house (SAH), Low rise apartment (LRA), and High rise apartment (HRA). The main objective of this study is to evaluate and compare the primary energy use and the potential environmental impacts (EI) associated with the alternatives for residential buildings by using the concepts of LCA. This study considered whole life cycle phases of buildings that are located in Vancouver (BC, Canada) with 50 years lifespan. In order to attain the main objective, the following sub objectives have to be fulfilled:

- Perform the building energy simulation to identify the operational energy of the buildings
- Select the best housing type, which consumes low energy and contributes least environmental impact throughout its life cycle
- Perform the sensitivity analysis for four types of houses over 50, 75, and 100 year lifespan

The following sections present and compare the life cycle energy use and EI of each type of the house. It is anticipated that the results of this study would be beneficial for a wide range of stakeholders, including planners, engineers, developers, and policy makers.

II. METHOD STATEMENT

This section represents the methodology of the present study. The energy use and environmental impacts of residential buildings are carried out as following approach:

A. Life Cycle Analysis (LCA)

In order to attain the defined objectives, the Life Cycle Assessment (LCA) methodology was selected for this study. Though, there are various methods available to estimate the environmental impacts, in spite of being adequate to an extent for a particular purpose, those methods are having various shortcomings. LCA is a structured approach and it is performed based on ISO 14040 – 43 standards [9]–[12]. The LCA modelling has been carried out in Athena Impact Estimator (Athena IE) for buildings [13] and US EPA's TRACI method has been used for estimating environmental impacts. According to ISO 14040, LCA method consists of four distinct analytical stages:

1. Defining the goal and scope of the LCA
2. A life-cycle inventory (LCI) of the materials and their associated environmental impacts
3. A life-cycle impact assessment of the system using the LCI data
4. Interpretation of the results

The stage one of LCA study is to state the purpose, scope, and system boundaries. The goal of the study is to evaluate the life cycle energy use and EI of typical types of houses in Canada and to scrutinize whether the obtained results are significantly skewed by the type of house. These results are

then used to evaluate the overall energy use and impacts from the Canadian housing sector with the aim of identifying the best alternative.

The functional unit is considered as 1m² of floor area of a house over its lifetime. A 50 year lifespan was assumed for this study, which is commonly used by researchers in LCA study of building. Also, this allows for a significant time period for repair, and replacement of building materials. The brief description of each type of house is summarized in section B. The framework for system boundaries and outputs of this LCA study are shown in Fig. 1. As can be seen, the system boundaries can be divided into three distinct phases, i.e. the pre-occupancy, the occupancy, and the post-occupancy. The outputs comprises of the total primary energy use and the EI for all phases.

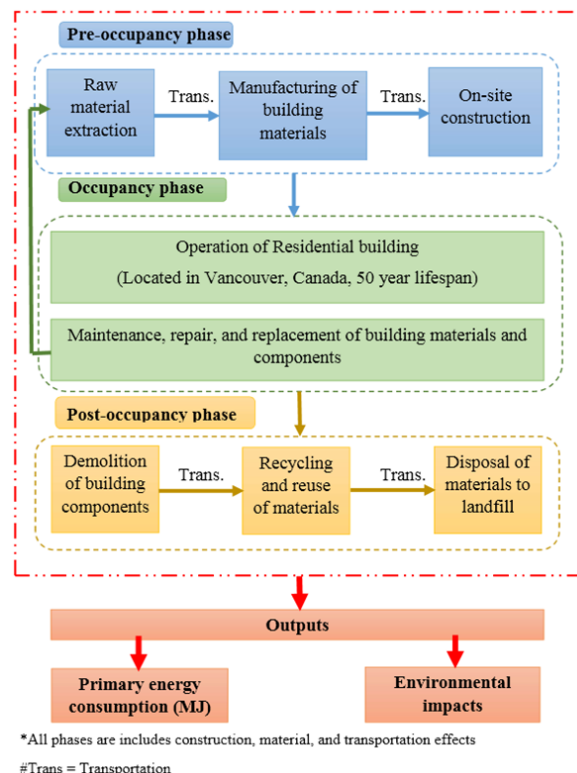


Fig. 1 LCA system boundaries and outputs

The stage two of LCA study is life cycle inventory (LCI), starts with making a process tree or a flow-chart classifying the events in a building's life-cycle which are to be considered in the LCA, plus their interrelations. This procedure is followed by data collection, where quantitative and qualitative data for all inflows and outflows, such as raw materials, energy, ancillary products, land use and emissions are gathered. The next step in LCI is to calculate the amount of energy used and emissions of the studied system in relation to its functional unit [10], [14]. In this study, the Athena IE software is used to assess the material and energy inputs and outputs.

The stage three of LCA study is life cycle impact assessment (LCIA), which calculates the potential EI and estimates the energy used in the studied system or process. The detailed LCIA results are presented in results and discussion section

Finally, the last stage of LCA study is interpretation, which is an iterative process present during all phases of the study. The findings of the LCI and LCIA are combined here in order to achieve the recommendations and conclusions for the study.

B. Description of the Case Study

In this study, four types of residential buildings in Vancouver (BC, Canada) are used as a case study to demonstrate the mechanism of this research method. The basic parameters of these buildings are provided in Table I. In which, floor area and building orientation are shown explicitly. SDH and SAH have two floors (first and basement) and the layout is identical, and it is assumed that the kitchen and living area are on the basement with the bathroom and the bedrooms on the first floor. Whilst it was assumed that LRA, and HRA has single floor for each family. HRA comprises of concrete columns and beams for structure load bearing, whereas, other houses have traditional strip footing foundations. The type and quantity of construction materials have been estimated from literature, direct observations, drawings from local contractors, and expert consultation.

Other than the identified building components (Table I), the four houses share the following characteristics:

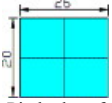
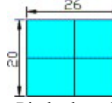
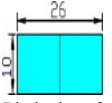
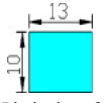
- Each of the house is standalone residential building
- Long side of the house aligned along E-W axis
- Hours of occupancy (HOC): default residential HOC from DesignBuilder software

- Lighting system: Florescent T5 with linear controlling and occupancy sensor
- Building structure designed according to the national building code of Canada, 2005.
- These building characteristics were chosen based on a combination of ASHRAE standard 90.1-2007 requirements for climate zone 5 (British Columbia, Canada).

C. Athena Impact Estimator for Buildings

Athena Sustainable Materials Institute, a non-profit organization based in Ontario, Canada developed the ATHENA[®] Impact Estimator for Buildings. The Institute's mission is to promote sustainability in the built environment through the use of LCA in North America. Notably, it is the only software tool presently available in North American context. The Athena IE was developed as a support tool to aid in the decision making process at the conceptual design stage. The software provides a cradle-to-grave LCA for a building and individual assemblies. This software generates the bill of materials based on the given inputs, this can be compared with expected outcome, and in case of any discrepancies the material quantities can be adjusted using 'additional materials' input feature. The Athena IE takes into account any or all of the following building characteristics and life-cycle factors to measure the impact in each of the metrics: Material manufacturing, including resource extraction and recycled content, transportation, On-site construction, regional variation in energy use, transportation and other factors, type of building and lifespan, maintenance and renovation effects, end of life management.

TABLE I
BASIC PARAMETERS OF EXAMINED RESIDENTIAL BUILDINGS [15]

Building component	HRA	LRA	SAH	SDH
No. of floors	8	3	2	2
Area of unit (m ²)	520	520	260	130
Height (m)	26.4	9.9	6.6	6.6
Gross floor area (m ²)	4160	1560	520	260
No. of family	8*4=32	3*4=12	2*1=2	1*1=1
Load bearing structure	Concrete columns and beams	Wood joist and truss	Wood joist and truss	Wood joist and truss
Foundation type	Individual concrete shallow foundation for basement columns	Concrete strip footing	Concrete strip footing	Concrete strip footing
Building orientation				
Roof type	Pitched roof	Pitched roof	Pitched roof	Pitched roof

D. Calculating Embodied Energy Use and Environmental Impacts

Calculating the environmental damage caused by houses over its life cycle is a challenging task. Embodied energy is the energy used during the construction stage of a building, it includes the energy incurred at the time of erection/construction of materials, as well as the renovation of building components [16]. According to [17], LCI involves the collection of data and modeling to estimate the total

amounts of emissions, waste, energy used, and materials used throughout the life cycle of a building [18]. Although specific techniques are available to manually conduct LCI, various computer software tools develop in the recent past have superseded these techniques. Calculating the energy use and environmental impacts at each stage of the house including raw materials extraction, manufacturing of building materials, construction, maintenance, end-of-life management, and

transportation during all of these stages is computationally intense.

In this study US EPA's TRACI 2.1 method is selected for LCIA. Currently it is the only method available for North America. The method evaluates different categories of environmental impacts, including, acidification, eutrophication, smog potential, fossil fuel consumption, global warming, human health particulate, non-renewable energy, and ozone depletion.

Each house in this study is separately modeled as precisely as possible using the gathered inputs. Athena IE generated the detailed bill of quantities for each house however HRA is presented in Table III for detailed clarification. Unfortunately, the embodied effects associated with the electrical, HVAC, and plumbing services in a building cannot be calculated using Athena IE. Hence, these embodied effects have not been considered in this study.

The Athena IE can evaluate only the embodied energy, and currently there is no option for evaluating the operational energy of a building. Yet, it consists of a calculator that transforms the estimated operational energy into primary energy over a building's life cycle. However, this estimation of operational energy use must be calculated using additional building energy simulation software tool.

E. Calculating Operational Energy Use and Environmental Impacts

During occupancy in a building, operational energy is required for space heating, space cooling, lighting, domestic

hot water, and equipment; however, it varies significantly based on the level of comfort, climatic conditions and the operating schedules [16]. Currently, various computer applications are available to calculate the operational energy of a building. For this study, DesignBuilder software tool is selected for the purpose. DesignBuilder is the building energy simulation software for modeling building heating, cooling, lighting, ventilating, and other energy flows. It is the first software tool with wide-ranging user interface to the Energy Plus. The software allows for prompt building modeling and ease of use with state of the art dynamic energy simulation. This software provides the comprehensive and detailed output, i.e. hourly, monthly, and annual energy use of a building.

In general, energy can be classified in to two major types, primary and secondary energy. As mentioned earlier, in this study, the Athena IE for buildings evaluates embodied energy in terms of primary energy and the DesignBuilder evaluates the secondary energy. The estimated secondary energy (i.e. operational energy or site energy) and energy mix (i.e. electricity, natural gas, geothermal, etc.) have been used as the inputs to Athena IE to calculate the resulting total primary energy use and total environmental impacts. [2].

In this study, the annual energy consumption for each type of housing unit is modeled in DesignBuilder version 3.1.0.068; and the results are presented in Table II. Later, the obtained annual energy use values are entered in Athena IE to get the total operating energy and environmental impacts.

TABLE II
ANNUAL ENERGY CONSUMPTION OF HOUSING UNITS

	Heating	Cooling	Lighting	DHW	Misc. Equipment	Total Energy Use	Energy intensity (kWh/m ²)
SDH	342099	6443	765	1676	735	39002	311
SAH	57276	11506	1580	3398	1489	75248	296
LRA	131830	33173	9651	20481	8976	204111	133
HRA	169529	67496	25716	54617	23938	341295	84

Note – All the values are equivalent to kWh, except energy intensity

F. Calculating Total Life Cycle Energy Use and Environmental Impacts

The two major outputs of this study are the total life cycle energy consumption and the total life cycle environmental impacts. The total life cycle energy consumption in million joules (MJ) of each house is the sum of total embodied energy and the total operational energy over the lifespan of 50 years. In this study, total embodied energy, total operational energy, and total life cycle energy are presented in terms of primary energy consumption.

The total life cycle EI is also estimated similar to total energy use. The total life cycle EI of each house is the sum of total embodied EI and the total operational EI over 50 years of lifespan.

III. RESULTS AND DISCUSSION

In this section, the results of a comprehensive LCA study of four types of residential buildings in BC, Canada are presented. The presentation of results is divided into the

following categories: total embodied energy and environmental impacts, total operating energy and embodied impacts, and total life cycle energy and environmental impacts.

A. Total Embodied Energy Use and Environmental Impacts

A breakdown of total embodied energy for four types of buildings for a service life of 50 years is illustrated in Fig. . The results are divided into the relevant building life stages: product, construction process, use or maintenance, end of life, and beyond building life. The total embodied energy of buildings is about 2700MJ, 1750MJ, 2000MJ, and 2170MJ for HRA, LRA, SAH, and SDH respectively. This clearly indicates that HRA has high-embodied energy than other residential buildings. This result is logical, as HRA comprises of concrete columns and beams whereas other buildings are constructed on traditional strip foundations. Besides, the large majority of the impact (~70%) is from the product stage, with the construction contributing 10%,

utilization (9%), and demolition and disposal stages with the remaining ~8%.

Though SDH claims least with 68% in product stage, LRA consumes least total embodied energy among the other alternatives. In order to get a more insight in total embodied energy, the results are also analyzed based on building material group (see Fig.). The four major building assemblies, i.e. foundations, walls, floors, and roofs are considered for this study.

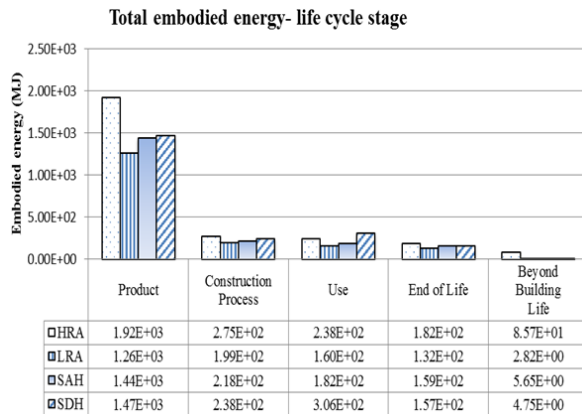


Fig. 2 Total embodied energy for building life cycle stages

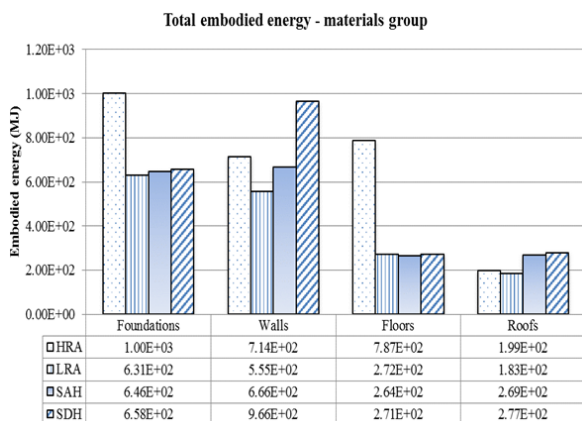


Fig. 3 Total embodied energy for building materials group

The summation of foundation and walls consumes about 60% of the total embodied energy for HRA, LRA, and SAH; whereas, SDH claims the highest embodied energy around 75%. HRA has a load bearing structure different from other houses; it comprises of columns and beams to transfer the building load. However, it was considered as foundations to ease the analysis. HRA accounted for higher embodied energy for floors (29%), primarily because of more number of floors than other houses. These results reveal that LRA consumes the minimum total embodied energy amongst all the alternatives.

A breakdown of embodied EI is illustrated in Fig. 4. In terms of the total embodied EI, the relationship between the EI and the embodied energy are much the same.

The foundation and walls for all the building types are responsible for maximum embodied EI. In addition, the columns and beams, and floors of HRA have high influence on embodied environmental impacts. This is mainly due to the fact that the columns, beams, and floors are comprised of concrete and steel, which tend to have higher embodied environmental impacts than many other building materials when used in large quantities. Out of eight categories of environmental impacts, non-renewable energy is the major contributor with 50% of total environmental impacts (50%), followed by fossil fuel consumption (48%), and global warming with the remaining 2% for all types of houses. Other impact categories are found to be negligible. In most cases, the embodied environmental impact for the product stage (70%) was the highest contributor toward the total embodied impacts followed by construction (11%), and maintenance (9%) stages of the buildings. Similar to the total embodied energy consumption, LRA has the least total environmental impacts after 50 years.

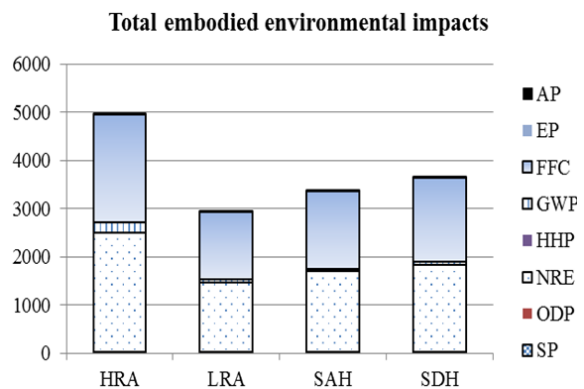


Fig. 4 Total embodied environmental impacts

B. Total Operational Energy Use and Environmental Impacts

Annual energy use was calculated by simulating the building models in DesignBuilder software tool and listed in Table II in which, space heating accounted for high energy use with 75% for SDH and SAH, 65% for LRA, and 50% for HRA. HRA has high-energy use for space cooling (20%) and domestic hot water (16%). In general, the building height and energy use is indirectly proportional, especially in cold climate. This energy use is provided as an input for calculating life cycle operational energy in Athena IE. Generally, in Canada, energy sources for space heating are electricity (53%), natural gas (25%), wood and propane (13%), and oil (10%). Space cooling and lighting system use only electricity (100%) for operation. Energy sources for domestic hot water are electricity (68%), natural gas (25%), oil (5%) and other (2%). Electrical appliances use 96% of electricity and 4% of natural gas energy sources. All these details are proportionately entered in Athena IE to calculate total operational energy use, which is shown in Fig. 5. Therefore, over a 50-year lifespan total operational energy for HRA is 18484MJ, which is the least with 87% of total life cycle

energy. SDH claims high total operational energy of 95%. It is important to note that the operating energy is highly dependent on the degree of thermal resistance provided by the building enclosure and height of building. In cold climates, space heating claims vast amount of energy, when a building height increases it shares the heating gains among the floors and the area of sun exposure is less compare to other houses, hence the performance for space heating is improved accordingly and overall it claims low energy demand. The operational energy use gradually increase when the building height decrease. In a result LRA, SAH, and SDH claim 94%, 95% and 95% of total operational energy. If a decision making process is only based on energy use, HRA is the best among the four housing types.

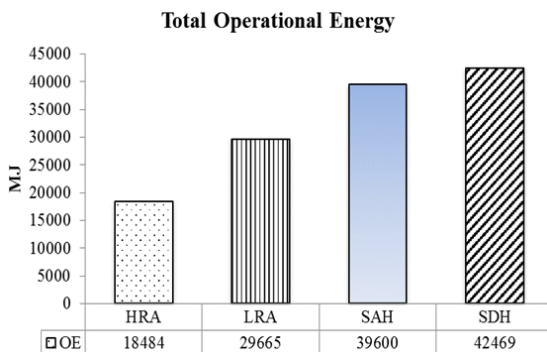


Fig. 5 Total operational energy (per m²)

A breakdown of EI for operational stage of buildings is illustrated in Fig. . In terms of operational environmental impacts, the relationships between the various building components are almost same as the relationships for operational energy, which is 14%, 23%, 30%, and 33% for HRA, LRA, SAH, and SDH respectively. Hence it can be concluded that the operating energy and EI for all the building types are identical.

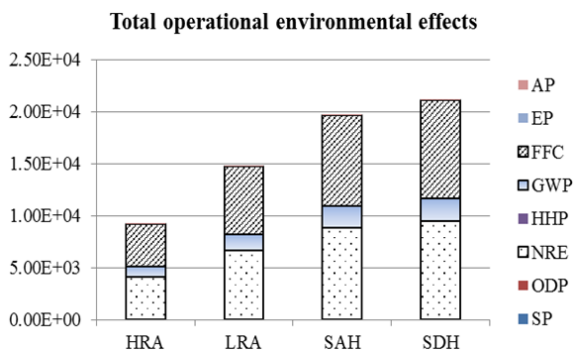


Fig. 6 Operational phase environmental impacts

Fig. 6 illustrates that, both non-renewable energy and fossil fuel consumption has the highest EI with 45%, followed by global warming with the remaining 10% for all types of

houses. Other impact categories are causing least or negligible amount of impacts to the buildings.

C. Total Life Cycle Energy Use and Environmental Impacts

Total life cycle energy use is defined as the summation of total embodied energy and total operational energy. A breakdown of the total life cycle energy for 50-year lifespan for four types of houses is shown in Fig. 7. Over a 50-year lifespan, HRA consumes 21184 MJ of primary energy to fulfill the operational need of the building. Similarly LRA, SAH, and SDH consume 31415 MJ, 41608 MJ, and 44641 MJ of primary energy respectively.

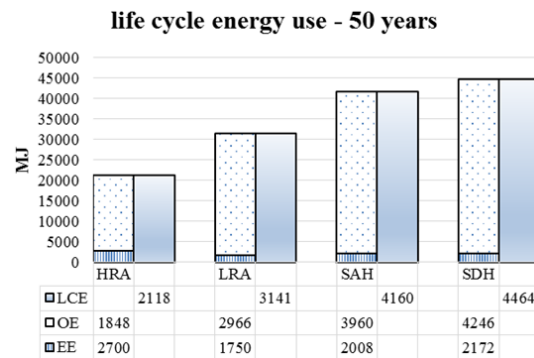


Fig. 7 Total life cycle energy use for 50-years lifespan

It has been noted that the total life cycle energy has predominant operational energy for the building types. Operational energy for HRA represents about 87% of the total life cycle energy after 50 years, while the embodied energy is only about 13%. Other types of house consume around 94%, during the operational stage and the remaining 6% as embodied energy. Clearly, the operating energy of typical residential buildings in Canada represents significantly larger proportion of the total life-cycle energy than the embodied energy of the building components.

A breakdown of life cycle EI for four types of buildings is illustrated in Fig. 8. In terms of life cycle EI the relationships are similar to lifecycle energy. For example, the total operating EI for HRA also represents about 87% of the total life cycle EI after 50 years.

Life cycle energy analyses over lifetimes of 50, 75, and 100 years were carried out for the four types of residential buildings. However, the lifespan of buildings over 75 and 100 years indicates that the operational energy and associated EI has slightly increased with about 2% over 25 years. Hence, the total operating EI has increased to 92.5% of the total EI after 100 years. Similarly total EI of LRA increase from 94 to 97%, SAH 95 to 97%, and SDH increase from 95 to 97%, which is the least among the four types of buildings. However, total EI for HRA are least with 18% and SDH accounts for 31% between the buildings.

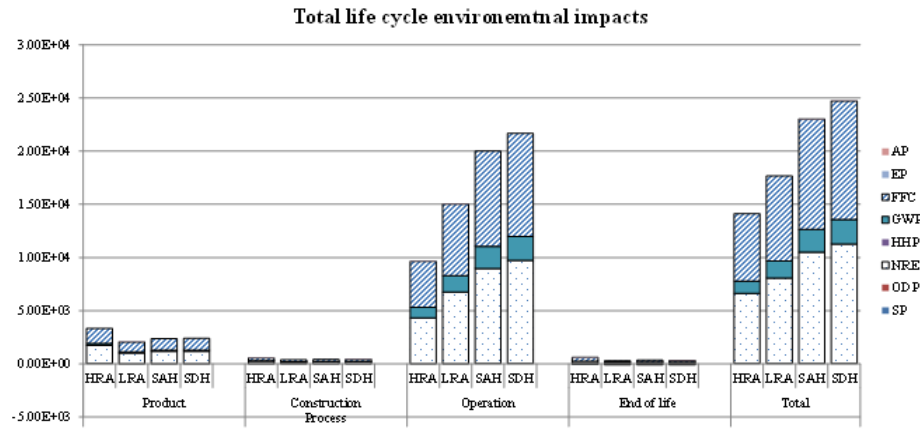


Fig. 8 Total life-cycle environmental impacts

IV. SENSITIVITY ANALYSIS

Sensitivity analysis (SA) is used to generalize the method across a range of building types and design parameters [19]–[21]. In this study, SA was performed to determine the influence of variations in life cycle stages of building in terms of embodied energy and operational energy on the total life cycle energy. The SA was carried out using @risk software tool, it's an excel add-on tool, and it performs the Monte Carlo simulation and other statistics calculations. The SA was performed for the total life cycle energy over 50, 75, and 100-year (Fig. 9) lifespan for four types of buildings.

The SA for embodied energy results shows that, when the service lifespan of building increased the maintenance phase of SDH has a significant effect towards total embodied energy (Fig. 10) followed by maintenance phase of HRA. However, SA for the total primary energy of buildings results illustrates that the SDH highly influenced (see Fig. 11) the total life cycle primary energy over the years.

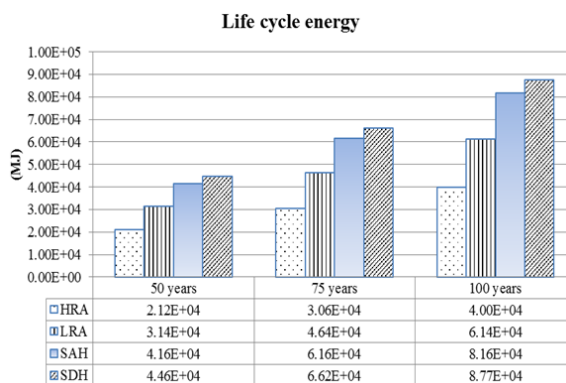


Fig. 9 Life cycle energy for residential buildings

The result is logical because as seen earlier SDH's total operational energy and maintenance phase of embodied energy consumes very high energy comparing to other buildings. Operational energy is the most pre-dominant factor

in all types of building, which is above 80%, so when the service lifespan increases this directly impact the results.

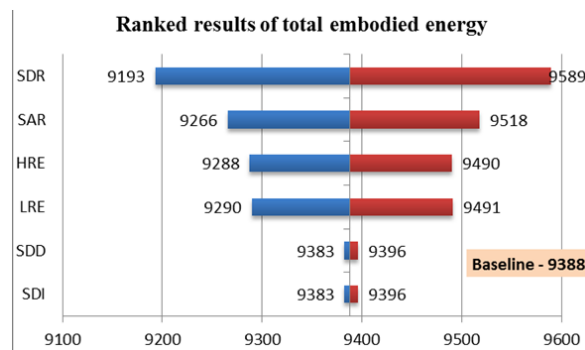


Fig. 10 Sensitivity analysis for total embodied energy

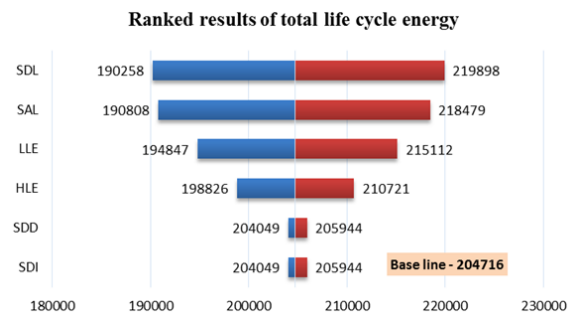


Fig. 11 Sensitivity analysis for total life-cycle energy

V. CONCLUSION

Many of the researchers studied the building types in terms of building materials such as concrete, wood, steel, etc. especially in residential buildings sector. Also, numerous LCA studies focused single family house, apartment building or combination of single family houses. Despite the many differences in terms of the LCA scope, system boundaries, and LCI data between these studies, virtually all of them reach the same general conclusion that after any significant lifespan, operating effects far outweigh embodied effects. However,

none of the research conducted in life cycle energy use and environmental impacts of residential buildings in Canada. Hence, this study aimed to compare the life cycle energy use and environmental impacts of most common housing types (i.e. HRA, LRA, SAH, and SDH) in Canada. In order to attain this, the total embodied energy and embodied EI, and the total operational energy and operational EI was calculated using Athena Impact Estimator for buildings and Design Builder software. A case study houses located in Vancouver (BC, Canada) with 50 year lifespan was used for this analysis. The results of this study are summarized below:

- **Total embodied energy use and EI:** $HRA > SDH > SAH > LRA$
- **Total operational energy use and EI:** $SDH > SAH > LRA > HRA$
- **Total life cycle energy use and EI:** $SDH > SAH > LRA > HRA$

The results show that LRA consumes least energy and has least EI, in terms of embodied effects. However, HRA consumes least energy and has least EI, in terms of operational and total life cycle effects.

Similar to other researches, this study also found that operational energy represents the large majority of energy use in a building during its life cycle. It also presents a linear relationship between the operational and total life cycle energy, valid through all the cases regardless of climate and other significant differences. Therefore, HRA results in being

more energy efficient than the other housing types, despite it has the highest embodied energy.

Therefore, strategies that directly or indirectly reduce the demand for operational energy and operational EI of residential buildings should be the first priority if reducing the total energy and EI of the building is a concern. Once the operating energy and EI are reduced by around 50%–90% from typical values today, then optimizing the embodied energy and EI becomes important. Whilst occupancy behavior plays a huge role in energy use, the highest opportunities for improvement lies in the design phase of the house because a decision taken in this phase determine the energy use and EI throughout the life cycle of a house. For example, when a renewable or low EI energy source is introduced in building operation, it will directly impact the studied results. Hence, proper care should be taken while decision making process. Therefore, this study emphasizes the importance of sustainable building design, including energy efficient building materials, thermal insulation, and building envelope. Coupled with smaller floor areas, energy efficient appliances, renewable energy sources could aid to deliver a more sustainable housing stock in Canada.

With the knowledge from this paper, further research can be conducted to develop multi-criteria multi- objective algorithm for the selection of residential buildings. In addition, with the help of questionnaire survey from public, social impact factor can be included in the building selection process.

APPENDIX

TABLE III
BILL OF QUANTITIES FOR HRA

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Mass Value	Mass Unit
#15 Organic Felt	m2	2460	0	0	0	0	2460	1.80	Tonnes
1/2" Regular Gypsum Board	m2	11306	0	0	0	0	11306	91.13	Tonnes
Air Barrier	m2	2289	0	0	0	0	2289	0.14	Tonnes
Ballast (aggregate stone)	kg	149557	0	0	0	149557	0	149.56	Tonnes
Blown Cellulose	m2 (25mm)	12364	0	0	0	0	12364	7.91	Tonnes
Concrete 30 MPa (fly ash 25%)	m3	425	0	178	35	0	212	987.43	Tonnes
Concrete 30 MPa (fly ash ave)	m3	1251	510	537	105	98	0	2907.63	Tonnes
Double Glazed Hard Coated Argon	m2	384	0	0	0	0	384	6.21	Tonnes
Expanded Polystyrene	m2 (25mm)	354	0	0	0	0	354	0.25	Tonnes
Extruded Polystyrene	m2 (25mm)	2259	0	0	0	2259	0	2.78	Tonnes
Fiber Cement	m2	2374	0	0	0	0	2374	33.21	Tonnes
Galvanized Sheet	Tonnes	4	0	0	0	0	4	3.90	Tonnes
Glass Fiber	kg	4480	0	0	0	0	4480	4.48	Tonnes
Glazing Panel	Tonnes	5	0	0	0	0	5	5.12	Tonnes
Joint Compound	Tonnes	11	0	0	0	0	11	11.28	Tonnes
Laminated Veneer Lumber	m3	5	0	0	0	0	5	2.58	Tonnes
Nails	Tonnes	2	0	0	0	0	2	1.98	Tonnes
Oriented Strand Board	m2 (9mm)	8684	0	0	0	0	8684	52.43	Tonnes
Paper Tape	Tonnes	0.1	0	0	0	0	0	0.13	Tonnes
Polyester felt	Tonnes	0.9	0	0	0	1	0	0.87	Tonnes
Polyethylene Filter Fabric	Tonnes	0.2	0	0	0	0	0	0.19	Tonnes
PVC Membrane 48 mil	kg	5466	0	0	0	5466	0	5.47	Tonnes
PVC Window Frame	kg	8237	0	0	0	0	8237	8.24	Tonnes
Rebar, Rod, Light Sections	Tonnes	168	113	41	0.80	5	8	167.51	Tonnes
Screws Nuts & Bolts	Tonnes	2	0	0	0	0	2	2.01	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	117	0	0	0	0	117	52.28	Tonnes
Solvent Based Alkyd Paint	L	56	0	0	0	0	56	0.04	Tonnes
Water Based Latex Paint	L	39565	0	19688	0	0	19876	29.67	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0	0	0	0.47	0	0	0.47	Tonnes

REFERENCES

- [1] R. M. Cuéllar-Franca and A. Azapagic, "Environmental impacts of the UK residential sector: Life cycle assessment of houses," *Build. Environ.* vol. 54, pp. 86–99, 2012.
- [2] K. Van Ooteghem and L. Xu, "The life-cycle assessment of a single-storey retail building in Canada," *Build. Environ.* vol. 49, pp. 212–226, Mar. 2012.
- [3] A. Ganjidoost and S. Alkass, "Environmental Life Cycle Analysis of Office Buildings in Canada," *Int. J. Eng. Technol.*, vol. 4, no. 5, pp. 602–606, 2012.
- [4] M. Asif, T. Muneer, and R. Kelley, "Life cycle assessment: A case study of a dwelling home in Scotland," *Build. Environ.* vol. 42, no. 3, pp. 1391–1394, Mar. 2007.
- [5] K. Adalberth, "Energy use during the life cycle of buildings: a method," *Build. Environ.* vol. 32, no. 4, pp. 317–320, Jul. 1997.
- [6] K. Adalberth, "Energy use during the life cycle of single-unit dwellings: Examples," *Build. Environ.* vol. 32, no. 4, pp. 321–329, Jul. 1997.
- [7] J. Basbagill, F. Flager, M. Lepech, and M. Fischer, "Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts," *Build. Environ.* vol. 60, pp. 81–92, Feb. 2013.
- [8] J. Norman, J. Norman, H. L. MacLean, H. L. MacLean, C. a. Kennedy, and C. a. Kennedy, "Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions," *J. Urban Plan. Dev.*, vol. 132, no. 1, p. 10, 2006.
- [9] W. Zhang, S. Tan, Y. Lei, and S. Wang, "Life cycle assessment of a single-family residential building in Canada: A case study," *Build. Simul.*, vol. 7, no. 4, pp. 429–438, 2014.
- [10] B. Reza, R. Sadiq, and K. Hewage, "Emergy-based life cycle assessment (Em-LCA) of multi-unit and single-family residential buildings in Canada," *Int. J. Sustain. Built Environ.* vol. 3, no. 2, pp. 207–224, Oct. 2014.
- [11] I. O. for S. ISO 14040, "Environmental management: life cycle assessment. Principles and framework," 2006.
- [12] I. O. for S. ISO 14041, "ISO 14041 Environmental management — Life cycle assessment — Goal and scope definition and inventory analysis," 1998.
- [13] I. O. for S. ISO 14042, "ISO 14042 Environmental management - Life cycle assessment - Life cycle impact assessment," 2000.
- [14] I. O. for S. ISO 14043, "ISO 14043 Environmental management — Life cycle assessment — Life cycle interpretation," 2000.
- [15] A. I. E. AIE, "Athena Impact Estimator for Buildings and the Athena EcoCalculator for Assemblies," <http://www.athenasmi.org/>, 2015. .
- [16] H. Baumann and A.-M. Tillman, *The Hitch Hiker's Guide to LCA*. 2004.
- [17] O. S. Asfour and E. S. Alshawaf, "Effect of housing density on energy efficiency of buildings located in hot climates," *Energy Build.*, vol. 91, pp. 131–138, Mar. 2015.
- [18] I. O. for S. ISO 14044, "ISO 14044: Environmental Management — Life Cycle Assessment— Requirements and Guidelines," 2006.
- [19] S. L. Hsu, "Life Cycle Assessment of Materials and Construction in Commercial Structures: Variability and Limitations," *Massachusetts Institute of Technology*. 2010.
- [20] X. Li, F. Yang, Y. Zhu, and Y. Gao, "An assessment framework for analyzing the embodied carbon impacts of residential buildings in China," *Energy Build.*, vol. 85, pp. 400–409, Dec. 2014.
- [21] T. J. Wen, H. C. Siong, and Z. Z. Noor, "Assessment of Embodied Energy and Global Warming Potential of Building Construction using Life Cycle Analysis Approach: Case Studies of Residential Buildings in Iskandar Malaysia," *Energy Build.*, vol. 93, pp. 295–302, Dec. 2014.

Venkatesh Kumar was born in Salem, India, in 1988. He received the Bachelor of Engineering in civil engineering from Anna University, Chennai, India in 2008. From 2014, pursuing Master of Applied Science in civil engineering from the University of British Columbia, BC, Canada.

In 2008, he joined in the department of civil engineering in ESSAR group as a Graduate Engineer Trainee, and got promoted to Deputy Manager in 2011. In 2012, he joined in LARSEN & TOUBRO as an Assistant Manager. His main areas of interest are life cycle assessment, sustainable energy, and project management.