Exploring the Intersection of Science and Policy: The Case Study of Installing Solar Panels and Energy Storage System at the University of Ottawa

Eslam Elshorbagy

Under supervision of
Dr. Miroslava Kavgic

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Department of Civil Engineering

Faculty of Engineering

Institute of Science, Society, and Policy

Faculty of Social Science

University of Ottawa

Abstract

Buildings account for up to a third of total world greenhouse gas GHG emissions, and this pattern is expected to persist. By 2050, cities will be home to 70 % of the world's population, demanding a significant number of buildings to be constructed. Efforts to reduce these emissions in the past had varied performance. However, several examples indicate that well thought and adequately executed mix of building technology coupled with environmental policies may reduce emissions. Therefore, cities worldwide are joining the race to decarbonize their buildings to become net-zero carbon and support green economies through a diversified bundle of policies. However, designing and selecting the appropriate mix of building technology and environmental policies is challenging to generate the most outlast net-zero carbon impacts. This research aims to uncover the intersection between science and policy's role in achieving a global net-zero energy building sector. First, an urban comparative analysis for ten environment-leading cities has been made to understand the latest progress in the building sector and draw on future recommendations. The findings are thematically grouped into five themes a) Building's energy efficiency (energy demand sector). (b) Electrified renewable grids (energy supply sector). (c) Green fiscal incentives (d) Education and capacity building. (e) Governance and collaboration. Second, the University of Ottawa has been utilized as a part of the campus as a living lab initiative to examine installing photovoltaic panels over the campus buildings as part of the university expansion program to achieve net-zero operations by 2040. The following parameters have been considered to address the PV systems viability, 1) the expected electricity output. 2) the initial and operational costs. 3) the GHG reductions in operational energy. 4) the PV system embodied carbons. RETScreen Expert software has been used to perform the Life Cycle Cost Analysis (LCCA) to assess PV system output and financial viability. One Click-LCA software to carry-out Life Cycle Assessment (LCA) to assess embodied carbons. The results indicate from analyzing 31 buildings that 20% - 107% of electricity can be offset depending on each building's energy use and solar collector area. Additionally, the 31 buildings analyzed for electricity generation collectively have the potential to save around 23% of the total campus electricity consumption with a production capacity of 18 million units (kWh) annually, including 21,108 solar panels. Also, the project shows financial viability only if the PV systems are installed as part of the whole campus with a Net Present Value (NPV) of $4,985,89 and an Internal Rate of Return (IRR) of 11.4%. The analysis shows 24% and 18% maximum sensitivity to increased initial cost and decreased electricity generation/rate. Finally, the GHG estimated reductions over 25 years from generated electricity are 14,445 tCO2, and the estimated increased embodied carbons from the Life Cycle Assessment are set to be 1,023 tCO2. Additionally, drawing upon urban analysis and the case study, the research highlights the dynamic nature of the building sector emissions reduction and city initiatives. Thirdly, a detailed analysis was carried out in the System Advisor Model (SAM) software to integrate the solar system with energy storage in the Advanced Research Complex (ARC) Building at the University of Ottawa. The study assesses the system viability and helps the university to reduce its monthly electricity bill and help Ontario to maintain its grid reliability by keeping the electricity demand low at peak times. The findings show that using an integrated solar system with an energy storage system by mitigating 100%, 90%, 75%, and 50% of the building electricity demand during the Ontario gird peak could lead to a Net Present Value of $2,01, $1.70, $1.30, and $0.864 million over 25 years the lifetime of the project through the Ontario Global Adjustment Program. The study also shows that with the absence of the Ontario Global Adjustment Program as a fiscal reform tool and relying only on the time of use electricity rates, the solar panels with an energy storage system could lead to a negative Net Present Value of $-550 thousand.

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List of Symbols

Symbol	Description	Unit
SCA	Solar collector area	m^2
BRA	Building roof area	m^2
D	Deductions	m^2
FPC	Final system power capacity	kWh
X	Power capacity adjustment factor	%
PC	Power Capacity	kWh
η_p	Average system efficiency	%
η_r	Solar panel efficiency	%
β_p	Temperature coefficient for panels efficiency	%/℃
T_c	The average panel temperature	℃
T_r	Specific temperature	℃
T_a	Mean monthly ambient temperature	℃
$NOCT$	Nominal Operating Cell Temperature	℃
K_t	The monthly clearness index	-
C_f	Correction factor	-
S_M	The optimum tilt angle	°
S	actual tilt angle	°
E_p	PV electricity generation before adjustment	kWh
S_a	Area of the module	m^2
H_t	Hourly irradiance	kWh/m^2
E_A	PV electricity generation after adjustment	kWh
λ_p	PV miscellaneous losses	%
λ_c	PV power conditioning losses	%
IRR	Internal Rate of Return	%
N	Project life	$year$
C_n	Cash flow for year n	$
SP	Simple Payback	$year$
C	Initial project cost	$
IG	the incentives and grants	$
C_{ener}	yearly energy savings or earnings	$
C_{capa}	annual capacity savings or earnings	$
C_{RE}	yearly renewable energy production credit	$
C_{GHG}	reduction earnings	$
$C_{O\&M}$	yearly operation and maintenance costs	$
C_{fuel}	yearly fuel or electricity cost	$
N_{PCF}	Equity / Discounted Payback	$year$
$\tilde{C}_n$	after-tax cash flow in year n	$
NPV	Net Present Value	$
r	discount rate	%
$ALCS$	Annual Life Cycle Savings	$\$/year$

$B-C$	Benefit Cost ratio	-
f_d	debt ratio	-
T_n	Tax at year n	$
$C_{in,n}$	In-cash flow at year n	$
$C_{out,n}$	Out-cash flow at year n	$
C_{prod}	Energy production cost	$/kWh
r_i	inflation rate	%
r_e	cost escalation rate	%
Δ_{GHG}	annual GHG emission reduction	tCO_2
GRC	GHG emission reduction cost	$
e_{base}	base case GHG emission factor	tCO_2/MWh
e_{prop}	proposed case GHG emission factor	tCO_2/MWh
E_{prop}	proposed case annual electricity produced	kWh
λ_{prop}	fraction of electricity lost in transmission and distribution	%
e_{cr}	GHG emission reduction credit transaction fee	$\$/tCO_2$).
q	Total charge	Ah
I	Current	A
Δt	timestep	hr
E	Energy	Wh
V	Voltage	V
P	Power	W
ΔE	difference in energy	Wh
Δq	difference in total charge	Ah
V_o	battery constant voltage	V
R	internal resistance	A
K	polarization voltage	V
q_{max}	the maximum charge	Ah
a	exponential zone amplitude	V
B	exponential zone time constant inverse	Ah^{-1}
e	Euler's constant	-
dt	timestep	hr
$\int Idt$	amount of removed capacity	Ah
q_{full}	fully charged cell capacity	Ah
$q_{exp,\%}$	the precent of q_{full}	%
t_{exp}	time at which q_{full}	hr
t_{nom}	time at which q_{nom}	hr
f	battery heat transfer	W
T_{room}	room temperature	$°C$
T_{batt}	battery temperature	$°C$
V_{full}	fully charged voltage	V
V_{exp}	voltage at the end of the exponential zone	V
m	Mass	kg
C_p	specific heat	$J/(kg.K)$
h	transfer coefficient	$W/(m^2.K)$

A	battery surface area	m^2
C_t	capacity modifier	%
T_{batt}	Battery temperature	$°C$
PDF	Peak Demand Factor	%
$\sum PDB$	Sum of the building peak demand	kWh
$\sum PDO$	sum of the Ontario peak demand	kWh
5PH	Ontario five peaks	hr
$GACs$	Global Adjustment Cost share	$
$LCOEGA$	The Levelized Cost of Energy (LCOE) for the GA	$\$/kWh$
BD	yearly electricity building demand	kWh

List of Abbreviation and Acronym

Acronym	**Description**
PV	Photovoltaic
LCCA	Life Cycle Cost Analysis
LCA	Life Cycle Assessment
GHG	Greenhouse gas emissions
NDCs	National Determined Contributions
CO2	Carbon dioxide
BAU	Business as Usual
SAM	System Advisor Model
WHO	World Health Organization
HVAC	Heating, Ventilation, and Air Conditioning
LED	Light-emitting diodes
BEMS	Building Energy Management system
AC	Alternating Current
DC	Direct Current
HRE	Heat Roadmap
CHP	Combined Heat and Power
GFP	Green Fiscal Policy
GFR	Green Fiscal Reform
ESG	Environmental, Social and Governance Investment
UNFCCC	United Nations Framework Convention on Climate Change
ACE	Action for Climate Empowerment
ZCB	Zero carbon building
R&D	Research and Development
IPCC	Intergovernmental Panel on Climate Change
CVG	Civil Engineering
HKUST	The Hong Kong University of Science and Technology
IST	The Instituto Superior Técnico
KTH	Royal Institute of Technology
CDP	The Carbon Disclosure Protocol
ICLEI	Local Governments for Sustainability
CNCA	Carbon Neutral Alliance
C40 Cities	Cities Climate Leadership Group
Transform TO	Transform Toronto
NYC	New York City
DHW	Domestic Heat Water
LEED	Leadership in Energy and Environmental Design
MEELS	The Mandatory Energy Efficiency Labeling Scheme
BEEO	Building Energy Efficiency Ordinance
MEPS	Minimum Energy Performance Standards
MELS	Mandatory Energy Labelling Scheme
BCA	Building and Construction Authority
ZEB	Zero Emission Buildings
EPC	Energy Performance Certificate

MEES	Minimum Energy Efficiency Standards
SLE	Singapore Super Low Energy Building Program
FiT	Feed in Tariff
PPA	Power Purchase Agreement
PPP	Public Private Partnership
SMEs	Small and medium-sized enterprises
HELP	The Home Energy Loan Program in Vancouver
HKGBC	Hong Kong Green Building Council
NGOs	Non-Governmental Organizations
ICAP	International Action Partnership
OREC	Ottawa Renewable Energy Co-operative
O&M	Operation and maintenance
EPW	Energy Plus Weather
T&D	Transmission and Distribution
ISO	The International Standard Organization
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
IEA	The International Energy Agency
EPDs	Environmental Product Declarations
IRENA	The International Renewable Energy Agency
EUI	Energy Use Intensity
DR3	Demand Response 3
IESO	The Independent Electricity Operator
NMC	Nickel, Manganese, Cobalt
GA	GA Global Adjustment
ICI	Industrial Conservation Imitative
HOEP	Hourly Ontario Energy Price
PDF	Peak Demand Factor
Covid-19	Coronavirus disease
SAM	The System Advisor Model
ARC	Advanced Research Complex
CO2	Carbon dioxide
PV	Photovoltaic
NPV	Net Present Value
LCOE	Levelized Cost of Energy
TA	Teaching Assistant

1. Introduction

1.1 Problem Statement

Cities have been regarded as significant contributors to overall carbon dioxide levels, and this trend is expected to continue. Roughly seven out of ten people will live in cities by 2050 [1]. According to the United Nations Environmental Program (UNEP), to meet the growing number of city inhabitants, the construction industry is expected to add 230 billion square metres of new development worldwide between now and 2060 [2]. As a result, the number of buildings on the earth in the next four decades is expected to double. We are constructing a similar New York City monthly over the upcoming 40 years to put this into perspective [3]. With the new construction expected to occur, we must make it standard practice for all new buildings to mitigate environmental impacts and reduce greenhouse gas emissions. Under the Paris Agreement, several countries pledge to decrease emissions by implementing the goals and policies described in their Nationally Determined Contributions NDCs [4]. However, numerous studies on energy efficiency show multiple and ongoing systemic problems, situational deviations (e.g. bias, context, incentive), and other barriers preventing the implementation of these efficiency measures. The barriers necessitate government intervention to address these issues and produce the intended levels of energy savings [4,5]. Several cities have pledged to achieve carbon neutrality within a particular time frame and, in some cases, ahead of national commitments [6]. Because of the seriousness of the issue, organizations such as C40 Cities Climate Leadership Group [7], Covenant of Mayors [8], Local Governments for Sustainability (ICLEI) [9], Carbon Neutral Cities Alliance (CNCA) [10], and Carbon Disclosure Project (CDP) [11] have been formed to help cities achieve carbon neutrality and take broad carbon reduction initiatives.

The greenhouse gas GHG Protocol [12] is one widely acknowledged scope scheme. They have established three distinct levels: Scope 1 refers to GHG emissions originating within the city limits; Scope 2 refers to GHG emissions caused by using electricity from the grid inside the city limits; Scope 3 refers to every GHG emissions originating beyond the city limits because of activities occurring within the city limits. However, cities have had complexity in addressing scope three, which deals with the embodied carbons in buildings. Embodied carbons or embodied energy represent the carbons emitted through the whole life cycle from the materials extraction, manufacturing, transportation, installation, maintenance, and end of life and disposal [13].

The built environment decarbonization heavily depends on buildings' decarbonization [14]. Hence, the overall goal is to make building net-zero carbon. For this research, a Net-zero carbon/energy building is defined as an energy-efficient structure that generates or obtains clean electricity on-site to satisfy the annual energy needs of the building's operations [15,16]. Whether the facility uses oil and gas sources to make up for occasional shortages in clean energy supply or uses carbon offset, the terms zero-carbon and net-zero carbon are frequently interchanged. Hence, the structure is known as a "net" zero structure [15].

In order to achieve the net-zero energy building sector, the environmental, economic, and societal aspects need to be integrated to maintain sustainable growth and enable the accessible net-zero transition. Many facets of knowledge are required to be incorporated simultaneously. For instance, research and development had advancements in building technology, construction and refurbishments provide the chance to shift structures in various climates, geographies, and cultures toward climate neutrality. Increased insulation, improved windows, external solar shadings, recycled materials, natural ventilation, heat recovery ventilation, mechanical systems, and enhanced lighting are technical measures to reduce thermal loads. Additionally, the breakthrough in the prices of buildings integrated renewables such as solar panels has helped achieve zero-energy buildings. However, building codes are the major driver and generally implemented climate policies, yet they are still only applied to a limited extent [17]. Even when they are, their application is fraught with difficulties. There may be insufficient enforcement and training and not updated to accommodate the recent technological developments. One example is that building codes are designed to be the minimum requirement to construct a building; eventually, the building sector perceives it as the needed requirement to comply with it. Energy supply is another part of the equation. For example, electric grids face increasing demand, with more buildings being electrified to avoid using fossil fuel derivatives for heating and cooling. The electricity demand rises, jeopardizing the health of the grid during peak hours [18]. The increased demand to be reduced must be met by increasing buildings' energy efficiency and renewable energy capacity.

Education and capacity building is the third facet. To achieve net-zero energy building, citizens' engagement and awareness are critical as they are the end-users who consume the energy in buildings [19]. Educational institutions play an essential role in preparing future generations to face such challenges. Preparing the workforce for the new jobs available is also critical as the workforce needs to adapt to using the continuous new building technologies in the market. The fourth facet is green fiscal policies; despite the benefits of low-energy buildings, caution must be taken to prevent pitfalls that could act as roadblocks to their widespread adoption. One major impediment is funding; comprehensive energy retrofits and technology need a significant upfront expenditure yet pay off over time, with a payback period of 10–20 years [20]. Most homeowners, for example, do not have the considerable funding required for major renovations. As a result, fiscal incentives are required to bridge the payback time gap.

The last facet is governance and collaboration. International and national actions escalate climate action to decrease energy uptake in the building sector and improve energy resiliency. However, many scholars have pointed out the importance of taking many actions on multiple levels instead of actions stemming from one authority exemplified in the national or federal government [21,22]. It situates cities at the forefront to take more decisive and tailored actions to achieve a net-zero energy building sector [23].

In order to provide evidence-based decision-making on determining which technology would be suitable to be implemented, it must be strengthened by an analytical process and feasibility study on the available technology. The evaluation process allows for technology diffusion or crafting interventions to help in the technology adaptation; this can happen through more Research and Development (R&D) and fiscal incentives.

1.2 Research Objective

The main objective of this thesis is to explore the intersection between science and policy to help in achieving a global net-zero energy building sector. The thesis work is twofold: (1) performing an urban comparative analysis for net-zero energy policies for the building sector in 10 cities tackling all types of energy, such as electricity and gas. (2) utilizing the University of Ottawa campus to examine the viability of installing photovoltaic panels over the campus building's roofs through assessing running cost, operational and embodied energy and carbon as a part of the campus as a living lab imitative. Additionally, the study investigates the viability of integrating energy storage with a solar system to reduce buildings' electricity at Ontario's peak to achieve monetary savings from the Global Adjustment Program. The case studies focus on the electricity facet of the building’s energy demand.

The following sub-objectives have been carried out to meet the thesis objective:

1. Carrying out thematic qualitative analysis for ten cities' climate mitigation plans into five themes, (a) building technology and standards, (b) electrified grids, (c) education and capacity building, (d) green fiscal incentives, (e) governance and collaboration.
2. Investigating the viable campus places to install PV panels with the participation of 51 graduate students as a part of the course *"CVG 6310 Net Zero Energy Buildings in Canada"*. The campus was divided into 15 zones; 2-3 students investigated the project viability within each zone. In addition, we exchanged information with the campus sustainability office to enhance project relevancy.
3. Performing Life Cycle Cost Analysis (LCCA) for the photovoltaics project using RETScreen Expert Clean Energy Management Software. The current cost for the PV panels technology was identified through market research based on Ottawa prices. Ottawa's economic situation, such as Canada's inflation rate, was also considered through Canada's governmental websites. This step obtains the annual energy generation, financial viability, operational yearly GHG emissions reduction, and risk and sensitivity analysis. Additionally, the expected electricity generation from the PV panels is compared with the actual building's electricity consumption and overall campus needs.
4. Performing Life Cycle Assessment (LCA) for the photovoltaics project using One Click-LCA software to evaluate the energy and carbon savings and expenditures through the life cycle of the project
5. Developing a survey to assess the students learning from participating in the project and how the campus as a living lab imitative can be improved in the future.

6. Integrating energy storage with the solar system using the Advanced Research Complex (ARC) building to mitigate its electricity demand at Ontario peaks through the System Advisor Model (SAM) software.

7. Calculating potential Global Adjustment monetary savings from mitigating ARC building demand at Ontario peak and integrating it into the SAM software's financial analysis to obtain an accurate Life Cycle Cost Analysis (LCCA).

1.3 Contribution to the body of knowledge

This thesis makes two essential contributions stemming from combining two distinct fields: building science (engineering) and social science (policy). To achieve a net-zero energy building sector and overcome the many facets of impediments that acts as a roadblock to building technology wide-scale adaptation and diffusion.

First:

- The urban comparative analysis for the ten cities is crucial to fill the literature gap regarding cities' approach toward the net-zero building sector. One impediment to understanding the city's progress is that each city has its documents and reporting structure, leaving the academic nation and decision-makers dazzled with tens of lengthy documents to be analyzed. Some studies have analyzed the cities' climate action progress. However, none of the previous studies comprehensively focused on the building sector. The cities' progress toward net-zero is fast and progressive; such analysis enables scholars and professionals to learn from each city's various and novel approaches.

Second:

- The research extends the existing knowledge to the viability of installing PV panels over the campus buildings. Additionally, The participation of 51 graduate students in the course *"CVG 6310 Net Zero Energy Buildings in Canada"* and the participation of the campus sustainability office as a novel pedagogical approach for knowledge co-production and co-creation to find sustainable solutions. The findings could help achieve net-zero energy buildings at the University of Ottawa and extend the findings to the City of Ottawa. Furthermore, most of the previous photovoltaic studies focused on the carbon and energy savings from the energy generated from the PV panels. In contrast, in this study, the environmental impacts of installing, manufacturing, and transporting the PV system have been considered to obtain a holistic perspective on the PV system.

- The research also extends the literature on the vitality of integrating fiscal incentives to help diffuse integrated buildings' renewable energy technology and maintain reliable electric grid health. Integrating energy storage with a PV system showed an ability to reduce the load on the electricity grid at peak times, marinating its reliability. Also, the findings show that with governmental financial mechanisms (Global Adjustment Program), energy storage offers a high return on investment for large electricity consumers. The results would help the government authorities to maintain and innovate more fiscal incentives and motivate facility owners/managers to utilize renewable technologies in their buildings.

1.4 Thesis structure

This thesis is broken down into a total of seven chapters. The titles and a brief description of each chapter are as follows:

Chapter Two: Literature Review

this chapter extensively covers the literature review on the technology used to achieve the net-zero energy building sector. The technologies cover building envelope, mechanical systems, appliances and lighting, automation systems and controls, and on-site renewables. The literature also covers the vital role of electric grids in feeding the building sector with clean energy. Green fiscal incentives, education, capacity building, and governance were also covered to understand the building sector's interdisciplinary factors. The campus as a place for knowledge co-production was illustrated to highlight the connection between cities and campuses. Finally, the relation between the building's electricity demand and the Ontario province peak is explained, and the Global Adjustment Program is illustrated in detail.

Chapter Three: Policy for Science

This chapter includes a thematic qualitative analysis of ten cities' climate mitigation plans to provide evidence of the current cities' initiatives to achieve a net-zero energy building sector. The chapter findings are later synthesized with the case study (University of Ottawa) results to propose technology diffusion to a city scale.

Chapter Four: Methodology

This chapter first clearly outlines the methodology phases to install the PV panels over the campus buildings. The phases include 1) campus screening and zoning, 2) market research, 3) Life Cycle Cost Analysis, 4) Life Cycle Assessment, and 5) campus as a living lab survey. Second, the chapter illustrates the process of integrating energy storage with solar panels at the ARC building by defining the building electric load, PV system, battery characteristics and dispatch algorithm and the Global Adjustment calculations.

Chapter Five: Results

This chapter presents the results of the Photovoltaic analysis, including the expected electricity generation, finical indicators such as Net Present Value (NPV), and Internal Rate of Return (IRR). In addition to the energy and carbon savings. The chapter also includes the results from the campus of a living lab survey. Additionally, the chapter includes energy storage with PV system potential savings from the Ontario Global Adjustment Program.

Chapter Six: Discussion

This chapter explains the intersection between science and policy by drawing on the case study results and synthesizing them with the urban comparative analysis.

Chapter Seven: Conclusion

This chapter summarises the thesis findings, limitations, and future recommendations.

1.5 Summary

This chapter introduced the problem statement and explained the objective, scope, and research contribution. Finally, the thesis structure was defined.

2. Literature Review

A comprehensive literature evaluation is an integral part of any research project. The research problem is adequately defined, gaps in the literature can be found, and study objectives can be clarified by analyzing earlier published literature. Nowadays, 99 % of the world's inhabitants live in locations with higher levels of air pollution than the World Health Organization (WHO) recommended limit [24]. Cities are expected to accommodate more than two-thirds of the world's population by 2050. Buildings alone are responsible for significant CO_2 emissions, demanding immediate action. However, the continuously increased complexity in the city's dynamic shows that there is no quick fix to achieve net-zero energy/carbon buildings. The interdisciplinary nature of cities and buildings requires collaboration between engineers, decision-makers, financial intuitions, and academia to be acknowledged.

2.1 Building Technology (Energy Demand)

Two types of carbon emissions are associated with the building sector: operational and embodied. Operational emissions accounted for 29% of worldwide demand in 2018 [25]. Building materials and goods such as concrete, metals, and glass (embodied emissions) accounted for 11% of total emissions in 2018 [25]. In the 1970s, Fanger [26] introduced the low-energy building foundational building science and updated it in 1981 by Givonini [27]. An airtight building enclosure without energy bridging minimizes heat energy transfer through high energy resistance and efficient mechanical systems. However, a net-zero building includes other factors such as appliances and lighting, system controls, and incorporation of renewables. Lately, the world is moving to have embodied carbons in the total CO2 emissions budget [28–30]. Energy efficiency comes first by decreasing the energy demand from buildings. Then cleaning the energy supply comes second

[31]. As a result, specialists in the United Kingdom, for example, have two distinct ideas for the future: Passivhaus and Smart Homes [32]. Passive and low-tech designs are used extensively in Passivhaus to create homes that are so energy efficient that regular heating and cooling systems are unnecessary. On the other hand, Smart Homes are high-tech structures that use information and communication technology to automate domestic environment control [32].

2.1.1 Building Envelope

Reducing demand through low-energy building enclosure design or retrofitting is one viable solution. Building enclosure measures include efficient wall and roof assemblies with high thermal resistance and highly insulating materials, double or tribble glazed windows, adjusting window-to-wall ratio, and increasing airtightness to prevent air infiltration [33,34]. A single-story dwelling was modelled in Melbourne, Australia using the Australian AccuRate energy modelling. It shows that the house's efficiency can go up to 74% when increasing the star rating from 2.5 to 7 stars as it rates the thermal performance of the envelope and starts from 0 to 10 [30]. Becqué [15] identified that basic energy efficiency measures comply with countries' and cities' codes and regulations. In addition to advanced energy efficiency measures, which are more stringent and go one step further toward carbon and energy reductions. For example, a northern European passive house needs just 15kWh/m2/y of heating energy [35]. A modern house would require 150kWh/m2/y. A leaky house would need 300 kWh/m2/y [36–39]. One of the limitations is that it’s hard to retrofit all houses to the passive house standards. In such cases, it is recommended to use EnerPhit certification. The energy demand for an EnerPhit certification is less than 25kWh/m2/y [40]. PASSIPEDIA [41], a reference for Passive Houses, illustrates a comparison between an EnerPhit 149m2 house and a regular residential unit over 30 years. The investment saved 15,000 euros (8%) extra in 2010. The result is reducing the annual cost burden by 432 euros/year; passive houses save around 90% of the total heating and cooling load.

2.1.2 Mechanical Systems

Another term used for mechanical systems, Heating, Ventilation. and Air Conditioning HVAC, is "Built-in appliances" since they are permanently considered part of the houses as they have long life- cycles that could go up to the exact age of the building [30]. Heating equipment examples (gas ducted, electric, and reverse cycle "Heat Pump"). Cooling equipment examples (Electric evaporative ducted electric reverse cycle). Hot water equipment examples (gas storage, gas instant, electric storage). The ducted gas systems consume more energy but produce less CO2-e emissions than electric systems unless connected to an electric grid-connected to renewable energy sources [42]. Deploying electrified heat pumps is one of the promising tools to decarbonize the building sector [43] while having a tight building envelope can reduce the size of the selected heat pump. Heat pumps are highly efficient and use electricity to heat a building diverging from the traditional fossil fuel-based systems such as boilers [44]. Additionally, a mechanical ventilation system with heat recovery is crucial to reducing the heating load [45].

2.1.3 Appliances and Lighting

Appliances are split into two categories: cooking appliances (ovens and cooktops); both can be powered by electricity or gas. Secondly, standby appliances such as (fridges, microwaves, tv, laptop, eclectic kettle, and small miscellaneous such as mobile phones and clocks) [46]. Appliances consume from 10% to 30% in a residential house from standby appliances alone. Using efficient appliances can save up to 25% of the emitted CO2e emissions [30]. In 2019 Khosla et al. [47] found that CO2e emissions in India caused by appliances in buildings such as (Television, air conditioning, fans) and lighting are around a third of the world average. Still, that ratio will increase in the following years as India is poised to change the residential sector consumption behaviour of low-income households rapidly. However, behavioural patterns shift toward LED bulbs, but the same pattern is not followed for the appliances. For example, lighting types in the residential sector are (incandescent, halogen, linear fluorescent, compact fluorescent, and light-emitting diodes). Halogen lights are the least energy-efficient, but LEDs and Compact fluorescent are the most efficient lighting [30].

2.1.4 Automation Systems & Controls

In residential structures, household appliances, water, and space heating are causing increased energy consumption, but in non-residential buildings, space heating and other miscellaneous equipment are to blame. Building Energy Management Systems (BEMS) assist building managers and owners increase energy efficiency in new and existing structures. Both non-residential and residential facilities can benefit from BEMS to reduce energy consumption [48]. BEMS utilize buildings' energy and can be defined as strategies and methods for improving a system's performance, efficiency, and energy usage [49]. This technology facilitates the execution of critical energy management tasks such as automating demand response techniques, monitoring energy costs, detecting energy use abnormalities, and organizing energy use data [50]. Building management's primary goal is to create a comfortable atmosphere with excellent energy efficiency; sensors help balance thermal comfort and energy consumption [51]. A building could be built and developed as energy-efficient and environmentally friendly. Still, if the BEMS is not implemented correctly, a significant amount of energy could be lost [52], resulting in building operation costs [53].

2.1.5 On-Site Renewables

Renewable energy sources can be used as an on-site integrated energy supply system in buildings [54,55]. Buildings can generate energy through photovoltaic panels, solar water heaters, ground-source heat pumps, and micro wind turbines [56].

2.1.5.1 Photovoltaic Panels

Photovoltaics technology is considered a promising tool to convert solar radiation into electricity to aid in the transition of net-zero energy buildings due to its practicality, ease of operations and maintenance [57]. Additionally, PV systems in the last decade have dramatically increased the power capacity and decreased the capital cost due to the extensive research and development done in this area [58]. A typical Photovoltaic system comprises solar panels, mounting structures, inverters, wires, and cables. The photovoltaic system works through the PV panels absorbing solar radiation, transforming it into usable electricity through the inverter. By default, the system is connected to the grid and uses it as a storage system. Any extra electricity production can be sold to the utility company by sending the electricity to the grid and vice versa, as indicated in Figure 2.1.

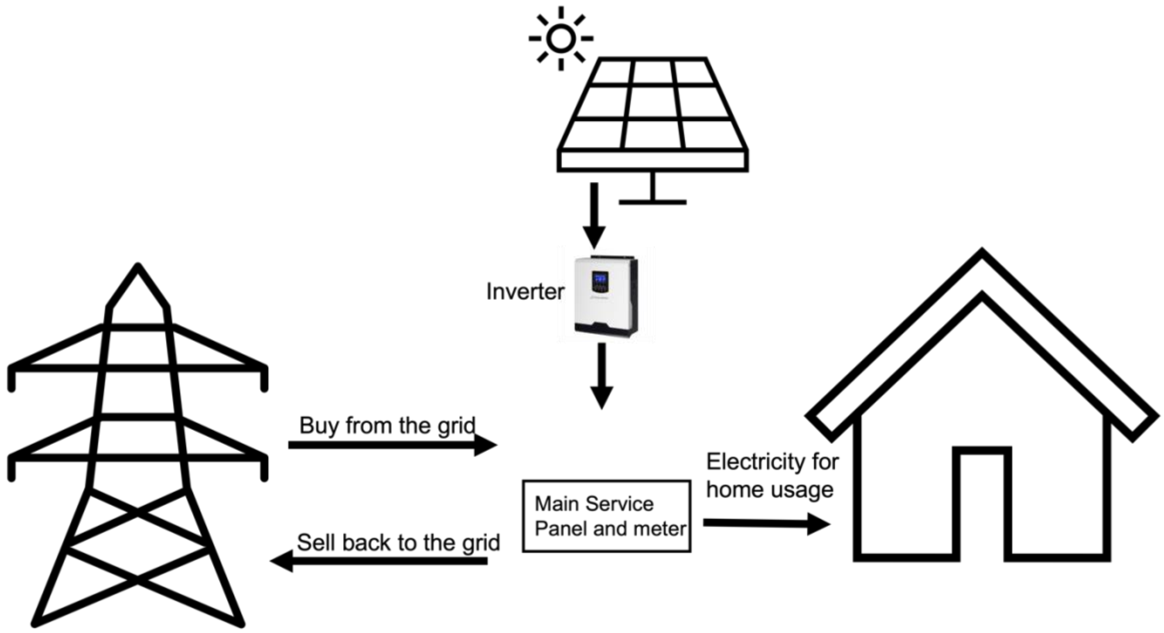

Figure 2.1 Photovoltaic system mechanism

There are many technologies related to solar panels. However, mono-crystalline and poly-crystalline silicon are the most common material types with the highest efficiency and reasonable cost [59,60]. Three types of mounting structures, either fixed or single or dual tracking systems, affect the panel's orientations and energy yield, as indicated in Figure 2.2 [61]. Inverters are mainly used to convert the Direct Current (DC) current from solar radiation to an Alternating Current (AC) current that can be used in buildings for daily electricity usage [62]. The two most common types of inverters are “string," one big central inverter and a microinverter installed at each solar panel. The micro inverter provides more power capacity as it overcomes shading issues by treating each solar panel as a standalone [63]. When shading occurs on one of the solar panels, the effect cause disturbance to the whole installed solar panels. Many leading photovoltaic manufacturers are located in China, Germany, the USA, and Japan. Some top PV manufacturers are First Solar, Trina, LG, SunPower, Panasonic, and Canadian Solar.

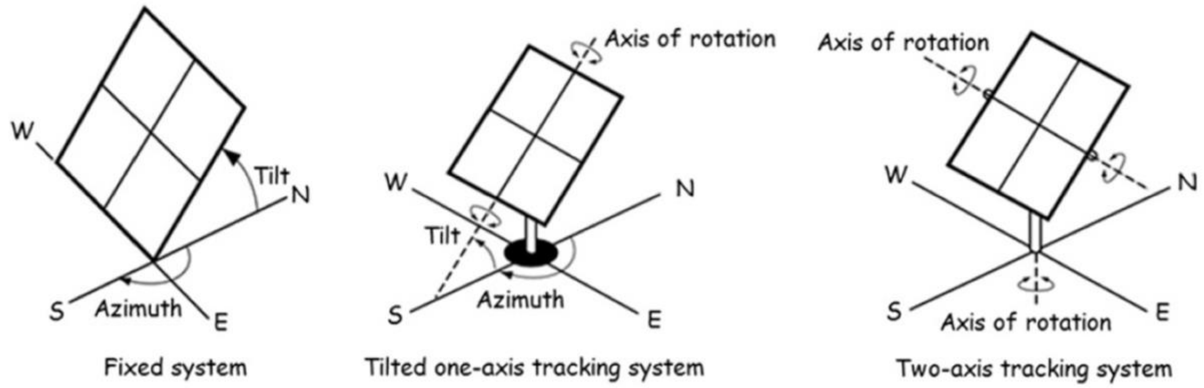

Figure 2. 2 Fixed, single, and dual tracking systems [60]

2.1.6 Embodied Carbons

All the mentioned previous tools are tackling operational energy/emissions. It's observed that operational energy is the primary energy consumption in the building sector. However, with the rapid technological advancements in reducing operational energy by increasing the efficiency of the building envelope and operating systems, decarbonizing the electricity grid, and using clean energy sources, operating energy is projected to fall drastically. Additionally, it is worth noticing that all the previously mentioned energy efficiency measures would require a considerable amount of materials that will release a significant amount of embodied carbons [64]. Architecture 2030 [65] reveals that embodied carbon is expected to account for 49 % of the overall emissions from these buildings if we look only at the new construction between now and 2050 while operating carbon emissions account for the remaining 51 % over the next three decades. Assessing embodied carbon caused by the manufacturing, transportation, installation, maintenance, and end of the material life process is done by performing Life Cycle Assessment (LCA). The Environmental Protection Agency [66] describes life cycle analysis (LCA) as a method of "evaluating the environmental impacts associated with any given industrial operation from the initial collection of raw materials from the earth to the point at which all residuals are returned to the earth" or "cradle-to-grave.". Hence, many jurisdictions worldwide are starting to address embodied carbons in their regulations. One of the issues is the carbon loophole, a policy gap that permits one region to cut emissions on paper by exporting industrial emissions to another region [67].

2.2 Electrified renewable grids (Energy Supply)

Developing a carbon-free energy supply sector that depends on renewable energy generated will significantly decarbonize cities' electricity grid and building sector. Lund [68] identified three key technological breakthroughs required to create 100 % renewable energy systems: energy savings on the demand side [69,70], energy production efficiency improvements [71,72], and the substitution of fossil fuels with alternative renewable energy sources [73,74]. As a result, substantial renewable energy initiatives must incorporate ways to incorporate renewables into integrated energy systems impacted by energy reductions and efficiency initiatives.[75,76]. In 2012, The Heat Roadmap (HRE) in Europe's research looked at the synergy between these demand-side energy savings and new supply possibilities [77,78] to reinforce the importance of balancing the energy demand and supply.

2.2.1 Renewable Sources

Clean energy sources such as solar, wind, geothermal, hydropower, hydrogen and biomass are incorporated into the energy mix to regenerate clean energy [79,80], making them a core competency in fighting climate change and aiding the net-zero carbon transition in buildings. Qazi and colleagues [81] showed that despite substantial efforts to minimize reliance on fossil fuels by promoting renewable energy as an alternative, the literature research revealed that fossil fuels accounted for 73.5 % of global power production in 2017. According to Gielen et al. [82], energy efficiency and renewable energy technologies are vital components of the shift, and their synergies are critical. Gielen et al. also state that renewable energy sources can meet two-thirds of world energy demand.

2.2.2 District Energy

Research has shown in the last decade that district energy which comprises district cooling facilities [83] and district heating facilities [84], is an untapped key enabler that would help in meeting the heating and cooling increasing demand from buildings in cities worldwide [85-87]. Heating, hot water, and cooling account for 60% of global energy use in buildings, with fossil fuels providing most of this energy [88]. Since 1990, space cooling energy consumption has tripled, posing considerable challenges for electricity systems, particularly during peak demand periods and extreme heat events. In 2020, global space cooling demand grew again, partly due to increased house cooling as more people spent more time at home. In 2020, space cooling accounted for about 16% of final electricity consumption in the construction sector (around 1885 TWh) [89]. District energy facilities consider a system approach, which means that heating and cooling networks are combined with thermal storage [89,95], decentralized energy sources [91], waste [92], biomass [93], heat recovery technology, heat pumps [84,90], [94–96], and Combined Heat and Power (CHP) technology [97]. District energy allows connecting buildings, neighbours, and districts to integrate significant renewable energy sources that cannot be used individually. Integrating clean energy sources enables communities to overcome the fluctuations in separately clean energy sources such as wind or biomass and capitalize on the combined collective power [93,98].

2.3 Green Fiscal Incentives

In recent years, the continuance of interlinked economic, environmental, and social concerns necessitates cross-cutting policies and instruments; This is reflected in green fiscal reform as a novel policy strategy [99]. Fiscal policy influences and incentivizes the economy through government expenditure, taxation, and price mechanisms [100]. It exemplifies a critical function of the modern state: the ability to generate revenue and spend according to political goals outlined in national decision-making procedures. Green Fiscal Policy (GFP) is a method of restructuring government expenditure and revenues to promote long-term sustainability. Enhancing energy efficiency can significantly benefit businesses and private users who want to minimize their energy consumption [101]. Fiscal policy can soften the severity of business cycles in macroeconomic settings by controlling economic activity's top and bottom peaks [102]. Governments can participate actively or passively in a country's economy [103]. Historically, climate change policy has been based on prescriptive guidelines. However, this trend is changing. The instruments utilized were primarily regulatory. On the other hand, fiscal tools are based on incentives [104]. Concentrating on short-term political results can jeopardize the validity of green fiscal reforms. Fiscal reforms necessitate gradual and predictable economic adjustments to avoid political displeasure or civil upheaval. [105,106].

2.3.1 Green Fiscal Tools

Green Fiscal reforms (GFR) work at the fiscal and environmental policy interface. it includes three instruments [105,106]. First, revenue-generating instruments include taxes, tax credits, "rebates," tax shifts, charges, fees, removal of subsidies, cap and trade [107]. Second, revenue spending instruments such as subsidies, feed-in-tariffs, loans below market rate, and cash transfers—compensation schemes, tax exemptions, grants, sustainable public procurement, and reforming harmful subsidies [106,108]. Third are revenue-neutral instruments / market-based mechanisms such as emission target schemes, cap and trade permits, deposit and refund schemes, and offset systems [109]. Through tailored policy responses, appropriate instrument development can accommodate stakeholders' concerns. Decades of pricing reform experience suggest that fiscal instruments can aid in the prevention of environmental damage by correcting market failures [110]. They use full life cost accounting and tax externalities, which drive market actors to change their economic activities to reduce their tax burden. Similarly, eliminating environmentally detrimental subsidies removes unreasonable incentives to extract or use energy resources at rates that exceed sustainable levels [111].

2.3.2 Environmental, Social, and Governance (ESG) Investments

The term "responsible investment" refers to a plan that considers environmental, social, and governance (ESG) aspects before deciding on an investment [112]. Environmental taxation, known as carbon pricing, is a method that allows consumers and corporations to mitigate ecological damage at the lowest possible cost. It assigns a monetary value to the use of fossil energy. The cost to use any energy source that contributes to GHG emissions is expressed as a per-ton cost of emissions [113]. This pricing can be converted into a fee depending on the fuel emissions intensity; the typical unit is sold in cubic meters of natural gas and a ton of coal. Other objectives could include repurposing tax income to fund new green initiatives. Subsidies for renewable energy, for example, will encourage businesses and consumers to innovate more [114]. Subnational or national governments' uncoordinated fiscal policy actions can have significant environmental and social consequences. Environmental leakage [115], race to the bottom, tax dynamics, and excessive free-riding [116] are linked to poorly conceived or misaligned fiscal policies.

Complementary non-fiscal policies can be combined with fiscal policies to form a reform package. These non-fiscal policies typically address the more central fiscal policies [117].

2.4 Education and Capacity Building

The United Nations Framework Convention on Climate Change (UNFCCC) coined the phrase "Action for Climate Empowerment" (ACE). ACE's overarching purpose is to encourage all people in the community to participate in climate change through education, training, community engagement, participation, access to information, and worldwide collaboration on such concerns.[118]. Furthermore, the United Nations proclaimed a Decade of Education for Sustainable Development (2005–2014) to encourage behavioural change by incorporating sustainable development into all educational processes [119].

2.4.1 Citizens

Buildings' energy efficiency can't be improved without significant citizen participation. From a societal standpoint, citizens must learn and develop new skills and values to bolster individual and collective behaviour [120]. The European Green Deal, for example, considered citizen participation essential for a just and inclusive energy transformation [121]. As a result, integrating social, environmental, and economic aspects into the design of zero-carbon buildings ZCBs is critical [122].

Inadequate education, training, public and industry awareness, and public acceptance, among other variables, are all obstacles to zero-carbon building development [123–125]. Due to a lack of skills and information and intricate financial and cultural issues, UK residents' views regarding acquiring energy-efficient homes and managing low-carbon building technology, for example, are cautious.

User views of ZCBs and related technologies may impact market adoption and demand [123], [126]. Heffernan pointed out [123] that having an energy-efficient home is still unusual. According to Judson and Maller, [127] the shift to a zero-carbon economy necessitates a greater focus on the social aspects. Berardi [128] claimed that additional research is needed into the necessity of socioeconomic factors in sustainable buildings. The non-technical aspects of ZCB development have sparked increased interest, with most studies focusing on occupant perceptions and behaviours [129,130]. The accomplishment of ZCB is mainly centred on the operation stage and is highly dependent on end-user perceptions and behaviour. On the other hand, practical occupant training is required to understand better building energy reduction strategies [19], especially in cities with limited renewable energy [126].

2.4.2 Industry

There is a scarcity of skilled green professionals, high initial investment expenses, and a lengthy renovation [131]. A shift to net-zero could harm the labour market through rapid structural change, resulting in unemployment and labour shortages. The development should be faster than society in training or reskilling new and existing workers to achieve a just net-zero carbon transformation without exacerbating disparities [132,133]. It is inevitable to prepare a workforce for vocations that may soon become obsolete [134].

2.4.3 Higher Education

Many international studies have identified serious concerns regarding integrating sustainability into educational institutions [135]. Most higher education institutions incorporate sustainability into their core activities, research, and courses [136]. Following that, universities were honoured for their significant contributions to sustainability programs [137]. According to Huertas et al.

[138], the campus as a living lab project equips students to handle various government, community, industry, and academic concerns. Institutions of higher learning can stimulate national and international communities in radical learning on sustainability methods. Fostering world-class research and development (R&D), fostering creative pedagogy, and knowledge mobilization and sources are critical vehicles for meaningful change and long-term sustainability [139].

2.4.4 Middle and Secondary education

Three thousand seven hundred eight secondary students in New York State, USA, filled out a written questionnaire to assess energy literacy. The findings indicate that while students are aware of energy issues, they may lack the knowledge and ability to contribute meaningfully to solutions [140]. Those in high school performed much better than students in middle school. As a result, several studies have emphasized the critical role that carbon-neutral schools play as a live model for teaching students about energy efficiency in buildings. Orr (1994), in Higgs & McMillan (2006), p.45, [141], argues that buildings contain a hidden curriculum because he states, "We have not thought of academic buildings as pedagogical, although they are." According to Higgs and McMillan's (2006) research on sustainable schools, a net-zero building aids with implicit teaching.

2.5 Governance

The Intergovernmental Panel on Climate Change (IPCC) [142] defines climate governance as "mechanisms and measures aimed at guiding societal systems toward preventing, reducing, or adapting to the dangers posed by climate change," citing Jagers and Stripple. It also states that it extends beyond conventional regime or national power conceptions and includes various levels of social structure, systems, institutional arrangements, and reward systems [143].

Cities and regions are becoming more involved in global climate change governance. They pledge their GHG reduction goals, join international organizations, and employ thousands of subnational governments [144–147]. Local governments are generally in charge of enacting and enforcing various facilities' energy reduction policies. Their strategies, however, are directly influenced by advice and directives from federal, provincial, or national governments. Guidelines and standards for building performance are frequently developed and published at the state scale. Municipal governments often serve as regulators, facilitators, owners/investors, and complementary or strategic partners [148]. Local governments have also formed transnational networks focusing on local climate governance and attempted to leverage these new political venues to assist low-carbon transitions [149]. However, various obstacles to urban climate governance have been challenging to overcome, resulting in primarily incremental rather than systemic changes to urban systems [150,151], according to cities' mitigation results and performance analyses. On-target cities have less aggressive goals and a big carbon emissions base. The cities are also located in nations with strict national climate policies than off-target cities [152,153].

2.5.1 Polycentric System

Many analysts believe that the only solution to handle the problem of reducing GHG emissions is to reach an enforceable worldwide accord. Global solutions at the international level are not guaranteed to work well unless they are supported by numerous national, regional, and local activities [154]. Without a doubt, an international treaty is a huge step. However, instead of focusing solely on this critical stage, it is essential to recognize the growing polycentric system. There is an increasing body of research on polycentricity in climate administration, unlike the monocentric approach, which is exemplified in the national government as the only administrator. Polycentricity offers many institutions, organizations, and actors the opportunity to involve and collaborate to find sustainable solutions considering the structures, connections, and social relations between players and stakeholders [155–157]. Understanding a country's institutions, players, and interest groups are crucial for understanding intervention success factors and fostering opportunities for climate action [158]. Each unit in a polycentric system has significant autonomy in establishing regulations in a particular location (for example, a household, a company, a city, a provincial government, a federal government, a national government, or a global accord) [159]. There is no perfect governance system, but polycentric systems offer considerable benefits due to systems for mutual assessment, gained knowledge, and adjustment of improved techniques gradually [160].

As previous studies [21,22] have noted, identifying which technical and regulatory solutions effectively reduce emissions in local governments is crucial for facilitating experience transfer and understanding how to fully realize the contributions of multilateral climate initiatives to the polycentric approach [161,162].

We have yet to see a roadmap to assist multi-sector national coalitions dealing with various climate governance issues. Some of the challenges are improving coordination between industries and levels, improving the effectiveness and incentive scheme for accountability systems to function, and allowing for more transparent policy execution.[163]. More work is required to link present climate targets to achievable, net-zero policies suited globally for different stakeholders and realities.[164].

2.6 Campuses

Campuses are similar to mini-cities as they share many attributes and environmental challenges [165]. Partnerships between cities and universities are promoted because they are mutually advantageous in stimulating innovation [166]. University-city partnership enables scaling up innovation from the campus level to the city level. According to Heijer and Magdaniel [167], future campuses have the potential to be “the city or a city” in itself. Many authors have identified the importance of utilizing campuses as a living lab, a place for knowledge co-production [168–170]. Campuses have the potential to leverage their extensive resources exemplified by professors, researchers, students, facility managers, and sustainability consultants and bring industry partners to work on environmental sustainability challenges such as climate change and low carbon economy [171].

According to the University of Ottawa Master Plan 2015 [172], one of the university's priorities is to become a carbon-neutral campus by 2040. uOttawa recognizes the importance of supporting talks with action, such as signatory to the Talloires Declaration, the Halifax Declaration, the "Ontario Universities Committed to a Greener World" pledge, the Montreal Carbon Pledge, and the "Investing to Address Climate Change" Canadian Universities Charter [172,173]. The Environmental Management and Sustainability Policy (policy 72) [174] and Strategic Plan (Transformation 2030) [175] reaffirm university pledges as guiding texts that will assist the university in focusing its efforts on fostering a sustainable culture. uOttawa participates in various energy programs to reduce energy consumption. For example, uOttawa is working with Hydro Ontario to save electricity consumption through the Embedded Energy Manager [176]. The university also reduced its electrical consumption by energy-saving measures such as turning off not required lights and ventilation during peak hours to maintain the providence electricity grid health through the Demand Response 3 (DR3) [176].

Additionally, the University participates in the Ontario Global Adjustment Program [177]; the university works to reduce significant buildings' electricity peaks to reduce the electricity bill and maintain grid reliability. The university's goal is to reduce energy use by 2% annually [176]. However, the campus performs minimal clean self-generation energy, increasing its carbon footprint. To tackle that, the university established the campus sustainability office in 2006 to coordinate, promote, and implement sustainable development activities on the campus [178].

Many campuses have been investigating and installing PV panels on their campus. The Hong Kong University of Science and Technology (HKUST) announced in 2020 that the largest PV system was to be installed in more than 50 locations on the campus. The system will compose 8000 solar panels with an annual capacity of 3 million units (kWh) and generate up to $160 million over its 25 years life cycle while saving 1500 tCO2e annually [179]. Another study by The Instituto Superior Técnico (IST) [180] utilizes its central campus in Lisbon and 100 residential buildings within a 500 m radius to generate electricity since the campus uses 81% electricity and 19% natural gas. The campus examined two technologies PV panels and solar thermal collectors with thermal storage. The findings show that PV panels are the only viable solution with expected 8.61% monetary savings for the campus and 24% to 29% for the residential buildings. A PV case study in a finance campus in Turkey [181] identified a potential reduction in electricity peaks up to 30.8% of the total campus consumption. The project covered 3,158 m2 and produced 567,000 kWh with a positive Net Present Value and 13 years payback period. A study [182] done at the Royal Institute of Technology (KTH) in Sweden reinforces that energy efficiency comes first and renewables come second. The study shows that PV panels' electricity production is significantly lower than the university needs. Therefore, energy efficiency measures must be considered to cover a more significant share of the demand.

Some studies have focused on the PV Projects Life cycle Assessment (LCA) or embodied carbons [183]. Ito and colleagues [184] did a cradle-to-grave LCA study on mono-silicon modules at Ouarzazate in Morocco and Carpentras in France, showing the expected PV system to have (40.1 g-CO2eq/kWh) emissions. Another study done by Kim et al. [185] in Korea evaluated cradle-to-grave mono-silicon and Poli-silicon PV systems showing emissions equivalent to (41.8gCO2eq /kWh) and (31.5g-CO2eq/kWh). A third study [186] by Stylos and Koroneos evaluated the cradle-to-use stage by analyzing multiple scenarios of mono-silicon PV systems showing an embodied carbon range of (12.28-58.81g-CO2eq/kWh). A Comparative Study by Luo et al. [187] in Singapore on three mono silicon PV systems showed embodied emissions equivalent to (30.2, 29.2, and 20.9 gCO2e/kWh) respectively.

A recent comparative analysis [188] was published in Applied Science between five PV modelling software: RETScreen, System Advisor Model (SAM), PVGIS, PVSyst, and PV*SOL. The results show that SAM and RETScreen provided the most accurate data with deviations lower than 10%. For the first project to perform Life Cycle Cost Analysis (LCCA) and model the PV system, RETScreen Clean Energy Management software developed by Natural Resources Canada has been identified [189]. One-Click LCA software [190] is used to perform Life Cycle Assessment (LCA) and assesses the PV system's life cycle carbon. One-Click LCA is a Finnish software developed by Bionova company and operating since 2001. Through the Life Cycle Assessment (LCA)

Initiative by the National Research Council Canada, a study done in 2019 [191] showed that One-Click LCA is considered one of the most advanced, comprehensive LCA tools.

This research first study (campus as a living lab) is part of the University's expansion program through the graduate course *"CVG 6310 Net-zero Energy Buildings in Canada"* at the civil engineering department. The study is done with the participation of 51 graduate students and partnering with the campus sustainability office. We examined photovoltaics technology installation over the campus buildings' roofs to help the campus achieve carbon neutrality, transforming uOttawa into an energy hub and testbed for renewable energy utilization and maximizing the electricity generation from the PV panels with the least possible cost.

2.7 Ontario Electricity Demand Peaks

Electrifying buildings is crucial to achieving net-zero energy operations by 2040 and meeting the climate neutrality targets [192]. Meanwhile, cities, provinces, and national governments are still transitioning from traditional fossil fuel to renewable and clean-based energy sources, and Ontario province is not excluded. The increase in electricity demand, especially during peak hours, jeopardizes the electric grid's health reliability and maintains uninterrupted operations [193]. Peak hours are often between 4:00 and 6:00 PM in summer, when citizens return home and start turning on air conditioning and other equipment [194,195]. One of the primary tools regulatory authorities use to overcome the peak hours challenge is higher billing rates when electricity demand is high to encourage consumers to decrease their consumption and obtain enough credit to upgrade and maintain the grid [196]. A recent study by the Fraser Institute states that large electricity consumers in Ontario, specifically in Ottawa and Toronto, are paying 65% more than large consumers in the rest of Canada [197].

The integrated buildings solar system is considered a promising technology to help reduce electricity demand and cost over its lifetime. However, the solar system is associated with daily solar radiation. Solar radiations start in the morning, reach a maximum at noon, and decrease till evening [198]. This process provides an abundance of renewable energy during the sunlight. However, at peak times (4:00 – 6:00 PM), solar systems are not contributing to solving this riddle which results in what is known as the duck curve [199]. Figure 2.3 is utilized based on data from the Ontario utility company, the Independent Electricity System Operator (IESO); it represents the curve of a typical day for the Ontario electricity grid demand [200].

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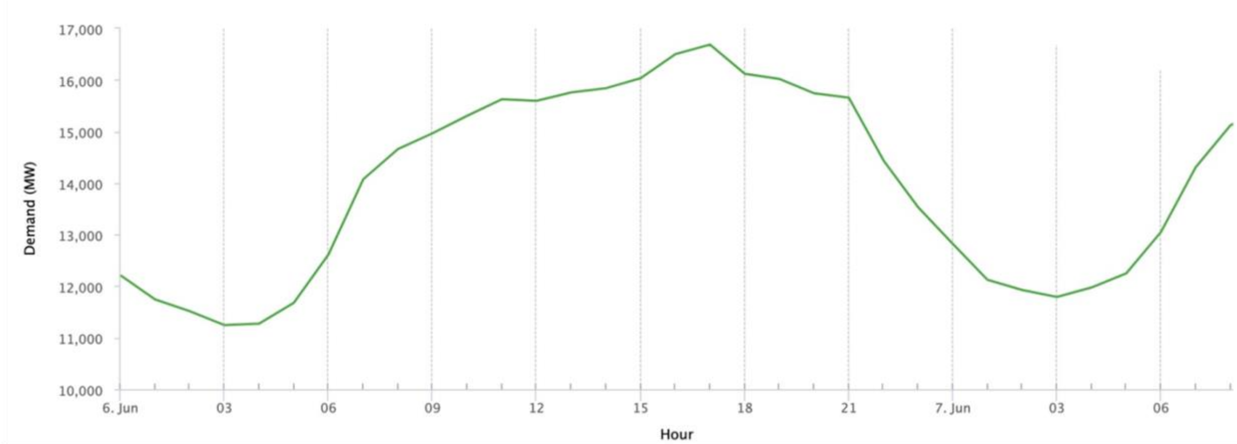


Figure 2. 3 June 6th 2022, taken from IESO Power Data [200]

In order to overcome the duck curve symptom, integrated energy storage (batteries) with solar systems is introduced as a clean source to mitigate some of the peak effects. Energy storage gets charged from the solar panels when there is no high electricity demand and then releases this energy back to reduce load at peak hours [201]. The most common type of battery is Lithium-Ion [202,203]. Lithium-Ion batteries' most reliable and used chemistries are Nickel, Manganese, Cobalt (NMC) and Iron Phosphate.

In Ontario, the Global Adjustment Program (GA) [204] under the Industrial Conservation Imitative (ICI) [205] is introduced as a response program (a financial mechanism) to help reduce peak hours demand on the electricity grid by shifting electricity consumption from on-peak hours to off-peak hours.

Buildings whose hourly electricity usage is over 500 kWh have the potential to be eligible to shift from Time of Use rates [206] and Class B [207] to be classified as Class A (large consumers) [204]. The Global Adjustment Program Class A has two main cost components [177]. The Hourly Ontario Energy Price (HOEP) and the Global Adjustment. The HOEP is the hourly fluctuating market price of the electricity in Ontario, it sets every five minutes, and a monthly weighted average is used for billing. The GA component is the cost-share associated with maintaining health maintenance and reliability. The GA billing cost is determined through the total of the highest five Ontario peaks divided over the corresponding facility peak. This process produces the Peak Demand Factor (PDF) [208] that will determine the upcoming GA cost in the following year. The PDF is multiplied by the total grid cost to determine the building cost share. Figure 2.4 shows the average cost of HOEP plus the average cost of GA combined over ten years [177].

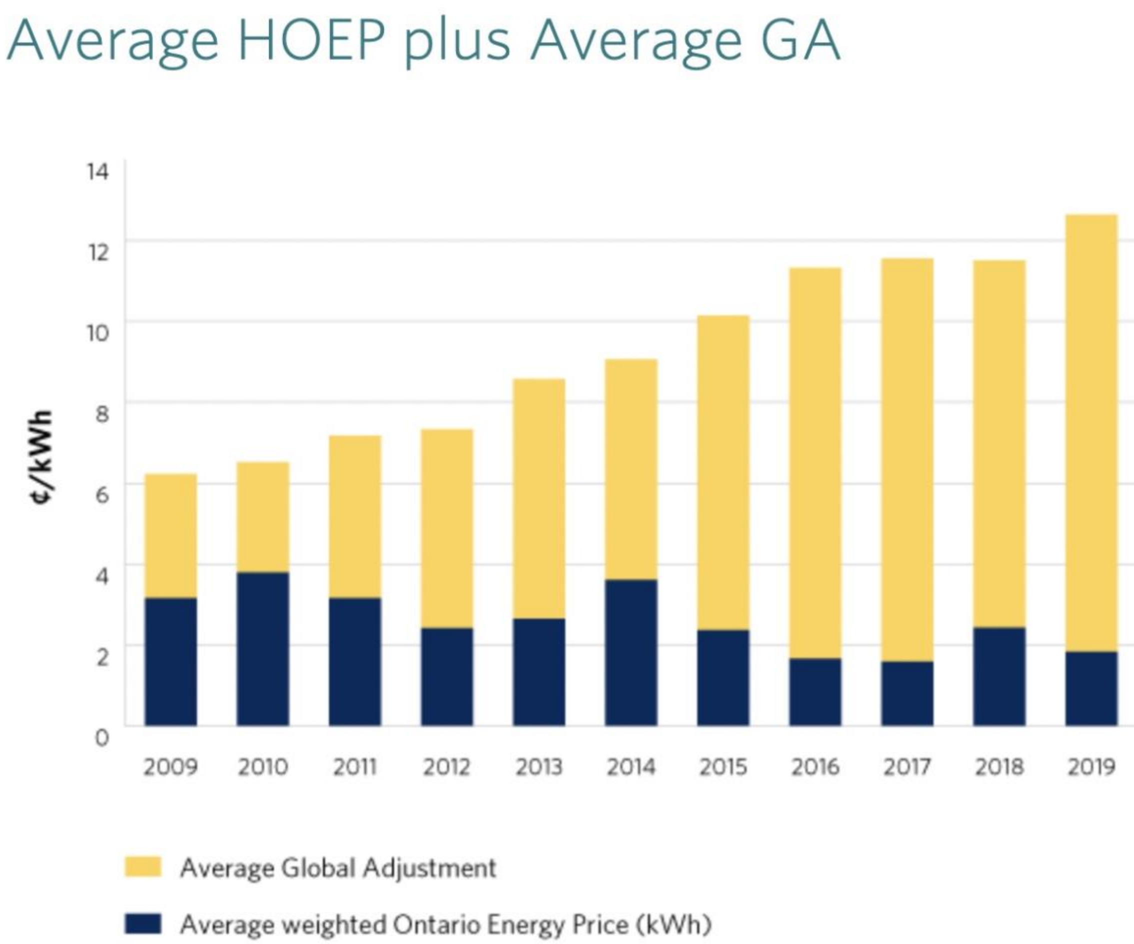


Figure 2. 4 Average HOEP Plus Average GA [177]

The Global Adjustment program has been on hiatus from May 1st, 2020, to April 30th 2021 [209]. The rationale was to encourage commercial users (Class A) to return to normal operations before Covid-19 without fearing an increase in the electricity cost. The peak Demand Factor (PDF) from 2019 was used for two years instead of the usual one-year cycle. As illustrated in Figure 2.5, adapted from the IESO data directory [210], the results show an increase of around 3,000 MW in Ontario province demand in July and August 2020 compared to 2019. Without the ICI and GA, there is a potential for the Ontario grid to reach its reserve market.

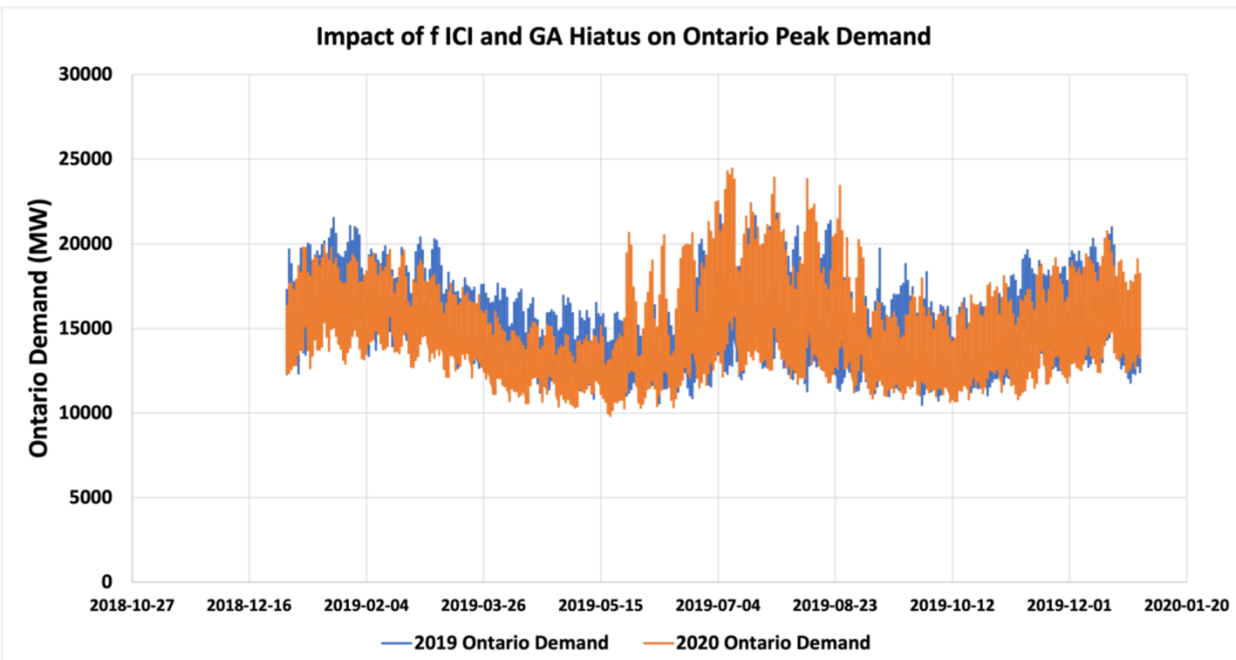


Figure 2. 5 Impact of ICI and GA Hiatus on Ontario Peak Demand based on IESO data [210]

This research second study investigates the viability of integrating energy storage with a solar system using the System Advisor Model (SAM) software [211] developed by the U.S National Renewable Energy Laboratory for the Advanced Research Complex (ARC) building at the University of Ottawa to achieve monetary savings from the Ontario Global Adjustment Program. The study highlights the vitality of financial mechanisms as enabling tools to help in clean technology diffusion. Second, the study shows that by using building-integrated advanced technology, Ontario's electricity peaks can be reduced, reducing the amount of CO2 emissions released that Ontario at peak times use natural gas to meet the increased demand during this period [212].

2.8 Summary

The literature review aims to highlight the interconnection between building science and policies; the literature shows that advancements toward the net-zero energy building sector are continually solidified by increased R&D, societal and behavioural changes, fiscal incentives, and polycentric system approaches. Twofold pathways have been identified to build on for this research. The first is "policy for science," which discuss what cities have been doing to achieve a net-zero energy building sector. Second, the potential for "campuses to act as a living lab" to find solutions for urban sustainability pressing issues has been identified. Plus, the prospect of energy storage with a PV system offers mutual benefits for government authorities to lower the electricity peaks and for facility owners/managers to reduce their electricity bills.

3. Policy for Science

This section illustrates the vital role of initiatives and policies in supporting the net-zero energy building transition (building science) in cities. Climate change and air pollution are heated topics that could only be mitigated by all stakeholders working together in a collaborative and synergetic environment.

3.1 Data Collection

This study qualitatively focuses on the net-zero carbon strategies and plans for the built environment in ten cities. The carbon reduction plan, such as local government climate action plans, annual reports, and other selected city publications, has been collected through publicly available documents from the official municipality's website.

The governance documents were written at the municipal level. However, they frequently contained inputs from local stakeholders and extensively referenced sources outside the local government's official scope. Every municipality has its climate action plan, including energy and carbon emissions plans. These cities' governmental documents have been evaluated and analyzed. In this research, the focus is kept on the building's pathway to provide recommendations for governors and decisions makers. The governmental reports included in this study between 2015 to 2021 include the latest evidence and best practices. All the documents utilized are in the English language and are freely publicly provided on the official municipal websites.

The Carbon Disclosure Protocol CDP 2021 Cities database [213] was also examined as a valuable data source for the research. The CDP is a global platform for cities to record and disclose environmental statistics annually and provide public, open-access data on all cities' voluntary reporting. To expedite the local climate reporting process and establish a consistent reporting platform, the CDP collaborates with the Global Covenant of Mayors, ICLEI Local Governments for Sustainability, and C40. Over 300 cities reported an emission reduction target aligned to 1.5°C worldwide. Ten Cities were selected to represent four regions and eight countries. The city's selection was driven by the municipal level's availability of climate mitigation documents. Most of the cities in Canada and around the world still have climate mitigation documents that are not accessible, or they don't have their own municipal website to gather the necessary information to carry out a thematic qualitative analysis.

The city's population size ranges from (600,000 - 14 million). The selected cities are considered pilot cities in decarbonizing the built environment and becoming net-zero because of their publicly available data, reporting transparency, and net-zero progress, as illustrated in Table 3.1. The climate change mitigation documents that have been analyzed and synthesized are represented in the table.

3.2 Research Design

Thematic qualitative data analysis was conducted following Lester et al.'s [214] seven phases for thematic analysis. Phase 1: preparing and organizing the data for analysis, phase 2: transcribing the data, phase 3: becoming familiar with the data, phase 4: memoing the data, phase 5: coding the data, phase 6: moving from codes to categories and categories to themes, phase 7: making the analytic process transparent. Inductive/thematic analysis indicates that "the patterns, themes, and categories of analysis arise from the data rather than being imposed on them before data collection and analysis," according to Patton [215]. The data obtained were synthesized and grouped into five main themes: (a) Building's energy efficiency measures. (b) Electrified renewable grids. (c) Green fiscal incentives. (d) Education, communication and capacity building. (e) Governance and collaboration.

Data from several sources, including climate action plans and the (CDP) database, were collected for each city to assure internal validity, and source aggregation was utilized to minimize bias [216]. Cross-checking and cross-case pattern matching of the results ensured coherent findings [217,218]. To ensure external validity, the sample cities represent the targeted urbanized theme population in four regions [219].

Table 3. 1 Cities information, including Their overall and buildings' CO_2 emissions, primary and secondary outcome and climate mitigation plans included in the study.

	Country	City	Population (million) + year	Annual CO2 Emissions +Baseline	Buildings ' annual CO2 emissions	Secondary Outcome	Primary Outcome	Climate Change Plans Included in The Study
1	Canada	Ottawa	0.994 (2017)	4.82 (2016)	2.25	reducing emissions by 50% from operations & 68% from the community by 2030	Net-zero by 2050	Climate Change Master Plan 2020 [220]; Energy Evolution 2020 [221]; The New Official Plan Volume 1, 2021 [222]
2	Canada	Vancouver	0.675 (2017)	2.805 (2007)	1.57	halving emissions by 2030	Net Zero by 2050	Climate Emergency Action Plan 2020 [223] ; Greenest City 2020 [224]; Zero Emission Building Plan 2016 [225]
3	Canada	Toronto	2.93 (2017)	43.78(1990)	24.08	Green economic growth	Net-zero by 2040	Transform TO Net Zero Strategy 2021 [226]; Net Zero Existing Buildings Strategy 2021[227]
4	United Kingdom	London	8.98 (2019)	45.054 (1990)	27.236	60% CO2 reductions by 2028 -2032	Net-zero by 2050	Zero carbon London, A 1.5ºC compatible plan 2018 [228]; CAP Technical Assistance for London Work Package 2 – Zero Carbon Building Policies 2018 [229]; London Environment Strategy [230]
5	Japan	Tokyo	14 (2021)	63.93 (2018)	41.75	Carbon - Half Style by 2030	Net-zero by 2050	Zero Emission Tokyo Strategy 2020 [231]; Tokyo Green Building Program 2018[232]; Tokyo Cap and Trade Program 2010 [233]
6	United States	New York	8.49 (2019)	55.11 (2019)	32.01	--------	80 % reductions by 2050	Pathways to Carbon – Neutral NYC 2021 [234]; One City Built to last 2014 [235]
7	Denmark	Copenhagen	0.602 (2017)	2.3 (2005)	0.4	--------	Net Zero by 2025	CPH 2025 Climate Plan 2020 [236]; Copenhagen Energy Vision 2050 “2015” [237]
8	South Africa	Cape town	4.7 (2021)	21.28 (2015)	10.21	Buildings Carbon neutrality by 2030	Net Zero by 2050	Climate Change Action Plan [238]; Resource Efficiency For Development 2019 [239]; Smart Living Handbook 2020 [240]; Getting to Zero 2020 [241]; State of Energy 2015 [242]
9	China	HongKong	7.2 (2015)	40.1 (2012)	26.46	Carbon - Half before 2035	Net-zero before 2050	Hong Kong's Climate Action Plan 2050 2021 [243]; Deepening Energy Saving In Existing Buildings 2017 [243]; Energy Saving Plan for Hong Kong's Built Environment 2015 [243]
10	Singapore	Singapore	5.6 (2017)	52 (2017)	7.8	Peaking emissions (65mtonnes) by 2030	halve 2030 emissions by 2050 and net zero in the century's second half.	Climate Action Plan [244]

3.3 Themes

3.3.1 Energy Efficiency

All the cities are implementing fundamental science principles to achieve energy efficiency in buildings. Cities have a different timeline for constructing new buildings to achieve net-zero energy efficiency standards. **Copenhagen** has already reached 2019, and all new buildings are designed to be net-zero. **Ottawa, Cape Town, Vancouver, Toronto, and London** aim to achieve net-zero new facilities in 2030. **New York** in 2035. **Tokyo** in 2050. **Hong Kong and Singapore** didn't specify when they would have new buildings to be constructed to meet net-zero standards. The following paragraphs will introduce notable initiatives from each city toward net-zero buildings, as indicated in Table 3.2

Table 3. 2 Building's Energy Efficiency

Category	Focus	City
Energy Efficiency	Building Enclosure Retrofit	All
	HVAC, Domestic Heat Water (DHW) & Heat Pumps Installation	All
	On-Site Renewables	All
	Appliances & Lighting	All
	Automation Systems & Control	All
	Net Zero New Buildings 2030	Ottawa, Cape Town, Vancouver, Toronto, London, New York 2035
	Net Zero New Buildings 2050	Tokyo
	Net Zero New Buildings achieved	Copenhagen
	Tackling Embodied Carbon	Copenhagen, Tokyo, Cape Town, Singapore, Vancouver, Toronto, Ottawa, London

3.3.1.1 Policies and Regulations

Ottawa: is implementing the following initiatives in buildings; Green Building Policy: since 2005, new city buildings of at least 500 m2 must be LEED (Leadership in Energy and Environmental

Design)-certified, with LEED Gold as a goal. Ottawa building's energy efficiency is subjected to the national energy code of Canada for buildings. Every five years, it is updated and intended to provide recommendations on retrofits, net-zero energy buildings, and substantial modifications to increase energy efficiency.

Tokyo: The Tokyo Green Building Program encourages the development of buildings with higher energy efficiency by employing a zero-energy building evaluation and making renewable energy an obligatory factor. Existing large buildings through the Tokyo Cap & Trade Program will strengthen energy efficiency measures and boost the usage of renewable energy. The Carbon Reduction Reporting Program encourages existing small and medium buildings to reduce and report CO_2 emissions and utilize renewable energy. The Tokyo Zero Emission House Standards foster the widespread adoption of zero-emissions houses.

Hong Kong: The City aims to strengthen regulations to include all buildings, carry out more energy audits, impose energy management, encourage retrofitting, and investigate reinforcing a minimum energy management efficiency requirement for appliances. The Mandatory Energy Efficiency Labeling Scheme (MEELS), which went into effect in 2009, includes a wide range of electrical appliances and is expected to save 800 million kWh annually by 2025. By 2025, the Buildings Energy Efficiency Ordinance (BEEO) implemented in 2012 and accompanying Building Energy Codes will have saved 1,000 million kWh. Green certification is required for future government facilities with a total floor area of 5,000 m2, core cooling equipment or bigger than 10,000 m2 and new public housing.

Singapore: aims by 2030 to raise the minimum energy efficiency performance criteria and requirements for home equipment and construction of energy-efficient houses. Singapore has implemented Minimum Energy Performance Standards (MEPS) and the Mandatory Energy Labelling Scheme (MELS) to encourage more energy-efficient household equipment. MELS enables customers to make better purchasing decisions, whereas MEPS eliminates inefficient equipment from the market. All new public sector buildings must meet the Green Mark Platinum level, and all large, air-conditioned buildings must meet the Green Mark Gold plus criteria at the very least. Buildings by 2030 will achieve Building and Construction Authority BCA Green Mark requirements for 80% of buildings. Singapore has created the Super Low Energy (SLE) Building Program to encourage the construction sector to attain best-in-class building energy performance at a low cost.

Cape Town: All solar PV systems must be registered with the municipality and comply with their regulations. Future projects with high potential energy consumption equal to the monthly consumption of l000 kWh or more must install a smart metre. All developments with grid-tied, feed-in solar PV systems must have metres installed by the city at the developer's expense. Cape Town will facilitate the adoption of energy performance certificates so that all relevant municipal buildings submit their energy usage information.

Vancouver: For existing buildings, Vancouver has enacted an energy bylaw (the first in Canada), setting yearly carbon pollution restrictions on the maximum amount of fossil fuels a structure can consume in its operations. Vancouver will restructure the city's green building rezoning regulations for new buildings to focus on GHG emission reductions and update the building code's minimum energy efficiency. The city plans require all new buildings to have zero-emission heating and hot water systems by 2025. The city has authorized adjustments to build energy regulations since 2007 to lower emissions from new buildings by more than 70% by 2022. To achieve it, significant residential and commercial buildings must do annual energy benchmarking and reporting. Additionally, the city recognizes Passive House certified structures and LEED Gold certified buildings as a display of authentic leadership in ecologically responsible design.

Toronto: The Toronto Green Standard for new buildings has been modified to align with the Toronto Zero Emissions Buildings Framework. It's a set of environmental performance indicators for long-term development that includes a step code for achieving Zero Emission Buildings (ZEB) by 2030.

London: the city aims to set regulations and enforcement to upgrade buildings to an Energy Performance Certificate (EPC) C rating to achieve the needed building energy efficiency. London districts will mentor future buildings to adapt to London's strategy for a zero-carbon plan. London businesses will follow the Minimum Energy Efficiency Standards (MEES) building policies.

3.3.1.2 Embodied Carbon

Cities are moving forward with the embodied carbon challenges. **Copenhagen:** has a procurement policy for energy-efficient appliances, construction machinery, and recyclable materials, also collaborating with European cities through big buyers' initiatives to stipulate requirements for zero-emissions construction sites in the tendering process. **Ottawa:** has a finance enabling policy for green Procurement policy for building materials. **Tokyo:** aims to achieve entirely green procurement by 2030. **Cape Town:** has detailed procurement guidelines and pushes for a more circular economy. **Singapore:** is taking steps for green procurement in the public sector. **Vancouver:** has embodied carbon policy, aiming to reduce embodied carbon from new buildings by 40% in 2030. **Toronto:** there is increased interest regarding embodied carbon policy and reporting. Toronto's action in 2022-2025 evaluates and limits the impacts of embodied carbon in construction. **London, Hong Kong:** encourages the construction sector to reduce embodied carbons yet doesn't have an enforcement policy. **New York:** didn't mention embodied carbon or green procurement in its climate mitigation plans.

3.3.1.3 Innovative Practices

Ottawa: The City features one of North America's largest web-based building control systems, saving time and effort to collect data without visiting sites. **New York:** Building energy efficiency retrofits are classified into Tier 1, Tier 2, and Recladding. Tier 1 represents minimum improvements "low hanging fruit," Tier 2 moves toward the building envelope, and recladding involves deep retrofits. **Copenhagen:** There are 21,500 eco-labelled appliances and products on the market, and the City of Copenhagen is working on adding even more conditions for ecolabelling its purchases. The City of Copenhagen will create and implement a photovoltaic action plan by 2025, requiring PV modules to generate 1% of baseline 2010 electricity usage or 26,000 MWh. **Tokyo:** In response to the COVID-19 problem, Tokyo will support deploying highly efficient ventilation and air conditioning equipment. **Hong Kong:** Hong Kong is planning to utilize smart management strategies by using smart technologies through leveraging big data and artificial intelligence to minimize energy usage and carbon emissions. The city plan to compare building energy consumption performance and establishes two-way cooperation in carbon reduction by providing energy data and benchmarking tools. The two Hong Kong power providers are gradually installing smart metres for their clients across the region to better monitor and control their electricity use and encourage energy saving. **Singapore:** recognize city buildings' data annually in the publication of building energy performance to benchmark and promote retrofitting actions to increase energy efficiency. **London:** Identifies energy network potential using heat mapping and the city's official energy maps.

3.3.2 Electrified Grids & District Energy

The electricity grid should be carbon-free to achieve the building sector's net-zero target. As indicated in Table 3.3, those strategies enable similar costs. Business as Usual (BAU), where cities keep their normal operations without further carbon reductions, is not the optimal solution according to climate mitigation plans.

Table 3. 3 Electrified Grids & District Energy

Category	Focus	City
District Energy	Heating	Ottawa, New York, Copenhagen, Vancouver
	Cooling	Hong Kong,
	Co-Tri Power Generation	Singapore
	Community Solar	Toronto
Renewable Electrified Grid	Wind	Ottawa, New York, Copenhagen, Cape Town, Hong Kong, Singapore, Vancouver, Toronto, London
	Solar	All
	Floating PV (Solar)	Singapore, Hong Kong
	Hydro	Ottawa, Cape Town, Hong Kong
Other Clean Sources	Hydrogen/ Town gas/ Renewable Natural gas	New York, Copenhagen, Tokyo, London, Cape Town
	Nuclear	Cape Town, Hong Kong
	Waste/ Biogas	Hong Kong, Vancouver
	Battery Storage	Toronto, London, Ottawa, New York, Hong Kong
Fossil Fuel Phase-out	2050	Ottawa, Copenhagen, Tokyo, London
	2040	New York, Toronto
	2035	Hong Kong
	Net-Phased Out	Vancouver

3.3.2.1 District Energy

Ottawa: The federal district's energy system will be converted to geothermal by 2040, and all-district energy systems will be geothermal by 2050. The Community Building Heating Strategy (2020-2025) is being carried out to meet the needs of heating in new buildings, which resulted in a 30% energy drop in the federal district energy systems. District energy will supply 15% of residential structures, and 80% of existing commercial and apartment buildings will be served by district energy by 2050. **Copenhagen:** Carbon emissions were lowered by over 1.2 million tonnes between 2013 and 2018, mainly owing to the green conversion of power generation and district heating systems. Copenhagen aims by 2025 to convert 500,000m2 of buildings to renewable energy sources, district heating, or town gas. **Hong Kong:** Cities 100, a C40 publication, named the Hong Kong District Cooling System as one of the action plans that might proactively tackle climate change in 2019. A district cooling system can save up to 35% on energy compared to traditional central air-conditioning systems in individual buildings. **Singapore:** In a case study, the tri-generation plant at GlaxoSmithKline Vaccines in Tuas, for example, could provide 1.8 megawatts of electrical power and steam and hot and chilled water. GlaxoSmithKline Vaccines has saved roughly 35.8TJ ($1.4 million) each year because of this expenditure, which has a payback time of about five years. Another case study by ExxonMobil Asia Pacific has also implemented high-efficiency cogeneration units. In 2017, a new 84 MW plant was finished, generating energy and steam while reducing GHG releases by around 140 kilotons per year. **Vancouver's:** Greenest City 2020 Action Plan identifies Neighborhood Energy Centers as critical to reducing Vancouver's greenhouse emissions. It provides thermal energy for space and hot water heating, and industrial activities on a neighbourhood scale involve large-scale heat pumps and wood-burning or gasification equipment. Example: The False Creek Neighborhood Energy Utility provides buildings with space heating and hot water. Since its inception in 2010, the utility has grown significantly, serving 534,000 m2 of residential, commercial, and institutional space in 2019. Before implementing fuel switching and renewable energy strategies**, Toronto:** explores zero/low-emissions cogeneration and district energy opportunities in high-intensity areas. Community Solar is an example of a project where multiple participants can own or lease a portion of a solar project. **London:** London will enable a heat zoning policy by connecting the existing building to decentralized district heating facilities resulting in 1.4 million district heating connections.

3.3.2.2 Renewable Electrified Grids

All the cities are increasing the grid's renewable electricity mix, mainly from wind, solar, and hydro resources.

New York: The clean grid policy's implementation will mostly drive building sector CO2 reductions. The city has three pathways in their plan. Pathway1: Electrification: Increase reliance on electricity. Pathway2: Low Carbon Fuel: using more renewable natural gas. Pathway 3: Diversified: Using a mix of the measure of pathways 1 and 2. Pathways 1 & 2 both achieve at least 80% direct emissions reduction. The Diversified Pathway reduces more than 90% of direct emissions (relative to the 2005 baseline).

Hong Kong: Given the limited land-based renewable energy resources, Hong Kong could look at using space and the ocean's potential to build wind farms. In 2018, a government case study launched the Feed-in Tariff (FiT) scheme, where power companies buy renewables generated by the private sector at a higher rate than the electricity tariff. In a second case study, in 2017, the

Shek Pik Reservoir and Plover Cove Reservoir pilot projects to build floating solar energy generation systems were completed to overcome the limited available land.

Singapore: Singapore's compact size, congested cities, modest wind speeds, flat terrain, and lack of geothermal assets make alternative energy choices like nuclear, hydroelectric, wind, land and floating solar and geothermal power challenging to pursue. Singapore has been labelled a country with a lack of alternative energy resources. However, Singapore plans to increase solar power adoption to at least a 2-gigawatt peak (GWp) by 2030, around 10% of the current daily peak electricity demand.

Cape Town: Electricity accounts for 57% of the Cape Town GHG emissions, making it an effective mitigation option. The city promotes Grid-connected feed-in systems. The city now permits customers to send surplus power generated by solar panels back into the grid for a discounted electricity cost.

Vancouver: Vancouver's electricity is near 100 % renewable. Provincial legislation mandates that the British Columbia grid be supplied with at least 93 % clean sources, and the present grid energy is over 97 % renewable, resulting in insignificant CO_2e emissions.

London: The carbon intensity of the electricity grid is falling. However, one of the key limitations when financial incentives are available to electrify homes, inadequate current supply networks discourage homeowners from engaging in building modification solutions. Incremental electricity grid upgrade costs less than £4bn to 2050. To put this into perspective, London's electricity bills incrementally will be over £200bn by 2050. In addition to the climate change adaptation cost if London didn’t reduce its GHG emissions.

Toronto: Toronto consumes a lot of energy in buildings and has low energy generation, as most energy comes from the provincial electricity grid. Toronto Hydro will increase clean energy resiliency by generating locally renewable energy within the city's boundary.

3.3.2.3 Other Clean Energy Sources

Other clean energy sources help increase the net-zero building's transition resiliency. **New York**, **Tokyo, Hong Kong,** and **London:** consider low carbon renewable energy such as hydrogen. **Cape Town:** is considering a plan to establish a nuclear facility to meet energy demand after 2024. **Hong Kong:** considers nuclear, hydro and waste to energy facilities to achieve carbon neutrality. **Toronto, Ottawa, New York, Hong Kong,** and **London:** plan to utilize energy storage to satisfy electricity demand when solar panels and wind turbines are not generating. **Vancouver:** considers converting waste to biogas.

One of the downsides of nuclear facilities is that it produces a considerable amount of radioactive wastes and produce a high amount of thermal pollution to marine life and water bodies.

3.3.2.4 Fossil Fuel Phase-out

The cities are planning to end the use of fossil fuels from both the energy supply and demand. **Ottawa, Copenhagen, Toyo, and London:** are phasing out from fossil fuel derivatives by 2050. **New York** and **Toronto:** in 2040. **Hong Kong:** in 2035. **Singapor**e: uses only natural gas as a clean source of fossil fuel. **Vancouver:** has nearly 100% renewable sources. **Cape Town:** didn't indicate when they will phase out from fossil fuels as almost 85% of energy in South Africa is derived from coal.

3.3.3 Green Fiscal Incentives

The third theme is green fiscal incentives. The cities' contributions are indicated in Table 4.3 and discussed below.

Table 3. 4 Financial Mechanisms

Category	Focus	City
ESG Investments & Incentives	Licensing/ Permitting	Ottawa, Toronto
	Energy Efficiency/ Retrofitting	Ottawa, New York, Copenhagen, Cape Town, Hong Kong, Vancouver, London
	Renewables (PV panels)	New York, Copenhagen
	Appliances & HVAC	Singapore, Copenhagen, Vancouver
	ESG Investments	All
Taxes & Emission Trading Schemes	Carbon pricing/Taxes enforcement	Ottawa, Hong Kong, Vancouver, Toronto
	Retrofits taxes reductions	New York, Hong Kong, Vancouver
	Renewables support	Cape Town, London
	Emission trading	Tokyo, Hong Kong
Landlord & Tenant	Resolving energy efficiency barriers	Ottawa, Hong Kong, New York, Copenhagen, London, Singapore, Toronto, Vancouver
Power Purchase Agreements PPA & Public-Private Partnerships	District Energy & PV panels	Ottawa, New York, Copenhagen, Cape Town

3.3.3.2 Environmental, Social, and Governance (ESG) Investments

Ottawa: provides grants based on carbon emissions and licensing exemptions for achieving low carbon in buildings.

New York, **Copenhagen,** and **Cape Town:** enhance financial incentives for energy efficiency, renewable energy and funding PV upgrades.

Cape Town: In July 2017, the city issued a green bond listed on the Johannesburg Stock Exchange's green bond sector.

Singapore's: $24.8 million Climate-friendly Household Package in 2020 encourages households to buy energy-efficient appliances and water-efficient shower fixtures.

Vancouver: is incentivizing the purchase of equipment such as heat pumps and is expanding to include airtightness and heat-recovery ventilation and windows for all residential buildings. **Toronto:** collaborates with provincial and federal associates to initiate a green bank. Toronto provides finances for building retrofits through The Energy Retrofit Loan programme, which offers reduced-interest financing to commercial, institutional, and big houses. The High-Rise Retrofit Improvement Support Program offers residential apartment funding for 20 years. These programmes can fund up to 100 % of a project's costs. The Home Energy Loan Program (HELP) offers homeowners up to $75,000 in financing.

London: considers using GHG offset funds from future developments to reduce GHG emissions in existing buildings. Additionally, London will argue for and collaborate with the national government to allocate funds to tackle expensive energy efficiency measures and support homeowners and small and medium-sized enterprises SMEs to improve their buildings.

Hong Kong's: two power providers created energy efficiency funds for energy-saving renovation works. For every kWh of power saved by its customers, the power company will subsidise the cost of electricity for individuals in need.

3.3.3.3 Taxes & Emissions Trading Schemes

Ottawa, Toronto, and **Vancouver:** carbon tax rates are equivalent to 50$ per tCO2e by 2022 and will increase by 3% annually. Vancouver advocates increasing its rate by 10% per tCO2e to enable more funding opportunities for green buildings. **Singapore** and **Vancouver:** use carbon tax income to subsidize enterprises and individuals to reduce emissions and become more energy-efficient. **New York:** has tax exemptions for energy retrofits or converting industrial to residential buildings. **Toronto:** leverages reported building performance data to determine tax reductions. **Cape Town**: Solar PV installations cost can be used for income tax deductions.

London: encourages the national government to ensure the tax structure enables the diffusion of thermal storage, PV panels and other renewables. **Tokyo:** has a cap and trade program for high energy-consuming facilities.

3.3.3.4 Landlord-Tenant

Hong Kong: Green Building Council HKGBC has launched a Green Tenancy Driver handbook to promote green leasing (landlords and tenants working together to improve the building performance). One misaligned incentive that a green lease solves is landlords pay for the energy efficiency upgrades, and the tenant enjoys lower utility costs. The green lease offers the landlord to pass a share of the cost of the improvements to the tenant while the tenant enjoys lower utility costs reaching a win-win situation. **Ottawa:** considers the Green lease as an enabling policy. **New York:** is developing building owner incentives. **Copenhagen** and **London:** address overcoming the conflict of interest between landlords and tenants regarding energy retrofitting in rental buildings. **Singapore:** focuses on improving how building tenants and occupants utilize energy, recognizing that renters spend around 50% of the energy in a commercial building. In addition to using the current Green Lease Toolkit20**. Toronto:** is seeking a way to overcome transferring the cost of deep retrofitting to tenants. **Vancouver:** has Energy Retrofit PLUS Reinvestment Program for rental apartments and Housing Retrofit Program for Non-Market Housing. Additionally, Vancouver will begin a Green Condominium Program and broaden the scope of the Green Landlord Program.

3.3.3.5 Power Purchase Agreement (PPA) and Public-Private Partnerships (PPP)

Ottawa: is considering funding district energy projects through PPP. **New York:** developed a PPA agreement to fund the combined heat and power project (CHP). **Copenhagen:** aims to use PPP financial scheme for private building owners financed by the municipality and national government for large retrofits. **Cape Town:** companies will fund and install solar PV on buildings allowing facilities to purchase electricity generated through PPA. **Toronto:** will collaborate with industry allies to investigate the possibility of PPA.

3.3.4 Education & Capacity Building

The fourth theme is education and capacity building. The cities' contributions are indicated in Table 3.5 and discussed below.

Table 3. 5 Education and Capacity Building

Category	Focus	City
Citizens	Civic Engagement	All
	Public Education	All
Corporates, authorities, NGOs	Public Staff/ City Authorities	Ottawa, Copenhagen, Cape Town, Vancouver
	Corporations	Ottawa, New York, Copenhagen, Tokyo, Singapore, Toronto, Cape Town, Vancouver
	NGOs	Tokyo, Singapore, Toronto
	Community Partners	Ottawa, Singapore, Toronto
	Living Labs, R&D	Copenhagen, Singapore
Workforce	Industry Professionals	New York, Toronto, London, Vancouver, Cape Town
Students	Schools Renovations	New York, Hong Kong
	Curriculum	Hong Kong, Singapore, Vancouver, Ottawa
	City Programmes	Copenhagen
	Living Labs, R&D	Singapore, Hong Kong, Copenhagen

3.3.4.1 Citizens

Ottawa: will provide education and civic engagement through training to staff and the public to immerse climate action into the community and corporations. **New York:** published GreeNYC and NYC CoolRoofs Public programs for citizens to provide public education. **Copenhagen:** uses The Climate Action Showroom for citizens and policymakers. **Tokyo** and **London:** encouraging buying efficient appliances and renewable electricity. **Hong Kong:** established The Energy Efficiency Centre in the Hong Kong Science Museum, which gives information about energy labelling and encourages consumers to buy energy-efficient items. **Hong Kong** and **Singapore:** created Energy Saving for All website (www.energysaving.gov.hk) and the National Environment Agency's Energy Efficient Singapore microsite (www.e2singapore.gov.sg) to enable access to energy reduction information. **Cape Town:** created the Smart Living Handbook to increase energy literacy and enable citizens to perform energy audits for their homes. **Vancouver:** designed The Climate Emergency Action Plan Survey to involve the public. People urge the city to educate residents on why these changes are required and how they work.

3.3.4.2 Business

New York, Toronto and **Cape Town:** developing educational material on energy efficiency to corporates and the building industry. **Toronto:** collaborates with trade associations to highlight buildings that have undergone extensive renovations through testimonies and collaborate with real estate institutions to educate realtors about the benefits of energy-efficient structures. **Vancouver:** spur new training and education efforts and increase industry confidence in the feasibility of low-embodied carbon buildings. **Copenhagen, Hong Kong** and **Singapore:** explore turning the city into a living laboratory for sustainable climate solutions to enable companies to test green solutions.

3.3.4.3 Workforce

New York: will provide a curriculum to teach municipal building operators about building optimizations and education on code requirements and laws. **Toronto:** is creating education and training to strengthen the workforce in deep emissions retrofits. Toronto is also developing contractor databases to connect homeowners with licensed contractors. **London:** is creating training and job opportunities for apprentices and contractors. **Vancouver:** the skilled professionals are ageing, which made Vancouver subsidize trades training to encourage high school students for jobs such as HVAC technicians. The Centre of Excellence for Zero Emissions Building (https://www.zebx.org/) aims to educate industry professionals.

3.3.4.4 Educational Institutes and Research and Development R&D

Ottawa: considers further development in post-secondary education institutions. **New York:** and **Hong Kong:** are creating free solar energy systems for schools to enable learning opportunities for students about net-zero buildings. **Singapore:** Ministry of Education collaborates with government departments to raise climate change awareness within the national curriculum at multiple levels. Singapore is investing in solar R&D. **Vancouver:** citizens urge the city to engage school students about buildings' energy efficiency. The Centre of Excellence in sustainability at the Nicola Valley Institute of Technology (NVIT) will be a central hub for disseminating case studies and resource guides for net-zero buildings.

3.3.5 Governance

The fifth theme is governance. The cities' contributions are indicated in Table 3.6 and discussed below.

Table 3. 6 Collaboration

Category	Action / Focus	City
National government	Funding	Ottawa
	Public housing	New York
	Legislation	Copenhagen
	Grid decarbonization	Tokyo
	Coordination	Cape Town, Vancouver,
Sub-national Government	City Institutions	All
	Utility companies	Ottawa, New York, Copenhagen, Tokyo, Vancouver, Toronto, Hong Kong, London
	Property Owners	Copenhagen, Toronto, Hong Kong
	Universities	Ottawa, Cape Town, Hong Kong, Singapore
Businesses	Energy Contractors Partnerships	Ottawa, London
	Business Alliances	Ottawa, Toronto, Tokyo, Hong Kong, Cape Town
	NGOs & Community Partners	Toronto, Hong Kong, Cape Town, Vancouver, London
International & Regional knowledge mobilization	City-to-city partnerships	Ottawa, Cape Town, London
	Regional collaboration	Ottawa, Copenhagen, Vancouver, Toronto, London
	IGOs	All

There are many spheres of interconnection between national, sub-national government, business, and international and non-governmental organizations. **Copenhagen, Tokyo, Cape Town, Vancouver, Toronto, London, and Ottawa:** highlighted the authority needed to implement mandatory emissions performance targets and provide funding; most of it is outside their direct control. Hence, cities are calling on provincial, federal, and national governments to have them engaged in increasing energy efficiency and decarbonizing energy sources.

Identifying and collaborating with city stakeholders is another key enabler. The cities are increasing synergy between city institutions, utility companies, property owners, and universities. The third enabler is businesses; cities partner with energy contractors to offer lower prices to public housing and citizens. Cities are creating strategic alliances with companies and corporates such as IKEA and TD bank to mobilize knowledge and best practices. Additionally, cities are leveraging on Non-governmental Organizations (NGOs) and community partners to ensure taking actions on all levels to achieve a net-zero energy building sector.

Finally, On the international level, all the cities share their best practices by participating in initiatives such as The Global Covenant of Mayors. Local Governments for Sustainability ICLEI, C40 Cities Climate Leadership Group, Carbon Neutral Cities Alliance (CNCA), International Carbon Action Partnership (ICAP). Cities have also been reporting their carbon emissions inventory, and climate plans to the Carbon Disclosure Project (CDP) annually. For example, **Ottawa:** partnered with Hanover city in Germany and Malmo City in Sweden. **Cape Town:** is a partnering city of Aachen in Germany.

3.4 Summary and Discussion

This section builds on the literature and the thematic qualitative analysis to better understand the current opportunities and challenges facing the building and construction industry to reach net zero energy in cities.

Science is inherently uncertain, especially when dealing with highly complicated and politically heated problems [245]. Scientists tend to test more than one hypothesis to accommodate (decrease risk or uncertainty), leaving them with more options to be selected. Even when a threat is discovered, science cannot advise us on how to respond. A political process of negotiation, bargaining, and compromise is used to decide what to do [245].

The first theme is energy efficiency; the higher the efficiency, the lower the energy demand from buildings. It makes energy efficiency the fundamental cornerstone in climate change mitigation and achieving a net-zero building sector. Energy efficiency comes first, and then decarbonizing the energy supply comes second. Cities start their energy efficiency measures with "low hanging fruit," such as window replacement, as it's the most cost-effective approach. However, it doesn't tackle 80%-100% decarbonization scenarios [246]. Another limitation is that building codes are released on the national level, and cities don't have the authority to upgrade or create their building codes to a higher stringent requirement. Vancouver is the only city with its building code as it's a chartered city possessing a unique legal foundation. On the other hand, a considerable leap in addressing the embodied carbon challenge or scope three emissions. Cities are releasing policies to encourage green procurement for materials and appliances and setting a GHG budget for embodied carbon when constructing or renovating a building.

The second theme is energy supply; a fully decarbonized building sector won't be achieved without a clean energy source. Cities have been working in three directions to acquire a carbon-neutral electricity mix. They were first utilizing district energy units for building heating and cooling. District energy systems use renewable sources to generate clean electricity to feed multiple buildings or neighbourhoods. District energy enables buildings to acquire clean electricity that buildings won't be able to obtain individually—second increasing the renewable electricity mix in the grid through wind, solar, and hydro. Third, cities incorporate R&D to investigate the adoption and diffusion of new technologies such as hydrogen and biomass.

In many cases, grid ownership lies outside the city boundaries and belongs to the national or federal government. Hence, many cities call to increase their electricity resiliency by having their renewable energy supply feed the electric grid. Another limitation is space; for example, floating photovoltaic panels were introduced in Singapore and Hong Kong to increase solar uptake due to the limited land space.

Politics (the process of bargaining and negotiation to reach net zero) without policy (a clear inclusive plan to reach net zero) threatens the democratic process for two reasons. For instance, it may result in limited participation in decision-making processes because certain groups may be excluded. Second, if decision-makers do not have appropriate options for action, the political authority will do little to benefit the general good. If politicization refers to circumstances in which politics takes priority over policy, what about those in which policy considerations prioritize politics? [245]. Hence, to make sure that the building's energy transition is inclusive and equitable, the third theme, green fiscal policy, is a means to ensure equity and inclusion among the population. Four strategies are critical to achieving just, equitable, and inclusive energy transition in the building sector. First, ESG Investments and incentives are a way to correct market failures and balance the high upfront energy transition cost; it exemplifies government expenditures. The upfront transition cost is evident for property owners, small and medium business SMEs, and new technology diffusion. Second, taxes and emissions trading schemes exemplify the government revenue mechanisms. Taxes and emission trading schemes help the government set carbon pricing on fossil fuel and carbon emissions and set a maximum CO2 allowance for facilities. Thirdly, cities acknowledge the overarching push and pull between landlords and tenants. Cities are trying to find common ground through green leases and other incentives to facilitate wise energy operations and encourage building energy retrofits. Fourth, a key enabler is Power Purchase Agreement PPA and Public-Private Partnerships PPP. PPA enables cities to purchase green materials and appliances in bulk, enabling lower prices for citizens. PPP enables cities to construct systems and buildings to facilitate the net-zero transition through partnerships with other stakeholders to overcome the city's limited financial and technical resources.

Four strategies have been identified for the fourth theme, education and capacity building. Following the notable remark of the UK House of Lords in 2020 [247], as a global commitment, scientific and policy institutions have to use science to ensure citizens' awareness and engagement to alleviate this crisis of public mistrust. Citizen engagement and public awareness are vital as most of the energy consumed during the building life cycle during the operation phase and determined mainly by end-user habits. Second, businesses must be aware of the city's net-zero roadmap, and education should be provided to help the city achieve carbon neutrality. Third, workforce training will help in smoothing the transition without causing inequalities. Fourth, the social contract for science is a closed-loop, through a degree of trust, transparency, and accountability; the society provides funding for science, with expected returns on the society [248]. It can be inferred that the social contract is driving innovation, research, and development (R&D) worldwide. Higher educational institutes can potentially prepare industry professionals to occupy various energy efficiency and carbon management roles within the building industry. Education can be done through creating new programs, updating the curriculum, and utilizing campus as a living lab imitative. On the other hand, schools can embed sustainability and energy efficiency literacy for children at a young age through, for example, installing solar panels to serve as an educational opportunity.

The fifth theme is governance and collaboration. One of the significant limitations that cities face is that most of the legislation and financial resources are driven by the national, federal, or provincial government directions. Even when cities aim to achieve more ambitious CO_2 reductions than the national government, they face difficulties. For example, Toronto calls on other municipalities to cultivate the required moves at the federal and provincial levels. London keeps pushing the UK government to enforce more stringent energy efficiency measures. Climate governance needs city stakeholders to be identified and participate in the transition as cities become more extensive and complex. Most GHG reductions lay at the intersection of more than one authority or department. Cities also leverage their global position by partnering with other cities and participating in global climate governance networks.

4. Methodology

The research methodology builds on the literature review and policy for science chapters and comprises two sections, as identified in Figure 4.1. The first section explains the methods and data used to perform the first case study (Campus as a Living Lab). The second section illustrates the process and utilised data to achieve monetary savings from the Ontario Global Adjustment Program through integrating energy storage with PV systems at the ARC building.

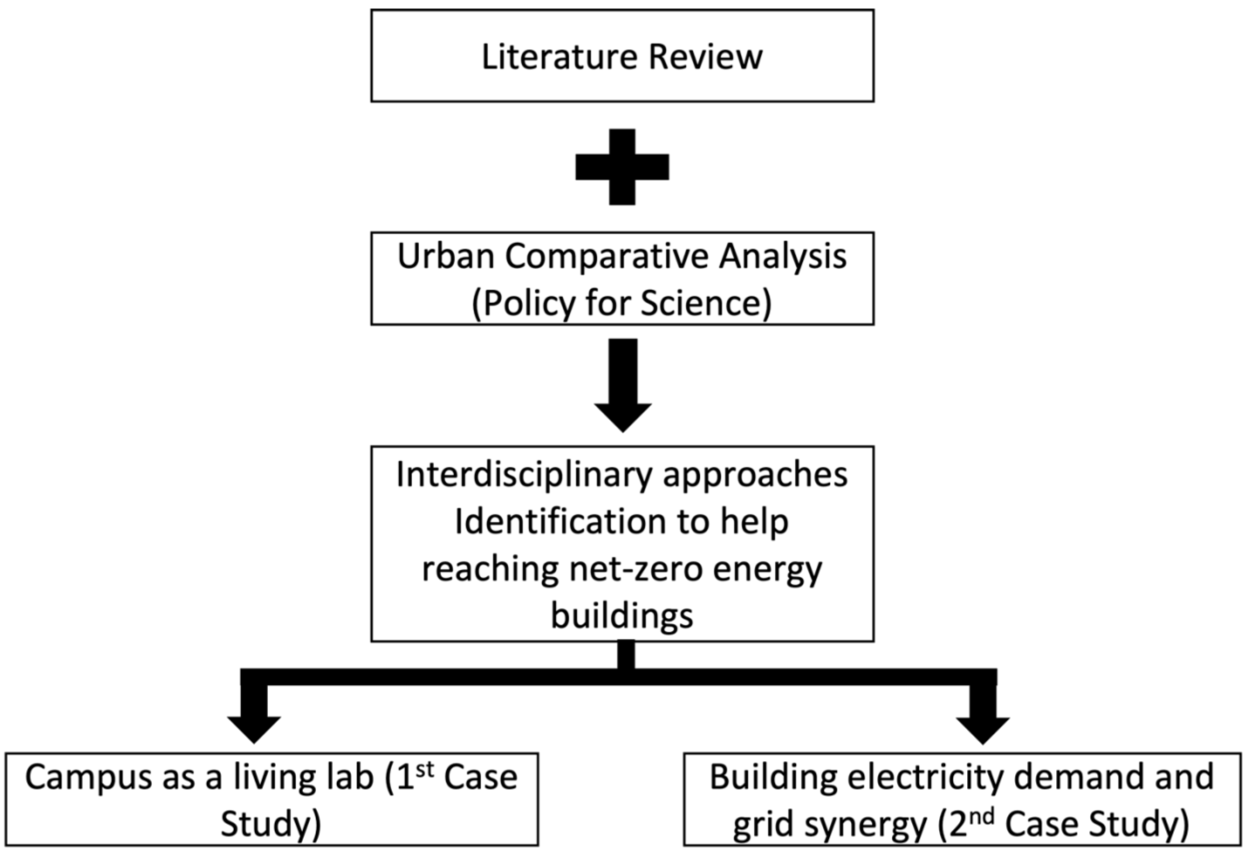


Figure 4. 1 Whole research methods and approach

4.1 Campus as a Living Lab Methods and Data

As mentioned in the previous sections, the first case study objective is to examine the viability of installing PV panels at the University of Ottawa to help achieve carbon neutrality by 2040 and meet the City of Ottawa's climate targets. As a part of the campus as a living lab initiative. The following actions have been considered to meet this goal, as indicated in Figure 4.2.

Phase 1: This phase consists of dividing the campus into 15 zones and grouping 51 students into groups of 3-4 students to work in each zone and identify the best possible places to install PV panels to generate the most electricity with the least life cycle cost. Phase 2: consists of each group doing market research to identify the latest available PV technologies in the market and project costs in Ottawa. This phase is critical as it defines the data inputs that will shape the PV analysis. Phase 3: consists firstly of measuring buildings' roof areas through Google Earth and doing shading analysis through Climate Consultant 6.0 software to model the PV system in RETScreen and obtain annual energy generation, financial viability, operational yearly GHG emissions reduction, and risk and sensitivity analysis. This stage gives an overall view of the Life Cycle Cost of the Project. Phase 4: consists of performing a Life Cycle Assessment through One-Click LCA software to the PV system to assess embodied carbon potential. In addition to carrying out the campus as a living lab survey to assess the initiative's effectiveness. This phase is carried out after completing the campus as a living lab initiative.

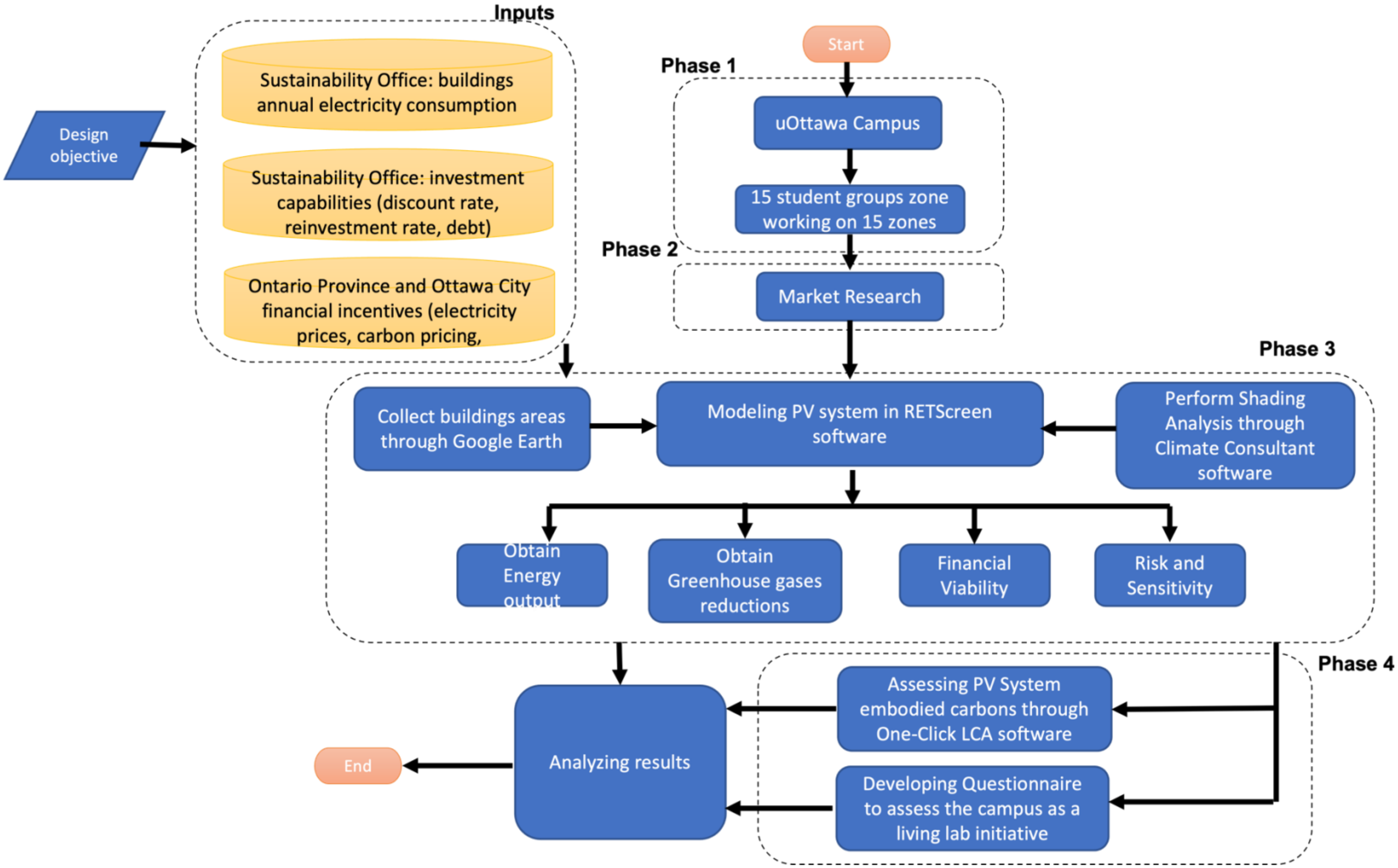


Figure 4. 2 Campus as a Living Lab research methodology flowchart

4.1.1 Phase 1

4.1.1.1 Campus Screening and Zoning

The campus was divided into 15 zones at the beginning of the work. A group of 3-4 students were assigned to identify the best locations to install PV panels to generate maximum solar gains within each zone, as indicated in Figure 4.3. After the initial screening, it was identified that many of the current campus buildings would be subjected to demolishing and others for renewals and upgrades. Meeting and exchanging information with the university sustainability office in parallel made the zones narrowed to 28 buildings that are suitable for installing PV panels. Additionally, the health science campus with three buildings was added to the total sum of buildings, turning them into 31 building. Buildings identification, as indicated in Figure 4.4, is made by eliminating buildings that will be demolished or having significant renovations that would change the building structure. Buildings constructed in the future were eliminated due to the limited information received about their area and size. Also, buildings that suffered significant shading effects or roofs that were overpopulated with mechanical equipment were not considered for the analysis.

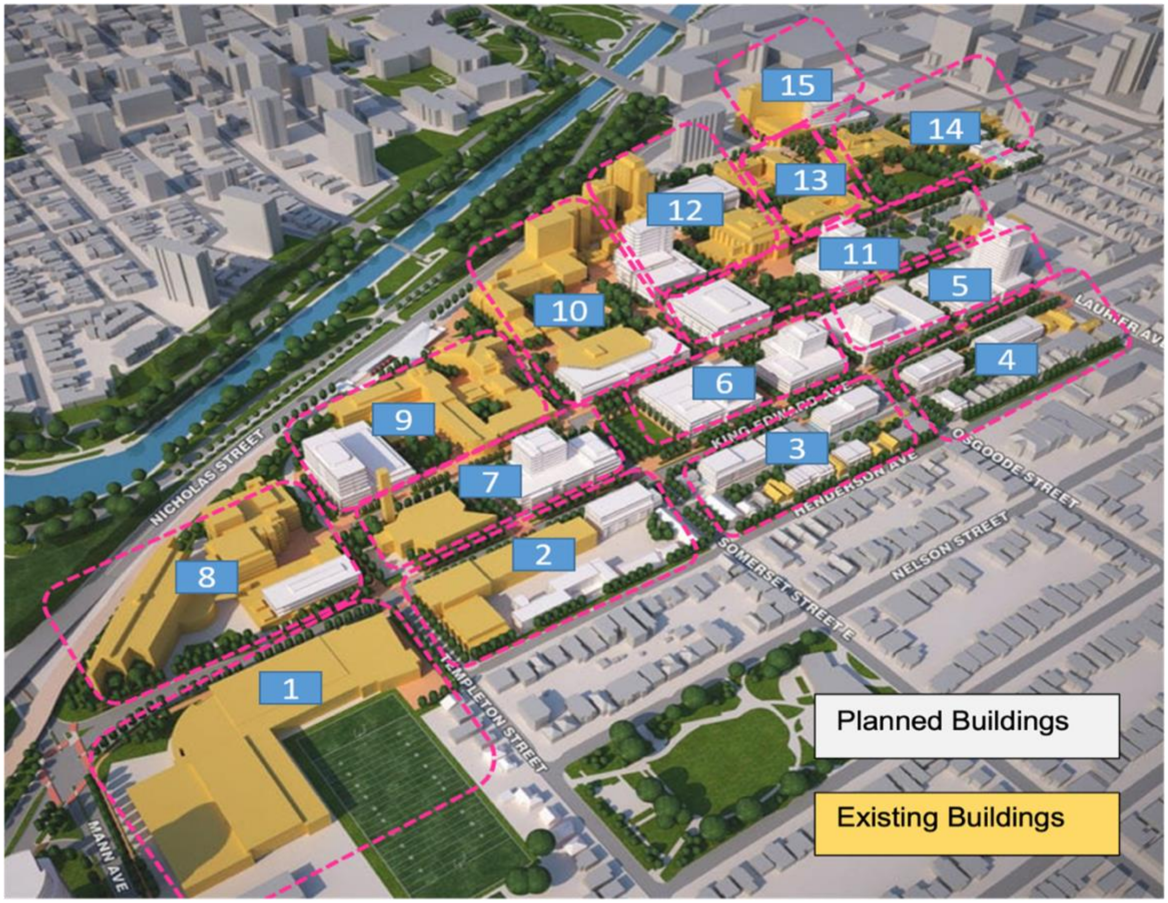


Figure 4. 3 Working groups and zones at the uOttawa campus

Figure 4. 4 uOttawa campus plan for buildings [172]

4.1.2 Phase 2

4.1.2.1 Market Research

Market research is a critical component of the PV study; It helps identify the market's latest available PV technology and the corresponding project cost. This phase enables accurate predictions of the financial viability of the project and total expected electricity output. All the costs indicated are in Canadian Dollars.

4.1.2.1.1 PV Manufacturers

According to market research, it shows that PV panels costs have dropped significantly in 2022. Manufacturers such as Canadian Solar [249] and Trina Solar [250] are considered reliable companies are leading the solar industry. The two companies offer commercial PV panels with the highest power capacity, up to 670 W and an efficiency of 21.6%. For example, Canadian Solar prices for panels with 670W are equal to CA$0.3669 for a collective power system capacity of 200KW - 999KW. And CA$0.329 for a collective power capacity bigger than 1000KW [251]. Trina Solar offers the same price range [252] for the same power capacity and efficiency, as indicated in Table 4.1. It has been decided to use Canadian Solar PV panels for their high efficiency, market availability and competitive prices. The detailed characteristics of the selected PV panel are provided in Appendix A.

Table 4. 1 Canadian Solar and Trina PV panels efficiency and price

Manufacturer	Location	Model	Material Type	Panel Power (W)	Efficiency %	Cost $/W >999kW
Canadian Solar [249]	Canada and China	HiKu7 Mono PERC	Monocrystalline	670	21.6	0.3302 [251]
Trina [250]	China	Vertex670 W TSM-DE21	Monocrystalline	670	21.6	0.3302 [252]

4.1.2.1.2 Project Cost

The following estimate indicated in Table 4.2 was provided by a board member in the SES Solar Co-op in Saskatchewan, based on the estimated costs for a 375kW flat rooftop project at a recreation centre in Saskatchewan in 2022 [253]. SES Solar Co-op recommended costs to be increased by 15% for smaller projects, such as 100kW projects. Material and labour prices are estimated to be similar for the Ottawa region.

Table 4. 2 PV project breakdown structure [253]

Item	Cost/kW ($)	% Of total
Solar Panels	$500.00	26%
Inverters	$200.00	10%
Metal Racking and Brick Ballast	$250.00	13%
Wiring & Grounding	$100.00	5%
Labour, Admin, Overhead	$550	29%
Other	$0.00	0%
Transformer (480V/600V if required)	$50.00	3%
Online metering, commissioning	$20.00	1%
Sub-total	**$1,670.00**	**87%**
Project Management (5%)	$83.50	4%
Contingency (10%)	$167.00	9%
Total Cost/kW	**$1,920.50**	**100%**
Total Project (375kW)	**$720,187.50**	

In another PV project, costs sourced from the Ottawa Renewable Energy Co-operative (OREC) [254], as indicated in Table 4.3, reinforce the previous numbers. Comparing the SES Solar Co-op project cost estimate [253], it can be seen that there is a very high similarity between them. For example, in the 2020 project, Paul-Desmarais was constructed with a power capacity of 286kW and cost $1,958,04/kW and the Mer Bleue project with a power capacity of 350kW costs $1,828,57/kW. It can also be inferred that recent Projects in 2020 demonstrate a lower price trend than older projects. For example, project Hovey, constructed in 2015 with a capacity of 385kW, costs $3,098,70, around 50% higher than the Mer Belue project. The projects also show a reasonably linear correlation between cost and power capacity. The higher the power capacity, the lower the cost per kW, as indicated in Figure 4.5.

Table 4. 3 PV project costs adopted from Ottawa Renewable Energy Co-operative (OREC) [254]

Project Name	Location	Project date	Total Cost ($)	Power Capacity (kW)	Cost/kW ($)
Paul-Desmarais	Stittsille	2020	$560,000.00	286	$1,958.04
Mer Bleue	Orleans	2020	$640,000.00	350	$1,828.57
Museum	Alta Vista	2019	$425,823.00	215	$1,980.57
Hawkesbury	Hawkesbury	2019	$1,527,922.00	500	$3,055.84
KIN Vineyards	Carp	2018	$71,000.00	30	$2,366.67
Twin Elm	Nepean	2018	$221,000.00	100	$2,210.00
Alfred	Alfred	2017	$1,471,000.00	500	$2,942.00
Fenton	Ottawa South	2017	$216,000.00	100	$2,160.00
Maurice-Lapointe	Kanata	2016	$705,000.00	190	$3,710.53
Manotick Station	Manotick Station	2015	$20,500.00	50	$410.00
Smith Farm	Dunrobin	2015	$166,000.00	75	$2,213.33
Hovey	Ottawa South	2015	$1,193,000.00	385	$3,098.70
Franco-Ouest	Bells Corners	2015	$327,500.00	100	$3,275.00
Franco-Cite	Alta Vista	2015	$537,500.00	150	$3,583.33
Samuel-Genest	Gloucester	2014	$525,000.00	75	$7,000.00
Presland I & II	Overbrook	2013	$148,500.00	20	$7,425.00
LaFontaine	Gloucester	2013	$45,000.00	10	$4,500.00

Figure 4. 5 Correlation between PV project power capacity and total project cost

4.1.2.1.3 Summary

Since our Project is in Ottawa and Canadian Solar is the only Canadian company offering the same quality and price as the other companies, we selected Canadian Solar PV panels. Due to the limited space on the campus and the reasonable price difference between the PV panels, it has been decided to use the PV panels with the highest capacity and efficiency. It offers higher electricity generation, lower depreciation rate, better quality, and less maintenance. Collectively the expected generated electricity from uOttawa is more than 999KW. Hence the solar panel rate will be around 0.329 $/kW. Since there is a high similarity between projects in Ottawa and Saskatchewan, it can be inferred from SES Solar Co-op in Saskatchewan that solar panels in a 375KW project have a percentage of 26% of the total cost. In a large project such as the uOttawa campus, it is predicted that the cost percentage of the solar panels will decrease to be lower than 26% of the total cost, which means that opting for the highest PV power capacity is the optimal solution. Additionally, the total project cost from OREC and SES Solar Co-op is very similar to the cost database within

RETScreen software used for the analysis. Hence, using the RETScreen built-in cost database is reliable for the initial, operation, and maintenance (O&M) costs.

4.1.3 Phase 3

4.1.3.1 Buildings Roof Areas

The actual building's rooftop areas were determined to calculate the solar collector areas of the campus buildings. One obstruction is the limited access to the building's engineering plans and the areas. Hence, Google Earth [37] measuring tool was utilized. The gross roof areas were calculated then any obstructions such as installed mechanical equipment were deducted. According to Natural Resources Canada Photovoltaic Ready Guidelines [256], there have to be clear pathways, and rigid setbacks for edge must be considered of the usable roof area. To achieve that, approximately 80% of the functional roof area was considered for the analysis. The building's solar collector areas ranged from approximately 7000m2 to 250m2. The total resulting roof areas of the 31 buildings collectively equals 655,569 m2. The solar collector area is calculated according to equation (1) as follows:

$$SCA = (BRA - D)\ X\ 80\% \qquad (4.1)$$

Where SCA is the solar collector area (m^2), BRA is the building roof area (m^2), D is the deductions (m^2) for any obstructions available on the roof and 80% to comply with the safety guidelines from Natural Resources Canada.

4.1.3.2 Solar Shading

Shading caused by the solar panels is considered one of the major losses to the power capacity of a PV system. Climate Consultant 6.0 software [257] developed by the University of California Los

Angeles (UCLA) is used to calculate the shading effects to account for the shading. The software uses energy plus weather (EPW) [258] files for North America to simulate the buildings within the Ottawa region. Since RETScreen doesn't perform shading analysis, the solar radiation loss percentage was roughly estimated and multiplied by the power capacity of the PV system. As indicated in Figure 4.6 for the William Commanda building, the building suffered shading effects from the west direction from 15 to 17 hours. The shading loss is calculated according to equation (4.2) as follows:

$$FPC = [\frac{12-X}{12}\ X\ adjustment\ factor]\ X\ PC \qquad (4.2)$$

Where FPC is the final system power capacity (kW), X is the number of hours suffering from shading, the adjustment factor ranges from 0 to 1 according to which hour of the day and its solar radiation, and PC is the system power capacity before adjusting to shading (Kw),.

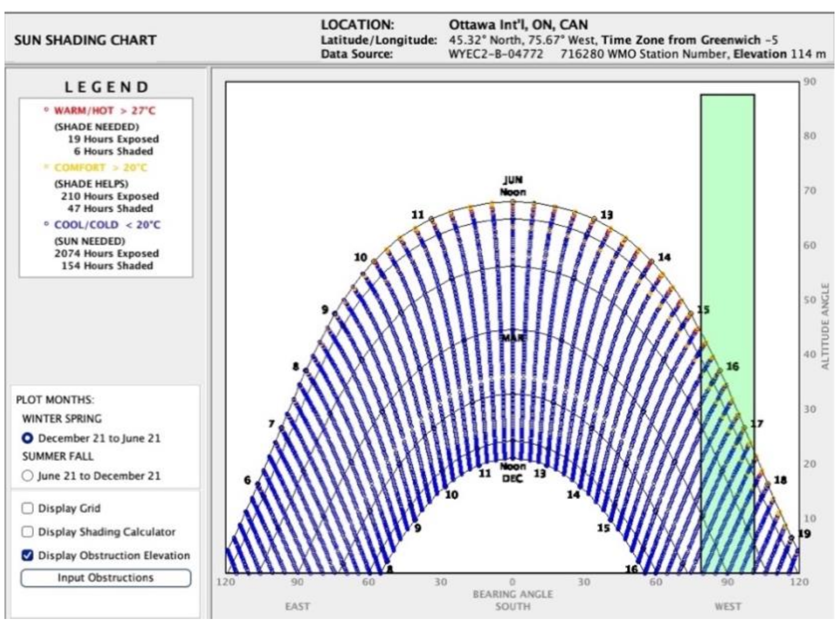


Figure 4. 6 Shading Analysis in Climate Consultant 6.0

4.1.3.3 Modelling and Life Cycle Cost Analysis in RETScreen

4.1.3.3.1 Location and Weather

To model the PV system with accurate precision. RETScreen uses global climate meteorological data derived from NASA's satellite and ground station data covering the whole earth. The ground database includes ground-based observations from over 4,700 locations. For the uOttawa campus location, the ground station is located at Ottawa International Airport, 11 km from the uOttawa location, as indicated in Figure 4.7.

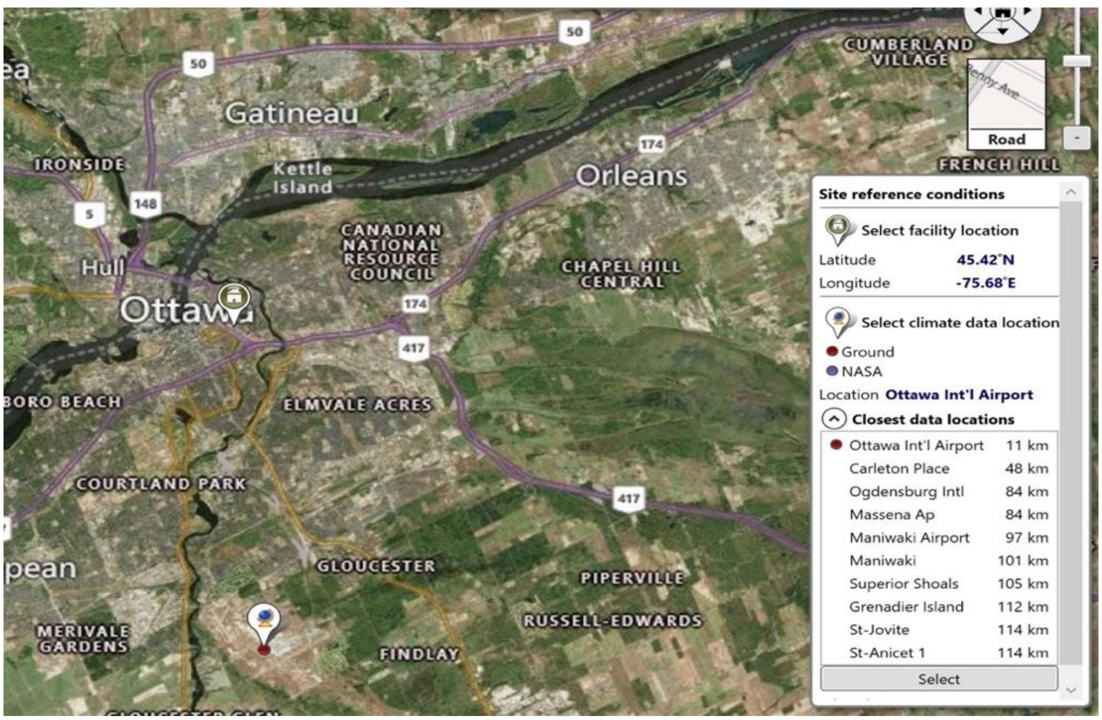


Figure 4. 7 Facility and ground station location identification at RETScreen

Table 4.4 shows the location of the facility and climate data: latitude, longitude, climate zone, and location. The latitude is considered one of the essential location data as it represents an optimal angle for the PV panels installation. Additionally, the monthly solar radiation in Ottawa is illustrated in Figure 4.8. The solar radiation is higher in the summer season, with maximum daily radiation up to 19 $(kWh/m_2/d)$ and lower in the winter to reach 1.5 $(kWh/m_2/d)$

Table 4. 4 Facility and climate data location

	Unit	Climate data Location	Facility Location
Name		Canada – Ontario – Ottawa Int’l Airport	Canada – ON – Ottawa
Latitude	°N	45.3	45.4
Longitude	°E	-75.7	-75.7
Climate Zone		6A – Cold – Humid	6A – Cold – Humid
Elevation	m	114	73

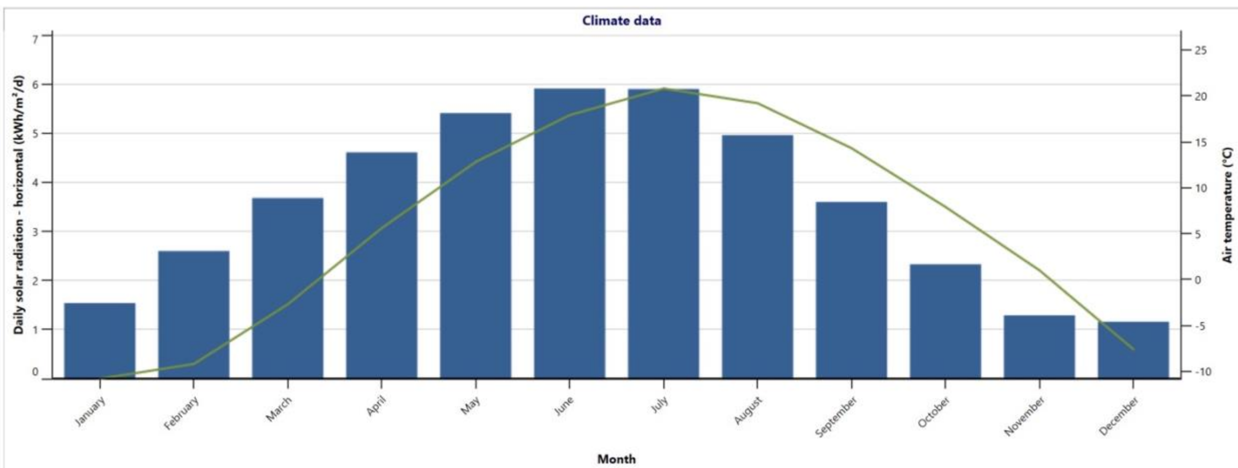


Figure 4. 8 Monthly solar radiation in Ottawa

4.1.3.3.2 Energy

In this stage, the photovoltaic system is defined. The system includes photovoltaic panels, an inverter, and a mounting structure. The system characteristics are inserted to obtain the expected electricity generation according to the technical specification and the weather data. This study has selected a simple PV system with a HiKu7 Mono PERC PV panel from the Canadian Solar company, a fixed mounting structure, and central inverters. The PV installation, the inverter and the technical specification are described in Table 4.5. The slope of the PV panels is considered 36.5 lower than the altitude to avoid the PV panel's self-shading effects. The azimuth is deemed equal to zero; since the project is in the northern hemisphere, and the PV panels are best to face the equator. The PV average efficiency is calculated according to the following equations (4.3-4.7) [259]:

$$\eta_p = \eta_r - \beta_p (T_c - T_r) \qquad (4.3)$$

η_p is the average system efficiency (%), η_r is the PV panels efficiency (%) at a specific temperature T_r (=25°C), and β_p is the temperature coefficient for panels efficiency (%/°C), T_c is the average panel temperature (°C), T_c relates to the mean monthly ambient temperature T_a (°C) through Evans' formula [260] as follows (4):

$$T_c - T_a = (219 + 823K_t)\frac{NOCT - 20}{800} \qquad (4.4)$$

Where $NOCT$ is the Nominal Operating Cell Temperature (°C), and K_t is the monthly clearness index range from (0 – 1), η_r, $NOCT$, and β_p are based on the PV type.

The equation above is valid when the array's tilt is optimal (i.e. equivalent to the latitude subtracting the declination). If the angle is not optimal, the right side of equation (4) must be multiplied by a correction factor C_f, which is defined by equation (5):

$$C_f = 1 - 1.17 \times 10^{-4} (S_M - S)^2 \qquad (4.5)$$

Where S_M is the optimum tilt angle (°) and S is the actual tilt angle (°).

The electricity generation delivered by the PV array, EP (kWh), is calculated according to equation (6,7):

$$E_p = S_a \eta_p \, H_t \tag{4.6}$$

Where S_a is the module area (m^2), $and \; H_t$ is the hourly irradiance (kWh/m^2). It has to be reduced by "miscellaneous PV modules losses" λ_p (%) and "other power conditioning losses" λ_c(%):

$$E_A = E_p \left(1 - \lambda_p\right) (1 - \lambda_c) \tag{4.7}$$

Table 4. 5 PV system assessment and inputs

Resource Assessment		PV Assessment	
Solar Tracking mode	Fixed	Efficiency	21.6%
Slope	36.5	Nominal operating cell temperature °C	41
Azimuth	0	Temperature coefficient % / °C	-0.34%
		Bifacial call adjustment factor %	0%
		Miscellaneous losses	10%
		Frame area	3.1m^2
Inverter Assessment			
Efficiency	98%		
Capacity	80% of the PV power capacity		
Miscellaneous losses	1%		

4.1.3.3.3 Cost

As previously stated in the market research, the cost database in RETScreen is very similar to the information gathered from the literature and industry professionals. Hence, the RETScreen database has been used for this project. The collective power capacity of the 31 buildings at the campus is expected to be around 14,000 kW making the corresponding initial cost between $1,450 and $1,200, as shown in Table 4.6. And the operation and maintenance costs are between $13 and

$10. the initial cost is set to be 1412 $/kW, and the annual operation and maintenance cost is set to be 12.54 $/kW according to the following equation (4.8) [261]:

$$y = y_1 + (x - x_1)\frac{(y_2 - y_1)}{(x_2 - x_1)} \quad (4.8)$$

Where y is the unknown cost value per kW ($/kW), x is the independent electricity production value (kW), x_1 and y_1 are values of the production (kW) and cost function ($) at one point, respectively, and x_2 (kW) and y_2 ($) are values of the production and cost function at another point, respectively.

Table 4. 6 Installation costs for PV projects adopted from the RETScreen database [189]

Technology	Power plant – Typical installed cost ($/kW)					
PV Capacity (kW)	10	100	1,000	10,000	100,000	1,000,000
Initial Cost ($)	2,700	2,100	1,800	1,450	1,200	1,000
Operation and Maintenance Cost ($)	33	25	18	13	10	8

4.1.3.3.4 Financial Parameters

The financial parameters are vital inputs to obtain an accurate life cycle costing of the PV project, as indicated in Table 4.7. HyrdoOttawa [262] has specified three electricity prices depending on the time of use. The electricity rates from HyrdoOttawa, effective May 1, 2022, are Off-Peak: 0.082 $/kWh, Mid-Peak 0.113 $/kWh, and On-Peak 0.17 $/kWh. The electricity cost rate for this study is 0.1 $/kWh as an average for daily electricity consumption. According to Statistics Canada, the inflation rate is 5.1% [263]. RETScreen doesn't have an option to account for the module's annual degradation. Hence, the electricity escalation rate has been lowered than the inflation rate of 0.7% to account for the PV modules degradation. It must be noted that this will be reflected only in the project's profitability. However, the power generation will stay the same. The Canadian interim guidelines of the Treasury Board Secretariat (2007) [264] recommend a discount rate of 8% for projects to be profitable. Hence, a discount rate of 9% has been identified for this project.

The reinvestment rate has been considered the same as the discount rate. The project life is the same as the PV module life equals 25 years. There is no incentive, grants or debit considered when performing the analysis, and we didn't account for revenue for the GHG reductions. The financial indicators formulas used in the study are listed below based on Brealey and Myers (1991) financial textbook [265].

Table 4. 7 Financial parameters

Electricity cost rate	0.1 $/kWh
Electricity cost escalation rate	4.4%
Inflation rate	5.1%
Discount rate	9%
Reinvestment rate	9%
Project life	25 years
Incentives and grants	$0
Debt ratio	0%
GHG reduction revenue	$0

The internal rate of return IRR is the discount rate (%) that brings the Project's Net Present Value (NPV) to zero. It is computed through the following equation for IRR (4.9):

$$0 = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} \tag{4.9}$$

Where N is the project life in years, and C_n is the cash flow for year n ($).

The simple payback SP is the number of years it takes for cash flow (excluding debt payments) to equal total investment (the sum of debt and equity). It is calculated as follows (4.10):

$$SP = \frac{C - IG}{\left(C_{ener} + C_{capa} + C_{RE} + C_{GHG}\right) - \left(C_{O\&M} + C_{fuel}\right)} \tag{4.10}$$

Where C is the initial project cost ($), IG is the incentives and grants value, C_{ener} is the yearly energy savings or earnings ($), C_{appa} is the annual capacity savings or earnings ($), C_{RE} is the yearly renewable energy production credit earnings ($), C_{GHG} is the reduction in earnings ($), $C_{O\&M}$ is the yearly operation and maintenance costs caused by the clean energy project ($), C_{fuel} is the yearly fuel or electricity cost ($).

The Equity / discounted payback N_{PCF} is the first year the Project's total cash flows are positive ($). It is calculated by solving the following equation for N_{PCF} (4.11):

$$0 = \sum_{n=0}^{N_{PCF}} \tilde{C}_n \tag{4.11}$$

Where $\tilde{C}_n$ is the after-tax cash flow in year n ($).

A project's net present value NPV is the present value of all future cash flows, discounted at the discount rate ($). It's determined by discounting all future cash flows as given in the following formula (4.12):

$$NPV = \sum_{n=0}^{N} \frac{\tilde{C}_n}{(1+r)^n} \tag{4.12}$$

Where r is the discount rate (%).

The annual life cycle savings $ALCS$ is the Project's Levelized nominal annual savings with the same life and net present value (%/year). It is calculated using the following formula (4.13):

$$ALCS = \frac{NPV}{\frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right)} \tag{4.13}$$

The benefit-cost ratio, $B - C$, measure the Project's relative profitability. It's computed as a percentage of the project equity divided by the present value of annual revenues (income and savings) (4.14):

$$B - C = \frac{NPV + (1 - f_d)\, C}{\frac{1}{r}\,(1 - f_d)\, C} \tag{4.14}$$

Where f_d is the debt ratio.

The energy production cost is the avoided energy cost that makes the net present value zero. The energy production cost, C_{prod} ($/kWh), is acquired by solving for (4.15-4.18):

$$0 = \sum_{n=0}^{N} \frac{\tilde{C}_n}{(1+r)^n} \tag{4.15}$$

Where,

$$\widetilde{C_n} = C_n - T_n \tag{4.16}$$

$$C_n = C_{in,n} - C_{out,n} \tag{4.17}$$

$$C_{in,n} = C_{prod}\,(1+r_e)^n + C_{capa}\,(1+r_i)^n + C_{re}\,(1+r_e)^n + C_{GHG}\,(1+r_{GHG})^n \tag{4.18}$$

Where

T_n, is the tax at year n (\$), r_i is the inflation rate (%), r_e is the cost escalation rate (%), and $C_{in,n}$ is the in-cash flow at year n (\$), $C_{out,n}$ is the out-cash flow at year n (\$).

The GHG Emission reduction cost GRC reflects the Levelized nominal cost of avoiding one tonne of GHG ($\$/tCO_2$). It is calculated by (4.19):

$$GRC = -\frac{ALCS}{\Delta_{GHG}} \quad (4.19)$$

Where $ALCS$ is the annual life cycle savings calculated in equation (13), and Δ_{GHG} is the annual GHG emission reduction (tCO_2).

4.1.4 Phase 4

4.1.4.1 Operational Carbon

To understand the emissions savings from reducing the number of emissions released in the atmosphere due to installing the PV panels and generating clean electricity. As specified in Table 4.8, the following parameters have been inserted to estimate the GHG savings accurately. The GHG emissions factor in Ontario is set to be 0.031 tCO2/MWh according to The Atmospheric Fund report in 2021 [266], and grid transmission and losses are set to be 7%.

Table 4. 8 GHG emissions data

Country -region	Canada- Ontario
Fuel Type	All types
GHG emission factor excluding T&D losses	0.031 tCO2/MWh
T&D losses	7%

The annual GHG emission reduction is calculated as follows (4.20):

$$\Delta_{GHG} = \left(e_{base} - e_{prop}\right) E_{prop} \left(1 - \lambda_{prop}\right)(1 - e_{cr}) \qquad (4.20)$$

Where e_{base} is the base case GHG emission factor (tCO_2/MWh), e_{prop} is the proposed case GHG emission factor (tCO_2/MWh), E_{prop} is the proposed case annual electricity produced (kWh), λ_{prop} is the fraction of electricity lost in transmission and distribution (T&D) for the presented case (%), and e_{cr} the GHG emission reduction credit transaction fee ($\$/tCO_2$).

4.1.4.2 LCA Method and Boundary (Embodied Carbon)

Life Cycle Assessment (LCA) of Photovoltaic system previous studies has shown various results. The wide range of outcomes is that each researcher uses different methods, software, sourced data, and boundary conditions. In addition, each region's grid electricity uses a diverse energy mix with varying carbon intensities. The grid carbon intensity would affect the amount of greenhouse gas emissions emitted to produce the same materials. Other manufacturers use a different amount of energy or carbon to produce the materials [267]. One measure cause of results discrepancies is the lack of transparency regarding the LCA modelling process, especially in new technology equipment such as PV. Figure 4.9 show Life Cycle Assessment phases according to the International Standard Organization (ISO) series, ISO 14040 [268], and ISO 14044 [269]:

1) Goal and scope definition: This phase involves the study goals, the functional unit, the system's boundaries, the necessary data, the assumptions, and the limits that must be established. In particular, to equate all the inputs and outputs, the functional unit is the reference unit used to normalize them.

2) Life Cycle Inventory (LCI): Identifying and quantifying the use of energy, materials, water, and resources. During this stage, the available data is converted to appropriate indicators. The indicators are given per functional unit used.

3) Life Cycle Impact Assessment (LCIA): quantifying the expected environmental impacts stemming from using energy, water, and materials included in the life cycle inventory.

4) Interpretation: Examine the life cycle assessment results to determine the best material, method, or service while considering the uncertainty and hypotheses used in the conclusions.

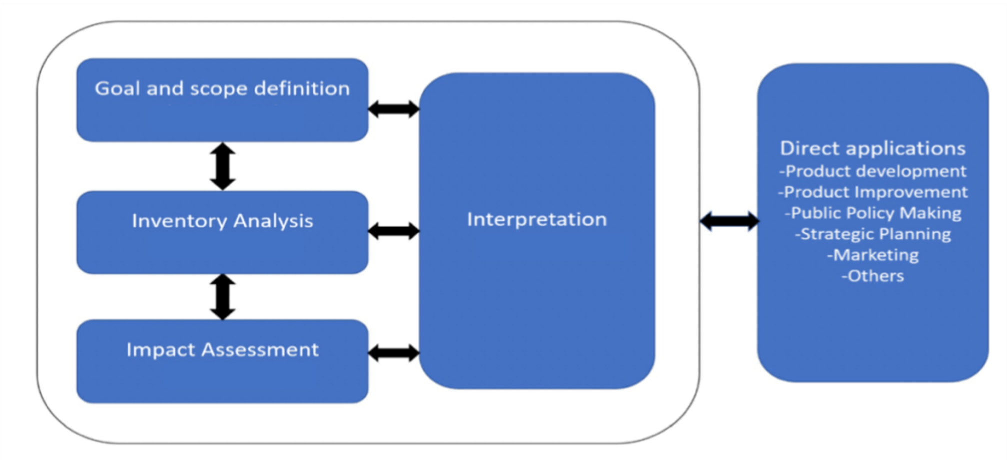


Figure 4. 9 Life Cycle Assessment (LCA) Phases based on ISO 14040 [268], and ISO 14044 [269]

Any Industrial system can be represented by a system boundary that gathers all the operations through its life cycle, as shown in Figure 4.10. All the inputs (raw material, energy) and outputs (emissions to air, water, land) and solid waste are represented; according to the International Energy Agency (IEA) PV methodology [270], the guidelines to perform an LCA photovoltaic presented in Figure 4.11.

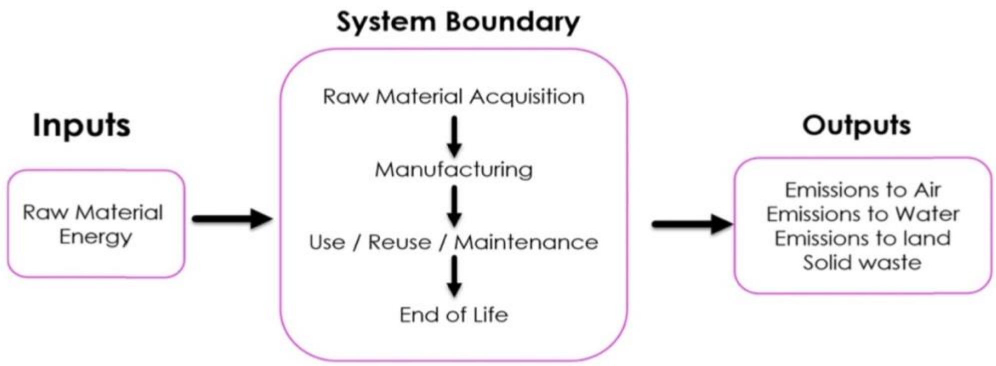


Figure 4. 10 Life Cycle stages

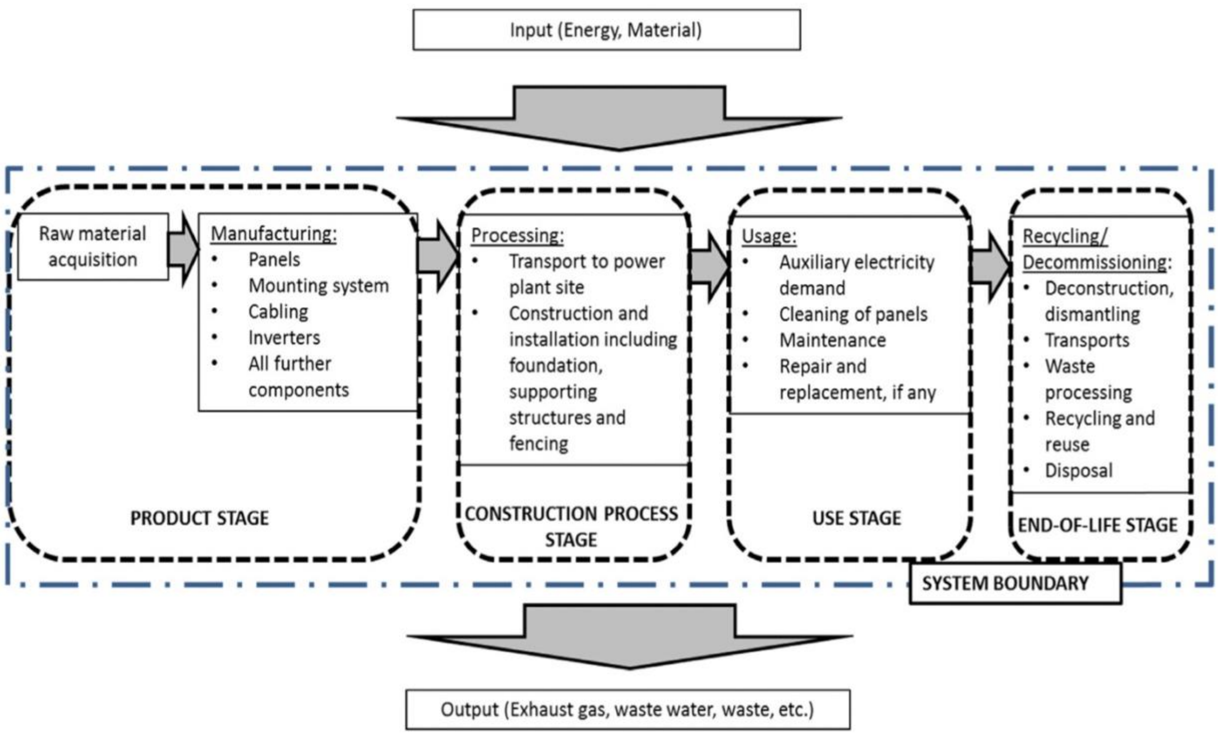


Figure 4. 11 The solar PV system boundary according to the International Energy Agency IEA [270] utilized by Ludin and colleague [79]

4.1.4.2.1 Data Estimation

The suggested PV system is modelled through One-Click LCA software and consists of mono-crystalline PV panels, a fixed mounting structure, an inverter, and wire and cables. The electricity and energy data used through the PV system life cycle are obtained from the One-Click LCA software database. Additionally, Canada – Ontario electricity data is obtained from One-Click LCA. The lack of available Environmental Product Declarations (EPDs) [271] for PV technology in the North American context was one of the significant challenges to performing the LCA, hence estimating the original raw materials to produce a PV system was needed [272]. EPDs are transparent products about the embodied energy/carbons consumed or emitted to be manufactured. Therefore, the analysis data was sourced from a 2019 report from the International Renewable Energy Agency (IRENA) [273] to obtain transparent and accurate results, as indicated in Table 4.9. The data represents the number of raw materials needed to produce a 1 MW solar PV plant. The raw materials include glass, steel, concrete, aluminium, silicon, copper, and plastic. However, the report sourced data dating back to 2015-2018; it is estimated that due to the increased efficiency of the PV systems, the number of raw materials needed to install a one MW PV system has been lowered more than twice. Therefore, for this analysis, the raw materials numbers have been adjusted. Table 4.9 shows the amount of needed raw materials to install a PV system of 1 MW and a 14.195 MW (expected power capacity of uOttawa PV system). The full details about the inputs of the material are in Appendix B.

Table 4. 9 uOttawa PV system expected needed material adopted and adjusted from IRENA (2019) [273].

	PV Materials	1 MW PV system (ton)	14.195 MW PV system (ton)
1	Glass	35	496
2	Steel	28	397
3	Concrete	23.5	333
4	Aluminium	9.5	134
5	Silicon	3.5	49
6	Copper	3.5	49
7	Plastic	3	42

The following assumptions for materials transportation have been made based on the data stored in One-Click LCA, as shown in Table 4.10. The first column represent the material type and. The second column is the distance needed to transport the materials to the site. The third column represents the truck type required to transport the material. The fourth column is the space capacity of the truck. The last column is the filling rate to populate the truck with materials. All the assumptions are based on the Canadian context based on identifying the project location in Ottawa at the beginning of the LCA analysis.

Table 4. 10 Transportation assumptions to ship the materials to the site

	PV Materials	Km	Truck Type	Truck Capacity	Truck fill rate
1	Glass	321.8	Trailer Combination	40 ton	100%
2	Steel	933.4	Trailer Combination	40 ton	100%
3	Concrete	321.8	Concrete Mixer	Average	100%
4	Aluminium	933.4	Trailer Combination	40 ton	100%
5	Silicon	1287.4	Large Delivery Truck	9 ton	100%
6	Copper	1367.9	Large Delivery Truck	9 ton	100%
7	Plastic	563.2	Trailer Combination	40 ton	100%

4.1.4.3 Campus as a Living Lab Survey

The Campus as a living lab initiative was done by participating 51 graduate students through the graduate course *CVG 6310 Net Zero Energy Buildings in Canada* in winter 2022 hosted at the department of civil engineering at The University of Ottawa. As indicated in Table 4.11, The student's represented MSc and PhD students from civil, environmental, and mechanical engineering departments. The students represented two universities in the Ottawa region, The University of Ottawa and Carleton University. The initative is a pilot study as it's the first of its kind to be implemented at the University of Ottawa to foster more research in this knowledge co-production and interdisciplinary and collaborative research. The students were grouped into 15 groups; each group had 2-3 students responsible for a zone to examine and install PV panels in the appropriate places.

The teaching assistant (TA), Eslam Elshorbagy, provided guidance and support to the students to allow them to finish their projects on time and facilitate the learning process. The involvement included meetings with each group of the 15 individually to understand their needs and unique site characteristics. The meetings also involved brainstorming, identifying opportunities and obstacles, and sharing best practices from other groups' work. The main objective of the structured meeting was to solidify and strengthen the student's research skills and make the determined project methods easily digested in a structured manner rather than using a data dumping approach that might jeopardize the research quality and integrity. Furthermore, the TA provided instructions and guidance about the RETScreen software during the class required for students to complete their project time efficiently. The instructions also included weekly presentations at the beginning of the course to explain how to execute the project and provide a live demonstration of RETScreen capabilities and the project concept.

The University of Ottawa sustainability office provided us with the necessary data to carry out the project and introduce the most pressing issues the campus faces and needs to find solutions to overcome. The data was exchanged through meetings and emails with the sustainability office coordinator and facility managers.

The campus as a living lab survey was designed to assess and understand the learning outcomes and the academic and professional progress of the participating graduate students. The survey is a short online questionnaire with 12 items. To be completed in five minutes. 32 students out of 51 students completed the survey indicating a response rate of 62%.

Table 4. 11 uOttawa students' distribution

Characteristics	%Distribution
University	
uOttawa	68.75
Carleton	31.25
Total	**100**
Program	
Master of Engineering	90.63
PhD	9.38
Total	**100**
Specialization	
Civil	93.75
Environmental	3.13
Mechanical	3.13
Total	**100**

The survey was disseminated to the students online after the students finished the course and were designed to be anonyms. Moreover, the survey was voluntary to be completed to avoid results bias [274] and establish internal validity [216]. The questions were kept general and not specific to a technical challenge within the project so they could be replicated or compared to other researchers' work to ensure external validity [275]. The survey questions also were designed progressively and tackled many aspects of the learning outcome to establish validity [276].

4.2 Global Adjustment Program Cost Savings Methods and Data

As mentioned in the previous section, the second case study aim is to integrate the solar system with battery storage at the Advanced Research Complex (ARC) building to understand the viability of reducing building load demand at the Ontario peak to achieve monetary savings through the Global Adjustment Program over 25 years. Hence, the following steps are taken to achieve this aim. First, the building's hourly electric load is measured and utilized. Second, the solar system is defined. Third, the battery system, life, cost, and dispatch algorithm are determined. Fourth, the calculation of the GA cost is presented. Finally, six PV systems and battery storage scenarios are presented to evaluate the cost-effectiveness of integrating GA savings to install the proposed system, as illustrated in Figure 4.12.

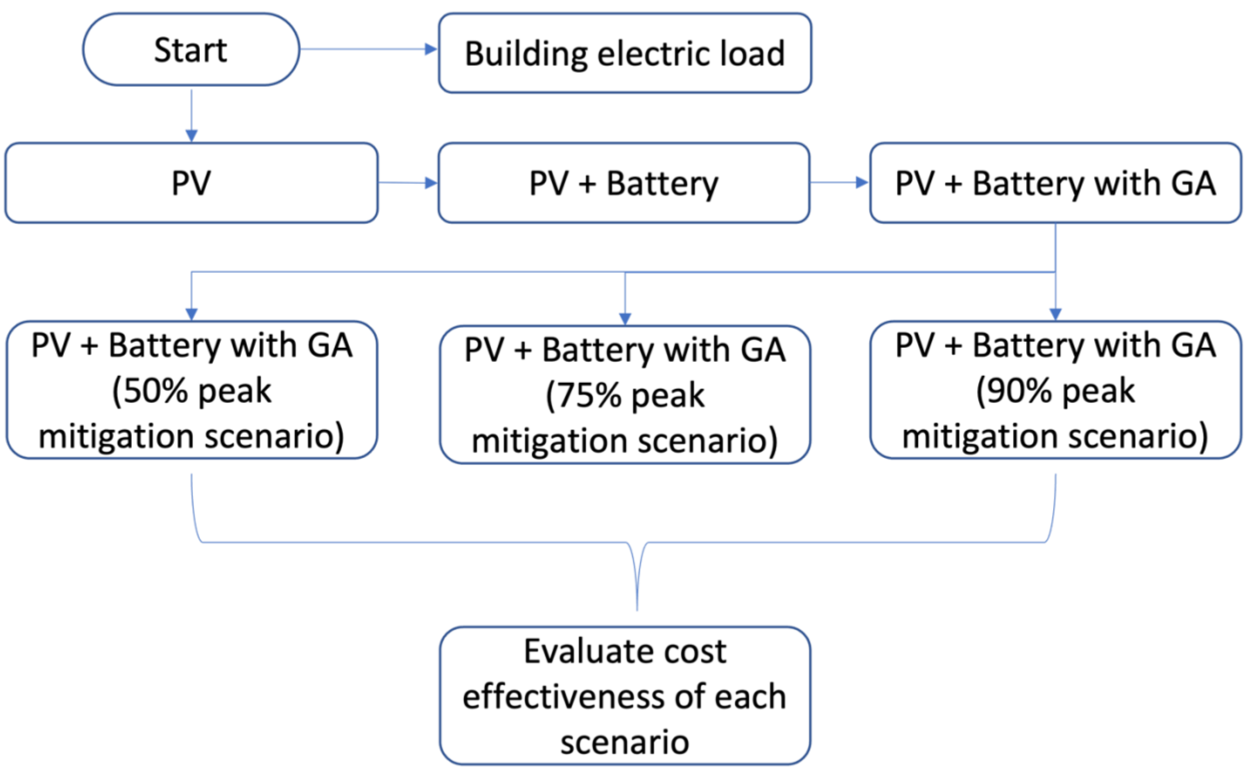


Figure 4. 12 Integrated photovoltaic and energy storage six scenarios

4.2.1 Building Electric Load

In order to have an accurate representation of the building electricity load, the average annual hourly electric load of the building for 2017 and 2018 were considered. The data for 2019, 2020, and 2021 was not considered because of the effects of Covid-19 on the building operations. Table 4.12 summarise the ARC building's monthly electricity load in kWh and the monthly electricity peak in kW. The building load data is an essential input based on it; the battery system is defined to cover the building load and peaks.

Table 4. 12 ARC building monthly electricity load and peak demand (averaged from 2017 and 2018 hourly electricity demand)

Month	Electricity (kWh)	Peak (kW)
January	355,643.82	559.66
February	341,341.24	588.78
March	380,500.79	606.96
April	370,561.09	622.49
May	394,006.18	630.18
June	376,303.95	619.20
July	393,727.14	623.21
August	390,505.10	599.53
September	378,870.17	621.63
October	374,956.38	596.25
November	381,768.61	609.08
December	405,012.24	626.00
Annual	**4,543,196.72**	**630.18**

4.2.2 PV System

The location and weather, energy, financial, and cost configuration are set to be the same as the modelling process in the previous work (campus as a living lab) for the PV system using SAM Photovoltaic model technical specification [277]. However, according to Deline et al. [275], SAM can account for the self-shading of PV panels.

4.2.3 Battery

The battery system, lifetime, voltage, and thermal model are vital characteristics that will determine the technical performance of the battery and, in return, will determine the economic performance of the storage system.

4.2.3.1 Battery Cell and System

Lithium-Ion: Nickel Manganese Cobalt Oxide (NMC/Graphite) is the battery type used in this simulation. The battery capacity performance model is calculated using equations (4.21-4.23) [278].

$$q = q - I\Delta t \tag{4.21}$$

Where q is the total charge (Ah), I is the current (A), and Δt is the timestep (hr)

$$E = qV \tag{4.22}$$

Where E is the energy (Wh), and V is the voltage (V)

$$P = IV = \frac{\Delta E}{\Delta t} = \frac{V\Delta q}{\Delta t} \tag{4.23}$$

Where P is the power (W), ΔE is the difference in energy (Wh), Δq is the difference in total charge (Ah)

As shown in Table 4.13, for the 100% mitigation scenario, the battery desired bank is designed to be higher by 5% than the highest building demand peak because the battery's maximum charge is set at 95% to ensure a longer lifetime. The desired bank capacity is set to equal to or more than double the bank power to afford mitigating two hours of the proposed demand peak. The total number of cells configured to have the battery desired power and capacity. The Max C-rate indicates the battery can discharge the bank capacity in two hours or more. The max discharge power is similar to the bank power, and the max discharge capacity is similar to the bank capacity. Time at maximum power indicates that the battery can operate for two hours at maximum power. In the case of the 100% scenario, the battery can operate for more than two hours (2.273) at maximum capacity.

Table 4. 13 Desired bank power and capacity and battery properties to simulate peak demand mitigation scenarios

Property/ Scenario	100%	90%	75%	50%
Desired bank power (kWdc)	660	600	540	350
Desired bank capacity kWh (DC)	1500	1200	1080	700
Time at maximum power (h)	2.273	2.000	2.000	2.000
Nominal bank voltage (VDC)	500.400	500.400	500.400	500.400
Total number of cells	130,243	104,111	93,686	60,743
Cells in series	139	139	139	139
Strings in parallel	937	749	674	437
Max C-rate of discharge (per/hour)	0.440	0.500	0.500	0.500
Max C-rate of charge (per/hour)	0.440	0.500	0.500	0.500
Maximum discharge current (A)	1,319.29	1,198.40	1,078.40	699.20
Maximum charge current (A)	1,319.29	1,198.40	1,078.40	699.20
DC Maximum discharge power (kW)	660.176	599.679	539.631	349.880
DC Maximum charge power (kW)	660.176	599.679	539.631	349.880

The desired bank voltage is 500 VDC, cell nominal voltage is 3.6 VDC, and the cell capacity is 3.2 Ah. The battery is connected to the AC side of the PV inverter with AC/DC to DC/AC conversion efficiency equal to 96%.

The battery lifetime depends strongly on conditions under which the battery is operated, such as temperature, state of charge, total energy through output, and the charge and discharge rate. The battery is replaced at 50% capacity so that the battery can continue to meet its load. SAM is set to automatically replace the battery when the life model reaches the available capacity. The initial battery cost is considered to be 344$/kW and 125$/kWh for the battery DC capacity [279]. In addition to 10$/kWh for operation and maintenance.

4.2.3.3.1 Battery Voltage

The electrochemical model [280] is a semi-empirical voltage model that determines the voltage discharge curve of the battery into three zones. The model is used to calculate battery voltage properties. As batteries age, the resistance increases and the usable voltage decreases, reducing the battery capacity. The voltage model is given by equation (4.24-4.33) [278].

$$V = V_o - RI - K\left(\frac{q_{max}}{q_{max} - \int Idt}\right) + ae^{-BIdt} \tag{4.24}$$

Where V is the terminal voltage (V), V_o is the battery constant voltage in (V), R is the internal resistance (A), K is the polarization voltage (V), q_{max} is the battery capacity (Ah), dt is the time step (hr), a is the exponential zone amplitude (V), B is the exponential zone time constant inverse (Ah^{-1}), e is the Euler's constant =2.718281828.

$\int Idt$ indicates the amount of removed capacity and can be calculated as in Equation (4.25)

$$\int Idt = q_{max} - q \tag{4.25}$$

The battery constant voltage is computed as follows

$$q_{exp} = q_{full} - It_{exp} \tag{4.26}$$

$$q_{nom} = q_{full} - It_{nom} \tag{4.27}$$

$$q_{exp\%} = 100 \times \frac{q_{exp}}{q_{full}} \tag{4.28}$$

$$q_{exp\%} = 100 \times \frac{q_{nom}}{q_{full}} \tag{4.29}$$

$$a = V_{full} - V_{exp} \tag{4.30}$$

$$B = \frac{3}{q_{exp}} \tag{4.31}$$

$$K = \frac{\left(V_{full} - V_{nom} + a(e^{-Bq_{nom}} - 1)\right)(q_{max} - q_{nom})}{q_{nom}} \tag{4.32}$$

$$V_0 = V_{full} + K + RI - a \tag{4.33}$$

Where q_{full} is the fully charged cell capacity (Ah), $q_{exp,\%}$ is the precent of q_{full} that has been removed at the end of the exponential zone (%), Where q_{nom} is the nominal charged cell capacity (Ah), V_{full} is the fully charged voltage (V), V_{exp} is the voltage at the end of the exponential zone (V), t_{exp} is the time at which q_{full} (hr) , t_{nom} is the time at which q_{nom} (hr).

The battery voltage properties and the electrochemical model data are outlined in Table 4.14. The voltage curve indicated in Figure 4.14 is a function of the battery state of charge, operating current, resistance, and capacity. The first zone in the voltage curve is the exponential zone towards a zero-depth of discharge; when the battery is full, there is a sharp increase in the voltage. The second zone is the nominal zone, where the decrease in voltage is nearly linear, and the deep reciprocal zone (third zone), where the voltage drops off quickly.

Table 4. 14 Battery Voltage properties and electrochemical model data

Voltage properties	
Cell Internal resistance (Ohm)	0.001155
Nominal bank voltage (VDC)	500.400
Nominal cell voltage (VDC)	3.600
Electrochemical Model	
Cutoff cell voltage (V)	0
Nominal zone cell voltage (V)	3.342

Exponential zone cell voltage (V)	3.53
Fully charged cell voltage (V)	4.2
Charge removed at exponential point %	80.75
Charge removed at normal point %	97.6875
C-rate of discharge curve	0.2

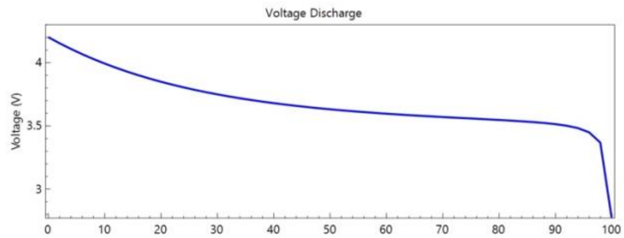


Figure 4. 13 Voltage Depth of Discharge (%)

4.2.3.3.2 The Battery Thermal Model

The battery thermal model calculates the battery temperature in each simulation time step. Battery temperature affects battery capacity and degradation. The model's two main heat-transfer terms are transfer between the battery and its environment and energy generated by resistive heating inside the battery. The battery heat transfer is described according to equation (4.34 – 4.36), [278].

$$f(T_{batt}) = \frac{dT_{batt}}{dt} = \frac{hA(T_{room} - T_{batt}) + I^2R}{mC_p} \tag{4.34}$$

Where m is the mass (kg), C_p is the specific heat ($\frac{J}{kg.K}$), h is the heat transfer coefficient ($\frac{W}{m^2.K}$), A is the battery surface area (m^2), and R is the battery's internal resistance (Ω). T_{batt} is the battery temperature ($°C$), T_{room} is the room temperature ($°C$).

To avoid stability concerns, equation (4.35) is used:

$$T_{batt,n+1} = T_{batt,n} + \frac{\Delta t}{2}[f(T_{batt,n+1}) + f(T_{batt,n}] \tag{4.35}$$

The capacity modifier represents the percentage of loss that applies at a particular temperature. The capacity is affected by the loss as follows:

$$q = q \times 0.01C_t \tag{4.36}$$

Where C_t is the capacity modifier (%).

Table 4.15 shows the thermal properties, where specific heat capacity C_p equals 1500 $\frac{J}{kg.K}$. The specific heat capacity is 30% higher than the standard lithium-Ion battery because the thermal properties of the whole battery system containing the racking components, the battery management system, and the extra needed space are modelled. The heat transfer coefficient h value of 7.5 $\frac{W}{m^2.K}$ corresponds to forced air convection. The battery room temperature is set to be 25 $°C$. Table 4.16 shows the physical properties of the proposed batteries. The specific energy per mass and specific energy per volume determine the battery mass, volume, and surface area. The specific energy per mass /volume is the ratio of the battery capacity to its mass/volume.

Table 4. 15 Thermal Properties

Specific heat C_p J/KgK	1500
Heat transfer coefficient h (W/m^2K)	7.5
Single environment temperature $°C$	25

Table 4. 16 Physical Properties for each peak mitigation scenario

	100%	90%	75%	50%
Specified energy per mass (Wh/kg)		101		
Specific energy per volume (Wh/L)		70		
Battery mass (kg)	13,063.908	11,874.839	10,685.770	6,928.310
Battery volume (m3)	18.849	17.134	15.418	9.997
Battery surface area (m2)	42.496	39.877	37.168	27.843

4.2.3.2 Battery Dispatch

The battery is dispatched according to the schedule that would maximize savings from the Global Adjustment program. Table 4.17 outlines the battery charge limits and priority. The minimum battery state of charge is set to be 30%, the maximum state of charge is 95%, and the initial state of charge is 50%. As specified in Figures 4.14 and 4.15, the battery won't be charged or dispatched at the weekend as Ontario doesn't have any peak. During the weekday, the battery is set to charge at period one from the system where solar radiation is abundant. In period three, the battery is charged from the system and the grid at a capacity of 30% to maintain a reliable state of charge in case of any shortage in solar generation from period one. Period two is when the battery discharges electricity to reduce the building electricity load at Ontario peak time. The battery in period two is discharged at a capacity of 100% to cover the building load. The battery charge from the system only when system output exceeds load.

Table 4. 17 Charge Limits and Priority

Minimum state of charge	30%	Initial state of charge	50%
Maximum state of charge	95%	Minimum time at charge state	10 min

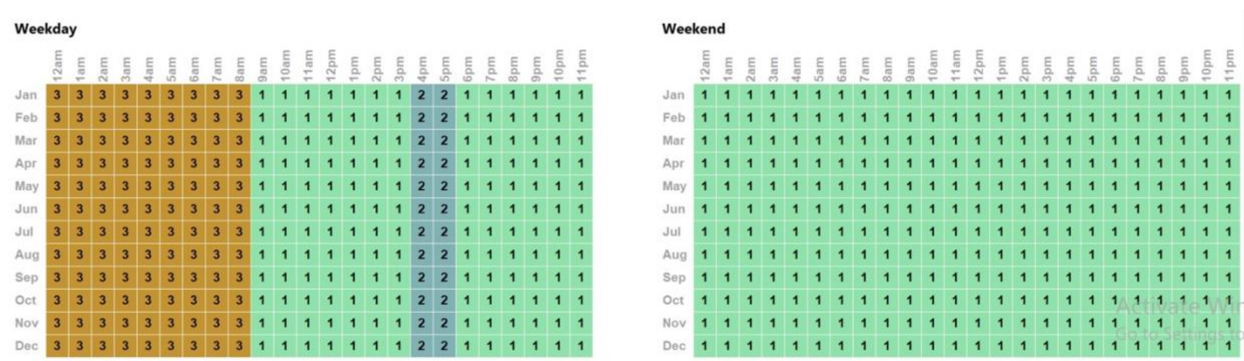


Figure 4. 14 Weekday and Weekend manual dispatch schedule in SAM software

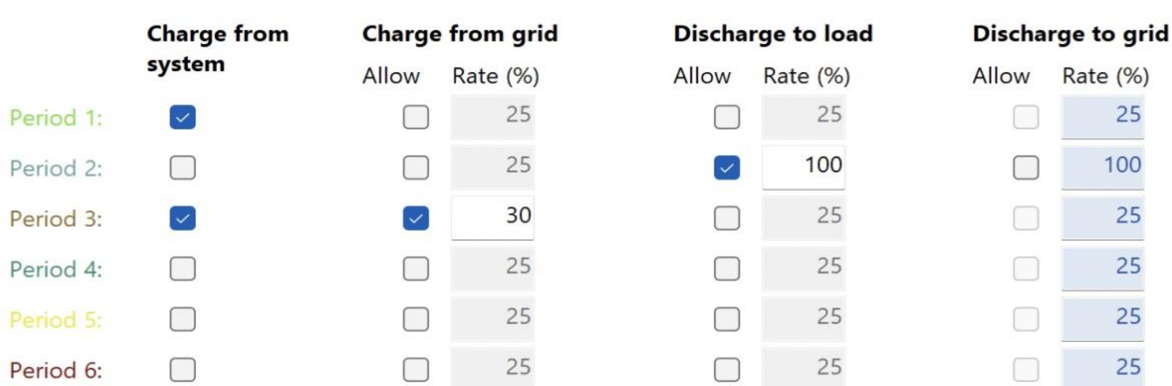


Figure 4. 15 Dispatch Algorithm in SAM Software

4.2.4 Financial Mechanism (Global Adjustment)

Energy storage is an effective solution to dispatching electricity to reduce the load at peak hours. However, it's associated with increased costs that might reduce the feasibility of implementing storage projects. The Ontario Government has implemented the Global Adjustment Program to increase the feasibility of energy storage projects. The financial calculations are done according to the System Advisor Model (SAM) financial model [281], and the GA financial mechanism is described below and added to be modeled in SAM.

For this study, first, the Global Adjustment five peak data for Ontario province has been gathered from the IESO Data Directory [210] for the years 2017 and 2018, and the average of the years has been computed. The total electricity cost includes the GA cost [282] and HOEP cost [283]; first, the calculation of the GA cost is presented, followed by the HOEP cost. Table 4.18 provides detailed cost calculations for the GA cost. The first column represents the data of the Ontario peak. The second column represents the peak start and end hour, the fourth column represents the Ontario Peak (MW) at this specific hour. and the third column represents the corresponding ARC building load at the Ontario peak hour.

The Peak Demand Factor is calculated by equation (4.37)

$$PDF = \frac{\sum PDB}{\sum PDO} \in 5PH \tag{4.37}$$

Where $\sum PDB$ is the sum of the building peak demand (kWh), $\sum PDO$ is the sum of the Ontario peak demand (kWh), and 5PH is an expression for the Ontario five peaks.

The PDF is multiplied by the Ontario total cost to maintain the grid health and reliability to determine the yearly Global Adjustment Cost-share (GCACs) amount to the ARC building as indicated in equation (4.38)

$$GACs = PDF \times OGC \tag{4.38}$$

Where OGC is the Ontario Global Adjustment cost per year ($/year)

The Levelized Cost of Energy (LCOE) for the GA cost is calculated according to equation (4.39)

$$LCOEGA = \frac{GACs}{BD} \tag{4.39}$$

Where BD is the yearly electricity building demand (kWh)z

Table 4. 18 Average 2017 and 2018 Global Adjustment cost for ARC building based on the building electricity load obtained from the campus sustainability office and Ontario load from the IESO Data Directory [210]

Date of Peak	Hour End	Facility (ARC) Load (MW)	Ontario Peak (MW)
25-Sep-17	4 PM – 5 PM	0.54	22.74
26-Sep-17	4 PM – 5 PM	0.57	22.75
12-Jun-17	5 PM – 6 PM	0.56	22.42
05-Jan-17	5 PM – 6 PM	0.52	21.80
19-July-17	5 PM – 6 PM	0.55	21.58
Average		**0.55**	**22.26**
total		**2.74**	**111.29**
Peak Demand Factor PDF		0.000024619	
2017 + 2018 average Global Adjustment ($/year)		272,523	
2017 + 2018 average Global Adjustment ($/month)		22,710	
Building yearly demand (kWh)		4,543,197	
LCOE ($/kWh)		0.06	

Note: The Date of Peak and Hour End is for only the year 2017; they can't be averaged.

The Hourly Ontario Energy Price (HOEP) is considered for 2017 and 2018. The HOEP data was aggregated from hourly to daily to monthly and finally to yearly average to be considered for the simulation. Table 4.19 represents the monthly average HOEP rates for 2017 and 2018. The final

HOEP rate for 2017 and 2018 is equivalent to (0.02 $/kWh). The average electricity cost (GA + HOEP) in the years 2017 and 2018 for the ARC building is 0.08 $/kWh

Table 4. 19 HOEP Rates based on IESO Data Directory [210]

Month / Year	2017 ($/kWh)	2018 ($/kWh)
January	0.02155	0.03212
February	0.02111	0.01901
March	0.02603	0.01720
April	0.01114	0.02966
May	0.00317	0.01312
June	0.00589	0.01834
July	0.01361	0.03038
August	0.01728	0.03059
September	0.02313	0.02994
October	0.00875	0.01384
November	0.01401	0.02514
December	0.02063	0.02789
Average	**0.01553**	**0.02394**
Average 2016 + 2017	**0.02**	

4.3 Summary

This chapter first included detailed methods and data for implementing the campus as a living lab imitative to install PV panels over the campus buildings. The methods covered the campus screening and zonings, market research, Life Cycle Cost Analysis (LCCA), Life Cycle Assessment (LCA) and the survey design. Second, the methods and data to integrate energy storage with PV systems were presented to illustrate the potential of reducing the electricity bills for facilities and reducing Ontario grid peaks to maintain grid health.

5. Results

This section first represents the detailed results of installing the solar panels over the campus buildings' roofs as a part of the campus as a living lab imitative. The sections then illustrate the effects of achieving monetary savings from the Ontario Global Adjustment Program through integrating energy storage with a solar system at the Advanced Research Complex building.

5.1 Campus as a Living Lab Results

5.1.1 Whole Campus Buildings Analysis

The modelling was done through RETScreen Expert software to obtain the number of panels, power capacity, electricity generation and revenue, and Net Present Value (NPV), for each building at the campus, as indicated in Table 5.1. The identified 31 buildings were selected after a campus screening process to make sure the buildings are economically viable for PV installation during their lifecycle. The results indicate that the solar collector area range from (243 – to 10,264 m^2). The PV panel number in each building range from (52 to – 3,304) panels. The PV power capacity range from (52 – 2,217 kW), the annual electricity generation range from (68,389 – 2915770 kWh), and the annual electricity revenue range from (6,838 – 291,577 \$). The NPV (the final project profit after the 25 years life cycle) ranges from (18,466 to – 787,321\$). The project is estimated to have a solar collector of 65,569 m^2And total PV panels equal 21,108, a power capacity of 14,195 kW, an annual electricity generation of 18,668,995 kWh, an annual electricity revenue of \$1,866,899 and an NPV of \$4,985,288. The project deemed financially viable is expected to be a valuable clean energy self-generation source that will increase the energy resiliency within the uOttawa campus.

Table 5. 1 Photovoltaic analysis for 31 buildings at the University of Ottawa

	Building Code	Building Name	Solar Collector Area (m2)	PV panels number	Power Capacity (kW)	Electricity generation (kWh)	Electricity revenue ($)	NPV ($)
1	MNO	Minto Sports Complex	6,979	2,247	1,507	1,981,987	198,198	535,179
2	ARC	Advanced Research Complex	2,969	956	641	843,035	84,303	227,637
3	HNN	Henderson Residence	865	278	186	244,624	24,462	66,054
4	600	Health Science Campus	986	317	213	280,134	28,013	75,642
5	850	Health Science Campus	1,043	336	225	295,917	29,591	79,904
6	MNN	Mann Residence	1,530	493	330	434,011	43,401	117,192
7	RGN	Roger Guindon Hall	10,264	3,304	2,217	2,915,770	291,577	787,321
8	SITE	School of Information Technology	2,715	874	586	770,699	77,069	208,105
9	CBY	Colonel By	2,518	811	543	714,146	71,414	192,835
10	STEM	STEM Complex	2,742	883	592	778,590	77,859	210,236
11	MR	Marion Hall	1,421	457	307	403,762	40,376	109,024
12	DRO	D’lorio	1,235	398	266	349,839	34,983	94,464
13	GNN	Gendron Hall	1,976	636	426	560,269	56,026	151,285
14	CRG	CARE	902	290	195	256,461	25,646	69,250
15	FSS	Social Science Building	3,136	1,010	677	890,381	89,038	240,422
16	VNR	Vanier Hall	2,181	702	471	619,453	61,945	167,265
17	LMX	Lamoureux Hall	2,852	918	616	810,155	81,015	218,759
18	CRX	Learning Crossroads	2,026	652	480	631,289	63,128	170,461
19	HSY	Hyman Soloway Residence	1,492	480	322	423,490	42,349	114,351
20	MOD	Marchand Residence	874	281	188	247,255	24,725	66,764
21	90U	90 University	2,268	730	489	643,126	64,312	170,461
22	PRZ	Perez Hall	1,217	392	263	345,894	34,589	93,398
23	LR	100 Laurier	940	303	203	266,983	26,698	72,091
24	WCA	William Commanda	243	78	52	68,389	6,838	18,466
25	SMD	Simard Hall	929	299	200	263,037	26,303	18,466
26	MHN	Hamelin Hall	954	307	206	270,928	27,092	73,156
27	TBT	Tabaret Hall	3,538	1,139	764	1,004,803	100,480	271,318

28	ATK	Alext Trebek Alumni Hall	362	117	78	102,584	10,258	27,700
29	SMN	Academic Hall	877	282	189	248,570	24,857	67,119
30	HGN	Hagen Hall	558	180	120	157,822	15,782	42,615
31	DMS	Desmarais Building	2,977	958	643	845,665	84,566	228,348
Buildings Total			**65,569**	**21,108**	**14,195**	**18,668,995**	**1,866,899**	**4,985,288**

The buildings are listed below to understand the current uOttawa buildings representation [172]. However, for example, the highly consuming buildings are because they are buildings that have highly consuming equipment for research and lab proposes, so building renovations won't contribute much to decreasing their annual consumption.

New Buildings: MNO, HNN, MNN, SITE, STEM, FSS, CRX, DMS, ARC

Renovations: 600, 850, RGN, CBY, LMX, HSY, MRD, 90U, VNR, PRZ, WCA, SMD, MHN

Highly consuming buildings: MRN, DRO, GNN, CRG, RGN

Heritage Conservation buildings: TBT, ATK, SMN, HGN, LRR

5.1.1.1 Buildings' Electricity Usage

Up to this point, it is understood that the project is expected to be financially successful with high energy generation. However, an analysis of the expected annual electricity generation and the campus buildings' electricity consumption has been done to further investigate the numbers contributing to the campus's annual electricity consumption.

Nine buildings' electricity consumption was obtained from the campus sustainability office. The electricity consumption was taken for three consecutive years 2016, 2017, and 2018. The electricity consumption was converted from hourly rate to monthly and yearly rate. The average of the three years was considered; if one year's consumption was out of range, it was eliminated to avoid any pitfalls or discrepancies in the values. It has been decided not to use 2019, 2020 and 2021 data because of the effects of COVID19 during this period.

Table 5.2 shows that the amount of electricity offset from each building's annual consumption ranges from (20 to -107%). The 107% indicate that there might be a surplus in the electricity generation that covers the building's consumption and can be transferred back to the electricity grid to be sold at a price for the utility company. Figure 5.1 graphically illustrates electricity consumption and generation.

Table 5. 2 Expected electrical demand offset from nine buildings, based on electricity consumption and excepted generation

Building Code	Electricity Consumption (kWh)	Electricity generation (kWh)	Electricity usage Offset
MNO	3,646,399	1,981,987	54%
ARC	4,157,512	843,035	20%
HNN	442,285	244,624	55%
600	606,286	280,134	46%
850	275,667	295,917	107%
MNN	1,003,767	434,011	43%
RGN	12,842,768	2,915,770	23%
HSY	896,006	423,490	47%
DMS	2,678,983	845,665	32%

The offset percentage depends mainly on the available building roof solar collector area and the consumed electricity amount of each building. However, Figure 5.2 shows no correlation between the solar collector area and the offset percentage. RGN building, for example, has the biggest solar collector area, and the expected PV electricity generation offsets 23% of the total building electricity needs. On the other hand, 850 building has a small solar collector area, and the expected PV electricity generation offsets 107% of the building's annual electricity needs. In the case of the RGN building, the building consumes too much electricity; for example, it includes the Faculty of Medicine, Faculty of Health Sciences, School of Nursing, School of Rehabilitation, and much more. RGN total consumption share of the Campus is 1.6%.

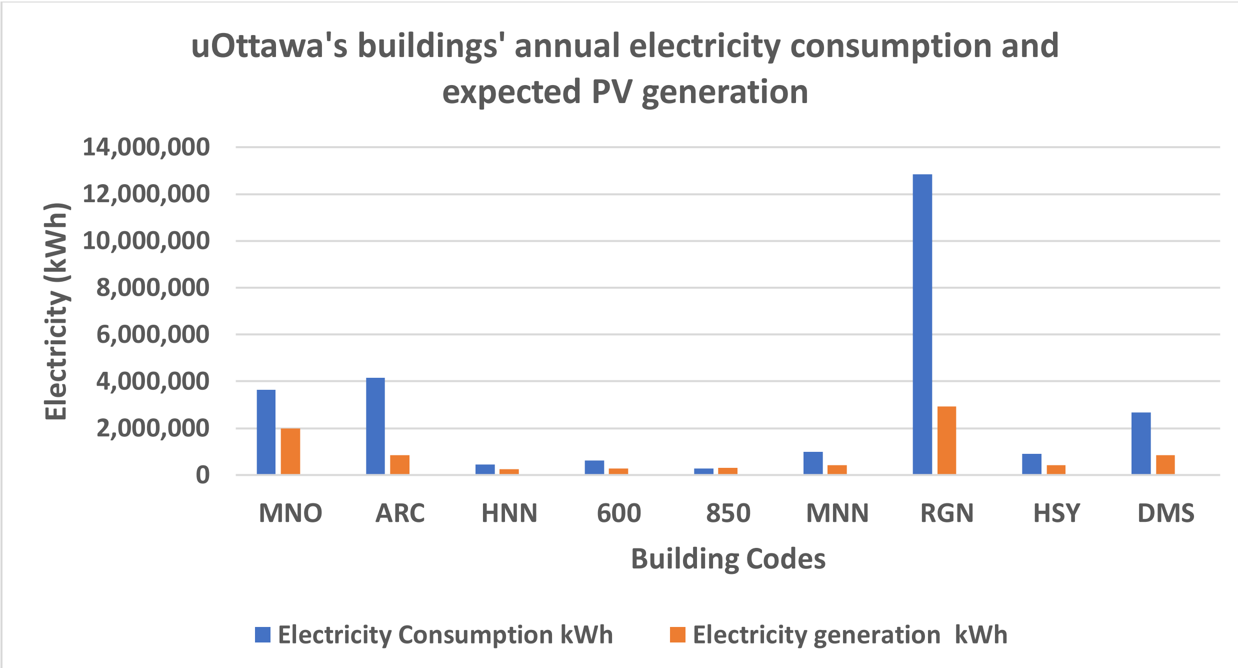


Figure 5. 1 uOttawa's buildings' electricity consumption and expected electricity generation

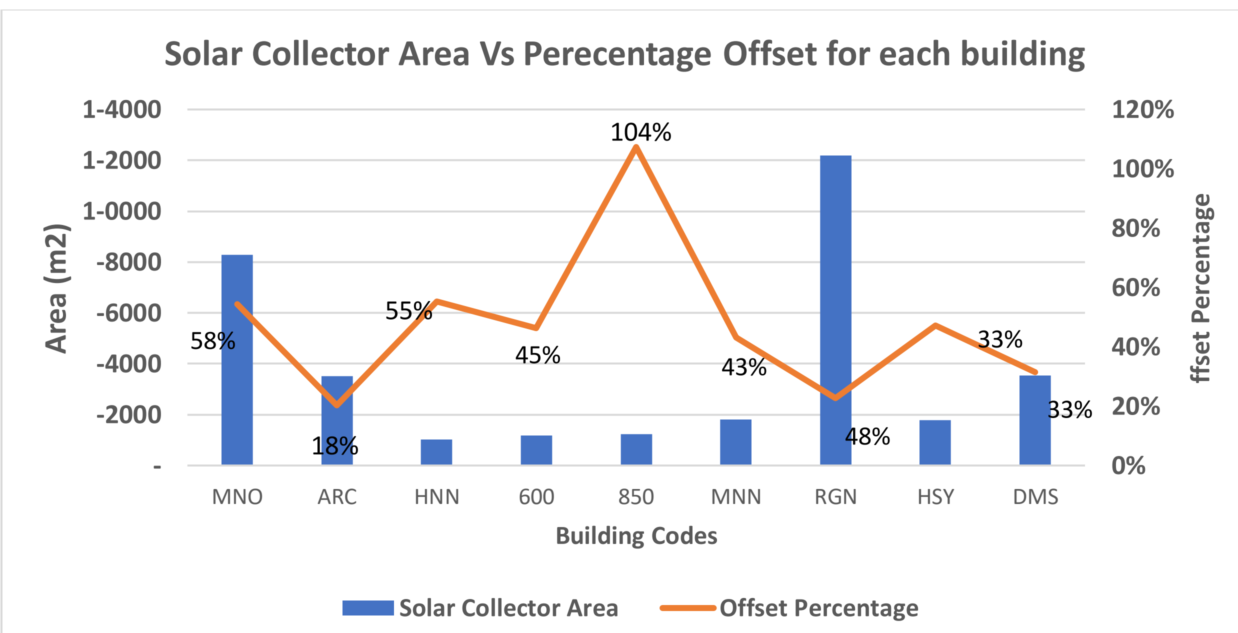


Figure 5. 2 Solar Collector Area Vs Percentage offset of each building

5.1.1.2 Total Campus Electricity Usage Offset

The monthly electricity generation from the 31 buildings is indicated in Table 5.3 below. The electricity generation is lowest in the winter (October, November, December, January, and February) and highest in the summer (May, June, July and August). The results resonate with the monthly solar radiation analysis from Figure 4.7. The total expected electricity generation from the identified 31 buildings is 18,668,995 kWh. The total electricity consumption from the whole campus obtained from the campus sustainability office (including the current buildings that will be demolished) is 79,571,931 kWh. The entire electricity generation is expected to offset 23% of the total current campus electricity consumption, as indicated in Figure 5.3.

Table 5. 3 Total buildings monthly expected electricity generation and consumption

Month	Electricity Generation (kWh)	Electricity consumption (kWh)	Offset (%)
January	1,004,992	-	-
February	1,375,803	-	-
March	1,769,481	-	-
April	1,829,119	-	-
May	2,048,369	-	-
June	2,107,682	-	-
July	2,243,676	-	-
August	2,032,799	-	-
September	1,580,402	-	-
October	1,213,934	-	-
November	703,591	-	-
December	759,140	-	-
Total	**18,668,995**	**79,571,931**	**23%**

Note: The monthly electricity consumption of the University of Ottawa buildings wasn't available at the study's time.

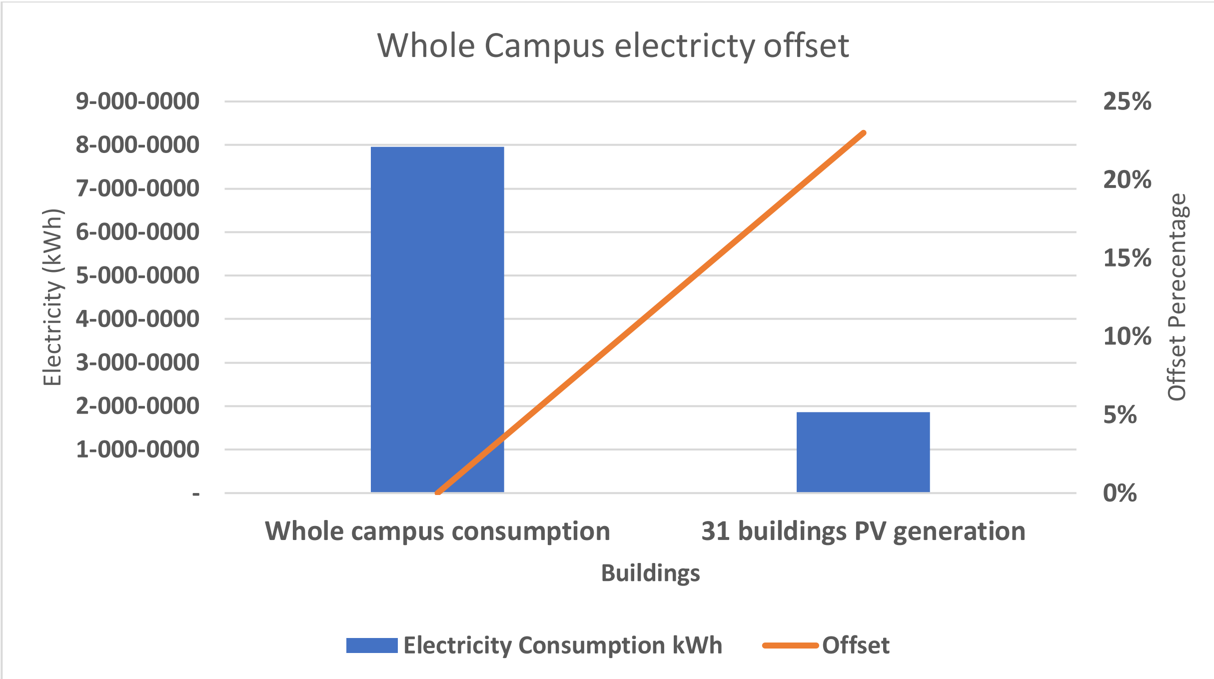


Figure 5. 3 Whole campus electricity offset from the electricity generated from installing PV panels over 31 building's roof

5.1.2 Financial Results (Life Cycle Cost Analysis Results)

Financial indicators are essential factors when decision-makers decide to invest in a project or not. Decision-makers must constantly trade social, environmental, and economic factors [284]. Because PV projects are a clean, renewable energy source, more emphasis is needed on the financial side. Hence, this section presents the economic analysis of the project life cycle or Life Cycle Cost Analysis (LCCA) to help The University of Ottawa take decisive actions toward the environment and achieve a carbon-neutral campus by 2040. Table 5.4 shows the initial and annual operation and maintenance (O&M) costs. The total 31 building initial cost is expected to be around 20 million Canadian Dollars, and the annual operation and maintenance (O&M) cost is 1,780,05 thousand Canadian dollars.

Table 5. 4 Buildings PV system Initial cost and Operation and Maintenance (O&M) cost

	Building Code	Building Name	Initial Cost	(O&M) cost
1	MNO	Minto Sports Complex	2,127,884	18,898
2	ARC	Advanced Research Complex	905,092	8,038
3	HNN	Henderson Residence	262,632	2,332
4	600	Health Science Campus	300,756	2,671
5	850	Health Science Campus	317,700	2,822
6	MNN	Mann Residence	465,960	4,138
7	RGN	Roger Guindon Hall	3,130,404	27,801
8	SITE	School of Information Technology	827,432	7,348
9	CBY	Colonel By	766,716	6,809
10	STEM	STEM Complex	835,904	7,424
11	MR	Marion Hall	433,484	3,850
12	DRO	D'lorio	375,592	3,336
13	GNN	Gendron Hall	601,512	5,342
14	CRG	CARE	275,340	2,445
15	FSS	Social Science Building	955,924	8,490
16	VNR	Vanier Hall	665,052	5,906
17	LMX	Lamoureux Hall	869,792	7,725
18	CRX	Learning Crossroads	677,760	6,019
19	HSY	Hyman Soloway Residence	454,664	4,038
20	MOD	Marchand Residence	265,456	2,358
21	90U	90 University	690,468	6,132
22	PRZ	Perez Hall	371,356	3,298
23	LR	100 Laurier	286,636	2,546
24	WCA	William Commanda	73,424	652
25	SMD	Simard Hall	282,400	2,508
26	MHN	Hamelin Hall	290,872	2,583
27	TBT	Tabaret Hall	1,078,768	9,581
28	ATK	Alext Trebek Alumni Hall	110,136	978
29	SMN	Academic Hall	266,868	2,370
30	HGN	Hagen Hall	169,440	1,505
31	DMS	Desmarais Building	907,916	8,063
		Buildings Total	**20,043,340**	**1,780,05**

Based on the methodology and data inputs in the methodology section, the following results in Table 5.5 have been obtained. The 31 buildings analyzed collectively show an Internal Rate of Return (IRR) equal to 11.40% for all the projects, higher than the (8-9%) discount ratio recommended by the Canadian guidelines for investing in projects. The project profit return is high and considered a valued investment opportunity. In its final year, the project yields a positive Net

Present Value (NPV) of $4,985,288. The Benefit-Cost Ratio is 1.2 showing 20% more benefits than the cost. The Simple payback (without adding the installed PV value) is 11.8 years. The Equity payback is 9.4 years. The project is expected to save 532,799 $/year from the generated electricity. The economical GHG reduction cost is -906 $/tCO2, meaning that the amount spent in this project to lower the cost is negative, which indicates that the project is making a profit while reducing GHG emissions. The energy production cost, also known as the Levelized cost of energy, is 0.125 $/kWh, indicating that the cost of producing 1kWh of solar electricity is $0.125. Overall, the project's financial parameters show that the project is financially viable and considered a good investment.

Table 5. 5 Financial viability results

Pre-tax IRR - equity	11.4%	Simple payback	11.8 year
Pre-tax IRR - assets	11.4%	Equity payback	9.4 year
Net Present Value	4,985,288 $	Annual life cycle savings	532,799 $/year
Benefit-Cost ratio	1.2	GHG reduction cost	-906 $/tCO2
Debt service coverage	No debt	Levelized cost of energy	0.125 $/kWh

The project cash flow strengthens the previous results, as indicated in Table 5.6, by showing at the beginning of the project at year zero that the cash flow equals -20 million Canadian dollars. And each year, a positive value stemming from the electricity generation revenue is shown in the Pre-tax ($) column and illustrated in Figure 5.4. It must be noted that at year 13, it can be shown that there is a lower revenue than any other year; this is because the inverter lifetime is around 15 years, and for this project, it has been determined to be changed at year 13. On the other hand, the negative value in the cumulative cash flow keeps decreasing because of the yearly electricity revenue, as illustrated in Figure 5.5.

Table 5. 6 Cash Flow Table

Year	Pre-tax ($)	Cumulative ($)	Year	Pre-tax ($)	Cumulative ($)
0	-20,043,340	-20043340	13	2215624	9,334,407
1	1,773,720	-18269619	14	3077151	12,411,559
2	1,850,559	-16419059	15	3210245	15,621,805
3	1,930,717	-14488341	16	3349078	18,970,883
4	2,014,337	-12474004	17	3493896	22,464,780
5	2,101,569	-10372434	18	3644956	26,109,736
6	2,192,568	-8179866	19	3802527	29,912,264
7	2,287,495	-5892370	20	3966888	33,879,153
8	2,386,521	-3505848	21	4138330	38,017,483
9	2,489,821	-1016027	22	4317158	423,34,641
10	2,597,579	1581551	23	4503687	46,838,329
11	2,709,986	4291538	24	4698249	51,536,579
12	2,827,244	7118783	25	4901189	56,437,768

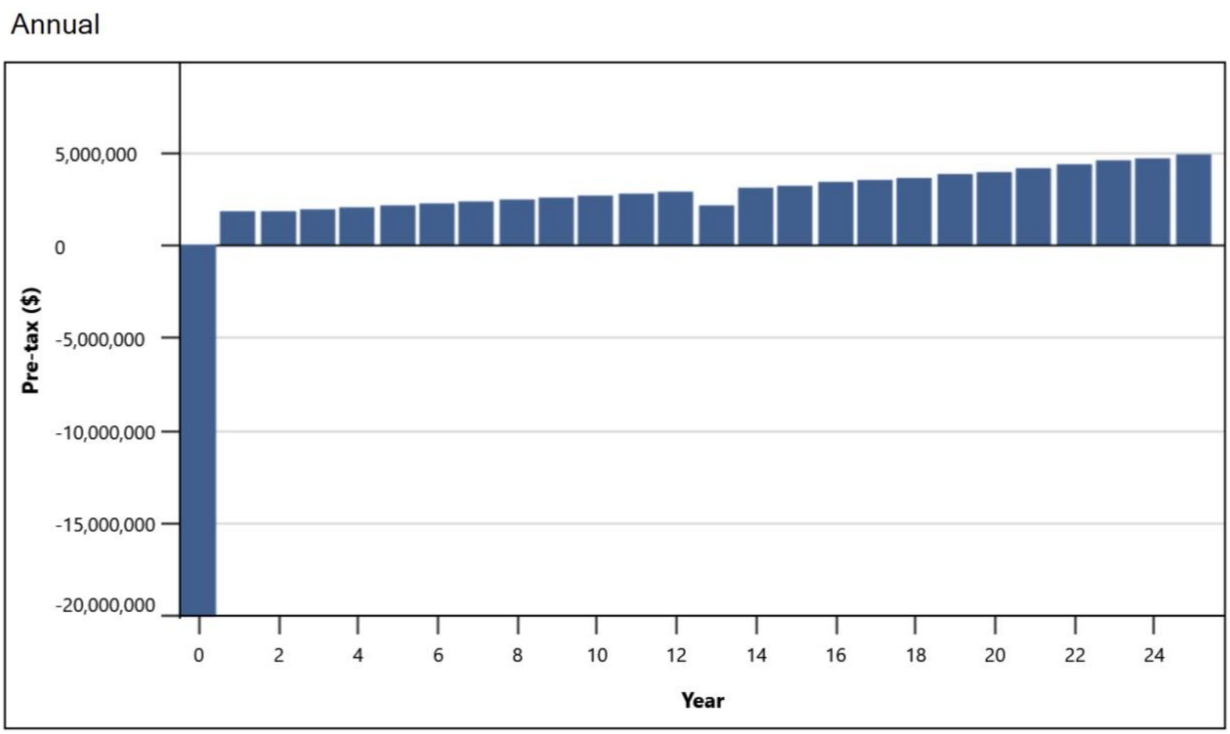


Figure 5. 4 uOttawa PV panels in 31 buildings' annual cash flows

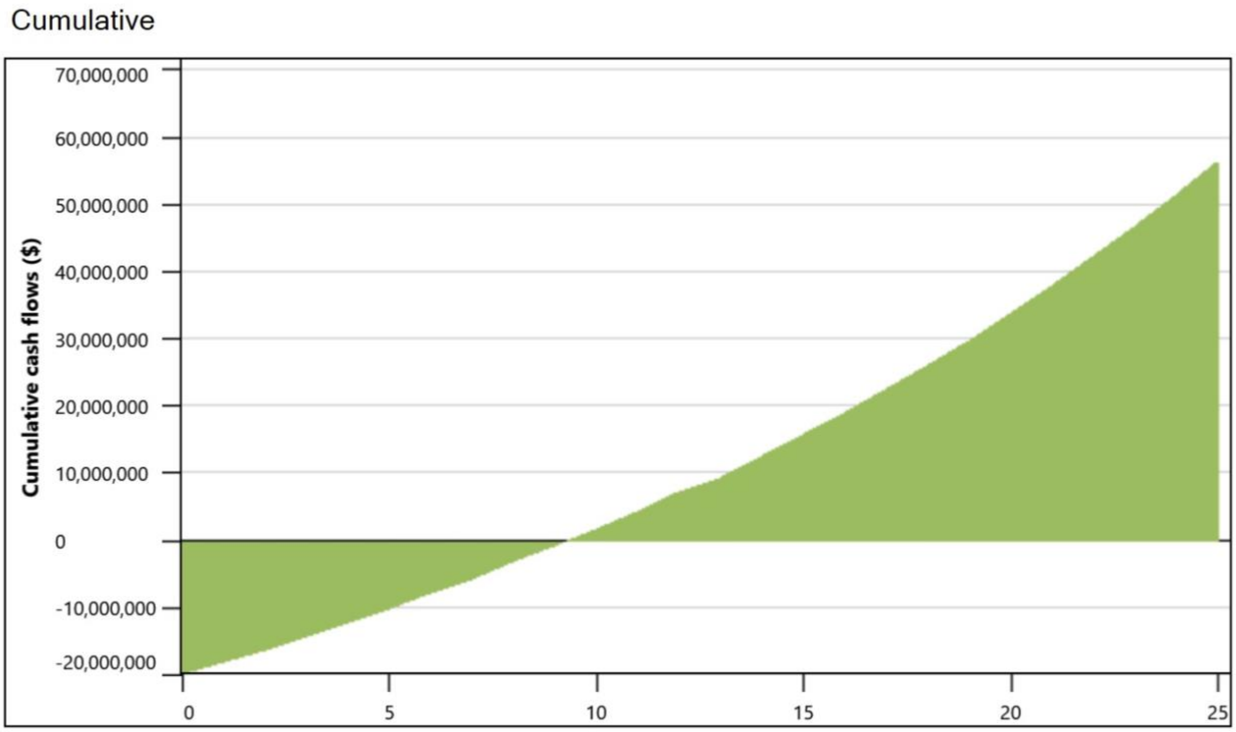


Figure 5. 5 uOttawa PV panels in 31 buildings cumulative cash flows

5.1.3 Risk and Sensitivity Analysis

RETScreen has performed a risk analysis to assess the impact on the Net Present Value (NPV) using Monte Carlo simulation with 500 combinations. The parameters considered are electricity generation, electricity exported rate, initial cost, and O&M cost with a range of $(+/-)$ 25%. As indicated in Figure 5.6, the risk analysis shows that the increase in the electricity exported to the grid and the increase in electricity export rate could affect the project profitability by up to 63%. The increase in initial cost could affect the project negatively up to 46%, and the increase in O&M cost affects the project negatively up to 6%.

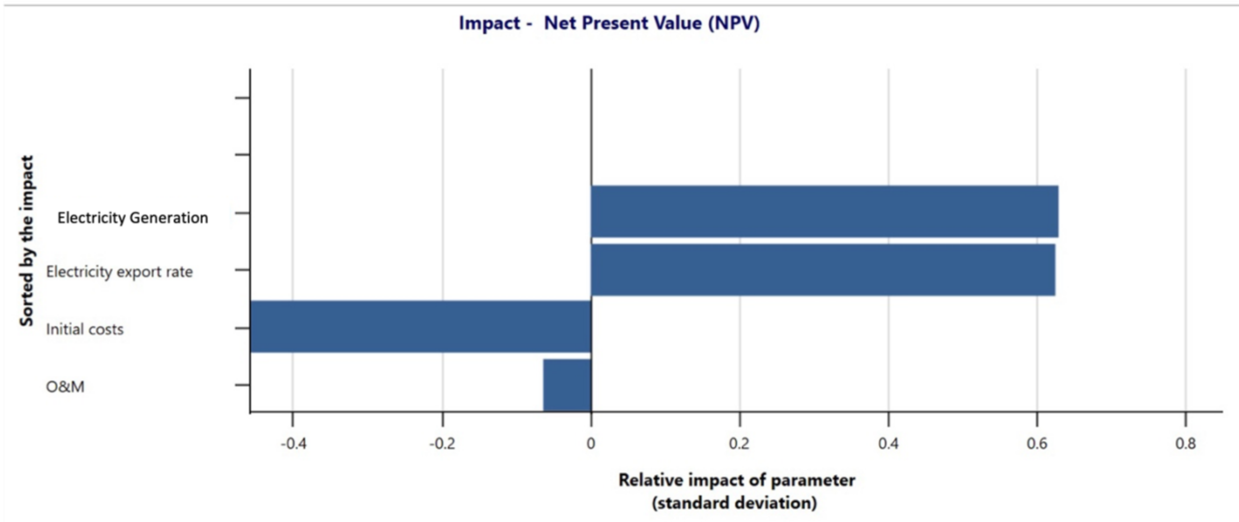


Figure 5. 6 Risk analysis in RETScreen (Relative impact of parameters)

A sensitivity analysis has been carried out in RETScreen to assess the impact on the Net Present Value with a sensitivity range equal to 25%. According to the previous risk analysis, the parameters selected were the initial cost and electricity export rate/amount, as they are considered the most influential parameters on the project. The sensitivity analysis shows that the increasing the initial cost by more than 24%, the project loses its profitability and incurs losses. The study also shows that the electricity export rate/amount decreases by more than 18%, the project loses its profitability and incurs losses, as indicated in Figure 5.7

- Remove analysis

		Initial costs $				
Electricity Generation / rate		15,032,505	17,537,923	20,043,340	22,548,758	25,054,175
$/MWh		-25.0%	-12.5%	0.0%	12.5%	25.0%
75.00	-25.0%	3,008,262	502,845	-2,002,573	-4,507,990	-7,013,408
87.50	-12.5%	6,502,289	3,996,872	1,491,454	-1,013,963	-3,519,381
100.00	0.0%	9,996,316	7,490,899	**4,985,481**	2,480,064	-25,354
112.50	12.5%	13,490,343	10,984,926	8,479,508	5,974,091	3,468,673
125.00	25.0%	16,984,370	14,478,953	11,973,535	9,468,118	6,962,700

Figure 5. 7 Sensitivity analysis in RETScreen (sensitivity range of 25% on Net Present Value (NPV)

5.1.3.1 Further Investigation of PV Technology Components

This section compares different technology alternatives upgrades to the original modelled PV system in RETScreen to understand the range of improvements in the annual generated electricity and project Net Present value as presented in Table 5.7.

The analysis shows that changing the tracking system to one-axis and two-axis could increase the annual electricity ratio to 1.27 and 1.32 and NPV to 6.35 and 6.62, respectively. The one-axis and two-axis tracking system using bifacial modules (absorbing solar radiation from two sides) results show an improvement ratio of 1.33 and 1.38 for the annual electricity generated and 7.29 and 7.60, respectively, for the NPV. However, according to Gonzalez-Pena and colleagues [30], RETScreen software shows that deviation could go up to 10% and 20% in the case of one-axis and two-axis systems, respectively.

Table 5. 7 Comparison of different PV system technology combinations

System / Category	Fixed	One-axis	Two-axis	One-axis + bifacial modules	Two-axis + bifacial modules
Annual Electricity output (kWh)	18,669,068	23,739,124	24,644,873	24,759,907	25,704,603
Electricity improvement ratio		1.27	1.32	1.33	1.38
NPV ($)	4,985,288	31,644,952	33,001,088	36,322,766	37,878,711
NPV improvement ratio		6.35	6.62	7.29	7.60

5.1.4 Life Cycle Assessment Analysis

5.1.4.1 Operational Carbon

An emission analysis worksheet is given as part of the RETScreen Clean Energy Management software to assist the user in estimating the CO2 emissions reduction potential for the study. The estimated GHG emission reductions are 578 $tCO2$ annually. For a better perspective, Table 5.8 shows the savings concerning various pollutants and fuels. The results are based on the Ontario GHG emission factor identified in Table 4.8.

Table 5. 8 Annual CO2 savings from the PV electricity generation and equivalent savings from various alternatives

Amount of annual CO2 savings	Equivalent savings
578 $tCO2$	106 cars & lights trucks not used 248 litres of gasoline not consumed 1343 barrels of crude oil not consumed 578 people reducing energy use by 20% 131 acres of forest absorbing carbon 53.1 hectares of forest absorbing carbon 199 tonnes of waste recycled

5.1.4.2 Embodied Carbon

The Life Cycle Assessment (LCA) performed in One-Click LCA shows the environmental impact of the materials used to install the PV system in the 31 buildings. The results are illustrated at seven indicators covering the life cycle stages of the PV system lifetime. The seven indicators cover global warming potential, acidification, eutrophication, ozone depletion, formation of tropospheric ozone, fossil fuel primary energy, and total use of primary energy excluding raw material, as indicated in Table 5.9. The most significant environmental indicator is the global warming potential causing $1023tCO_2e$ embodied carbons. The table also shows the life cycle stages and corresponding carbon emissions illustrated in Figure 5.8. Construction materials emissions are responsible for the extraction and manufacturing part. The transportation to the site is the carbon-emitting from the fuel used in the vehicles transporting the materials to sites, including trucks, airplanes, and ships. Deconstruction is responsible for the end-of-life emissions resulting from demolishing the system. It must be noted that the material instalments, repair and maintenance are considered in the construction materials part; the sourced data was raw materials, so it was hard to identify which part should be repaired, installed and so on.

Figure 5.9 shows the global warming potential broken down by the materials type—coating and pastes- the silicone material account for 33.5%. Silicone is considered the main ingredient in producing PV panels. Metals include aluminium used for the mounting structure and steel for the PV panels' frames. Both account for 21.8%. Glass is the second main ingredient in producing PV panels, responsible for 33% of global warming emissions. Concrete accounts for 6%, used mainly for fixing the mounting structure. Installations and systems account for 3.1% represent the wires, cable, and other electrical components. Plastics account for 2.7% used for the tubes that cover the wires from sun and rain.

Table 5. 9 Whole-building Life Cycle Assessment, ISO 14040 & ISO 14044 for the 31 building

Result Category / Stage	Global warming	Acidification	Eutrophication	Ozone depletion	Formation of tropospheric ozone	Fossil fuel primary energy	Total use of primary energy, ex. raw material
Unit	tCO_2e	tSO_2e	t_{he}	$t\ CFC11e$	$Kg\ O3e$	kWh	kWh
Construction Materials	971.2	4.1	22	0.00002	53	12,114,922	14,448,106
Transportation to site	47.3	0.2	0.0357	0.00001	5.4	322,673	326,639
Deconstruction	4.3	0.025	0.009	0	0.274	56,130	62,540
Total	1023	4.4	22	0.0003	58.7	12,493,726	14,837,286

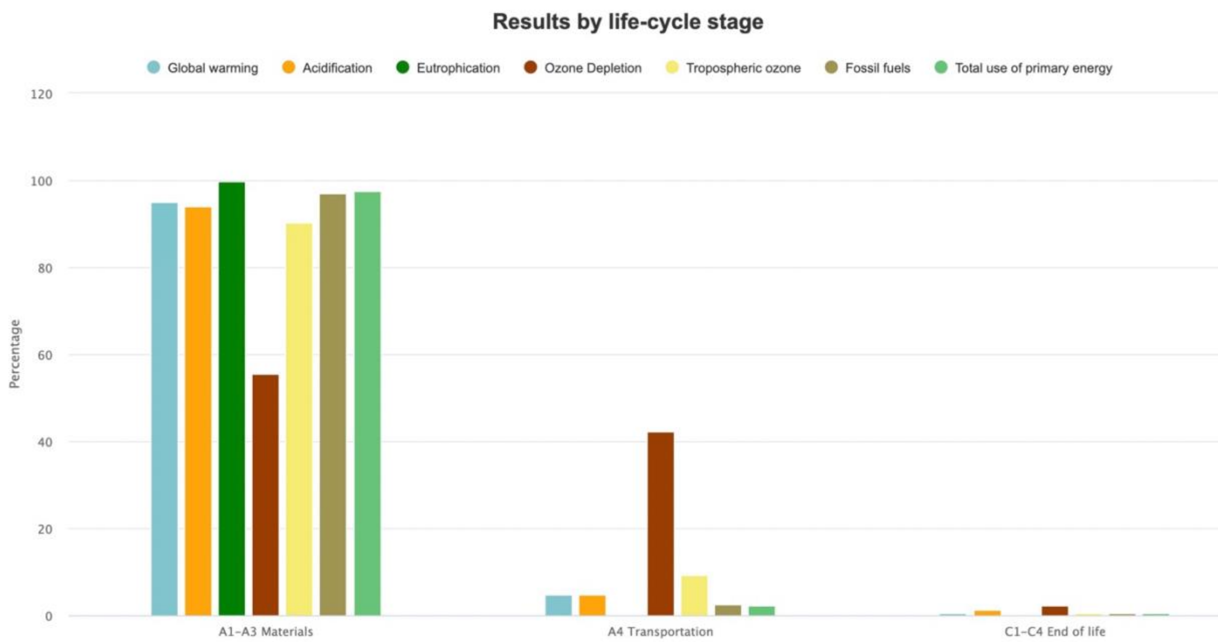


Figure 5. 8 The stages of the whole life cycle carbon emission of the PV system

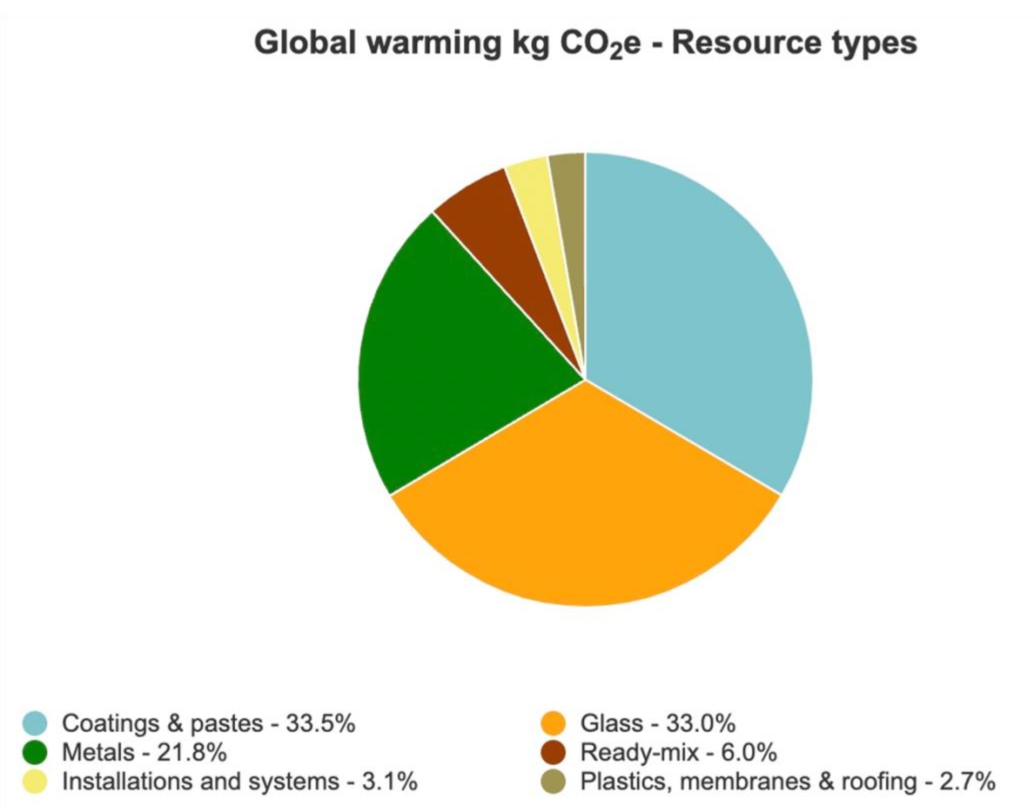


Figure 5. 9 Materials global warming potential percentage

5.1.4.3 Embodied and Operation Carbon Comparison

This section is made to understand better the difference in numbers between the operational and embodied carbon/energy of the proposed PV system at the University of Ottawa.

Table 5.10 compares the operational and embodied energy of the PV system. The annual expected generated electricity from the PV system is 18,668,995 kWh multiplied by the project's lifetime of 25 years, making the total generated electricity (operational energy) 466,724,875 kWh. The embodied energy stemming from the material's life cycle is 14,837,286 kWh. The embodied energy represents the energy consumption side, and the operational energy represents the energy production side. The embodied energy is 3.18% of the total operational energy, with energy payback of less than one year. If the IRENA report data were used without adjustment, the following embodied carbon would double to 6.36% of the total generated electricity and energy payback in less than two years.

Table 5. 10 Operational and Embodied Energy Comparison

Operational energy (kWh)	Embodied energy (kWh)	Embodied / Operation energy Percentage	Energy Payback period
466,724,875	14,837,286	3.18%	<1year

Table 5.11 compares the operational and embodied carbon of the PV system. The annual expected reduced emissions from the PV panel are 577.8 $tCO2e$ multiplied by the project's lifetime of 25 years. The total reduced emissions (operational emissions) are 14,445 $tCO2e$. The embodied carbon stemming from the material's life cycle is 1,023 $tCO2e$. The embodied carbon represents the carbon production side, and the operational energy represents the carbon reduction side. The embodied carbon is 7% of the total operational carbon, with carbon payback equal to less than one

year. If the IRENA report data were used without adjustment, the following embodied energy would double to 14% of the total generated electricity and energy payback in less than four years.

Table 5. 11 Operational and Embodied Carbon Comparison

Operational Carbon (tCO2e)	Embodied Carbon (tCO2e)	Embodied / Operation carbon Percentage	Carbon Payback period
14,445	1,023	7%	< 2 years

5.1.5 Survey Results

The students were asked to rate how strongly they agreed or disagreed with five written statements. The results in Table 5.12 and Figure 5.10 show that for the first statement, "*The Campus as a Living Lab initiative contributed to my overall understanding of the course content*." 43.75% strongly agree, and 56.25% agree. The sconed statement "*The Campus as a Living Lab project bridged the gap between my theoretical knowledge and practical experience*."37.50% strongly agree, 56.25% agree, and 3.13% neither agree nor disagree. The third statement is, "*I feel more confident applying to relevant industry/ research positions*."46.88% strongly agree, 46.88% agree, 3.13% disagree, and 3.13% neither agree nor disagree. The fourth statement is, "*I feel more connected to my campus and community*."25% strongly agree, 56.25% agree, 13% disagree, and 6.25% neither agree nor disagree. The fifth statement, "*Interactions with my colleagues, Teaching Assistant (TA), professor, and the sustainability office helped me overcome project obstacles*." 56.25% strongly agree, 34.38% agree, and 9.38% disagree. The fourth statement results show lower consensus than the others because the project was done at The University of Ottawa campus, with 31.25% of the students from Carleton University.

Table 5. 12 Campus as a living lab survey result

No.	Rate how strongly you agree or disagree with the following statement	Strongly agree	Agree	Neither agree or disagree	Disagree	Strongly disagree
1	The Campus as a Living Lab initiative contributed to my overall understanding of the course content.	43.75%	56.25%	0.00%	0.00%	0.00%
2	The Campus as a Living Lab project bridged the gap between my theoretical knowledge and practical experience.	37.50%	56.25%	3.13%	3.13%	0.00%
3	I feel more confident applying to relevant industry/ research positions.	46.88%	46.88%	3.13%	3.13%	0.00%
4	I feel more connected to my Campus and community.	25%	56.25%	6.25%	13%	0.00%
5	Interactions with my colleagues, TA, professor, and the sustainability office helped me overcome project obstacles.	56.25%	34.38%	0.00%	9.38%	0.00%

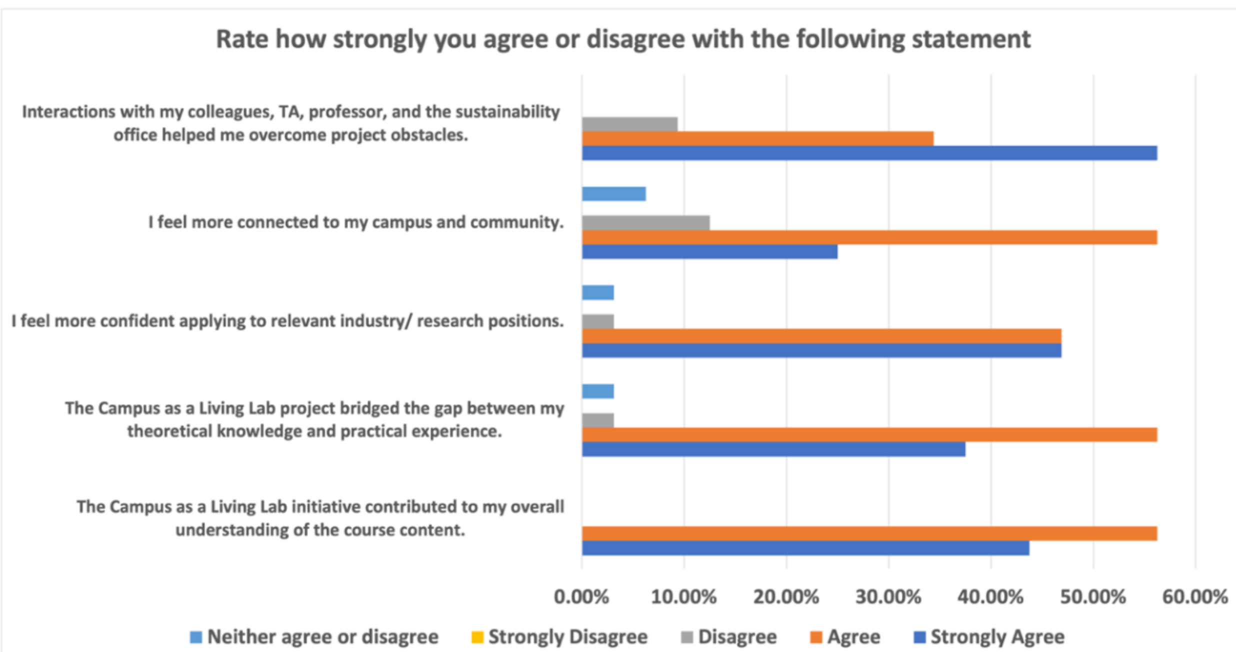


Figure 5. 10 Survey results on the five statements to rate how strongly they agree or disagree

In another question to assess the student's experience, the following question was asked: "*How likely is it that you would recommend this course/ campus as a living lab experience to a colleague?"* as indicated in Table 5.13 and illustrated in Figure 5.11. 68.75% reported that they would recommend the course with a score from (9-10), 21.88% reported a score of (7-8), and 9.38% reported a score of (0-6).

Table 5. 13 How likely is it that you would recommend this course/ campus as a living lab experience to a colleague

Score	Promoters (9-10)	Passive (7-8)	Detractors (0-6)
Percentage	68.75%	21.88%	9.38%
Student number	22	7	3

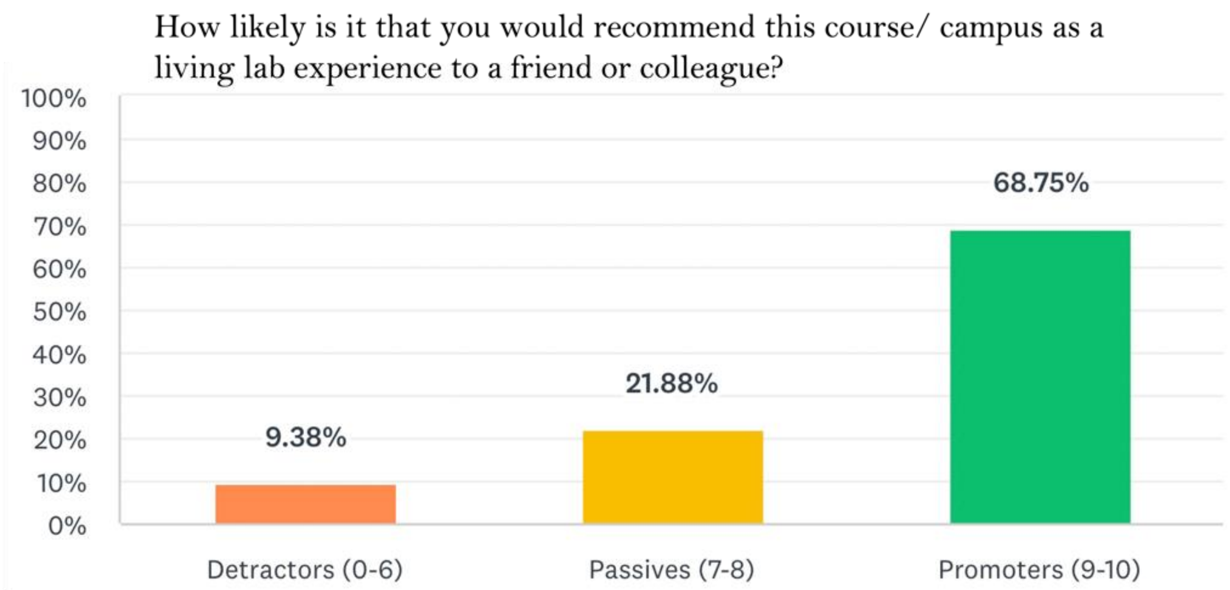


Figure 5. 11Survey results on the question (How likely you would recommend this course /campus as a living lab experience to a friend or colleague)?

The last part of the survey was an open-ended question to ask students, "what future improvements should be considered?". The students reported that the experience would have been better if it was on-campus to have a more interactive experience. However, due to COVID-19 health measures, the course was held online. It was also reported that more involvement from the sustainability office and data sharing would improve their ability to execute the project and deepen their understanding. The students also indicated that the initiative could benefit from industry professionals incorporated in the projects. Last, more class engagement regarding the project in the weekly lectures helped the students in the various projects step.

5.2 Global Adjustment Cost Savings Results

This section represents the results of the second case study of integrating energy storage with a solar system and using the Advanced Research Complex (ARC) as a case study to reduce building electricity at the Ontario gird peak. The results show the reduced cost associated with the monthly/annual electricity bill.

5.2.1 ARC Building Load (Yearly, Daily, Hourly)

Analyzing the Advanced Research Complex (ARC) presented in Figure 5.12, building electricity load based on yearly, daily, and hourly demand is key to identifying the proper mitigation scenarios and battery sizing and dispatch. The analyzed building load, as mentioned before, is the average ARC building demand for 2016 and 2017. As indicated in Figure 5.13, the yearly results show that the building electricity consumption throughout the year fluctuates from 500 kW to 630 kW. The daily results show that the building has a consistent on-peak and off-peak during the year, as indicated in Figure 5.14. A closer look at the hourly demand of the ARC building is illustrated in Figure 5.15, showing the building peak occurs around noon (noon time) and starts decreasing till it's reached its minimum around midnight (midnight time). It's also noted that the building load demand is moderate at the Ontario Peak time, around 17:00 to 18:00, as illustrated in Figure 2.3. It can be inferred that the building peak is different from the Ontario Peak, although they are close to each other.

Figure 5. 12 The Advanced Research Complex (ARC) building at the University of Ottawa

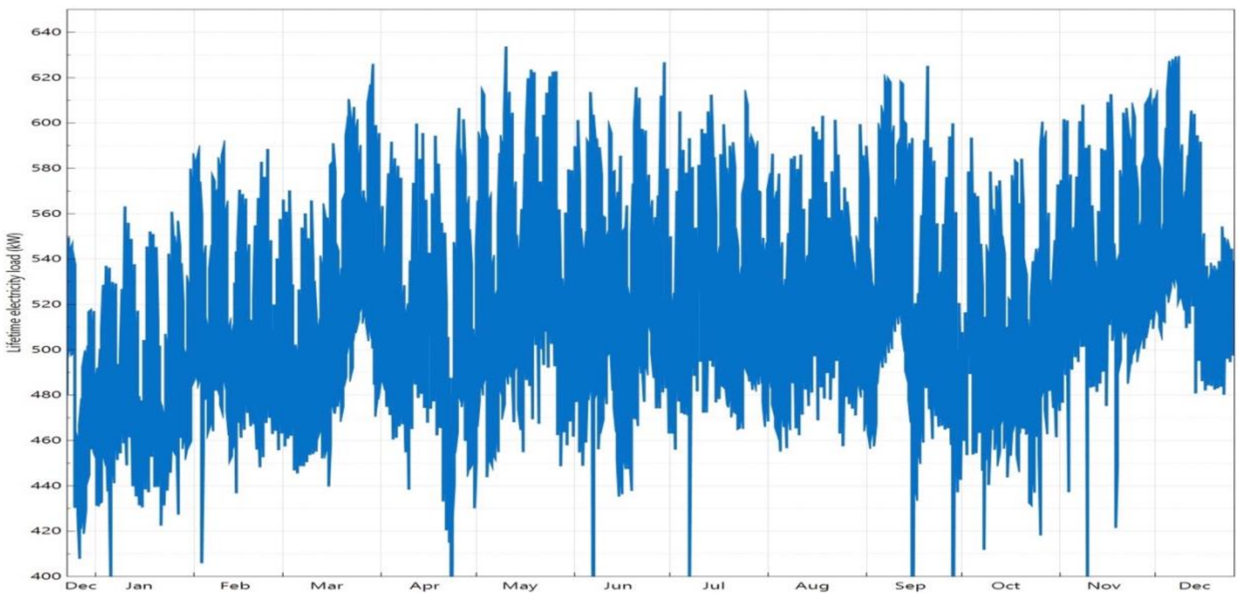


Figure 5. 13 ARC Building Annual electricity demand (aggregated from the average of the hourly data of year 2017 and 2018)

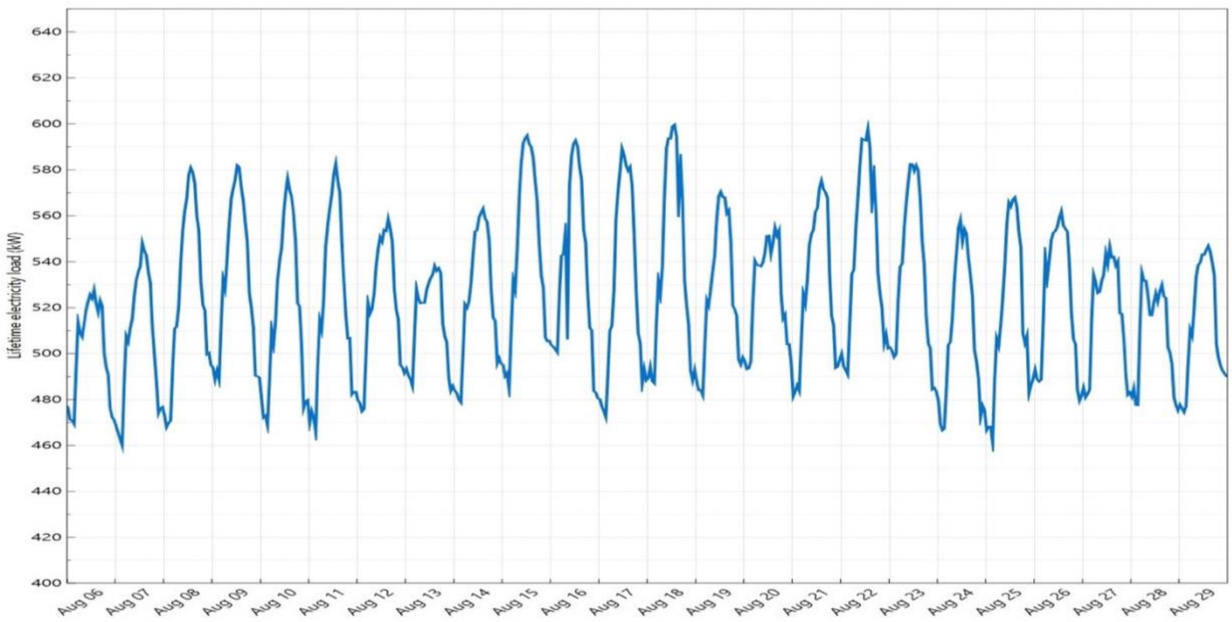


Figure 5. 14 Building daily load (aggregated from the average of the hourly data of year 2017 and 2018)

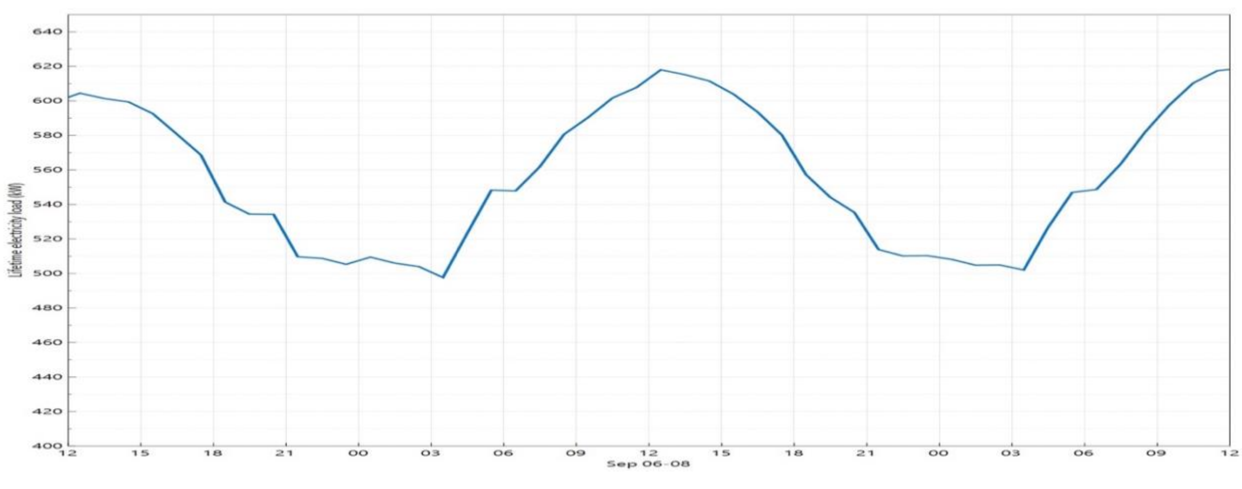


Figure 5. 15 Building hourly load (aggregated from the average of the hourly data of year 2017 and 2018)

5.2.2 Electricity from System to Load (Yearly, Daily, Hourly)

In order to better understand whether the building would need energy storage to mitigate the building demand at Ontario peak, a further investigation has been done on the yearly, daily, and hourly solar electricity generation. Figure 5.16 shows that the annual electricity generation is to a great extent providing consistent electricity to reduce the building load. The results show that the solar system is peaking when approaching the summer season, including March, April, May, June, July, August, and September. The electricity generation declines in October, November, December, January, and February. Further investigation on the amount of daily electricity shows that the electricity generation is consistent throughout the year. However, the electricity produced daily fluctuates in a wide range, approximately from 150 kW to 300 kW, which is lower than the building peak (500 kW to 630 kW), as indicated in Figure 5.17. It's worth noting that the high range of solar generation has implications. On some days that might intersect with one of Ontario's peak hours, the system might not be able to feed the building to mitigate the building demand, which could jeopardize the system integrity and cause profitability losses. The hourly analysis in Figure 5.18 shows that the system generation is at its maximum at noon and has little to no production capacity during the Ontario peak hours (17-18). Hence, to maintain reliable energy production capacity at Ontario peak hours, two actions have been utilized. First, integration of energy storage to charge at off-peak hours and discharge at on-peak hours. Second, charging the battery from the grid when there is a shortage in electricity production from the solar system.

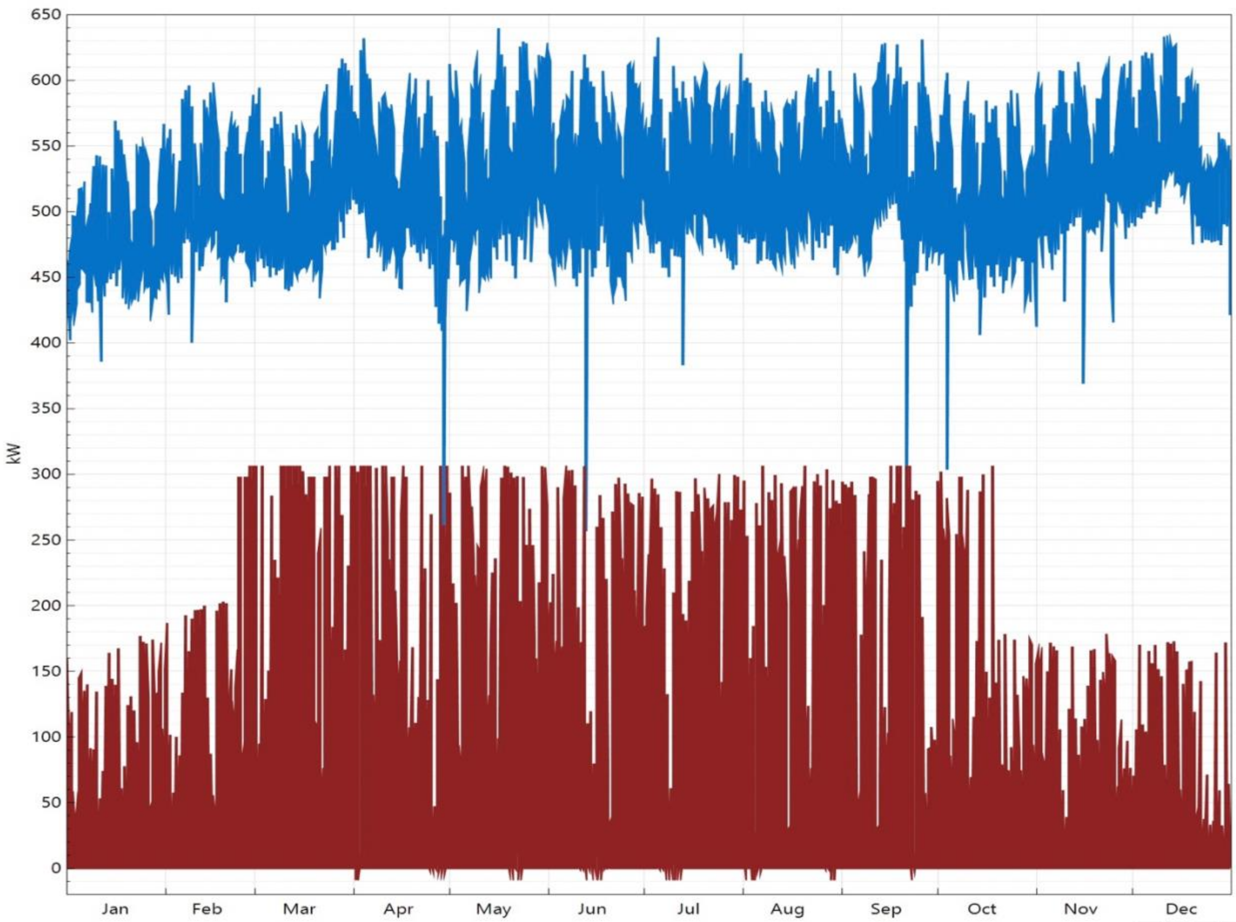


Figure 5. 16 Solar system yearly electricity generation and the electricity demand for the ARC building

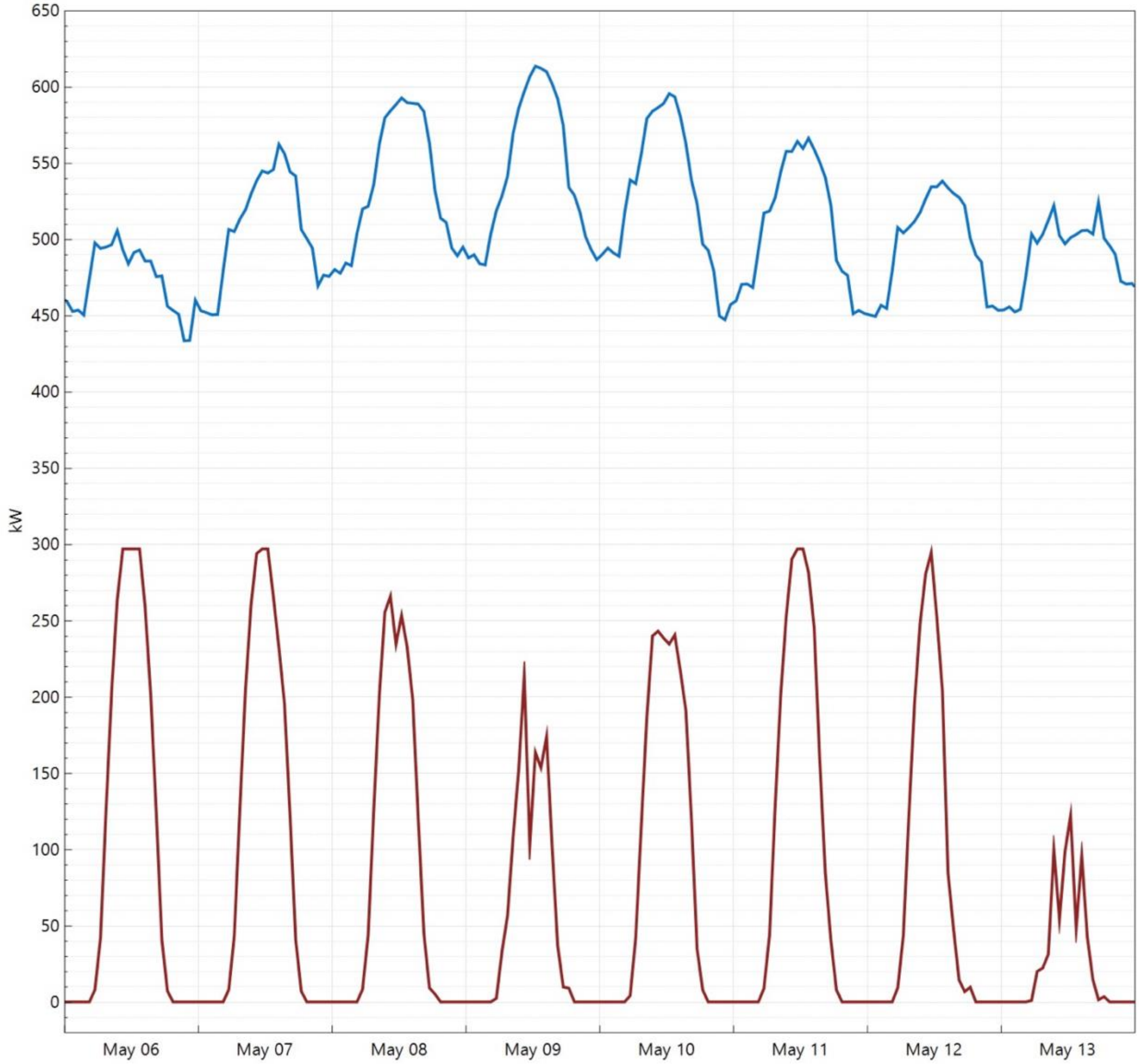


Figure 5. 17 Solar system daily electricity generation and the electricity demand for the ARC building

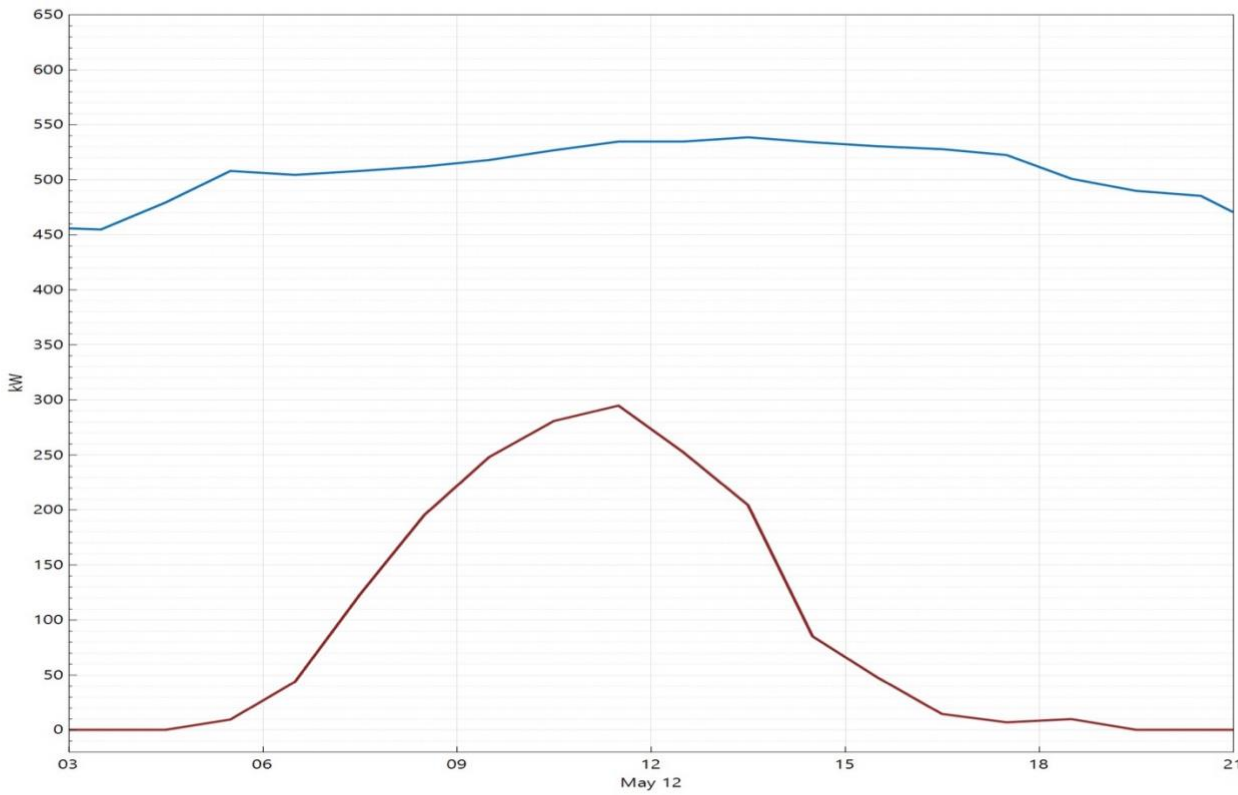


Figure 5. 18 Solar system hourly electricity generation and the electricity demand for the ARC building

5.2.3 Electricity from Battery to Load (Yearly, Daily, Hourly)

As identified from the previous analysis, battery storage is vital to mitigate the Ontario peak and obtain monetary savings from the Global Adjustment program. The following study has been done to achieve the objective. The dispatch algorithm for the battery shows viability and consistency to feed building demand peak over the year, as illustrated in Figure 5.19. The battery dispatch algorithm considers dispatching only on the weekdays and neglects the weekend days as there are no peaks in Ontario at weekends, illustrated in Figure 5.20. Figure 5.21 shows that the battery consistently dispatches to cover an hour (17-18) each day for the hourly investigation. The battery analysis shows that the system has been able to meet the building demand over the year. The 100% scenario can cover the building peak when it reaches its highest 630 kW, the 90% scenario covers a peak up to 564 kW, the 75% scenario covers a peak up to 470 kW, and the 50% scenario covers a peak of 345 kW.

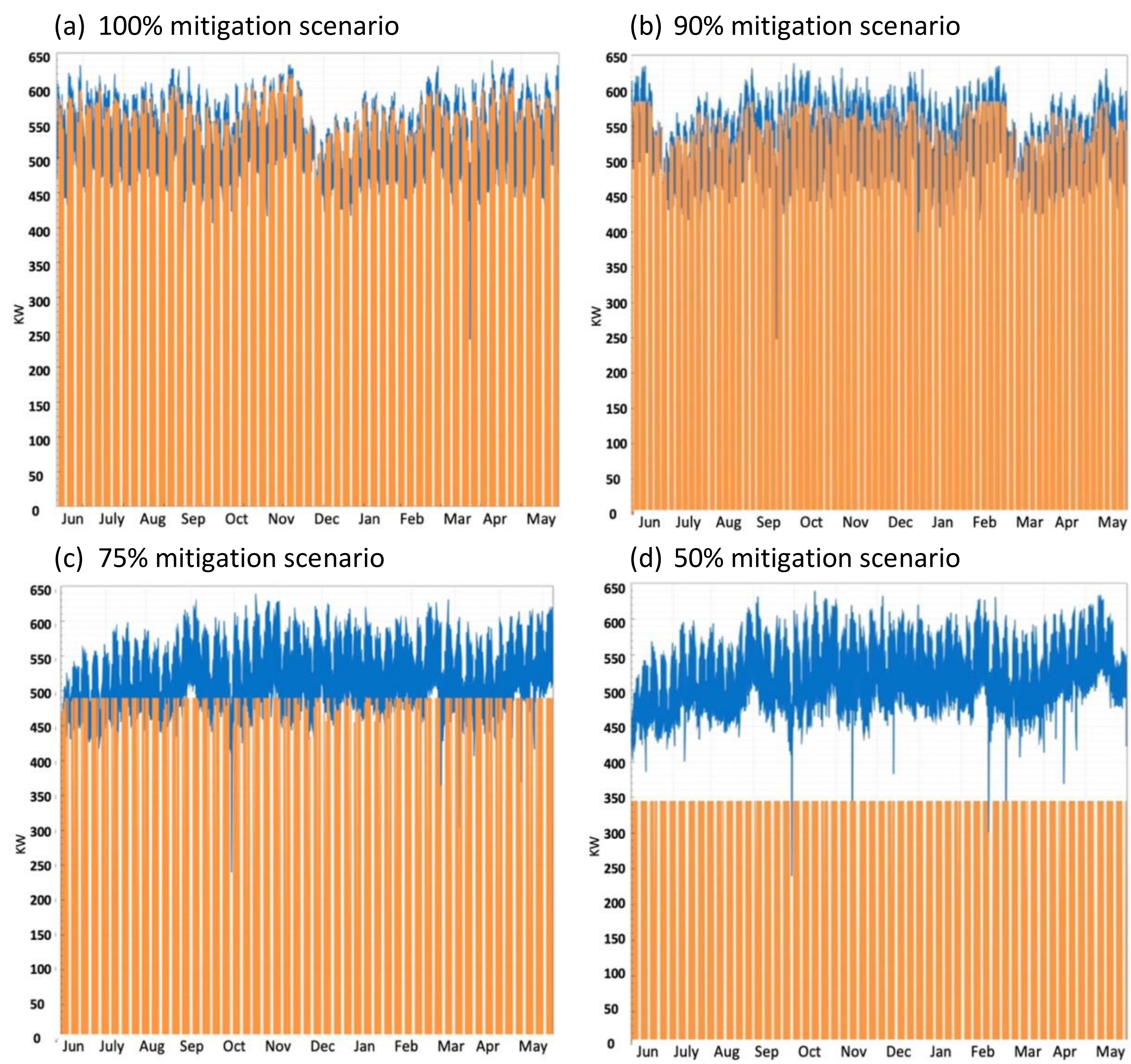


Figure 5. 19 Battery yearly electricity dispatch and the electricity demand for the ARC building (100%, 90%, 75%, 50% mitigation scenario)

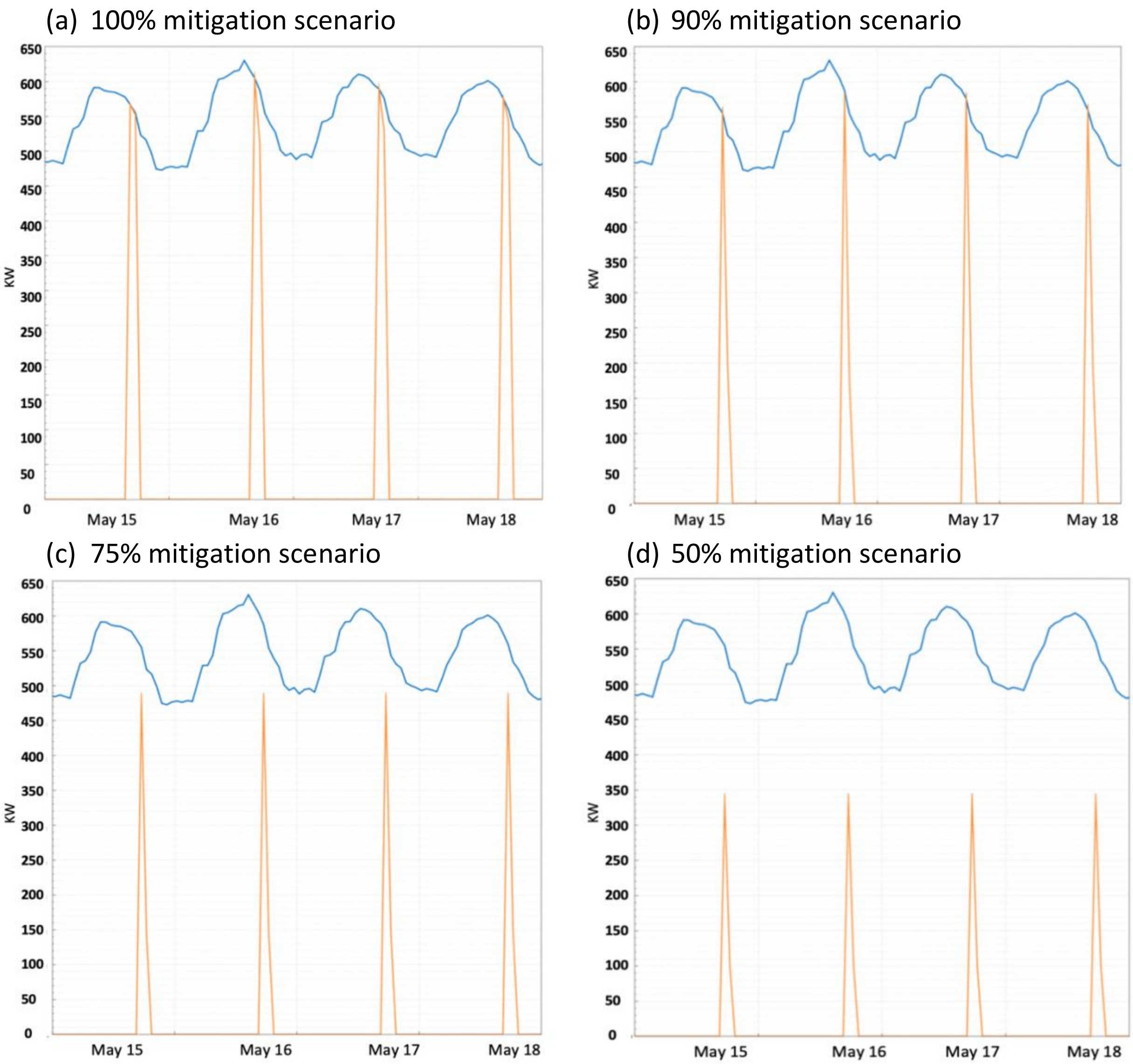


Figure 5. 20 Battery daily electricity dispatch and the electricity demand for the ARC building (100%, 90%, 75%, 50% mitigation scenario)

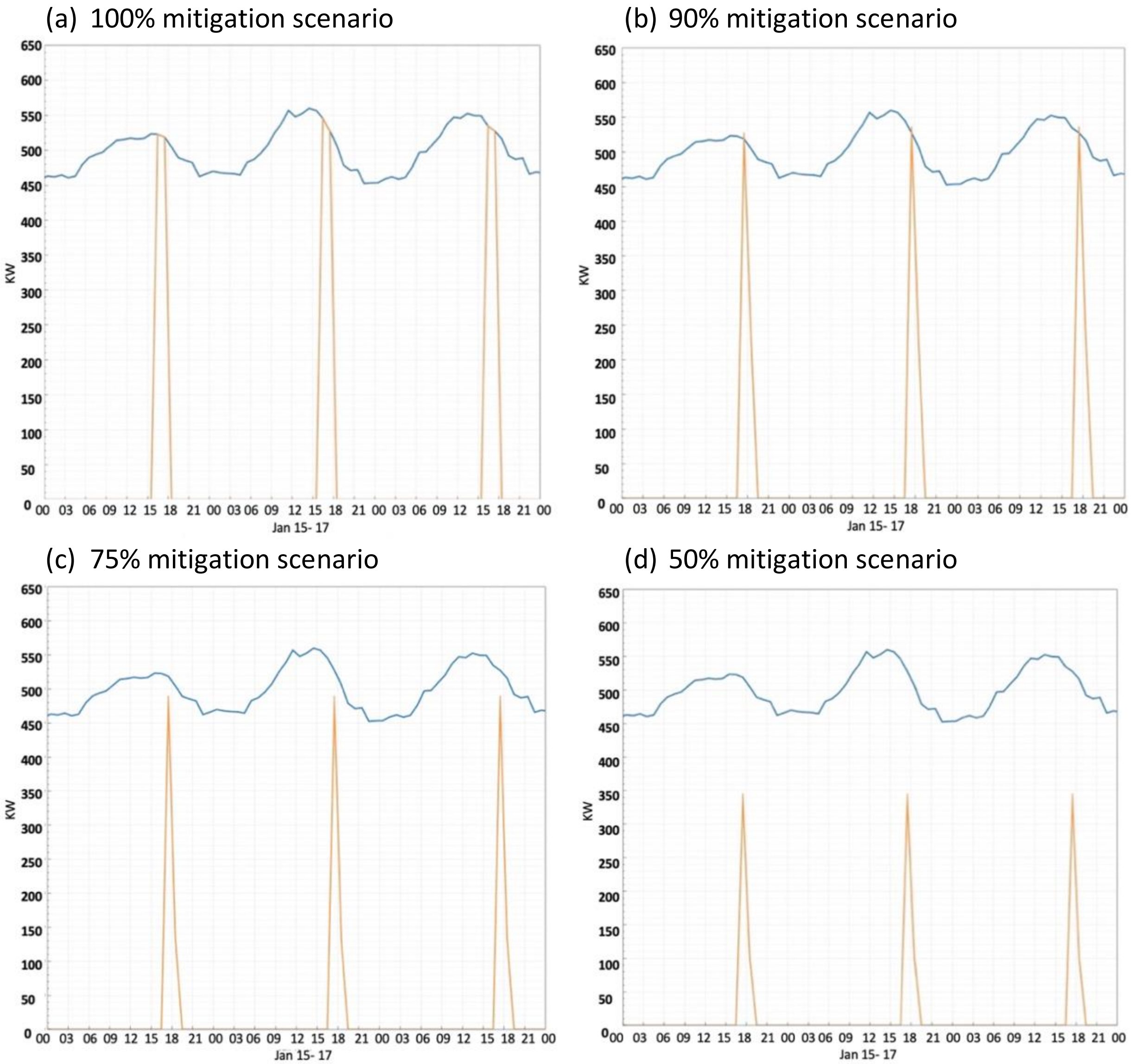
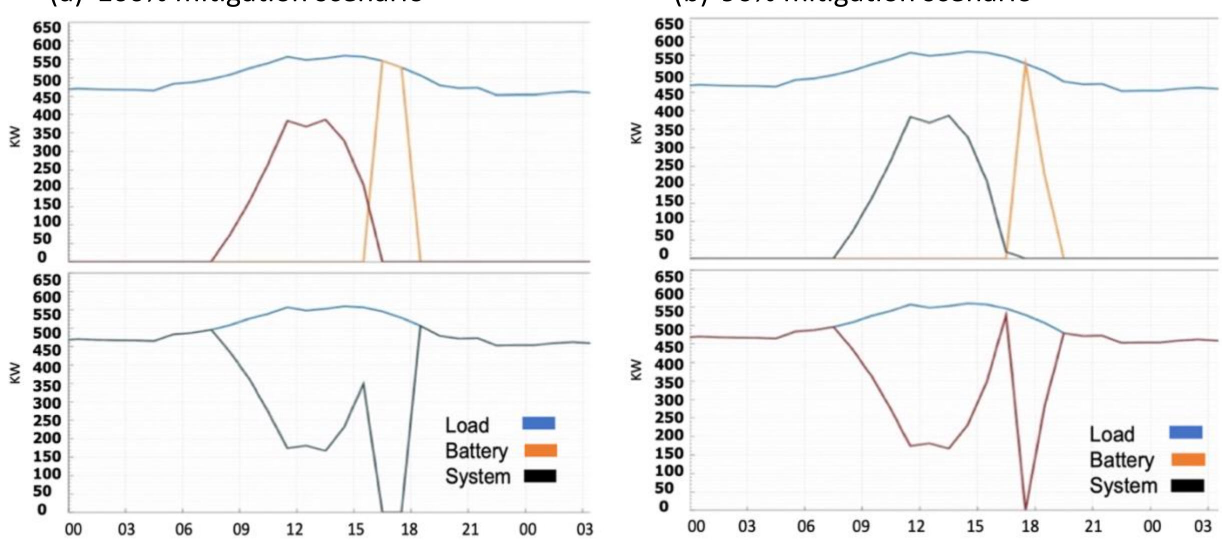


Figure 5. 21 Battery hourly electricity dispatch and the electricity demand for the ARC building (100%, 90%, 75%, 50% mitigation scenario)

5.2.4 Electricity from Battery, System and Grid to Load

In order to better visualize and understand how the solar system, storage, grid and building interact with each other, Figure 5.22 has been created to analyze one-day hourly electricity fluctuations. In the upper part of each graph of the figure, the blue line represents the building electricity load, the orange line represents the battery discharge, and the black line represents the solar generation. The solar electricity production starts around 7:00 AM and ends by hour 15, and the battery dispatch starts to cover hours 17 and 18. The lower part of the graph represents the electricity consumed from the grid to fulfil the rest of the building demand. Such representations enable a better decision-making process to select the best viable option. Additionally, the battery characteristics are presented in Appendix C

(a) 100% mitigation scenario (b) 90% mitigation scenario



(c) 75% mitigation scenario (d) 50% mitigation scenario

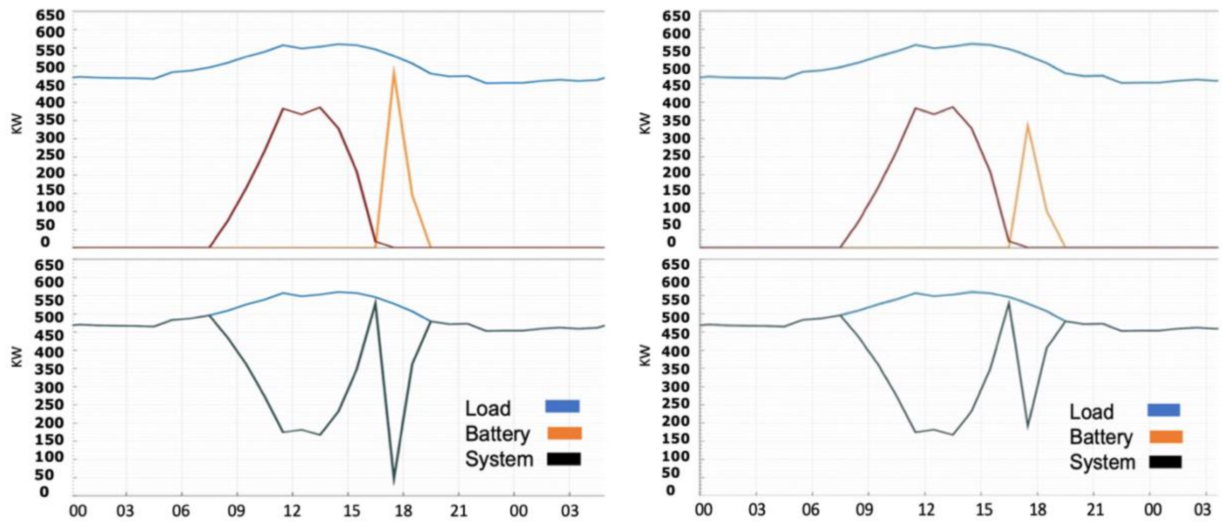


Figure 5. 22 Electricity from the solar system, battery, and grid to the demand for the ARC building (100%, 90%, 75%, 50% mitigation scenario)

5.2.5 Financial Viability Scenarios Comparison

This section evaluates and compares different metrics to assess the proposed system's financial viability. Six scenarios have been simulated in the System Advisor Model (SAM) software to have a better perspective and solid background for an informed decision-making process. The scenarios are as follows: (1) the PV system as a standalone. (2) the PV system with battery without adding potential savings from the Global Adjustment Program. (3,4,5,6) the PV with battery mitigating 50%, 75%, 90%, and 100% of the corresponding building Ontario peak. Table 5.14 represent the comparison in 12 metrics. Five are technical: annual generated energy in year 1 (kWh), battery power (kW), battery capacity (kWh), DC capacity factor in year 1 (%), and battery roundtrip efficiency in year one. And seven are financial: LCOE Levelized cost of energy nominal and real ($/kWh), Net Present Value ($), Simple and discounted payback period (years), battery cost ($), and net capital cost ($).

Table 5. 14 Solar system with energy storage system comparison for six scenarios at the ARC building at uOttawa to assess potential monetary savings from the Ontario Global Adjustment Program

Metric/ Case	PV	PV + battery without GA	PV + battery (GA 50% scenario)	PV + battery (GA 75% scenario)	PV + battery (GA 90% scenario)	PV + battery (GA 100% scenario)
Annual energy generated in year 1 (kWh)	441,600	407,867	425,042	417,924	413,732	407,867
Battery Power (kW)	-	660	350	500	600	660
Battery Capacity (kWh)	-	1500	700	1000	1200	1500
DC capacity factor in year 1 (%)	13.2	12.2	12.7	12.4	12.3	12.2
Battery roundtrip efficiency in year 1	-	87.2	86.27	86.24	86.6	87.2
LCOE Levelized cost of energy nominal ($/kWh)	0.17	4.51	2.42	3.06	3.40	3.92
LCOE Levelized cost of energy real ($/kWh)	0.12	3.09	1.65	2.10	2.33	2.68
Net Present Value ($)	42,893	-550,329	864,056	1,307,837	1,704,451	2,012,865
Simple payback period (years)	8.1	17.2	3.7	4	2.7	2.5
Discounted payback period (years)	21.5	-	5.6	4.4	3.7	3.4
Battery Cost	-	493,522	278,220	371,295	432,685	493,522
Net capital cost ($)	545,189	994,106	770,193	866,991	930,836	994,106

The annual electricity generated from the PV system as a standalone is 441,600 kWh, the highest. With more charging and discharging processes from and to the battery, energy loss occurs until the generated electricity reaches its lowest in the 100% mitigation scenario with 407,867 kWh, as indicated in Figure 5.23. However, as illustrated in the following section, the integrated battery's benefit outweighs the extra energy's lost profit from the energy reductions.

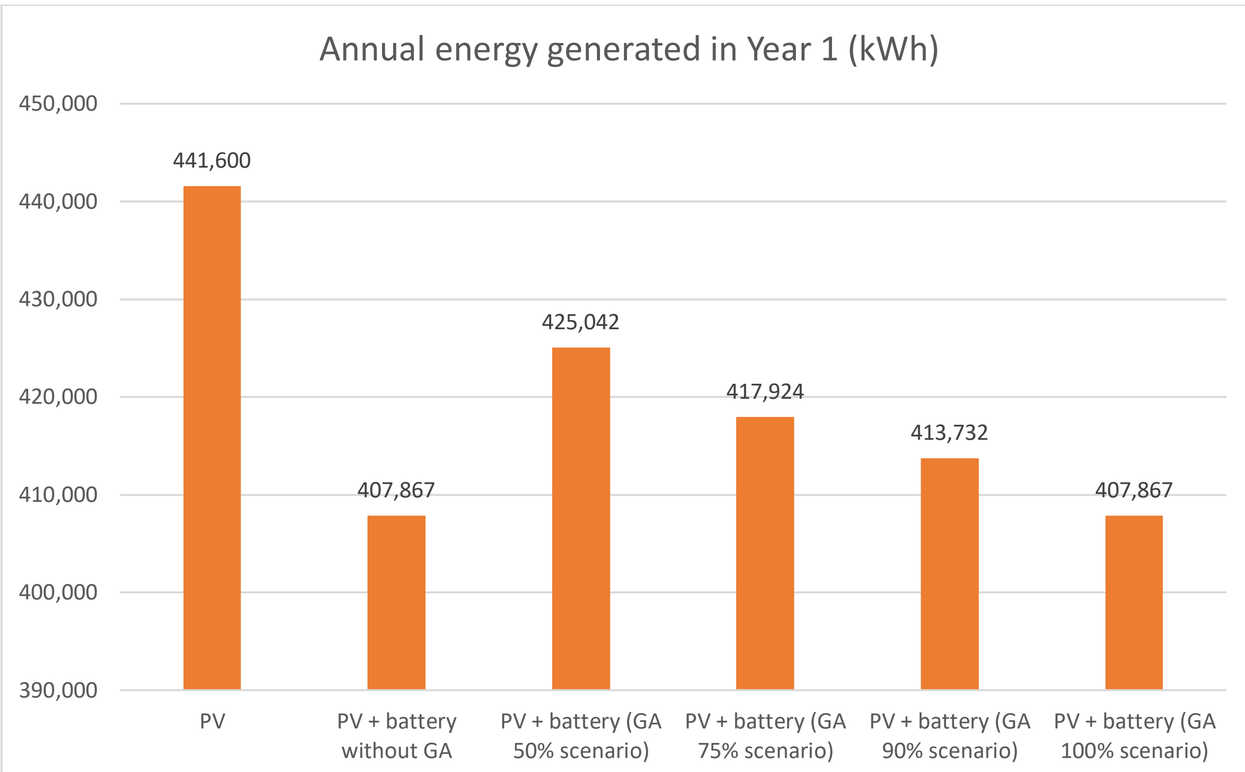


Figure 5. 23 Annual generated electricity from the system in year 1 (kWh) for the six scenarios

The Net Present Value (NPV) is considered the most important metric of all metrics. The reason is that it gives the final value of the project at the end of its lifetime, either in negative or positive value. As presented in Figure 5.24. First, the solar system as a standalone shows a positive NPV of $42,893. Second, the solar system with battery storage without including any incentives from the Global Adjustment Program shows that including a battery in the system would make it incur losses with a negative NPV of -$550,329. Finally, the results for the solar system with energy storage for the mitigation scenarios show an upward trend in the NPV with the increase of mitigation percentage as follows. 50%, 75%, 90%, 100% mitigation scenarios have a positive NPV of $864,056, $1,307,837, $1,704,451, $2,012,865 respectively. Without the Global Adjustment, the university or any commercial institution won't be incentivized to decrease its load at the Ontario peak as it's simply unviable and incurs losses.

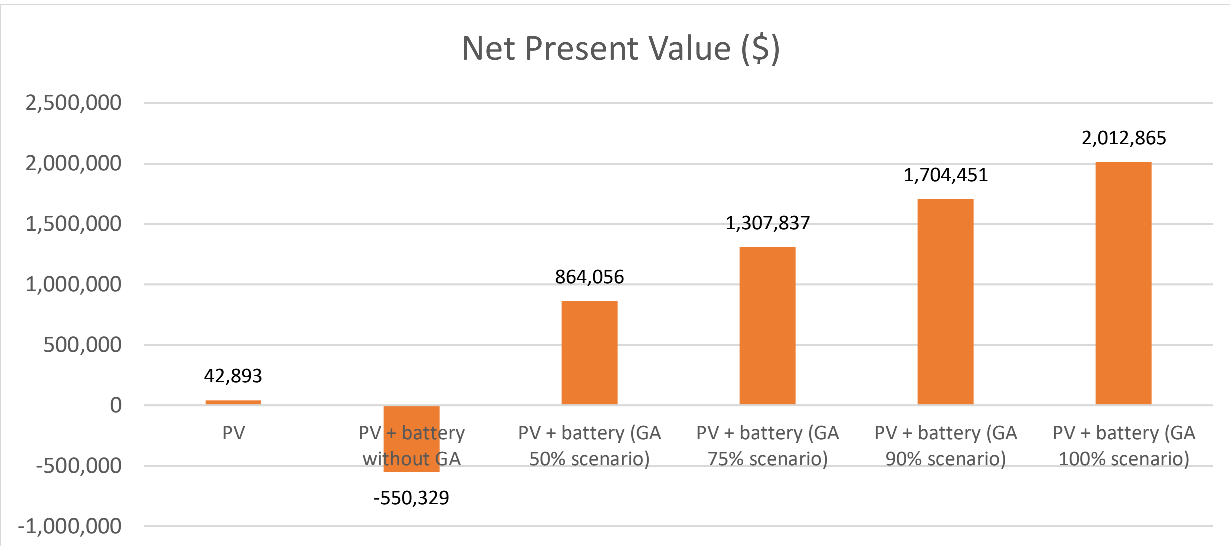


Figure 5. 24 Net Present Value over 25 years for the six scenarios

Another essential cost metric is the payback period, which states when the project recovers the initial investment cost. As indicated in Figure 5.25, the standalone system would take 8.1 years for simple payback and 21.5 years for the discounted payback. The system with the storage without the GA savings shows 17.2 years for the simple payback, and the system won't recover the initial capital cost for the discounted payback. Considering the GA savings, the results show that the higher the mitigation scenario, the lower the simple and discounted payback period with simple payback periods of 3.7, 4, 2.7, 2.5 years, and discounted payback periods of 5.6, 4.4, 3.7, 3.4 years for the 50%, 75%, 90%, and 100% mitigation scenarios.

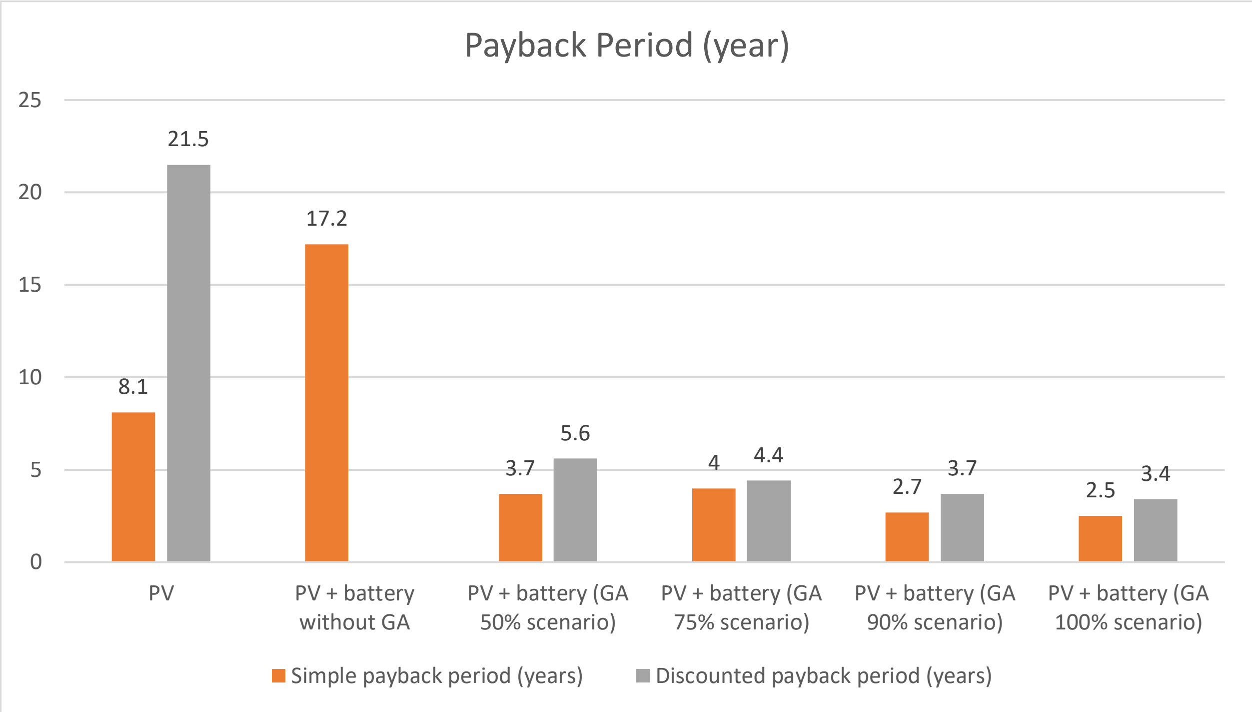


Figure 5. 25 Simple and Discounted Payback Period for the six scenarios

Another Interesting cost metric is the Levelized Cost of Energy (LCOE). The LCOE represents how much is paid to produce one kilowatt of electricity per hour. However, this metric alone doesn't represent the value-added from the storage system because those batteries add more cost to the initial investment without increasing the energy output. Indeed, the batteries increase the overall project's financial viability. As illustrated in Figure 5.26, The PV system has the lowest LCOE nominal and real, with 0.17$/kWh and 0.12$/kWh. The PV + Battery without the Global Adjustment savings scenario shows the highest LCOE nominal and real with 0.45$/kWh and 0.309$/kWh.

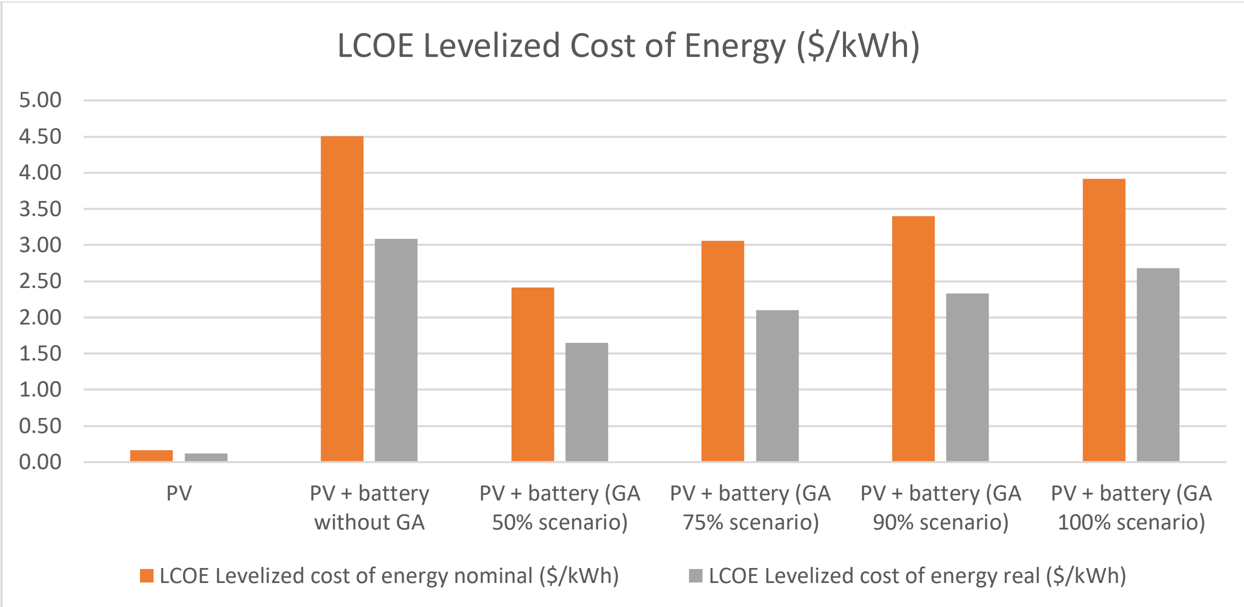


Figure 5. 26 LCOE Levelized Cost of Energy nominal and real ($/kWh) for the six scenarios

The net capital cost reinforces the LCOE results. Figure 5.27 shows the lowest cost is associated with a standalone PV system with $545,189 and the highest in the 100% mitigation scenario, PV with battery with a net capital cost of $994,106.

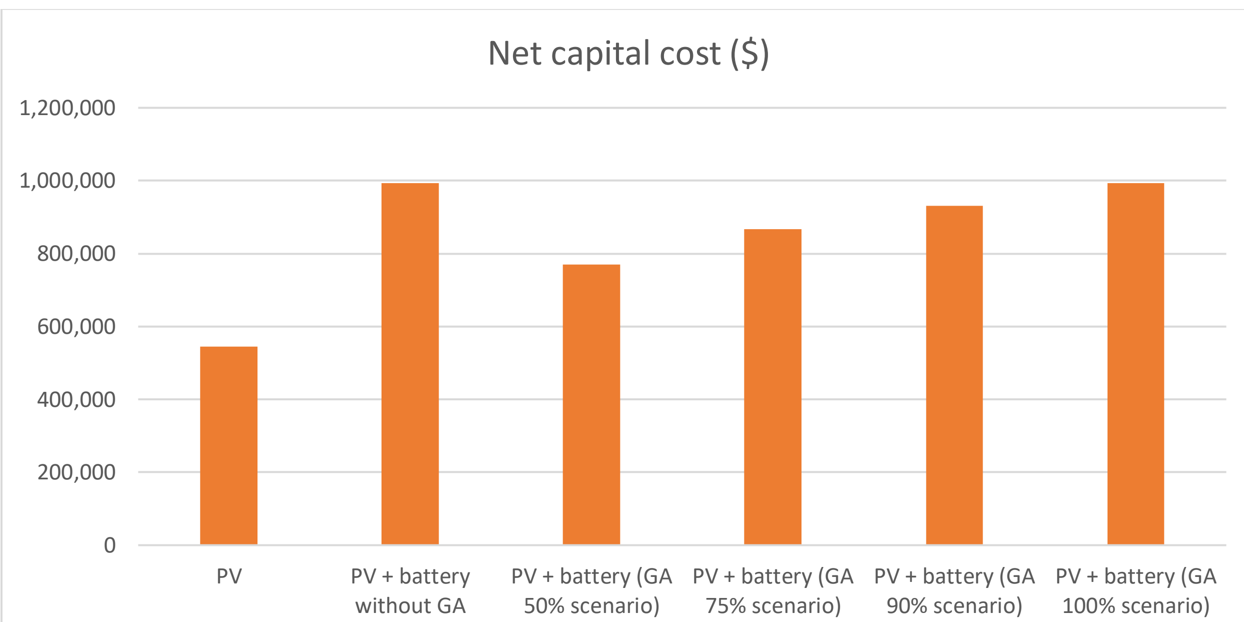


Figure 5. 27 Net capital cost ($) for the six scenarios

5.3 Summary

This section included the results for installing the solar system at the University of Ottawa building roofs. The analysis included the financial viability of the project, Life Cycle Cost Analysis (LCCA), expected production capacity, and environmental impacts of the project (Life Cycle Assessment (LCA). The section also included the results of the Campus as a Living Lab survey. Moreover, the section presented the results of integrating batteries with the solar system using the ARC building as a case study. The findings showed the battery, system, and grid interconnected behaviour. Comparisons were made for different scenarios to assess the suggested approach financial viability and cost savings from the Ontario Global Adjustment Program.

6. Discussion (Uncovering Science and Policy Intersection)

This research builds on the literature review and the urban comparative analysis. In relation to the PV system case study, it is clear that PV system diffusion wouldn't be possible without governmental financial mechanisms. As shown in the first study, the PV system's financial viability could only be achieved by considering installing the system in many buildings (Power capacity of more than 1,000 kWh) simultaneously to reduce initial and operations costs. Residential buildings wouldn't have enough roof area to install high-capacity solar systems. Hence, as identified in the urban comparative analysis, Public Purchase Agreement would play a vital role in solar panel diffusion. Governments could target each district progressively to install PV systems at one time. The district approach would incentivize residential owners to install PV systems at lower possible costs.

The energy storage case study shows a high potential to reduce buildings' electricity demand at the Ontario province peak time. The electricity reductions would smooth the electricity demand curve in Ontario. Smoothing demand would help maintain grid health reliability and resiliency without installing or constructing additional energy sources or using fossil fuel-based energy to cover the extra energy demand during the peak. However, the ARC case study shows that the energy storage only showed viability when the Ontario Global Adjustment Program cost savings were considered. Hence, the government should maintain financial programs and innovate more fiscal opportunities to increase the adaptation and diffusion of renewable and building technology.

In relation to the "Campus as a Living Lab" case initiative survey results, the results support the literature findings and the urban comparative analysis. The University of Ottawa has the potential for knowledge co-production and preparing students to find solutions for pressing sustainability issues within the campus boundary. Such findings could be scaled to a city scale. The case study also showed that students seek to put more effort into learning and apply ways to overcome heated topics such as climate change and energy efficiency. Also, students called to include industry partners to work with them closely during projects to enable a more impactful experience.

In relation to integrating the Campus into the city, campuses have the potential to transform cities. They closely interact with each other and could profoundly impact achieving climate neutrality goals. It is recommended to have a carbon/energy manager be hired within the campus sustainability office to manage the many facets of reducing energy demand from the campus buildings. Building decarbonization is scattered among more than one department, including facility managers, asset managers, and the sustainability office, leaving the university with two significant implications. First, it makes reducing campus footprint and energy demand a daunting task. Second, it limits the coordination and communication channels with the city for knowledge co-sharing and developing solid partnerships needed to mitigate climate change and high energy consumption behaviours.

In this research, steps were taken to uncover the intersection of science and policy to help reach the net-zero building by connecting the urban comparative analysis results with the case studies results. The intersection between renewable technology diffusion, fiscal incentives, education and capacity building, and campuses for knowledge co-production were examined and solidified by two case studies at the University of Ottawa.

7. Conclusion

This thesis conclusion is threefold. First, the PV system case study findings are presented. Second, the energy storage with PV system integration to meet the Ontario Global Adjustment Program is outlined, followed by the urban comparative analysis remarks. The PV case study offers The University of Ottawa decision-makers a comprehensive overview of the technical, economic, and environmental performance of installing a photovoltaic system over the campus buildings' roofs to achieve net-zero operations by 2040 and comply with the City of Ottawa climate policy. The dramatic cost reduction and increased power capacity of PV panels offer an excellent opportunity to lower the number of greenhouse gasses and electricity usage during the building's operating life cycle. In addition, the embodied carbon of PV systems is usually overlooked when determining the environmental performance of a PV system. The campus inspires this study as a living lab imitative for knowledge co-production as a novel pedagogical approach to finding solutions to cities and communities' most pressing sustainability issues. Furthermore, the pedagogical approach shows that gradually, the approach could yield more hands-on experience for engineers and contribute to the university's research capacity. The main conclusions achieved in this study can be summarised as follows:

- The excepted electricity generation from the analyzed nine buildings could offset (20-107%) each building. Additionally, the expected 31 building electricity generation is 18 million units (kWh) annually, offsetting 23% of the current campus electricity consumption.
- The project is deemed profitable, showing a Net Present Value (NPV) of 4,985,288 $ and an Internal Rate of Return of 11.4% higher than the (8-9%) recommended discount rate to invest in projects in Canada.

- The estimated annual operational carbon reduction from installing the PV panels at the 31 buildings is 14,445 tCO_2.
- The project is expected to cause 1,023 tCO_2 life cycle GHG emissions from the embodied carbon, responsible for the manufacturing, transportation, installation, maintenance, and operation. The project is expected to have had less than two years of payback period to recover the released embodied carbons.
- The campus as a living lab imitative is a promising pedagogical approach. The initiative provides a two-way road of mutual benefits. The students experience a real challenge that provides a stimulating learning experience. And the university's research capacity increases to overcome pressing sustainability issues within the campus boundary. Plus, the opportunity to scale up the solutions from the campus boundary to the city.

Second: The study investigated the viability of integrating solar panels with an energy storage system at the Advanced Research Complex building at the University of Ottawa. The study's purpose is to reduce the building electricity bill by reducing the building cost share of the Ontario Global Adjustment. The analysis showed that the building demand peak starts around hour 09 and finishes around hour 18. The PV system generation can mitigate most of the building peak without an energy storage system, generating electricity from hour 06 to hour 16. However, the PV system can't mitigate the Ontario Peak, which starts around hours 16 and 17, making the energy storage system a clean and viable solution to minimise the building electricity demand at the Ontario grid peak. Six scenarios have been simulated to assess the financial viability of mitigating the peak. The results are summarised as follows:

- PV standalone scenario: This scenario has a Net Present Value (NPV) of $42,893 from the electricity generated and a discounted payback period of 21.5 years. However, it doesn't contribute to mitigating the building demand at Ontario's peak.
- PV + battery without GA savings: This scenario has a negative NPV of $-550,329 and won't be able to recover the initial investment cost at a discounted rate because of the increased cost of the battery without the ability to achieve cost savings from the Global Adjustment Program.
- PV + battery 50%, 75%, 90%, and 100% GA cost mitigation scenarios: this scenario has a positive NPV of $864,056, $1,102,340, $1,307,837, $2,012,865 and discounted payback period of 5.6, 4.4, 3.7, 3.4 years. The results show that despite the cost increase because of the battery size, the project shows greater financial return resulting from the higher savings from the GA costs.

Third: Achieving the net-zero energy building sector is challenging because buildings are not standalone systems; instead, they are interconnected with other systems such as electric grids that supply buildings with energy. Moreover, buildings energy is heavily influenced by end-users. Citizen engagement, public awareness, and trust-building will play a major role in decarbonizing the sector. Another major impediment is funding; comprehensive energy retrofits need a significant upfront expenditure yet pay off over time, with a payback period of 10–20 years. Most homeowners, for example, do not have the significant amount of funding required for major energy renovations. As a result, initiatives and policies are required to bridge the payback time gap. Another issue is that building codes are still only applied to a limited extent; even when they are, their application is fraught with difficulties [17]. In addition, those codes are released on the national level leaving no space for local governments to upgrade or improve building codes. There may be insufficient enforcement, training, and oversight.

Moreover, embodied carbons have been gaining global attention in the past ten years with decreasing the carbon intensity in electricity grids; they are becoming significant contributors to the overall CO2 emission from the building's life cycle [65].

- The urban comparative analysis showed that each city has unique characteristics and novel attributes to reach the net-zero building sector. The evidence supports the polycentric system and anticipatory governance approaches as promising ways to tailor climate solutions. More work is required to link present climate targets to on-ground initiatives that can work in various realities [164].

- The use of multiple instead of single policy tools, and a greater range of regulatory actors, will result in better regulation. Furthermore, this will permit the implementation of a complementary mix of mechanisms and participants designed to meet the context of specific environmental challenges. By implication, this means a far more creative, flexible, and pluralistic approach to environmental regulation than has been adopted in most jurisdictions [285].
- The findings can help policymakers, urban planners, and government officials tailor the appropriate interventions to decarbonize the building sector and achieve an inclusive carbon-neutral transition by 2050 without exasperating inequalities.

To conclude, cities are in the frontline to drive carbon reductions and meet the Paris Agreement goals well below 2°C and pursue reductions further to 1.5 °C. However, without careful consideration of society's needs through public engagement, education and capacity building, green fiscal incentives, and governance, reductions can't be achieved by relying only on building science and technology.

7.1 Limitations

The research limitations are as follows for the University of Ottawa PV system case study:

- *Cost* – One of the limitations is that aggregating the project cost based on the materials and equipment quantities is a very tedious process. The cost estimate would need information and disclosures from contractors for the installation cost, so the cost was identified based on the expected power capacity of the project sourced from different PV installation companies. Therefore, it is recommended to aggregate the project cost based on the actual materials used to obtain a more accurate cost estimate, which will be reflected in the project's financial viability.

- *Materials* – To perform the Life Cycle Assessment, all information about the materials and equipment must be specified to obtain a precise amount of the expected GHG emissions. However, most PV system manufacturers still don't report or register their products to be certified EPDs (Environment Product Declarations) [271]. To overcome this issue, the quantities of the raw materials to manufacture a PV system of a 1 MW plant was used to estimate the embodied GHG emission from installing the system. Therefore, it is recommended that with more manufacturers reporting and disclosing the environmental impacts of the products, the analysis is to be made based on the EPDs.
- *Campus buildings* – Another limitation of the study is that the analysis of installing PV systems on the whole campus was not manageable due to the lack of the campus urban plan information about the new buildings to be constructed. Additionally, the building plans were unavailable, so Google Earth was used to measure roof areas. Therefore, using the actual building plans to calculate the solar collector area for sharper results is recommended.
- *Software* – RETScreen Clean Energy Management software developed by Natural Resources Canada doesn’t include analysis for self-shading, which might impact the project production capacity from (10- 40%). Careful consideration must be taken when designing the PV system layout to avoid over-condensation. For a better perspective to avoid self-shading, the number of installed PV panels might be decreased to 70% of the original capacity; this, in return, will reduce the amount of generated electricity. However, simultaneously will lower the capital cost of the project. In other words, self-shading would

lead to less electricity generation, but profitability will not have a high impact because of the decrease in capital cost; Figure 5.7. clearly illustrate the relationship between the initial cost and electricity generation on the NPV of the project. The software also doesn't have the ability to model additional technologies such as DC optimizers to increase solar gains (10-20%) and reduce losses from shading effects.

The following are the limitations of the urban comparative analysis:

- *Developing countries* – The city selection process included cities covering different urban geographies and contexts. However, the research was faced with a scarcity of developing countries' climate change and energy plan documentation. The document scarcity was mainly for two reasons: cities' plans and documentation are driven by directions from the United Nations organizations. Developing countries sometimes don't have the necessary capital cost or knowledge to develop and act on climate mitigation plans. Second, some developing countries' reports and demounts are in languages other than English. Therefore, with the upward climate change trajectories, future research should include actions from developing countries to ensure inclusivity.
- *Interviews* – some of the city's documents lacked information about their actions or weren't clear enough. It is suggested to conduct structured interviews with city officials to ensure that the research covers critical actions.
- *Quantitative analysis* – The analysis carried out is qualitative; future analysis should have quantitative methods to assess the influence of different policies on climate mitigation and achieving a net-zero energy building sector.

7.2 Future research

The following are the future research for the campus as a living lab (installing solar panels at the University of Ottawa building's rooftop):

- The solar system's techno-economic performance depends on two streams. The first stream is the technical performance, such as the expected electricity generation, the system power capacity, shading, and weather. The second stream is the financial and economic atmosphere, such as inflation rate, electricity prices, and fiscal incentives. Future research should investigate performing uncertainty analysis to measure the output variance that might occur due to variance in inputs.

The following are the future research for the Global Adjustment Program (integrated energy storage with PV system):

- The energy storage with PV system study only considered the return on investment from the Ontario Global Adjustment cost. Future research should investigate other financial savings from the Hourly Ontario Energy Price (HOEP), the Demand Response Program, Ontario electricity rebates and other existing financial incentives.

- Additionally, caution must be taken into consideration regarding the hourly Ontario peaks. The hourly Ontario peaks don't have a specific time; it occurs based on the day-to-day electricity supply and demand. According to the IESO Historical data [200] for this study, the peak happens mostly in hours 16 and 17. However, it might occur at another time. Close monitoring of IESO Power Data [200] and Peak tracker [286] must be taken into consideration. Future research could include developing an artificial intelligence algorithm with higher accuracy to detect peak hours.

The following are the future research for the Urban Comparative Analysis:

- Future research could investigate and track the effectiveness of the interventions quantitively collectively within a city or perform a parametric analysis to understand which policies are the most effective and economically feasible. While considering contextual assumptions, such findings can be shared and transferred with different cities worldwide through mechanism mapping.

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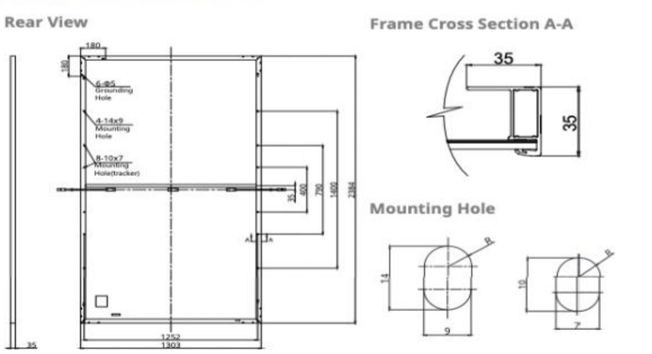
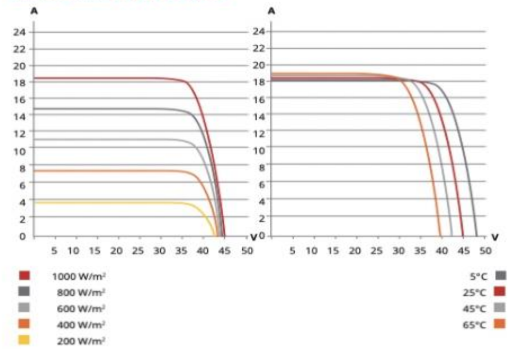
Appendix A: Canadian Solar panels technichal specifications

Appendix A. 1 Canadian Solar selected PV panel for the project technical specification (1)

ENGINEERING DRAWING (mm)



CS7N-650MS / I-V CURVES



ELECTRICAL DATA | STC*

CS7N	640MS	645MS	650MS	655MS	660MS	665MS	670MS
Nominal Max. Power (Pmax)	640 W	645 W	650 W	655 W	660 W	665 W	670 W
Opt. Operating Voltage (Vmp)	37.5 V	37.7 V	37.9 V	38.1 V	38.3 V	38.5 V	38.7 V
Opt. Operating Current (Imp)	17.07 A	17.11 A	17.16 A	17.20 A	17.24 A	17.28 A	17.32 A
Open Circuit Voltage (Voc)	44.6 V	44.8 V	45.0 V	45.2 V	45.4 V	45.6 V	45.8 V
Short Circuit Current (Isc)	18.31 A	18.35 A	18.39 A	18.43 A	18.47 A	18.51 A	18.55 A
Module Efficiency	20.6%	20.8%	20.9%	21.1%	21.2%	21.4%	21.6%
Operating Temperature	-40°C ~ +85°C						
Max. System Voltage	1500V (IEC/UL)) or 1000V (IEC/UL))						
Module Fire Performance	TYPE 1 (UL 61730 1500V) or TYPE 2 (UL 61730 1000V) or CLASS C (IEC 61730)						
Max. Series Fuse Rating	30 A						
Application Classification	Class A						
Power Tolerance	0 ~ + 10 W						

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

ELECTRICAL DATA | NMOT*

CS7N	640MS	645MS	650MS	655MS	660MS	665MS	670MS
Nominal Max. Power (Pmax)	480 W	484 W	487 W	491 W	495 W	499 W	502 W
Opt. Operating Voltage (Vmp)	35.2 V	35.3 V	35.5 V	35.7 V	35.9 V	36.1 V	36.3 V
Opt. Operating Current (Imp)	13.64 A	13.72 A	13.74 A	13.76 A	13.79 A	13.83 A	13.85 A
Open Circuit Voltage (Voc)	42.2 V	42.3 V	42.5 V	42.7 V	42.9 V	43.1 V	43.3 V
Short Circuit Current (Isc)	14.77 A	14.80 A	14.83 A	14.86 A	14.89 A	14.93 A	14.96 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

MECHANICAL DATA

Specification	Data
Cell Type	Mono-crystalline
Cell Arrangement	132 [2 x (11 x 6)]
Dimensions	2384 × 1303 × 35 mm (93.9 × 51.3 × 1.38 in)
Weight	34.4 kg (75.8 lbs)
Front Cover	3.2 mm tempered glass with anti-reflective coating
Frame	Anodized aluminium alloy, crossbar enhanced
J-Box	IP68, 3 bypass diodes
Cable	4 mm² (IEC), 12 AWG (UL)
Cable Length (Including Connector)	460 mm (18.1 in) (+) / 340 mm (13.4 in) (-) or customized length*
Connector	T4 series or MC4-EVO2
Per Pallet	31 pieces
Per Container (40' HQ)	527 pieces

* For detailed information, please contact your local Canadian Solar sales and technical representatives.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.34 % / °C
Temperature Coefficient (Voc)	-0.26 % / °C
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	41 ± 3°C

PARTNER SECTION

* The specifications and key features contained in this datasheet may deviate slightly from our actual products due to the on-going innovation and product enhancement. CSI Solar Co., Ltd. reserves the right to make necessary adjustment to the information described herein at any time without further notice.
Please be kindly advised that PV modules should be handled and installed by qualified people who have professional skills and please carefully read the safety and installation instructions before using our PV modules.

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Appendix A. 2 Canadian Solar selected PV panel for the project technical specification (2)


NEW

CanadianSolar

BiHiKu7

BIFACIAL MONO PERC

640 W ~ 665 W

CS7N-640|645|650|655|660|665MB-AG

FRONT BACK

MORE POWER

665 W — Module power up to 665 W
Module efficiency up to 21.4 %

Up to 8.9 % lower LCOE
Up to 4.6 % lower system cost

Comprehensive LID / LeTID mitigation technology, up to 50% lower degradation

Compatible with mainstream trackers, cost effective product for utility power plant

Better shading tolerance

MORE RELIABLE

40 °C lower hot spot temperature, greatly reduce module failure rate

Minimizes micro-crack impacts

Heavy snow load up to 5400 Pa, wind load up to 2400 Pa*

* For detailed information, please refer to the Installation Manual.

12 Years — **Enhanced Product Warranty on Materials and Workmanship***

30 Years — **Linear Power Performance Warranty***

1st year power degradation no more than 2%
Subsequent annual power degradation no more than 0.45%

*According to the applicable Canadian Solar Limited Warranty Statement.

MANAGEMENT SYSTEM CERTIFICATES*

ISO 9001:2015 / Quality management system
ISO 14001:2015 / Standards for environmental management system
ISO 45001: 2018 / International standards for occupational health & safety

PRODUCT CERTIFICATES*

IEC 61215 / IEC 61730 / CE / INMETRO / MCS / UKCA
CEC listed (US California) / FSEC (US Florida)
UL 61730 / IEC 61701 / IEC 62716 / IEC 60068-2-68
Take-e-way

* The specific certificates applicable to different module types and markets will vary, and therefore not all of the certifications listed herein will simultaneously apply to the products you order or use. Please contact your local Canadian Solar sales representative to confirm the specific certificates available for your Product and applicable in the regions in which the products will be used.

CSI Solar Co., Ltd. is committed to providing high quality solar photovoltaic modules, solar energy and battery storage solutions to customers. The company was recognized as the No. 1 module supplier for quality and performance/price ratio in the IHS Module Customer Insight Survey. Over the past 20 years, it has successfully delivered over 63 GW of premium-quality solar modules across the world.

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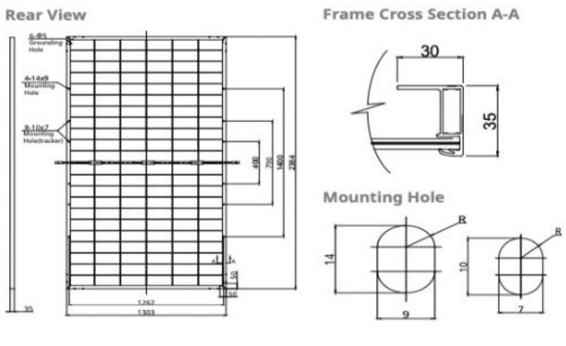
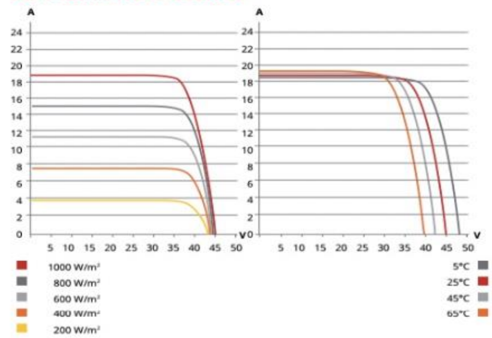
Appendix A. 3 Canadian Solar selected bifacial PV panel for the project technical specification (3)

ENGINEERING DRAWING (mm)



CS7N-650MB-AG / I-V CURVES



ELECTRICAL DATA | STC*

		Nominal Max. Power (Pmax)	Opt. Operating Voltage (Vmp)	Opt. Operating Current (Imp)	Open Circuit Voltage (Voc)	Short Circuit Current (Isc)	Module Efficiency
CS7N-640MB-AG		640 W	37.5 V	17.07 A	44.6 V	18.31 A	20.6%
Bifacial Gain**	5%	672 W	37.5 V	17.92 A	44.6 V	19.23 A	21.6%
	10%	704 W	37.5 V	18.78 A	44.6 V	20.14 A	22.7%
	20%	768 W	37.5 V	20.48 A	44.6 V	21.97 A	24.7%
CS7N-645MB-AG		645 W	37.7 V	17.11 A	44.8 V	18.35 A	20.8%
Bifacial Gain**	5%	677 W	37.7 V	17.97 A	44.8 V	19.27 A	21.8%
	10%	710 W	37.7 V	18.84 A	44.8 V	20.19 A	22.9%
	20%	774 W	37.7 V	20.53 A	44.8 V	22.02 A	24.9%
CS7N-650MB-AG		650 W	37.9 V	17.16 A	45.0 V	18.39 A	20.9%
Bifacial Gain**	5%	683 W	37.9 V	18.03 A	45.0 V	19.31 A	22.0%
	10%	715 W	37.9 V	18.88 A	45.0 V	20.23 A	23.0%
	20%	780 W	37.9 V	20.59 A	45.0 V	22.07 A	25.1%
CS7N-655MB-AG		655 W	38.1 V	17.20 A	45.2 V	18.43 A	21.1%
Bifacial Gain**	5%	688 W	38.1 V	18.06 A	45.2 V	19.35 A	22.1%
	10%	721 W	38.1 V	18.93 A	45.2 V	20.27 A	23.2%
	20%	786 W	38.1 V	20.64 A	45.2 V	22.12 A	25.3%
CS7N-660MB-AG		660 W	38.3 V	17.24 A	45.4 V	18.47 A	21.2%
Bifacial Gain**	5%	693 W	38.3 V	18.10 A	45.4 V	19.39 A	22.3%
	10%	726 W	38.3 V	18.96 A	45.4 V	20.32 A	23.4%
	20%	792 W	38.3 V	20.69 A	45.4 V	22.16 A	25.5%
CS7N-665MB-AG		665 W	38.5 V	17.28 A	45.6 V	18.51 A	21.4%
Bifacial Gain**	5%	698 W	38.5 V	18.14 A	45.6 V	19.44 A	22.5%
	10%	732 W	38.5 V	19.02 A	45.6 V	20.36 A	23.6%
	20%	798 W	38.5 V	20.74 A	45.6 V	22.21 A	25.7%

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

** Bifacial Gain: The additional gain from the back side compared to the power of the front side at the standard test condition. It depends on mounting (structure, height, tilt angle etc.) and albedo of the ground.

ELECTRICAL DATA

Operating Temperature	-40°C ~ +85°C
Max. System Voltage	1500 V (IEC/UL) or 1000 V (IEC/UL)
Module Fire Performance	TYPE 29 (UL 61730) or CLASS C (IEC61730)
Max. Series Fuse Rating	35 A
Application Classification	Class A
Power Tolerance	0 ~ + 10 W
Power Bifaciality*	70 %

* Power Bifaciality = $Pmax_{rear}$ / $Pmax_{front}$, both $Pmax_{rear}$ and $Pmax_{front}$ are tested under STC, Bifaciality Tolerance: ± 5 %

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Please be kindly advised that PV modules should be handled and installed by qualified people who have professional skills and please carefully read the safety and installation instructions before using our PV modules.

ELECTRICAL DATA | NMOT*

	Nominal Max. Power (Pmax)	Opt. Operating Voltage (Vmp)	Opt. Operating Current (Imp)	Open Circuit Voltage (Voc)	Short Circuit Current (Isc)
CS7N-640MB-AG	480 W	35.2 V	13.64 A	42.2 V	14.77 A
CS7N-645MB-AG	484 W	35.3 V	13.72 A	42.3 V	14.80 A
CS7N-650MB-AG	487 W	35.5 V	13.74 A	42.5 V	14.83 A
CS7N-655MB-AG	491 W	35.7 V	13.76 A	42.7 V	14.86 A
CS7N-660MB-AG	495 W	35.9 V	13.79 A	42.9 V	14.89 A
CS7N-665MB-AG	499 W	36.1 V	13.83 A	43.1 V	14.93 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

MECHANICAL DATA

Specification	Data
Cell Type	Mono-crystalline
Cell Arrangement	132 [2 x (11 x 6)]
Dimensions	2384 × 1303 × 35 mm (93.9 × 51.3 × 1.38 in)
Weight	37.9 kg (83.6 lbs)
Front Glass	2.0 mm heat strengthened glass with anti-reflective coating
Back Glass	2.0 mm heat strengthened glass
Frame	Anodized aluminium alloy
J-Box	IP68, 3 bypass diodes
Cable	4.0 mm² (IEC), 10 AWG (UL)
Cable Length (Including Connector)	460 mm (18.1 in) (+) / 340 mm (13.4 in) (-) or customized length*
Connector	T4 series or MC4-EVO2
Per Pallet	31 pieces
Per Container (40' HQ)	527 pieces or 465 pieces (only for US)

* For detailed information, please contact your local Canadian Solar sales and technical representatives.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.34 % / °C
Temperature Coefficient (Voc)	-0.26 % / °C
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	41 ± 3°C

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199 Lushan Road, SND, Suzhou, Jiangsu, China, 215129, www.csisolar.com, support@csisolar.com

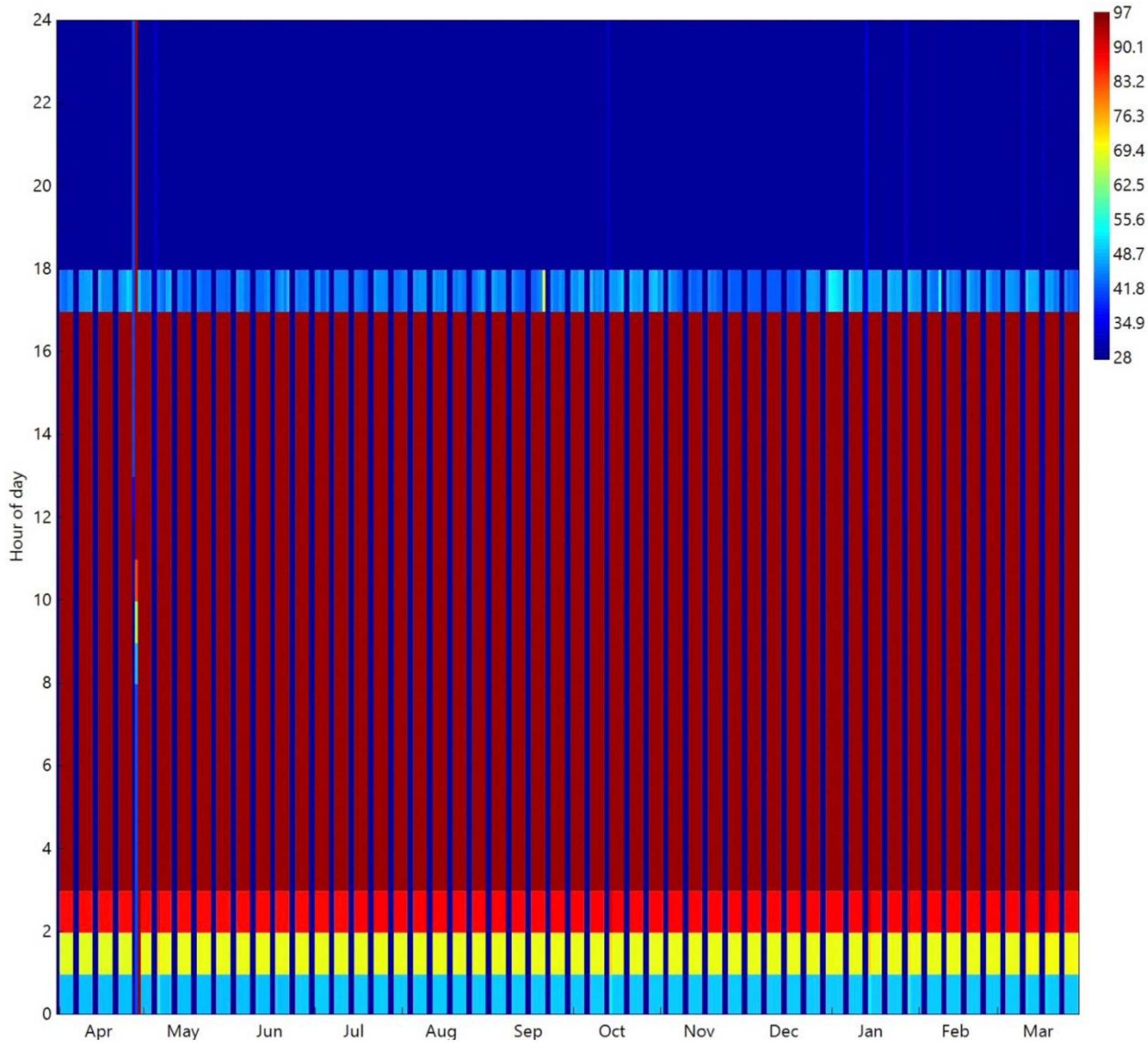
Appendix A. 4 Canadian Solar selected bifacial PV panel for the project technical specification (4)

Appendix B: Life Cycle Assessment materials

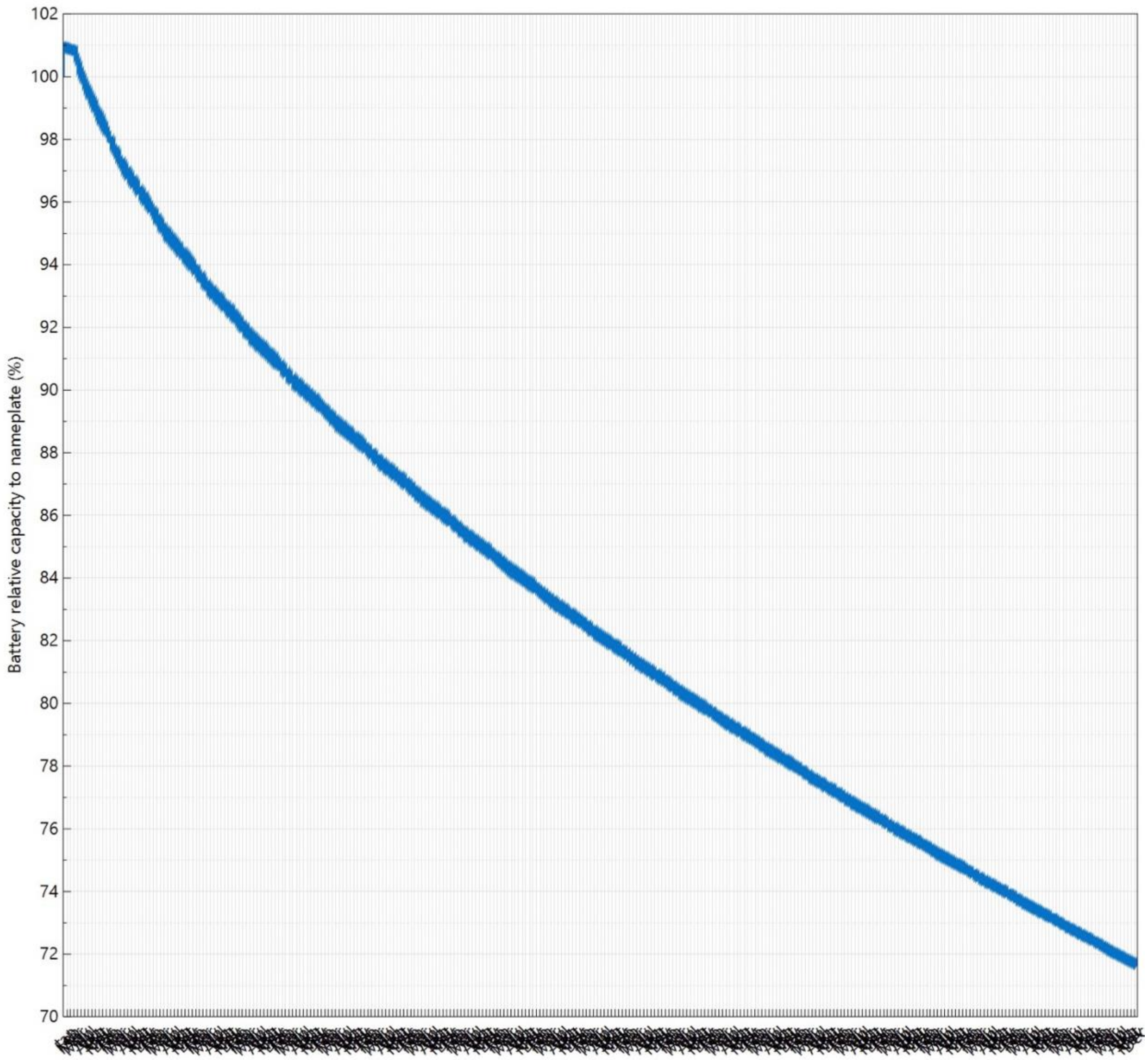
Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Density	Product Category Rules (PCR)	Notes about PCR	Performance ranking
Aluminium sheet, generic	20% recycled content, average European technology		One Click LCA 2022	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2022	LOCAL	ecoinvent	2700.0	EN15804+A1	-	CO2 TRACI: 68 / 122 See full ranking:
Concrete, ready mix	2501 - 3000 psi (C18/20)	3000-00-FA/SL	NRMCA	NRMCA	NRMCAEPD:10294	EPD NRMCA MEMBER INDUSTRY-AVERAGE EPD FOR READY MIXED CONCRETE	ISO14040	Third-party verified (as per ISO 14025)	2019	USA, canada	ecoinvent	2400.0	NSF PCR for Concrete Version 1 (February 22, 2019)	Only with EN15804	CO2 TRACI: 803 / 1602 See full ranking:
Copper data networking cable	0.04 kg/m	Panduit TX6™ Category 6, U/UTP, Panduit TX6000™ Category 6, U/UTP, Panduit TX6500™ Category 6, U/UTP	Panduit Corporation	UL Environment	4790076521.103.1	EPD Panduit Category 6 Riser (CMR) Data Networking Cable	EN15804+A1	Third-party verified (as per ISO 14025)	2021	northAmerica	ecoinvent		PCR 027 Part B: Electrical Cables and Wires, v1.0, October 2020.	Only with EN15804	CO2 TRACI: 9 / 18 See full ranking:
Corrugated galvanized steel conduits	7830 kg/m3		Corrugated Steel Pipe Institute	SCS Global	SCS-EPD-05002	EPD Corrugated Steel Pipe Institute	ISO14040	Third-party verified (as per ISO 14025)	2018	canada	GaBi	7830.0	PCR for Designated Steel Construction Products	Only with EN15804(TRACI 2.1 units only)	CO2 TRACI: 1 / 28 See full ranking:
Flat glass, clear and colored	8 mm, 20 kg/m2, 2500 kg/m3	PLANILUX, PARSOL	Saint Gobain Mexico	International EPD System	S-P-01743	EPD FLAT GLASS SAINT-GOBAIN GLASS MEXICO From 3 mm to 10 mm Patterned glass	EN15804+A1	Third-party verified (as per ISO 14025)	2020	mexico	GaBi	2500.0	PCR 2012:01 Construction products and construction services, version 2.32 2020-07-01	Only with EN15804	CO2 TRACI: 12 / 24 See full ranking:
High density polyethylene (HDPE) plastic pipe	0% recycled content (CML)			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	ecoinvent		EN15804+A1	-	CO2 TRACI: 45 / 81 See full ranking:
IGU silicone sealant				Quartz	CP051	Quartz 2015	ISO14040	Third-party verified (as per ISO 14025)	2015	USA	GaBi	1178.9615999999999	LCIA: TRACI 2.1, GWP IPCC 2013	LCIA: TRACI 2.1, GWP IPCC 2013	

Appendix B. 1 Materials used for the Life Cycle Assessment at One Click-LCA

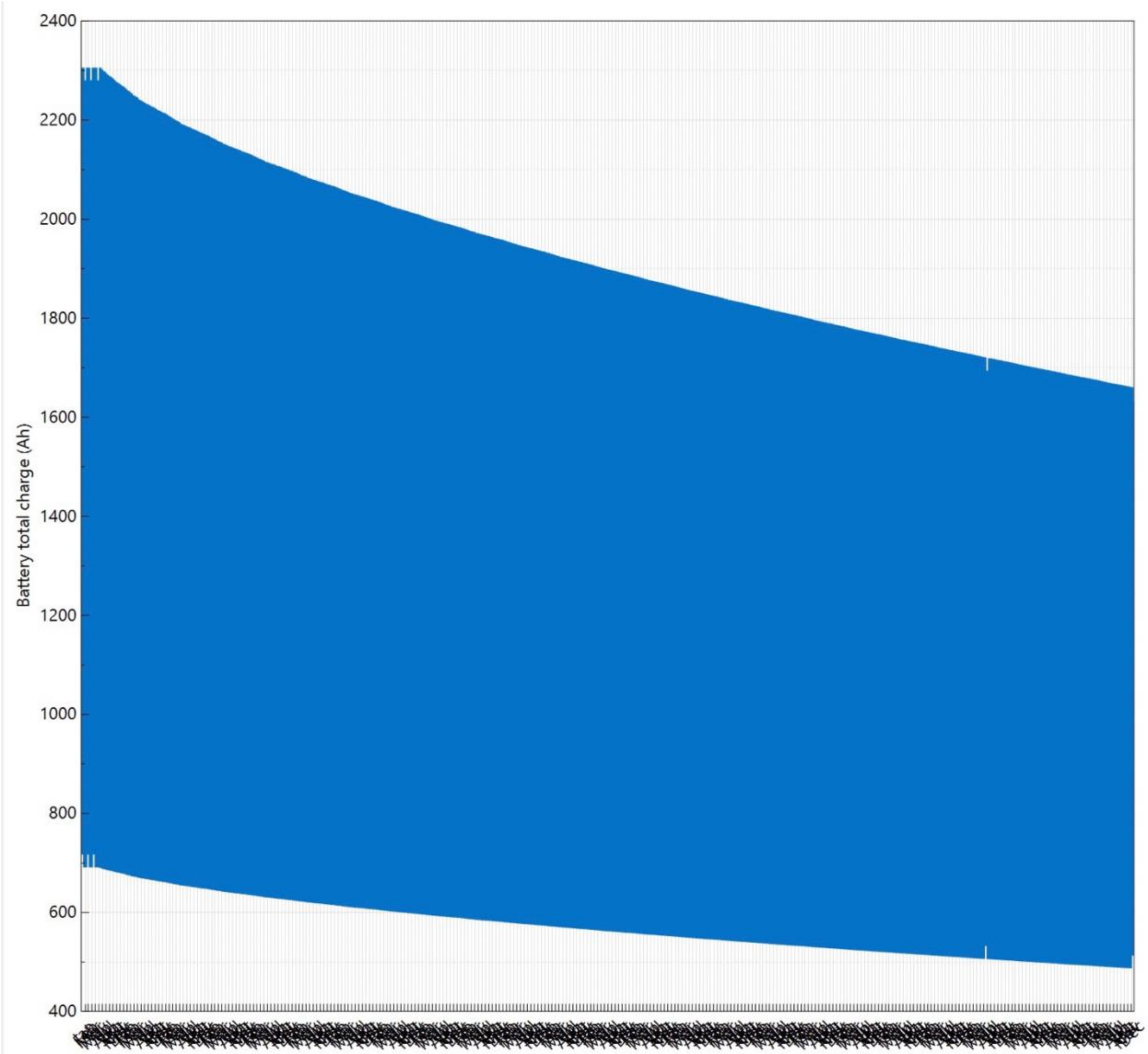
Appendix C: Battery characteristics



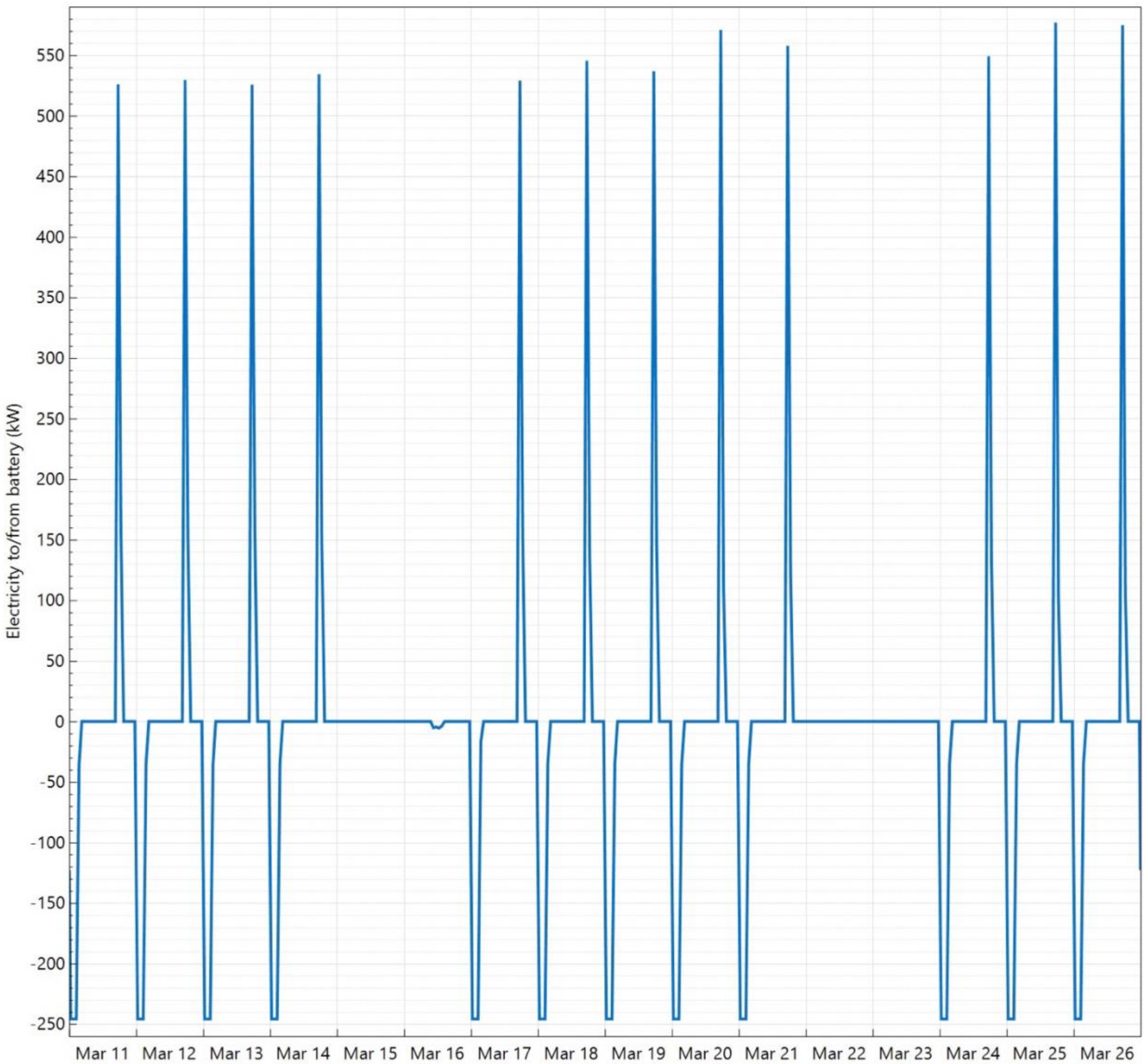
Appendix C. 1 Heat map for the battery state of charge (%)



Appendix C. 2 Battery Relative Capacity to nameplate (%) over 25 years



Appendix C. 3 Battery total charge (Ah)



Appendix C. 4 Electricity to/from battery (kW)