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Design and Deployment of a Hybrid Solar-Battery System for Efficient Energy Management

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Abstract

The global demand for energy and the price of electricity are on the rise, while conventional energy sources are being depleted at an accelerated pace, thereby raising significant environmental concerns such as global warming and fluctuations in temperature. Moreover, the innovative practice of providing electric vehicles' retired batteries as a storage solution, commonly referred to as second-life batteries storage system. The primary aim of this study is to undertake a techno-economic-environmental feasibility assessment of a grid-connected campus building that incorporates a solar photovoltaic (PV) system and second-life battery storage within a campus microgrid, utilizing HOMER Pro software. In particular, we will employ this software to analyze the net present cost, cost of energy, operational cost and greenhouse gases emission associated with the system. This research aspires to provide valuable insights and guidance to decision-makers who are exploring alternatives for energy production and infrastructure that are technically, economically, and environmentally sustainable, thereby supporting sustainable operations in both residential and commercial buildings.

Keywords
Second life batteries; sustainable development goals; renewable energy; solar PV.

1. Introduction

The world is seeing a shift towards more sustainable development practices, but with only 23 years left to achieve global net-zero emissions as laid out by the objectives in the Paris climate agreement, there is a need for acceleration for these endeavours. Whitmee et al. (2023) report that by 2030, the emissions from buildings globally must be at least halved if we wish to mitigate global warming, and they must reach net-zero by 2050 at the latest. That being said, according to the United Nations Environment Program (UNEP), the building sector's peak emissions was estimated to be 12 Gt of CO2-eq. from 1990 to 2019, which is about 38% of the total global CO2 emissions, even though the sector's final energy demand was only 35% of the global energy demand (UNEP, 2020). In fact, an analysis done by Kaya and Scolaro (2023) says that the sector's energy consumption accounts for 40% of global energy consumption, and its emissions account for 37% of the global GHG emissions. As such, mitigating climate change must involve reducing emissions from this sector, hence why do we see a rise in the topic of net-zero energy buildings across international markets.

Renewable Energy Sources (RES) possess intrinsic limitations when utilized independently because of their intermittent nature. The delivery of a consistent power supply becomes unfeasible, as solar photovoltaic (PV) energy is not accessible at night and during cloudy weather, while wind energy experiences variations throughout the day. Nevertheless, by integrating various RES with Energy Storage Systems (ESS), it is feasible to improve efficiency and guarantee a more dependable energy supply (Akram and Abdul-Kader, 2025). Due to the environmental and economic advantages, there is a global transition towards the adoption of electric vehicles (EVs), with lithium-ion batteries (LIBs) serving as the catalyst for this change. However, because of their degradative characteristics, LIBs lose their storage capacity over time. According to Akram and Abdul-Kader (2021), LIBs have an operational lifespan of approximately 12 years in EVs. Upon reaching their end-of-life, these batteries typically retain 70–80% of their original capacity. Although these batteries may no longer be suitable for deployment in EVs, there exists a variety of alternative applications where they can be applied, like residential buildings, commercial buildings, solar, wind, microgrid, fast EV charging stations and many more that can effectively utilize this residual capacity (Akram and Abdul-Kader, 2024).

Hybrid systems present a cost-effective alternative to current energy sources, with the potential to decrease energy bills by 10% to 60%, contingent upon specific circumstances. Such systems combine RES such as solar, wind, and hydrogen with conventional sources like fossil fuels, resulting in a sustainable and more efficient energy solution. Currently, heating accounts for 80% of energy consumption in Canadian households, and the integration of hydrogen with natural gas provides a viable option for emission reduction (Gabbar and Ramadan, 2025). This combination improves energy efficiency, diminishes reliance on conventional sources, lowers emissions, and reduces operating costs for property owners. As more individuals acknowledge these benefits, the adoption of hybrid systems in both commercial and residential buildings is on the rise, aimed at decreasing energy costs and promoting sustainability.

The motivation behind this research is to develop knowledge regarding the usage of second-life batteries (SLBs) from EV in Joyce Entrepreneurship Center at University of Windsor by utalizing HOMER Pro software. In particular, we leverage this software to analyze the net present cost (NPC), cost of energy (COE), operational cost and GHG emissions. Additionaly by considering the reduction of energy expenses and GHG emissions through SLB use in ESS and progressing the attainment of sustainable development goals (SDGs).

The subsequent sections are structured as follows: Section 2 presents the literature review, while Section 3 outline the system architecture, Section 4 presents the mathematical model and information about meteorological and load data, and Section 5 is comprised of results and discussion case studies and analysis. The conclusion of the findings is presented in Section 6.

2. Literature Review

At present, the generation of electricity through photovoltaic (PV) technology is emerging as a significant option for renewable energy (RE) (Fu, X. 2022). Given the inherent unpredictability of RES, the integration of energy storage systems (ESS) with RES provides a pragmatic strategy to enhance system reliability (Wang et al., 2021). Xu et al (2022) note that, at present, electrochemical energy storage systems, such as LIBs and lead-acid batteries, are prevalent in the market.

Gabbar and Ramadan, (2025) presents a thorough strategy that combines RE and green hydrogen to facilitate small-scale applications in Canada. Their research investigates various scenarios within a building as a case study, concentrating on the economic implications and GHG emissions. Their optimal scenario employs a hybrid RE system which allocates 53% for lighting and 10% for equipment, which satisfies two electrical requirements, leading to yearly savings of 87,026.33 CAD. Their second scenario considers the use of a hydrogen-LPG mixture as fuel for thermal loads, addressing 40% and 60% of the overall demand, respectively. This method decreases GHG emissions from 540 tons of CO_2/year to 324, resulting in yearly savings of 251,406 CAD. Soleimani et al., (2025) conducted a study at Abu Musa Island in Iran on HRES configurations utilizing HOMER Pro to evaluate cost optimization, energy distribution, and the integration of RE. In Scenario 1, which depended entirely on power from a grid, electricity was provided without much instability, and without scarcity in supply to meet load demands; however, this scenario resulted in CO_2 emissions ranging from 2593 kg to 2599 kg per year, with a renewable fraction (RF) of less than 0.3%. In Scenario 2, the introduction of photovoltaic (PV) systems and batteries led to a reduction in GHG emissions to 2441 kg per year and an increase in RF to 6.1%, although operational and replacement costs caused the net-present cost to rise. Scenario 3, featuring off-grid configurations, harnessed 100% RE, brought CO_2 emissions to near zero, and greatly enhanced energy efficiency.

Medghalchi and Taylan (2023) developed a Hybrid Energy System for a Mediterranean island campus in Türkiye, which incorporates wind turbines, solar PV systems, and BESS. The configuration comprising the wind and PV systems along with BESS was determined to be the most efficient, resulting in an optimal energy cost of €0.1838 per kilowatt-hour. Their system effectively satisfied 44% of the energy demand while achieving RF of 60%. Zhang et al. (2023) conducted an optimization study on off-grid PV-BESS and DG-PV-BESS specifically designed for smart buildings in China. Their findings revealed that the PV-BESS configuration, with a total yearly expenditure of \$780,000, successfully achieved zero emissions. However, while the incorporation of a diesel generator within their system led to a reduction in costs to \$46,478, it was accompanied by a yearly increase of 50,000 kg in CO2 emissions. Allouhi and Rehman (2023) proposed a hybrid energy source connected to the grid, which includes PV systems, wind energy, and BESS to provide energy for supermarkets located in Casablanca, Morocco. Their system was designed to utilize 71% RE, resulting in a \$0.0841/kWh cost of energy, and an annual operating cost of \$124,000.

Heris and Asadi (2023) presented a reliability-based Energy Management System (EMS) for residential buildings, which incorporates a distributed energy system. The model developed demand response (DR) with various participation rates, optimization flows, photovoltaic (PV) power utilization, and grid interaction with the intention of minimizing the levelized cost of energy (LCOE). Their numerical analysis indicated that participation in DR of 30% led to a 33% reduction in LCOE during off-peak hours and a 76% reduction during peak hours. Khezri et al. (2020) conducted an optimization of two system configurations, one that used PV only and one that used PV and a BESS, for grid-connected households in Australia. The study concluded that a system leveraging 9 kW of PV has the potential to decrease energy costs by approximately 41% for an average household connected to the grid, with an annual electricity demand of 5.7 MWh.

2.1 Primary Contributions

- This study presents a comprehensive analysis of a grid connected Campus building leveraging optimal energy generation, storage, cost and GHG emission.
- The model we present integrates an approach that harnesses solar PV, campus power plant, an energy storage system based on second-life batteries and Ontario grid.
- The research includes a cost-benefit analysis and an assessment of environmental impacts, thereby guaranteeing economic viability and conformity with the SDG.
- The data inputted comes from university of windsor, winter electricity load and their NPC, COE and operational costs are calculated, thus providing a basis for policy makers when considering their own geographical nature.

3. System Architecture

The suggested site for this research work is Joyce Entrepreneurship Center at the University of Windsor. Specifically, the model incorporates a blend of solar photovoltaic (PV) technology, SLB-based energy storage system, the campus power plant, and the Ontario grid, as shown in Figure 1.

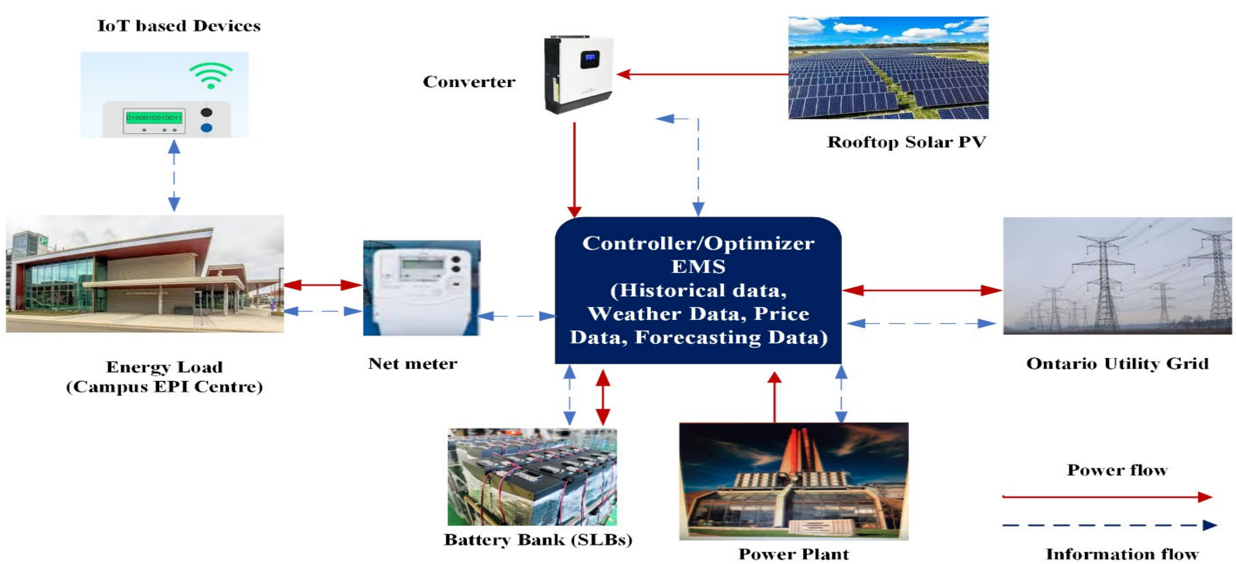


Figure 1. Propose System Architecture

Any solar energy is harnessed as DC electricity, which must be converted to AC electricity to ensure compatibility with the overall system. The surplus energy gathered by our RES can be stored in a battery bank for utilization during periods of low generation or peak demand, thereby simulating a continuous energy supply. To manage the flow and distribution of energy, EMS makes decisions based on real-time demand and generation, as well as the charge and discharge cycles of the batteries to achieve optimal efficiency and cost-effectiveness. Various devices are configured to transmit real-time monitoring data to the EMS; these metrics encompass energy generation and consumption, storage levels, and load of the building. The red arrows represent the flow of electricity, while the blue arrows indicate the flow of information, meaning data being transmitted to and from the EMS. This system ensures the energy supply to the building connected to the Ontario grid, while incorporating greener energy, optimizing energy distribution, and enabling real-time monitoring to improve the environmental footprint, decrease costs, and enhance system reliability, respectively.

4. Mathematical Modeling

This research presents a techno-economic-environmental analysis of a campus building connected to a microgrid grid that is powered by RES, Ontario grid and Campus power plant. Specific inputs have been provided for the selected location which includes site-specific data such as meteorological information, global horizontal irradiance (GHI), wind speed, and temperature variations. Additionally, the input data encompasses load demand and component specifications, which include efficiency and lifespan, as well as economic data for the components covering capital, replacement, operations, and maintenance costs. Technical data, such as power ratings and equipment dimensions, along with inflation rates and discount/interest rates, among other factors, are presented in the following subsections.

4.1 Homer Pro Simulation Tool

For the analysis Homer pro software version 3.18.3 is used for simulation. HOMER Pro software is capable of optimizing microgrid designs across several sectors, including rural areas, island locations, military sites, and grid-connected buildings. It was developed by the National Renewable Energy Laboratory and subsequently enhanced and distributed by HOMER Energy.

4.2 Renewable Fraction (RF)

The RF is defined as the proportion of total energy consumption met by RE resources relative to the total loads, as articulated in equation (1). (Oladigbolu et al., 2023).

$$\mathrm{RF} = \frac{\mathrm{P_{solar\ pv}} + \mathrm{P_{wind}}}{\mathrm{P_{Load}}} \tag{1}$$

4.3 Net Present Cost (NPC)

The NPC is defined as the distinction between the current value of all capital expenditures and the aggregate lifetime costs related to the energy supply system of the selected building. This is represented in equation (2) below (Kumar et al., 2024).

$$\mathrm{NPC} = \frac{\text{Total annual cost}}{\mathrm{CRF(i,R_{project})}} \tag{2}$$

Where:

CRF = Capital recovery factor
i = Discount rate/interest rate
$\mathrm{R_{project}}$ = Lifetime of the project

4.4 Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE), also known as the Cost of Energy (COE), is defined as the ratio of the total annual expenses incurred by the system to the total annual energy supplied to the load, which is commonly referred to as the unit cost of electricity as shown in equation (3) (Güven et al., 2025)

$$\mathrm{LCOE} = \frac{\text{Total Annual Cost}}{\text{Total Annual Energy Served}} \tag{3}$$

4.5 Interest Rate/Discount Rate

The Bank of Canada decided to keep its benchmark interest rate at 2.75% on June 04, 2025. For the purposes of this research, we are using an interest rate of 6% (Mortgage Capital Investment 2025).

4.6 Inflation Rate

In Canada, the annual inflation rate fell to 1.7% in April 2025, a decrease from 2.3% in the previous month (Bank of Canada, 2025). For the purposes of this research, we are considering an inflation rate of 2%.

4.7 Economic Data

In a hybrid RE system, the equipment is associated with various cost data, including operational and maintenance expenses, capital costs, and replacement costs. Additional factors to consider include the cost of fuel utilized, the cost of energy purchased from the grid, interest rates, fixed capital, maintenance and operational costs, emissions factors, the project's lifespan, and other relevant data that can be incorporated into the HOMER software. By taking these costs into account during simulation and optimization processes, the NPC of a project can be accurately calculated. Table 1 presents the cost of each component used in this study.

Table 1. Cost of Each Component

Components	Unit (kw)	Capital Cost ($)	Replacement Cost ($)	O&M Cost $/KW/year	Source
Longi Solar LR6-72	1	640	640	10	Oladigbolu et al., 2023
Lithium-ion Battery	1	550	550	10	AL Wahedi and Bicer, 2022
Converter	1	300	300	0	Praveen kumar et al.,2022

4.8 Technical Data

The technical specifications for solar photovoltaic (PV) systems, energy storage system and converter are presented in Table 2 below.

Table 2. Technical Specification of Components

Component	Model	capacity	Efficiency (%)	Lifetime Year	Source
Solar PV	Longi solar LR6-72	400KW	18.10	25	Oladigbolu et al., 2023
Lithium- Ion Battery	Power Wall	1000 KW		10	AL Wahedi and Bicer, 2022
Converter	Generic		95	15	Praveenkumar et al.,2022

4.9 Meteorological Data

Meteorological data for the selected location has been analyzed, including Global Horizontal Irradiance (GHI), wind speed and temperature. The selected location has coordinates 42°18.3 N, 83°3.8 W. Figure 2 present the street location of Joyce Entrepreneurship Center University of Windsor.

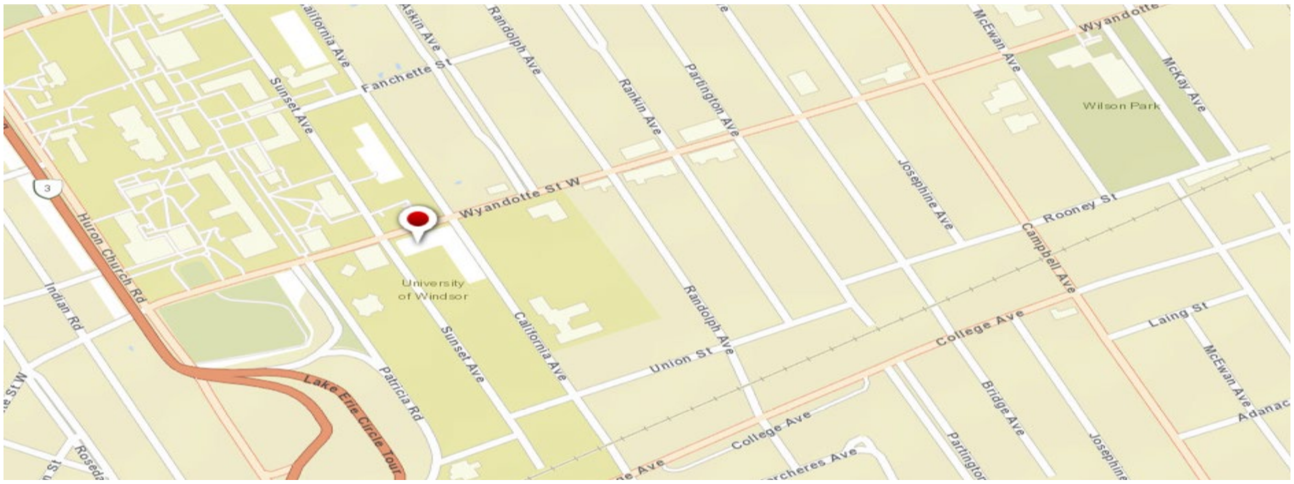


Figure 2. Location Joyce Entrepreneurship Center University of Windsor (Source: NASA, 2025)

4.9.1 Global Horizontal Irradiance (GHI)

Utilizing information from the National Renewable Energy Laboratory (NREL) Database, The annual average solar GHI for the respective location is 3.67 kWh/m²/day. The data collection spans a duration of 22 years, starting in July 1983, and ending in June 2005. (NASA 2025).

4.9.2 Wind Speed Data

From NASA surface metrology, data on wind speed was collected for 30 years, from January 1984 to December 2013, at a height of 50 meters above Earth's surface. The average wind speed across the years for the selected location is 6.89 m/s (NASA, 2025).

4.9.3 Temperature Data

From the NASA Prediction of Worldwide Energy Resource, data on average air temperature was collected for 30 years, from January 1984 to December 2013. The annual average air temperature for the selected location is 8.96°C (NASA, 2025).

4.10 Load Data

In the realm of simulation and optimization, load constitutes the most critical factor. Actual load consumption data from various locations, such as universities, hospitals, industries, and hotels, provide reliable information suitable for simulation, which is subsequently input into Homer as time series data. However, in rural and remote areas where actual load consumption data is unavailable, forecasted data is utilized and entered into Homer as daily load data, which is then employed in the power balance constraint. For this research work, Joyce Entrepreneurship Center, at University of Windsor is taken for the analysis, which covers 9,000 ft^2 of dedicated space. The load data is taken from the facility planning, renovation & construction department, University of Windsor. The load pattern for one day (24 hours) winter is considered and shown in Figure 3.

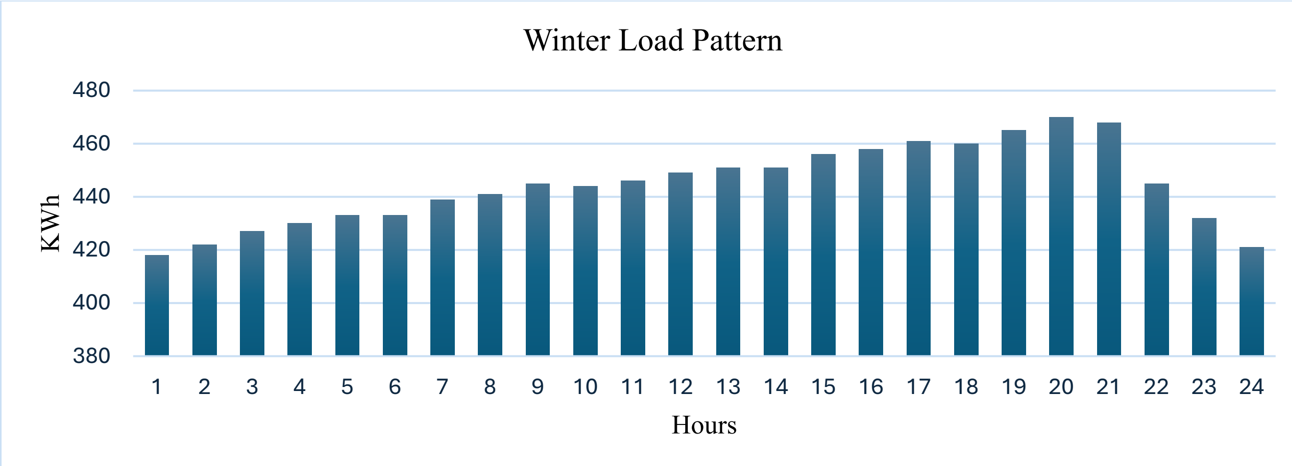


Figure 3. Winter Energy Demand of Joyce Entrepreneurship Center
Source: (Facility Planning, Renovation & Construction Department, University of Windsor)

5. Results and Discussion

This section discusses the results and scenarios considering the proposed location. For the analysis Homer pro platform version 3.18.3 is used for simulation. In the analysis a grid connected system is initially investigated, comprised of solar PV, ESS, power plant and converter as shown in Figure 2. For the analysis, we take a discount rate/interest rate of 6%, an inflation rate of 2%, and duration of the project as 25 years. The optimization strategy of cycle charging (charging a battery from 0% to 100%) is used to examine the proposed system.

5.1 Scenario 1: Grid, PV, ESS, and Power Plant

In this scenario the NPC, COE, operational cost (OPEX), and capital expenditures (CAPEX) are $1.9 million, $0.0868/KWh, $81,023/year and $624,533, respectively. The renewable fraction (RF) is observed to be 56.3%.

5.2 Scenario 2: Grid, PV, and ESS

In this scenario the NPC, COE, OPEX and CAPEX are $1.95 million, $0.0923/kWh, $83,782/year and $630,938, respectively. The RF is noted to be 59%.

5.3 Scenario 3: Grid, PV, and Power Plant

In this scenario the NPC, COE, OPEX and CAPEX are $1.64 million, $0.0754/kWh, $68,447/year and $557,584, respectively. The RF is examined to be 55.7%.

5.4 Scenario 4: Grid and PV

In this scenario the NPC, COE, operational cost (OPEX), and capital expenditures (CAPEX) are $1.69 million, $0.079/kWh, $70,500/year and $575,072, respectively. The RF is noted to be 59%.

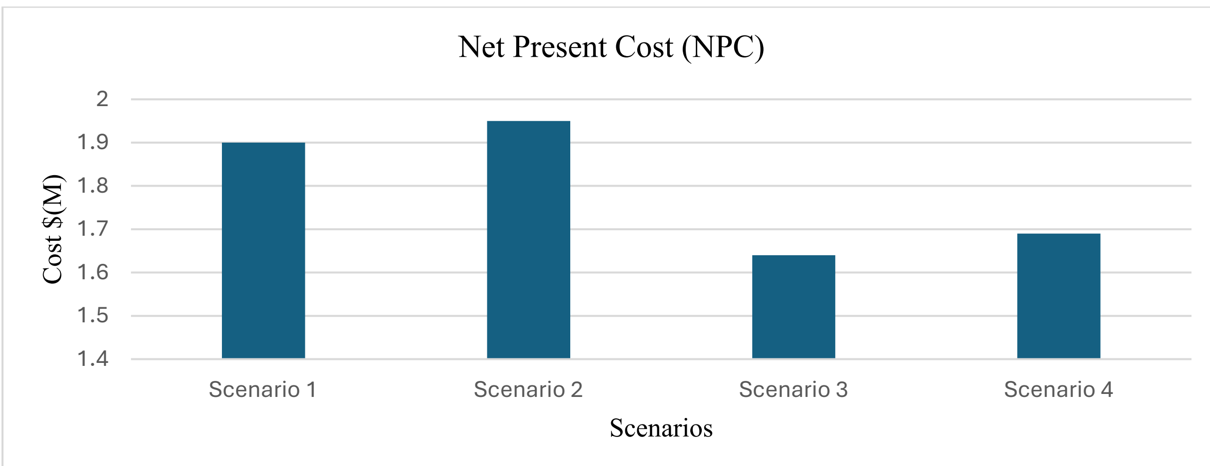
5.5 Scenario 5: Grid only

In this scenario when energy is bought from the Ontario grid the cost of energy is $0.15/ kWh. Table 3 shows the results for all the scenarios.

Table 3. Results for all Scenarios

Scenarios	Configuration	NPC ($M)	COE ($/kWh)	OPEX ($)		CAPEX ($)	Renewable Fraction (%)
Scenario 1	Grid, PV, ESS, and Power Plant	1.9	0.0868	81,023		624533	56.3
Scenario 2	Grid, PV and ESS	1.95	0.0923	83,782		630938	59
Scenario 3	Grid, PV and Power Plant	1.64	0.0754	68,447		557584	55.7
Scenario 4	Grid and PV	1.69	0.079	70,500		575,07	59
Scenario 5	Grid only		0.15				

Figures 4, 5, 6 and 7 present the NPC, COE, operational cost, and capital expenditure for the four scenarios, respectively.



Figures 4. Net Present Cost

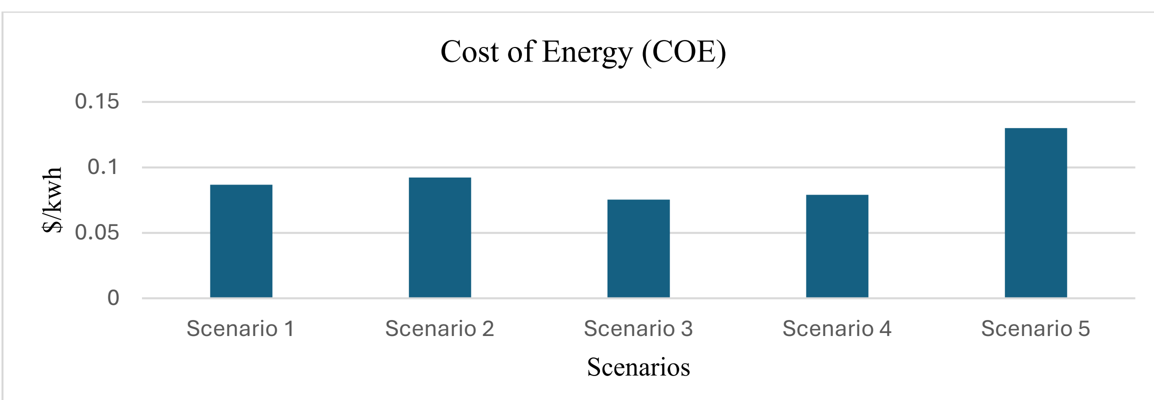


Figure 5. Cost of Energy

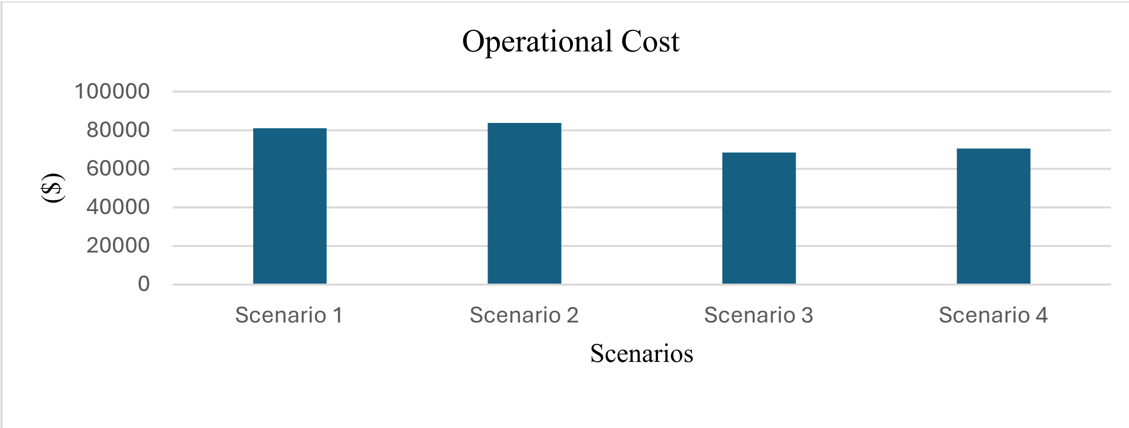


Figure 6. Operational Cost

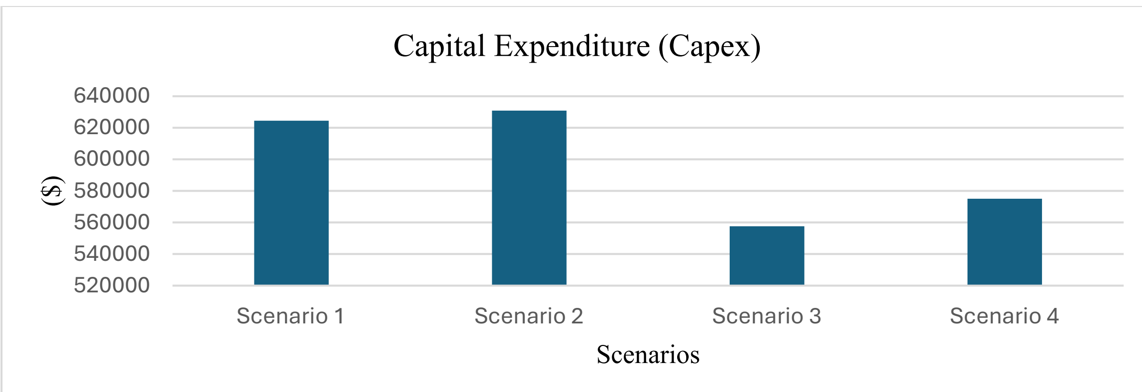


Figure 7. Capital Expenditure

The solar photovoltaic (PV) system generates a total energy of 869,738 KWh annually, and the output power of the solar PV is illustrated in Figure 8.

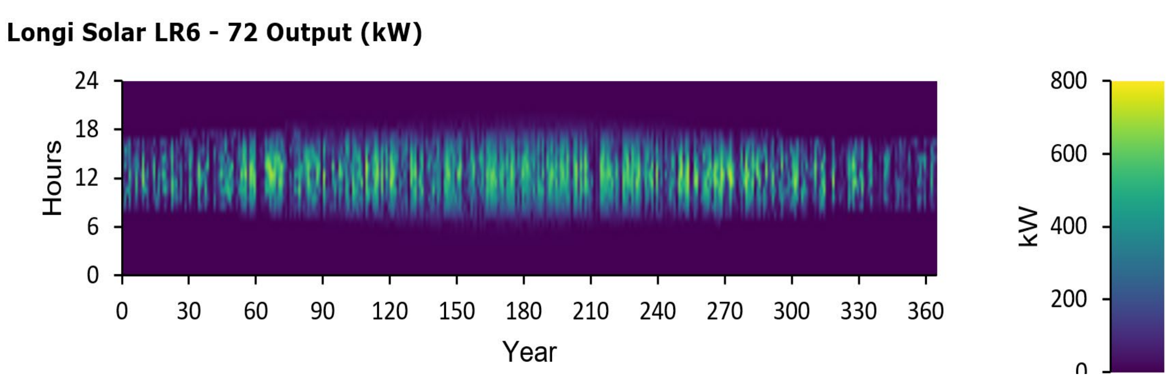


Figure 8. Solar PV output Power

Figures 9 and 10 below present the procurement of energy from the grid and energy sold to the grid.

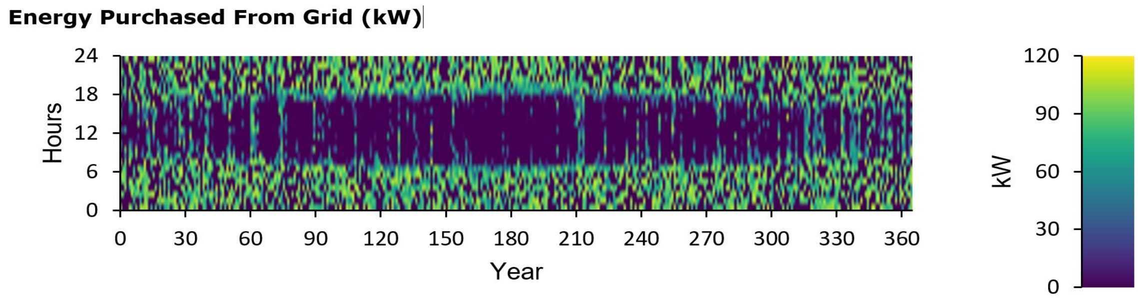


Figure 9. Energy Purchased From the Grid

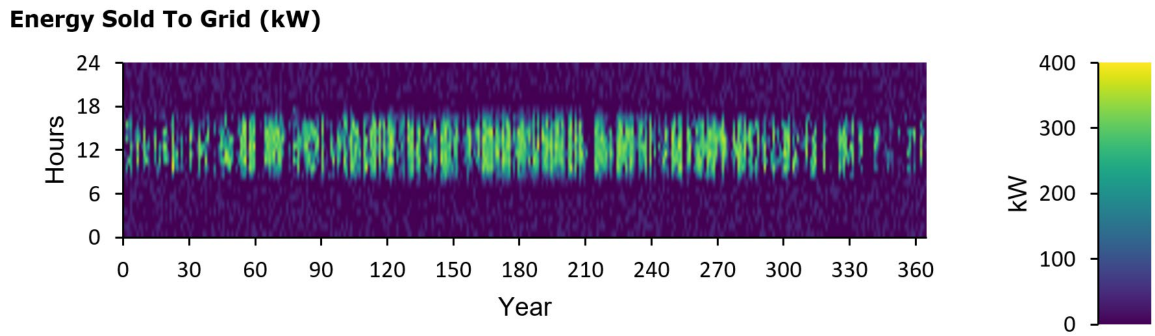


Figure 10. Energy Sold to the Grid

5.6 GHG Emission

GHGs emissions are based on the electricity taken from utility grid. As per the Canada Energy Regulator (2024), the carbon emission rate for energy generated by the Ontario utility grid is 0.035 kg CO2/kW. The per day winter load for the EPI center is 10665KWh. The GHG emission if we buy energy only from the Ontario grid is 136 tons. The GHG emission for scenarios 1, 2, 3 and 4 is 42 tons, 58.88 tons, 51.56 tons and 59.14 tons, respectively. Figure 11 presents the GHG emission in different scenarios.

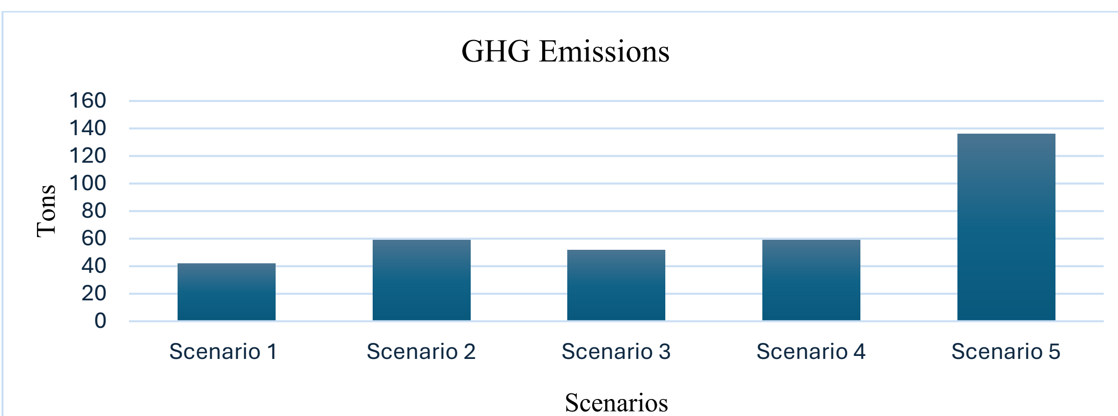


Figure 11. GHG Emission

5.7 Contributions to Sustainable Development Goals (SDGs)
Our analysis above shows that by integrating RE into a grid-connected system in a variety of configurations, we see a significant decrease in GHG emissions. In particular, scenario 5, which considers only grid power, emits 136 tons of GHGs per year, while scenarios 1 to 4 show under 60 tons. This investigation gives insights into what the impacts are of renewable energy and BESS integration and can help propel progress to Goal 13: Climate Action. Furthermore, we can see a decrease in energy costs, given that we leverage more RE and thus less grid-energy, which can assist in moving towards Goal 7: Affordable and Clean Energy.

5.8 Contributions to Policy Makers and Legislators
The energy sector consists of a wide range of stakeholders, including those in charge of writing rules and regulations. With the current state of the energy market being dominated by non-renewable energy, legislators are forced to adapt their rules in accordance with present trends and would only consider shifting their view if reasonable incentives are involved. The configurations we present show meaningful economic and environmental optimizations, which directly motivate policymakers to pass legislation that mandates or promotes the use of RE integration, thus incentivizing residential and commercial property owners to move towards more sustainable and economical options.

5.9 Comparative Analysis
A comparative analysis for present research and this research work is presented in Table 4.

Table 4. Comparative Analysis

Author	Year	Country	Configuration	COE($/KWh)	NPC($M)
Güven et al.	2025	Türkiye	Grid, PV, BG, Elz, HT, Inv	0.0215	0.6112
Das	2024	Bangladesh	Grid, PV, Battery, WT	0.11	0.4706
Rehman et al.	2023	Saudi Arabia	Grid, PV, Battery	0.064 - 0.403	10.33- 35.7
Al Abri et al.	2022	Oman	Grid, PV, WT, DG	0.257 - 0.566	14.9- 31.02
This Study		Canada	Grid, PV, Battery	0.075 - 0.15	1.64 – 1.9

6. Conclusion
With climate issues becoming more prevalent, we have seen the rise of distributed energy sources, as well as RE and BESS integrations for the sake of system reliability and sustainability. This work tackled five configurations of hybrid energy systems, leveraging energy combinations of grid, solar PV, BESS, and power plant. Through the use of Homer Pro version 3.18.3, we have analyzed these five scenarios to investigate NPC, operational costs, and COE. Scenario 1 (Grid, PV, BESS, and Power Plant) showed an NPC of $1.9 million, an OPEX of $81,023, and COE of $0.0868/kWh. Scenario 2 (Grid, PV, and BESS) showed an NPC of $1.95 million, an OPEX of $83,782, and COE of $0.0923/kWh. Scenario 3 (Grid, PV, and Power Plant) showed an NPC of $1.64 million, an OPEX of $68,447, and COE of $0.0754/kWh. Scenario 4 (Grid, and PV) showed an NPC of $1.69 million, an OPEX of $70,500, and COE of $0.0790/kWh. Scenario 5 (Grid only) has COE of $0.1300/kW.These scenarios present choices to both commercial and residential areas to adopt cleaner energy in accordance with what is feasible for them. Such a shift would decrease overall energy costs and reduce emissions, thus assist us in moving towards the SDGs.

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