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Optimizing PV-Battery Grid-Connected Power Systems with Peak Shaving Control: A Techno-Economic Feasibility Analysis for Metro Vancouver, BC

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SUMMARY

This study presents a detailed analysis of a grid-connected residential photovoltaic (PV) and battery energy storage system (BESS) in Metro Vancouver, British Columbia, utilizing BC Hydro's proposed time-of-use rates. Real-world measurements gathered over a single day in July are thoroughly evaluated to assess the system's performance. A peak shaving control strategy is proposed for the BESS to investigate whether BC Hydro's time-of-use tariffs improve the utilization of the batteries. The PV-BESS system is modeled in MATLAB/Simulink, and simulations are conducted to demonstrate the system's peak shaving capabilities. To evaluate the system's techno-economic feasibility, HOMER Grid is utilized, incorporating local weather data and residential energy consumption patterns to determine the system's levelized cost of energy (LCOE). This study provides valuable insights for policymakers, energy system designers, and building owners in Metro Vancouver and other similar cities, encouraging the adoption of sustainable and cost-effective energy solutions.

KEYWORDS

Battery Energy Storage Systems, Solar PV, Peak Shaving, Renewable Energy Optimization

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1. INTRODUCTION

The increasing demand for energy, coupled with the need to reduce greenhouse gas emissions and achieve energy independence, has led to the development of renewable energy sources such as photovoltaics (PV). The integration of PV systems with battery storage has become an attractive solution to improve the stability and reliability of renewable energy systems. Although the economic viability of solar PV projects tends to be more difficult for regions like British Columbia, where solar irradiance levels are lower compared to other regions in Canada [1], there are still over 5,000 customers who participate in BC Hydro's net metering program, the majority who utilize a rooftop PV grid-tied system [2].

An example of a typical PV-BESS system located in Metro Vancouver, BC, is examined for this study. In the existing system, the batteries are mainly used as backup power sources in case of grid outages and are kept at a high level of state of charge (SOC). To enhance the battery's utilization and decrease the levelized cost of electricity (LCOE), a peak shaving control strategy will be proposed, considering BC Hydro's proposed time-of-use rates.

The paper is structured as follows: Section 2 overviews a residential PV-BESS system and presents real-world measurements for a single day in July. Section 3 details BC Hydro's proposed time-of-use tariffs. Section 4 describes the components and simulation aspects of the Simulink model, including the proposed peak shaving strategy and simulation results. Section 5 presents the modelling and simulation results of the system using HOMER Grid. Finally, conclusions are provided in Section 6, highlighting the contributions of the study as well as recommendations for future research.

2. OVERVIEW OF A RESIDENTIAL SOLAR AND BATTERY STORAGE SYSTEM

The parameters for the residential PV-BESS system are shown in Table 1. The system consists of three strings of PV modules, with each string consisting of three PV modules connected in series. Each PV module has a power output of 155 W; the total rated power output of the solar PV system is approximately 1.4 kW. The system also incorporates 8, 6 V lead-acid batteries which are connected in series and have a capacity of 235 Ah. To examine the system, a set of field data has been gathered, which comprises actual measurements taken at a sample rate of 30 seconds for a 24-hour period on July 9, 2022. The collected measurements are aligned with the overall system layout as illustrated in Fig. 1.

The PV-BESS system's maximum power point tracking (MPPT) input DC voltage and power are shown in Fig. 2a and Fig. 2b. The DC-DC converter incorporates MPPT functionality to regulate the voltage (Vpv) and current output (Ipv) of the PV panel arrays. This ensures the panels operate at their maximum power point, maximizing power output. The DC-DC converter adjusts the DC voltage from the PV panels to meet the specific voltage requirements of the storage system. Fig. 3a illustrates that the DC-DC converter maintains an average output DC voltage (Vdc) of 52 V. By observing Fig. 3b, it is evident that most of the output MPPT DC power, the DC solar PV output power that has been optimized by an MPPT device, is generated between 8:00 am and 4:00 pm. This can be attributed to the fact that the solar irradiance levels are at their highest during this time, resulting in peak power generation from the PVs. During the evenings when there is no sunlight, the output power of the PV system drops to zero.

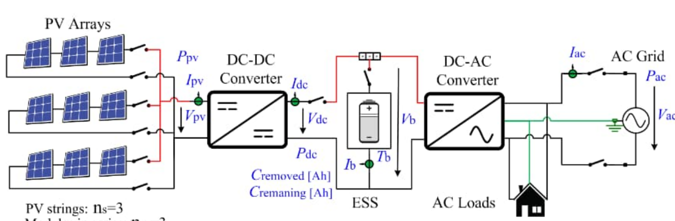
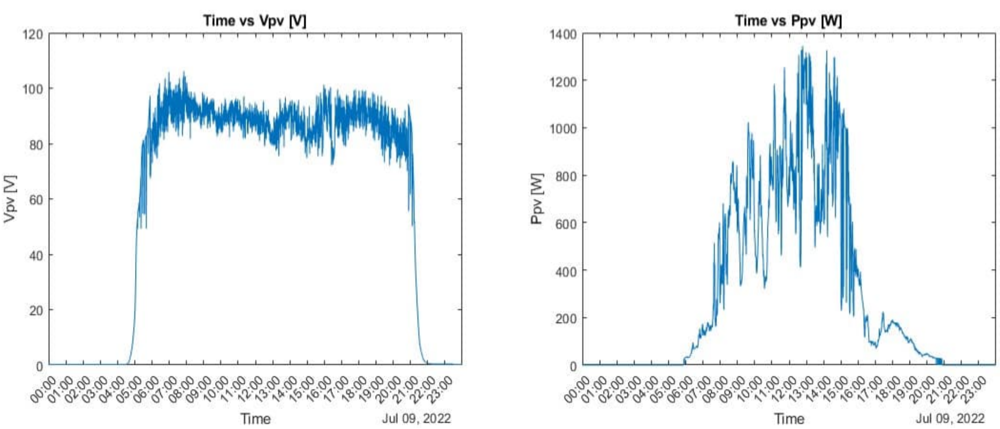


Fig. 1. Example of a typical PV-BESS system for residential applications.

Table 1: System Parameters

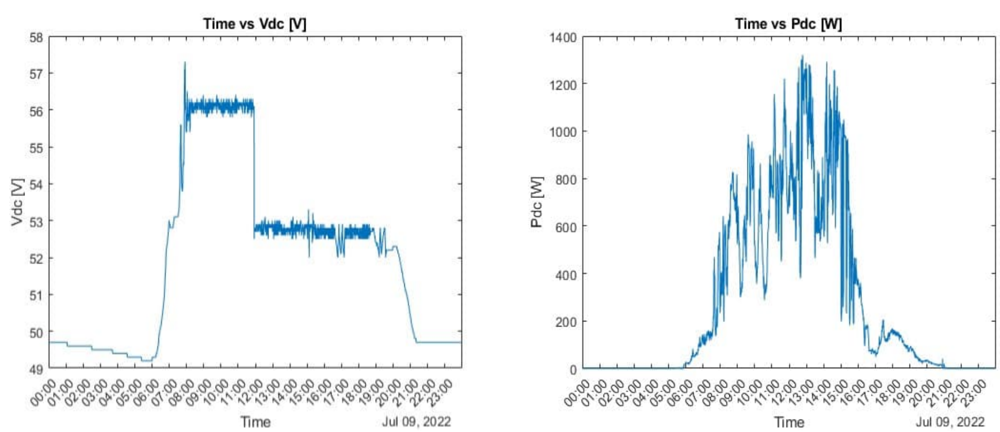
Parameter	Value
Number of strings	$n_s = 3$
Number of modules in series	$n_m = 3$
PV Module Power	$P_m = 155$ W
Total Installed PV power	$P_{pv} = 1395$ W
Battery capacity	$C_b = 235$ [Ah]
Battery voltage system	$V_b = 235$ [Ah]
PV module MPPT voltage	$V_{mp} = 34$ V
PV module MPPT current	$I_{mp} = 4.6$ A
PV module short circuit current	$I_{sc} = 4.8$ A
PV module open circuit voltage	$V_{oc} = 43$ V
PV module temperature coefficient	$\beta_v = -158$ mV/ °C
Module specification at STC (standard test conditions)	$1000\,\frac{W}{m^2}$, 25°C

By monitoring the Grid Output Power (Pac) and the battery system's State of Charge (SOC), we can determine how the system is being used. As depicted in Fig. 4a, Pac, the power being fed back to the grid, is closely aligned with the Output MPPT DC power. This indicates that during the day, most of the solar PV power generation is being fed back to the grid. Furthermore, Fig. 4b confirms that the battery system maintains a consistently high SOC over a 24-hour period, suggesting that it serves primarily as backup power.



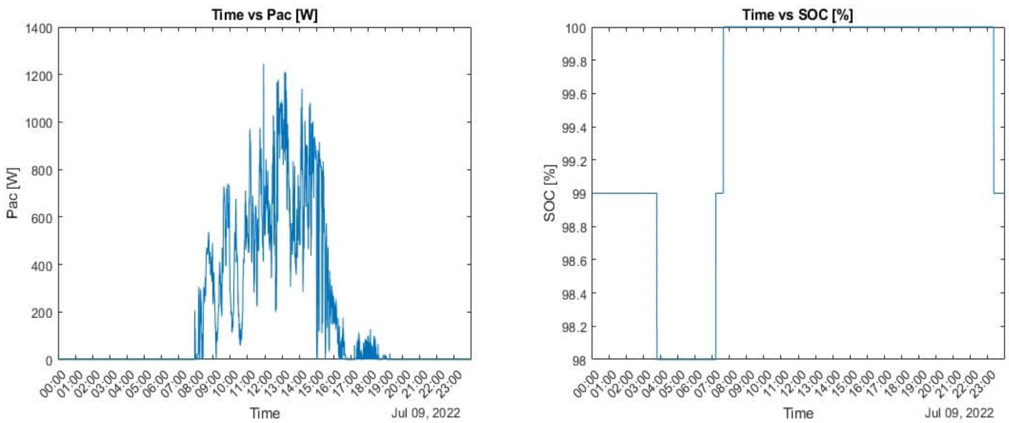
(a) (b)

Fig. 2. Experimental Results: MPPT Input DC Voltage (a) MPPT Input DC Power (b).



(a) (b)

Fig. 3. Experimental Results: MPPT Output DC Voltage (a) MPPT Output DC Power (b).



(a) (b)

Fig. 4. Experimental Results: Output Grid Power (a) and Battery State of Charge (b) over 24 hours.

3. BC HYDRO TIME-OF-USE RATE STRUCTURE

To encourage the adoption of clean electricity and to incentivize customers to shift their electricity usage to times when greater capacity is available in the existing electrical infrastructure, BC Hydro has recently proposed an optional Time-of-Use (TOU) rate structure for its residential customers. The proposed TOU rate is currently pending approval from the British Columbia Utilities Commission (BCUC).

Under the proposed Time-of-Use (TOU) rates, residential customers are billed based on a two-tier rate structure for total electricity usage. During off-peak periods, there is no credit or charge, while on-peak usage incurs a charge of 5 cents per kilowatt-hour (kWh). Conversely, customers receive a credit of 5 cents per kWh for overnight usage. By shifting electricity usage to off-peak periods, there is a potential for significant cost savings. Additionally, this incentivizes the adoption of battery storage systems. These systems allow for storing excess electricity generated during low-cost periods, which can then be utilized during high-cost periods.

The energy rates for BC Hydro's proposed TOU rates are summarized in Table 2. A basic charge of $0.2110 per day will also apply to the optional TOU rates. The $/kWh values are in 2025 fiscal dollars, as per the 2023 BC Optional Residential Rate Time-of-Use Exhibit B-1 application [3].

Table 2: BC Hydro Optional Time-of-Use Residential Energy rates in 2025 fiscal dollars [3].

Energy Charge	**On–Peak Period** **(4 pm - 9 pm)**	**Off–Peak Period** **(9 pm- 11 pm & 7 am - 4 pm)**	**Overnight Period** **(11 pm - 7 am)**
Step 1: Up to 1350 kWh	$0.1510 / kWh	$0.1010 / kWh	$0.0510 / kWh
Step 2: Over 1350 kWh	$0.1908 / kWh	$0.1408 / kWh	$0.0908 / kWh

4. PV-BESS SIMULINK MODEL AND PEAK SHAVING STRATEGY

To implement a simple peak shaving strategy for a PV-BESS system, the system is first modelled using Simulink. For this study, a three-phase power system was modelled including the primary grid, the solar PV system, a residential load, and a BESS. The Simulink model is shown in Fig. 5. The peak shaving strategy used to dispatch the BESS was implemented using various logical operators from the Simulink library. A phasor solution mode was implemented for the Simulink simulation, which calculates voltages and currents as phasors using simplified equations. This approach allows for faster simulations while still providing valuable insights into the system's overall behavior.

A. PV Generation
To optimize a typical PV-BESS system, real-world power output measurements from the 1.395 kW PV system were incorporated into the Simulink model using a lookup table. This data was then fed to the PV conversion block which converts the output power signals to currents. The details of the PV conversion block are shown in Appendix A.

B. Residential Load
To accurately model the Residential Load subsystem, a synthetic residential load profile was extracted from HOMER Grid and implemented in the Simulink model using a lookup table. To convert the output power signals to three-phase currents, the same conversion scheme from the PV block was used. The residential load in the model is based on an average daily consumption of 22 kWh, providing a realistic representation of typical household energy usage.

C. BESS
A 240 V, 4.8 kWh BESS was considered for the purposes of the simulation. The specifications for the system were based on four parallel connected Enphase 1.2 kWh Lithium Iron Phosphate (LiFePO4) batteries. To estimate the SoC of BESS for the simulations, the Coulomb Counting method [4] is implemented in the model:

$$\mathrm{SoC} = \mathrm{SoC}(0) - \frac{\eta}{\mathrm{NominalCapacity}} \int \mathrm{I}\,\mathrm{d}t$$

Where:

- SoC(0) is the initial SoC of the BESS;
- I is the measured current;
- η is the efficiency of the BESS;
- NomCap is the nominal capacity of the BESS.

This method estimates the SOC by keeping track of the charge and discharge current that flows into and out of the batteries over time. By monitoring the current, the algorithm can determine the amount of charge that has been added or removed from the battery, allowing it to estimate the SOC. To implement the Coulomb Counting method, the Simulink model includes integrators for the charge and discharge currents. The technical specifications for the BESS are detailed in Table 4. Details of the Simulink BESS model and charging/discharging functions are shown in Appendix A.

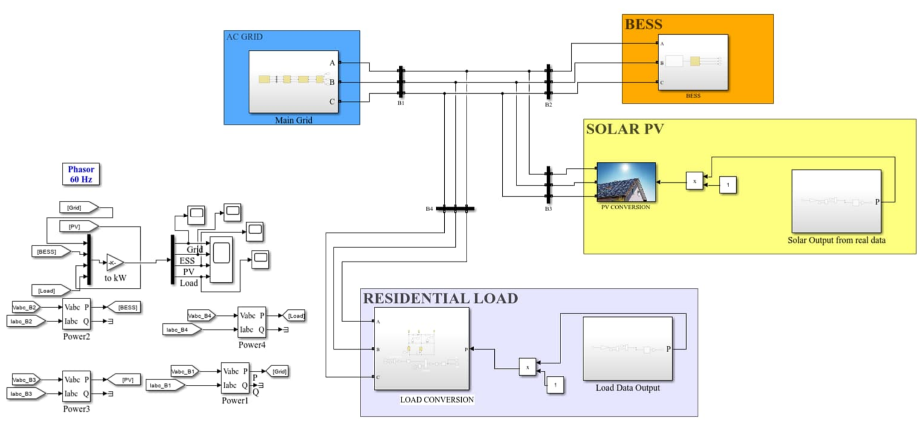


Fig. 5. Simulink Model for the PV-BESS power system.

Table 3: Simulink BESS Model Specifications

Nominal Capacity	Voltage	Efficiency	Initial SoC	SOC Range
4.8 kWh	240 V	93.4 %	20 %	20 – 90 %

D. Peak Shaving Strategy
A heuristic algorithm has been developed to optimize the charging and discharging of the BESS based on TOU rates and the battery's SOC. The peak shaving strategy is illustrated in the flowchart seen in Fig. 6.

The algorithm avoids charging during on-peak hours when electricity rates are high and prioritizes charging during off-peak or overnight hours. When the SOC falls below 90%, the BESS charges at a maximum capacity of either Pchrgmax1 (0.4 kW) or Pchrgmax2 (0.25 kW). During the overnight period (11:00 pm to 7:00 am), the BESS charges from the grid at a higher capacity of 0.4 kW to benefit from the 5 cents per kWh credit for overnight usage. However, during peak solar production (9:00 am to 4:00 pm), the charging rate is limited to 0.25 kW to maximize solar generation and minimize reliance on the grid while also preserving battery life.

The BESS discharges only when the SOC is above 20% and the system is not charging, specifically during on-peak hours (4:00 pm to 9:00 pm) which typically correspond to high residential loads. The discharge capacity is determined by the difference between the residential load and Pshave. The value for Pshave is based on the nominal capacity of the BESS and the residential load profile and has been set to 0.5 kW in this study. The control strategy for the charging and discharging the BESS is implemented using logical operators in Simulink. After completing its charging cycle, the BESS remains idle until 4:00 pm when it starts its discharge phase during on-peak hours, aligning with BC Hydro's TOU rates. The discharge operation adheres to additional restrictions to maintain the SOC above 20% and ensure the battery is not charging. Peak shaving occurs effectively between 4:00 pm and 6:00 pm, reaching the SOC limit of 20% before ceasing operation.

E. MATLAB/Simulink Simulation
To observe the peak shaving capabilities of the BESS, a 24-hour simulation was conducted for the Simulink model, capturing the power response of each component of the system. Fig. 6 and Fig. 7 depict the simulation results, which indicate that the BESS charges and discharges are in accordance with the proposed control strategy.

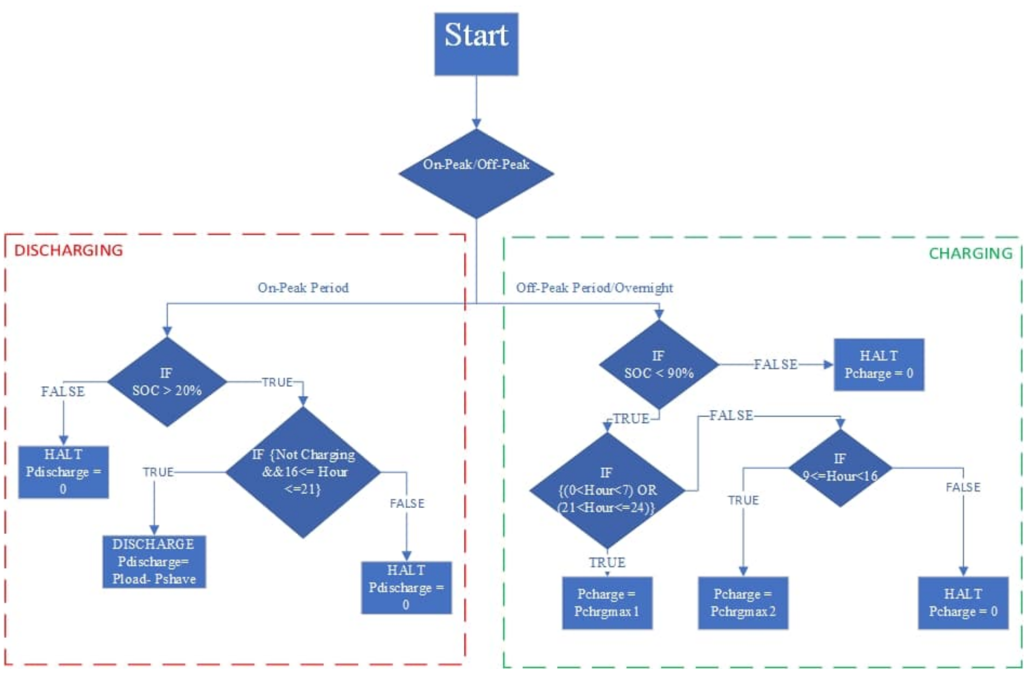


Fig. 6. Flowchart illustrating the control strategy for the BESS.

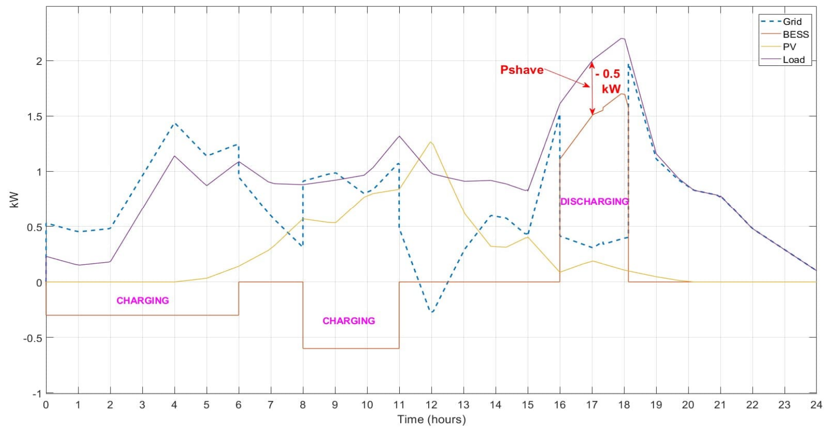


Fig. 7. Simulink Simulation: Power output of the grid-connected PV-BESS model.

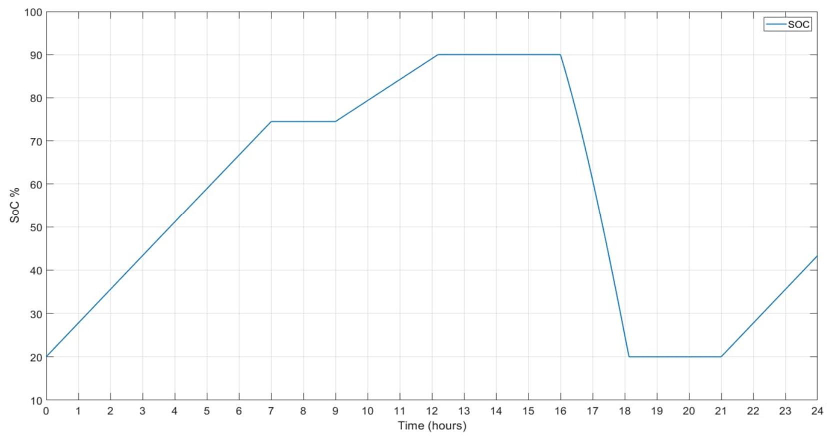


Fig. 8. Simulink Simulation: State-of-Charge (SOC) of the BESS model.

5. TECHNO-ECONOMIC ANALYSIS USING HOMER GRID

To determine whether a grid-tied PV-BESS system is economically feasible in Metro Vancouver, BC, we used HOMER Grid software to calculate the system's LCOE. Using HOMER Grid, we can design a grid-tied PV-BESS system and simulate its performance under different scenarios. These scenarios include different PV and BESS sizes, load profiles and utility rate structures. The system configuration used in HOMER Grid for this study is shown in Fig. 9.

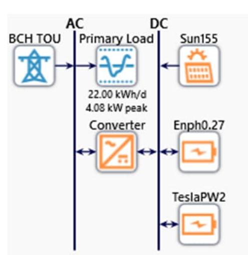


Fig. 9. System configuration in HOMER Grid

A. Primary Load

A synthetic residential load profile with an average load of 22 kWh/day was utilized for the simulations.

B. Solar PV & Battery Storage
To examine the system outlined in Section 2, a 1.395 kW PV system was modelled in HOMER Grid, consisting of nine Sun Earth polycrystalline 155 W PV modules. Two battery systems were considered in the HOMER model, the Enphase 1.2 kWh (LiFePO4) battery unit as well as the 13.2 kWh Lithium-Ion Tesla Powerwall. Both units have peak shaving capabilities.

C. Utility Rates and Incentives
A custom tariff based on BC Hydro's proposed TOU rates was implemented in HOMER. Minimum charges as well as relevant taxes were included in the custom tariff to acquire an accurate LCOE. Applicable government incentives based on the Canada Greener Homes Grant (maximum of $5000) were also incorporated in HOMER Grid's analysis. This includes a $1000 grant per kW of installed solar PV capacity and a single $1000 grant for a BESS [5].

D. Simulation and Analysis
HOMER Grid includes 3 different processes that are nested together, including simulation, optimization, and sensitivity analysis. First, HOMER employs an hourly time series simulation of the designed power system for a duration of one year. At each time step of the simulation, HOMER evaluates the most cost-effective way to meet the load based on the set of constraints that have been defined by the user. After simulating the system, HOMER's optimization algorithm finds the system configuration with the lowest Net Present Cost (NPC). An optional sensitivity analysis is also available, which allows to investigate the impact of changing various variables including discount rates, equipment prices, different load profiles, and so on.

The HOMER Grid simulation results for a PV system with a 4.8 kWh Enphase battery system and a 13.2 kWh Tesla Powerwall 2 are shown in Fig. 10 and Fig. 11, respectively. The results of the optimization analysis are presented in Table 5.

Table 4: HOMER Grid Economic Analysis Results

PV (kW)	Enph1.2 (#)	TeslaPW2 (#)	BESS Capacity (kWh)	Converter (kW)	NPC ($)	LCOE ($/kWh)
1.395	0	0	0	0.984	19,599	0.188
1.395	1	0	1.2	0.802	21,613	0.208
1.395	4	0	4.8	1.02	27,871	0.268
1.395	0	1	13.2	1.75	28,864	0.276

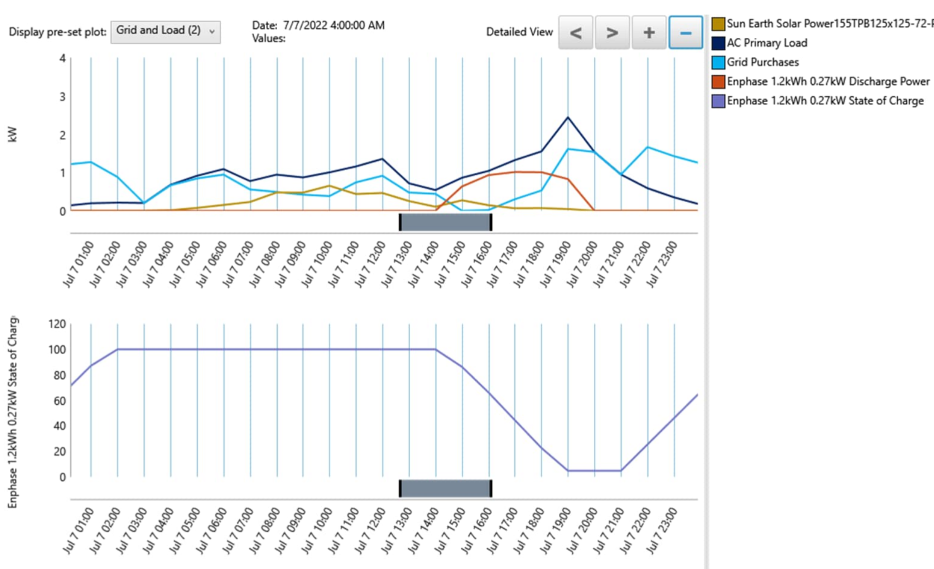


Fig. 10. HOMER Grid Simulation Results for Grid-Connected PV system with 4.8 kWh BESS: Power Output and SOC %.

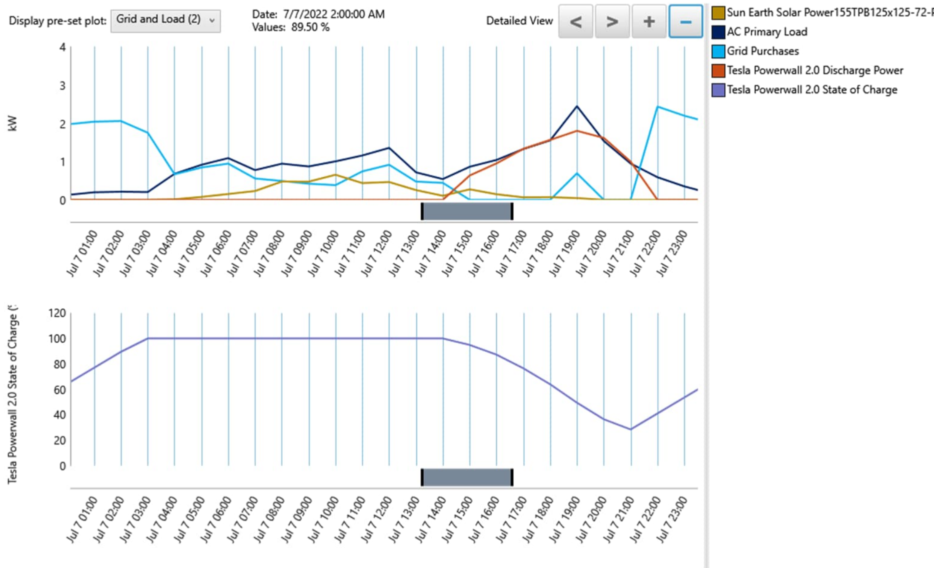


Fig. 11. HOMER Grid Simulation for Grid-Connected PV system with a 13.2 kWh BESS: Power Output and SOC %

6. CONCLUSION

The purpose of this paper is to study a typical residential PV-BESS system in Metro Vancouver, Canada. The existing system consists of a 1.395 kW PV system as well as a battery system that is primarily used as a backup power source. To investigate whether BC Hydro's purposed TOU rates encourage the utilization of a BESS capable of peak shaving capabilities, a heuristic control strategy was used for the operation of the BESS.

A grid-tied PV-BESS system incorporating the peak-shaving control strategy was modeled and simulated using MATLAB/Simulink. The simulation demonstrated that the BESS successfully participated in peak shaving by utilizing the proposed control strategy.

To examine the economic feasibility of a residential PV-BESS system in Metro Vancouver, HOMER Grid was used to assess the system's lower LCOE. The results indicate that, despite BC Hydro's proposed TOU rates, the incorporation of a BESS with peak shaving capabilities leads to a higher LCOE than that of a standalone residential PV system. However, when a smaller battery capacity of 1.2 kWh is used, the LCOE becomes much closer to that of the standalone PV system. These outcomes indicate that both the size of the battery system and the consumer's load demand significantly influence the economic feasibility of a PV-BESS system with peak-shaving capabilities.

To promote the wider adoption of BESS among residential consumers, policymakers should consider implementing incentive programs at the provincial level. At present, the CleanBC Better Homes program provides substantial rebates for upgrading heat pumps and water heaters, yet it does not cover upgrades related to solar PVs or battery technologies. Despite BC's reputation for renewable energy generation through Hydro, batteries can enable homeowners to further reduce their carbon footprint as well as lower the overall demand on the grid during peak hours through peak shaving.

Moreover, further research is needed to assess the economic viability of PV-BESS systems in applications with different load demands, such as commercial or industrial settings. These environments often exhibit substantially higher energy demands, potentially influencing the cost-effectiveness and overall feasibility of grid-connected PV-BESS power systems.

BIBLIOGRAPHY

[1] J. Prive and N. Sands, "Implementing Solar Electricity On-Farm Final Report" (British Columbia Ministry of Agriculture, March 2018, pp. 79 – 80).

[2] BC Hydro,"Generate your own electricity," [Online]. Available: https://app.bchydro.com/accounts-billing/electrical-connections/net-metering.html

[3] British Columbia Utilities Commission, "BC HYDRO - Optional Residential Time-of-Use Rate Application", (Exhibit B-1, February 17, 2023). Available: https://docs.bcuc.com/Documents/Proceedings/2023/DOC_70443_B-1-BCH-Optional-Residential-TOU-Rate-Application.pdf

[4] D. Saji, P. S. Babu and K. Ilango, "SoC Estimation of Lithium Ion Battery Using Combined Coulomb Counting and Fuzzy Logic Method," (IEEE 4th International Conference on Recent Trends on Electronics, Information, Communication & Technology (RTEICT), 2019, pp. 948-952).

[5] Natural Resources Canada, "Eligible retrofits and grant amounts," [Online]. Available: https://natural-resources.canada.ca/energy-efficiency/homes/canada-greener-homes-grant/start-your-energy-efficient-retrofits/plan-document-and-complete-your-home-retrofits/eligible-grants-for-my-home-retrofit/23504#s6

APPENDIX A: SIMULINK BLOCK DETAILS

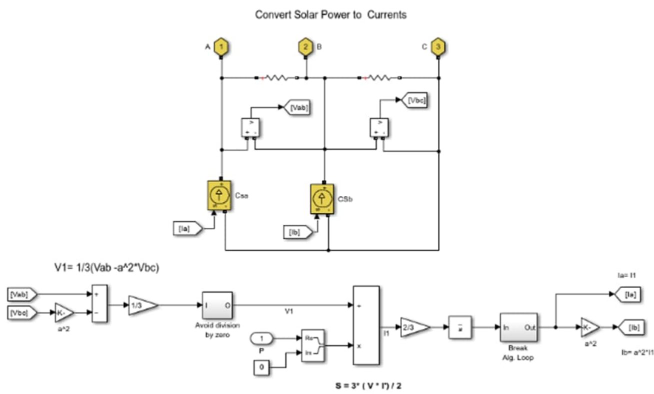


Fig. 12. Simulink model for PV conversion block.

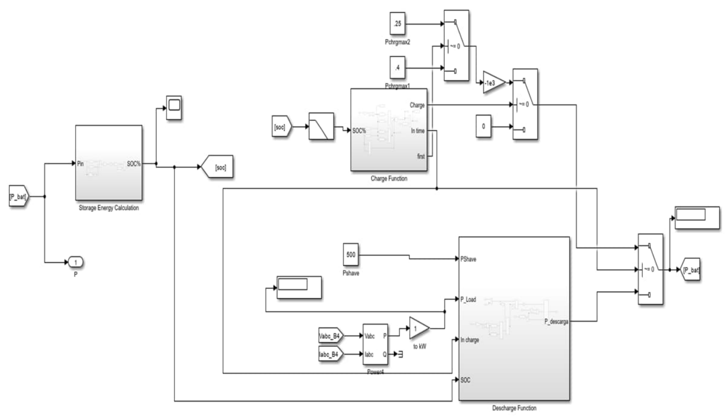


Fig. 13. Simulink model of the BESS.

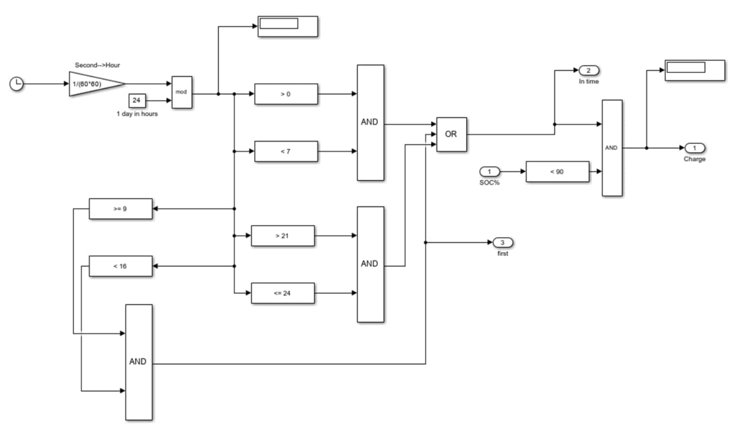


Fig. 14. Simulink model for the charging function of the BESS.

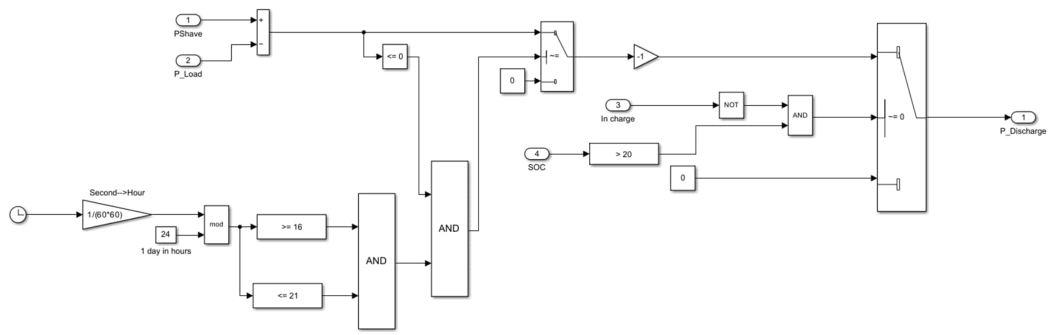


Fig. 15. Simulink model for the charging function of the BESS.