Comparison of Sensible Thermal Storage and Battery Storage for Excess PV Generation

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Abstract

With the price of electricity rising and the cost of PV systems decreasing, there is interest in the residential sector to use PV arrays to reduce home heating/electricity costs. PV systems can store excess electricity in battery storage or as hot water (sensible thermal storage). In Canada, 61% of the residential energy consumption is caused from space heating, where sensible thermal storage could provide economic and energy benefits. Through TRNSYS simulation, this paper compares different sensible thermal storage and battery storage configurations. The simulation results contrast the energy benefits between different storage configurations to a base case without PV generation and suggests economic advantages. The simulations were run for 10-year periods in Toronto, with building loads indicative of two occupants. It was found that a hybrid storage system with large battery storage and a buffer hot water tank can be largely self-consuming with only 4 MWh required from the grid.

Introduction

In Canada and many other countries, adoption of residential solar photovoltaic (PV) systems are increasing as the principal costs for the systems decrease (Urban 2021). In Ontario, the early adopters of PV were incentivized by the Provincial Government through a Feed-In Tariff (FIT) program starting in 2009 and ending in 2016, where the participants were paid per kWh supplied to the electrical grid (Ontario Ministry of Energy 2019). However, residents that installed PV systems since 2016 or did not participate in the FIT program are not paid a set price per kWh generated to the grid. Currently, Ontario offers net metering where you primarily use the electricity generated and any excess can be sent to the grid for credits towards electricity costs (Hydro One Networks Inc. 2021). Where the credits can be carried over for a 12-month period to decrease electrical costs. Both the FIT and current net-metering program for Ontario were limited to systems with a capacity of less than 10 kW.

The initial systems with a FIT contract allowed participants to profit off the excess electricity generated to alleviate the high initial capital costs. Newer incentives provide less of a direct monetary value as you gain credits for excess energy, known as net metering, and a large ratio of PV output to electrical consumption may cause some credits to go unused over the year. Net-metering is less beneficial for 'large' PV systems that can cover most of their winter load and produce significant excess electricity in the summer; but more beneficial to a balanced system, where the excess generation in the summer months can be used to credit majority of the winter electrical consumption.

With changes in policy already being discussed, many provinces may shift to a model commonly seem in the European market, where residential PV is widely adopted (Canada Energy Regulator 2020). Excess PV generated will either yield no benefit to send to the grid or a fee structure will be in place where the owner pays a fee to be connected to the grid. This occurs because the utility provider has costs associated with receiving and distributing the excess electricity generated from residents and infrastructure is needed to continue with increasing residential capacity (Appunn and Wehrmann 2019). In Nova Scotia a new proposal of fees was delayed until 2023, which would charge residents that provide electricity to the grid, a "system access charge" of $8 per kW of installed PV capacity each month. The utility company delayed the new fees due to received concern but suggest changes to the net-metering program will occur over the next year (Tisheva 2022).

As policy changes and FIT programs come to an end, it is important that excess PV generation is self-consumed to maximize energy out of the system and not stress infrastructure. A viable solution to excess generation is to store it as sensible heat. Converting excess PV generation to sensible energy (hot water) allows for large storages to be used for DHW and home heating. This type of system would also use an electric tankless hot water heater to provide heat when required, and excess electricity would charge the storage tank (PV Europe 2017).

Providing excess PV generation to the electrical grid poses challenges to the utility company as they need to distribute it, where many regions do not have microgrid infrastructure for local distribution (Hirsch, Parag, and Guerrero 2018; Warneryd, Håkansson, and Karltorp 2020). Self-consumption along with the topics of net-metering and net-billing are highly discussed as policy will shape consumer

uptake (Mehta et al. 2019; Luthander 2018). Regardless of policy, it is certain that maximizing self-consumption will be the most beneficial than relying on net-metering, as it is likely in the near future exporting excess electricity to the grid will yield no gain to consumers (Mateo et al. 2018).

There has been research investigating using sensible heating as storage for PV but few that directly compare residential base electrical loads, DHW, and a system with battery storage, battery storage with a buffer tank and heating coil, and full sensible storage system with a heating coil for Canadian residential applications.

A paper by Thygesen and Karlsson (2014) investigates two 5 kW PV systems, one uses a 48 kWh battery pack the other utilizes a 225 L hot water tank as storage. The house modelled was 138 m^2 with four occupants in Sweden. The reference system had a PV array but no storage, where any electricity not consumed was exported to the grid. The annual consumption of electricity from the grid was 7350 kWh. When battery storage was added to the system the self-consumption was increased causing the grid electrical consumption to drop to 5660 kWh with 14 kWh exported to the grid over the year. The 48 kWh battery pack was found to be oversized where a battery pack of 10 kWh would have had the same total cycles over the year but come at a lower cost. The storage tank system consumed 5700 kWh from the grid, self-consumed 4555 kWh, and exported an excess of 605 kWh of electricity to the grid. Overall, the simulations found that the storage tank system performed similarly to that of a lead-acid battery system in Sweden.

An analysis of a PV system in Australia with 315 L of hot water storage was done by Clift and Suehrcke (2021), where using excess PV generation to provide a source of water heating was analysed. It was noted that the control scheme of the PV system and storage interaction is very important and can largely vary results. The control logic used in their study was consuming PV output (after inverter losses) for the non-heating electric load. The excess electricity is then used to heat the hot water storage tank to the setpoint. Once the tank reaches the setpoint the remaining power was exported to the electrical grid. Similarly, when there was not enough electrical power to charge the storage tank electricity was imported from the grid. The results found 0.4 MWh of electricity was consumed from the grid with 2.1 MWh of electricity provided by PV generation for an annual 2.5 MWh demand of electricity.

Based off examples in the literature, this paper aims to utilize a control scheme to maximize self-consumption from PV generation through various storage systems. This study focuses on Canadian climate as the heating demand is much higher compared to countries with milder winters or smaller heated floor space per capita (smaller houses with more occupants). The PV storage systems in this study are not to be optimized for net-metering and balance throughout the year, but rather to limit the use of electricity from the grid. As policy changes, net-metering may no longer be applicable, so a storage system that allows for maximum self-consumption would be beneficial. As FIT programs are being phased out new policy will need to be implemented regarding the handling of residential PV generation (IEA 2020). An example of this in Europe is Spain, which has allowed self-consumption but provides no remuneration for excess energy in their hopes on 100% renewable electrical grid by 2050 (Georg et al. 2020; Winkler, Ragawitz, and Isi 2016).

Methods

To compare the potential benefit of switching to a system that stores excess PV generation as sensible storage a TRNSYS model was used. A representative house model for a standard newly built home in urban Ontario developed by Baldwin and Cruickshank (2016) was used and modified for this study. The goal of the simulation is to compare which systems would have the most self-consumption, which would be beneficial if no solar subsidies, such as net metering or credit systems, were available.

The house model is a two story, single detached home with a basement. The house has a total floor area of 330 m^2 divided evenly between the three floors. Each of the floors as well as the attic were divided into their own thermal zones. The heating and cooling setpoints were set on the main floor at 20°C and 23°C respectively. The house was oriented due south with the PV array at 60° to provide more generation in winter months. Additional detailed can be found in the publication by Baldwin and Cruickshank (2016).

The TRNSYS model was comprised of four main cases with some additional cases with larger electrical storage. The cases can be found in Table 1, with changes between the different cases bolded as the table progresses.

Table 1: Brief description of cases.

Case #	Description
Base Case	Standard AC, electric heating (furnace) with 100% efficiency.
Case 2a	Base Case with **37 m^2 PV & battery storage (12 kWh)**.
Case 2a2	Battery storage increased to 24 kWh.
Case 2a4	Battery storage increased to 48 kWh.
Case 2b	Std. AC, electric heating **(hot water coil)** with PV & battery storage (12 kWh).
Case 2b2	Battery storage increased to 24 kWh.
Case 2b4	Battery storage increased to 48 kWh.
Case 3	Std. AC, electric heating (hot water coil) with PV & **sensible storage (900 L)**.

The cases in Table 1 all share the same vapour compression air conditioner rated at 7.8 kW of sensible cooling with 2.5 kW of power consumption. The Base Case and Case 2a share the same 8.3 kW electric furnace with an assumed 100% efficiency. The photovoltaic (PV) array was comprised of 24 panels, each with an area of 1.54 m^2, resulting in a total system capacity of 7.2 kW

(Panasonic 2019). The voltage regulator and inverter efficiency were assumed to be 90% and 96% respectively. The battery had a charging efficiency of 90%

The size of the battery was chosen as 12 kWh as it falls between some common commercially available units (10-14 kWh) (Solar Edge 2021; Tesla 2019). The peak and continuous output from the battery of 7 kW and 5 kW was chosen based on a commercially available product (Tesla 2019).

Simple schematics of Case2a to Case 3 are presented in Figure 1 to Figure 3.

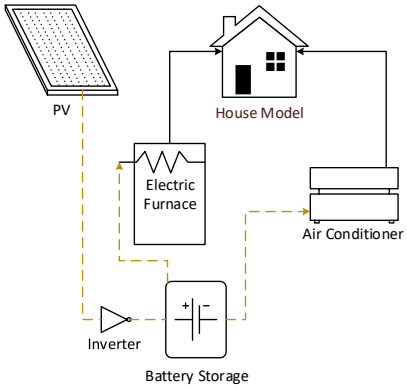

Figure 1: Case 2a system schematic.

Figure 1 shows Case 2a with a PV array that powers the air conditioner and electric furnace. The integrated battery charge controller will distribute electricity to the load first than use the excess to charge the battery. The battery is configured to only discharge between 80% and 20% to prevent deep cycling of the battery. Electricity is drawn from the grid when there isn't enough PV output or the battery is depleted, and the grid power is not used to charge the battery, only provide power to the HVAC equipment. Alternatively, the PV system provides excess electricity back to the grid when the battery is full and not discharging. Using cheap "off-peak" electricity was not considered for this study as it only has benefit in locations with TOU billing. When economics will be considered this method will be considered for Ontario. The schematic for Case 2b is shown in Figure 2.

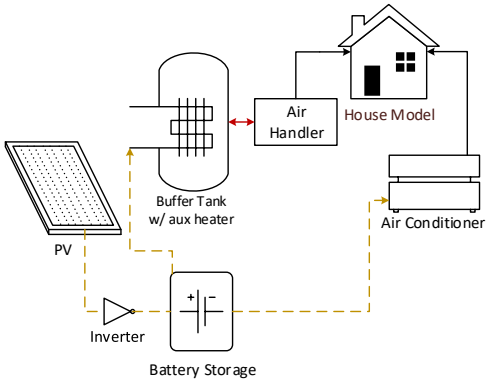

Figure 2: Case 2b system schematic.

In Case 2b, shown in Figure 2, the system still uses battery storage to store PV output, but provides heating through a heating coil in an air handler. The system is configured with a hot water buffer tank that is used to provide steady and reliable hot water flows to the heating coil in the air handler. A full sensible storage system, Case 3, is shown in Figure 3.

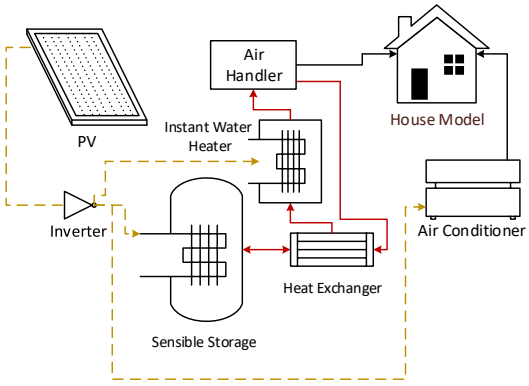

Figure 3: Case 3 system schematic.

Case 3, shown in Figure 3, is a fully sensible storage system. The 900 L hot water tank for sensible storage and DHW has five 1 kW auxiliary heaters, and the instant water heater (tankless water heater) is rated at 15 kW. PV output is used to supply power to the electrical loads and then to the instant water heater when heating is required. If there isn't enough PV power for the water heater to provide heating required, it is drawn from the sensible storage and any remaining electricity generated is used to maintain tank temperature. In the case the sensible storage is not able to provide enough thermal power, the instant water heater will use electricity from the grid to bring the indoor air temperature to the setpoint. The control logic is shown in Figure 4 for both sensible and battery storage.

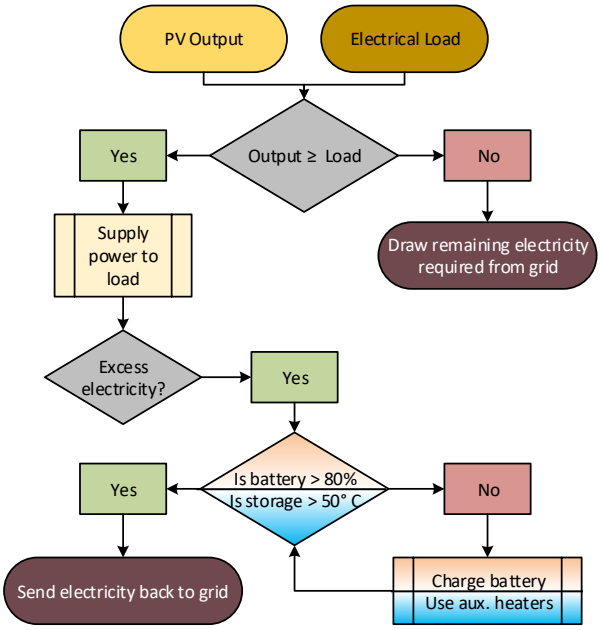

Figure 4: Control logic for storage.

The control flow chart in Figure 4 displays how the control system draws electricity from the grid when the electrical demand of the house cannot be met. When there is excess electricity after supplying power to the loads, the battery/sensible storage is checked to verify it is fully charged, and if so, the left-over electricity is sent back to the grid.

DHW

The house model considers electrical load for heating and cooling, but also the electrical demand from plug loads and DHW draws. The plug loads and DHW load is created by applying a randomly generated load profile to a predetermined "standard" load profile.

The "standard" DHW load profile was determined from a study by Edwards, Beausoleil-Morrison, and Laperrière (2015), where 73 homes in Quebec were analysed to determine representative hot water draw profiles, for the purposed of simulations. The dispersed throughout the day profile was used to model hot water draws every 15 minutes as a fraction of the daily consumption. From the same study the daily draw of 166 L was selected as a Median household of 2 people using a dispersed draw profile. The DHW profile and randomized draw is shown in Figure 5.

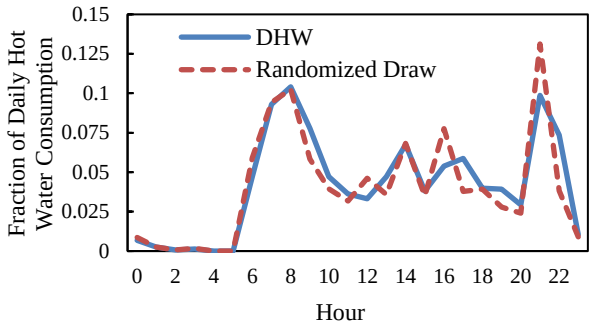

Figure 5:Representative DHW loads for 2 occupants.

The standard DHW profile in Figure 5 is shown by the blue solid line where there are peaks in consumption are in the morning and evening. A randomized draw of 50% is added at each point to allow for the variability of occupant behaviour, where the maximum and minimum water draw profiles from the study would represent profligate and sparing consumption respectively (Edwards, Beausoleil-Morrison, and Laperrière 2015). It should be noted simulations are run annually 10 times to provide averaged results. The random number generator uses the same seed for each case to provide consistent comparison across all cases. The DHW uses a 300 L tank set to 50°C with a 2.5 kW auxiliary heater and the mains supply water is assumed to be 10°C.

Base Electrical Loads

The plug load profile was generated in a similar manner to the DHW profile, where an electrical load profile as a percentage of baseline was used with a daily plug load value.

The electrical load profile normalized to a percentage of the peak was used from a paper by Zipperer et al. (2013), where they present a typical residential electrical load profile throughout the day. The daily electrical load was determined by combining data from a NRCan study on appliance electrical consumption (Parekh, Wang, and Strack 2012), residential end-use model data presented in the 2018 Energy Use Handbook (Natural Resources Canada 2019), and typical annual electrical consumption for Ontario (energyrates.ca 2021). The electrical consumption was calculated as an annual value where appliance, lighting and plug load values were assumed to follow similar trends daily. Table 2 displays the values used for the electrical loads.

Table 2: Summary of annual electrical loads.

	Energy (kWh/year)
Appliances	2750
Refrigerator Washer/dryer Oven	1000 900 850
Lighting	1300
Plug Loads	1700
Annual	5750
Daily	15.753 kWh/day

In Table 2, the breakdown of the annual and daily electrical loads is shown with appliances, plug loads, and lighting consuming 5750 kWh. When the annual DHW and cooling consumption of 2500 kWh and 1800 kWh, is considered the total annual electrical consumption (excluding heating) is 10,000 kWh which agrees with data for typical residential consumption (Natural Resources Canada 2019). The electrical load profile is shown in Figure 6.

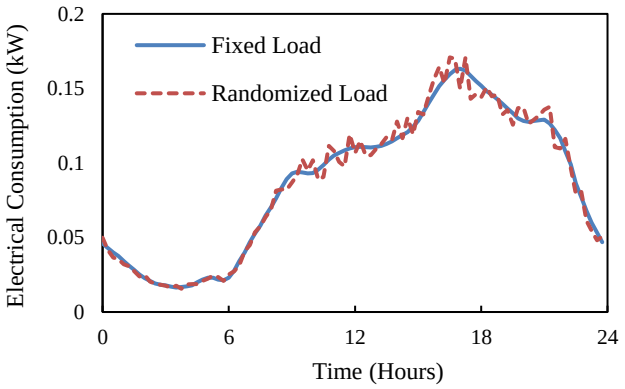

Figure 6:Base electrical (lighting, plug loads, appliances) daily load profile.

The electrical load in Figure 6 is shown to be at its lowest in the early hours of the morning and ramp up to peak around 7 PM. The randomized load profile is varied by 10% at each 15-minute timestep as phantom loads, lighting, and appliance use is assumed not to vary significantly from the 'typical use' case. Each day of the year uses a different series of randomized numbers to generate varying daily

electrical consumption data with the annual totals not varying more than a magnitude of 10%. Similarly, to the DHW profiles, the same random number seeds were used for each Case and 10, one-year simulations were performed to take an average of the values.

Results

The TRNSYS simulation was run at 15-minute time steps for an entire year, located in Toronto, ON, Canada. Each case was simulated 10 times using different random number seeds, where the same seeds were used across all cases. The average values of the 10 simulations were taken to compare the results.

The goal of the simulations was to compare how well the system self-consumes electricity, how battery sizing effects performance, and which system requires the least amount of electricity from the grid. The economic implications of these results are also discussed but an economic analysis was beyond the scope of this paper.

Annual electrical consumption for the house model was determined by combining the electrical loads required for heating and cooling, DHW, and base electrical loads (plug loads, lighting, appliances). The annual consumption is shown in Figure 7.

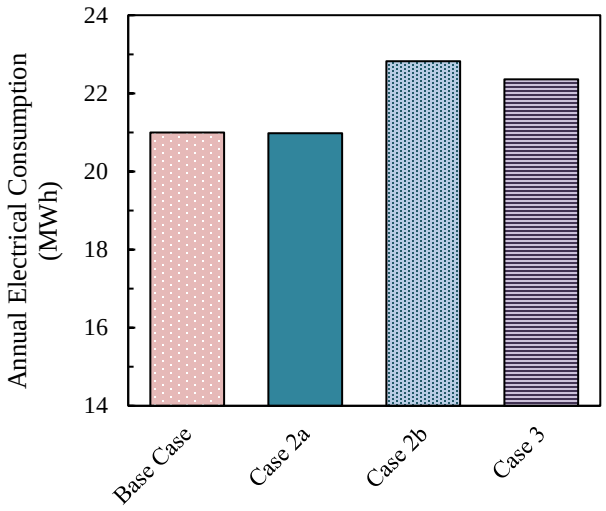

Figure 7:Comparison of annual electrical consumption.

The Base Case with no PV or energy storage (other than a DHW tank) required approximately 21 MWh of electricity with nearly 6 MWh from base electrical loads and 2.5 MWh from DHW loads. Case 2a with a PV array connected to a battery has similar electrical consumption as the Base Case. Case 2b and Case 3 have approximately 1-2 MWh larger consumption over the Base Case annually which can be due to additional power requirements of pumps, fans, and temperature dead bands on the tanks. Note: Case 2a and 2b don't show their successive cases as the annual electrical consumptions is nearly identical. Case 2b uses nearly 500 kWh more electricity than Case 3 as it has the most additional equipment as it is a hybrid system with battery storage and a hot water buffer tank.

For each case, the energy from PV generation (not including losses) is 62.4 MWh. The PV array could in theory provide nearly three times the amount of energy consumed from the household, on an annual basis. However, this is not possible as there will be times where the electrical demand will be high, and the system will require supplemental energy from the grid. It is expected that in winter, the heating demand will exceed the system's capacity, even with a PV tilt biased towards winter generation. The remedy to this issue would be largely oversizing the PV generation capability, which would work if there was solar radiation during the time of the demand, oversizing the battery storage, which comes at a higher cost, or a combination of both. Figure 8 compares the effects increasing the battery size has on the supplemental power required from the grid.

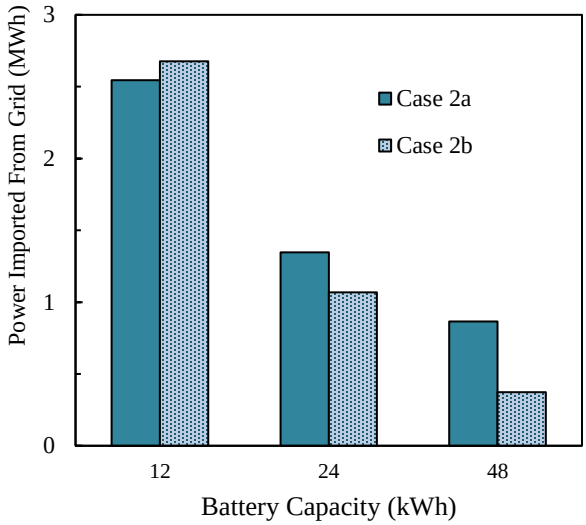

Figure 8: Electricity required from grid for increasing battery capacity.

Comparing the original battery capacity for Case 2a and 2b of 12 kWh to 48 kWh, it is apparent in Figure 8 that additional electrical storage helps heat the home in periods with low solar radiation as the demand for electricity from the grid is reduced. At 12 kWh of battery storage Case 2a and 2b import 2.5 MWh and 2.6 MWh of electricity from the grid. Meanwhile at a capacity of 48 kWh, Case 2a4 and 2b4 consume 0.9 MWh and 0.4 MWh from the grid. Power consumed from the grid as battery capacity increases does not appear to be a linear trend where the reduction in power imported from the grid is not reduced by the same amount each time. This suggests that there is a limit to which increasing battery capacity can make up for limited generation. A period in the winter season where there is little available solar radiation and cold temperatures is likely as even the 48-kWh battery is depleted.

Excess electricity from that is exported to the grid will be most prominent in the summer months where the cooling

load is much lower than the heating load and solar generation has higher yields, even at a 60° tilt. Figure 9 shows the excess electrical energy exported to the grid.

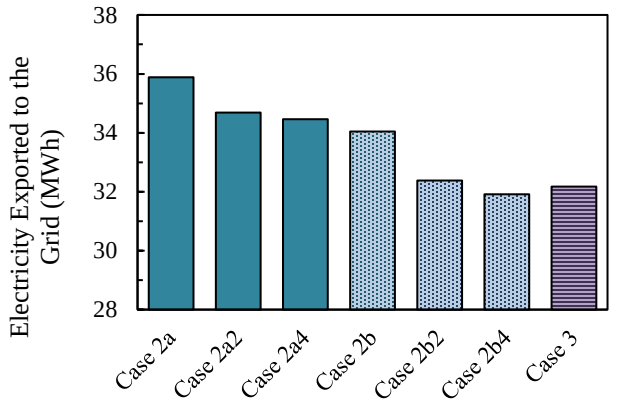

Figure 9: Energy exported to the grid for each case.

From Figure 9 we can see the trend of larger energy storage resulting in less energy exported to the grid as self-consumption is increased. Along with Figure 8, where larger storage capacity also shows that less energy is demanded from the grid. The amount of energy exported in Case 2a4 is within 0.5% of that from Case 2a2 despite being double the storage capacity, indicating that the benefit for increasing battery capacity is approaching its limit. Compared to excess energy exported in Case 2b4, which is 1.5% less than Case 2b2, the hybrid system is further from the beneficial limit compared to Case 2a4 but still approaching it. Case 3 is shown to be comparable with 32.1 MWh of electricity exported to both Case 2b2 and Case 2b4 where they have 32.4 MWh and 31.9 MWh respectively. Another factor of self-consumption is limiting the amount of energy is required from the electrical grid, which was analysed with respect to battery capacity in Figure 8 but is also show for each case in Figure 10.

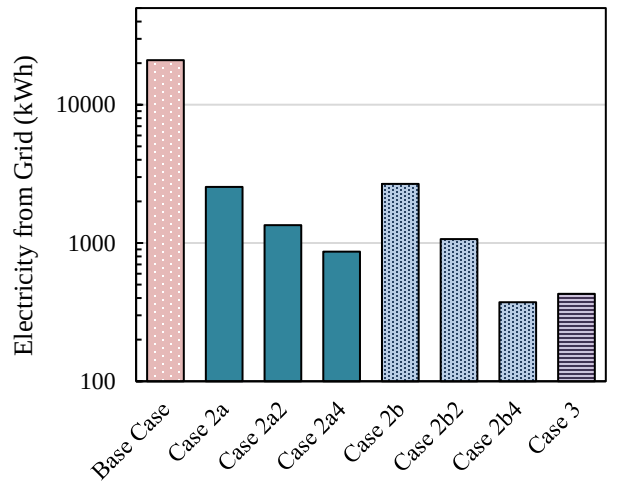

Figure 10:Comparison of energy required from the grid for each case.

Figure 10 uses a logarithmic scale to display the electrical energy required from the grid for the Base Case, which does not have PV generation. Case 3 requires 15% more electricity from the grid than Case 2b4 which is approximately 56 kWh. The difference between Case 3 and Case2b4 is equivalent to the annual consumption of burning a 40-Watt lightbulb for 4 hours a day.

The best case for self-consumption appears to be Case 2b4 and Case 3 with similar performance. However, it should be noted that Case 3 does not have a battery, therefore it will have a much lower capital cost. A large disadvantage for Case 3 would be the inability to utilize the energy storage for electricity over periods of no electrical generation or blackouts. The hybrid system, Case 2b4, would be more resilient for grid failure as well as for increased base electrical loads, where increase in plug loads or lighting would not directly demand more electricity from the grid if it was done in periods of excess generation or where the battery could be recharged before hitting the discharge limit. Case 3 indicates that it would be able to handle changes in DHW loads with little issue as there is still a significant amount of excess electricity exported to the grid. In summer months where high cooling may be required, there is also typically high PV generation, allowing the system to provide the required electricity. The only time the system may struggle is periods in the winter with no solar radiation, cold temperatures, and high DHW draws.

Conclusion

Overall, it was found that in Toronto, Canada, and potentially other regions in Canada, increasing battery storage in PV systems will increase the system's ability to self-consume electricity by decrease electricity exported and imported from the grid. The limit to the battery capacity is close to 48 kWh as the increase in performance becomes much smaller for such a large increase in capacity.

A hybrid system such as Case 2b shows that the utilizing both battery and sensible storage provides benefits from both methods, with little disadvantage, other then cost. In some regions the resiliency and adaptability of the hybrid system in Case 2b may prove to be worth the added cost if grid intermittency is an issue.

In situations with net-metering any of these systems would perform adequately where the PV array would be considered oversized and a reduction in panels would provide a greater economic benefit. However, if the system was provided a contract where electricity is purchased at a higher rate than it sells at, a higher self-consuming system would be advantageous. Similarly, if no monetary value or credit is given for excess electrical generation to the grid Case 2b4 would be most advantageous as self-consumption is highest.

In a situation where the utility provider charges fees for providing electricity back to the grid or based on the installed PV capacity, these systems may not be beneficial,

where future economic analysis must be performed, where TOU tariffs could be analysed.

Acknowledgments

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