

## Energy flexibility analysis for photovoltaic solar system with battery

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**Abstract:** The energy flexibility concept can be used to assess the performance of different systems and control strategies to implement demand-side management for the smart grid. Due to increasing penetration rate of onsite solar electricity generation, it is necessary to assess the impact of adding hybrid solar system with battery on energy flexibility. Integrating batteries within solar photovoltaic (PV) systems enables to control the power flow dispatch (based on supplied electricity and required load). In addition to modifying the electrical load profile (e.g. peak shaving, load shifting), battery storage units add resiliency to system in the case of power failures. This paper aims to investigate the energy flexibility of a typical Canadian house equipped with a PV+battery system by comparing Key Performance Indicators (KPI). For this purpose, a detailed model of the building (building envelope and all-electric HVAC system) as well as solar electrical system (PV arrays, charge controller, inverter and battery) is implemented in TRNSYS. Results show that the yearly KPIs (self-generation and self-consumption) are greatly improved by adding batteries to a conventional grid-tied PV system, with a saturation effect for larger battery capacities. Dynamic KPIs indicating the response to 1-h upward and downward flexibility event show that the conventional inverter control strategies (grid-support and UPS) present results at the two opposite ends of the spectrum, the UPS strategy offering the highest downward flexibility and the grid-support strategy offering the highest upward flexibility. Both KPIs are highly variable depending on the time of day and day of the year, with relatively stable median values.

**Keywords:** energy flexibility, electrical storage, hybrid solar system, energy control method

### INTRODUCTION

Financial incentives, a notable drop in market prices of photovoltaic (PV) panels and global concern for environmental issues over the last decade encouraged the electricity consumers to install and operate rooftop solar power systems. Due to generous subsidies, high feed-in tariffs and a substantial decrease of solar power cost, PV panels are close to reach grid parity over the world (i.e. the cost of solar electricity becomes close to utility rates) (Branker, Pathak, and Pearce 2011). However, increasing the share of solar energy in producing electricity without appropriate load management has major drawbacks for power utilities: over-generation during sunny days, and a high power ramp rate before evening peak hours, which increases the risk of failure in power plant facilities (Denholm et al. 2015). Adding well sized and well managed batteries to PV systems could allow to reduce these negative impacts, and even to improve the overall grid performance, in addition to providing distributed backup power to end-users.

Demand side management (DSM) in smart grid includes balancing the supplied electricity and load, which is more effective through appropriate interaction of the grid and buildings. Croc et al. (2017) discussed centralized management as a solution for smart grid which is equipped with local storage devices.

Hybrid PV System (HPSs) have the capability to improve grid stability through responding grid signals for

increasing/decreasing the load. O'Connell and Riverso (2017) evaluate energy flexibility provided by the integration of solar power system with batteries over different conditions (e.g. heating season, on/off peak hours and etc.) and energy control approaches.

According to the proposed definition by the International Energy Agency's (IEA) Energy in Buildings and Communities (EBC) Annex 67, energy flexibility is reshaping the load profile through distributed generation, storage and demand-side responses in reaction to the grid request while providing secure and reliable supply with least impact on occupants (Jensen 2017). Energy flexibility plays a major role in implementing peak shaving and load shifting to avoid transmission losses and grid perturbation.

Due to a lack of a uniform methodology for assessing the energy flexibility, performance is often assessed on a case-by-case basis (O'Connell and Riverso 2017). The energy flexibility KPIs should be selected with reference to the objective and proposed sources of flexibility. Clauß et al. (2017) conducted comprehensive review on previous researches in the area of flexibility and provided complete list of existing KPIs in a broad range of applications (e.g. on-site generation and storage). For instance self-generation and self-consumption appropriately identify the range of flexibility in the contexts of supplying the electricity demand through the renewable energy power system (Clauß et al. 2017). The aforementioned KPIs also play crucial role in the economic assessment of adding

roof-top solar systems for the site owners through quantifying the reduction in the grid usage.

Apart from commonly used KPIs such as self-generation and self-consumption as the label of installed PV system characteristics, it is also necessary to investigate dynamic performance indicators for complementing the flexibility assessment. These flexibility indicators quantify the building's dynamic interaction with the electricity grid. As an example the forced flexibility could be defined as photovoltaic (PV) system capability to increase (positive or upward flexibility) or decrease (negative or downward flexibility) the amount of imported electricity from the grid over the predefined events (Clauß et al. 2017).

## OBJECTIVES

This paper aims to study the offered energy flexibility of adding a solar power system with battery to a typical Canadian house from both end-users and utilities perspectives. This research investigates the impact of 2 key design parameters of a HPVS (PV peak power and battery capacity) on yearly KPIs, using a simple control strategy commonly implemented by commercially available inverters ("grid support", detailed below). Different usage patterns for non-HVAC electricity use, representing high-usage, average, or sparing occupants, are compared.

In the second part, dynamic flexibility KPIs are assessed for one PV system configuration and two basic control strategies ("grid support" and "UPS", explained below). In this study, the desired load is assumed to remain constant, i.e. the occupants comfort is not affected by flexibility events (whether the thermal comfort, the hot water temperature, or the ability to use any appliance at a given time).

## METHODOLOGY

### Energy flexibility scenarios

The study considers two opposite flexibility events: upward (or positive) and downward (or negative). During **upward flexibility**, the controller reduces on-site generation (by dumping PV power) and forces the battery to store energy through grid charging. It generally takes place over the solar window when the produced solar electricity is beyond the demand. During **downward flexibility**, the system uses the stored energy to reduce the amount of energy imported from the grid. This solution is usually applied to avoid high ramp rate over the peak hours. Currently the time of use scheme encourages the end-users to reduce their consumption on high demand hours.

### Control strategies

The employed load management approach has a notable impact on the provided energy flexibility offered by hybrid solar power system. The implemented rule based control methods in this study represent two extreme operation modes typically available in commercial grid-tied inverters.

- **Grid support (PV priority)**

In the grid-support mode, the system supplies the required load by prioritizing the electricity generation sources as the following order: 1<sup>st</sup>. PV panels, 2<sup>nd</sup>. Battery and 3<sup>rd</sup> Grid. This reduces the dependency on the grid, but it will not necessarily minimize the electricity bill since discharging the battery during off or mid peak hours is not always economically beneficial.

- **Uninterrupted power system (UPS)**

In UPS mode the primary task is to keep the battery fully charged in order to back up the grid for supplying the load over interruption or instability. Utilizing this mode of operation let the households have access the electricity over blackout as well as supporting the sensitive AC loads.

In this mode, since the battery bank is always fully charged, the surplus electricity is either dumped or exported to the grid. Therefore the system is unable to store the extra-generated electricity during the day to meet the load in absence of solar energy. It is interesting to note that, since the battery is not used under normal operation, this references scenario is very close to what a PV system without battery would provide.

### Key Performance Indices (KPIs)

The considered KPIs for evaluating the provided energy flexibility by the HPVS are briefly explained in this section.

#### Yearly KPIs (Salom et al. 2014)

- The **self-generation** (or load cover factor) estimates the share of demand met by on-site generation through various generator types (e.g. PV panels).

$$\text{Self - generation} = \frac{\int_0^T \min[g(t) - s(t) - \zeta(t), l(t)] dt}{\int_0^T l(t) dt} \quad (1)$$

Whereby the  $g(t)$  is the solar panels power at time  $t$  and  $s(t)$  represent the battery power balance.  $\zeta(t)$  is corresponding to the losses and  $l(t)$  indicates the load power.

- The **self-consumption** (or supply cover factor) displays the proportion of on-site generation which is utilised by the end-user. In fact this indicator quantifies the system potential to store and use the surplus generation.

$$\text{Self - consumption} = \frac{\int_0^T \min[g(t) - s(t) - \zeta(t), l(t)] dt}{\int_0^T g(t) dt} \quad (2)$$

### Grid interaction (Dynamic) KPIs (Jensen 2017)

The system capacity to modify the electricity demand upon receiving the grid signal needs to be evaluated for both upward and downward flexibility scenarios. Figure 1 provides graphical explanation of grid interactive KPIs for downward energy flexibility corresponding the two hours event (occurs at 8:00 AM)

- The **flexible energy ( $E_f$ )** reflects the amount of load that can be shifted (shed or added) through on-site generation and (de)store energy. This indicator measures the system flexibility in interaction with grid.

$$E_f = \int_0^{t_{dr}} (P_{dr} - P_{ref}) dt \quad (3)$$

Here  $P_{dr}$  and  $P_{ref}$  show the corresponding power consumptions at reference and demand response scenario respectively.

This KPI evaluates the system interaction with the grid during a particular event; however, it does not assess the impacts after the event, which is the focus of the next KPI.

- The **rebound energy ( $E_{rb}$ )** characterizes the change in the energy demand after the event. The battery state of charge will be affected by the system behaviour during the flexibility event, and this will have an impact on the system behaviour down the line, sometimes several hours after the event has taken place. In this study  $t_{\infty}$  is approximated by the end of a yearly simulation.

$$E_{rb} = \int_{t_{dr}}^{t_{\infty}} (P_{dr} - P_{ref}) dt \quad (4)$$

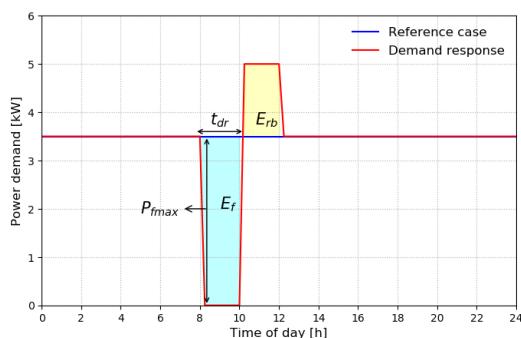


Figure 1 Flexible energy demand of buildings (downward flexibility)

### CASE STUDY

The selected site in this study is a typical two-story detached house (Swinton, Moussa, and Marchand 2001).

It was simulated using the Typical Meteorological weather data file for Montréal (CWEC) (Environment-Canada 2010). Initial sizing of the PV panels and battery bank is based on the available south-facing roof area and on an autonomy of 1½ day. The PV array nominal power is 16.1 kW (three 270 W panels are wired in series at each string) and the storage capacity of the battery bank is 61.2 kWh (48 V-1275 Ah). Twenty-four sealed advanced glass mat (AGM) lead acid battery modules, type Rolls (model S2-1275), 2V 1275Ah, are connected in series.

In order to study the impact of PV size and storage capacity on yearly energy flexibility KPIs, nine sizing variants were defined by combining 3 PV sizes and 3 battery sizes, as illustrated in Table 1.

Table 1 PV nominal powers and battery capacities

PV size	Battery capacity
[kW]	[kWh]
16.2	30.1
12.2	61.2
8.1	122.4

### SIMULATION SETUP

The simulation uses a detailed TRNSYS model of the house, the grid-tied solar system (composed of PV panels, charge controller, inverter and battery bank), as well as an all-electric HVAC system (Baseboard heating and conventional Air conditioner).

### Occupant-driven load profiles

The load profile in the residential sector consists of the electricity usage by the appliances, HVAC and hot water system. In this study, the assumed non-HVAC load profile is based on measured data for non-HVAC electricity load from 22 Canadian houses ranging from 6 to 30 kWh usage per day (Johnson and Beausoleil-Morrison 2017). The non-HVAC load profiles are categorized into three classes (low, average and high). In this study, one load profile in each category was selected following a methodology that imitates the selection of typical months for a Typical Meteorological Year: the cumulative distribution frequency (CDF) of all load profiles within one category were plotted, and the CDF that was the closest to the “average” of that class was selected. This allowed us to keep only 3 non-HVAC profiles, corresponding to high, average, and low usage categories. The selected electricity demands are added to the electrical load of the house but they are also used in the detailed simulation, as most of these usages are converted to internal gains.

The domestic hot water (DHW) load is derived from eight series of measured data containing DHW draw profiles (Edwards, Beausoleil-Morrison, and Laperrière 2015). The water draw profiles were categorized in three groups based on daily usage (low, average and high). The same method based on CDF comparison is used to select one profile in each category. The electricity usage associated with domestic hot water is obtained by running a separate 5-min simulation using a typical 270 L, 2-element water heater (Allard et al. 2011) and the 15-min integrated electrical load is then used in the main simulation.

The total electricity demand (non-HVAC, HVAC and DHW) for end-user categories (low, average and high) ranges from 70 kWh to 90 kWh per day in average. As explained above, the load profile is unaffected by flexibility event so that occupant comfort is assumed to remain constant.

### Controller

The control strategy which is employed in the TRNSYS model consists of two control layers: supervisory and real time. The supervisory layer implements the considered mode of operation by sending control commands to the inverter. Additionally during the event it applies the associated rule based scenario to govern energy dispatch to/from system components.

The real-time layer utilizes the equations and equalities to address the system operation constraints such as battery SOC set-points, voltage thresholds and the limits for the main components power rate.

- $P_{\text{Loads}}(t) = P_{\text{grid}}(t) + P_{\text{battery}}(t) + P_{\text{PV}}(t)$
- $SOC_{\min} < SOC(t) < SOC_{\max}$
- $P_{\text{battery}}^{\min} < P_{\text{battery}}(t) < P_{\text{battery}}^{\max}$
- $P_{\text{grid}}(t) < P_{\text{grid}}^{\max}$

The battery SOC remains constant at 0.9 when the system operates in UPS mode while the minimum and maximum SOCs for grid support mode are 0.3 and 0.9 respectively.

### Implementation of flexibility event

As mentioned above, when the inverter operates in grid-support mode the amount of electricity usage from the grid is minimized, so there is no potential for downward flexibility. During an upward flexibility event, the controller applies the following rules to minimize generation and maximize the delivered energy from the grid. The inverter shuts down the PV system and forces the battery to stop discharging in order to employ the grid for supplying the required load and charge the battery with maximum allowed current.

When the inverter works in UPS mode, the system has the capability to shift energy during upward and downward flexibility events. For the upward flexibility, the controller shuts down the PV and meets the load with the grid. Downward flexibility is obtained by readjusting the preset low set point of battery SOC to meet the load by discharging the battery. To put it simply, the controller switches to the grid-support mode and use the battery potential to offset the load that is not met by the solar panels.

### Running the simulations

For the assessment of yearly KPIs with different system sizing configurations, results are simply obtained by running 27 independent simulations (9 system designs combined with 3 usage classes).

For the assessment of dynamic KPIs, only one load profile is kept, and an independent simulation is run for each one-hour flexibility event. So for example the first simulation will have an upward flexibility event from 0 AM to 1 AM on January 1<sup>st</sup>, the second simulation will have an event from 1 AM to 2 AM, etc. This results in 8760 simulations for upward flexibility events and 8760 simulations for downward flexibility. Note that the calculation time is small for this study, so no attempt was made to reduce it. Under tighter constraints, it would be possible to fix a given limit to assess the rebound effect ( $t_\infty$  above) and simulate several flexibility events in the same simulation. For example, if a 1-week period is assumed to be long enough for the impact of the flexibility event to be “forgotten”, each simulation could include one event per week and the total number of simulations to run would be reduced to 168.

Matlab scripts were used to generate the input files, run TRNSYS simulations in batch mode, read and analyze the results.

## RESULTS

### Yearly KPIs

Figure 2 shows the self-generation for a whole year for three different load profiles associated with low, average and high electricity consumption patterns. The results are related to the “grid-support” mode of operation where the battery stores the surplus generation to supply the load over peak hours.

Points with a zero value on the x-axis represent conventional grid-tied photovoltaic systems without batteries. As mentioned above, the performance obtained is the same as a HPVS running in UPS mode, as in that case the battery is maintained fully charged under normal

operation and not used to compensate for the solar generation variations.

Adding a battery to a PV system allows to almost double the self-generation and more than double the self-consumption, and there appears to be a saturation of the battery benefits above a value of  $4 \text{ kWh/kW}_p$  for the selected load profiles.

Figure 2 shows that the installed PV capacity has a large impact on self-generation, which was expected. A more surprising result is that self-generation is also strongly affected by the total electrical load, with higher loads corresponding to higher self-generation. For the same HPVS configuration, the solar fraction (the potential share of on-site generation to cover the load) will decrease if the building load increases, but in all cases (with the selected assumptions and configurations) the self-generation will increase. This KPI does not “credit” the system for any exported energy, and increasing the building load will shift some of that exported energy towards directly used energy, therefore improving the self-generation.

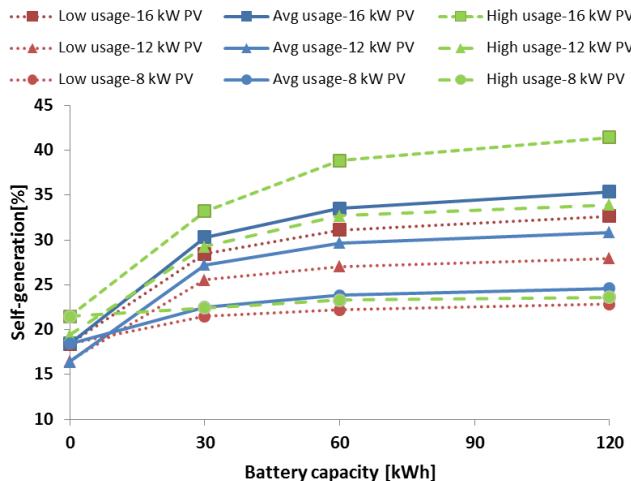


Figure 2 Self-generation vs battery capacity

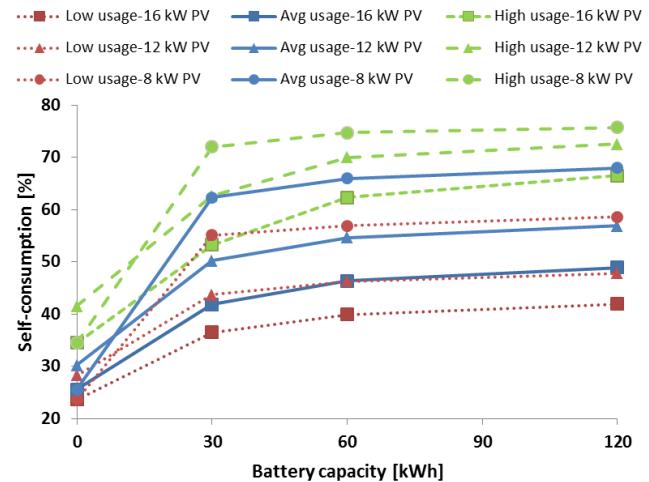


Figure 3 Self-consumption vs battery capacity

Figure 3 shows the results obtained for self-consumption. There is a direct relationship between the amount of exported (or dumped) energy and self-consumption, so adding a battery has a large impact on that KPI. The saturation effect observed for self-generation is even more present, showing that the sizing of HPVS systems will have a large impact on their energy flexibility, without necessarily requiring much larger investment costs than conventional (battery-less) PV systems.

A possible explanation for the relatively quick saturation of the two KPIs with increasing battery sizes is that the system performance is largely influenced by two extreme periods. In winter, an all-electric building load will be very high due to space heating, and solar generation will be low. So, the need for storage is relatively small, only representing a few extremely sunny days. In summer, on the other hand, the building load will typically be much lower, and the solar generation will be much higher. Adding a relatively small battery capacity allows dealing with the winter period, but not with the summer period. And the results seem to show that the investigated battery sizes (up to  $15 \text{ kWh/kW}_p$ ) do not result in significant improvements over much lower battery sizes – improving the self-consumption significantly would require a longer-term energy storage (closer to seasonal storage than to the type of short-term storage investigated in this paper).

## Dynamic KPIs

The KPIs presented above show a picture of the yearly system performance and are very relevant to end-users. This section will address dynamic KPIs which may be better suited to the priorities of utilities that need to balance demand and supply at a shorter time scale,

typically a few hours. All the results in this section were obtained for the system configuration with a 12 kW PV array and 120 kWh of battery capacity, using the “average” non-HVAC load profiles.

Figure 4 shows how the system reacts to an upward flexibility event (i.e. an event when the grid requests that the building use more energy) in grid-support mode where the horizontal and vertical axes represent hours of the day and the power in kW unit respectively. Figure 4a illustrates the dynamic variation of electricity load, PV panels output and the amount of imported power from the

grid (with and without event) over the day. In Figure 4b in addition to the input and output battery power the battery SOC is presented through secondary vertical axis. The event occurs at 12:00 and lasts for one hour. Figure 4b shows that the inverter starts to charge the battery by using the grid, so that the battery SOC rises up to 0.35. The system also shuts down the PV panels, so that the grid is used to supply the entire building load. The left graph (Figure 4a) shows the large impact on grid import during the flexibility event.

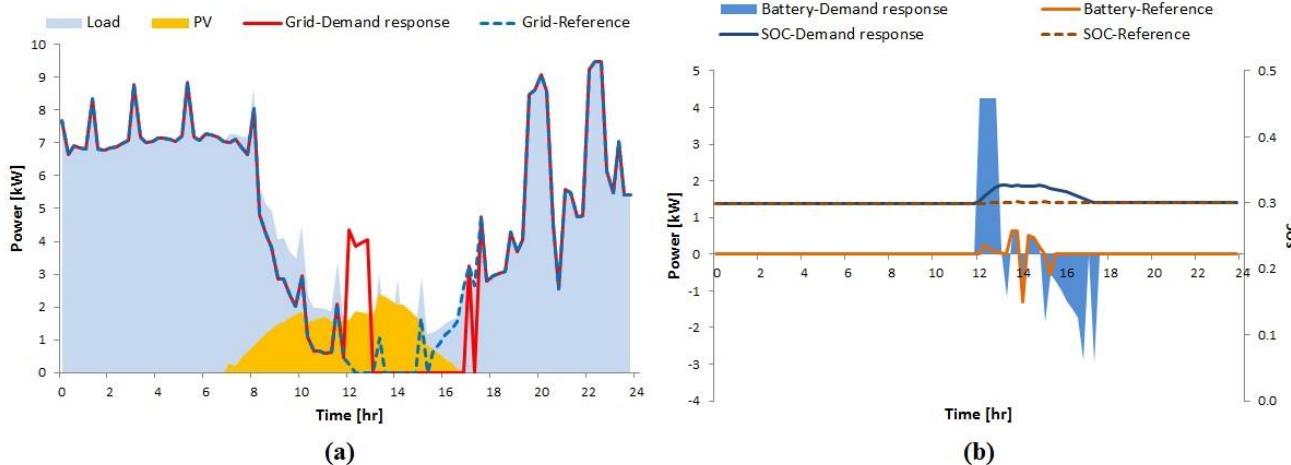


Figure 4 One-hour flexibility event for upward energy flexibility scenario (grid support mode)

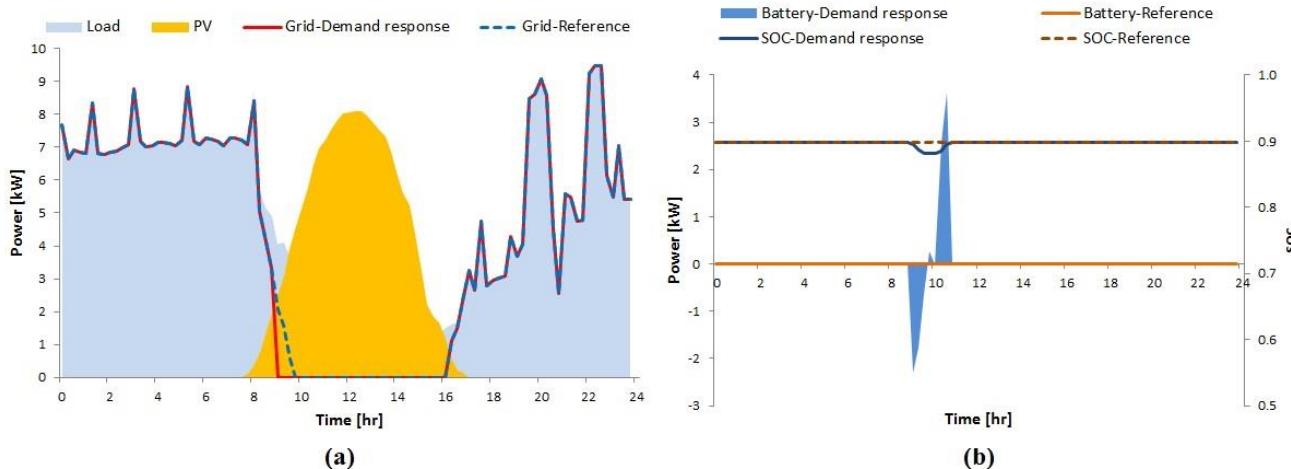


Figure 5 One-hour flexibility event for downward energy flexibility scenario (UPS mode)

After the event at 13:00 the inverter reverts to normal operation, using the battery to cover the load. A rebound effect can be observed between 13:00 and 16:45, when the energy stored in the battery is used. The rebound effect

ends when the battery SOC reaches the same value as for the reference scenario. The situation in Figure 4 shows a favorable case, since the battery SOC at the start of the flexibility event is low.

Figure 5 shows a downward flexibility event when the UPS mode of operation is selected. The event occurs at 9:00 and the controller acts to discharge the battery for supplying the load. Figure 5b indicates that while the discharging phase lasts for the whole period of the event, the discharge rate has been reduced gradually. This reduction is caused by solar electricity generation over the second half of the event. At the end of the event the battery charge level (SOC) has dropped to 0.87.

After the flexibility event (at 10:00), the battery will be recharged to its setpoint in UPS mode (0.9 here), in this case using PV generation. There is no rebound effect since the amount exported to or imported from the grid is not affected. The controller could be set to allow battery charging from the grid in UPS mode, in which case a rebound effect would be possible (although not on the day represented here). In UPS mode, the maximum downward energy flexibility will be achievable at times when the whole load is supplied through the grid.

The energy flexibility varies daily and hourly throughout the year. This KPI depends on various parameters including: on-site generation, demand, battery SOC and energy control approach. Figure 6 displays how this KPI varies depending on the start time of the event for the PV grid support mode. The PV power, load and battery SOC (at the start of the event) are presented in the same graph. On that graph, the blue line represents the flexibility KPI  $E_f$  defined above for a 1-h event that would occur at the given time. Since the event duration is 1 hour,  $E_f$  expressed in kWh has the same numerical value as the average power in kW.

Figure 6 shows hourly results for a typical day during the heating season. In the absence of PV power (in the period between 00:00 and 10:00 AM) the available upward flexibility is equal to the maximum battery charging power. It should be noted that over the mentioned period the whole demand is supplied through the grid for both reference and demand response scenario. Later in the day, when PV panels contribute to the load during the solar window, the upward flexibility increases as it represents the sum of the load that was covered by PV and the maximum battery charging power.

The maximum battery charging power (about 4 kW here) represents the minimum achievable flexibility during the day, as long as the maximum battery SOC is not reached.

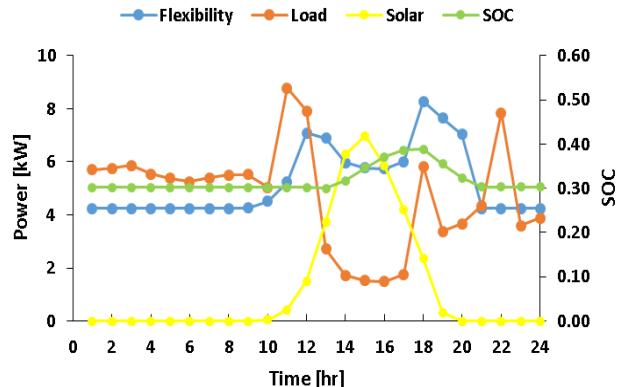


Figure 6 Hourly flexible power (upward flexibility-grid support mode-heating season)

Figure 7 presents the same results for a very sunny mid-season day. The low demand and high on-site generation keep the charge level of battery around the high limit over the major part of the day. Between 15:00 and 21:00, the battery is full and the KPI is equal to the amount of the load that was covered by solar electricity. Consequently, the energy flexibility is equal to the portion of the demand, which is supplied by the battery and PV.

For the UPS mode of operation, the upward energy flexibility is the same as for the grid-support operation when the battery is full: it is equal to the part of the load that is covered by PV, and it is always zero at night.

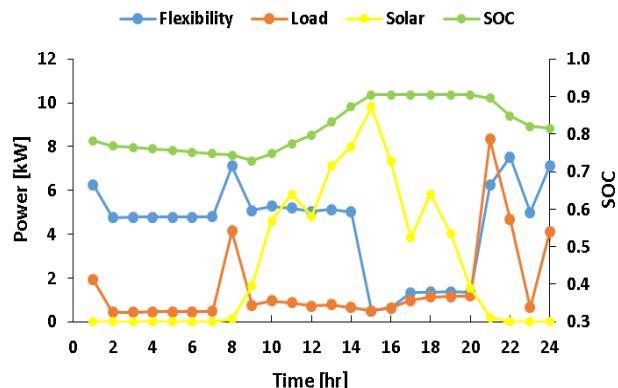


Figure 7 Hourly flexible power (upward flexibility-grid support mode-sunny day)

Downward flexibility is mainly affected by the maximum battery discharge power. Figure 8 displays how downward energy flexibility fluctuates hourly over a typical heating season day.

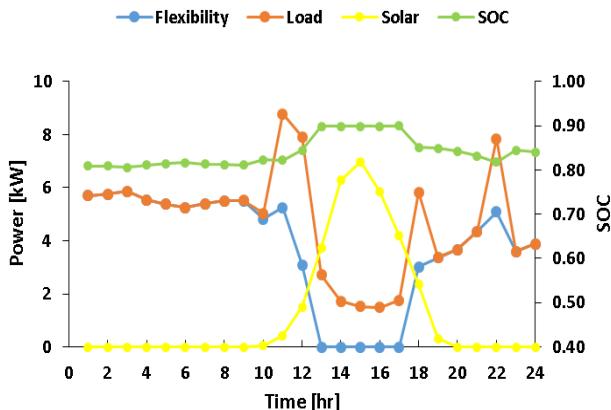


Figure 8 Hourly flexible power (downward flexibility-UPS mode)

Hereby the SOC indicates the battery charge level at the end of the event. As it is illustrated in Figure 8, when the PV power is negligible the downward energy flexibility is equal to the load as long as it is smaller than the maximum discharge rate. For instance at 22:00 the discharged energy is not adequate to cover the whole load which results in a lower KPI compared to the demand. When part of the load is covered by the PV and/or the battery, the available downward flexibility is equal to the share of the load which is still covered by the grid. Since we do not consider potential exports as “flexibility”, it is 0 the whole load is already met by the sun and or the battery.

Figures 9, 10, and 11 represent the same results as the figures above but combining all the days and event times for the entire year. Each data point in these figures depicts the value of  $E_f$  as a result of one simulation with one flexibility event taking place at the given time on one particular day. The color of each point denotes the month in which that day is falling. The blue line represents the

median value of the KPI, while the boxes represent the 25<sup>th</sup> and 75<sup>th</sup> percentiles.

Figure 9 shows that the available energy flexibility  $E_f$  ranges from 0 to slightly over 12 kWh, the lower values taking place during the day. The minimum flexibility at night is at 4 kWh except when the battery is full, as discussed above. The median value is relatively constant during the day, with higher values immediately after the solar day, when the battery is more likely to be charged and the load increases with late PM / early evening activities.

During the night time the higher  $E_f$  occurred over the months with higher solar radiation (e.g. June and July), when the surplus of generation during the day can be used at night to meet the load. Over the day time, usually on-site generation supplies the load and the system operates in semi-standalone mode. In these conditions, upward flexibility is gained by shutting down the PV panels and supplying the load with the grid, so that the shape of the flexibility matches the shape of the building load, and is higher during the winter months (e.g. December and January).

Figure 10 and Figure 11 display the upward and downward energy flexibility for UPS mode respectively in a same format as shown in Figure 9. As it is expected and explained previously in both upward and downward energy flexibility, the correspondent KPI depends on the share of on-site generation in supplying the load. The upward flexibility is a direct representation of PV generation that can be shut down, and the downward flexibility represents the share of the load that is not covered by PV, up to the maximum battery discharge current (about 8 kW here).

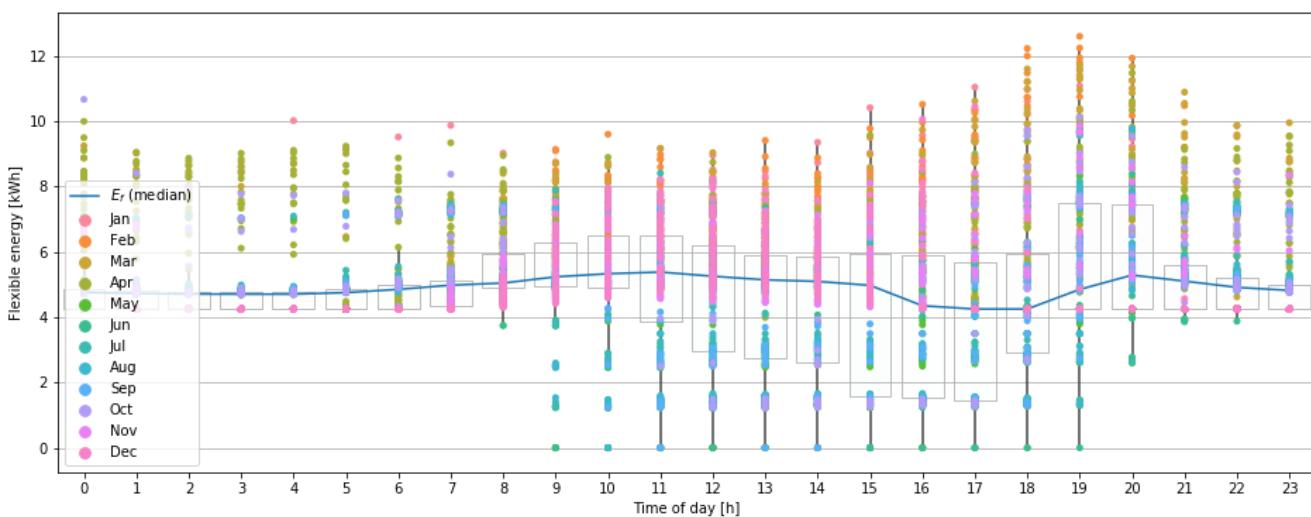


Figure 9 Upward flexible energy-grid support mode

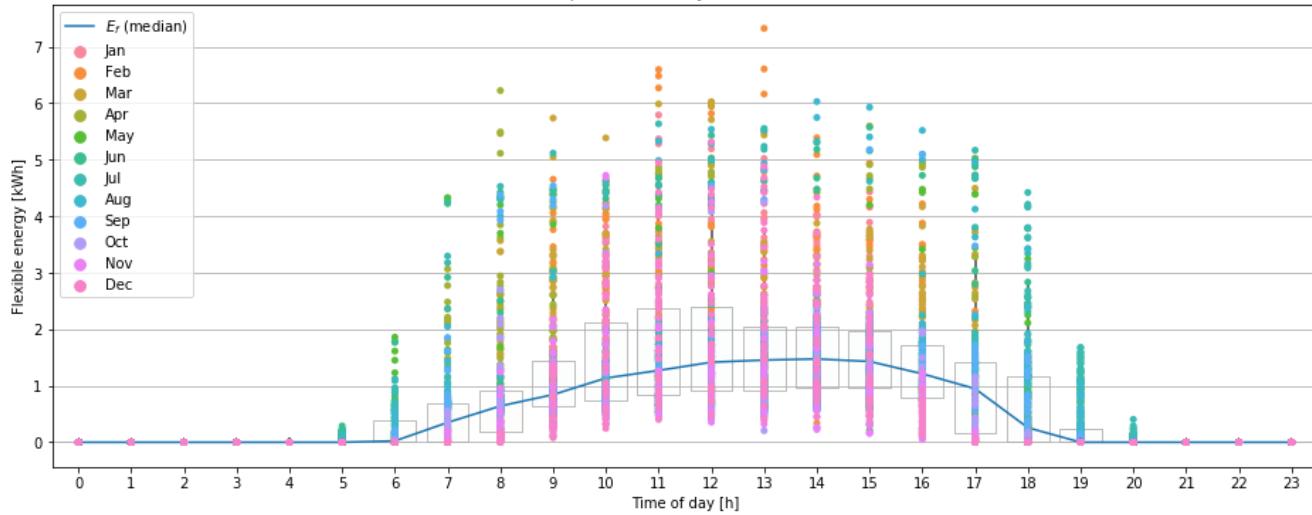


Figure 10 Upward flexible energy-UPS mode

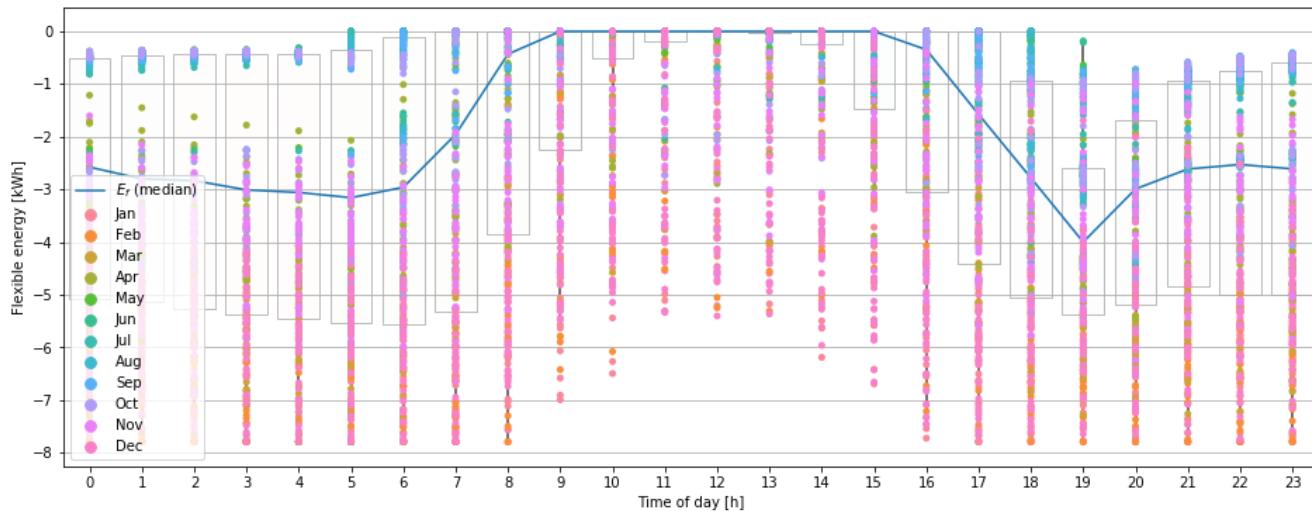


Figure 11 Downward flexible energy-UPS mode

## CONCLUSION

This paper assesses the energy flexibility provided by a Hybrid Photovoltaic System (HPVS) with batteries. Yearly and dynamic flexibility Key Performance Indicators (KPIs) are assessed for different system configurations (sizing) and non-HVAC load profiles through system simulation in TRNSYS. The simulated house is a typical Canadian single-family home and high-resolution load profiles are used for non-HVAC loads and domestic hot water.

Default control strategies in commercially available inverters are used: Grid support (or PV priority) and UPS-mode. No attempt is made to optimize these strategies in this paper.

Yearly KPIs such as self-generation and self-consumption show that adding batteries to a conventional grid-tied PV system can improve dramatically the available flexibility, with a saturation of the effects for battery capacity higher than 4 kWh/kW<sub>p</sub> under the selected assumptions.

Dynamic KPIs calculated for 1-h upward and downward flexibility events show that there is a large variability in available flexibility, depending on the day and time of the year and on the inverter control strategy. The UPS mode, which results in the lowest yearly self-generation and self-consumption, presents a significant downward flexibility potential, limited by the maximum battery discharge current. Its upward flexibility results from the ability to shut down PV generation and is entirely dependent on solar radiation. On the other hand, the grid-support (or PV priority) operation mode, which already minimizes grid imports, offers no potential for downward flexibility under

the current assumptions. Its upward flexibility is variable between 0 and 12 kWh in this study, with a relatively constant median value around 5 kWh.

Future work includes evaluating energy flexibility of more advanced inverter/charger controls, e.g. by adapting the State-of-Charge thresholds dynamically and/or implementing model predictive control). The impact of event duration on dynamic KPIs should also be assessed, as this study only considers 1-h events.

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