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Operationalizing Peak Shaving Optimization within the Lac-Mégantic Microgrid

Kevin MORRISSEY
Smarter Grid Solutions
USA

Mark JAGGASSAR
Smarter Grid Solutions
USA

David-Olivier GOULET
Hydro-Québec
Canada

SUMMARY

Hydro-Québec created the Lac-Mégantic Microgrid as a pioneering energy project during reconstruction of the downtown area after a rail disaster. The cutting-edge microgrid performs many advanced functions thanks to its advanced microgrid controller and the broad array of modern DERs that it enables. These functions include island transitioning, uptime management, building load management, forecasting, peak shaving optimization, and diesel generator optimization. The Lac-Mégantic Microgrid has been operating with core islanding capabilities since 2021 and with advanced analytics and optimization since late 2022.

This paper details the peak shaving optimization system within the microgrid controller and provides an opportunity to explore the interdependencies between advanced analytics and ruggedized failsafe DER control. The peak shaving system is comprised of two major components:

- Look-ahead optimization performed by an iterative algorithm using mixed-integer linear programming
- Real-time control for calculating DER dispatch based on live measurements in the context of the optimization result.

Advanced analytics can enable advanced DER optimization, but are subject to their own limitations such as a lack of determinism and the possibility of nonconvergence. Meanwhile, failsafe real-time DER control features its own complexities that can disrupt the intended behavior of advanced analytics. This paper explores the relationship between these two worlds in the real-world environment of the Lac-Mégantic Microgrid.

KEYWORDS

Microgrid, Operation, Islanding, Demand Response, Building Management System, Battery Storage, Optimization, Forecasting, Peak Shaving, Load Management

kmorrissey@smartergridsolutions.com

INTRODUCTION

Lac-Mégantic was the site of a severe rail disaster in 2013 which destroyed much of its downtown. As a result of the reconstruction efforts, the town of Lac-Mégantic approached Hydro-Québec with a desire to rebuild leveraging smart infrastructure and modern low carbon energy resources with the aim of becoming an energy transition leader in rural Canada. This complemented Hydro-Québec's desire to gain invaluable and exportable experience managing and optimizing energy resources on low voltage distribution networks, and mastering islanding in support of local grid resiliency. [1]

This project was a joint undertaking between the town of Lac-Mégantic, their distribution utility Hydro-Québec, contracting parties CIMA+ (lead contractor) and Smarter Grid Solutions (SGS) (microgrid controller vendor). Planning began in 2018 and the project was completed in 2022, with additional planned buildings & resources in 2023 and beyond.

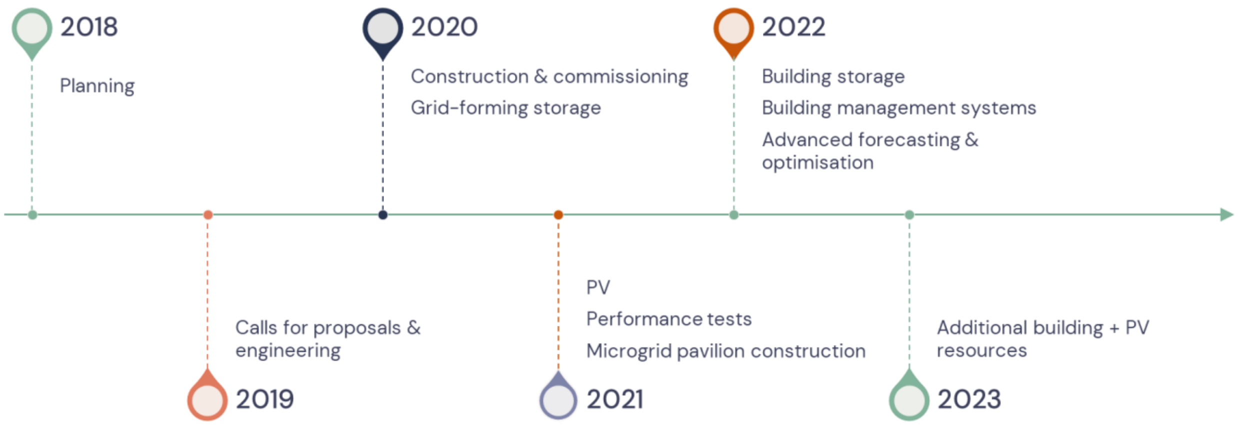

Figure 1: Lac Mégantic Microgrid Timeline

The microgrid controller designed for the Lac-Mégantic microgrid features several operational functions across islanded and grid-connected modes. While this paper provides a high-level overview of the full spectrum of functionality, it focuses on the complexities of operationalizing the grid-connected peak shaving optimization function. For additional context surrounding the other microgrid functions, reference [2].

MICROGRID OVERVIEW

Distributed Energy Resources

The Lac-Mégantic Microgrid is comprised of diverse above-the-meter (ATM) and behind-the-meter (BTM) distributed energy resources (DERs):

- 4 building management systems (BMS);
- 524 kW ATM solar PV array;
- 600 kW / 600 kWh in ATM energy storage;
- 855 kW ATM temporary diesel generator;
- ATM electric vehicle chargers;
- 113 kW across 4 BTM solar PV arrays;
- 36 kW / 52 kWh across 2 BTM battery energy storage systems (BESS); and
- energy efficiency developments.

Microgrid Structure

The BTM DER are distributed throughout several smart connected buildings, while the ATM DER are located in the Microgrid Substation - as shown in Figure 2.

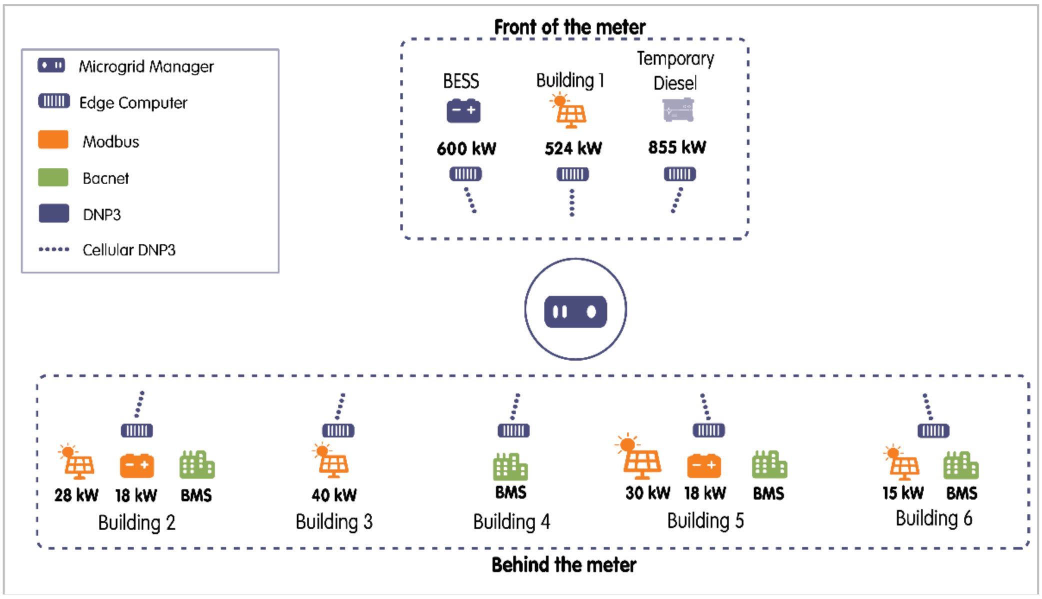

Figure 2: Lac-Mégantic Microgrid: A diverse DER and comms mix

Microgrid Controller

A microgrid substation hosts both the primary grid forming battery as well as SGS' microgrid controller (MGC), Strata Resilience. The MGC acts as the coordinating authority: it processes data from measurements on the system and issues control commands to underlying DER. It interfaces with 8 instances of Element Grid, a decentralized grid edge device that provides both a unifying control interface to diverse DER and additional control capabilities in support of advanced DER management.

Strata Resilience is responsible for executing and enabling all microgrid functions, communicating with all devices, and providing an interface to the system operators.

Microgrid Modes

The project partners designed and implemented a microgrid controller (MGC) which transitions between grid-connected and islanded modes, each with multiple sub-modes as defined in Table 1 [3]:

Mode	Sub-Mode	Control Actions
Grid-Connected	Peak Shaving	Energy Storage and BMS dispatched to reduce peak demand to an optimized minimum.
	Demand Response Events	Energy Storage and BMS dispatched to respond to demand response events.
Islanded	Planned Island	The ATM BESS becomes grid-forming, BTM BESS and BMS dispatched to maximize island duration. PV generation actively managed. Diesel generator optimally dispatched when connected.
	Unplanned Island	The ATM BESS becomes grid-forming, BTM BESS and BMS dispatched to maximize island duration. PV generation actively managed.

Table 1: Microgrid Controller Modes and Sub-modes

Microgrid Functions

The following functions were designed for this microgrid:

- Island Transitioning
- Island Generation and Uptime Management
- BMS Load Shedding
- Manual Dispatch

- Global Demand Peak Reduction Response
- Local Peak Shaving Optimization
- Diesel Generator Optimization
- Advanced Microgrid Analytics

Building Management Systems

Four of the microgrid buildings have building management systems (BMS), with new control sequences designed by CIMA+ for responding to MGC actions, such as pre-heating of the building spaces. The BMS control the operation of many sub-systems within the microgrid buildings, such as room temperatures, boilers, air conditioning, and humidifiers. They are controlled by the MGC via level-based load shedding thresholds. While the definition of each threshold varies amongst sites based on the underlying building mechanics, each BMS system follows a pattern of escalating load shedding similar to the following:

Level 0: No load shedding – full building operation.
Level 1: Controllable systems are curtailed by 25%.
Level 2: Controllable systems are curtailed by 50%
Level 3: Controllable systems are curtailed by 75%

Level 1 is designed to have near-zero impact on customer comfort, and this impact increases with each successive level. However, even the maximum Level 3, while it is only used in island scenarios, is not expected to make customers uncomfortable in their building.

ISLAND MANAGEMENT

An essential component of this microgrid is the ability to ensure service if the local distribution network fails. Therefore, while the focus of this paper is on the discussion of the grid-connected peak shaving optimization function, the most important function of the MGC is the safe transition and operation of islanded modes.

Island Transitioning

Hydro-Québec's priority in establishing the microgrid is to ensure safe and reliable islanded operation and where possible a seamless transition.

To enter a planned island, the following sequence occurs:

1. Operator issues planned island command.
2. The MGC performs safety checks then actively manages the ATM BESS to enforce 0 power flowing across point of connection (POC) between microgrid and distribution network, eliminating electricity draw between the systems.
3. Recloser at POC detects 0 power flow from grid and opens, forming an island.
4. ATM BESS now operating in grid forming mode.

For an unplanned island, the following sequence occurs:

1. MGC observes a loss of voltage indicating a fault.
2. MGC raises an event and awaits operator command to black start in island mode.
3. Upon receipt of operator command, MGC opens the recloser at the POC and initiates the black start process.
4. ATM BESS now operating in grid forming mode.

During re-synchronization, the following sequence occurs:

1. Operator issues re-synchronization command.
2. The MGC performs safety checks then commands the ATM BESS and recloser to enter resync mode: adjusting frequency, voltage, and phase to match grid supply.
3. Once frequency, voltage, and phase between microgrid and grid fall within tolerance, recloser closes to resynchronize the systems.
4. ATM BESS now in grid following mode.

Island Generation and Uptime Management

While in islanded mode, the microgrid's objective is to maximize islanded uptime, leveraging all available assets. While a diesel generator will be introduced for evaluation and to support planned islands once a year, most islands occur without any type of fuel-based generating unit. The 600 kWh ATM BESS is the grid-forming element in the microgrid. PV is the primary generation source during an island, and during times where generation exceeds demand, they are used to charge the BESS. However, if all BESS are already fully charged, the MGC curtails the excess PV to ensure the load is balanced and frequency remains stable.

Diesel Generator

Hydro-Québec will bring the 855 kW diesel generator onsite for short-term island testing, which replicates the remote off-grid networks that exist in northern Québec. The generator supports islanded operation with backup power should the PV and BESS resources be insufficient.

The MGC runs optimization in AMPL to schedule the diesel generator's dispatch to the microgrid at the lowest operating cost. This means it only engages when necessary to keep the island powered, and when operating it consumes a minimum amount of fuel. When the diesel generator is connected and the system is in island mode, the generator follows the optimized dispatch schedule.

GRID-CONNECTED MANAGEMENT

While critical, islanded operation represents the minority of operating time. During normal grid-connected operation, the focus shifts to the optimal management of DER to provide grid services and lower operational costs. This optimal management is achieved through the coupling of advanced analytics with ruggedized DER control strategies designed to safely leverage the benefits of advanced numerical methods while embracing their limitations. This section summarizes the various grid-connected modes supported by the MGC. A deeper exploration of the complexities of microgrid optimization is presented in the ***Optimization and Analytics*** section later in this paper.

Load and PV Generation Forecasting

Forecasts of building load and PV generation serve as inputs to many of the microgrid functions. The MGC produces both load and PV generation forecasts of active power at a resolution of 30 minutes, spanning a look-ahead period of 7 days.

Demand Response Events

One of the key opportunities in this region for supporting the distribution system while capturing energy cost savings is through demand reduction, a demand response (DR) program. [4] In this program, Hydro-Québec prepares for the highest demand peaks of the year (which occur in winter) by alerting program participants. It then rewards them for minimizing their load during the peak periods. The Lac-Mégantic Microgrid operators can schedule the participation of each BESS and BMS resource for the duration of the DR periods. The resources will contribute their response for the course of the DR event, and will return to normal grid-connected control priorities after it concludes.

Peak Shaving

While the GDP mode provides value during the winter-peaking months, there are additional year-round opportunities considering local tariff structures which incentive both energy and peak reduction. While the PV resources reduce total kWh energy charges, monthly peak demand charges can be minimized through optimal management of available BESS and BMS resources. The operator has individual control over which BESS and BMS resources participate in peak shaving and can also enable or disable peak shaving entirely. Peak shaving optimization, its complexities and its MGC implementation are discussed at length in the ***Operationalizing Peak Shaving Optimization*** section of this paper.

Microgrid Analytics

Alongside the applications described in this section, the MGC performs a number of analytics functions using the data it processes during operation. These analytics are not critical to system operation and do not require failure mitigation. Analytics include:

- Island Uptime Prediction
- Microgrid Peak Tracking
- BESS Cycle Tracking

OPERATIONALIZING PEAK SHAVING OPTIMIZATION

The MGC uses the AMPL optimization software to run iterative optimization algorithms. [5] While classical optimization is a powerful tool and can unlock a variety of advanced DER optimization techniques, it is also a complex iterative algorithm whose success is highly sensitive to variations in input data. SGS is an industry leader in deploying ruggedized and reliable DER control strategies, so preventing and planning for failure scenarios is vital when introducing such an algorithm to a critical control system.

Despite efforts to ensure that optimization will provide sensible results in a timely manner, determinism can never be guaranteed. Each optimization application is equipped with failure protocols designed to ensure that the system contains multiple levels of resiliency, so that it continues sensible operation during a failure event.

Peak Shaving Optimization: Layered Approach

The peak shaving optimization function is constructed from two layers of calculation:

1. AMPL-based optimization to calculate day-ahead optimal peak shaving thresholds
2. Real-time control loop to dispatch against the calculated thresholds

Figure 3: Peak Shaving Optimization Sequence

This two-layered approach is designed to maximize the effectiveness of the application in the context of uncertainty regarding the magnitude and shape of individual load peaks. The project team also considered a peak shaving approach whose output was a BESS dispatch schedule. However, a dispatch schedule-based approach has two main drawbacks:

- It is more sensitive to uncertainty in the forecast. If the forecast incorrectly estimates the time of the peak, then the dispatch schedule will tell the BESS to dispatch its energy at the wrong time.
- It is incapable of responding to load fluctuations occurring on a smaller timescale than the resolution of the forecast. If the forecast is provided at 30-minute increments, then any load changes between 30-minute dispatch intervals are not captured.

Using two layers of calculation allows the system both to optimize peak shaving effectiveness based on forecasts and to handle real-time discrepancies that are not considered by the optimization model. This allows the system to incorporate the individual considerations of both advanced analytical techniques and failsafe DER control.

Breaking Down Two-Layer Peak Shaving Control

The AMPL-based optimization uses mixed integer linear programming to minimize a threshold A which represents the maximum microgrid load in kW. Using 24-hour look-ahead forecasts, this threshold applies to the following calendar day and governs the real-time controller settings for 24 hours. This optimization model also calculates a lower threshold B which governs the recharging of all BESS. If microgrid load falls below this line, then the BESS are permitted to recharge up to this threshold. This calculation might result in thresholds such as those as shown in Figure 4.

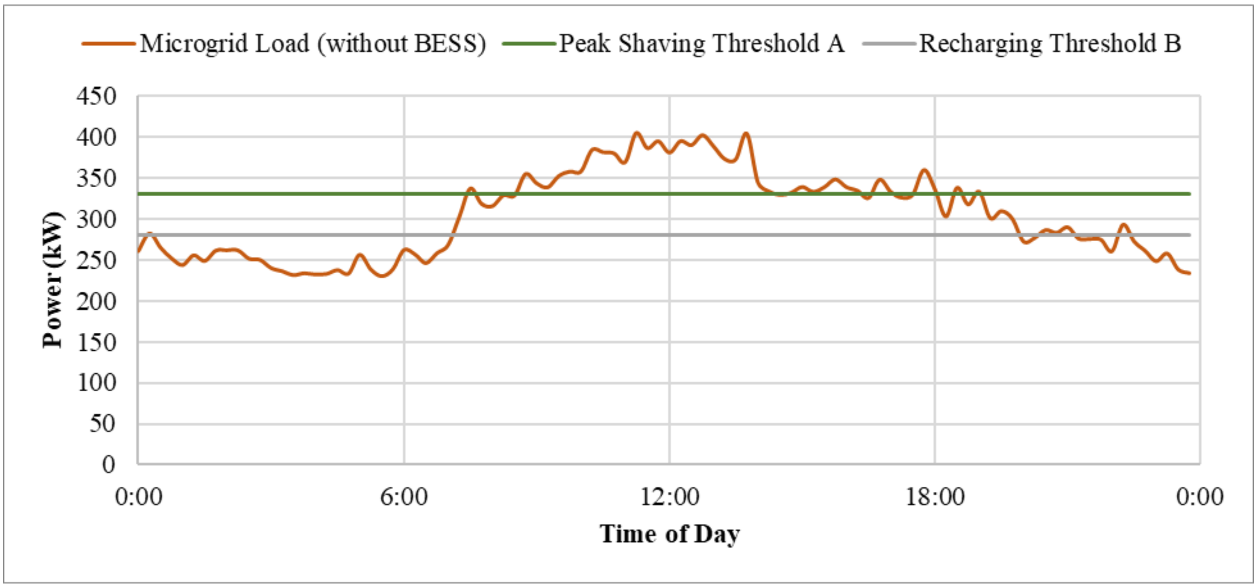

Figure 4: Peak Shaving Optimization Thresholds

The closed loop controller receives live measurements of microgrid load taken at the POC approximately every 2 seconds. This measurement is compared against thresholds A and B. Based on the result, the MGC deploys Strata Resilience's real time control algorithm to dispatch BESS resources on a second-by-second basis, adjusting the output based on updated measurements. This dispatch might result in a dispatch as shown in Figure 5.

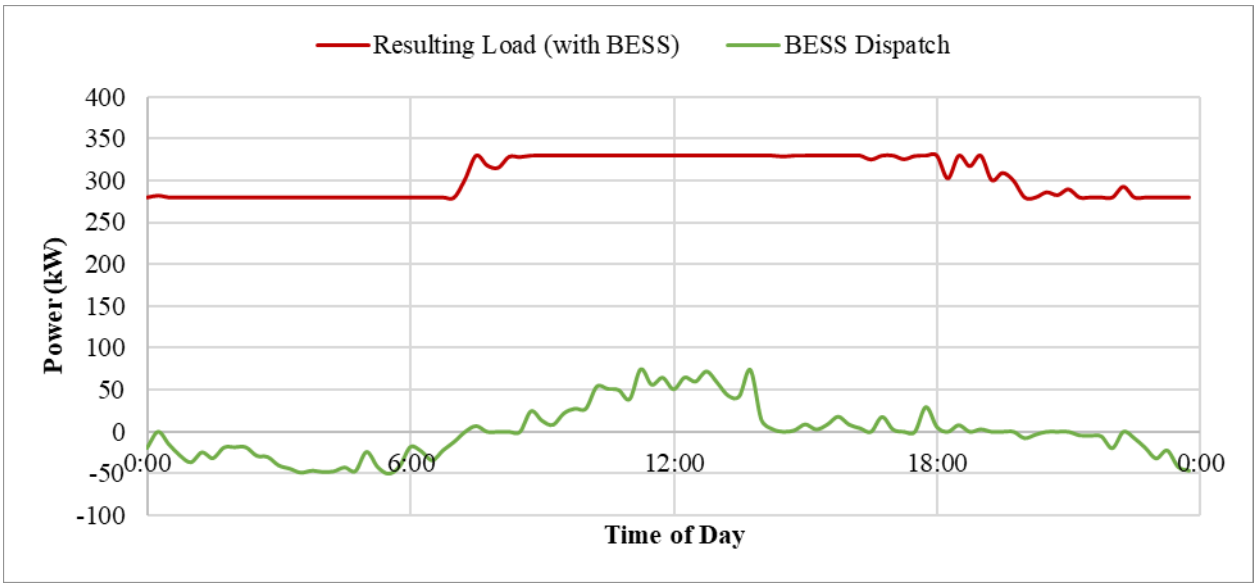

Figure 5: Peak Shaving Optimization Dispatch

The introduction of two thresholds A and B, separated by a buffer, prevents the real-time controller from exhibiting oscillating behavior. Without a separation between these thresholds, then any BESS discharge which drives microgrid power below the threshold A would immediately cause the BESS to enter a charging state, driving microgrid power back above threshold A. However, the separation between thresholds A and B (in kW) has an impact on the performance of the peak shaving system:

- If the thresholds are placed too closely, then the peak shaving system will oscillate as described above.
- The farther apart the two thresholds are, the fewer times in the day in which peak shaving can use the BESS resources – reducing the effectiveness of the application.

The team chose to implement the smallest kW separation between thresholds A and B that remained higher than the expected step change instituted by the real time controller. This allowed the system to avoid oscillation.

Incorporating an Energy Tariff
The high-level objective of peak shaving is to reduce the demand of the microgrid during peak periods in Winter, without increasing the electricity cost of the larger customers billed for energy use and maximum power measured during a consumption period. Most of the microgrid residential and business consumers are billed for energy use and are not billed for maximum power demand. While Hydro-Québec does not have a tariff structure adapted specifically to microgrids, they employ a hypothetical peak kW cost based on a large customers tariff for the purposes of evaluating microgrid optimization technologies. [6]

A key aspect of this tariff is that peak demand is measured over the course of a month. Because of this, each daily peak shaving optimization execution has to take into account the highest measured load in the month so far. There is no economic benefit in using peak shaving to reduce microgrid demand below this already highest measured load in a given month. The relationship between a daily optimization and a monthly tariff results in complexities such as:

- Creating a peak tracking application which constantly reevaluates the highest measured peak
- Initializing the peak tracking application at the start of each month to an expected peak value
- Managing peak loads at the start of each month, as a high peak occurring early in a month will reduce the effectiveness of peak shaving later in the month.

A key element in designing an operational optimization system is to ensure it takes into account the real-world economics of the subject application. Without anchoring the peak shaving application to the reality of a peak kW tariff there would be no tangible benefit to minimizing the peak microgrid load. Even though this peak shaving system was applied against a hypothetical tariff, Hydro-Québec's evaluation of the technology will allow it to transpose a similar application to a system which could show economic benefit from reducing peak kW.

Peak Shaving Optimization with Building Management Systems
In addition to BESS resources, peak shaving optimization makes use of the controllable aspects of BMS. Control strategies have been integrated into the BMS in the Lac-Mégantic Microgrid to reduce thermal setpoints when required for microgrid operation, without affecting comfort. Because setpoints are tied to thermal operation of internal systems, the tiered levels of load shedding available to the MGC do not correspond to any defined kW reduction. Because of the uncertainty regarding any expected kW output correlating to a given load shed level, the MGC cannot accurately predict the responsiveness of BMS. It is therefore unreliable to use BMS during AMPL optimization, as this would introduce error in the threshold calculation.

However, BMS do participate in peak shaving – load shed levels are dispatched alongside BESS setpoints by the real-time controller in real time based on the microgrid demand measurement. When the measured load approaches the peak shaving threshold A, BMS are set to a low load-shed level. When load exceeds this threshold, they are set to a higher load-shed level. In this way the BMS still contribute to the reduction of peak microgrid load, and can improve the performance of the peak shaving application.

Peak Shaving Optimization Failure Mitigation

Classical optimization can fail for a range of reasons:

- Non-convergence or infeasibility of the problem;
- Iterative solver hangups or extended searching; or
- Convergence to a non-acceptable solution.

To minimize the occurrence of the above failure scenarios, SGS thoroughly tests and tunes its optimization models. This included an input-variable-sweep simulation that generated thousands of scenarios leveraging and adjusting historical telemetry, increasingly incorporating operational realities. The outputs of which were analysed to surface up and resolve anomalous behavior in pursuit of building increasingly rugged optimization.

Because Strata Resilience isolates optimization from the closed-loop controller, failure of the optimization algorithm does not have a severe impact on system operation. If a failure occurs, the peak shaving threshold is automatically set to match the highest measured microgrid demand in the month thus far. This ensures continuity in the peak shaving application while continuing to minimize microgrid peak demand with respect to measured demand.

OUTCOMES AND LEARNINGS

Operational Outcomes

The Lac-Mégantic Microgrid has been operating with Island Management modes enabled since Fall 2021, and added the described Optimization and Analytics applications in November 2022. Since the initial deployment, The MGC has successfully islanded and re-synchronized the downtown area of Lac-Mégantic at least 10 times, with loads observed of up to 600 kW.

In grid-connected mode, Hydro-Québec has responded to GDP events using the MGC 16 times since 2021. Peak shaving optimization has been operating successfully since its implementation in November 2022.

The diesel generator has been integrated for short test periods in order to test control and optimization strategies, with the goal to transpose the technology to remote communities served by the same type of diesel generator. Optimization has been operating successfully in simulation mode, with the diesel generator device scheduled for field testing.

Learnings from Operationalizing Peak Shaving Optimization

Through the operation of peak shaving optimization, the team has uncovered a number of operational challenges:

- Due to the tariff being evaluated on a monthly basis, performance of the peak shaving application is highly dependent on results that occur early in the month. This makes it difficult to evaluate the peak shaving application beyond the first few days of the month.
- If peak shaving or BESS participation is disabled at any point, this might result in the high load peaks that peak shaving does not manage. This greatly impacts the performance of the application later in the month.
- The threshold and timing settings of the real-time controller have an impact on performance due to rapid variations in measured power. For example, if the responsiveness of the real-time controller is 10 seconds, then a spike in load has 10 seconds to exceed the peak shaving thresholds before the BESS kicks in to offset the peak. Accumulated over the course of a month this can cause the measured peak power to drift upwards.

The team has been able to make adjustments to the application to better suit the live environment. For instance, manual settings for recalibrating peak shaving during a given month were introduced. A combination of manual and automated threshold control were particularly beneficial for testing and evaluation. By implementing manual calibration, the team could “reset” the monthly peak kW tracking mid-way through the month in case there were load spikes early in the month due to natural behavior or controller configurations.

Another challenge in operationalizing peak shaving optimization was the shape of the load and generation profiles for the microgrid. In reviewing peak shaving results, the load profiles of Lac-Mégantic during the peak Winter months were relatively flat because they are driven by heating which operates 24 hours. Similarly, in the Summer, the PV generation can mask the daytime load such that there is no discernable peak but instead an anti-peak. These flat load profiles have a high "load factor" – meaning the average load value is close to the peak load.

Loads with high load factor are challenging for a peak shaving application because the peaks are not well defined. The ideal load profile for peak shaving has distinct peaks and valleys, such that the load during peak times can be shifted into the low demand period. If the peak is less distinct, then a given amount of BESS energy cannot reduce the peak load as much as it could with a different profile. Exacerbating this phenomenon is that the cold seasons exhibit the highest loads in the year, making them the most important times to save on energy costs.

On a smaller time scale, profiles with high load factor can lead to a situation where the "peaks" are actually short-term load fluctuation. It is common for higher-frequency fluctuations in the load on the order of minutes to appear as the highest peaks to shave. Figure 6 shows the peak shaving system operating in the face of short-term fluctuations. While there was not a distinct peak to shave, the controller demonstrated its effectiveness in maintaining microgrid load between the peak shaving threshold A and the recharge threshold B.

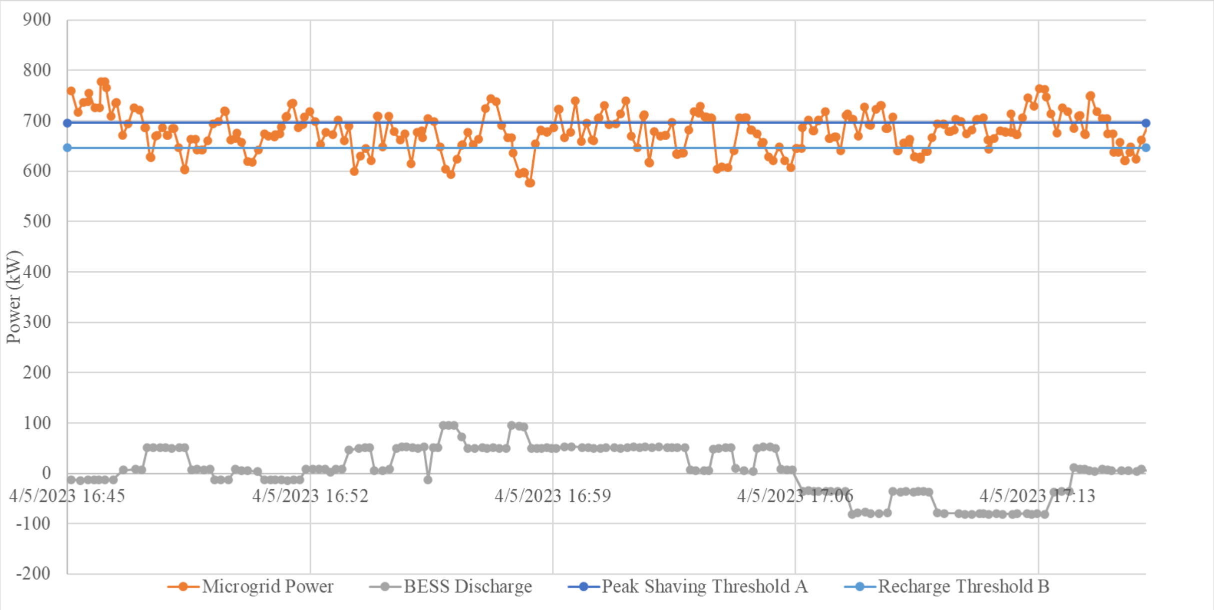

Figure 6: Peak Shaving Optimization During Operation

Looking forward, there is room for future improvements to this or similar microgrid systems. The project team is currently using operational data to evaluate the BMS responsiveness to load shed levels, and any predictable correlations between these levels and kW impacts on building load. If a consistent relationship is found between load shed levels and kW, the MGC would be able to more accurately predict and plan for the behavior of the system in the context of BMS load shedding. This could pave the way for integration of BMS load shedding into the optimization formulation.

Additionally, the design of the MGC enables the integration of new forecast technologies. This could mean a cutting-edge commercially available learning forecast model can replace the existing forecast models, which were built-for-purpose. Improving the quality of forecast data is foundational to improving the impact of look-ahead applications such as the peak shaving optimization model.

Overall Learnings

In the design and implementation of the MGC, the team learned that the successful optimal management of DER in a microgrid must be designed to holistically incorporate the inter-dependencies between advanced analytics and the operational realities of ruggedized failsafe DER control. This interdependency means that the limitations of real-time control must be considered during the formulation of advanced analytics. As the capabilities of either analytics formulation or real-time control mature, this creates additional opportunities for improvement for the other aspect of the system.

To maximize the effectiveness and limit unanticipated failure states, strategies that incorporate a "least trust" approach to the use of advanced analytics in operational settings are thus the most suited to unlocking their benefits. This is especially true when paired with a complex system for changing DER control strategies depending on the operating mode.

Thanks to the vision of Hydro-Québec, the Lac-Mégantic Microgrid is one of the most innovative fully-operational microgrids, with pioneering control modes across a wide array of BTM and ATM DER. With the recent completion of the microgrid, and the completed addition in 2023 of a new Fire Station building complete with BMS, PV and BESS, further insightful learnings from this 'living lab' will emerge as microgrid operation continues through 2023 and beyond.

BIBLIOGRAPHY

[1] Hydro-Québec, "Québec's first microgrid – A source of pride" (Retrieved June 15, 2023 from https://www.hydroquebec.com/microgrid-lac-megantic/)

[2] K. Morrissey et al, "The Lac-Mégantic Microgrid: A Shared Vision of Energy Transition and the New Role for Microgrid Control" (CIRED, 2023)

[3] D.R. Danley, 2019, "Defining a Microgrid Using IEEE 2030.7" (NRECA, Distributed Energy Resources Work Group)

[4] Hydro-Québec, "Demand Response Option" (Retrieved July 27, 2023 from https://www.hydroquebec.com/business/customer-space/rates/demand-response-option.html)

[5] AMPL, "The fastest optimization toolchains run AMPL" (Retrieved June 15, 2023 from https://www.ampl.com)

[6] Hydro-Québec, "Rate M" (Retrieved July 27, 2023 from https://www.hydroquebec.com/business/customer-space/rates/rate-m-general-rate-medium-power-customers-billing.html)