Micro-grid Design and Cost Optimization using Modelica

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Abstract

This paper describes the modeling capability for the National Research Council of Canada (NRC) Micro-Grid Testing and Training Facility, which will be used to advance energy generation and storage technologies and optimize integrated system operations for a variety of micro-grid applications. First, an integrated system model was assembled using the Microgrid Modelica library, developed by Modelon. Next, three use cases were defined based on the Whale Cove, Nunavut micro-grid operating in: 'island mode' without renewables (present mode), island mode *with* renewables, and grid-connected mode. Finally, various design, environmental, and economic analyses and optimizations were performed. Through these analyses, it was shown that each parameter domain could be successfully assessed using this modeling framework, demonstrating the flexibility of the modeling platform and the potential for the physical test facility to support in-depth analyses and optimizations for different micro-grid configurations, technologies, and applications.

Keywords: Micro-grid, remote area, grid-connected, island mode, distributed energy resources, renewables, energy storage, solar photovoltaics, combined heat and power generation, model, energy balance, optimization.

1 Introduction

Canada has an estimated 280 remote communities and commercial sites where power is predominantly supplied by standalone diesel generators (NRCan 1, 2018). Because of their high reliance on diesel, the remote micro-grids supplying power to these communities are expensive to operate, generate significant emissions, and can face substantial risk if critical supply shipments of diesel are disrupted. Introducing renewable energy sources provides an opportunity to increase energy security and reduce both operating costs and emissions; however, due to the variable energy output of renewables such as wind and solar, this can add complexity for maintaining the control and stability of the integrated electrical system. Optimizing the size of renewable energy installations can also be a challenge in northern communities due to seasonal variations, where solar generators produce less power in the winter when the demand for energy is the highest, and more power in the summer when the demand is low (sometimes resulting in curtailment).

Presently, a substantial amount of research is being directed at analyzing new and innovative micro-grid configurations and technologies. This includes evaluating micro-grids operating as a stand-alone system, as a building block in a flexible micro-grid 'network' consisting of various distributed energy resources and consumer loads, or as backup for those connected to a centralized grid. Particularly, in the case of micro-grid / grid integration, challenges associated with switching between grid-connected and island modes, as well as reliability, power quality, and protection requirements, have received limited investigation (Ackeby, 2017).

In all cases, these new and emerging technologies and micro-grid configurations will need to be successfully demonstrated to ensure that they are safe, reliable, and able to meet the strict performance and operational requirements of the communities or applications they are intended to support. To reduce the risks associated with initial deployment, it will also be essential to identify operating, maintenance, and / or repair challenges *before* these systems are delivered to remote communities, where issues will be more costly and challenging to resolve. Having the ability to integrate and operate these systems in a safe, controlled facility that can simulate both nominal and off-nominal operating conditions as well as facilitate operator / technician training (from suppliers and distributors to system integrators and end users) would offer the highest potential for successful integration. For this reason, the NRC is building a *physical* Micro-Grid Testing and Training Facility as well as a *virtual* modeling / simulation capability using the Microgrid Modelica library developed by Modelon. Although this initial study focused primarily on integrated system design and operating strategies that reduce costs, fuel consumption, and greenhouse gas (GHG) emissions, future modeling efforts will include the use of Modelon's Electric Power Modelica library (Modelon, 2019) for control, stability, and transient analysis.

2 Background

2.1 Micro-Grid Facility

The NRC Micro-Grid Testing and Training Facility has been designed to facilitate the analysis of the systems and technologies that support remote community micro-grids, grid-connected stand-by power plants, and off-grid residential, military, or commercial sites. Once construction is complete, this facility will allow the flexible integration of a range of power generation and storage technologies into an existing power network to support their assessment under a variety of real-world conditions. Testing capabilities will include evaluating different power / energy configurations, simulating transient conditions and events, supporting micro-grid control system design and optimization, and performing accelerated lifetime testing to optimize the reliability of pilot-scale systems and their components. Results of this testing will support the understanding, advancement, and deployment of micro-grid technologies, interfaces, and configurations, and be used to inform new policies and safety regulations. The facility will also offer a reduced-risk training environment for end-users to familiarize themselves with the operation and maintenance of new systems and to provide practical feedback to technology developers.

The facility will consist of a unique set of distributed energy resources including a:

- Biomass-fueled Combined Heat and Power (CHP) generator, ~40 kW of electricity (kW_e) and ~100 kW of heat (kW_{th})
- Flat-panel building-integrated solar photovoltaic (PV) system (~10 kW)
- Concentrating mirror Photovoltaic (CPV) system (~10 kW)
- Diesel generator
- Energy storage system

The facility will also have the ability to operate in grid-connected or island mode (i.e., as an isolated micro-grid). (NRC, 2019).

2.1.1 Biomass Combined Heat and Power

The biomass CHP generator, shown in Figure 1, uses renewable biomass as an alternative to fossil fuels to generate both heat and power. The unit gasifies wood chips to produce a synthetic gas ("syngas"), which is then cooled and filtered prior to fueling a conventional spark-ignition internal combustion engine. The engine is coupled to an electric generator to produce ~40 kW_e, as well as ~100 kW_{th} as warm water (Volter, 2019).

Biomass can be viewed as carbon neutral, in that the CO_2 the biomass removes from its environment during growth is equal to the CO_2 released during its combustion, resulting in 'net-zero' carbon emissions; however, because carbon storage in wood products only occurs gradually over a long period of time, compared with the rapid release of CO_2 that occurs when these feedstocks are processed, the environmental benefits of this approach are still the subject of much debate (Harvey, 2018). Typically, only low value biomass feedstocks are used as fuel for these generators (e.g., wood chips or pellets generated from forestry waste streams).
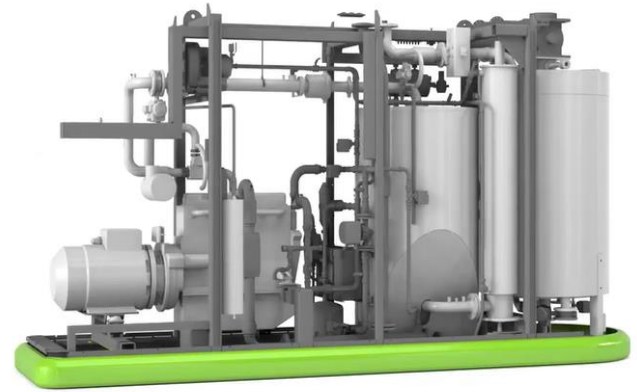

Figure 1. Biomass Combined Heat and Power Generator (Volter, 2019)

2.1.2 Solar Photovoltaic Systems

The solar PV arrays, shown in Figure 2, include both a CPV system and a conventional building-integrated flat panel PV system. Where conventional PV cells generate electricity from both direct and diffuse radiation, CPV systems use stationary mirrors to concentrate a large area of direct sunlight onto a small area of (typically) higher efficiency PV cells to generate electricity. The CPV controller adjusts the position of the solar cell collector to track the focal point of the mirrors across the sun's path to maximize PV energy conversion throughout the day.

Figure 2. NRC building-integrated flat panel (background) and concentrating mirror (foreground) solar PV systems

Some advantages of CPV systems are that they require fewer expensive solar photovoltaic cells relative

to flat panel PVs to generate the same amount of electricity. Disadvantages of CPV systems include the need for moving parts (compared with non-tracking PV systems) and large amounts of direct solar radiation. During cloud cover, CPVs will experience a significant drop in energy production, whereas a conventional PV system will still produce electricity from diffuse radiation (Kraemer, 2017). By including both types of PV systems in the facility power network, both approaches can be assessed to determine how each technology can be used to best support optimal micro-grid operation.

Challenges for all PV generation systems include changes in the availability of sunlight that occur seasonally (e.g., in northern communities, there is little or no sunlight during the winter). Under more favorable conditions, energy production can still vary on the order of seconds to minutes as the result of shading caused by cloud cover, resulting in momentary energy shortfalls that need to be made up by other energy sources. For a surplus of solar energy production, if using a fixed speed diesel generator, PV output may need to be curtailed if the generator is operating at minimum loading. This is an example of where incorporating energy storage systems, such as batteries, can improve the flexibility, performance, and reliability of micro-grid operations. (NRCan 1, 2018).

2.1.3 Diesel Generator (DG)

The NRC micro-grid facility will include a variable speed diesel generator. Although not yet installed, a candidate 80 kW$_e$ diesel generator is shown in Figure 3.
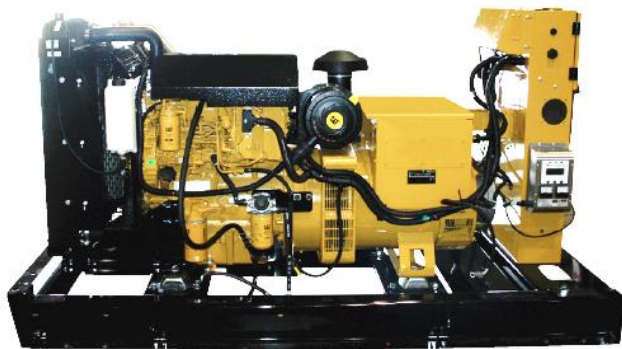

Figure 3. Variable Speed 80 kW Diesel Generator (Caterpillar, 2010)

Conventional fixed speed diesel generators are the most common and reliable systems for power generation; however, due to slow ramp rates, fixed speed generators can struggle to adjust their outputs in response to the variable generation from renewable sources (e.g., PV and wind). Fixed speed generators also have a minimum loading requirement (typically 30-50% of their maximum capacity) that they cannot operate below without reducing the life of the generator, preventing these systems from being significantly

ramped down to reduce fuel consumption and / or accommodate an increase in renewable energy production. In addition, the fuel efficiency of a fixed speed diesel generator drops significantly when the system is operating at or near minimum loading. (NRCan 1, 2018).

Although more complex than conventional fixed speed diesel generators, variable speed generators have faster ramp rates and operate more efficiently at lower minimum loads. They also provide greater flexibility for simulating different test conditions in the context of the NRC's micro-grid facility.

2.1.4 Energy Storage System (ESS)

The ESS can play a key role for micro-grid systems that incorporate renewable energy sources. For example, batteries have the ability to efficiently store surplus energy from renewables or other sources and can reliably supply their stored energy at much faster ramp rates than engine-driven generators. In this way, batteries can rapidly balance power generation with demand, resulting in improved power quality, system flexibility, and stability.

Figure 4. Single battery module from a commercial energy storage system (EV Shop, 2019)

2.2 Micro-Grid Use Cases

Figure 5. Qulliq Energy Corporation (QEC) partial service area map showing Whale Cove (QEC, 2018)

For the purposes of this study, three use cases were defined and analyzed based on the remote northern community of Whale Cove, Nunavut (see Figure 5):

1. 'Island mode' operation of the Whale Cove micro-grid without renewables (present state).
2. 'Island mode' operation of the Whale Cove micro-grid *with* renewables and an energy storage system.
3. Operation of the Whale Cove micro-grid including renewables and energy storage *with* a grid connection to the Manitoba Electrical Grid.

For the use cases that involve renewables (Use Case 2 and 3), technologies that are currently planned / included in the NRC facility power network were explored to see how they might benefit the existing Whale Cove micro-grid. Multiple design, economic, and environmental analyses were performed.

2.3 Micro-Grid Integrated System Model

Although there are multiple modeling tools available for micro-grid design, simulation, and optimization, the platform selected to model the micro-grid test and training facility was the Microgrid Modelica library developed by Modelon, along with a commercial modeling and simulation platform that uses the Optimica Compiler Toolkit for model simulation and optimization (Windahl, 2019). This platform was selected based on its flexible, multi-physics, and highly customizable modeling and optimization framework using the Optimica language extension (Åkesson, 2008), its ability to accommodate models of varying levels of fidelity, its ability to provide physical (rather than only mathematical) representation of micro-grid components, and its ability to support acausal analysis. A review of this and other modeling and optimization tools has been provided by (Windahl, 2019).
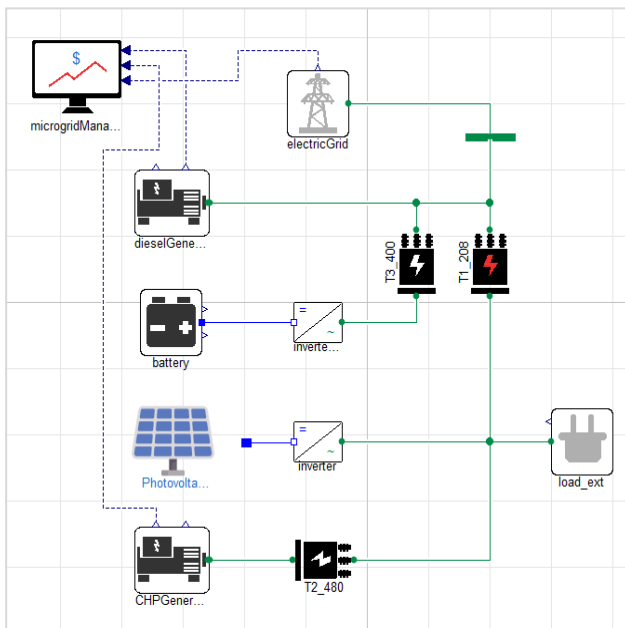

Figure 6. Micro-Grid Integrated System Model

Using the Microgrid Modelica library component models, an integrated system model (see Figure 6) was assembled, including a diesel generator, a battery-based ESS, a simple PV system, a biomass CHP generator, and a simplified representation of a grid connection, conversion components, and a configurable load.

2.3.1 Diesel Generator Model

The diesel generator model can be configured to represent both a fixed or variable speed diesel generator, as AC power is generated based on a control input signal and representative fuel consumption curve. The operational differences between the two types of generators can be defined as a function of acceptable ramp rates and load limits using a micro-grid control model (see Section 2.3.8). For the purposes of this study, however, the diesel generator was modeled as a fixed speed generator, to best represent the generators currently operating at Whale Cove.

Four generators are presently available to provide power to Whale Cove: two 300 kW Caterpillar D3412 units, one 150 kW Caterpillar D3406 unit, and one 320 kW Detroit Diesel (DD) Series 60 unit (ITP, 2019). The parameters for the diesel generator model are summarized in Table 1. Although the maximum rated capacity for Whale Cove is 1070 kW, the max load (demand) was estimated at 402 kW for 2018/19 (QEC, 2017). Despite the excess capacity, it is assumed that the recent acquisition of the DD Series 60 generator signals that older generators (installed in 1991) are in need of replacement (Nunavut, 2001). It is expected that up to two of the four available generators would be operating at one time with the remaining generators operating as backups. In addition, power generation loads / losses are expected to consume 9.6% of the total energy generated in order to satisfy the power demand (QEC, 2017).

Table 1. Diesel Generator Parameters and Constraints

Whale Cove	*Value*
Max Electrical Load for Whale Cove[1]	402 kW
Available Generator Capacity[2]	1070 kW
Max Capacity (DD 60 + D3412)[3]	620 kW
Max Operating Point (80% max)[3]	496 kW
Min Loading (30% of DD 60)[4]	96 kW
Max Capacity for renewables[5]	216 kW
Losses / Station Loads[1]	9.6%
Electricity Rates (averaged)[1]	$1.28 / kWh

[1](QEC, 2017), [2](ITP, 2019), [3]Based on combined capacity of DD 60 + D3412 = 620 kW, with a maximum operating point of up to 80% of the combined rated capacity (620*80% = 496 kW), [4]Defined for DD60 operating alone, [5]Capacity for renewables defined as the max load for Whale Cove (402 kW) minus the combined min loading for DD 60 and D3412 (620*30% = 186 kW): 402 kW – 186 kW = 216 kW.

Fuel consumption correlations for each generator type are listed in Table 2 (Das, 2017). Data points for each generator were plotted and used to generate a regression equation approximating the fuel consumption (L/h) as a function of power (kW) for the four generators operating as a single unit (see Figure 7). Since it is assumed that two generators will operate together to accommodate higher loads, the regression equation does not extend beyond ~80-85% of each individual generator's maximum capacity.

Table 2. Diesel Generator Parameters and Constraints

Fuel Consumption Curves (x = Power [kW], y = Fuel consumption rate [L/h]):	
Cat D 3412[1]	$Y = -0.0006x^2 + 0.5212x - 15$
Cat D 3406[1]	$Y = -0.0004x^2 + 0.3711x - 2.1447$
DD Series 60[1]	$Y = -0.0006x^2 + 0.5212x - 15$
Lin. Approx.[2]	$Y = 0.3329x - 2.5439$

[1](Das, 2017) [2]Linear regression for data at 80-85% generator capacity, assuming up to two generators in operation at a time.
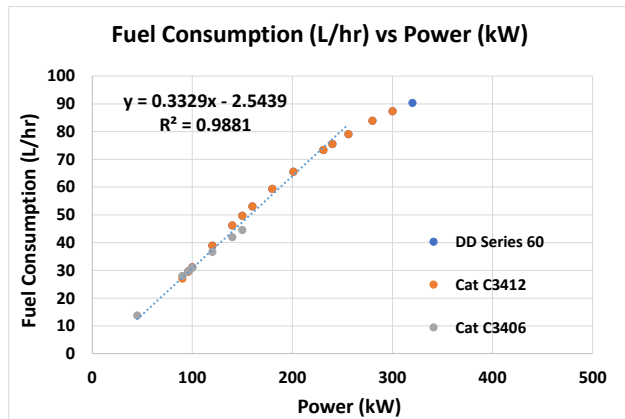
Figure 7. Diesel Consumption Correlation for Whale Cove Micro-grid Fixed Speed Generators

From (NRCan 1, 2018), the capacity to add renewables to this micro-grid was taken as the difference between the minimum loading (30%) output of the DD 60 and D3412 diesel generators (186 kW) and the maximum load for Whale Cove (402 kW). Based on this, the resulting combined PV and CHP maximum power output was limited to ~ 216 kW.

For cost analyses, the total weighted average cost of diesel based electric power generation was taken as $1.28 CDN per kWh based on current residential, commercial, government, and non-government consumer rates (QEC, 2017).

2.3.2 Solar PV Model / Data

The Microgrid library includes a PV model that can be configured to represent both flat panel PV and CPV systems, using panel surface area, solar irradiance, temperature, system capacity, and efficiency; however, for the purposes of this study, a simple PV model was used. PV DC power generation estimates were taken

from the National Renewable Energy Laboratory's (NREL) PVWatts® Calculator for a flat panel solar installation, with an array tilt of 55° and a system size of 176 kW (see Figure 8 and Figure 9). Note that PV output was limited to 176 kW to leave room for the 40 kW CHP power generator. PVWatts data is based on multi-year weather data averages for Whale Cove.
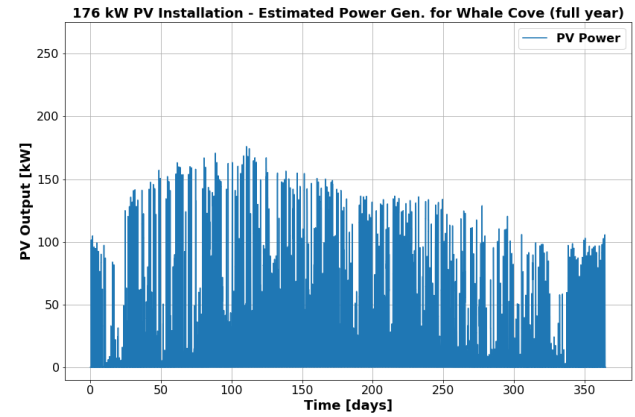
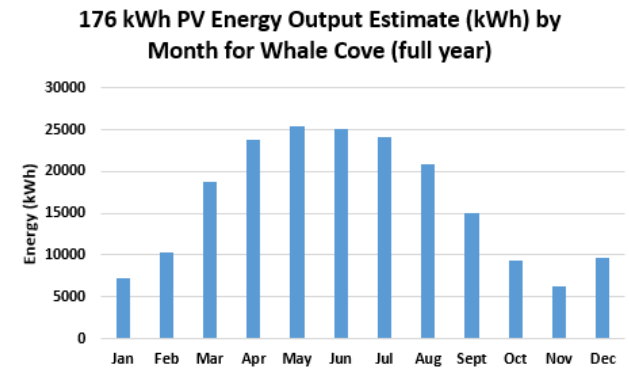**Figure 8.** DC PV Power Estimates for Whale Cove (NREL, 2019)

Figure 9. PV Energy Estimates for Whale Cove (NREL, 2019)

Based on the above data, the total energy produced by this installation for the full year is 195.5 MWh, equivalent to ~ 11% of the estimated total annual energy required for Whale Cove (~1713 MWh, see Table 6).

2.3.3 Battery Model

The battery system model was defined based on battery capacity, assumed minimum and maximum states of charge (SOC), and maximum charge and discharge rates. These and other relevant battery system data are listed in Table 3. Note that a detailed thermal model of the ESS was not applied for this analysis.

Table 3. Battery Model Parameters

Parameter Description	*Value*
Nominal Cell Capacity[1]	120 Ah
Module Configuration	12S1P
Max SOC	80 %

Parameter Description	Value
Min SOC	20 %
Discharge C-Rate (20-80% SOC) [1]	2C
Charge C-Rate (20-80% SOC) [1]	2C
Pack Configuration	98S1P
Total Pack Energy Capacity[1]	42.2 kWh
Pack Voltage[1]	352 V

[1]Data based on real-world battery system characterization tests performed at NRC Vancouver battery testing labs.

2.3.4 Transformer and Inverter Models

Transformers and inverters were characterized using linear efficiency-based models, selectable for voltage or current type units. For this study, voltage units were used and all efficiencies were assumed to be 95% and 96% for transformers and inverters, respectively.

2.3.5 Biomass CHP Generator Model

Parameters for the CHP generator are shown in Table 4. For the purposes of this study, only the electric power generated by the biomass CHP system was integrated into the micro-grid model. Since the Whale Cove generating station is located on the edge of town, connecting to a heat distribution network to make use of the available thermal energy was considered to be cost prohibitive (Nunavut, 2001). Note that the CHP generator's power output was constrained to 40 kW, 3 phase, 480 VAC. Fuel consumption was taken as 1:1 with energy output, per vendor specifications (i.e., 1 kg/h biomass is required to generate 1 kWh electricity) with an electrical efficiency of 20%.

Table 4. CHP Model Parameters

Parameters	Value
Rated CHP electrical / thermal power capacity[1]	40 kW_e / 100 kW_{th}
Fuel consumption[1]	40 kg / hr
Electrical efficiency[1]	20 %
Fuel cost (see below)	$0.78 / kg

[1](Volter, 2019)

For cost optimizations, CHP-based electricity generation was estimated at $0.78 CDN per kWh based on: a delivered cost of $300 / ton of wood pellets (Wood, 2019), $362 / ton shipping costs to Whale Cove from NEAS terminal in Valleyfield, QC (NEAS, 2018), $5 / ton for storage, 5% federal goods and services tax (CRA, 2019), and a Nunavut minimum wage labor cost of $13 / hr (GOC, 2019) with estimated 6 hr / day operational support requirements.

2.3.6 Ideal Grid Model

The use case where the Whale Cove micro-grid includes a connection to the Manitoba electrical grid is based on a feasibility study performed by (Karanasios, 2016) for northern communities in Nunavut. To model this use case, an ideal grid model was used (with constant voltage and frequency). Grid power can be purchased at a cost of $0.13 / kWh and sold back to the grid for $0.02949 / kWh (see Table 5). To connect 1,000 km of transmission lines to multiple Nunavut communities in the area, the estimated cost (in 2015) was ~ $900 million, with $40 million in diesel savings estimated per year. This cost was assumed to have been reflected in the $0.13 / kWh rate, since Manitoba commercial large service rates are $0.075 / kWh (Hydro Manitoba, 2021) and the project's estimated 40-year lifetime to achieve a return on investment. (Karanasios, 2016).

Table 5. Grid Parameters

Manitoba Grid Connection	Value
Grid Purchase Rate for QEC[1]	$0.13 / kWh
Grid Selling Rate[2]	$0.02949 / kWh

[1](Karanasios, 2016), [2](Hydro Manitoba, 2021) – May vary slightly, as this rate applies for ≤ 100 kW systems.

2.3.7 Load Data

The load for each simulation was supplied as a variable input from a real-world load profile sampled at 15 minute intervals (see Figure 10). In the absence of measured data from Whale Cove, load data derived from Old Crow (a northern community in the Yukon) was used. The load data was scaled by a factor of 0.74 to maintain the max load constraint of ~ 402 kW for Whale Cove. In addition, all zero load values were updated to their last non-zero value to avoid a no-load condition during simulation.
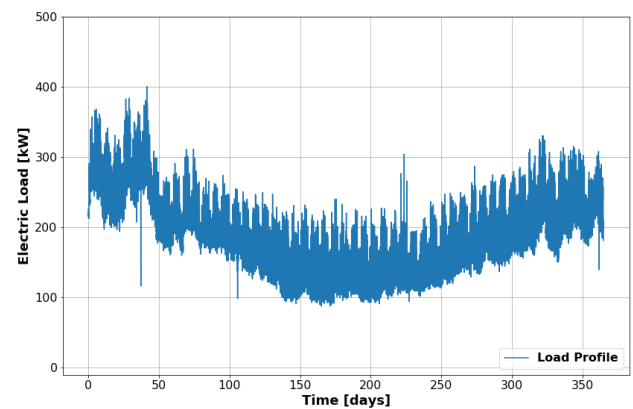

Figure 10. Scaled Jan-Dec 2015 load profile from Old Crow, Yukon

Although Old Crow is situated further north, review of the scaled dataset shows that the annual energy consumed (MWh) is a close match to QEC's published values for annual energy consumption in 2015 for Whale Cove (see Table 6). Based on this, the data set was assumed to be a sufficiently reasonable representation of both daily use and seasonal load variations for Whale Cove.

Table 6. Load Data Validation

Community	MWh
Scaled Old Crow, Yukon[1]	1713
Whale Cove, Nunavut[2]	1732

[1]Calculated from load data file (ATCO Electric Yukon, 2015),
[2]2015 MWh, avg. MWh for 2014/15 and 2015/16 (QEC, 2017)

2.3.8 Microgrid Control and Economy Models

The Microgrid Modelica library includes a micro-grid controller 'MicroGridControl', which contains the control rules for each controllable micro-grid component that is applicable to each use case (additional details provided below). In addition, the library includes an 'Economy' model that computes the cost for each power source.

3 Micro-Grid Analysis

3.1 Use Case 1 Simulation

The first use case analyzed the present diesel generator's ability to meet the power demand at Whale Cove. This simulation was performed as an initial validation of the integrated system model with respect to calculated power / energy generation, fuel consumption, cost, and GHG emissions (typically quantified as kg CO_{2e}), as well as for comparison with subsequent use cases. CO_{2e} emissions are defined as the CO_2 *equivalent* emissions for all combustion products (CO_2, NOx, HC, or other GHGs). An electricity generation rate of $1.28 / kWh was used for diesel-only power generation (see Table 1). CO_{2e} emissions were taken as 2.679 kg CO_{2e} per liter of diesel fuel (BCME, 2014).

3.2 Use Case 2 Simulation

The second use case evaluated the present micro-grid operating configuration at Whale Cove *with* renewables and energy storage added. This included the biomass CHP system, PVs, and a battery ESS.

The first analysis looked at the system's ability to match power / energy generation with demand curves using a rule-based simulation. For micro-grid reliability, the diesel generator was not permitted to operate below 30% or above a maximum of 80% of its rated capacity, with the CHP system and PVs meeting the remaining demand. Batteries were directed to discharge (supply) power when a shortfall was detected, and to charge power when there was a surplus (up to a maximum 2C charge / discharge rate). If power generated was in excess of the demand and available battery capacity, the CHP and PV outputs were curtailed.

Initial simulations were run on Day 0 (winter) and Day 220 (summer) to validate the rule-based simulations response with surplus power (Day 220) and without surplus power (Day 0). Once verified, a simulation was performed for the full year to identify seasonal variations with respect to renewable power

generation and consumer demand, and for comparison with diesel-only operation (Use Case 1).

Subsequent analyses assess the impact of various parameters or operating strategies on cost, fuel consumption, and CO_{2e} emissions, including:

- PV installation size
- Selective use of renewables (i.e. PV only, or CHP only)
- Operating strategies based on seasonal variations
- Battery size under the various operating scenarios considered above (with the goal of eliminating the need for curtailment).

3.3 Use Case 3 Simulation and Optimization

The third use case adds a bi-directional grid connection to the Manitoba electric system. A $0.13/kWh purchase rate and $0.02949/kWh selling rate were used (see Table 5). Power was purchased from the grid when a shortfall was detected and sold back to the grid when there was a surplus. For reliability, the diesel generator was not permitted to operate below 30% of its rated capacity

4 Results & Discussion

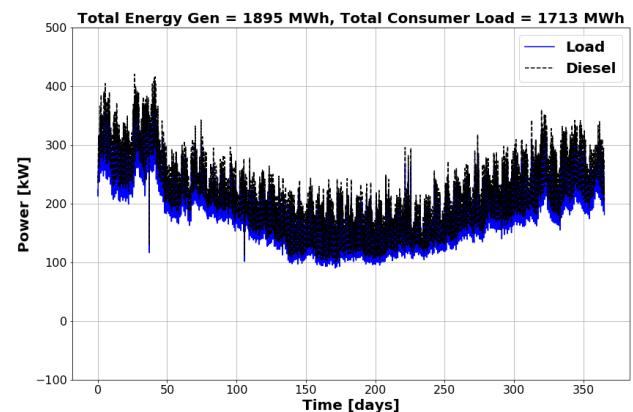### 4.1 Use Case 1 Simulation

Figure 11. Use Case 1 – Whale Cove power generation using diesel generators only (full year)
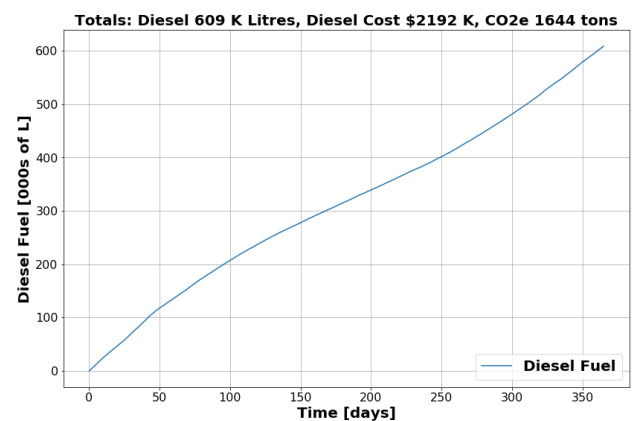

Figure 12. Use Case 1 Simulation – Baseline cost for diesel-only power generation (full year)

The results for Use Case 1, micro-grid operation with the diesel generator only, are shown in Figure 11 and Figure 12. Diesel power is shown to correctly track load over the course of the simulation, with a slightly higher power output level than consumer loads to cover upstream losses and station loads (see also, Table 1). A comparison of literature values ('Ref. Data'), independently calculated values using load data in Excel ('Calc. Data'), and simulation results ('Sim. Data') are provided in Table 7.

Table 7. Baseline Simulation Validation

Descript.	Ref. Data[1]	Calc. Data[2]	Sim. Data[3]
Load (kWh)	1732 K	1713 K	1713 K
Gen (kWh)	1910 K	1895 K	1895 K
Fuel (L)	532 K	609 K	609 K
CO_{2e} (tons)	1479	1644	1644
Cost (CDN$)[4]	2216 K	2192 K	2192 K

[1](QEC, 2017) and (ITR, 2019), [2]Calculated independently in Excel using scaled load data file (ATCO Electric Yukon, 2015), [3]Results calculated from model / simulation, [4]Based on load (kWh) at $1.28 / kWh (present day averaged cost).

Calc. Data and Sim. Data are equivalent, as required. All corresponding values in Table 7 compare closely with published data for Whale Cove, with the most notable discrepancy being fuel consumption and CO2 emissions. A closer evaluation reveals that QEC uses a fuel efficiency value of 3.6 kWh / L as a compared to a 3.1 kWh / L average fuel efficiency value derived here from the diesel consumption curves shown Figure 7. Using QEC's efficiency value, both the Excel and simulation calculations for annual fuel consumption are 512 K liters (vs. 532 K liters from QEC). Since CO_{2e} is directly proportional to fuel consumption, these values follow. However, it is noted that values used by (ITR, 2019) are based on more recent actual data with slightly higher load values (1755 K kWh) and an average fuel efficiency of 3.2 kWh / L. Since load discrepancies are expected, based on using the scaled load profile from Old Crow rather than Whale Cove, and since fuel efficiency values from (ITR, 2019) are much closer to the average efficiency values derived from the fuel consumption curves, the diesel consumption rates and CO_{2e} emissions rates used by this study were deemed acceptable and retained for the remainder of the analysis.

In addition to the results shown above, the 'net power' was plotted versus time (see Figure 13). For this use case, the net power represents the total minimum diesel electric power generated (at minimum loading, or 30% of the generator's rated capacity: 96 kW) minus the demand (load):

$$P_{net} = Min\ Diesel\ (96kW) - Load$$

This chart shows that the diesel generator will always need to operate above minimum loading of 96 kWh (see Table 1) to generate enough power to meet the demand. Alternately, it indicates that there is an opportunity for renewables to displace diesel on a continuous basis.
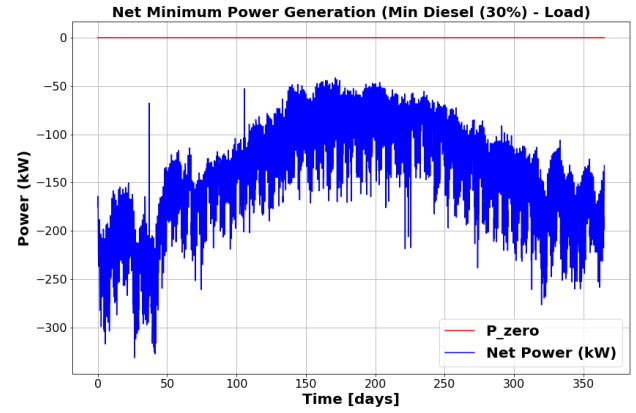

Figure 13. Use Case 1 Simulation - Net Power (full year)

4.2 Use Case 2 Simulation and Optimization

Initial results for Use Case 2 (micro-grid operation with a diesel generator, CHP generator, PVs, and a battery ESS) are shown in Figure 14. For both Day 0 (winter) and Day 220 (summer), the total power generated from all sources directly matches the load (with line losses accounted for), providing some initial validation of the rule-based simulation.
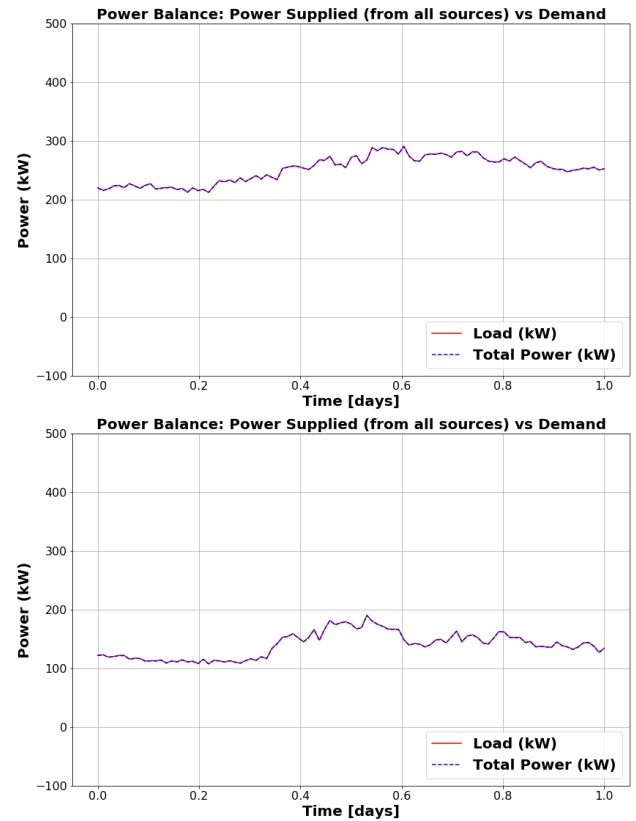

Figure 14. Use Case 2 Power Balance – Top: Day 0 (winter) and Bottom: Day 220 (summer)

These results also show that:
- The demand in winter is almost 100 kW higher than the demand in summer.
- The total demand in summer is very close to the minimum loading level (96 kW) for the diesel generator (showing that there is more room to accommodate power from renewables in the winter than in the summer).

The simulation results in Figure 15 show the power generation from each source with respect to load for Day 0. These results show the system behaving in accordance with the rules defined in the micro-grid controller (see Section 3.2). The diesel MG ('micro-grid') power is tracking below the load level, as the CHP generator is now providing a continuous 40 kW power output to the micro-grid. Since the initial SOC is set at 50%, at the beginning of the simulation, the battery is supplying power (discharging), until it reaches its minimum state of charge (20%). Midday, when PV power is available, the diesel power output is reduced accordingly (but still remains above the 96 kW minimum loading level). Because there is no case where there is surplus of power, the battery does not have the opportunity to recharge.
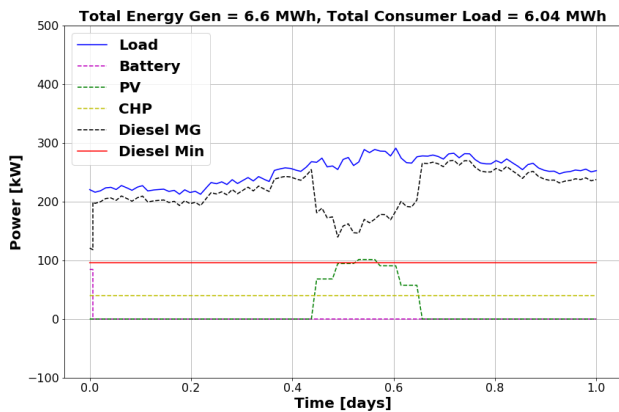

Figure 15. Use Case 2 – Day 0 – Power Generation

In Figure 16 and Figure 17, the operating costs, fuel consumption, and CO_{2e} emissions are shown for Day 0.
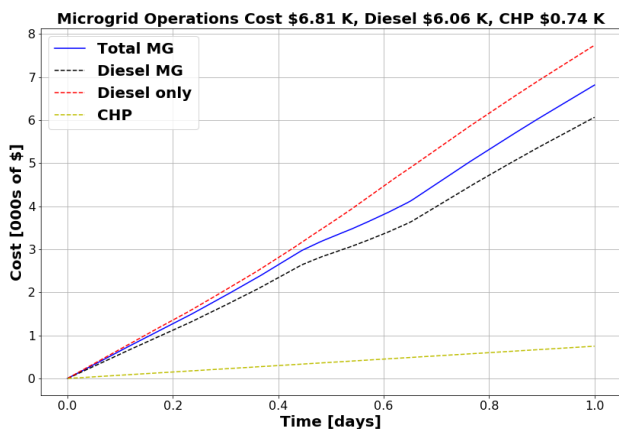

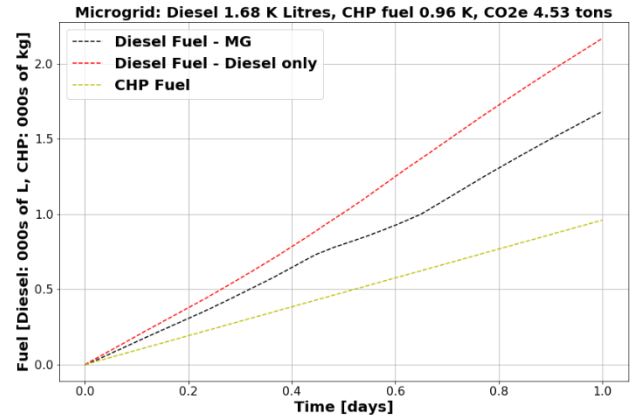**Figure 16.** Use Case 2 – Day 0 – Operating Costs

Figure 17. Use Case 2 – Day 0 – Fuel and CO_{2e}

In each chart, the Use Case 1 results (diesel-only) are compared with Use Case 2 results (diesel plus renewables and energy storage). Table 8 provides a detailed comparison between these two use cases.

Table 8. Simulation Use Case 1&2 Comparison – Day 0

Description	Use Case 1	Use Case 2
Total Energy Generated (MWh)	6.8	6.6
Diesel Fuel (L)	2.16 K	1.68 K
CHP Fuel (kg)	--	0.96 K
CO_{2e} (tons)	5.85	4.53
Cost (CDN$)	7.74 K	6.8 K
Load (MWh)	6.04	6.04

For Day 0 (winter), after only 1 day of operation, the results show a reduction in diesel consumption, CO_{2e} emissions, and micro-grid operating costs. In addition, the total energy that must be generated by the system is lower than in the diesel-only case. This is the result of having a higher PV load line efficiency (0.96) compared to the diesel load line efficiency (0.903).
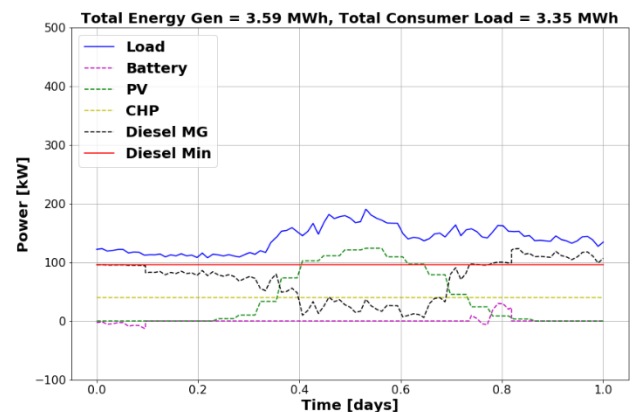

Figure 18. Use Case 2 – Day 220 – Power Generation

On Day 220 (summer), with lower overall demand and higher PV power generation relative to Day 0 (winter), a power surplus exists for a large part of the day. In order to define 'surplus' power for Use Case 2, net power needs to be defined.

For Use Case 2, net power is defined as:

$$P_{net} = Min\ Diesel\ (96kW) + CHP\ (40\ kW) + PV\ power - Load$$

Surplus power will exist when the net power exceeds both the load *and* the available capacity of the battery to store the excess energy. At the beginning of the simulation, the battery can be seen to initially charge due to the availability of surplus power. Once the battery is fully charged, however, the diesel generator power set-point dropped below the acceptable minimum loading level (red line), risking possible damage to the generator. Midday, as PV power became available, the diesel generator power continued to be driven down well below acceptable operating levels. To resolve this, the simulation was re-run with CHP and excess PV power curtailed (see Figure 19).
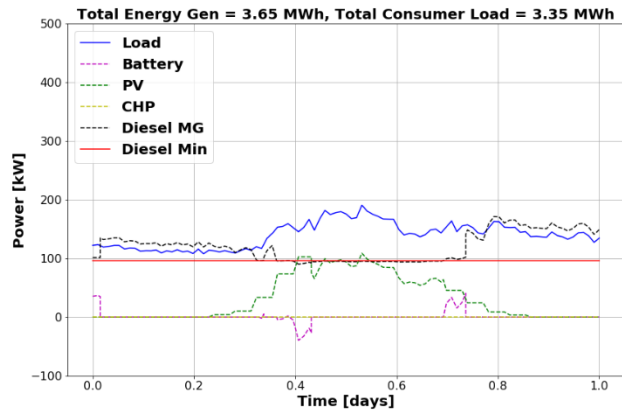

Figure 19. Use Case 2 – Day 220 – Power Generation with curtailment
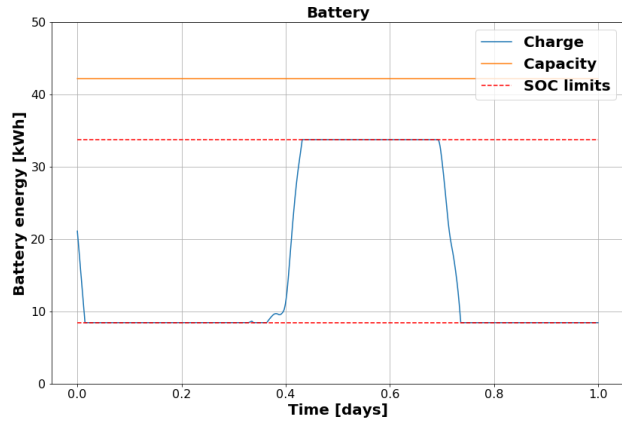

Figure 20. Use Case 2 – Day 220 - Battery Response with CHP and PV curtailment

Figure 19 shows Day 220 with the CHP system offline and excess PV output curtailed. With the reduction in power from renewables, the diesel generator is able to track near or above its minimum loading level. The battery can also be seen to charge when there is a surplus, and discharge when PV output starts to drop, while respecting SOC limits (see Figure 20). Table 9 shows the detailed comparison between the diesel-only and curtailed Day 220 simulation results.

Despite taking the CHP system offline and curtailing PV power, improvements can still be observed. Note again that the total energy generation required is lower for the micro-grid with renewables and storage, as it is more efficient than the diesel-only use case.

Table 9. Simulation Use Case 1&2 Comparison – Day 220 - Curtailed

Description	Use Case 1	Use Case 2
Total Energy Generated (MWh)	3.71	3.65
Diesel Fuel (L)	1.17 K	0.89 K
CHP Fuel (kg)	--	--
CO_{2e} (tons)	3.17	2.41
Cost (CDN$)	4.29 K	3.32 K
Load (MWh)	3.35	3.35

With the Day 0 and Day 220 results verified, the next step was to run the simulation for the full year with CHP and PV at full power to determine seasonally when a 'Day 0' approach (without curtailment) or a 'Day 220' approach (with curtailment) could be beneficial. From the plot of net power (P_{net}) versus time, surplus power could be expected between ~ Day 50 and 300, when $P_{net} \geq 0$ (see Figure 21). By operating the micro-grid without CHP during these periods of surplus, the net power can be reduced to minimize PV curtailment.
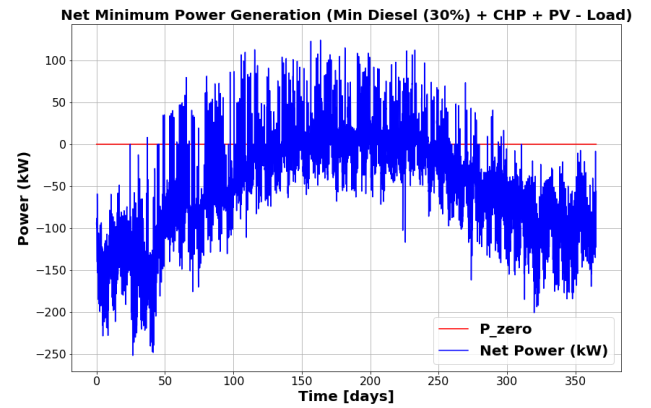

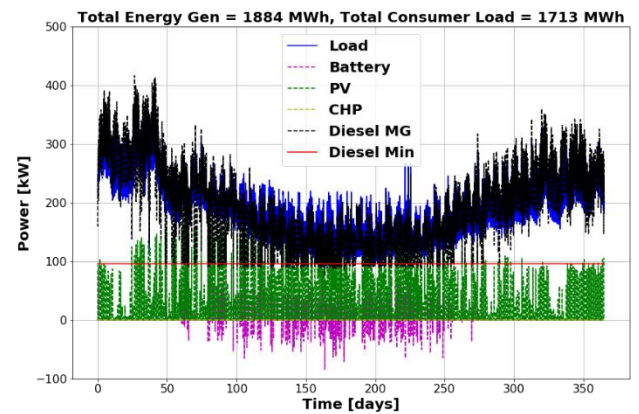**Figure 21.** Use Case 2 - P_{net} without curtailment (full yr)

Figure 22. Use Case 2 - Power Generation with curtailment (full year).

For the purposes of this analysis, 'seasonal' operations have been defined as running the micro-grid *without* curtailment of renewables in the winter, when there is higher consumer demand and lower PV production, and *with* curtailment (shutting the CHP generator down and curtailing excess PV power) in the summer, when demands are lower and PV production is higher. As a basis for comparison, the simulation for Use Case 2 was re-run *with* curtailment for the full year (see Figure 22). The simulations were then re-run *without* curtailment for Days 0-50 and Days 300-365, and *with* curtailment for Days 50 to 300. The total energy generated, fuel consumption, CO_{2e}, and cost (in Canadian dollars) were then added together to compare the benefits of taking a seasonal operating approach. The results of this comparison are provided in Table 10.

Table 10. Simulation Comparison – Seasonal Operation

Description	*Curtailed (full year)*	*Seasonally Curtailed*	*Diesel-Only Use Case 1*
Total Energy Generated (MWh)	1884	1890	1895
Diesel Fuel (L)	544 K	506 K	609 K
CHP Fuel (kg)	--	110 K	--
CO_{2e} (tons)	1470	1365	1644
Cost (CDN$)	1969 K	1920 K	2192 K

Although the energy efficiency of full curtailment is slightly higher, taking a seasonal approach results in the lowest operating cost, diesel consumption, and CO_{2e} emissions.
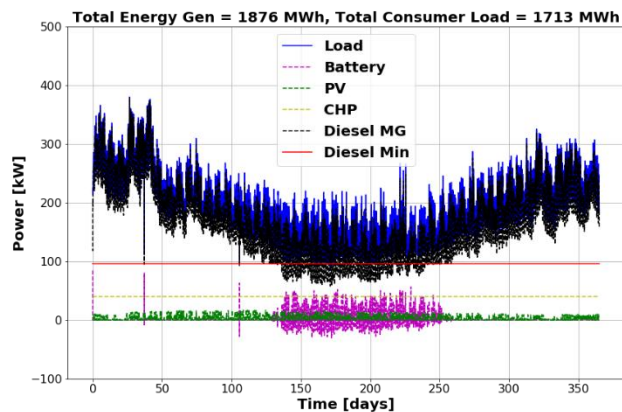
Figure 23. Use Case 2 – Power Generation without curtailment – PV installation re-scaled to 10%

The next analyses look at the impact of various parameters or operating strategies on cost, fuel consumption, and CO_{2e} emissions. First, simulations were run to see how a change in size of the PV installation would impact the overall cost, fuel consumption and CO_{2e} emissions. Multiple simulations

were run with the PV installation re-scaled from 0.1 to 1.0 of its current size (176 kW) initially without curtailment; however, even at the lowest PV installation size (10% of 176 kW), the diesel generator was forced to drop below its minimum loading level in the summer to accommodate surplus power (see Figure 23), getting progressively worse as the installation size increased. Simulations were next re-run *with* curtailment. The results are included in Figure 24.
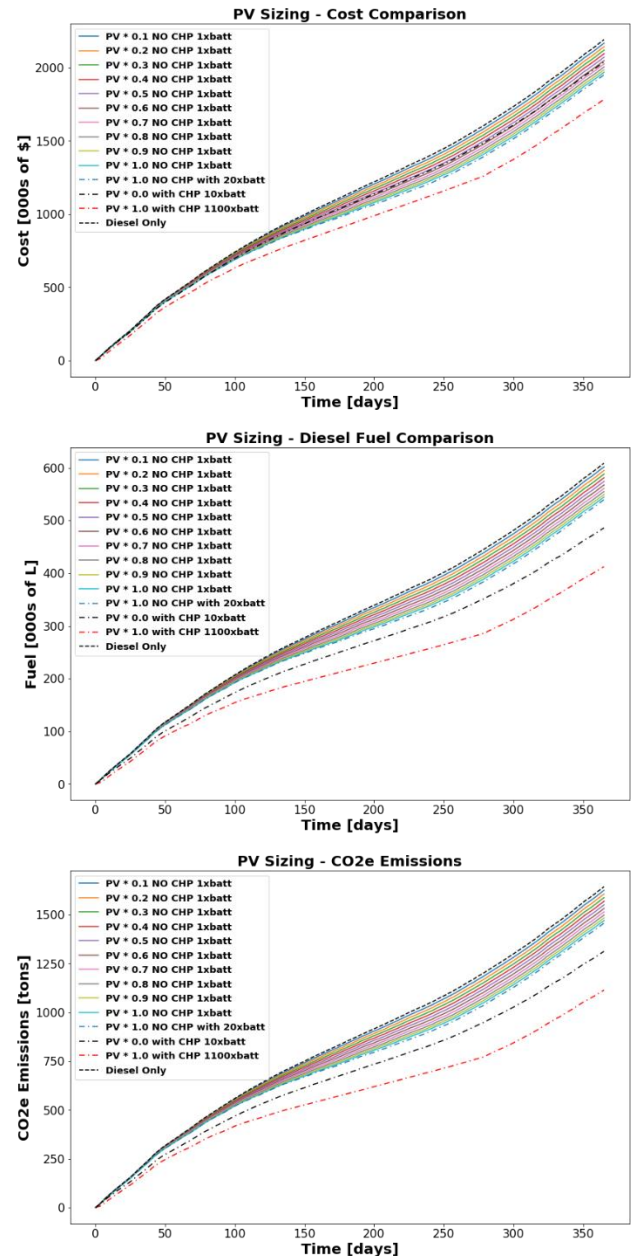
Figure 24. Use Case 2 – Impact on Cost, Fuel, and CO_{2e} for changes in PV size, battery size, and ops. (full year)

The black dashed line at the top of each plot in Figure 24 shows the diesel-only (Use Case 1) results for cost, fuel, and emissions for comparison. The next ten lines in the plot show how these same parameters vary with PV installation size, ranging from 17.6 kW (0.1 x original PV installation size) to 176 kW (1.0 x original

PV installation size). CHP was offline for each of these simulations, and excess PV power was curtailed, as required. Initial review of this data showed that during the winter season (~ Day 0-50 and 300-365), the cost, fuel consumption, and emissions were largely unaffected by the PV size, as the PV energy generation was low (relative to other sources) due to the limited availability of winter sunlight. During the rest of the year, the differences with respect to installation size became more apparent, with all parameters decreasing with respect to PV size. Note that in all cases, PV curtailment was required. Because the amount of surplus power that needed to be curtailed increased with increasing PV size, eventually the benefit of increasing PV size diminishes. Although this was not easy to see in the initial 0.1 – 1.0 test range, the range was expanded incrementally up to 2.0 x original PV installation size. The results are shown in Figure 25. Note that only operating cost was shown, as CO_{2e} emissions are directly proportional to the fuel used, which is directly proportional to cost.
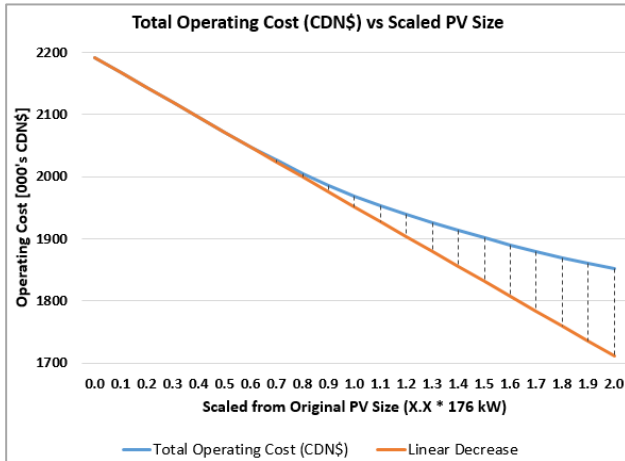

Figure 25. Use Case 2 – Total Operating Cost ($CDN) vs Scaled PV Size (full year)

In addition to varying PV installation size, micro-grid operation was also simulated with CHP and energy storage only (i.e., PV output = 0 kW). As with the PV simulations, there was substantial surplus power that needed to be curtailed to maintain balance, implying that the battery was largely undersized for this installation. To address this, multiple simulations were run for PV only, CHP only, and PV / CHP combined operation to find the battery size that eliminated the need for curtailment. The results are shown in Figure 26, and were included in Figure 24 for comparison with previous simulations. In each chart, the greatest reduction possible is when both CHP and full PV power are available with no surplus power (i.e., when the battery is large enough that no curtailment is needed). For the case where CHP and PV are available continuously throughout the year, a battery size of 1100 * 42.2 kWh was required to eliminate the need for curtailment; when operated seasonally, however (with

CHP offline from Days 50-300), the battery size could be substantially reduced down to 20*42.2 kWh while still achieving the same reduction in cost, diesel fuel consumption, and CO_{2e} emissions. This demonstrates the importance of accounting for seasonal differences when developing operating strategies for these communities.
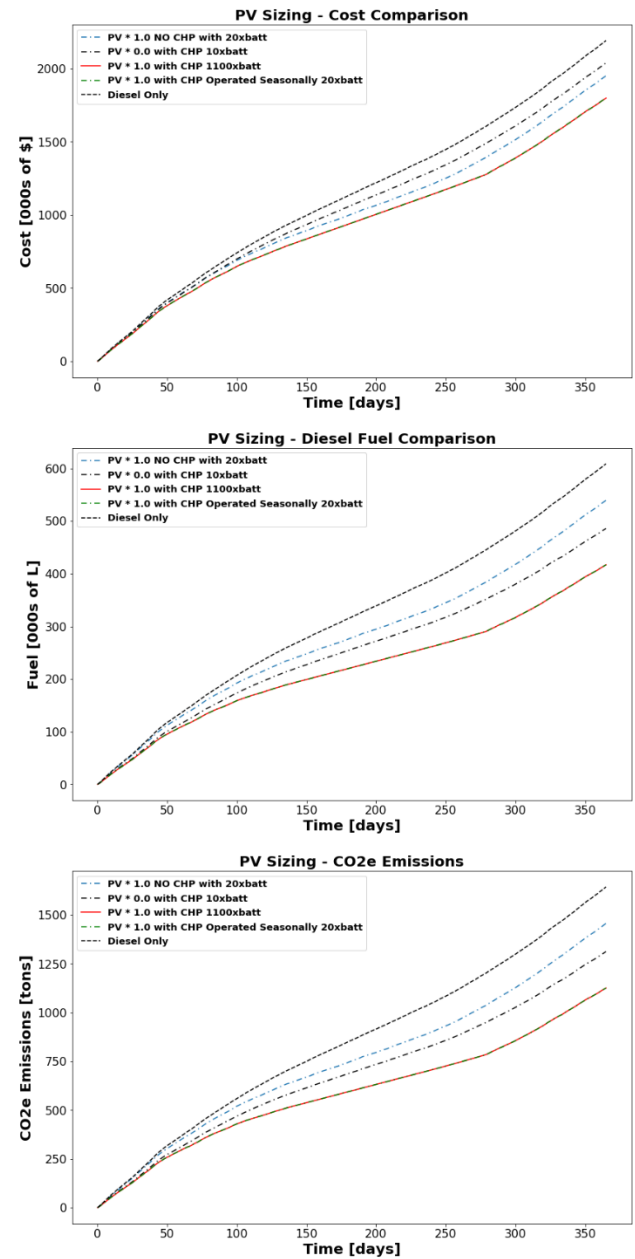

Figure 26. Use Case 2 – Impact on Cost, Fuel, and CO_{2e} for changes in PV size, battery size, and ops. (full year)

Having looked at optimal micro-grid component sizing and operating strategies, the next step is to look at the investment cost of each micro-grid component. For each case study shown in Figure 26, the cost of the installation and return on investment was computed. For PV system costs, the cost of $2.85 (CDN$) / Wac was used to include inverter costs (NREL, 2017). For the battery system, $509 (CDN$) / kWh was used, which

includes battery management and inverter costs (NREL, 2019a). The total cost for the 40 kW CHP generator unit was ~ $290K (or, $7.25 (CDN$) / Wac) (Volter, 2016).

	Operating Cost (000's $CDN)	CO2e Emissions (tons)	Annual Savings (000's $CDN)	Installation (000's $CDN)	Break Even (yrs)
Diesel Only	2192 K	1644	0	0	0.00
PV Only (17.6 kW)	2168 K	1625	24 K	71.6	2.98
PV Only (176 kW)	1969 K	1470	223 K	523.1	2.35
PV Only (176 kW) + 20xBatt	1951 K	1456	241 K	931.2	3.86
Seasonal Ops (see Table 10)	1920 K	1365	272 K	813.1	2.99
CHP Only + 10xBatt	2039 K	1312	153K	504.8	3.30
Full PV+ CHP + 1100xBatt	1784 K	1114	408 K	24419.4	59.85
Seasonal Ops with 20xBatt	1784 K	1114	408K	1221.2	2.99

Figure 27. *Use Case 2 Economic Analysis*

Although seasonal operations with sufficient battery capacity to eliminate the need for curtailment (20x the original battery capacity of 42.2 kWh) requires a slightly higher initial investment, it can be seen that the payback period ('break even' point) is less than all other options, with the exception of a PV only installation (176 kW + 1 x 42.2 kWh batt). However, since the annual savings with the PV only installation are just over half of the potential savings for seasonal operation (+ 20 x 42.2 kWh batt), the seasonal approach was determined to be the most favorable.

4.3 Use Case 3 Simulation

Use Case 3 represents grid-connected operation of the micro-grid (including the diesel generator, CHP generator, PVs, battery ESS, and a connection to the Manitoba electric grid). The definition of net power (P_{net}) is the same as in Use Case 2. Note that for these simulations, the original battery size (42.2 kWh) was used as the grid connection will provide an alternate load (for $P_{net} \geq 0$) and source (for $P_{net} \leq 0$) for the micro-grid. In both cases, the grid will only engage once available battery capacity (charge or discharge) has been used.

To start, Day 0 (winter) and Day 220 (summer) were re-evaluated as an initial verification of the rule based simulation in grid-connected mode. The results are shown in Figure 28 and summarized in Table 11 and Table 12. For Day 0, the diesel generator operates at the minimum loading level (96 kW) and the CHP generator provides continuous power at 40 kW. The battery begins at 50% SOC and can be seen to discharge power at the start of the simulation. As soon as battery power is depleted, the grid comes online, providing any additional power needed to satisfy demand. For Day 220, the system behavior is the same; however, where a surplus power is available, power is sold back to the grid. This can also be seen in the negative price for 'Grid Cost' in Table 12, where more power is sold to the grid than purchased.
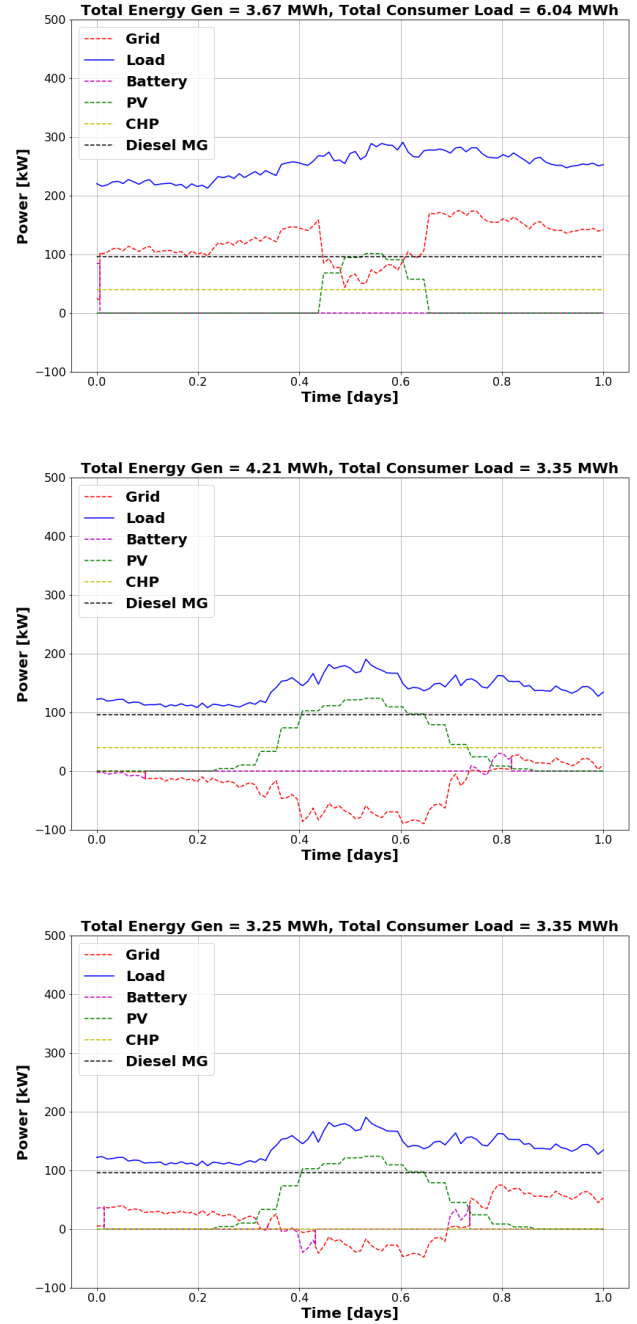

Figure 28. Power Gen. - Use Case 3 - Day 0 (top), Day 220 with CHP (middle), Day 220 without CHP (bottom)

Table 11. Sim. Use Case 1, 2 & 3 Comparison – Day 0

Description	Use Case 1	Use Case 2	Use Case 3
Total Generated / Load (MWh)	6.8 / 6.04	6.6 / 6.04	3.7 / 6.04
Diesel Fuel (L)	2.16 K	1.68 K	0.70 K
CHP Fuel (kg)	--	0.96 K	0.96 K
CO_{2e} (tons)	5.85	4.53	1.90
Grid Cost (CDN$)	--	--	380.00
Total Cost (CDN$)	7.74 K	6.8 K	3.79 K

Table 12. Sim. Use Case 1, 2 & 3 Comparison – Day 220 with CHP (3a), without CHP (1, 2, and 3b)

Description	Use Case 1	Use Case 2	Use Case 3a	Use Case 3b
Total Gen. / Load (MWh)	3.71 / 3.35	3.65 / 3.35	4.21 / 3.35	3.25 / 3.35
Diesel Fuel (L)	1.17 K	0.89 K	0.70	0.70
CHP Fuel (kg)	--	--	0.96	--
CO_{2e} (tons)	3.17	2.41	1.90	1.90
Grid Cost (CDN$)	--	--	-10.70	70.20
Total Cost (CDN$)	4.29 K	3.32 K	3.40 K	2.73 K

Because the cost of producing power using the CHP generator is higher than the purchase cost of electricity from the grid, an additional simulation was run for Day 220 without CHP ('Use Case 3b' in Table 12). This seasonal approach once again proves to be the best option for reducing cost, diesel fuel consumption, and CO_{2e} emissions. Although the battery plays a minor role due to its limited capacity, it could play a very important role in maintaining power quality or providing a buffer through various transient conditions including a switch between island and grid-connected modes. Sizing the battery for these conditions, however, is outside of the scope of this study.

The final assessment for Use Case 3 looks at the economic merits of different operating strategies for this configuration (see Figure 29). For the purposes of comparison, diesel-only (Use Case 1) and the best case from Use Case 2 (seasonal operations with 20xbatt) were included in the table. For Use Case 3, the system was operated using a seasonal approach (CHP offline during days 50-300) and fully curtailed (no CHP power for the full year). As expected, the grid greatly improves operational savings overall; however, due to the high initial investment, it will take much longer to recoup costs. In the case of full CHP curtailment (no CHP), higher savings can be realized as the cost of CHP power is higher than the cost to buy it from the grid.

	Operating Cost (000's $CDN)	CO2e Emissions (tons)	Annual Savings (000's $CDN)	Installation (000's $CDN)	Break-even (yrs)
Diesel Only	2192 K	1644	0	0	0
Use Case 2 Seasonal Ops with 20xBatt	1784 K	1114	408K	1221.2	2.99
Use Case 3 Seasonal Ops with Grid	1098 K	696	1094 K	Grid Install Cost + 813.1 K	22.5
Use Case 3 Full Curtailment with Grid	1083 K	696	1109 K	Grid Install Cost + 523.1 K	22.5

Figure 29. Use Case 3 Economic Analysis

Note that the breakeven value of 22.50 years for the grid-connected case was computed as the installation cost ($900M) divided by diesel savings across multiple Nunavut communities ($40M) (Konstantinos, 2016).

4.4 Use Case 3 Optimization

In addition to the rule-based simulation that has been used up to this point, optimization tools are also available for the Modelon Microgrid library using the Optimica Compiler Toolkit. Although computing resources were a limiting factor, short 1 day optimizations were run to demonstrate the capability of these tools in supporting additional analyses.

The first optimization performed looked to minimize micro-grid operational costs for Use Case 3 (in grid-connected mode). This use case was selected so that the state of all components in the full integrated system model would be included in the optimization. For initialization, specific parameters were set to known optimal values to reduce the time required for the optimization to converge (starting values for CHP and diesel generators were set to 0 kW and 96 kW, respectively, with battery SOC = 20%). An optimization was then performed for Day 0 and Day 220 to support comparison with the results previously obtained.

Note that for the optimizations, the rules defined for the rule-based simulations do not apply. Instead, the optimization seeks to minimize a pre-defined objective function while respecting specific constraints. For this initial cost optimization, the objective function and constraints are shown below:

$$\int_{t_i}^{t_f} d\big(total\ cost(t)\big) + (d(P_{batt})^2 + d(P_{diesel})^2 + d(P_{CHP})^2)dt$$

$$total\ cost(t) = cost_{grid}(t) + cost_{diesel}(t) + cost_{CHP}(t)$$

$$P_{batt}: Battery\ Power$$

$$P_{diesel}: Diesel\ Power$$

$$P_{CHP}: CHP\ Power$$

$$P_{diesel} \geq 96\ kWh\ (min\ loading)$$

Each squared term was included to minimize abrupt changes in these control parameters during the optimization. The results are shown in Figure 30.
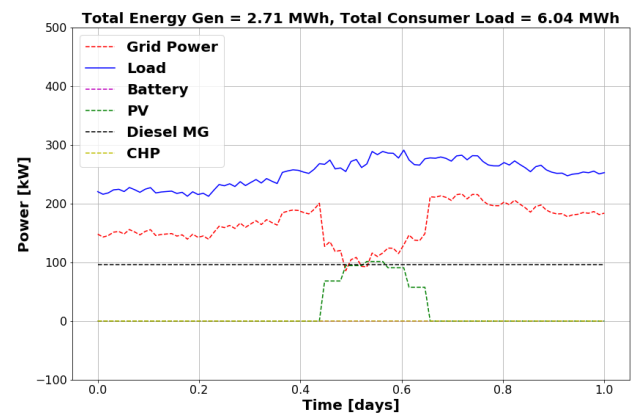

Figure 30. Use Case 3 Optimization - Day 0

With the rule-based simulation, multiple runs were required to evaluate different operational strategies in order to identify an 'optimal' operating approach; with the optimization, the results directly converged on the

optimal solution without the approach being pre-defined (i.e., the operating condition for grid-connected mode where CHP = 0 kW and diesel = 96 kW, with grid power making up the remaining power required).

The results for the cost optimization performed on Day 220 directly match the 'optimal' results shown in Figure 28 (lower plot) with the exception of the battery. In the rule-based simulation, the battery charged and discharged more rapidly (Figure 31 - bottom). With the optimization, the battery charged and discharged more gradually, having an almost imperceptible impact on the overall power balance (Figure 31 - middle and top). Since batteries prefer to be charged and discharged slowly, with costs, fuel consumption, and emissions remaining equal, the optimized approach is preferable with respect to maintaining battery health and having the potential to extend battery life.
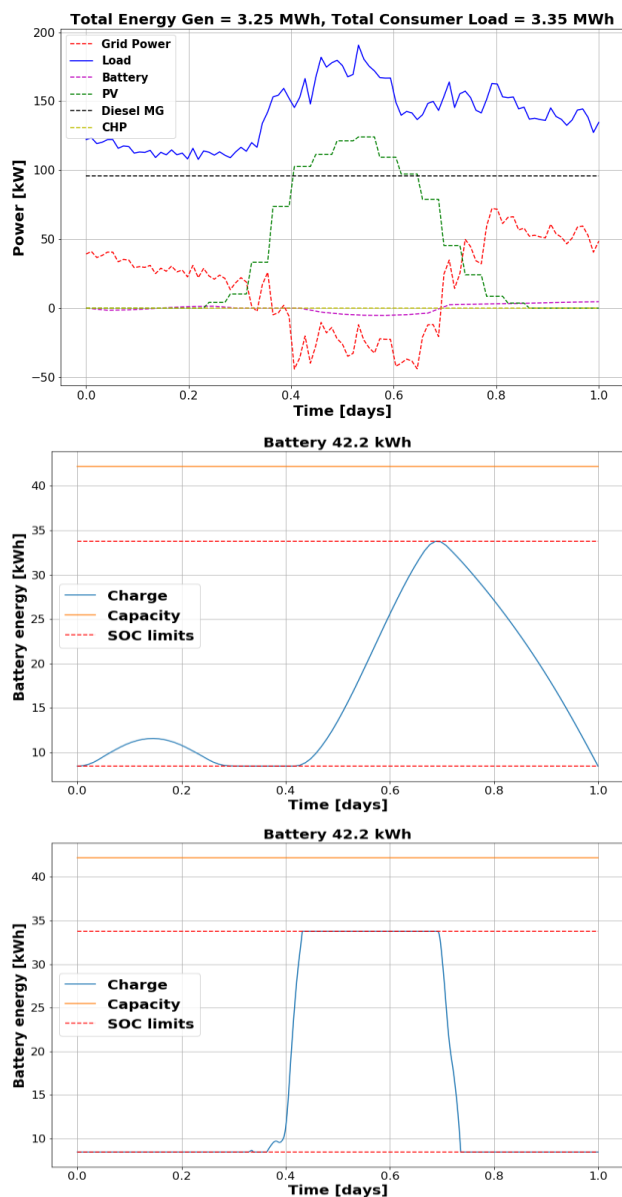

Figure 31. Use Case 3 - Optimization - Day 220 - Power Generation (top), Optimization Battery (middle), Rule-Based Simulation Battery (bottom).

5 Conclusions

The introduction of renewable energy sources into micro-grid applications offers the potential to reduce operating costs, reliance on diesel, and the environmental impact of micro-grids powered solely by diesel power plants. Having the ability to optimize system design, evaluate performance, and quantify the potential economic benefits of micro-grids that include renewables will be essential to moving these technologies forward. By using the Microgrid Modelica library models, many high-level analyses and optimizations can be performed to answer initial questions on equipment sizing, energy balance, fuel usage, GHG emissions, and costs. Combined with the physical Micro-Grid Testing and Training Facility, this simulation platform will help to support the future integration of renewable energy generation and storage technologies into a variety of micro-grid applications.

5.1 Future Work

Plans for future work include integrating higher fidelity models from Modelon's Electric Power Modelica library into a comparable model framework to analyze the micro-grid's response to transient conditions on both the supply and demand side with respect to performance, stability, and reliability (e.g., analyzing stability during switching from grid connected to island mode, system performance and limitations during rapid demand changes, etc.). The Microgrid Library used for this work will be integrated into Modelon's Thermal Power Library (Modelon, 2019) and available for simulation and optimization analyses on the simulation platform Modelon Impact (Modelon, 2020).

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