Micro-grid Design and Cost Optimization using Modelica

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Abstract

This paper describes the modeling of 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, integrated system models were assembled using the Microgrid Modelica library, developed by Modelon. Next, three use cases were defined based on a scaled down version of the Whale Cove, Nunavut micro-grid operating in: 'island mode' without renewables (present mode), island mode *with* renewables, and grid-connected mode. Various simulations, as well as design and economic optimizations were then performed. Through these analyses, it was shown that each parameter domain could be successfully assessed using this modeling framework, demonstrating the flexibility of both the modeling platform and the potential of the physical test facility to support in-depth analysis for different micro-grid configurations, technologies, and applications.

Keywords: Micro-grid, remote area, distributed energy resources, renewables, model, 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, these remote micro-grids generate significant emissions and are expensive to operate. Introducing renewable energy sources provides an opportunity to reduce both operating costs and emissions but, due to their variable energy output, they can add operational complexity with respect to maintaining the overall control and stability of the electrical system. New and emerging technologies are continuously being developed to address these and other challenges, but in order to reduce risk during deployment, it is essential that both the technologies and their applications are well understood. Even then, the successful integration of these technologies is not guaranteed, particularly if they require a high initial investment, have limited reliability, are not easy to operate, maintain, or repair, or if sufficient training is not provided.

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 electric micro-grid 'network' consisting of various distributed energy resources and customer loads, or as a compliment 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 components and micro-grid configurations will need to be analyzed and demonstrated to ensure that they are safe, reliable, and can meet the strict performance and operational requirements of the communities or applications they support. For this reason, the NRC is currently building a *physical* micro-grid testing and training facility as well as a complimentary *virtual* facility prototyping capability using the Microgrid Modelica library developed by Modelon. Although this initial study has focused on high level design and cost optimization, future model developments will include the use of Modelon's Electric Power Modelica library, for control, stability, and transient analysis (Modelon, 2019).

2 Background

2.1 Micro-Grid Facility

The NRC micro-grid testing and training facility has been designed to enable the analysis of the systems / technologies that support remote community micro-grids, grid-connected stand-by power plants, and off-grid residential, military, or commercial sites. 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 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 the system and components. Results of this testing will support the understanding, advancement, and deployment of micro-grid technologies, interfaces, and configurations, and will be used to inform new policies and safety regulations. The facility also offers a reduced-risk training environment for personnel to familiarize themselves with the operation and maintenance of new systems and provide practical feedback to technology developers.

The facility power network will consist of a unique set of distributed energy resources (NRC, 2019) including a:

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

2.1.1 Biomass Combined Heat and Power (CHP) Unit

The Biomass CHP unit, shown in Figure 1, uses renewable biomass as an alternative to fossil fuels to generate both heat and power. The unit converts wood chips to synthetic gas (“syngas”), which is then cooled, filtered, and mixed with air before being supplied to an 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).

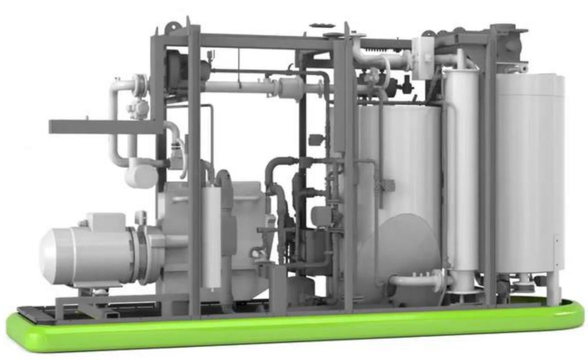

Figure 1. Biomass Combined Heat and Power Unit (Volter, 2019)

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). For this reason, only low value biomass feedstocks are typically used (e.g., wood chips or pellets generated from forestry waste streams).

2.1.2 Diesel Generator (DG)

The NRC micro-grid facility will include a variable speed diesel generator. Although not yet selected, a candidate 80 kWe diesel generator is shown in Figure 2.

Figure 2. Variable Speed 80 kW Diesel Generator (Caterpillar, 2010)

Conventional diesel generators are the most common and reliable systems for power generation; however, due to low ramp rates, fixed speed generators may struggle to adjust to the variable power output from renewables (e.g., PVs and wind turbines). Fixed speed generators also have a minimum loading requirement (typically 30-50% of maximum loading) 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 the ability to ramp up quickly and efficiently, and operate more efficiently at lower minimum loads compared to fixed speed generators. They also provide greater flexibility for simulating different test conditions in the context of the micro-grid testing facility.

2.1.3 Solar Photovoltaic Systems

The solar PV arrays, shown in Figure 3, include both a concentrating mirror PV (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 capacity PV cells to generate electricity. Throughout the day, the solar cell collector moves based on the sun's position to maximize the direct sunlight that can be collected.

Figure 3. NRC concentrating mirror and flat panel solar PV systems

The advantages of CPV systems is 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 solar power generation systems include changes in the availability of sunlight that can occur seasonally (e.g., in northern communities, there is little to 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 or wasted because the generator is operating at minimum loading and cannot be ramped down further to accommodate the additional energy. This is where incorporating energy storage systems, such as batteries, can improve both the flexibility, performance, and reliability of micro-grid operation. (NRCan 1, 2018).

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 as well as from diesel generator systems) and reliably provide energy during an energy shortfall at rates that a conventional fixed speed generator cannot. In this way, batteries can rapidly balance power generation with demand, resulting in improved power quality, system flexibility, and stability.

Figure 4. Battery Energy Storage System (single module shown) (EV Shop, 2019)

Although the ESS for the micro-grid facility has not yet been selected, for the purpose of this study, a battery system consisting of eight series-connected 12S1P modules with 120Ah lithium ion cells has been modeled (see Figure 4). Based on NRC's evaluation of these batteries, they have been specified to have an available discharge rate of up to 2C, a charge rate of 2C (between 20-80% state of charge (SoC)) and C/3 (>80% SoC), a nominal pack voltage of 352 V, and a total pack energy of 42.2 kWh.

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 a remote northern community: Whale Cove, Nunavut (see Figure 5):

1. 'Island mode' operation of the Whale Cove micro-grid without renewables (present mode).
2. 'Island mode' operation of the Whale Cove micro-grid *with* renewables (and energy storage).
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, technologies that are currently integrated into the NRC facility power network were explored to see how they might benefit the existing Whale Cove micro-grid. Multiple design and economic optimizations 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 commercial Microgrid Modelica library developed by Modelon, a web based 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 / optimization framework, 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. Note that a review of this and other modeling and optimization tools has been provided by (Windahl, 2019).

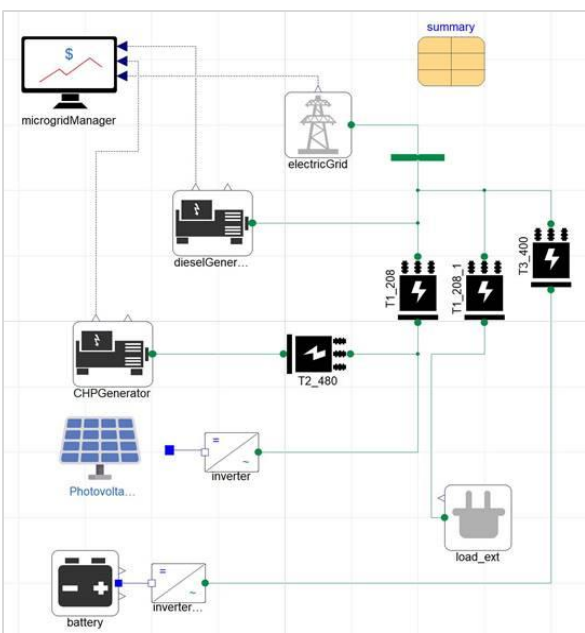

Figure 6. Micro-Grid Integrated System Model

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

2.3.1 Diesel Generator

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 the 'microgridManager' (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) and scaled to the maximum capacity of the NRC micro-grid facility.

Three generators currently provide power to Whale Cove: two 300 kW Caterpillar D3412 units, and one 150 kW Caterpillar D3406 unit (Nunavut, 2001). Although it is likely that at least one of these generators operates in standby at any given time, for simplicity, fuel consumption correlations from (Das, 2017) were used to compute the total fuel consumption (L/h) at max loading (100% capacity) and min loading (30% capacity) for all three generators. This value was then scaled to the rated capacity of the NRC micro-grid diesel generator to provide an equivalent fuel consumption correlation for the three generators operating as a single diesel generator (see Figure 7).

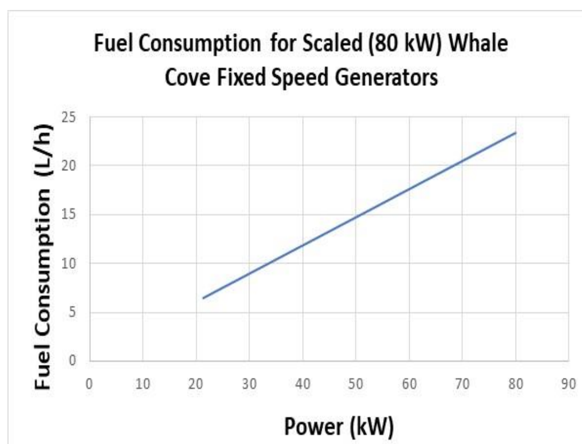

Figure 7. Diesel Fuel Consumption for Scaled (80 kW) Micro-grid Fixed Speed Generator

The parameters for the diesel generator model are summarized in Table 1. Although the peak load defined for Whale Cove is 402 kW, with the generator operating at a load factor of 56% (QEC, 2017), a scaled peak load was used based on an 80 kW generator operating at 56% loading (44.8 kW).

Table 1. Diesel Generator Parameters and Constraints

Whale Cove	*Value*
Rated Capacity[2]	750 kW
Remaining Capacity[1]	718 kW
Max Load[1]	402 kW
Load factor at Max Load[1]	56%
Micro-grid Test Facility	*Value*
Max Capacity	80 kW
Generator Min Loading	30%
Max Load (at 56% load factor)	44.8 kW
Min Load (at 30% gen. min loading)	24.0 kW
Fuel Consumption at Max Capacity[2]	23.4 L/h
Fuel Consumption at Max Load[2]	13.2 L/h
Fuel Consumption at Min Load[2]	7.2 L/h

[1](QEC, 2017), [2](Nunavut, 2001) and (Das, 2017)

From (NRCan 1, 2018), the capacity to add renewables to this micro-grid was taken as the difference between the min loading output of the scaled diesel generator (24.0 kW) and the max scaled loading for Whale Cove (44.8 kW). Based on this, the resulting combined PV and CHP maximum power output was limited to ~ 21 kW.

For cost optimizations, the total cost of diesel based electricity generation was $0.827 per kWh (QEC, 2017).

2.3.2 Solar PV Model

The Micro-Grid solar PV model can be configured to represent both flat panel PV and CPV systems, using panel surface area, solar irradiance data, system capacity, and efficiency; however, for the purposes of this study, one system model was developed to represent the combined capacity of the PV and CPV systems. DC power estimates were used based on actual solar irradiance data from (NREL, 2019) for a flat panel solar installation at Rankin Inlet (located in close proximity to Whale Cove, see Figure 5) and scaled to produce the desired net PV output (see Figure 8).

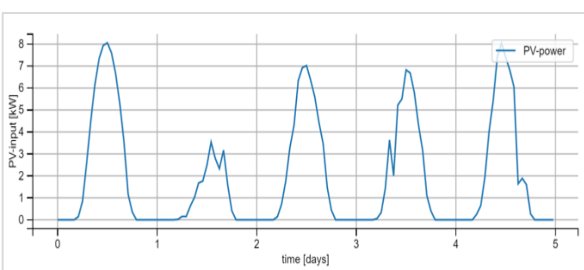

Figure 8. PV Power Output Approximation for Whale Cove (NREL, 2019) – Scaled for NRC Micro-Grid

Note that temperature effects on solar cell power generation were not considered.

2.3.3 Battery System Model

The battery system model was defined based on battery capacity, minimum and maximum state of charge, and maximum charge and discharge rates. These and other relevant battery system data are shown in Table 2. Note that a detailed thermal model was not included.

Table 2. Battery Model Parameters

Parameter Description	*Value*
Nominal Capacity[1]	120 Ah
Max SoC	95 %
Min SoC	20 %
Discharge C-Rate[1]	2C
Charge C-Rate (20-80% SoC) [1]	2C
Charge C-Rate (>80% SoC) [1]	C/3
Total Pack Energy Capacity[1]	42.2 kWh
Voltage[1]	352 V
Configuration	12S1P

[1]Data based on the characterization of a real-world battery system performed at the NRC Vancouver battery test facility.

2.3.4 Biomass CHP Model

Parameters for the CHP system are shown in Table 3. For the purposes of this study, the biomass CHP model was approximated as an electric generator only (i.e., thermal energy production was not considered). The unit power output was scaled (constrained) to ~ 13.8 kW, 3 phase, 480 VAC power. Fuel consumption was taken as 1:1 with energy output (i.e., 1 kg/h biomass to generate 1 kWh electricity) with an efficiency of 20%. For cost optimizations, CHP based electricity generation was estimated at $0.20 per kWh.

Table 3. CHP Model Parameters

Micro-grid Test Facility	*Value*
Rated CHP capacity[1]	40 kW
Scaled CHP system	*Value*
Rated CHP capacity	13.8 kW
Fuel consumption[1]	13.8 kg / hr
Electric Efficiency[1]	20 %
Fuel cost	$0.20 / kWh

[1](Volter, 2019)

2.3.5 Ideal Grid Model

For the use case where the Whale Cove micro-grid includes a connection to the Manitoba electrical grid, an ideal grid model was used (constant voltage and frequency). The Manitoba grid capacity was constrained at 45% of the full power demand for Whale Cove, with a cost of $0.13 per kWh (see Table 4). Note that to install the 1,000 km of transmission lines needed to complete the grid connection 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 is assumed to have been reflected in the $0.13 per kWh rate, given an estimated purchase price of $0.075 per kWh for QEC from Manitoba Hydro and the project's estimated 40 year lifetime to achieve a return on investment. (Karanasios, 2016).

Table 4. Grid Parameters

Manitoba Grid Connection	*Value*
Rated Grid capacity	45%
Grid energy costs[1]	$0.13 / kWh

[1](Karanasios, 2016).

2.3.6 Load Model

The load for each simulation was modeled as a variable input following a real-world load profile derived from an NRC building on March 3, 2016 (see Figure 9). This load data was scaled to allow the reduced load capacity of the micro-grid diesel generator (~80 kW) to be used to provide the baseline for evaluating the impact of introducing consumables into a Whale Cove power grid.

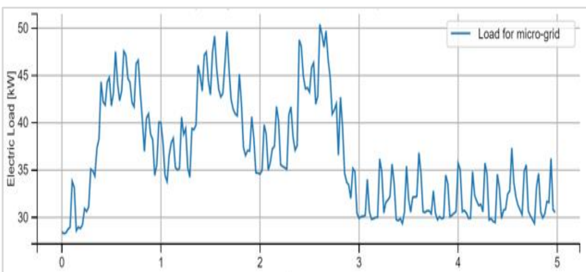

Figure 9. Load Profile for NRC-Van Building Mar, 2019

Note that the load data above has been used to represent 'scaled' daily use load variability only and does *not* reflect actual load profiles for Whale Cove, both in terms of daily use or seasonal load variations.

2.3.7 Transformer and Inverter Models

Transformers and inverters were characterized using 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%.

2.3.8 Micro-grid Manager

The micro-grid manager contains the control rules and constraints for the various controllable integrated micro-grid components. Using external sources, this manager was also used to support micro-grid optimization. Details related to configuration of the control algorithm for each simulation / optimization has been defined in each corresponding analysis below.

3 Micro-Grid Analysis

3.1 Use Case 1 Simulation

The first simulation performed evaluated 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 and to establish a baseline for cost and performance comparisons with subsequent use cases.

3.2 Use Case 2 Simulation

The second analysis was based on the present operating configuration at Whale Cove *with* renewables and energy storage added. This includes the biomass CHP system, flat panel PVs, CPVs, and batteries (with all components specified and scaled in relation to the NRC micro-grid test facility configuration).

The first analysis centered around the system's ability to match power generation and load curves based on the test facility configuration and a rule based simulation approach. For micro-grid reliability, the diesel generator was operated at minimum loading or higher, with the CHP system and combined PVs / CPVs meeting the remaining demand. Batteries were used to provide any additional power where there was power shortfall from all other sources. Once fully discharged, batteries were recharged from available sources.

The second analysis looked at the optimization of the micro-grid configuration with renewables and energy storage, to see how it could further improve upon the rule based simulation approach.

3.3 Use Case 3 Optimization and Analysis

The third use case included the addition of a grid connection (to the Manitoba electric grid). First an economic optimization was performed with electricity rates of $0.827 / kWh for diesel and $0.13 / kWh for the grid, and grid supply constrained to 20 kW. Using the same model, a design optimization was performed, where battery size was a degree of freedom.

4 Results & Discussion

4.1 Use Case 1 Simulation

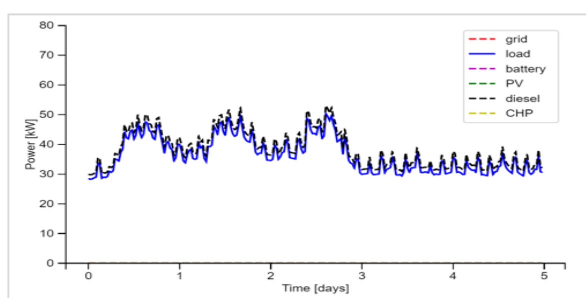

Figure 10. Use Case 1 – Whale Cove power generation using diesel generators only

The results for the use case 1 simulation are shown in Figure 10. Diesel power is shown to correctly track load over the course of the simulation, with a slightly higher power output level than demand (to cover transformer losses).

Based on the diesel electricity generation cost of \$0.827 per kWh, the total baseline cost for (scaled) power using the current configuration is ~ \$3800. Note that these costs are only defined for comparison purposes with other use cases (as the load data used is not representative of Whale Cove).

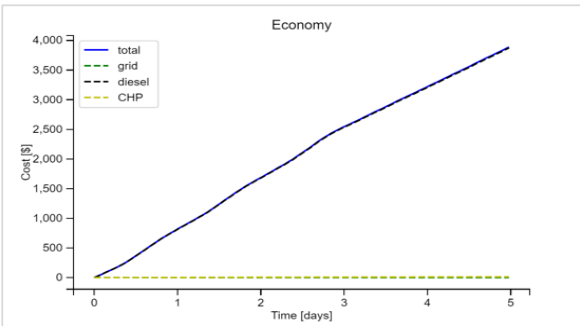

Figure 11. Use Case 1 Simulation – Baseline cost for diesel only power generation

4.2 Use Case 2 Simulation and Optimization

The results for the use case 2 simulation are shown in Figure 12.

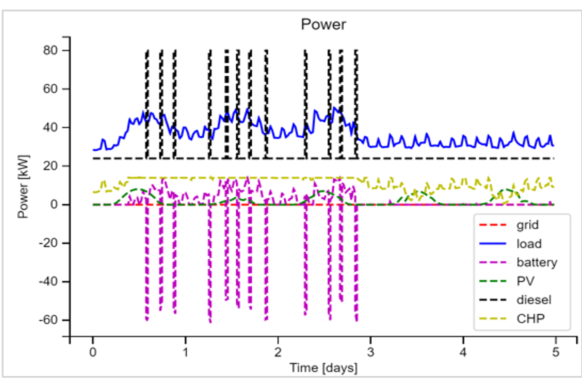

Figure 12. Use Case 2 Simulation – Whale Cove micro-grid with renewables and energy storage

The simulation above was configured to:

- Keep diesel generator operation to a minimum (not less than 30%, to prevent damage to the generator) to ensure the reliability of the remote community micro-grid.
- Use PV power directly, as generated.
- Engage the CHP and ESS systems, as required, to provide the remaining power.
- No contribution from the grid (island mode).
- Recharge the battery using available sources when the battery was discharged to its lower SoC limit (subject to C-rate constraints) – see Figure 13.

During high demand periods (Day 1 to 3), it can be seen that the battery is cycled much more than the on the weekend (Day 4 and 5), where the diesel generator, CHP, and PV systems are able to satisfy most of the demand. Also, where maximum PV and CHP capacity were required to satisfy the load during high demand periods, the diesel generator was required to ramp up to full capacity in order to recharge the batteries (where the battery power drops below zero, the battery is charging).

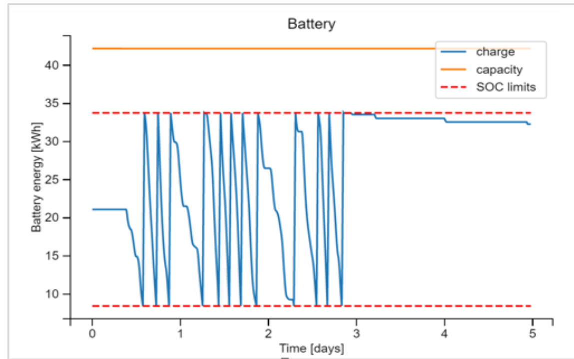

Figure 13. Use Case 2 Simulation - Battery charge and discharge cycles

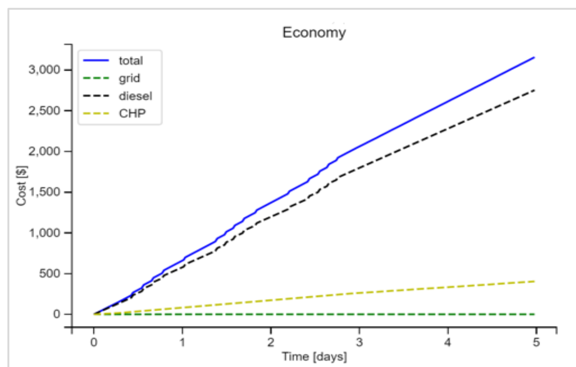

Figure 14. Use Case 2 Simulation – Cost of micro-grid operation with renewables and energy storage added

Based on the diesel generation cost of \$0.827 / kWh and a CHP cost of \$0.20 / kWh, the new *total* cost to satisfy the same demand dropped to \$3200 (almost 16%). Note that this was a rule based simulation (not an optimization).

For the economic optimization of the use case 2 configuration, the objective function shown in Figure 15 was used:

```
//%%%%%%%%%%%%%%%%%%%%%%%%% ECONOMIC DISPATCH %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
optimization economicDispatch(
    objectiveIntegrand=microgridManager.economy.der_cost/1e2+(dQ_battery/1e3)^2+(dQ_gen/1e2)^2+(dQ_CHPgen/1e2)^2,
    startTime=t_start,
    finalTime=t_end)
  parameter Real t_start=0;
  parameter Real t_end=24*3600;
  parameter Real fuel_total_max=30e3;

extends NRCMicrogrid.Examples.MicroGrid_Optimization(dieselGenerator.power_out(min=0.3*80e3),electricGrid(y_P_net(max=7.5e3)));
```

Figure 15. Use Case 2 Optimization – Economic Objective Function (placeholder)

The results from the optimization of the micro-grid with renewables and energy storage are shown in Figure 16 (load balancing) and Figure 17 (economic analysis).

 10.3384/ECP2016918 DOI

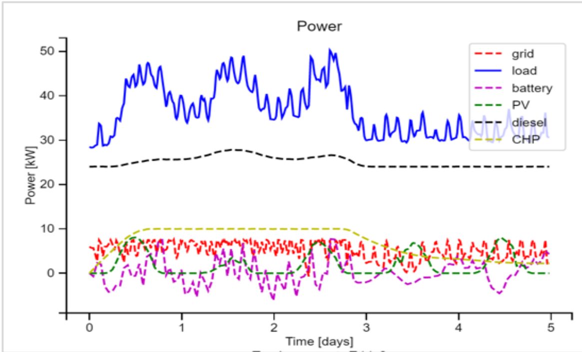

Figure 16. Use Case 2 Optimization (placeholder)

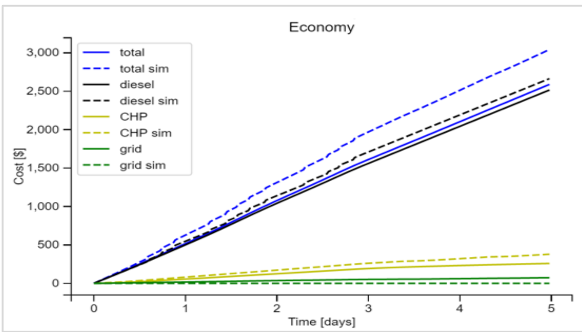

Figure 17. Comparative cost (placeholder) of Use Case 2 sim (dashed lines) and Use Case 2 optimization (solid)

It can be seen that the optimization reduces the total cost to $XX00 compared to the rule based simulation (~XX% compared to diesel only and ~XX% compared to the rule based simulation).

4.3 Use Case 3 Optimization and Analysis

The objective function for the use case 3 economic optimization is shown in Figure 18.

```
//%%%%%%%%%%%%%%%%%%%%%%%%% ECONOMIC DISPATCH %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
optimization economicDispatch(
    objectiveIntegrand=microgridManager.economy.der_cost/1e2+(dQ_battery/1e3)^2+(dQ_gen/1e2)^2+(dQ_CHPgen/1e2)^2,
    startTime=t_start,
    finalTime=t_end)
  parameter Real t_start=0;
  parameter Real t_end=24*3600;
  parameter Real fuel_total_max=30e3;

extends NRCMicrogrid.Examples.MicroGrid_Optimization(dieselGenerator.power_out(min=0.3*80e3),electricGrid(y_P_net(max=10e3)));
```

Figure 18. Use Case 3 Economic Optimization Objective Function (placeholder)

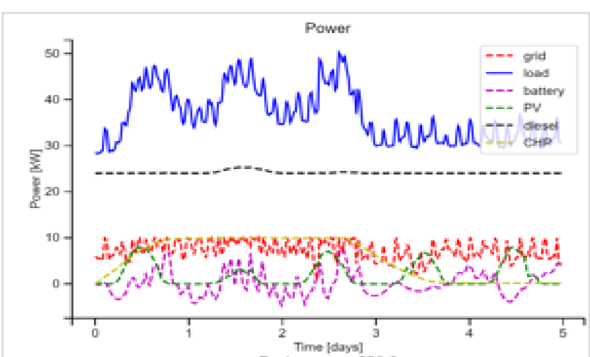

Figure 19. Use Case 3 Econ. Optimization – Whale Cove micro-grid with renewables, energy storage, and grid tie

The results from the economic optimization for use case 3 are shown in Figure 19. It can be seen that the micro-grid system is almost able to completely satisfy the demand using renewables, energy storage and the grid, without increasing the diesel generator operation beyond minimum loading (30%). Also, the CHP system operation is much less erratic (smooth ramp up and down).

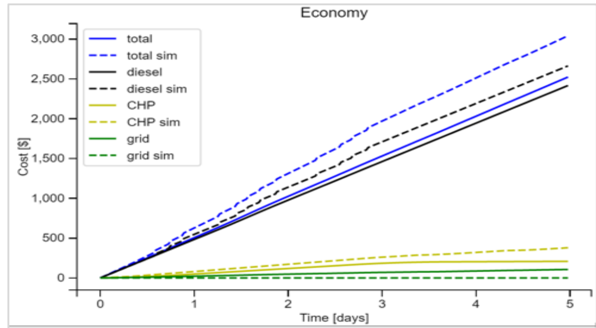

Figure 20. Comparative cost of Use Case 2 sim and Use Case 3 economic optimization

Figure 20 shows that the results of the optimization reduces the total cost to $2500 compared to the rule based simulation (~34% compared to diesel only and ~17% compared to the rule based simulation) with only 10 kW power supplied from the grid.

For the design optimization performed for use case 3, the objective function shown in Figure 21 was used. The results, shown in Figure 22, Figure 23, and Figure 24, show that with a grid connection present (with 20 kW max grid capacity), the original battery was oversized by 24 kWh for the same total energy cost.

```
//%%%%%%%%%%%%%%%%%%%%%%%%% PEAK SHAVING %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
optimization peakshaving(
    objectiveIntegrand=battery.capacity/1e14+(dQ_battery/1e3)^2+2*(dQ_gen/1e3)^2 +2*(dQ_CHPgen/1e3)^2
    + (dieselGenerator.m_fuel/1e3)^2+ (CHPGenerator.m_fuel/1e3)^2,
    startTime=t_start,
    finalTime=t_end)
  parameter Real t_start=0;
  parameter Real t_end=24*3600;
  parameter Real maxGridPower=20e3;
//  parameter Real fuel_total_max=675;

extends NRCMicrogrid.Examples.MicroGrid_Optimization(
     battery.capacity(free=true,min=5*3600*1e3,max=500*3600*1e3,nominal=40*3600*1e3),
//        dieselGenerator.fuel_total(max=fuel_total_max),
//      CHPGenerator.fuel_total(max=fuel_total_max),
     electricGrid(y_P_net(max=maxGridPower,min=0)),
     dieselGenerator.power_out(min=0.3*80e3),
     CHPGenerator.power_out(max=0*13.9e3));
end peakshaving;
```

Figure 21. Use Case 3 Optimization – Economic Objective Function (placeholder for equation)

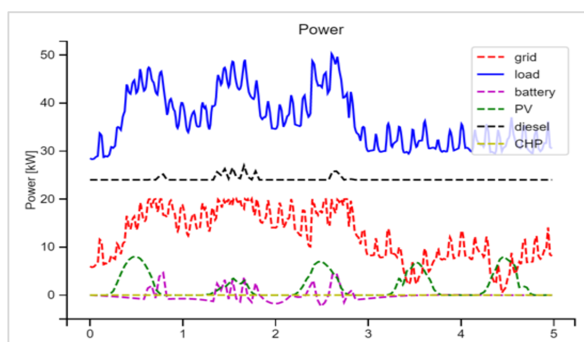

Figure 22. Use Case 3 Design Optimization with renewables, energy storage, and 20kW from grid

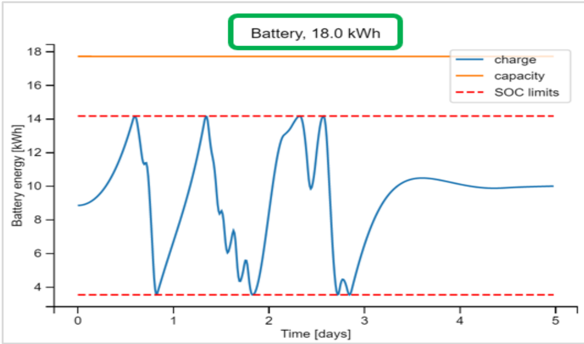

Figure 23. Use Case 3 Design Optimization

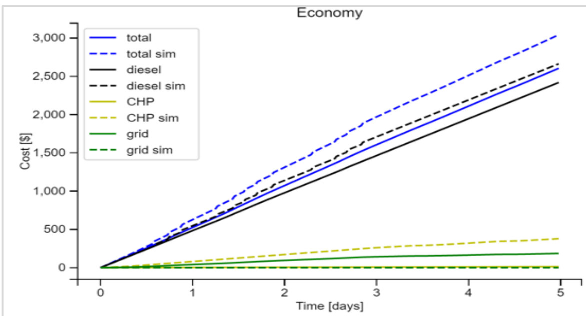

Figure 24. Comparative cost (placeholder) of Use Case 2 sim and Use Case 3 design optimization

5 Conclusions

The move towards increasing renewables for micro-grids operating in remote communities has provided the opportunity to investigate the potential to reduce fuel costs and emissions compared with traditional standalone diesel power plants. Additional work needs to be done to support the advancement and integration of new micro-grid technologies and to optimize overall integrated system design, performance, and overall costs. By using the Microgrid Modelica library models, many high level optimizations can be performed to answer initial questions on equipment sizing and economic dispatch. This, coupled with access to a physical micro-grid test environment, provides the added benefit of being able to eventually validate model results and develop higher fidelity models that can be integrated into a similar model framework.

5.1 Future Work

Plans for future work include:

- Generating data from the NRC Micro-grid Testing and Training facility using a configuration that mirrors this study in order to validate model results.
- Performing a design optimization of a combined PV and CPV system.
- Defining a more detailed co-generation model for the CHP system (i.e., with thermal energy generation considered).
- 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.).
- Using the above detailed integrated model framework to support micro-grid control system design and optimization.

Acknowledgements

The authors would like to thank Johan Windahl and Hakan Runvik for their part in the development of the Modelon Micro-Grid modeling / simulation platform.

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