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Modelon

Micro-grid Design and Cost Optimization using Modelica

National Research Council of Canada (NRC)

Modelon Inc. USA, Modelon AB, Sweden

OUR TEAM

WE ARE THE GOVERNMENT OF CANADA'S
LARGEST RESEARCH AND DEVELOPMENT ORGANIZATION
WITH OVER 100 YEARS OF EXPERIENCE

Specialized facilities in 179 buildings on 22 sites

1,577 R&D collaborations and helped over 8,000 SMEs

2,151 scientists, engineers, technicians, other specialists, and 255 NRC IRAP industrial technology advisors

Natesa MacRae

Senior Researcher / Systems Engineer

National Research Council Canada (NRC)

Aerospace Research Center, Low Carbon Technologies

B. Eng Chemical Eng.

M. Eng Aerospace

John Batteh

Director, Solutions Services

Modelon, Inc. USA

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Darren Jang

NRC Program Leader – Energy Storage for Grid Security and Modernization

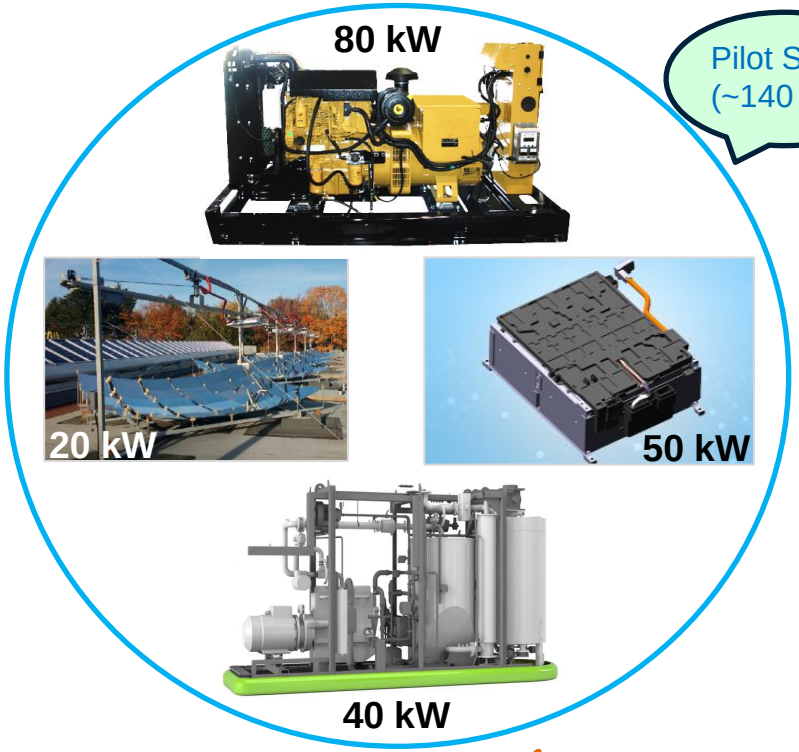
William Skrivan, Imran Khan

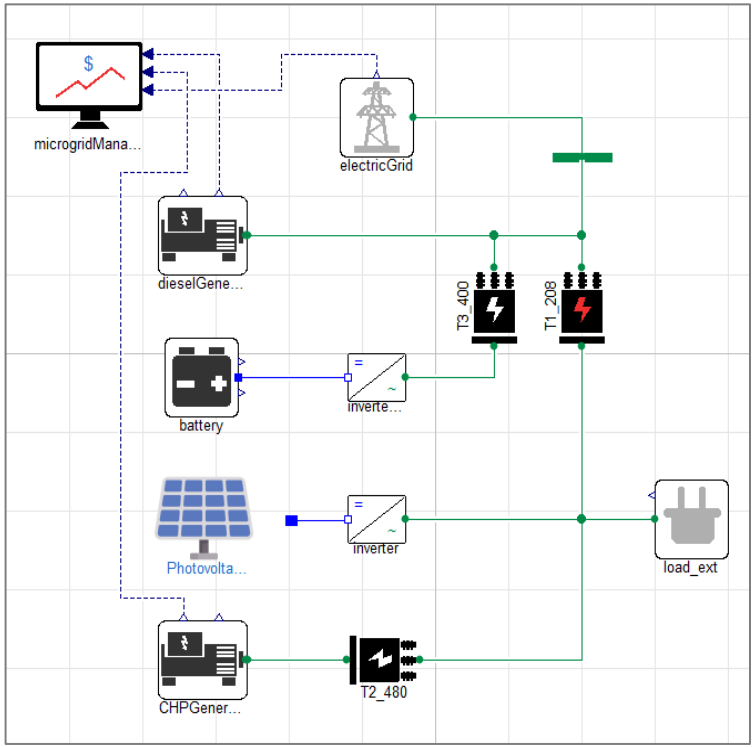
NRC Project Leaders – Microgrid Testing and Training Facility

Stéphane Velut

Modelon AB, Sweden – Industry Director Energy & Process

NRC Micro-grid Testing and Training Facility





Modelon Microgrid Modelica library

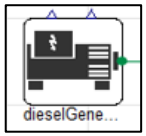
Selected Study – Whale Cove, Nunavut

Remote community in northern Canada selected: **Whale Cove, Nunavut**

- **Use Case 1: ‘**Island Mode’ without renewables – Diesel Only.
- **Use Case 2:** ‘Island Mode’ with renewables and energy storage.
- **Use Case 3:** ‘Grid Connected Mode’ with renewables and energy storage.

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

Micro-grid Integrated System Model

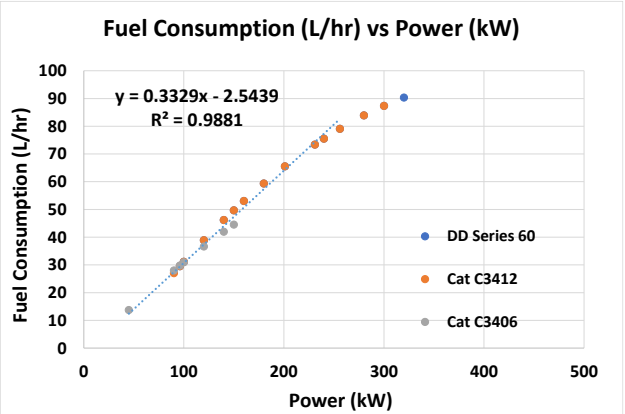


Diesel Generator

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

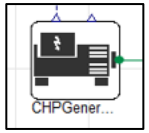
[1](QEC, 2017), [2]Based on combined capacity of DD 60 + D3412 = 620 kW, with a maximum operating point of up to 80% of the combined rated capacity (620*80% = 496 kW), [3]Defined for DD60 operating alone, [4]Capacity for renewables defined as the max load for Whale Cove (402 kW) minus the combined min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

- Multiple diesel generators modeled as one generator with extended capacity



Fuel consumption (L/hr) vs Power (kW): Correlation based on actual generator curves (Das, 2017)

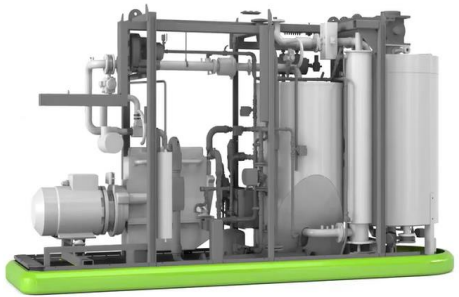
Micro-grid Integrated System Model



Combined Heat & Power (CHP) Generator

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)



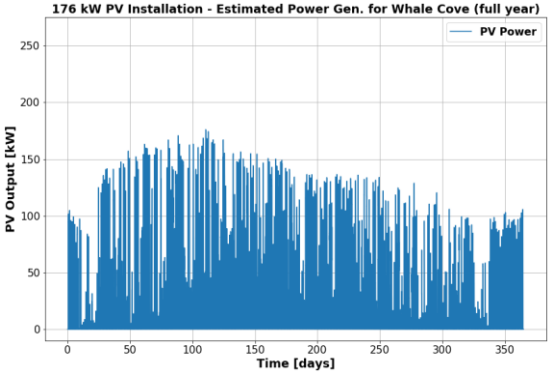
CHP-based electricity generation was estimated at $0.78 CDN per kWh based on:

- 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),
- Estimated $5 / ton for storage,
- 5% federal goods and services tax (CRA, 2019),
- Nunavut minimum wage labor cost of $13 / hr (GOC, 2019) with estimated 6 hr / day operational support requirements.

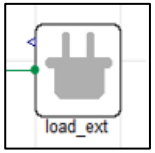
Micro-grid Integrated System Model

Solar Photovoltaics (PVs)

- 176 kW PV Output Data supplied as a variable input (from NREL PVWatts® Calculator)

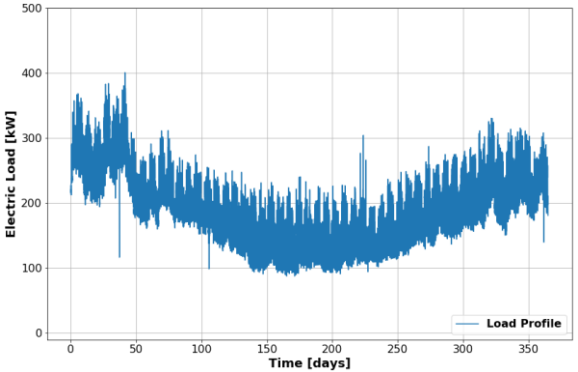


DC PV Power Estimates for Whale Cove (NREL, 2019)



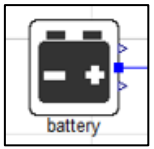
Whale Cove Load Profile

- Real world load profile scaled to max load of ~ 402 kW for Whale Cove (from Old Crow, Yukon)



Scaled Jan-Dec 2015 load profile from Old Crow, Yukon (ATCO Electric Yukon, 2015)

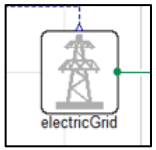
Micro-grid Integrated System Model



Energy Storage System

- Based on commercial battery tested at the NRC Vancouver Battery test facilities

Parameter Description	Value
Nominal Cell Capacity	120 Ah
Module Configuration	12S1P
Max SOC	80 %
Min SOC	20 %
Discharge C-Rate (20-80% SOC)	2C
Charge C-Rate (20-80% SOC)	2C
Pack Configuration	98S1P
Total Pack Energy Capacity	42.2 kWh
Pack Voltage[1]	352 V



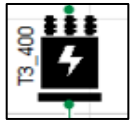
Manitoba Electric Grid

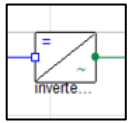
- Modeled as an ideal grid (constant voltage and frequency).
- Based on actual case study performed to connect the Manitoba Electric Grid to multiple Nunavut communities (Karanasios, 2016).
- Estimated cost to install transmission lines: $900 Million, with $40 Million diesel savings estimated per year.

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.

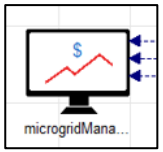
Micro-grid Integrated System Model





Transformers / Inverters

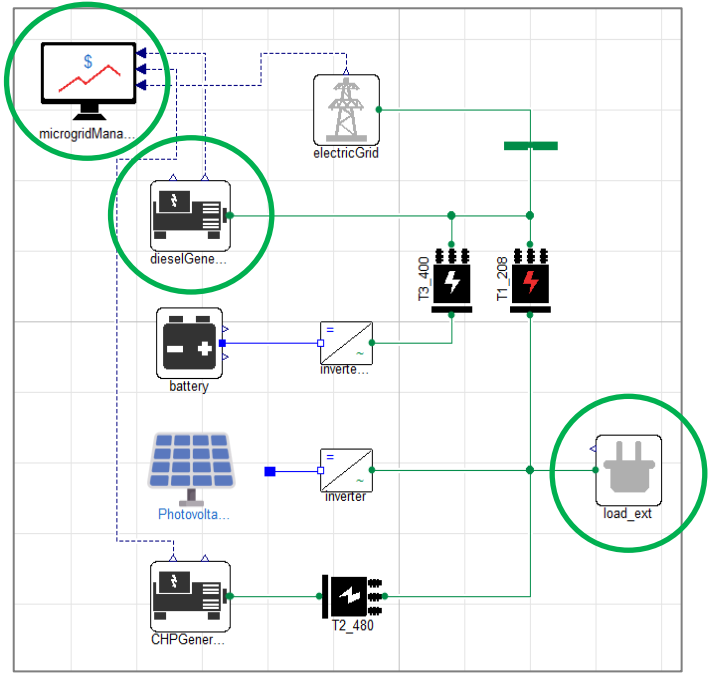
- Transformers and inverters were characterized using linear efficiency-based models.
- For this study, all efficiencies were assumed to be 95% and 96% for transformers and inverters, respectively.

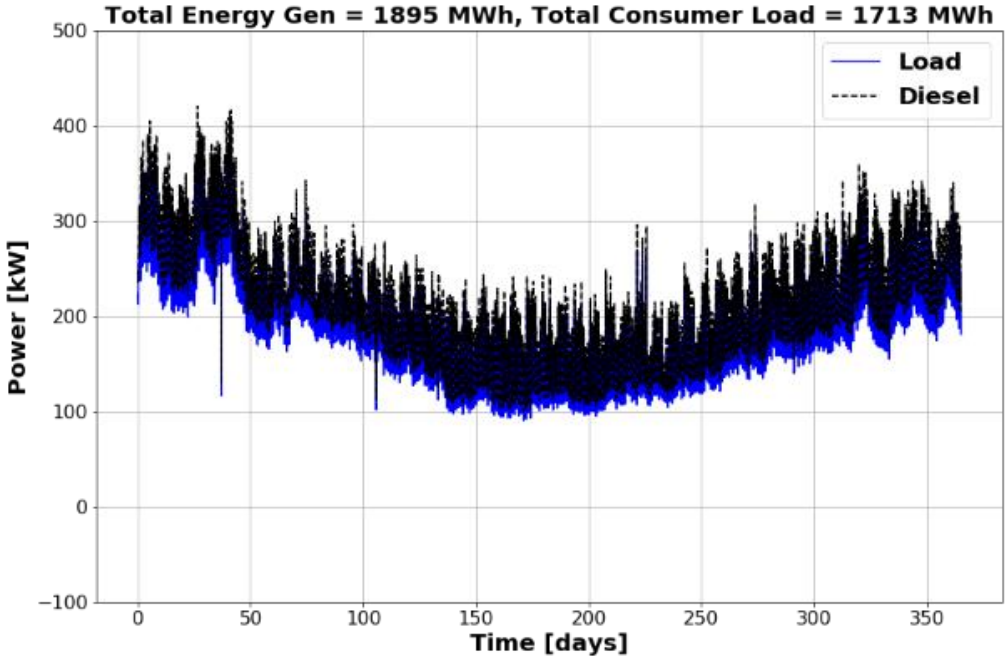


Microgrid Control / Economy

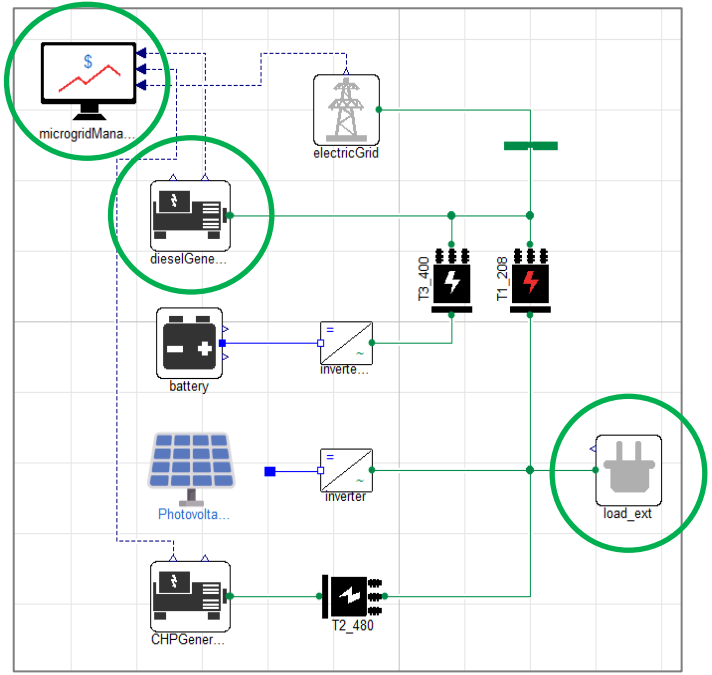
- The Microgrid Modelica library includes a micro-grid controller ‘MicroGridControl’, which contains the control rules for each controllable micro-grid component that is applicable to each use case
- The library also includes an ‘Economy’ model that computes the operating cost for each power source.

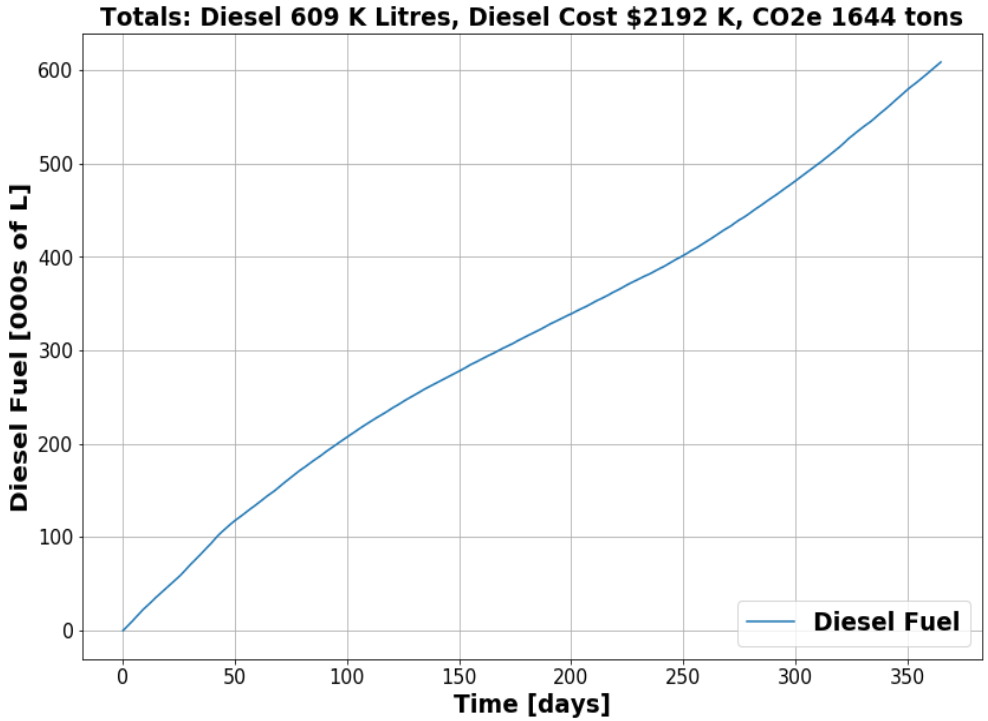
Model Validation – Use Case 1 - Diesel Only



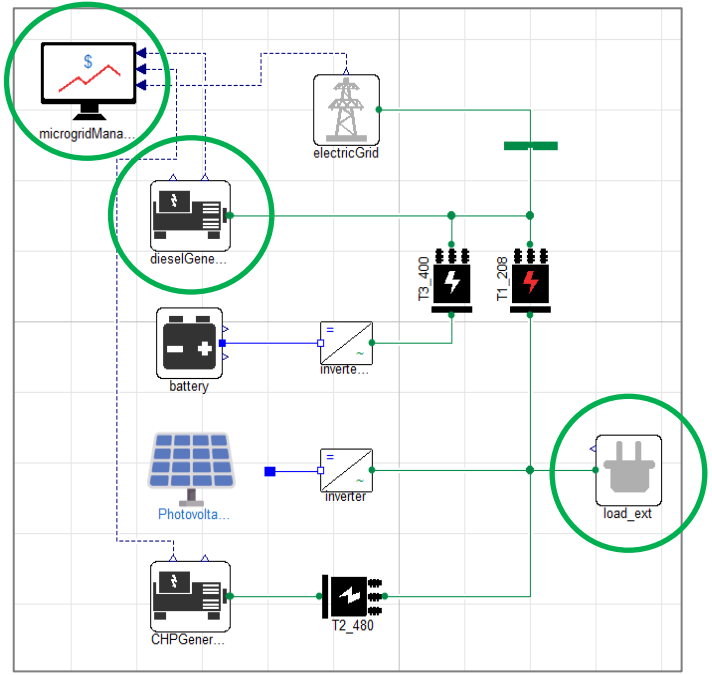


Model Results – Use Case 1 - Diesel Only





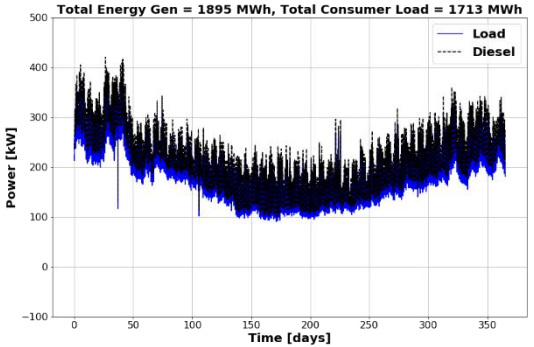
Model Validation – Use Case 1 - Diesel Only

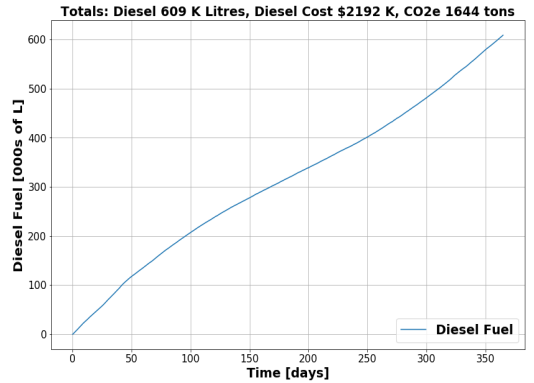


Descript.	Ref. Data[1]	Calc[2] / Sim. Data[3]
Load (kWh)	1732 K	1713 K
Gen (kWh)	1910 K	1895 K
Fuel (L)	532 K	609 K
CO_{2e} (tons)	1479	1644
Cost (CDN$)[4]	2216 K	2192 K

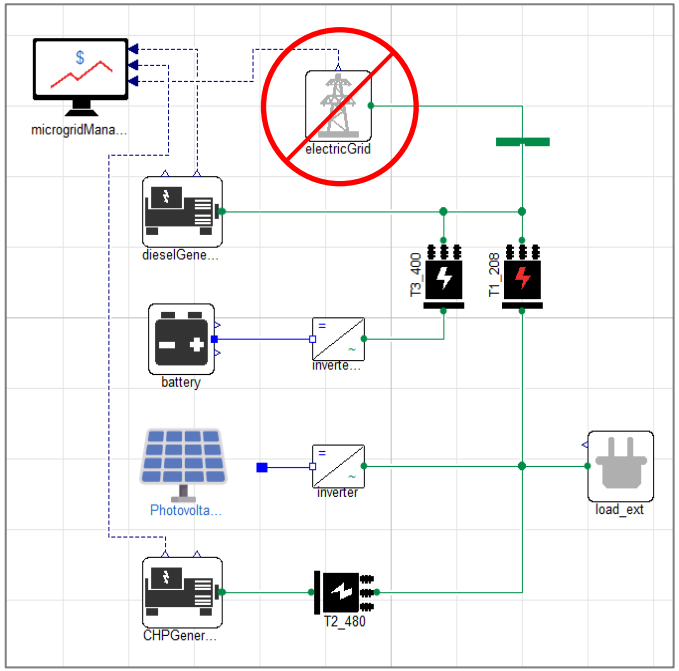
[1](QEC, 2017) and (ITR, 2019), [2]Calculated independently in Excel using scaled load data file (ATCO Electric Yukon, 2015), [3]Results calculated from model / simulation, [4]Based on load (kWh) at $1.28 / kWh (present day averaged cost).

- **Baseline for other use cases**





Model Validation – Use Case 2 – Island Mode

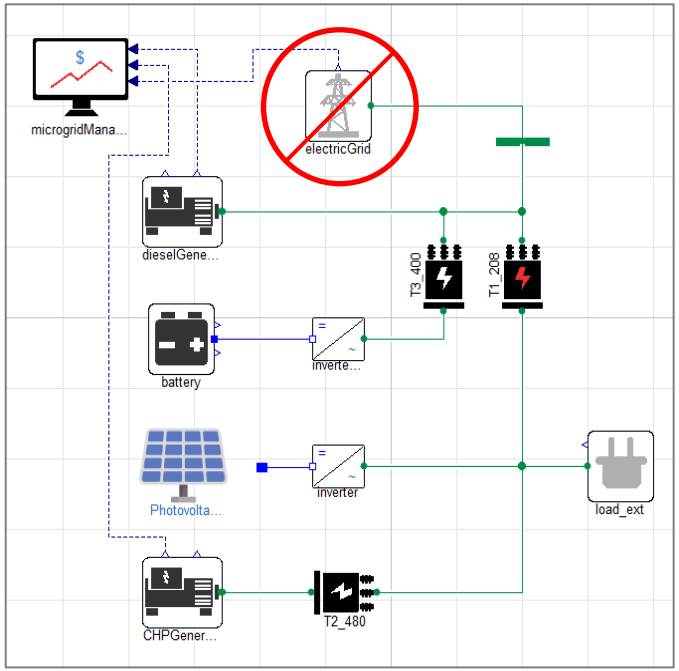


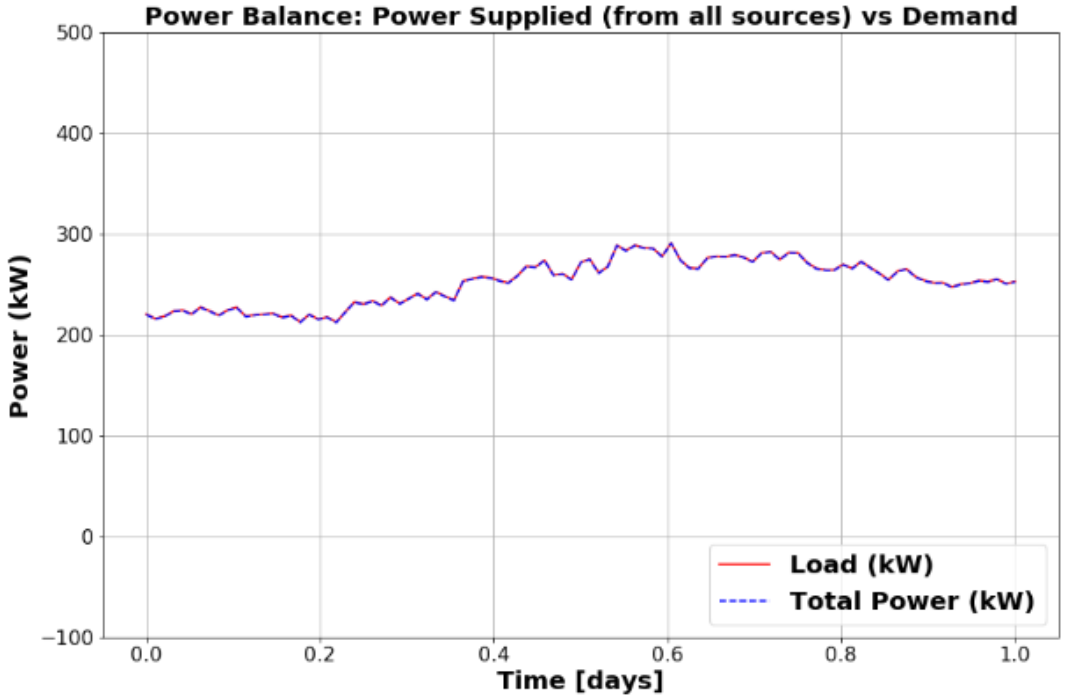
Rule Based Simulation:

- For reliability, the diesel generator was not permitted to operate below 30% 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).

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

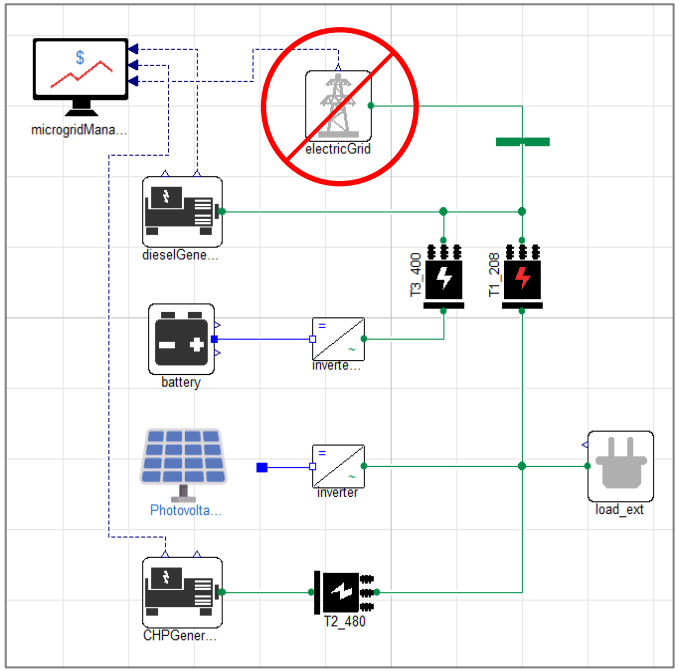
Model Validation – Use Case 2 – Island Mode

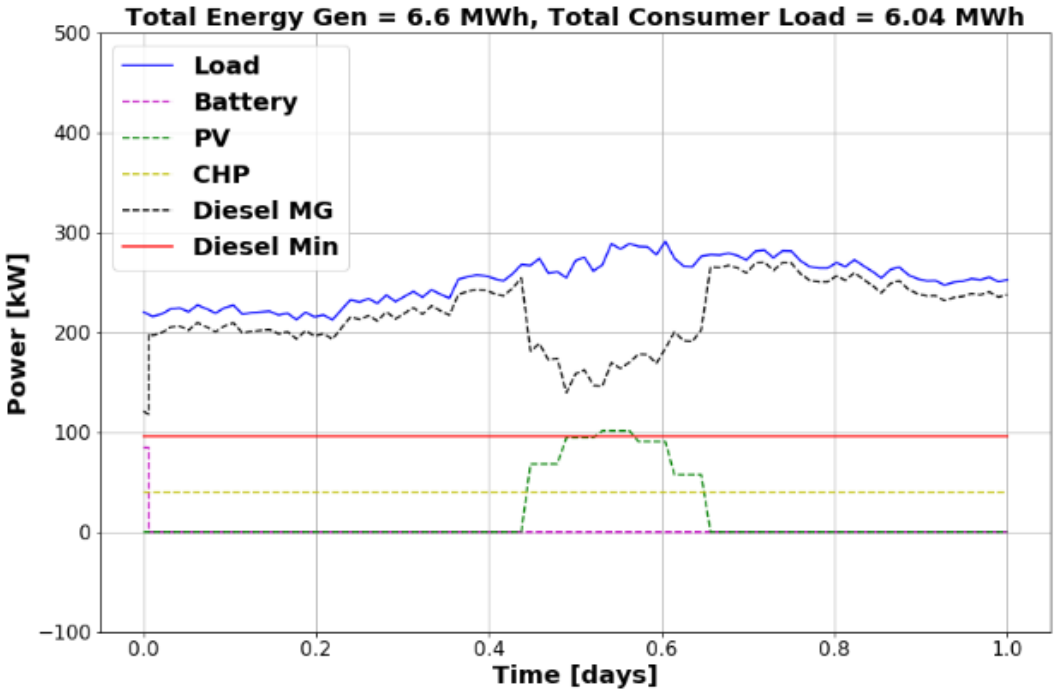




Test: Day 0 - Winter

Model Validation – Use Case 2 – Island Mode





Test: Day 0 - Winter

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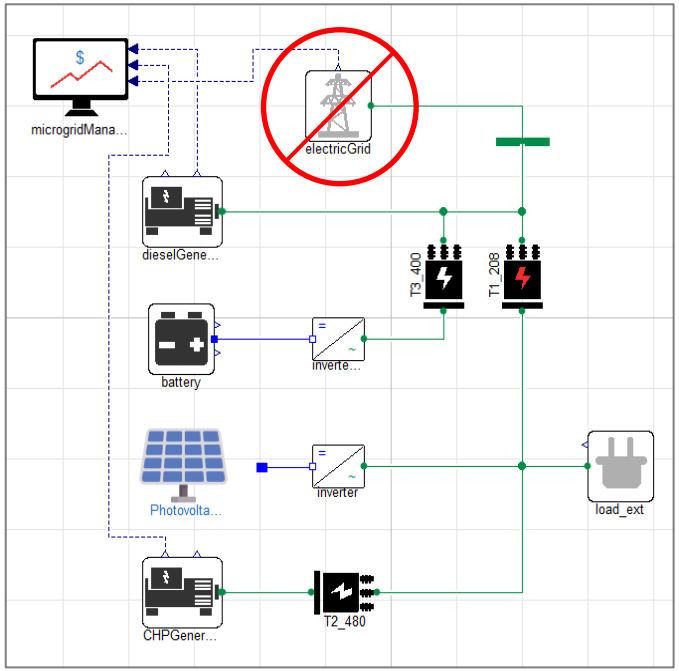
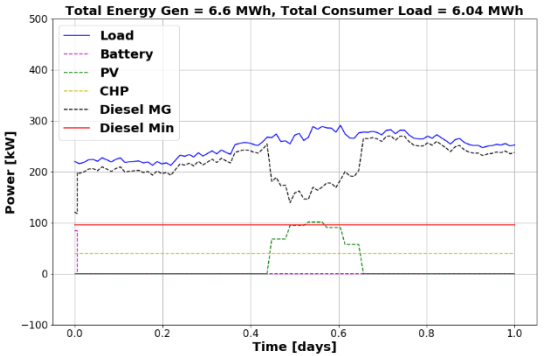
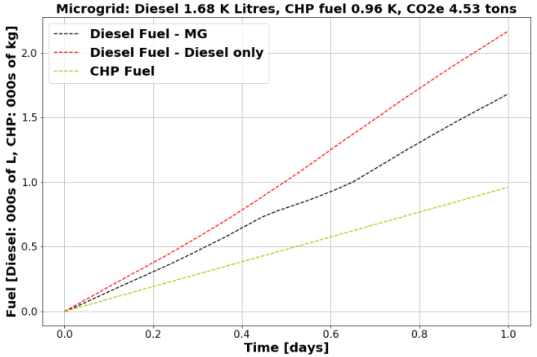
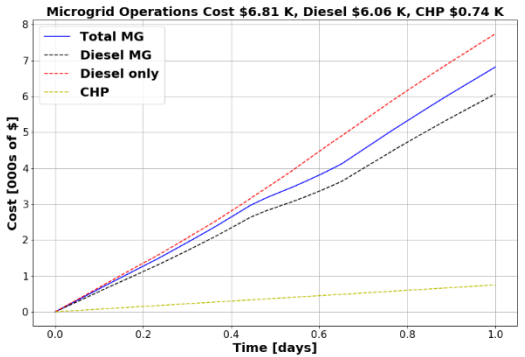


Description	Use Case 1	Use Case 2
Total Energy Generated (MWh)	6.8	6.6
Diesel Fuel (L)	2.16 K	1.68 K
CHP Fuel (kg)	--	0.96 K
CO_{2e} (tons)	5.85	4.53
Cost (CDN$)	7.74 K	6.8 K
Load (MWh)	6.04	6.04

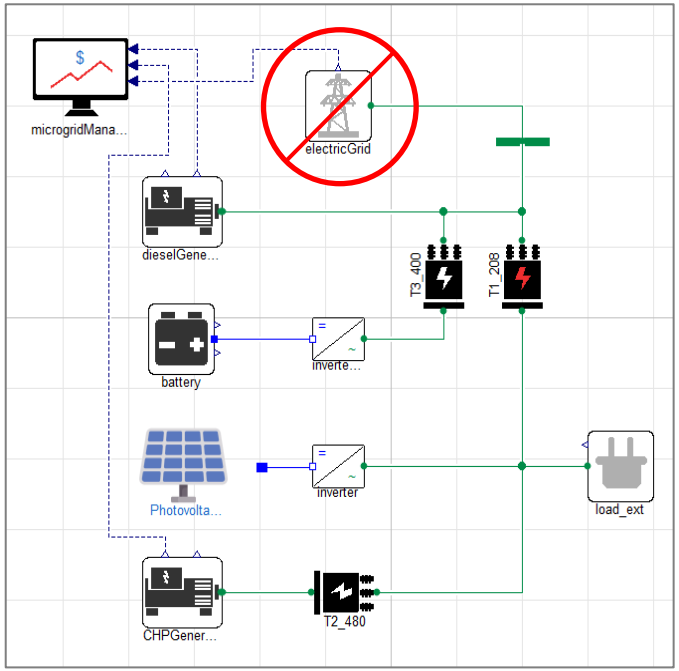


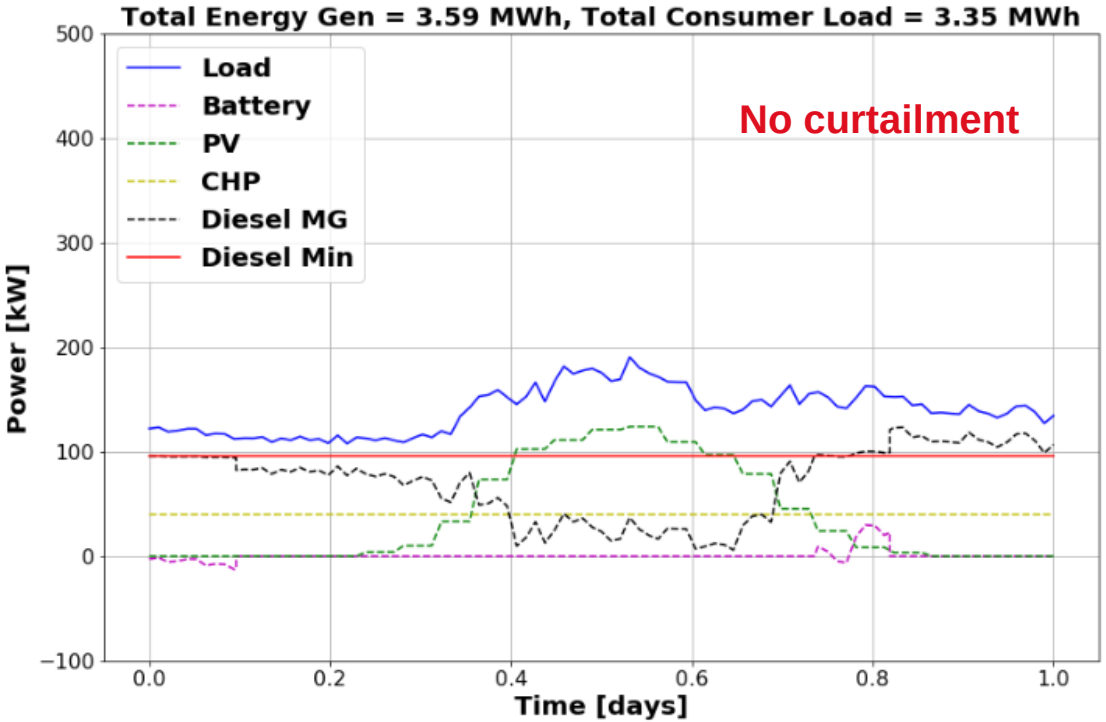




Test: Day 0 - Winter

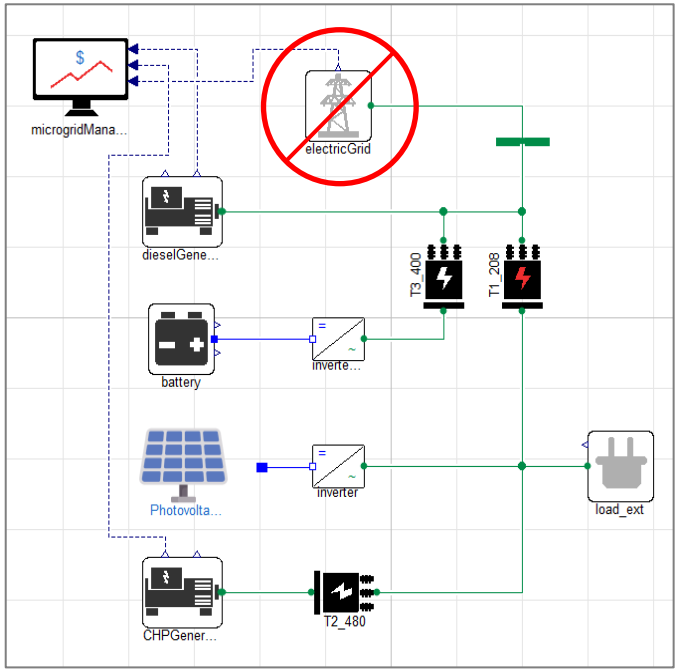
Model Validation – Use Case 2 – Island Mode





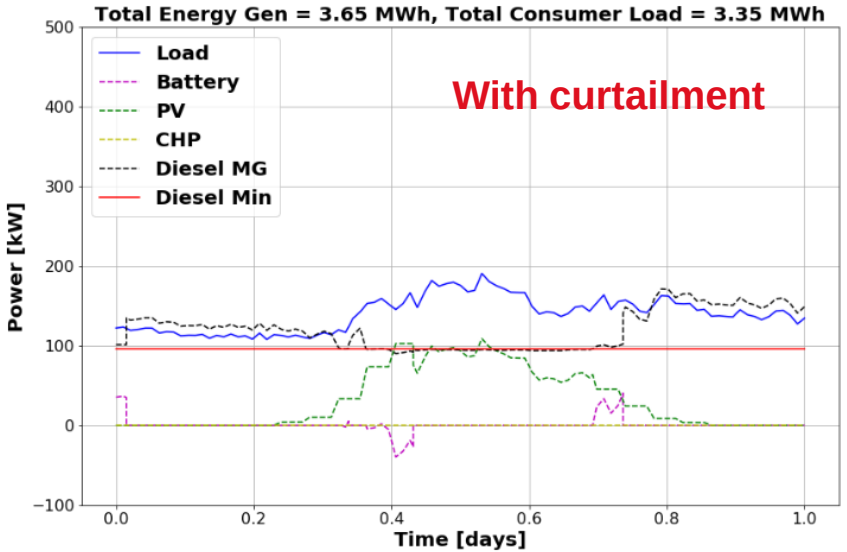
Test: Day 220 - Summer

Model Validation – Use Case 2 – Island Mode



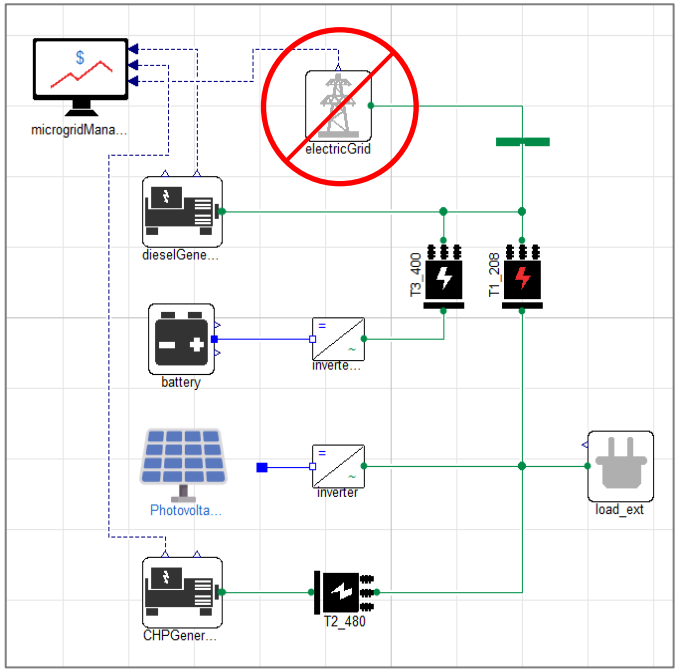
Rule Based Simulation:

- If power supplied > demand *and* available battery capacity, CHP and PV outputs were curtailed.



Test: Day 220 - Summer

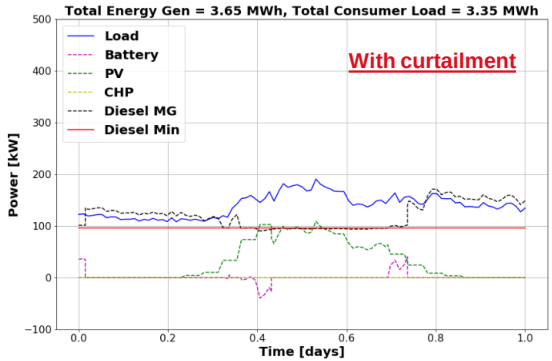
Model Validation – Use Case 2 – Island Mode

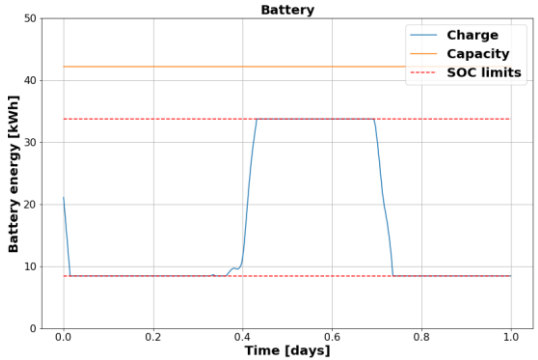


Rule Based Simulation:

- Early in the day, when there is a shortfall, the battery is fully discharged from its starting point (50% SOC).
- When there is more surplus power available, the battery charges up to its max SOC (80%), after which point, excess PV must be curtailed.
- Once PV output begins to decrease and Pnet < 0, the battery discharges.

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



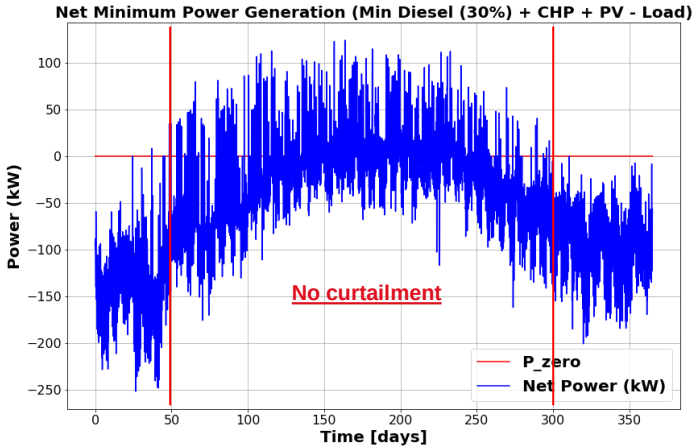


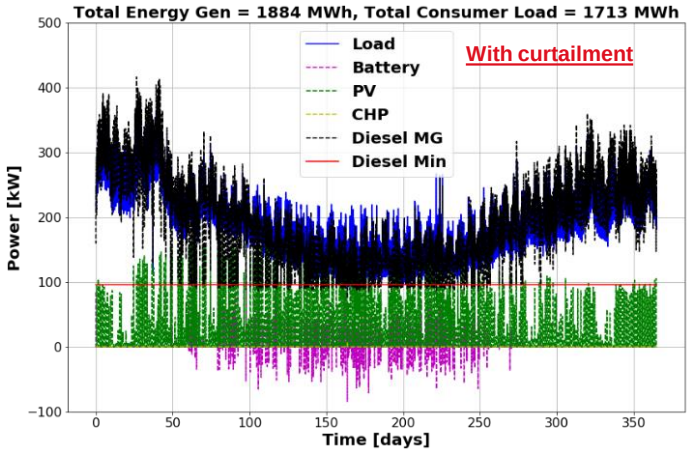
Test: Day 220 - Summer

Model Results – Use Case 2 – Island Mode

Operational Strategies – Seasonal Curtailment:

- Determined the ~ days each year where CHP and PV curtailment might be beneficial.
- Re-ran simulations to compare full curtailment (no CHP plus PV curtailment) versus seasonal curtailment (curtailment when Pnet > 0, ~Days 50-300).





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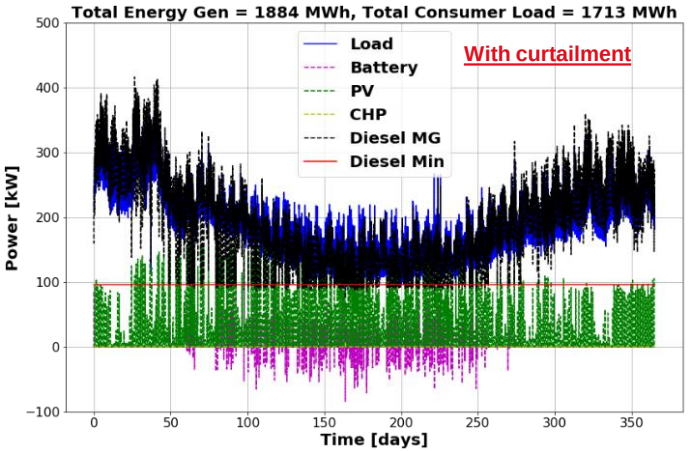
Operational Strategies – Seasonal Curtailment:

- Determined the ~ days each year where CHP and PV curtailment might be beneficial.
- Re-ran simulations to compare full curtailment (no CHP plus PV curtailment) versus seasonal curtailment (curtailment when Pnet > 0, ~Days 50-300).

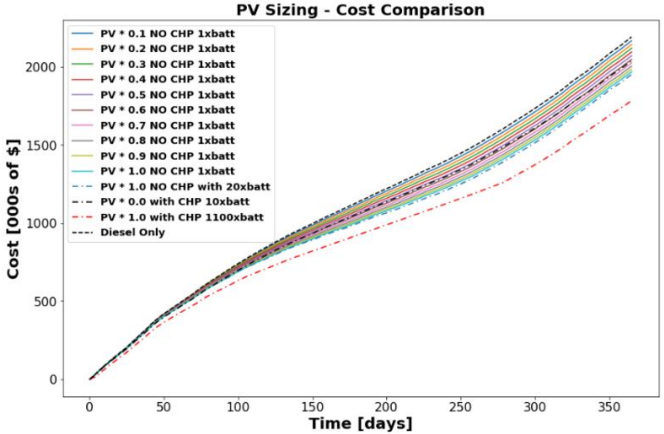
Description	Curtailed (full year)	Seasonally Curtailed	Diesel-Only Use Case 1
Total Energy Generated (MWh)	1884	1890	1895
Diesel Fuel (L)	544 K	506 K	609 K
CHP Fuel (kg)	--	110 K	--
CO_{2e} (tons)	1470	1365	1644
Cost (CDN$)	1969 K	1920 K	2192 K

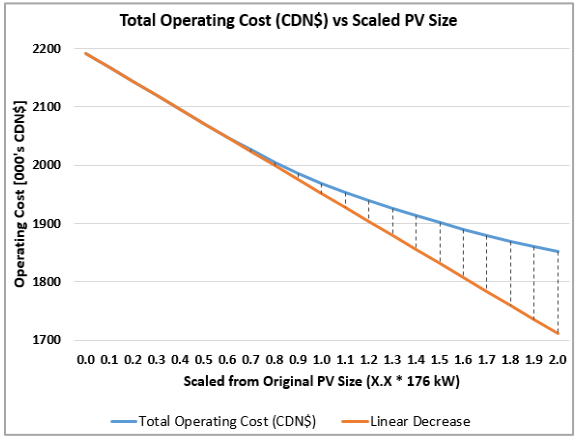


Model Results – Use Case 2 – Island Mode

Design Considerations – PV Installation Size:

- Simulations were re-run with PV scaled from 0.1 to 1.0 x the original PV installation size.
- These runs were performed *with* curtailment (without CHP and with excess PV curtailed).
- Although costs decreased with increasing PV size, at some point, the amount of additional power that can be effectively used (versus curtailed) starts to decrease.

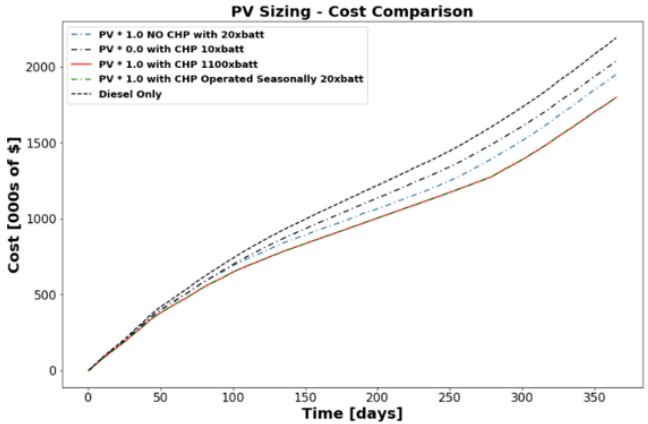


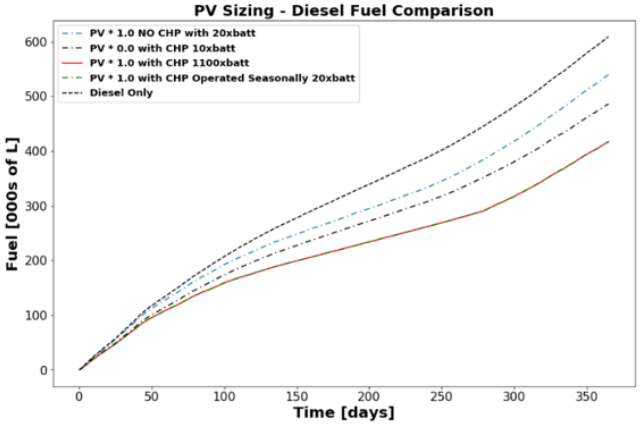


Model Results – Use Case 2 – Island Mode

Operational / Design Strategies – Battery Size:

- In addition to previous runs, the Microgrid was run with CHP and energy storage only (PV output = 0 kW).
- As with 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 evaluate further, multiple simulations were run with PV only, CHP only, and with both PV / CHP combined to determine the battery size that eliminated the need for curtailment.





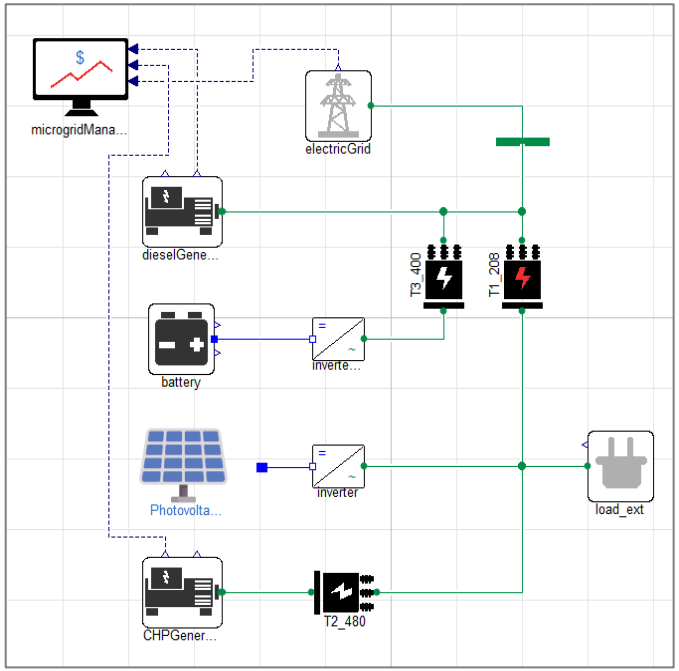
Model Results – Use Case 2 – Island Mode

Economic Assessment:

- Looked at the investment cost of each micro-grid component versus savings.
- For PV systems, 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

Model Validation – Use Case 3 – Grid Connected

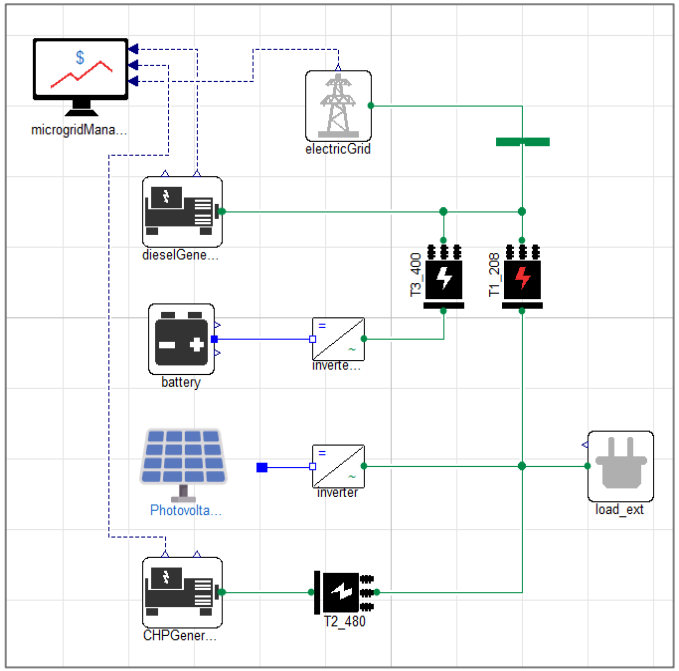


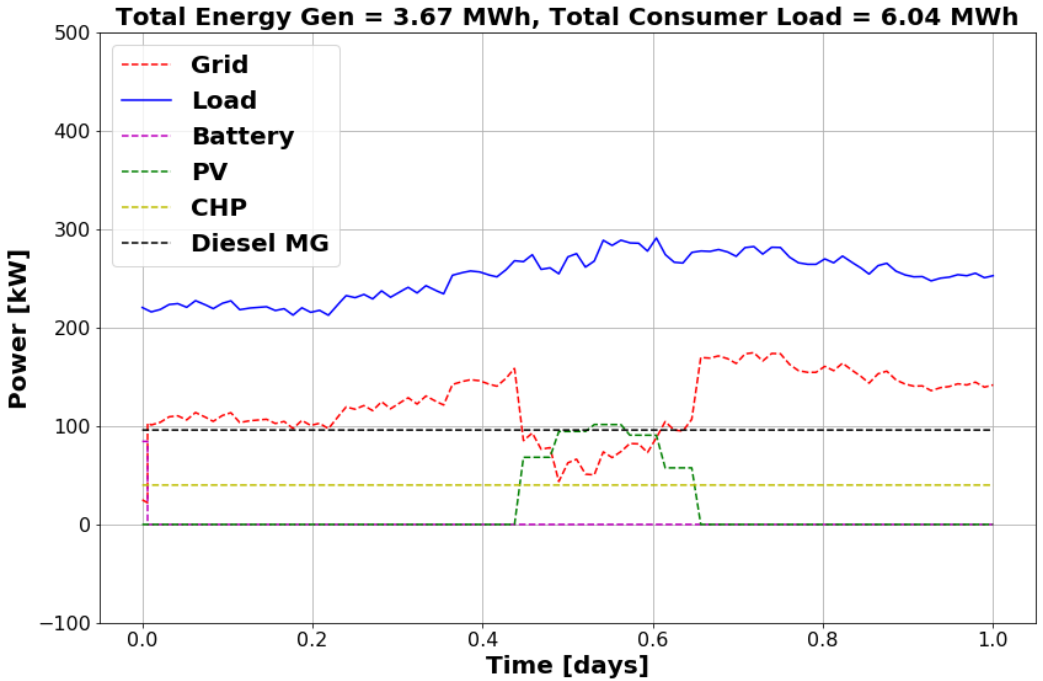
- Use Case 3 represents grid-connected operation of the micro-grid (including the diesel generator, CHP generator, PVs, battery ESS, and a connection to the Manitoba electric grid).
- The definition of net power (P_{net}) is the same as in Use Case 2.

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

- 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.

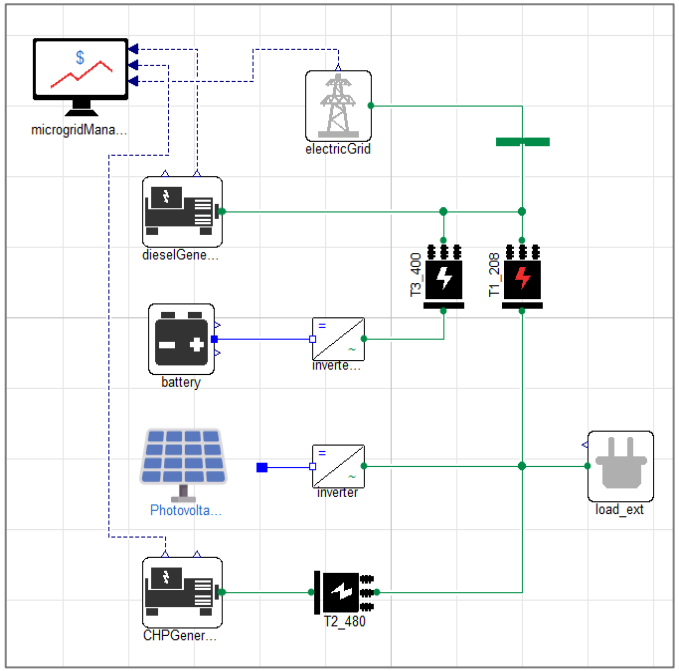
Model Validation – Use Case 3 – Grid Connected

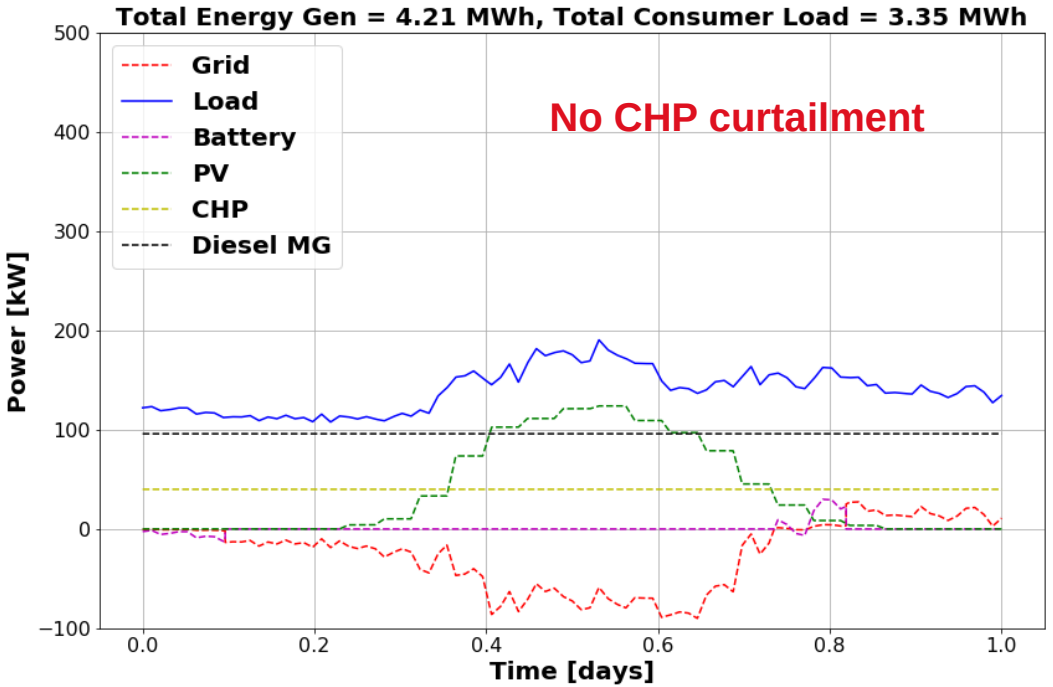




Test: Day 0 - Winter

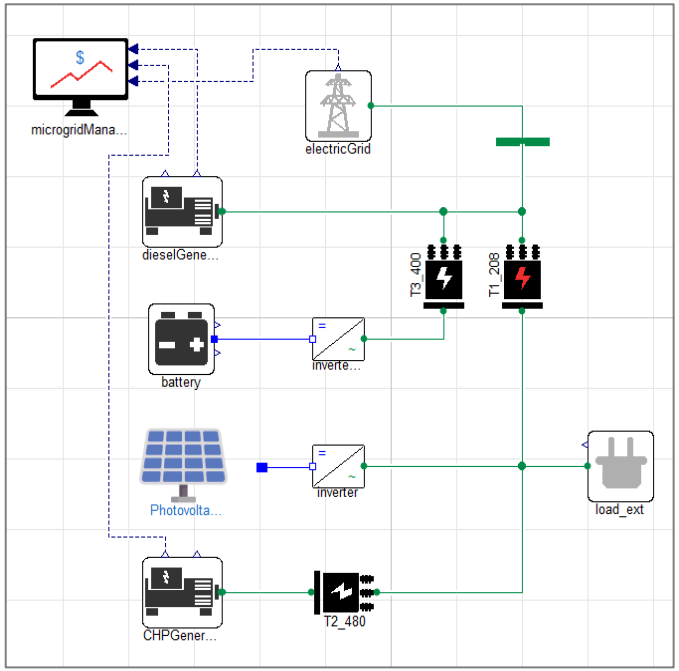
Model Validation – Use Case 3 – Grid Connected

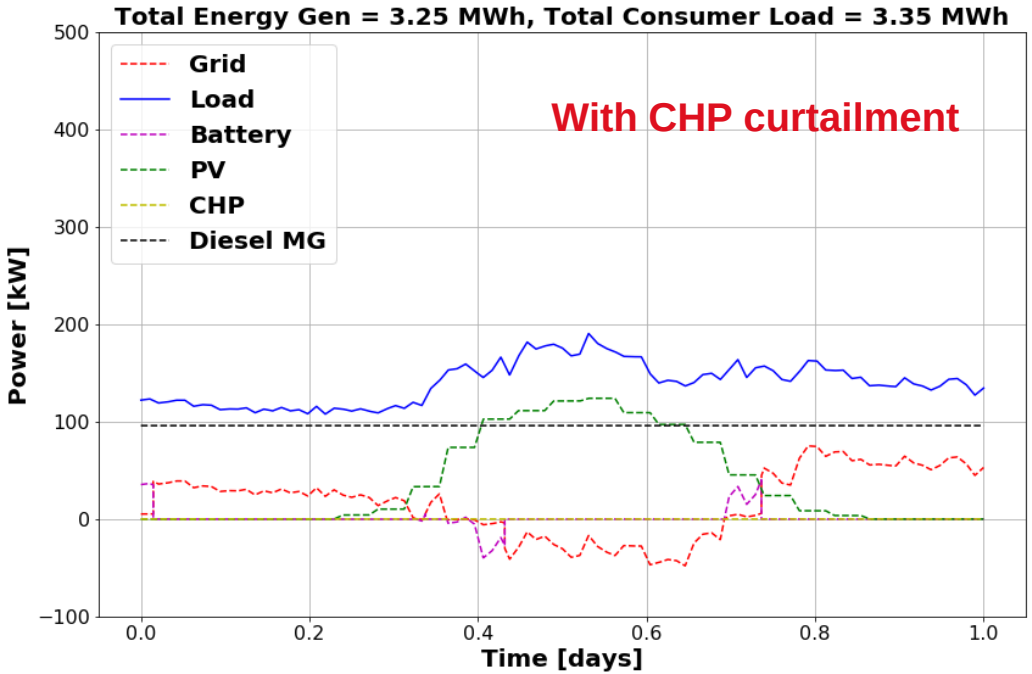




Test: Day 220 - Summer

Model Validation – Use Case 3 – Grid Connected



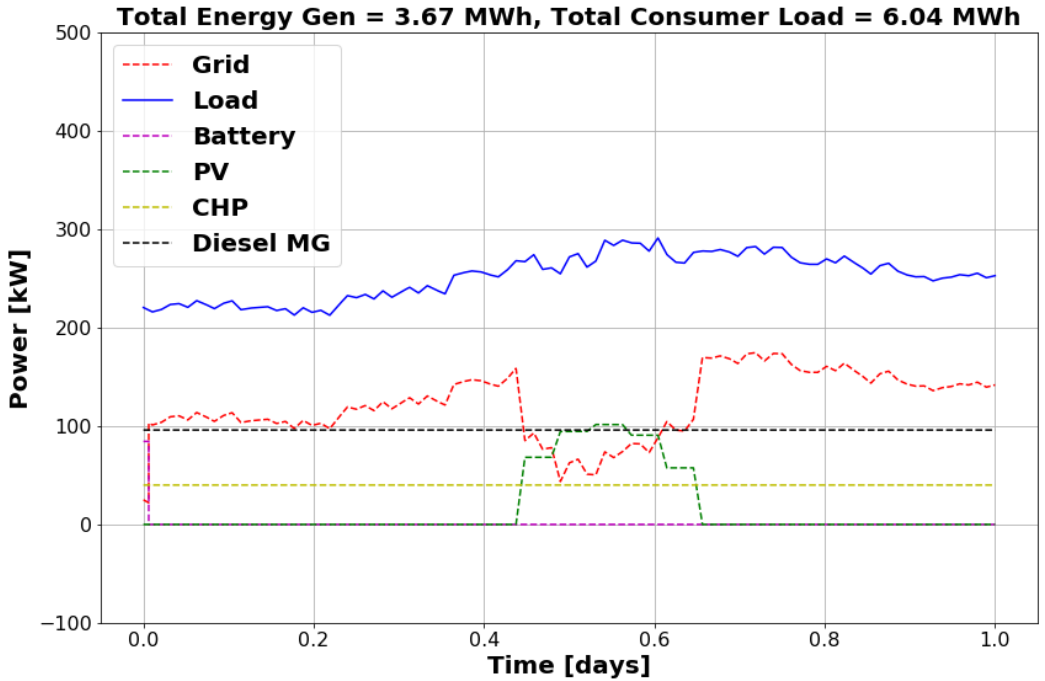


Test: Day 220 - Summer

Model Results – Use Case 3 – Grid Connected

Test: Day 0 - Winter

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

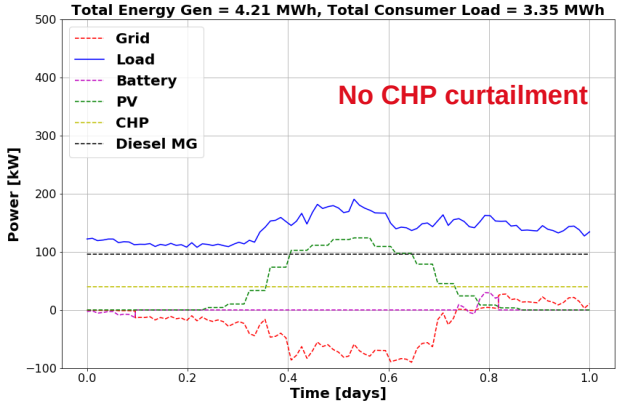


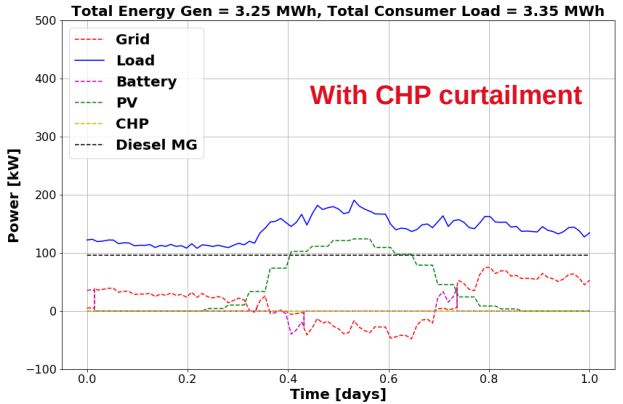
Test: Day 0 - Winter

Model Results – Use Case 3 – Grid Connected

Test: Day 220 - Summer

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





Model Results – Use Case 3 – Grid Connected

Economic Assessment:

- As expected, Use Case 3 with seasonal operations greatly improves operational savings compared to Use Case 1 (diesel only) and Use Case 2 seasonal operations.
- With Full CHP curtailment (no CHP), even more savings can be realized since the cost of CHP power is greater than the cost of grid power.
- However, due to high initial investment, it will take much longer to recoup costs.

	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

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).

Optimization – Use Case 3 – Grid Connected

Optimization Assessment:

- In addition to the rule-based simulation, optimization tools are also available for the Modelon Microgrid library using the Optimica Compiler Toolkit.
- A cost optimization was performed for Use Case 3, with the objective function and constraints defined below:

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

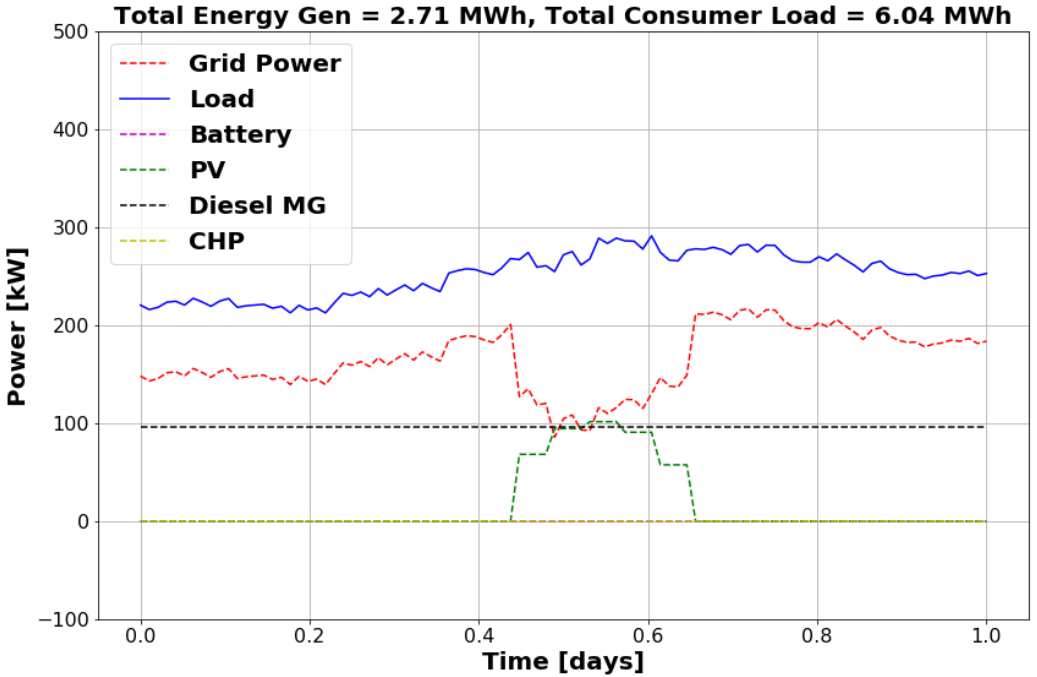
$$total\ cost(t) = cost_{grid}(t) + cost_{diesel}(t) + cost_{CHP}(t)$$

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

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

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

$$P_{diesel} \geq 96\ kW.\quad (min\ loading)$$



Test: Day 0 - Winter

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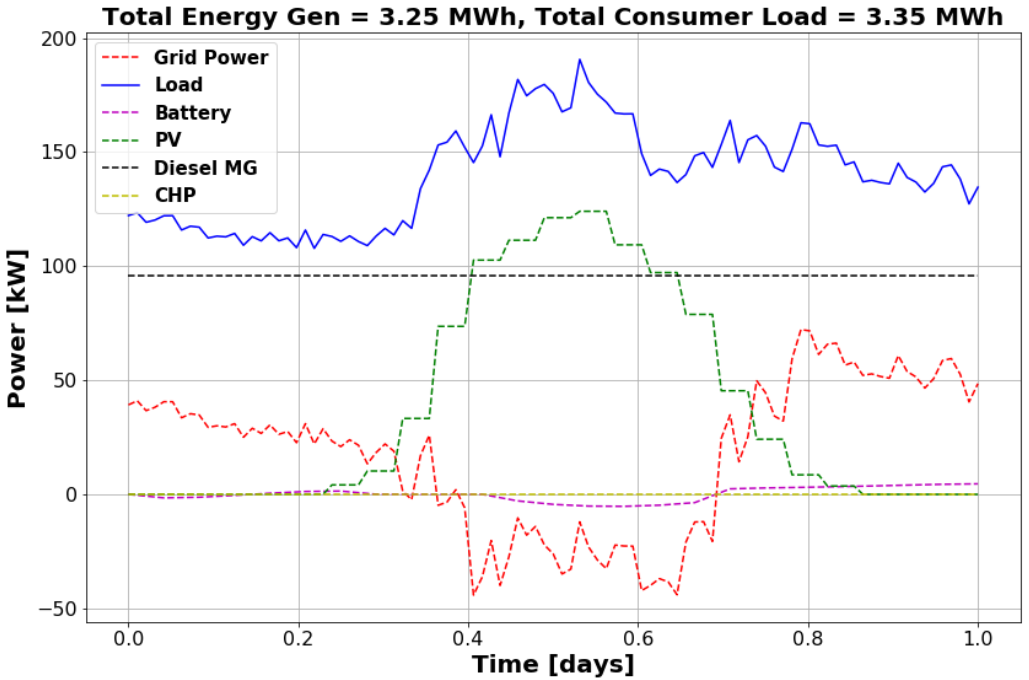

Test: Day 220 - Summer

Optimization – Use Case 3 – Grid Connected

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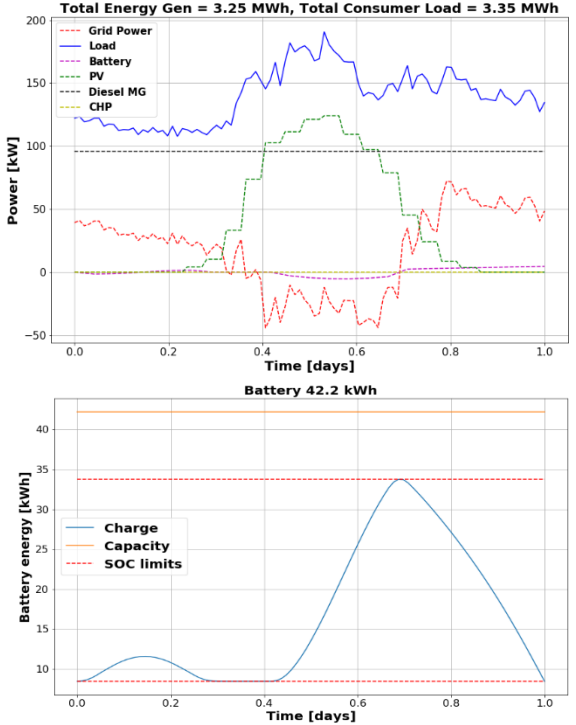

Test: Day 220 - Summer

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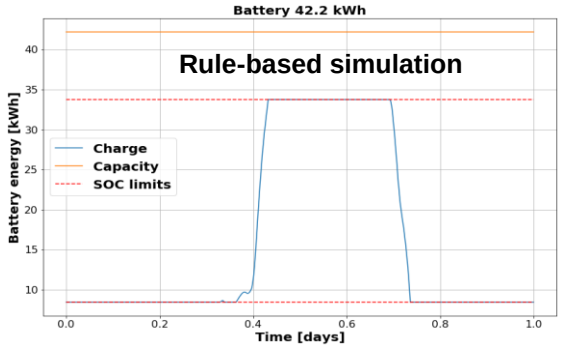

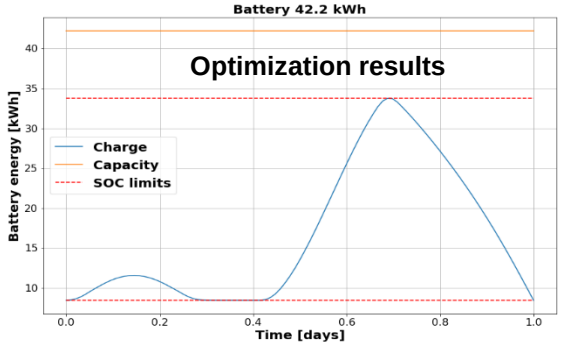

Test: Day 220 - Summer

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THANK YOU

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