ACEP Documentation

Diesel Generator Fuel Consumption Under Dynamic Loading

Power Systems Integration Program
Alaska Center for Energy and Power

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Glossary

Diesel Generator: A diesel generator is composed of a diesel engine which spins an electrical generator.

Fuel Efficiency: Fuel efficiency is the electrical energy that is generated per unit volume of fuel. The units used in this report are kWh/L.

Fuel Flow Meter: A fuel flow meter measures the volumetric flow of fuel in a fuel line. The volume is then normalized for the effect temperature has on density.

Fuel Return: The fuel supply of a diesel generator have a fuel return line, where excess fuel that was not injected into the engine is returned to the fuel tank. T

Loading: The power output of a generator. It can be given as an absolute value (in kW) or as a percentage of the nameplate capacity of the generator.

Minimum Optimal Loading (MOL): The minimum load that a diesel generator should be operated at for continuous operation.

Predictor: A predictor is an independent variable that is tested for influence on another variable.

Rainflow Analysis: A rainflow analysis is a technique to break up a complex waveform into numbers of specific wave amplitudes. It is commonly used to assess the fatigue life of structures, but can be applied to other fields as well. Here it is used to find the typical waveform amplitudes of diesel loading in an Alaska village.

Remote Microgrid: A remote microgrid is a small grid that is not connected to a larger regional grid. In Alaska, USA, remote villages are electrified with remote microgrids. Diesel generators are the most common method of generating electricity. This leads to high energy costs.

Significant Fit: A fit (or coefficients within a fit) is considered significant if it has a p-value less than 0.05. This means that the probability of the predictors in the fit not having any influence on the measured variable are less than 5%.

Steady State Fuel Curve: A fuel curve is the curve of fuel efficiency versus output power of a diesel generator. Fuel curves are measured using steady state loading and are referred to as ’steady state fuel curves’ in this paper. This paper seeks to determine if dynamic loading results in a difference in fuel efficiency from the steady state fuel curve.

Test Script: In this paper, test script refers to a time series of load steps that was programmed into the load-bank to load the diesel generators with a specific load profile.

1 Executive summary

The steady state fuel efficiency curve is well understood for diesel generators and is generally supplied by the manufacturer. However, there is no public data on the effect that dynamic loading has on the fuel efficiency of diesel generators. This is especially valuable information for microgrid situations where the loading is highly variable, especially with high contributions of renewable energy. A commonly held belief is that having high ramp rates on the diesel generator loading negatively affects the fuel efficiency. However, there is no data to quantify this belief. A significant fuel efficiency drop due to high loading ramp rates would negatively affect the fuel savings of adding a high contribution of renewable energy. It would also provide a significant value proposition for energy storage products to help smooth out the loading.

The goal of the tests described in this report was to quantify if and how much ramp rate affected the fuel efficiency of diesel generators. A 457, 320 and 190 kW diesel generator were tested. The tests replicated up to the highest ramp rates observed in a medium penetration remote wind-diesel microgrid.

The ramp rate had no significant effect on the fuel efficiency. However, air temperature had a significant effect with lower temperatures resulting in higher fuel efficiency. There was also an increased degree of non-linearity, or unexplained variation, in the efficiency of smaller and higher EPA Tier (emissions) rated engines. This was likely the effect of having a more active controller required to control emissions. Figure 1 shows the mean absolute deviation (MAD) in the fuel efficiency of the different tests compared to the measured steady state fuel efficiency curve for each diesel generator in the first set of bars. Some of this deviation was found to be the result of the air temperature and a perceived daily effect. The second set of bars show the remaining MAD in fuel efficiency after these effects were taken into account. The remaining deviation is very small and none of it is correlated with the ramp rate.

To address the need for imported fuel reduction in remote Alaska communities the U.S. Department of Energy is funding, through the Grid Modernization Program, the Alaska Microgrid Partnership (AMP), a multi-stakeholder collaborative comprised of national labs and Alaska based partners. The over-arching goal of AMP is to reduce diesel fuel consumption by at least 50% in Alaskas remote microgrids without increasing system lifecycle costs, while improving overall system reliability, security, and resilience. One goal of AMP is to investigate the impact of impact of dynamic loading on diesel fuel consumption.

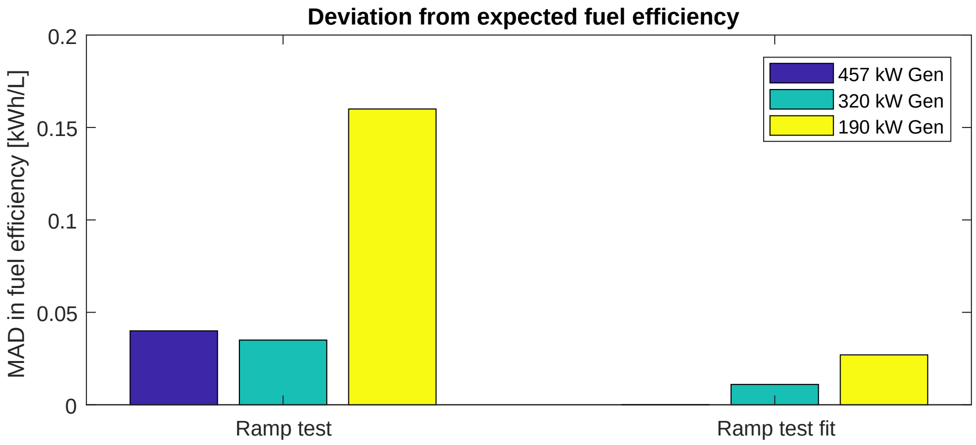

Figure 1: The mean average deviation (MAD) of the average fuel efficiency measured in each test compared to the expected fuel efficiency is shown in the first set of bars. The second set of bars shows the remaining MAD after accounting for the deviation resulting from air temperature and a daily effect. In other words, the remaining unexplained deviation. The MAD for the fitted values of the 457 generator is too low to be seen on this graph.

2 Introduction

Diesel generators are commonly used to generate electricity in remote microgrids. In these systems, the load is often highly variable. Likewise, highly variable renewable energy sources such as wind and solar are integrated into the system to provide some of the power. The diesel generator usually acts as the prime mover so it is responsible to make up the difference between the renewable energy sources and the load. This can result in a highly variable loading on the diesel generator.

The steady state fuel efficiency curve is well understood for diesel generators and is generally supplied by the manufacturer. However, there is no public data on the effect that dynamic loading has on the fuel efficiency of diesel generators. This is especially valuable information for microgrid situations where the loading is highly variable, especially with high contributions of renewable energy. A commonly held belief is that having high ramp rates on the diesel generator loading negatively affects the fuel efficiency. However, there is no data to quantify this belief. A significant fuel efficiency drop due to high loading ramp rates would negatively affect the fuel savings of adding a high contribution of renewable energy. It would also provide a significant value proposition for energy storage products to help smooth out the loading. The goal of this testing was to determine if, and how much, the fuel efficiency dropped due to increasing the ramp rates on the loading of a diesel generator.

2.1 Methodology

To investigate the influence of the dynamic loading on the efficiency of diesel generators in a typical remote microgrid with medium renewable penetration, measured load profiles of the diesel generators at Unalakleet, Alaska were studied to determine typical ramp rates and generator loading. A set of test profiles normalized on the generators capacity was synthezised replicating the observed ramp rates and generator loading.

Three different diesel generators were tested, with 190, 320 and 457 kW power capacities. A high resolution fuel flow meter was used to monitor fuel consumption while running tests (see Appendix A for the make, models, serial numbers and calibration numbers of the fuel meter). The steady state fuel efficiency curve was measured for each generator, followed by the dynamic loading tests. The measured dynamic fuel efficiencies was compared with the measured steady state fuel efficiency curve. A statistical analysis was performed to test for a relationship between changes in fuel efficiency and ramp rate.

3 Test plan development

3.1 Dynamic Loading Analysis

Test profiles were developed using diesel generator loading data from Unalakleet. The amplitudes and frequencies/ramp rates of diesel loading profiles were measured and used to generate load profiles for the test. Unalakleet has a wind power penetration of 120% and energy contribution of 26%. It was chosen as being representative of villages with a medium penetration of wind power (around 120 - 300% power penetration and 20-50% energy contribution). A medium penetration means that there is a significant amount of wind power, but not enough to warrant the additional equipment costs required to turn the diesel generators off during times of excess renewable energy. In many cases, this is the highest penetration of variable renewable energy sources that has been achieved in Alaska, although one of the primary goals of the Alaska Micrigrid Project is to expand the use of local and typically renewable energy sources. Medium penetration systems often result in an increase in ramping frequency and amplitude of the diesel generators in order to balance the variable resource, such as in Unalakleet.

The dataset from Unalakleet had 158 days of data for the output of their 4 diesel generators. Most of the data was measured at 5 s intervals, with 2 days being measured at 1 s intervals. Unalakleet has 4 diesel generators of 475 kW capacity each. The diesel loading was normalized by the online diesel generator capacity in order to obtain per-unit loading.

The load profiles used in the tests to load the diesel generators consisted of triangle waveforms with a certain amplitude and period. The greater the amplitude and shorter the period, the greater the ramp rate. In order to reproduce realistic operating scenarios, the amplitudes and periods of load waveforms on the diesel generators at Unalakleet were analyzed. The ramp rates at each time step in the data from Unalakleet were also analyzed. This information was used to generate test scripts that reproduced realistic loading scenarios.

Analysis of Amplitude and Duration

A rainflow analysis was used to assess the amplitudes and periods of the loading waveforms on the diesel generators at Unalakleet. Rainflow analysis is a technique used to break up a complex waveform into individual wave cycles with their own amplitude and period. The measured normalized amplitudes of the loading waveforms were used in the test waveforms. How common a certain amplitude was could be determined by the number of cycles at that amplitude and the amount of time spent cycling at that amplitude. The amount of time spent cycling at a certain amplitude was calculated by summing the periods of individual cycles. The periods of the cycles were also used to calculate the likelihood of certain ramp rates for a given cycle amplitude.

Figure 2 shows the number of cycles at each cycle amplitude during the 158 days of data for each generator and all generators combined. Figure 3 shows the cumulative distribution function of the number of cycles for each cycle amplitude. 99% of the load cycles on the diesel generators had an amplitude below 7.5%. Note that amplitude here refers to peak amplitude, not peak to peak. Thus the full range of the cycle loading on the diesel generator is twice the amplitude value. For example, one cycle on a generator that goes from 50% to 80% to 50% loading would be considered to have an amplitude of 15% and an offset of 65%. The full range of the cycle loading would be 30%. There are several cycles per year where the change in loading is over 100% of the generators' capacity. These are instances where the diesel generators are overloaded.

The cycle period is used to calculate typical ramp rates for a given cycle period as well as the total amount of time spent cycling at a certain period. Table 1 and Figure 4 show the cycle periods that correspond to different cycle amplitudes. Period refers to the amount of time required to complete 1 full cycle. Thus, a load cycle with a 50 kW amplitude and 1 hr period will hit a +50 kW and -50 kW deviation in a 1 hour period. The upper and lower percent bounds indicate the bounds within which a certain percentage of cycle periods occur for a certain cycle amplitude. For example, 50% of cycle periods will be between between the lower and upper 50% bounds for a given cycle amplitude.

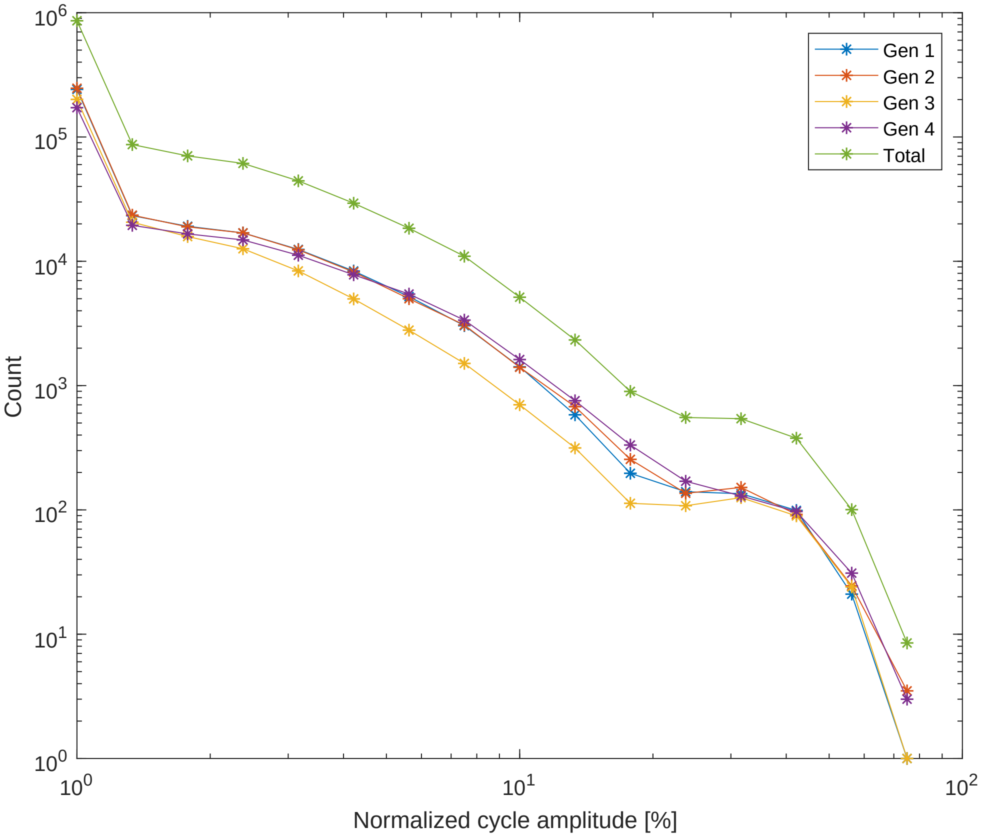

Figure 2: The number of cycles at each cycle amplitude during the 158 days of data from Unalakleet.

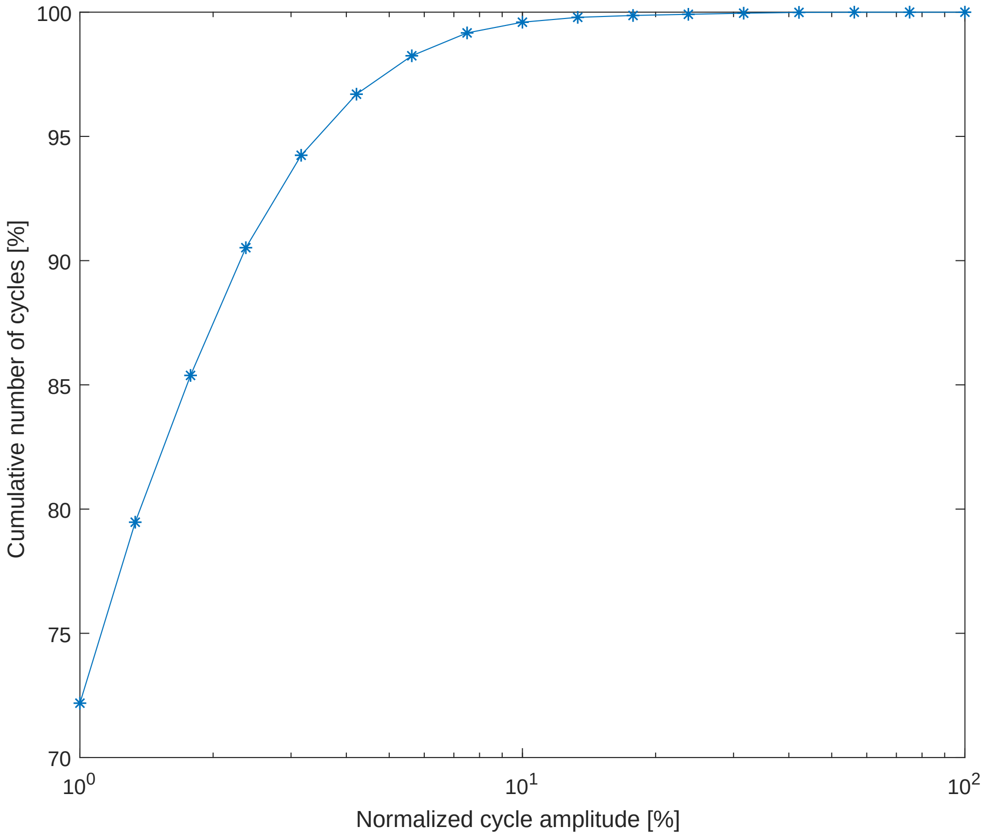

Figure 3: The cumulative number of cycles at each cycle amplitude.

Table 1: Cycle period statistics for specific cycle amplitudes.

Normalized cycle amplitude [%]	**Min. cycle period** [s]	**Median cycle period** [s]	**Max. cycle period** [s]	**95% cycle period lower bound** [s]	**75% cycle period lower bound** [s]	**50% cycle period lower bound** [s]	**30% cycle period lower bound** [s]	**30% cycle period upper bound** [s]	**50% cycle period upper bound** [s]	**75% cycle period upper bound** [s]	**95% cycle period upper bound** [s]
1.0	2	12	1.27E+06	8	10	10	10	16	20	30	65
1.3	2	28	10,190	8	10	13	20	40	52	88	182
1.8	4	36	11,558	8	10	18	22	58	80	130	308
2.4	4	50	12,084	8	12	20	30	84	120	220	558
3.2	2	62	8,692	10	15	24	35	118	180	370	1,080
4.2	6	72	14,468	10	18	30	40	142	242	562	1,829
5.6	6	90	24,104	10	20	40	50	170	290	741	3,066
7.5	7	140	61,578	10	30	55	80	262	420	1,060	5,196
10.0	8	240	80,324	20	50	98	140	434	690	1,720	10,182
13.3	8	450	194,354	38	100	180	250	810	1,292	3,405	22,843
17.8	10	1,028	3.55E+06	70	200	398	568	1,890	3,113	8,004	38,570
23.7	10	3,773	660,198	148	621	1,319	2,034	8,034	14,250	41,099	122,275
31.6	107	14,198	7.35E+06	370	1,411	3,095	5,677	31,420	64,560	95,331	357,338
42.2	340	63,790	7.82E+06	809	5,229	17,189	30,134	106,550	149,975	347,647	1.72E+06
56.2	750	173,852	1.85E+07	1,349	12,513	72,957	128,902	358,718	664,039	1.99E+06	9.88E+06
75.0	239,027	5.56E+06	1.83E+07	239,027	368,570	443,762	2.52E+06	1.33E+07	1.52E+07	1.67E+07	1.83E+07
100.0	-	-	-	-	-	-	-	-	-	-	-

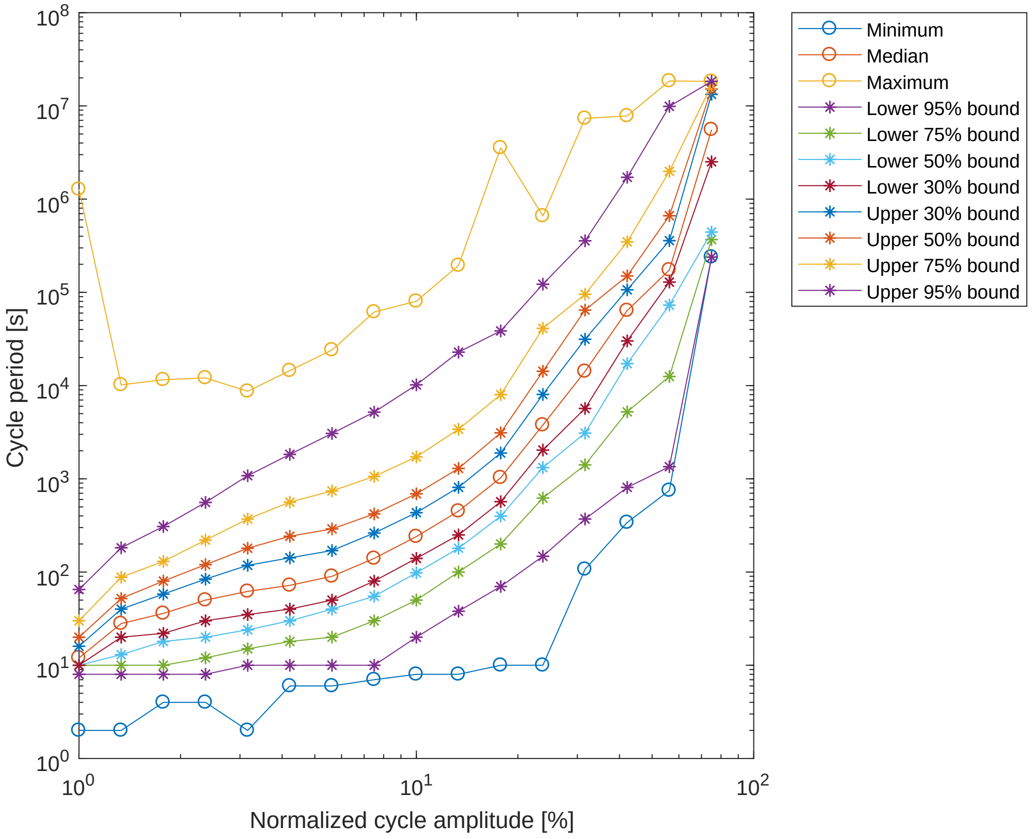

Figure 4: Cycle period statistics at each cycle amplitude.

Figure 5 shows the cumulative distribution function for the amount of time spent operating with a certain load cycle amplitude. Only individual cycles with periods under 1 hour were considered (see Table 1). 99% of the time the diesel generators were cycling with a normalized amplitude less than 10% while 99% of cycles had a normalized amplitude less than 7.5%. For the tests, 10% was the highest amplitude used. The minimum cycle period represents the highest ramp rates observed in the data set. Tests wave forms were created using these values as well as the 95% and 75% lower bounds on the cycle period for high ramp rate scenarios.

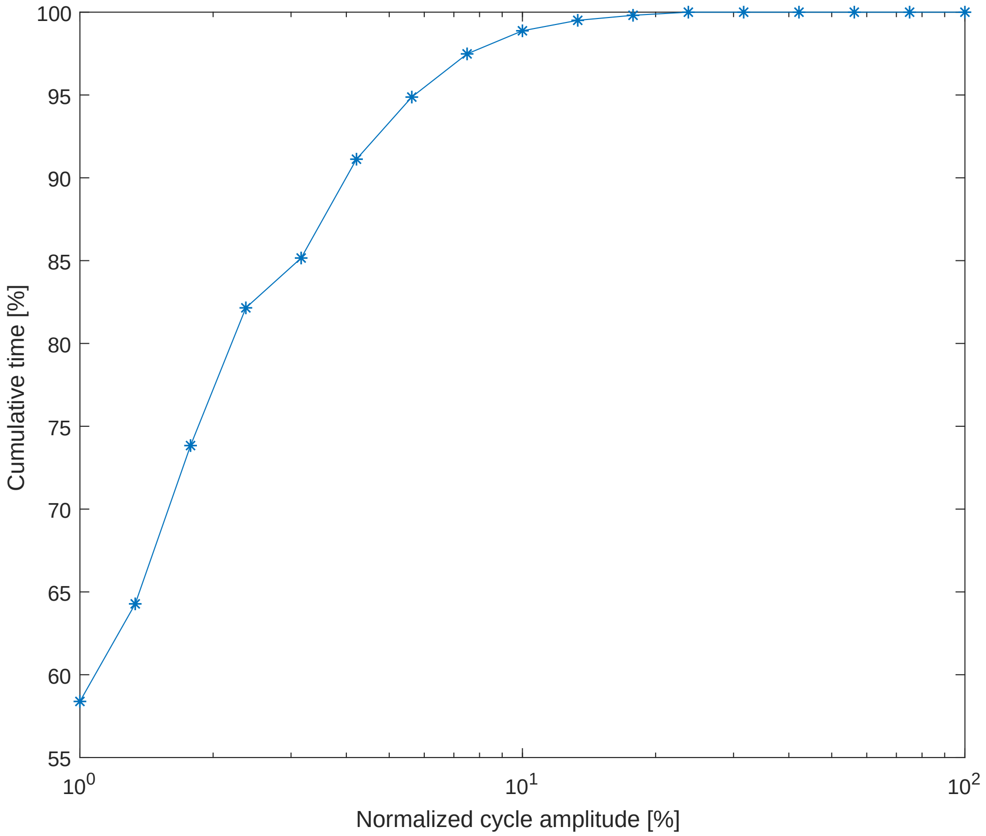

Figure 5: The cumulative time spent at each cycle amplitude.

Ramp Rate Analysis

Loading ramp rates for the diesel generators were calculated and analyzed for each time step in the data from Unalakleet. Figures 6 and 7 and Table 2 show the amount of time spent operating at specific ramp rates. 99% of the time, the diesel generators were operating with a normalized ramp rate less than 1.3%/s. Note that the majority of this data was measured at 5 s intervals. Having longer intervals between samples generally has a smoothing effect on data and the actual ramp rates experienced were likely higher. This is because fluctuations in the load with periods shorter than 5 s were not represented. There were two days of data measured at 1 s intervals. From this data, the diesel generators operated 99% of the time with normalized ramp rates under 3.2%/s. The energy stored in the rotating mass of the diesel generator will dampen the effect of high frequency small amplitude variations in the loading on the diesel generators. The diesel generators were tested with normalized ramp rates up to 5%/s to help account for any higher ramp rate values that could not be measured with a 1 sec sampling rate.

Interpretation and Selection of Dynamic Loading to be Tested

Table 3 shows select amplitudes and periods taken from the prior analysis to develop test profiles. The resulting ramp rates are also given. Using a shorter period results in a higher ramp rate. Using the minimum period gives the maximum ramp rate observed in the data for a load cycle of a given amplitude. As seen in Section 3.1, 99% of ramp rates were under 1.3% for the 5 s data and under 3.2% for the 1 s data. Since the data measured at 5 s intervals is naturally smoothed compared to the data measured at 1 s intervals, the difference in ramp rates is expected. The ramp rates listed in Table 3 are on the high end of the measured ramp rates, as expected. Although these higher ramp rate values do not represent the majority of grid operation in Unalakleet, they make sense for the development of test scripts for two main reasons:

- They provide a more significant difference from steady state behavior, making potential differences in fuel utilization more pronounced.
- Unalakleet is a medium penetration RE microgrid, and we expect that high penetration RE microgrids would exhibit larger ramp rates at times.

The normalized cycle amplitudes were be scaled by the diesel generator capacities. Three diesel generators were tested, rated at 190 kW, 320 kW and 457 kW. These test waveforms were run twice for each diesel generator, centered at 50 and

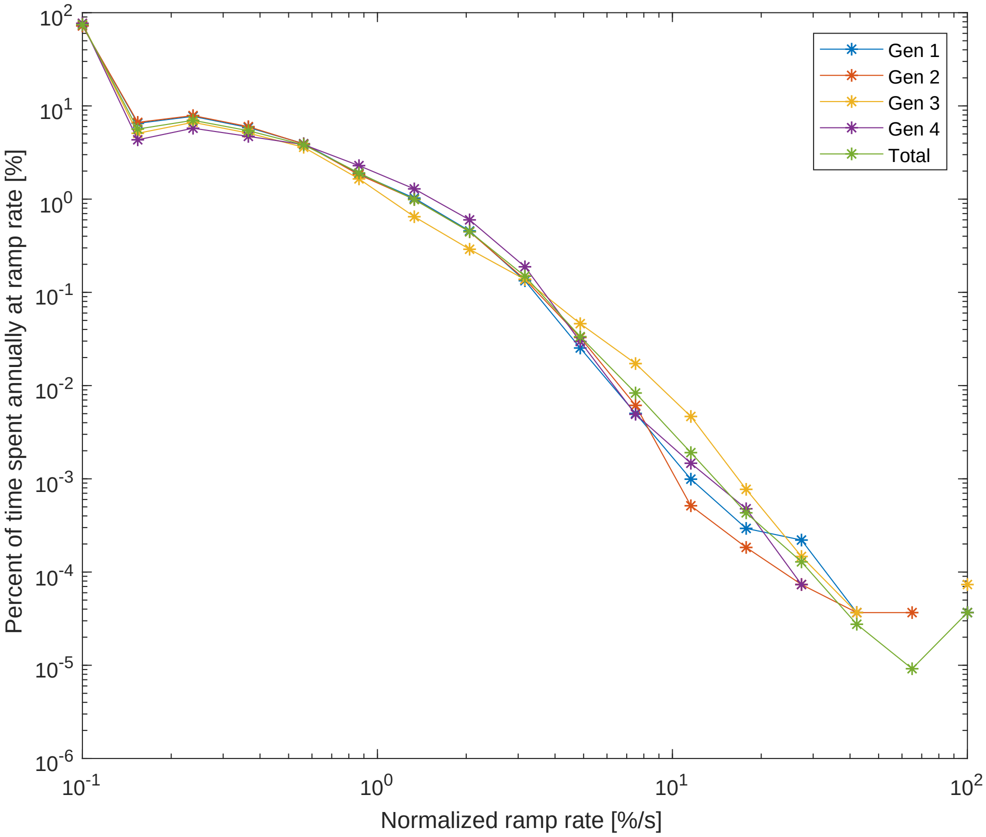

Figure 6: The percent of time spent annually, for each generator, operating at a specific ramp rate.

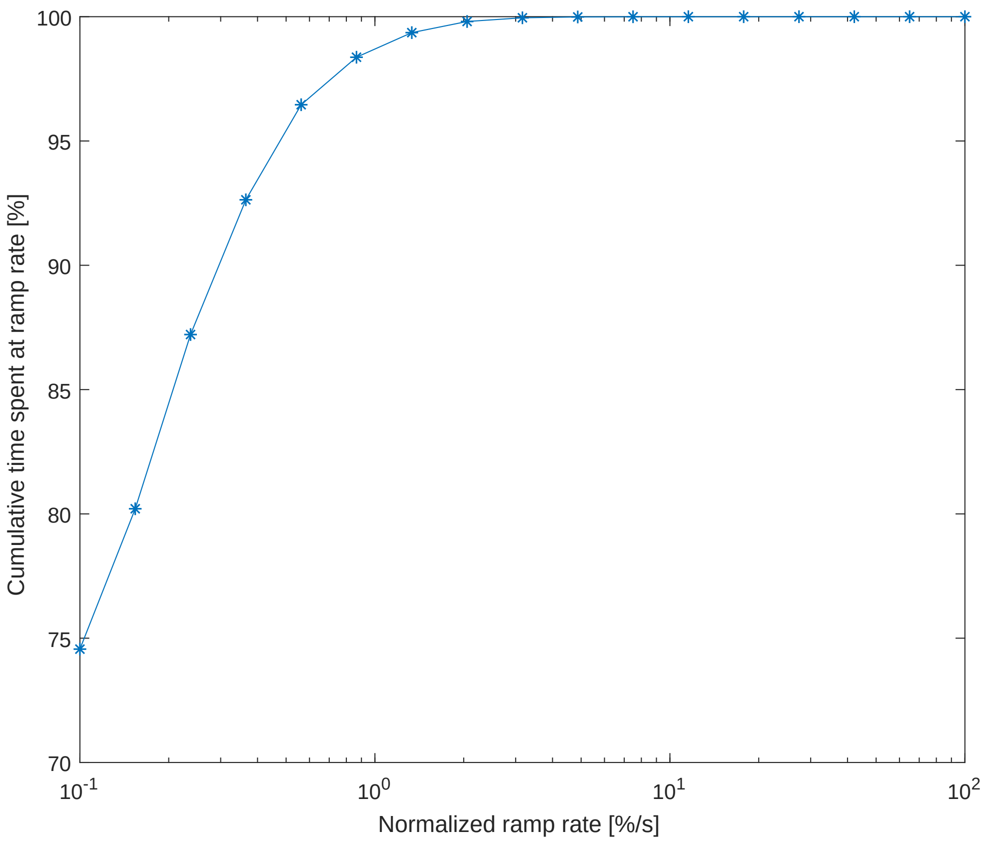

Figure 7: The cumulative distribution of time spent operating at different ramp rates in Unalakleet.

Table 2: Time spent operating at specific diesel ramp rates throughout the sample period.

Normalized ramp rate (%/s)	**Percentage of time spent at ramp rate (%)**
0.100	74.560
0.154	5.646
0.237	7.008
0.365	5.420
0.562	3.824
0.866	1.911
1.334	0.989
2.054	0.448
3.162	0.149
4.870	0.034
7.499	0.008
11.548	0.002
17.783	0.000
27.384	0.000
42.170	0.000
64.938	0.000
100.000	0.000

75% diesel capacity. Each test was run for 30 min. Figure 8 shows two cycles from an example test waveform for the 190 kW generator. This waveform has a normalized amplitude of 10%, a normalized offset of 50% and a period of 20 s.

The target waveform has a constant slope in order to get a constant ramp rate. However, the load-banks used in the test operate at 5 kW loadsteps. Thus, the waveform used in the test had the same average ramp rate as the target waveform, but was compromised of discrete 5 kW steps as shown in Figure 8. It is believed that the discrete waveforms used in these tests did not change the results significantly, especially considering the lag in fuel consumption observed for changes in the load.

Table 3: Overview of dynamic tests. Note that the amplitudes are peak, not peak to peak.

Normalized amplitude (%)	**Min. period (s)**	**Min. period mean ramp rate (%/s)**	**Lower 95% bound period (s)**	**Lower 95% bound mean ramp rate (%/s)**	**Lower 75% bound period (s)**	**Lower 75% bound mean ramp rate (%/s)**
1	2	2	8	0.5	10	0.4
2	4	2	8	1	12	0.67
5	6	3.33	10	2	20	1
10	8	5	20	2	50	0.8

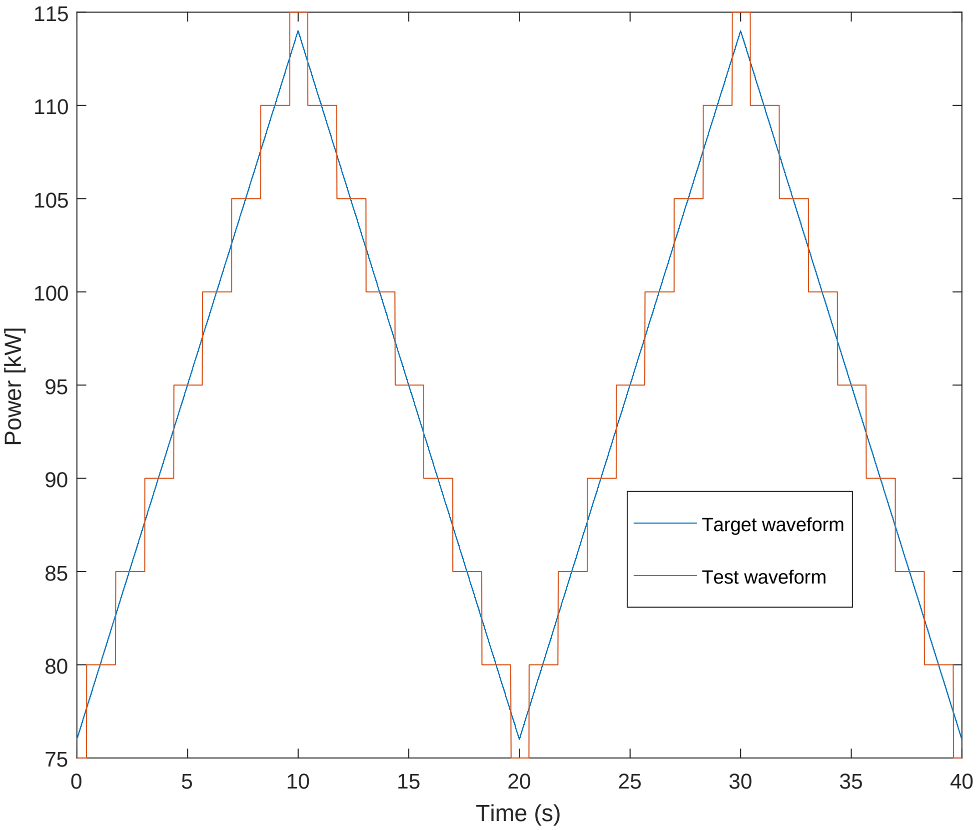

Figure 8: Sample two cycles of a test waveform for the 190 kW generator. This waveform has a normalized amplitude of 10%, a normalized offset of 50% and a period of 20 s.

3.2 Dynamic Loading Test Plan

Based on the dynamic loading test profiles testing regimes were developed for the three diesel generators.

457 kW Generator Dynamic Loading Tests

Table 4 shows the normalized offset, amplitude and period for the different test waveforms.

Table 4: 457 kW diesel generator test overview.

Test	**Generator capacity (kW)**	**Test offset (%)**	**Test amplitude (%)**	**Test period (s)**
Test 3.1	457	50	0	0
Test 3.2	457	50	1	2
Test 3.3	457	50	1	8
Test 3.4	457	50	1	10
Test 3.5	457	50	2	4
Test 3.6	457	50	2	8
Test 3.7	457	50	2	12
Test 3.8	457	50	5	6
Test 3.9	457	50	5	10
Test 3.10	457	50	5	20
Test 3.11	457	50	10	8
Test 3.12	457	50	10	20
Test 3.13	457	50	10	50
Test 3.14	457	75	0	0
Test 3.15	457	75	1	2
Test 3.16	457	75	1	8
Test 3.17	457	75	1	10
Test 3.18	457	75	2	4
Test 3.19	457	75	2	8
Test 3.20	457	75	2	12
Test 3.21	457	75	5	6
Test 3.22	457	75	5	10
Test 3.23	457	75	5	20
Test 3.24	457	75	10	8
Test 3.25	457	75	10	20
Test 3.26	457	75	10	50

320 kW Generator Dynamic Loading Tests

Table 5 shows the normalized offset, amplitude and period for the different test waveforms.

Table 5: 320 kW diesel generator test overview.

Test	**Generator capacity (kW)**	**Test offset (%)**	**Test amplitude (%)**	**Test period (s)**
Test 2.1	320	50	0	0
Test 2.2	320	50	1	2
Test 2.3	320	50	1	8
Test 2.4	320	50	1	10
Test 2.5	320	50	2	4
Test 2.6	320	50	2	8
Test 2.7	320	50	2	12
Test 2.8	320	50	5	6
Test 2.9	320	50	5	10
Test 2.10	320	50	5	20
Test 2.11	320	50	10	8
Test 2.12	320	50	10	20
Test 2.13	320	50	10	50
Test 2.14	320	75	0	0
Test 2.15	320	75	1	2
Test 2.16	320	75	1	8
Test 2.17	320	75	1	10
Test 2.18	320	75	2	4
Test 2.19	320	75	2	8
Test 2.20	320	75	2	12
Test 2.21	320	75	5	6
Test 2.22	320	75	5	10
Test 2.23	320	75	5	20
Test 2.24	320	75	10	8
Test 2.25	320	75	10	20
Test 2.26	320	75	10	50

190 kW Generator Dynamic Loading Tests

Table 6 shows the normalized offset, amplitude and period for the different test waveforms.

Table 6: 190 kW diesel generator test overview.

Test	**Generator capacity (kW)**	**Test offset (%)**	**Test amplitude (%)**	**Test period (s)**
Test 1.1	190	50	0	0
Test 1.2	190	50	1	2
Test 1.3	190	50	1	8
Test 1.4	190	50	1	10
Test 1.5	190	50	2	4
Test 1.6	190	50	2	8
Test 1.7	190	50	2	12
Test 1.8	190	50	5	6
Test 1.9	190	50	5	10
Test 1.10	190	50	5	20
Test 1.11	190	50	10	8
Test 1.12	190	50	10	20
Test 1.13	190	50	10	50
Test 1.14	190	75	0	0
Test 1.15	190	75	1	2
Test 1.16	190	75	1	8
Test 1.17	190	75	1	10
Test 1.18	190	75	2	4
Test 1.19	190	75	2	8
Test 1.20	190	75	2	12
Test 1.21	190	75	5	6
Test 1.22	190	75	5	10
Test 1.23	190	75	5	20
Test 1.24	190	75	10	8
Test 1.25	190	75	10	20
Test 1.26	190	75	10	50

4 Test Setup

4.1 Equipment under Test

457 kW diesel generator

The QAS600 is a diesel generator package from ATLAS COPCO. It is rated at 457 kW as a prime generator. Figure 9 shows the QAS600 and Table 7 shows its specifications.

Figure 9: The Volvo QAS 600 from Atlas Copco.

Table 7: QAS 600 specifications.

Parameter	Description
Engine Make and Model	Volvo Penta TAD1641 GE
Horsepower	660 hp @ 1,800 rpm
Rated AC Output	Standby: 503 kW (628 kVA) Prime: 457 kW (571 kVA)
Emissions Tier Level	Tier 2

320 kW diesel generator

The C15 is a diesel generator package from Caterpillar. It is rated as a prime generator at 320 kW. Figure 10 shows the C15 and Table 8 shows its specifications

Table 8: C15 specifications.

Parameter	Description
Engine Make and Model	Caterpillar C15
Horsepower	500 hp @ 1,800 rpm
Rated AC Output	Prime: 320 kW (400 kVA)
Emissions Tier Level	Tier 3

Figure 10: The C15 Caterpillar diesel generator.

190 kW diesel generator

The G240WCU-3A-T4I is a diesel generator package from Doosan. It is rated at 190 kW which it can run at for 26 hr. Figure 11 shows the G240WCU-3A-T4I and Table 9 shows its specifications.

Figure 11: The Doosan G240WCU-3A-T4I diesel generator.

Table 9: G240WCU-3A-T4I specifications.

Parameter	**Description**
Engine Make and Model	Cummins QSB7-G6
Horsepower	282 hp @ 1,800 rpm
Rated AC Output	190 kW (238 kVA) for 26 hr continuous
Emissions Tier Level	Tier 4-interim

4.2 Instrumentation

See Appendix A for a description of the laboratory data acquisition and management system. The following channels were sampled at 3 Samples per second (S/s) and used in these tests.

- Load (kW and kvar)
- Diesel Generator output (kW and kvar)
- Diesel fuel supply flow (L/min)
- Diesel fuel return flow (L/min)
- Diesel fuel supply temperature (°C)
- Diesel fuel return temperature(°C)

In addition, air temperature and pressure measurements from a meteorological tower 1 km away were used in these tests. They were recorded every half hour.

4.3 Order and timing of tests

Ideally, all tests would be performed in as similar conditions as possible, with the only difference being the ramp rate of the load. In practice, the tests for each diesel generator were spread out over several days. Thus there were different ambient conditions, such as temperature and air pressure, which had an impact on the operation of the diesel generators. Air temperature and pressure were included in the statistical analysis to determine their effect on efficiency.

The amount of time the diesel generator was in operation before running the test could also impact its efficiency. In order to minimize this effect, the diesel generators were warmed up untill they were thermally saturated and their temperature stabilized at 60% loading.

4.4 Steady State Efficiency Analysis

The steady state fuel curve was measured for each generator using two tests. The first test started at zero loading and increased the loading in 5 kW increments, spending 1 minute at each step, all the way to full load. The second test started at full load and decreased the load in 5 kW increments, spending 1 minute at each step, all the way back to zero loading.

Due to lags in the fuel supply system fuel consumption only settles to a steady state some time after a change in load. As a result, the first 20 seconds of each loadstep were discarded when calculating the fuel efficiency of each load level. The last 5 seconds of each load level were also discarded in order to simplify the automated procedure of detecting load steps in the test data to calculate a fuel curve. Thus, the fuel efficiency was averaged over 35 seconds for each load level on the fuel curve.

Seven load levels were measured a second time for 20 minutes each in order to spot check the measured fuel curve. These indicated how much of the variability in fuel consumption measurements 35 sec was able to average out. The mean absolute deviation (MAD) of 35 sec averages within the 20 min tests were calculated. This represented the expected deviation in the 35 sec averages used to generate the curve. If the deviation between the measured fuel curve and the spot checks was greater than expected, this indicated longer term drift in the fuel efficiency of the diesel generators. This seemed to be the result of different ambient conditions between tests.

4.5 Dynamic Loading Efficiency Analysis

The goal of these tests was to measure the change in fuel efficiency that resulted from ramping the loading on the generator as opposed to having a constant load. The expected fuel efficiency for each dynamic test was calculated by integrating their load levels over the measured steady state fuel efficiency curve. The calculated expected fuel efficiency was then compared with the actual measured fuel efficiency to get the difference in efficiency in the dynamic test compared to the steady state test. A statistical analysis was performed to determine if there was a significant correlation between the ramp rate and change in fuel efficiency, as described in Section 4.6.

Equation 1 shows the calculation for the expected fuel fuel efficiency from the measured steady state fuel curve. P_i is power measurement i out of N, the total number of measurements in a test, in kW. $FC_{ss}(P_i)$ is the fuel consumption from the measured steady state fuel curve that corresponds to the power P_i. Equation 2 shows the calculation for the measured fuel efficiency in a test. FC_i is the measured fuel efficiency at measurement i. The measurements were taken at a constant sampling rate.

$$\eta_{exp} = \frac{\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} FC_{ss}(P_i)} \tag{1}$$

$$\eta_{meas} = \frac{\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} FC_i} \tag{2}$$

The fuel efficiency was measured every 0.33 sec. The individual fuel efficiency measurements varied significantly due to the generators inertia and the governors regulation of fuel flow to maintain grid frequency, combustion temperature, and other parameters. As a result, an average fuel efficiency had to be calculated over an extended period of time. The amount of time required to smooth out the variability in individual fuel efficiency measurements was tested for each diesel generator by seeing what averaging period was required to average out most of the variability in fuel efficiency for a constant load.

4.6 Statistical analysis

The difference in the fuel efficiency of the dynamic tests compared to the expected efficiency from the steady state fuel curve was calculated as described in Section 4.4. The differences (or deviation) in efficiency were tested for a linear relationship with the loading waveform ramp rates and amplitudes of the diesel generator in the tests. If the coefficients of a linear fit had a p-value under 0.05 they were considered to be significant.

As ramping is only one of many effects that may influence the efficiency of a diesel engine, environmental effects known to be of thermodynamic significance were taken into consideration during the analysis to detrend the data accordingly. Linear fits of fuel efficiency with air temperature and barometric pressure were assessed and removed in order to isolate changes in efficiency resulting from changes in the ramp rate.

5 Test Results

This section describes the results of testing diesel generators for changes in their fuel efficiency as a result of changing the ramp rate of their loading. The expected fuel consumptions from the measured steady state fuel curves were calculated by integrating the power output over the measured steady state fuel curve. The deviation in the dynamic tests from the expected fuel consumption (based on the measured steady state fuel efficiency) was tested for correlations with the generator load ramp rate, ramp root mean squared (rms) amplitude, ambient temperature and ambient pressure.

5.1 Steady state measurements

457 kW diesel generator

Figure 12 shows the measured and averaged values at each load step. The average standard deviation (std) and mean absolute difference (MAD) of the individual measurements at each load level (taken every 0.33 sec over a 35 sec period) were 0.018 and 0.014 kWh/L. These were relatively low values which indicated low variability. Their averaged values formed a smooth fuel curve with a steady fuel efficiency at high loading. This showed the benefit of electronic fuel injection since the fuel efficiency of non-electronic fuel injection would taper off at high loadings.

Spot check In order to verify the accuracy of the measured fuel curve, several different load levels were measured for a 20 min duration. Figure 13 shows a comparison between the spot checks and the measured fuel curve. The average mean absolute deviation (MAD) of 35 sec averages within the 20 min tests was 0.014 kWh/L while the MAD of the differences between the fuel curve and the spot checks was 0.035 kWh/L. The higher deviation between the fuel curve and the spot check indicate a long term drift in fuel efficiency. As will be seen in the dynamic test results in Section 5.2, the fuel efficiency drift seems to result from different ambient operating conditions between tests and this trend was removed from the data set for final analysis.

The low variability in the 0.33 sec measurements from their 35 sec averages, the smooth nature of the fuel curve from the 35 sec averages and the low variability of 35 sec averages compared to 20 min averages all indicate that the fuel curve based on 35 sec averages is a very good approximation.

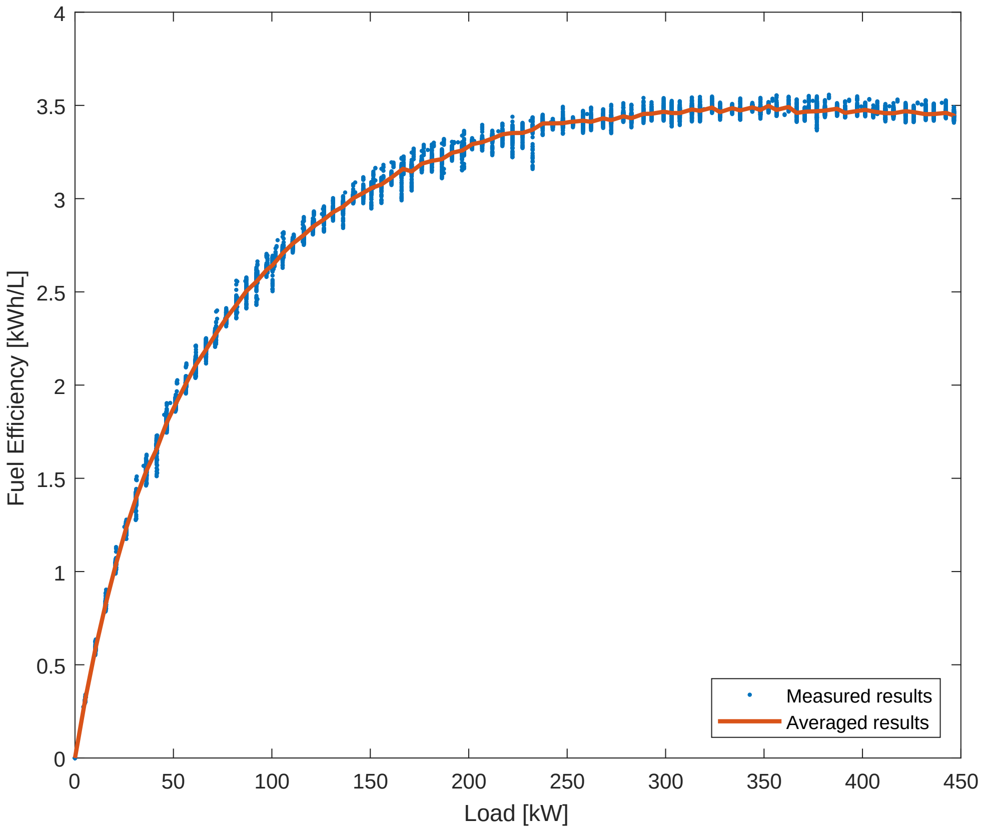

Figure 12: The Measured and averaged steady state fuel efficiency curve for the 457 kW diesel generator. This was measured with increasing incremental 5 kW loadsteps. 1 min was spent at each loadstep.

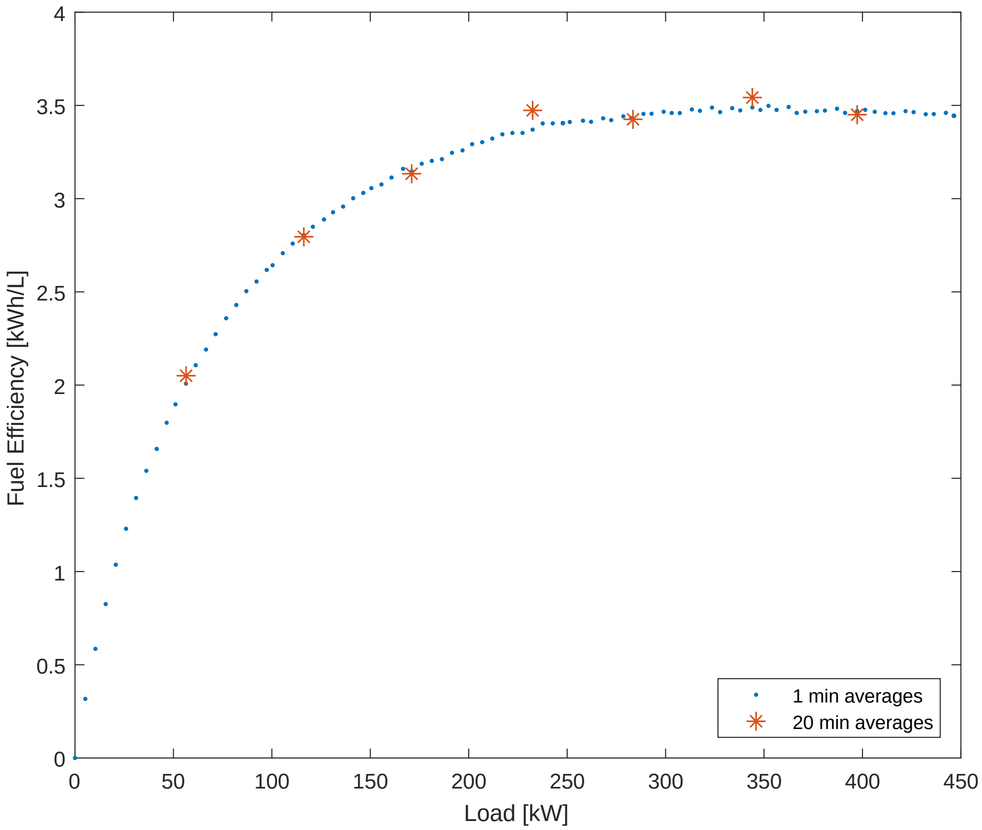

Figure 13: Comparison of 1 min and 20 min averages for steady state fuel efficiency. The differences appear to be from operating conditions and not the averaging period.

320 kW diesel generator

Figure 14 shows the measured and averaged values at each load step. The average standard deviation (std) and mean absolute difference (MAD) of the individual measurements at each load level (taken every 0.33 sec over a 35 sec period) were 0.036 and 0.029 kWh/L. While more than the 457 kW diesel generator, the variability in the steady state fuel efficiency is still relatively low.

The average fuel efficiency at each load level forms a smooth fuel curve with an apparent drop in efficiency between 184 and 302 kW. Figure 15 shows the measured fuel curve with the fuel curve that was provided by the manufacturer for this generator. The drop in efficiency is not expected from their specifications. The engine recently received a firmware update from Caterpillar to deal with some frequency regulation issues which could be the cause for the change in the fuel curve.

Spot check As described in the introduction for this section, in order to verify the accuracy of the measured fuel curve, several different load levels were measured for a 20 min duration. Figure 16 shows a comparison between the spot checks and the measured fuel curve. The average mean absolute deviation (MAD) of 35 sec averages within the 20 min tests was 0.0088 kWh/L while the MAD of the differences between the fuel curve and the spot checks was 0.053 kWh/L. The higher deviation between the fuel curve and the spot check indicate a long term drift in fuel efficiency. As will be seen in the dynamic test results in Section 5.2, the fuel efficiency drift seems to result from different ambient operating conditions between tests.

The low variability in the 0.33 sec measurements from their 35 sec averages, the smooth nature of the fuel curve from the 35 sec averages and the low variability of 35 sec averages compared to 20 min averages all indicate that the fuel curve based on 35 sec averages is a good approximation.

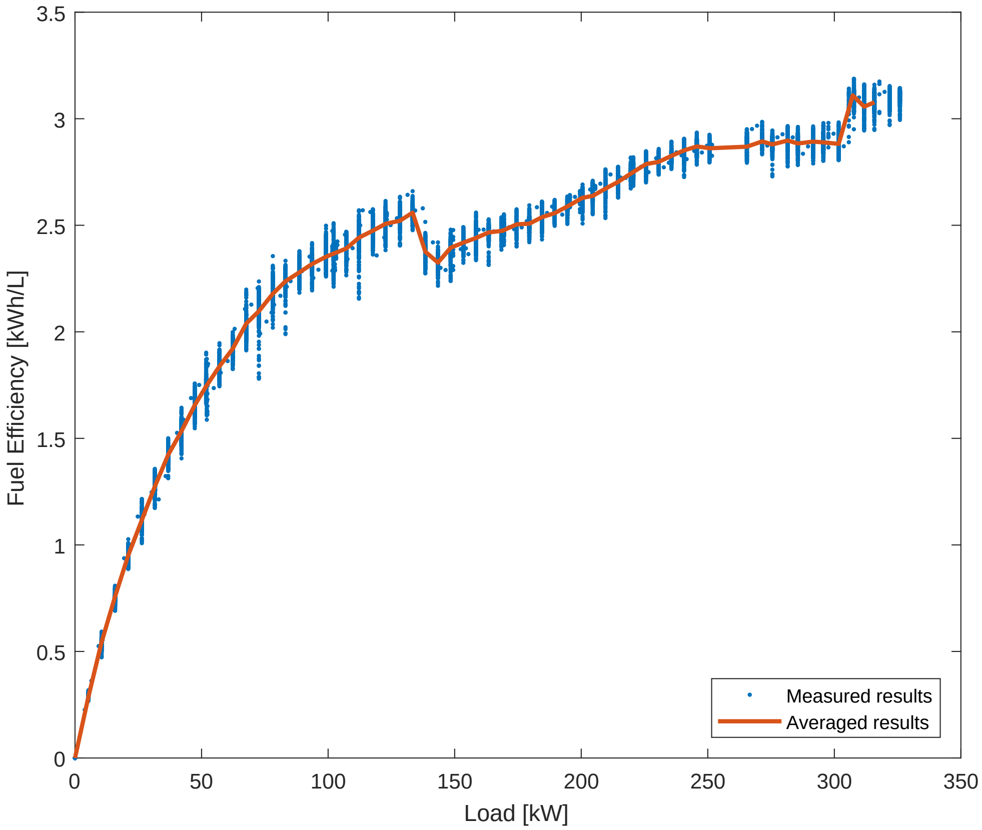

Figure 14: The Measured and averaged steady state fuel efficiency curve for the 320 kW diesel generator. This was measured with increasing incremental 5 kW loadsteps. 1 min was spent at each loadstep.

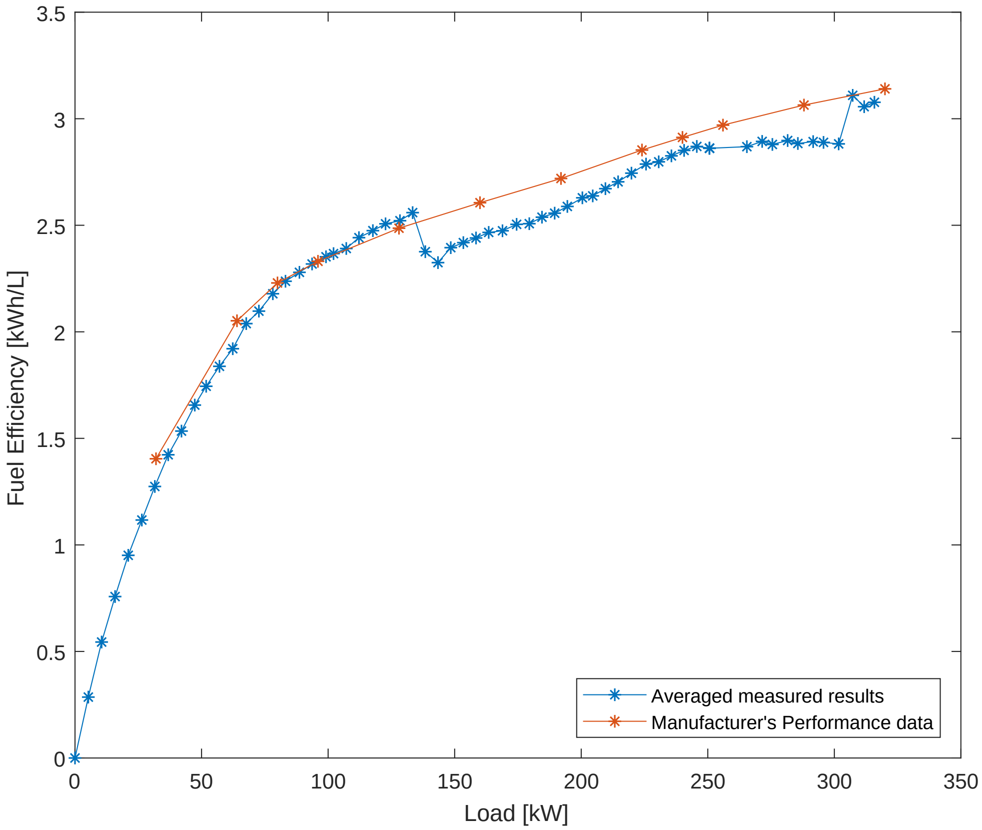

Figure 15: The measured fuel curve compared to the manufacturer performance specs for this generator. The drop in efficiency is not expected from the rated performance specs.

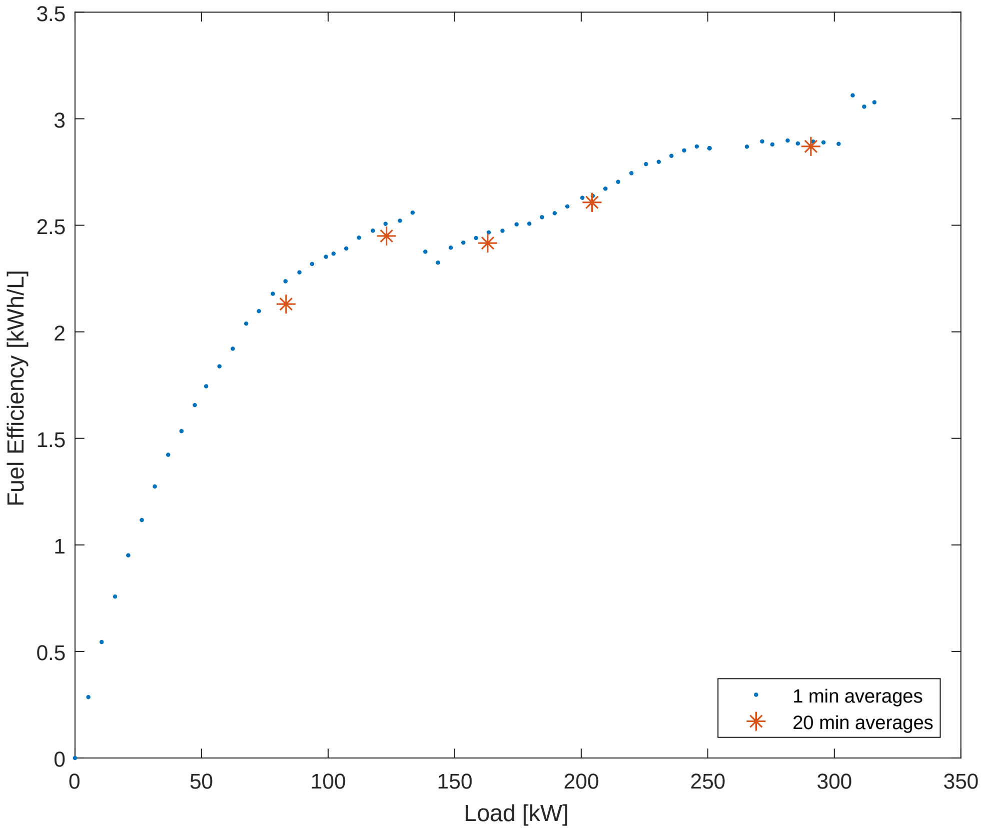

Figure 16: Comparison of 1 min and 20 min averages for steady state fuel efficiency.

190 kW diesel generator

Figure 17 shows the measured and averaged fuel efficiencies at each load level on the fuel curve. There was a huge amount of variation, with the average standard deviation (std) and mean absolute difference (MAD) of the individual measurements at each load level (taken every 0.33 sec over a 35 sec period) being 0.47 and 0.39 kWh/L respectively. The average values at each load level do not form a smooth fuel curve. This indicates that 35 sec was not enough time to average out the variability in the individual fuel efficiency measurements.

This engine has a Tier 4 emissions rating, which means there are extra emission regulating features which may affect the variability in its efficiency. This includes a catalytic cleaning operation which periodically uses extra diesel fuel to burn contamination off the catalytic converter on the exhaust system.

Spot check As described in the introduction for this section, in order to verify the accuracy of the measured fuel curve, several different load levels were measured for a 20 min duration. Figure 18 shows a comparison between the spot checks and the measured fuel curve. The average mean absolute deviation (MAD) of 35 sec averages within the 20 min tests was 0.14 kWh/L while the MAD of the differences between the fuel curve and the spot checks was 0.093 kWh/L. They are similar values, with apparent long term drift in fuel efficiency between tests. The fuel curve test and the 20 min spot check test were performed on the same day. As will be seen in the results of the dynamic tests, long term drift in fuel efficiency was measured.

A MAD of 0.14 kWh/L for a 35 sec average is significantly lower than the MAD of 0.39 kWh/L for 0.33 sec averages (individual efficiency measurements). However, it is still very high. It is still higher than the MAD of 35 sec averages for the 457 and 320 kW diesel generators.

In order to average out more of the variability, the fuel curve measurements and spot checks were combined and smoothed using a moving average. In the moving average, the spot checks were weighted by 1200 sec/35 sec $= 34$, which is the ratio of the measurement period of the spot checks over the measurement period of the fuel curve load level measurements. Figure 19 shows the measured fuel curve (blue line), the spot checks (red markers) and the new fuel curve from the moving average (yellow line). The moving average eliminated much of the variability seen in the 35 sec averages which resulted in a much smoother fuel curve.

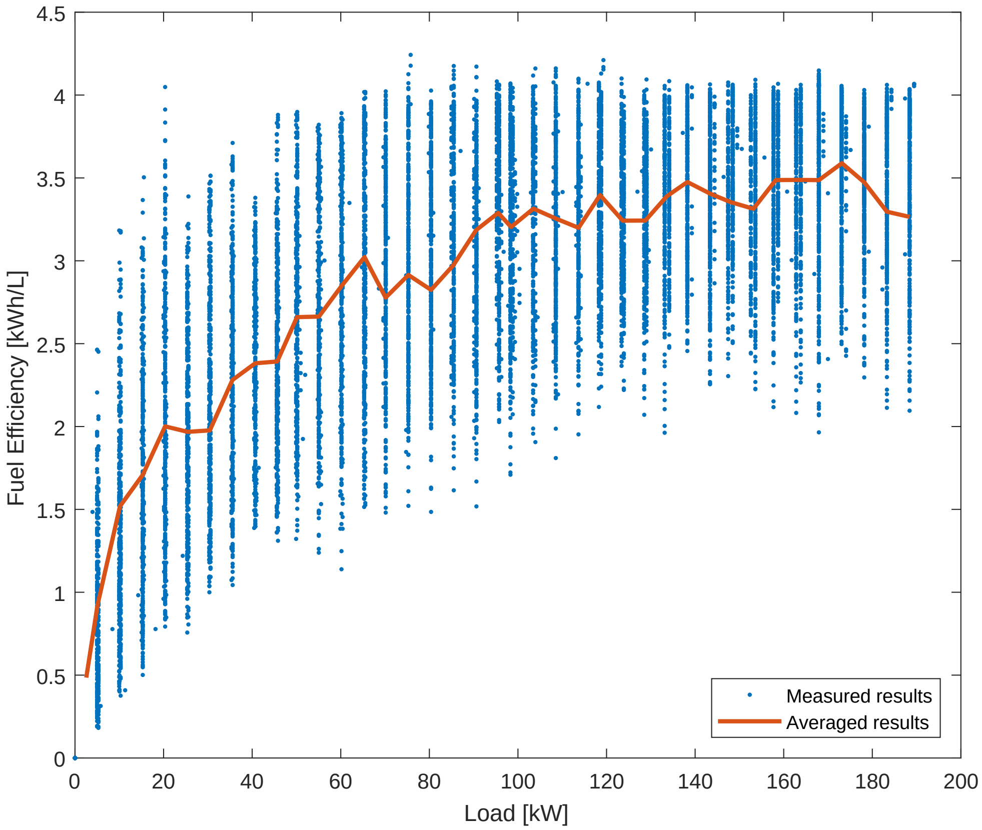

Figure 17: The Measured and averaged steady state fuel efficiency curve for the 190 kW diesel generator. This was measured with increasing incremental 5 kW loadsteps. 1 min was spent at each loadstep.

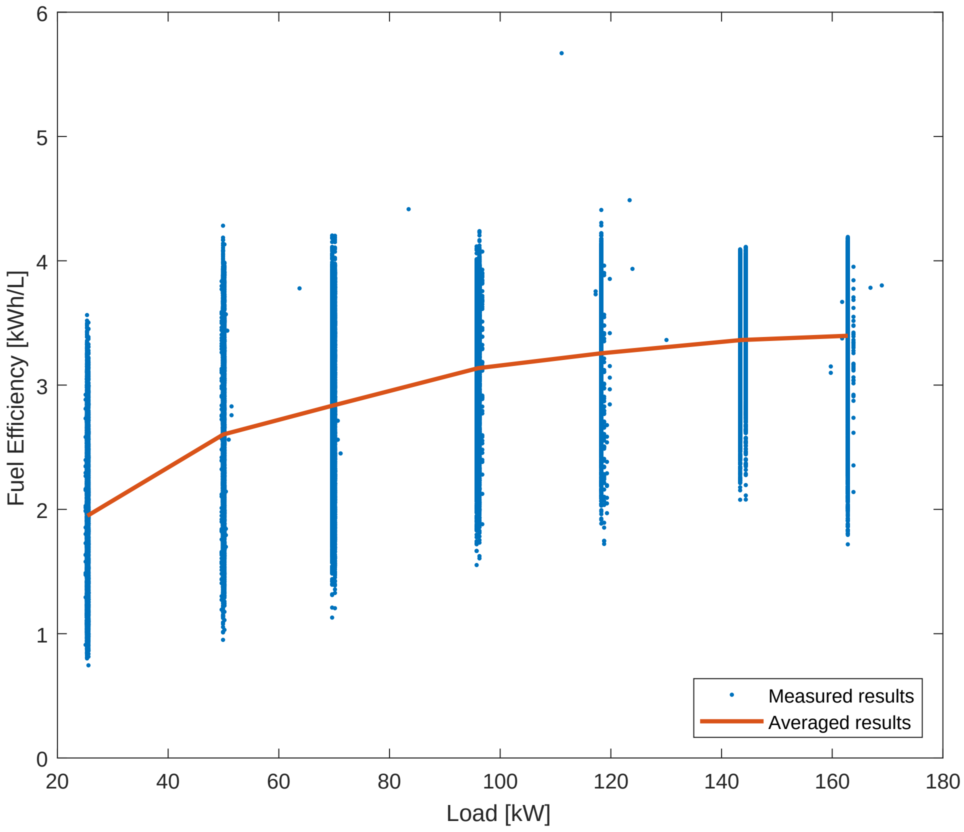

Figure 18: The Measured and averaged 20 minute spot checks for the steady state fuel efficiency curve for the 190 kW diesel generator.

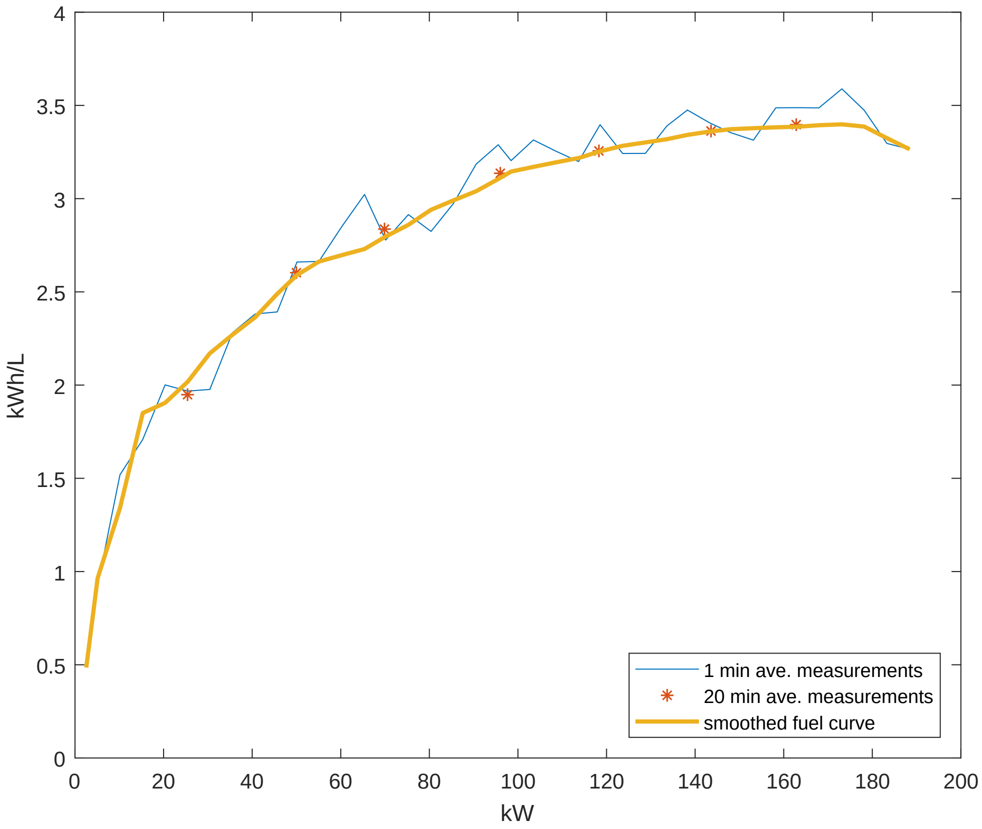

Figure 19: The smoothed fuel curve using the 1 min and 20 min steady state fuel efficiency measurements.

Summary: Steady State Efficiency Tests

Table 10 outlines the standard and mean absolute deviations for 0.33 sec averages in a 35 sec sample and for 0.35 sec averages in a 20 min sample for each diesel generator. A 0.33 sec period represents the sampling period of individual fuel efficiency measurements (3 Hz sampling rate). A 35 sec averaging period was used to measure the steady state fuel efficiency at each load level on the fuel curve. Figure 20 shows the MAD of 0.33 and 35 sec averages in fuel efficiency compared to a longer averaging period.

Table 10: Standard deviation and mean absolute deviation for 0.33 sec averages in a 35 sec sample and for 0.35 sec averages in a 20 min sample for each diesel generator.

Description	Units	457 kW		320 kW		190 kW	
		STD	MAD	STD	MAD	STD	MAD
0.33 sec ave. deviation	kWh/L	0.018	0.014	0.043	0.033	0.47	0.39
35 sec ave. deviation	kWh/L	0.011	0.0075	0.011	0.0088	0.18	0.14

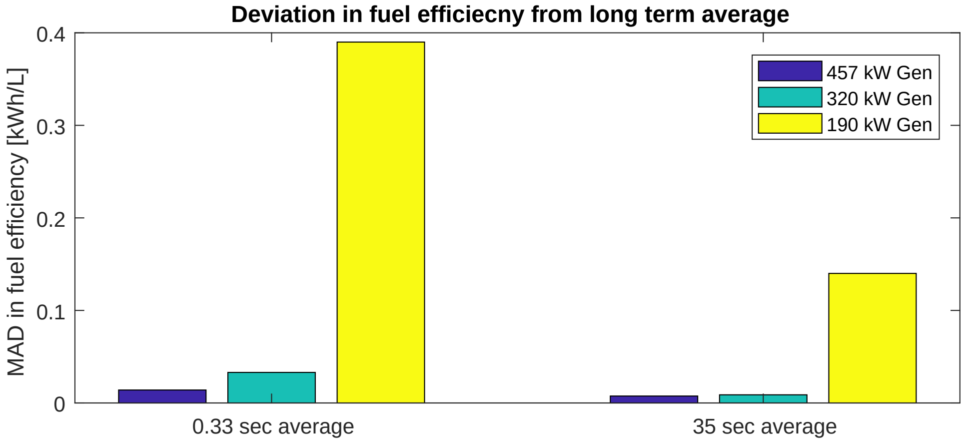

Figure 20: The deviation in fuel efficiency for 0.33 and 35 second averaging periods from a long term average.

The 457 kW generator had very little deviation in fuel efficiency from the steady state in all tests and averaging periods. The 320 kW diesel generator had more deviation in individual measurements, but averaging over 35 sec was enough to average out most of the variability. The 190 kW diesel generator had a very large amount of variability in the individual measurements and 35 sec averages were not enough to bring the variability sufficiently low. Thus, the steady state fuel curve had to be smoothed using a moving average and the 7 steady state load steps that were measured and averaged over 20 min. The measured fuel curves for the 457, 310 and 190 kW diesel generators are shown in Figures 12, 14 and 19.

5.2 Dynamic Loading Tests

457 kW diesel generator

A suite of tests were run on the diesel generator with different ramp rates, as described in Section 3.2. The difference in efficiency from the measured steady state (constant loading) fuel curve was calculated as described in Section 4.4 and a statistical analysis was performed as described in Section 4.6.

There was a small but significant deviation in the measured fuel efficiency of the dynamic tests from the expected fuel efficiency of the measured steady state fuel curve. A mean absolute deviation (MAD) of 0.040 kWh/L (1.2%) was measured. This deviation did not correlate well with the ramp rate or rms amplitude of the tests. Figure 21 shows the change in fuel efficiency, ambient pressure, ambient temperature, ramp rate and ramp amplitude amplitude with respect to the steady state fuel curve test for each test.

Correlation with Air Temperature and Air Pressure The change in ambient temperature provided the best fit for the change in fuel efficiency of the tests. It was able to explain 90% of the difference in fuel efficiency observed in the tests from the measured steady state fuel efficiency curve (R^2 value of fit). Equation 3 shows the equation for the empirical fit between the reduction in fuel efficiency (y) in kWh/L and increase in ambient temperature from when the fuel curve was measured (ΔT) in °C. Figure 22 shows the fit with the data. Essentially it shows that the fuel efficiency dropped around 0.01 kWh/L for every °C increase in temperature.

$$y \sim -0.0096 \cdot \Delta T \tag{3}$$

Resulting Effect of Dynamic Loading The effect of temperature was removed from the fuel efficiency of each test using Equation 3. Detrending the change in fuel efficiency for the effects of temperature removed most of the deviation. The MAD

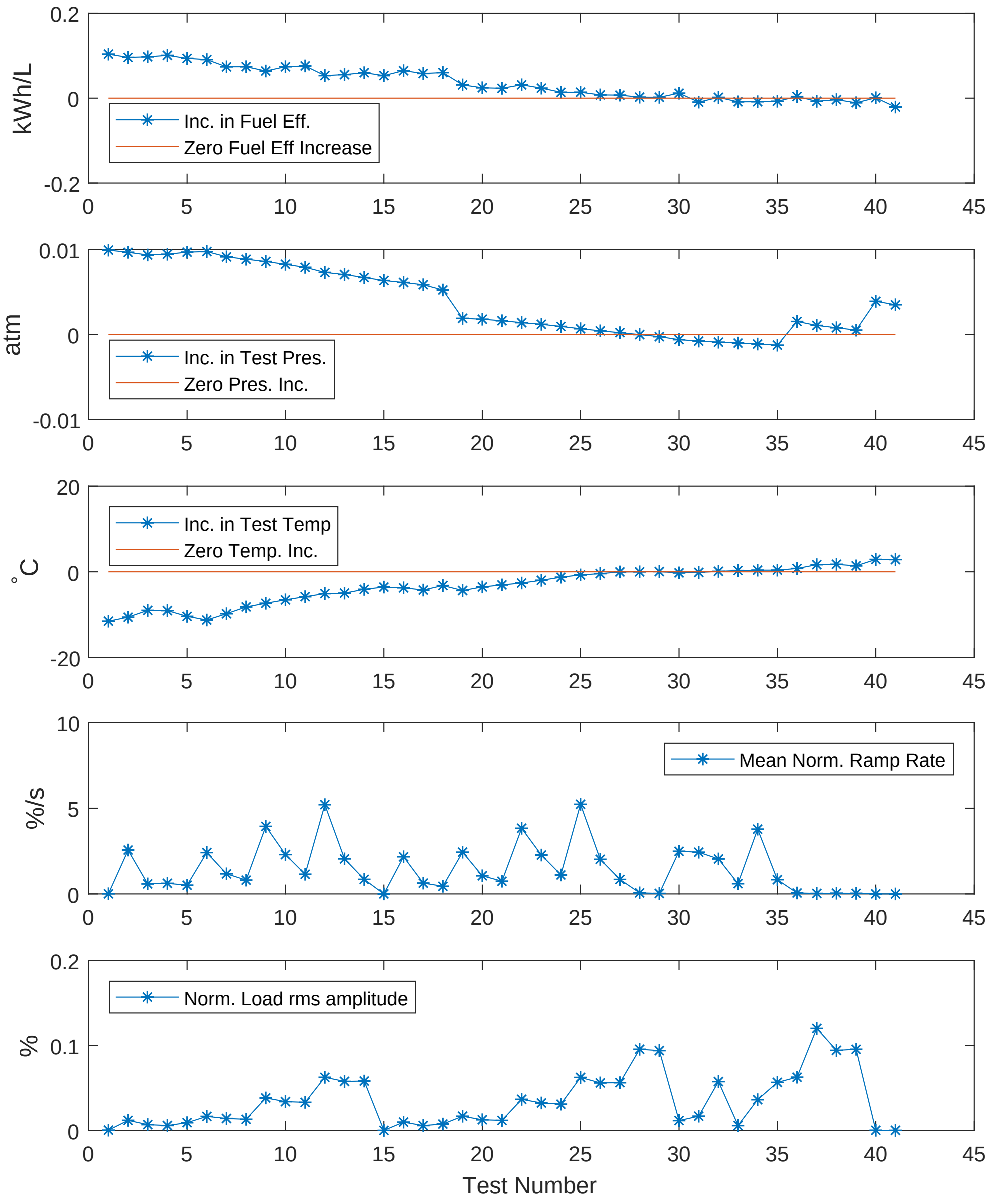

Figure 21: The reduction in fuel efficiency along with possible predictors for the 457 kW diesel generator. Each data point represents a test. The best correlation was with temperature.

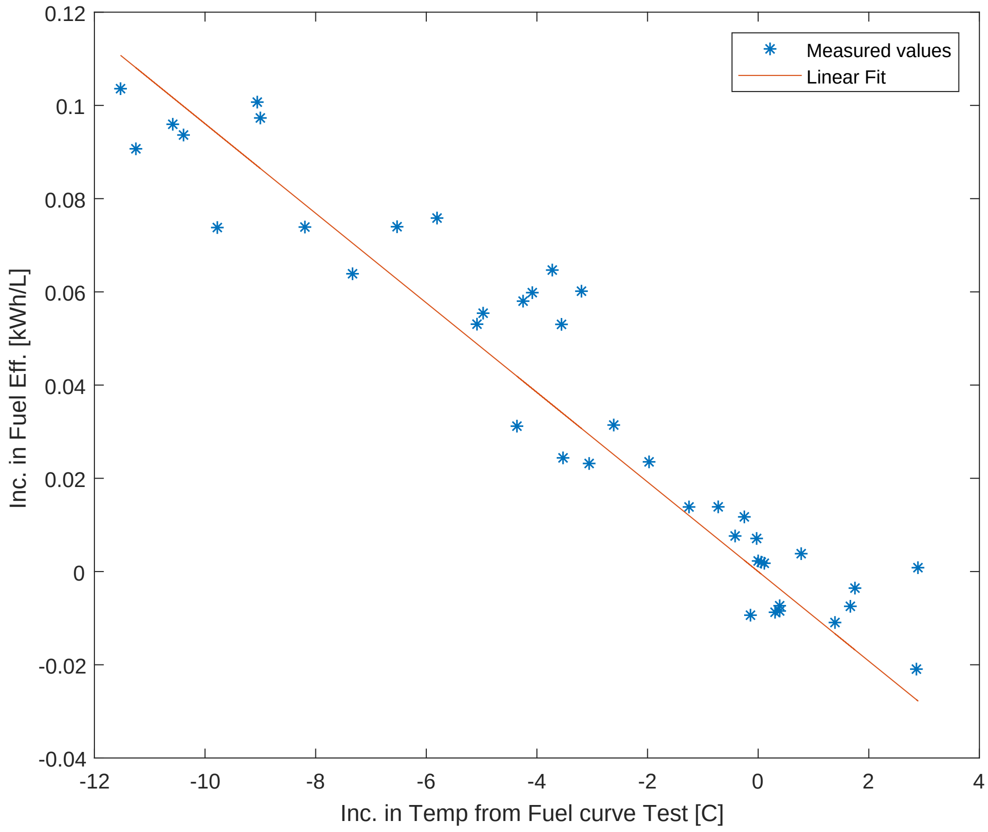

Figure 22: The change in fuel efficiency plotted against the change in temperature for each test and the linear fit between the two for the 457 KW diesel generator.

of the measured compared to the expected efficiency in all the tests was reduced from 0.040 to 0.0090 kWh/L. The remaining deviation in fuel efficiency was tested for correlations with ramp rate and amplitude but did not result in any significant correlations, as shown in Figures 23 and 24.

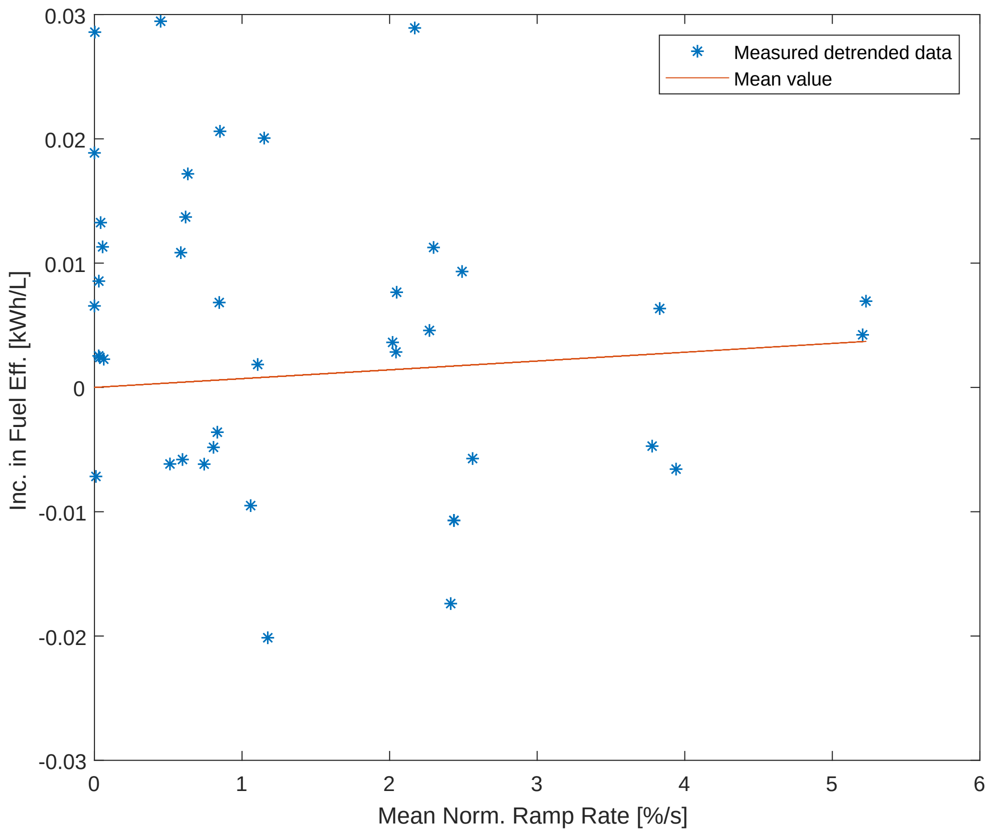

Figure 23: The change in fuel efficiency, detrended for temperature, plotted against the mean ramp rate for each test for the 457 kW diesel generator. The fit is not significants.

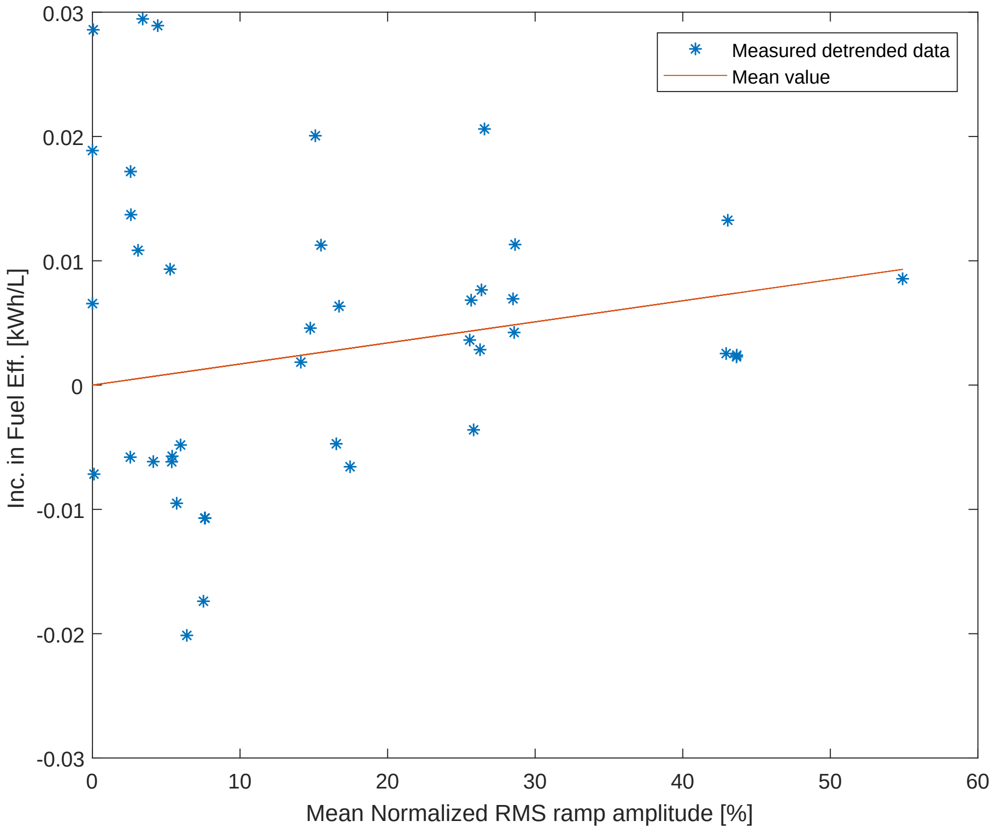

Figure 24: The change in fuel efficiency, detrended for temperature, plotted against the normalized load rms amplitude for each test for the 457 kW diesel generator. The fit is not significant (p value over 0.05).

320 kW diesel generator

A suite of tests were run on the diesel generator with different ramp rates, as described in Section 3.2. The difference in efficiency from the measured steady state (constant loading) fuel curve was calculated as described in Section 4.4 and a statistical analysis was performed as described in Section 4.6.

There was a small yet significant deviation in the measured fuel efficiency of the dynamic tests from the expected fuel efficiency of the measured steady state fuel curve. A mean absolute deviation (MAD) of 0.027 kWh/L (or 1%) was measured. Figure 25 shows the change in fuel efficiency, ambient pressure, ambient temperature, ramp rate and ramp amplitude amplitude with respect to the steady state fuel curve test for each test.

Correlation with Air Temperature, Air Pressure and Other Parameters

The 320 kW diesel generator had more instrumentation that the other diesel generators, and thus more data channels could be tested for correlations with changes in fuel efficiency. Tested predictors included air, fuel and coolant temperature, air and oil pressure and air humidity.

Out of all the individual predictors, fuel temperature resulted in the most significant correlation to the change in fuel efficiency, and could account for 64% of the observed differences in fuel efficiency from the measured steady state fuel curve (R^2 value). Air temperature was the only other predictor that resulted in a significant, although poor, correlation. For a second order fit with two predictors, air pressure and temperature resulted in the best fit (eff ~pres + temp + pres*temp) and could account for 83% of observed differences in fuel efficiency from the measured steady state fuel curve. Figure 26 compares the predicted values from the fits generated with the ramp rate, fuel temperature and air temperature and pressure.

Equation 4 shows the empirical fit between the increase in fuel efficiency (y) in kWh/L and increase in fuel temperature (ΔT_f) in °C. Figure 27 shows the change in fuel efficiency against the change in fuel temperature for each test. The linear fit is also shown. There is clearly some other effect besides just fuel temperature.

The temperature of the fuel would have an impact on its density. However, this is accounted for in the fuel flow measurements. The fuel temperature would also impact its injection properties which would affect the efficiency and emissions. The generator would have to compensate its operation to limit the emissions which could also impact fuel efficiency.

$$y \sim -0.0029 \cdot \Delta T_f \tag{4}$$

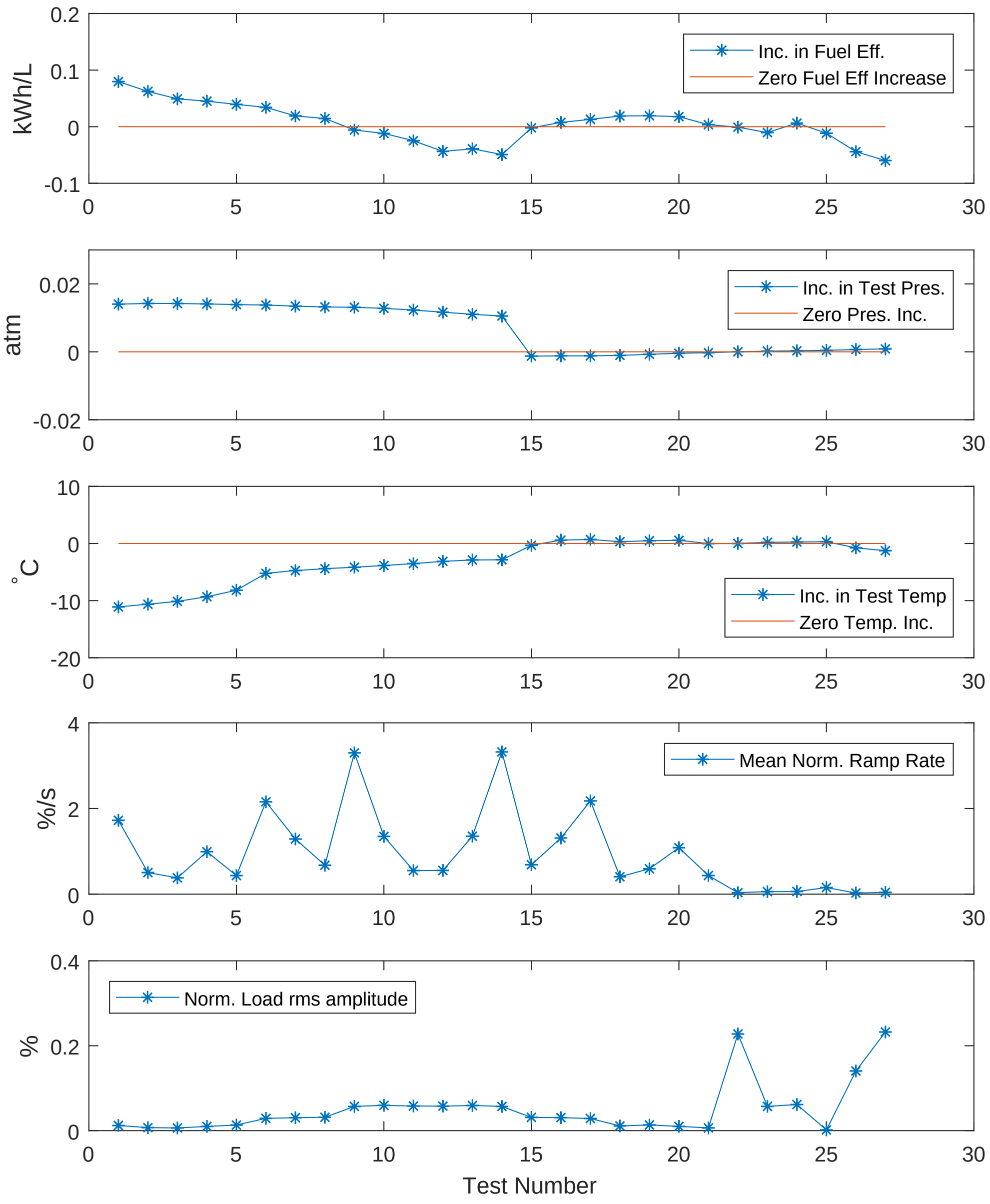

Figure 25: The reduction in fuel efficiency for the 320 kW diesel generator along with possible predictors. Each data point represents a test.

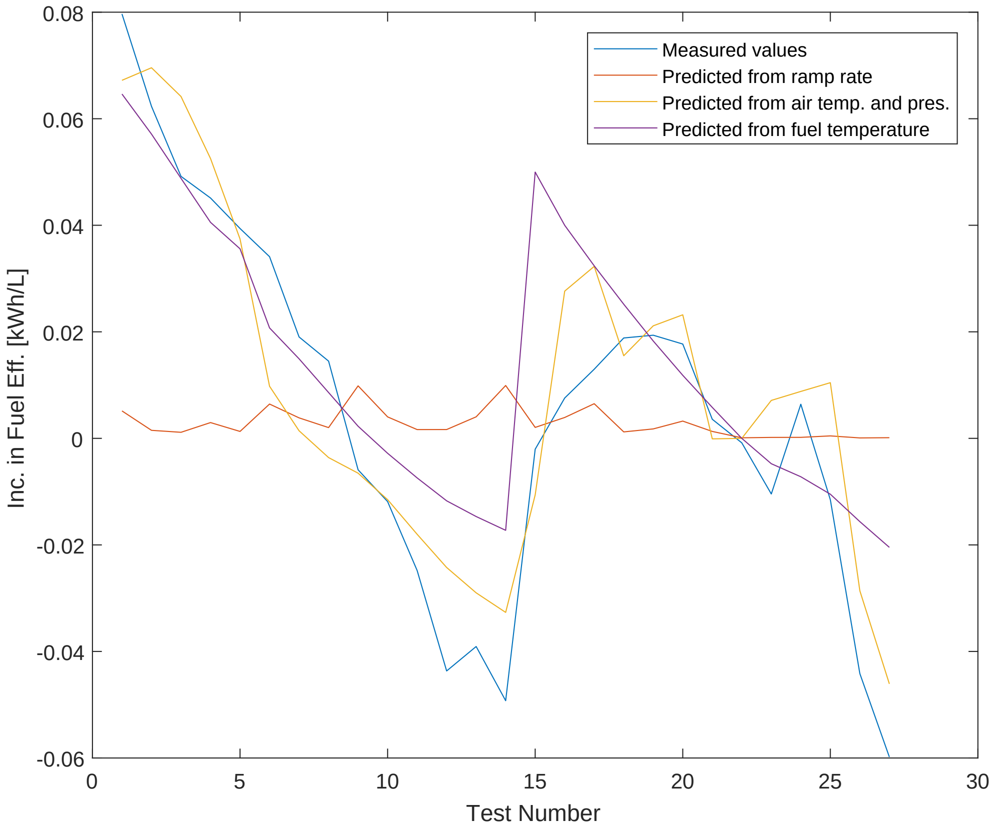

Figure 26: A comparison of different fits for the change in fuel efficiency for the 320 kW generator tests.

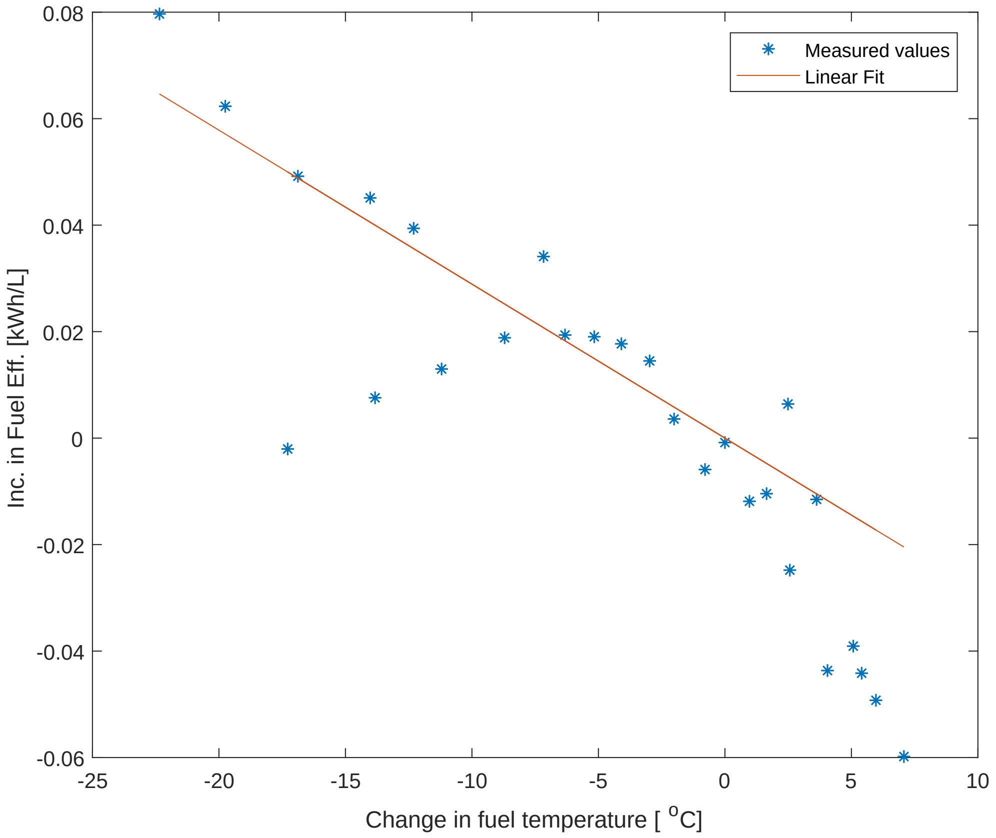

Figure 27: The change in fuel efficiency plotted against the fuel temperature for the 320 kW generator. There is clearly some other effect other than temperature on the change in fuel efficiency.

Equation 5 shows the empirical fit between the increase in fuel efficiency (y) in kWh/L, increase in ambient temperature (ΔT) in °C and the increase in ambient pressure (ΔP) from when the fuel curve was measured.

$$y \sim -2.38 \cdot \Delta P + 0.038 \cdot \Delta T - 3.34 \cdot \Delta P \Delta T \tag{5}$$

Figure 28 shows the predicted fuel efficiency from the fit for different changes in air temperature and pressure with the contour lines. The black dots are the air temperatures and pressures for each test. The predicted changes in fuel efficiency had a reasonably good fit for values of air pressure and temperature experienced in the tests (the regions with the black dots). However, it would most likely not hold outside of those areas. It would be expected that fuel efficiency would increase with air pressure and decrease with air temperature since this would increase air density. In general, the tests followed this trend although there were several tests that did not. This could be a result of the generator regulating emissions or the influence of an unmeasured variable.

The effect that pressure has in the fit is stronger than the impact it would have as a result of higher efficiency due to increased air density (more oxygen for combustion). Since the air pressure was relatively constant for each day, it is possible that the change in fuel efficiency that seemed to be caused by pressure was actually caused by some other unmeasured variable that changed from day to day. This was strongly suggested by the results for the 190 kW generator dynamic tests (see the next section). For the 190 kW generator, a significant fit between the change in fuel efficiency and change in temperature was found by adding a different offset for each day. For the 320 kW generator, a significant fit between the change in fuel efficiency and change in temperature was found by adding a different offset and slope for each day.

Equation 6 shows the equation for the fit between the reduction in fuel efficiency (y) in kWh/L, increase in ambient temperature (ΔT) in °C, and whether the test occurred on the second day (A_{day2}). A_{day2} equals 1 if the text occurred on the second day. Thus, there will be a different offset and slope with respect to temperature for each test day. There were only two test days for this generator. This fit was able to account for 85% of the observed differences between in fuel efficiency from the measured steady state curve.

$$y \sim -0.062 - 0.012 \cdot \Delta T + 0.055 \cdot A_{day2} + 0.050 \cdot \Delta T \cdot A_{day2} \tag{6}$$

Resulting Effect of Dynamic Loading The linear fit between the change in fuel efficiency and the ramp rate was not significant. Figure 29 shows the change in

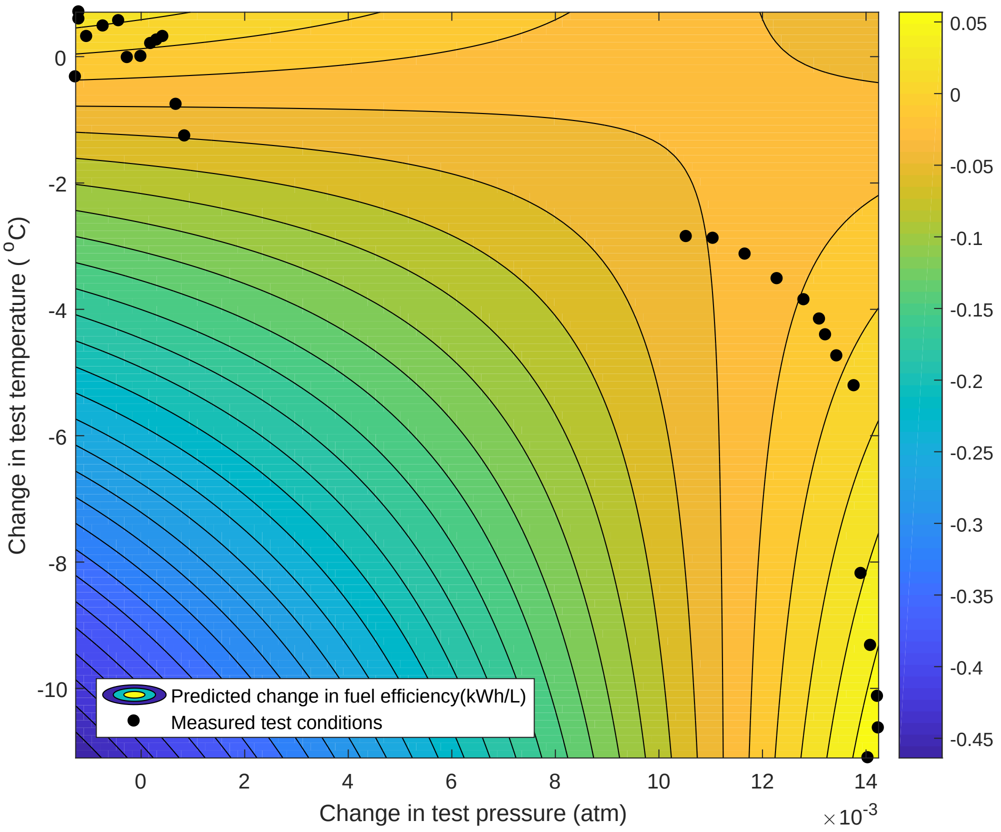

Figure 28: The change in fuel efficiency for different values of air pressure and temperature according the best fit for the 320 kW diesel generator. The values of temperature and pressure for each test are plotted as black dots. The prediction of the fit would only be valid in the region indicated by the black dots.

fuel efficiency against the mean ramp rate of each test. The non-significant linear fit between the two is also shown. According to these tests, the fuel efficiency does not decrease with the ramp rate.

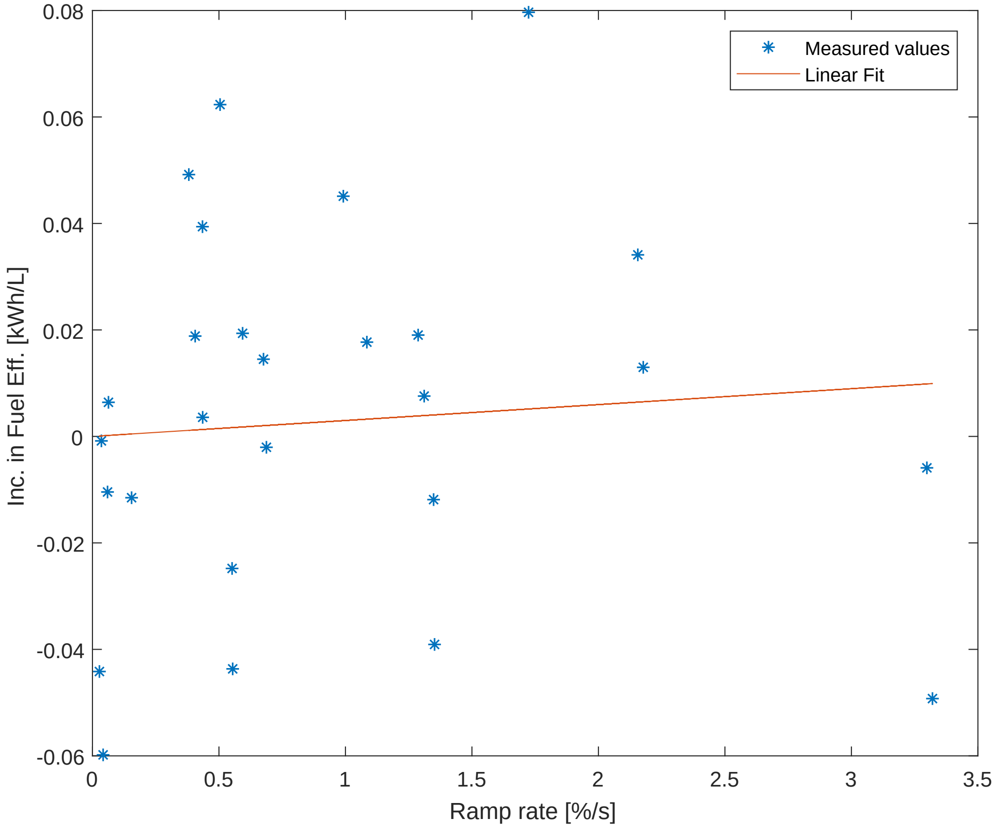

Figure 29: The change in fuel efficiency plotted against the ramp rate for the 320 kW generator. The linear fit between the two was not significant (p-value over 0.05).

No significant fit was found with ramp rate while considering the effect of test days. The predicted changes in fuel efficiency are shown in Figure 30 for both ramp rate and air temperature change with the effect of different days. The fit with ramp rate was not significant while the fit with air temperature was.

The change in fuel efficiency was detrending for the effect of temperature and test day (using Equation 6). The resulting detrended change in fuel efficiency was

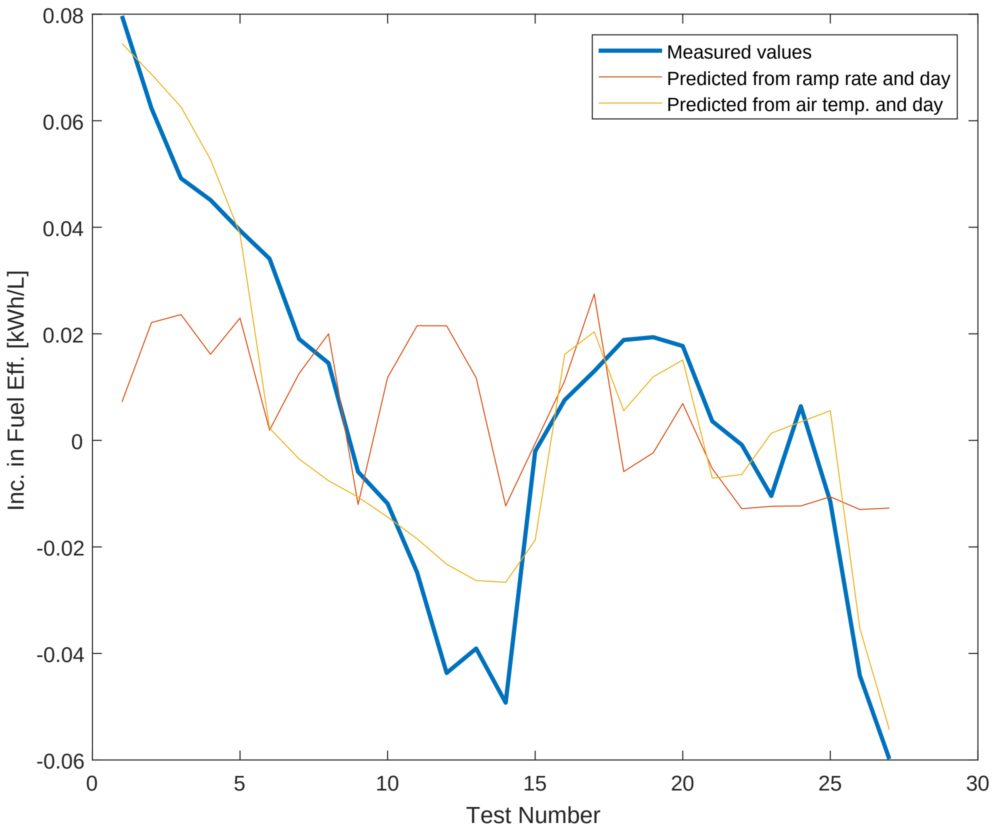

Figure 30: A comparison of different fits for the change in fuel efficiency of the 320 kW generator tests predicted including the interaction of the day the test was performed on.

still not significantly correlated with the change in ramp rate. Thus, ramp rate did not significantly impact the fuel efficiency.

190 kW diesel generator

A suite of tests were run on the diesel generator with different ramp rates, as described in Section 3.2. The difference in efficiency from the measured steady state (constant loading) fuel curve was calculated as described in Section 4.4 and a statistical analysis was performed as described in Section 4.6.

There was a significant deviation in the measured fuel efficiency of the dynamic tests from the expected fuel efficiency of the measured steady state fuel curve. A mean absolute deviation (MAD) of 0.16 kWh/L (4.9%) was measured. Figure 31 shows the change in fuel efficiency, ambient pressure, ambient temperature, ramp rate and ramp amplitude amplitude with respect to the steady state fuel curve test for each test.

Correlation with Air Temperature, Air Pressure and Other Parameters

When looking at the change in fuel efficiency for each test compared with different predictors, there appears to be a good correlation with the change in temperature. This holds well except for the last 4 tests, which were taken on the last day of testing. This can be seen in Figure 32. The resulting fit is not significant.

The best second order fit for the change in fuel efficiency with two predictors was with ambient temperature and pressure. This resulted in a significant fit which was able to explain 35% of the change in fuel efficiency. This is better, but still not great.

The effect that pressure has in the fits is stronger than the impact it should have solely based on higher efficiency due to increased air density (more oxygen for combustion). Pressure is mostly constant for each day and it is possible that the effect of pressure is actually the effect of some unmeasured variable or diesel generator controller setting that is different for each day.

In order to investigate this effect, a different offset was added to the fit for each day. The fit with temperature results in a much better fit than what was achieved with temperature and pressure and can account for 96% of the change in fuel efficiency.

Equation 7 shows the equation for the fit between the reduction in fuel efficiency (y) in kWh/L, increase in ambient temperature (ΔT) in °C, and the day that the test occurred on (A_{dayx}). A_{dayx} equals 1 when the test occurred on day 'x'. For example, for tests occurring on day 2, A_{day2} equals 1 and all other A_{dayx} values equal zero. That means that the equation for the fit on day 2 would be $y \sim -0.051 + 0.087 - 0.045 \cdot \Delta T$ which solves to $y \sim -0.036 - 0.045 \cdot \Delta T$.

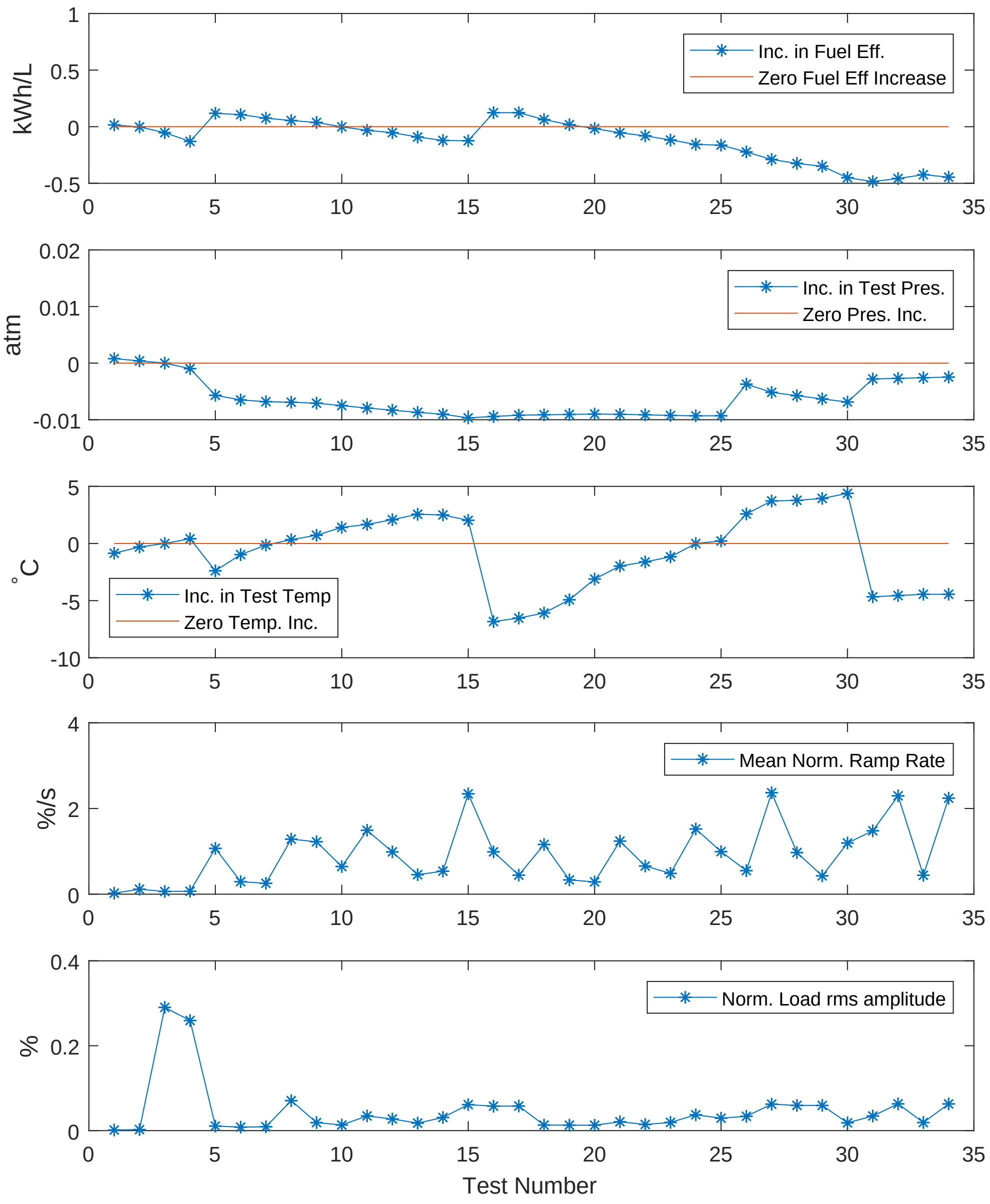

Figure 31: The change in fuel efficiency along with possible predictors affecting the efficiency for the 190 KW diesel generator. Each data point represents a test.

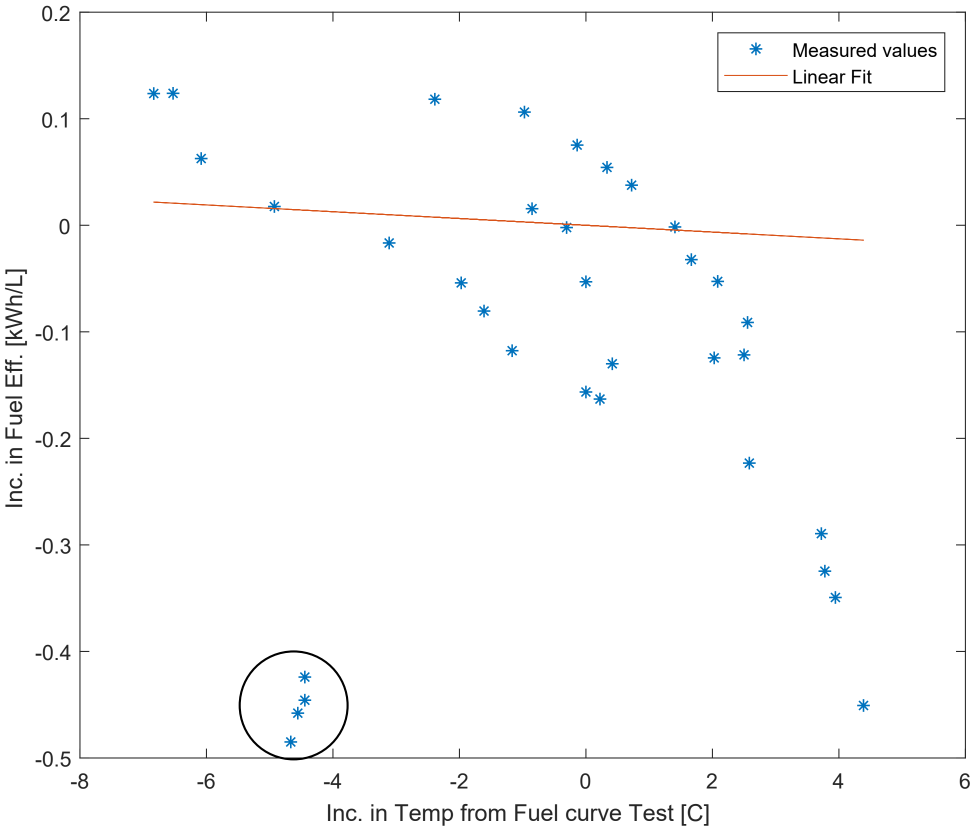

Figure 32: The increase in fuel efficiency plotted against the increase in temperature for all of the tests for the 190 kW generator. There appears to be some unmeasured factor affecting the fuel efficiency on the last day of tests (the four tests circled in the plot). The fit is not significant.

$$y \sim -0.051 - 0.045 \cdot \Delta T + 0.087 \cdot A_{day2} - 0.12 \cdot A_{day3} - 0.11 \cdot A_{day4} - 0.60 \cdot A_{day5} \quad (7)$$

The cause for the different offsets in fuel efficiency depending on the day is not known. The distance between the test site and the weather station is just over 1 km with an elevation difference of 57 m. Thus the there should be a close correlation between the air temperature of both locations. It could be an artifact of the diesel controller or an unmeasured variable. However, the high accuracy of the fit indicates that the change in efficiency is linearly related to temperature with some added offset for each day.

Correlation with Dynamic Loading Figure 33 shows the change in fuel efficiency for different test ramp rates. There is a significant decreasing trend, however it can only account for 20% of the change in fuel efficiency.

Figure 34 compares the change in fuel efficiency that is predicted by the ramp rate fit and the air temperature and pressure fit with the actual measured changes in fuel efficiency.

The fit between the change in fuel efficiency and change in ramp rate and test day results in a non-significant ramp rate coefficient. Only the coefficients for the fixed day offsets are significant. This means that when assuming a different fixed offset of fuel efficiency for each day, the effect of the ramp rate is not significant. Figure 35 shows the resulting fits plotted against the measured values for temperature and the ramp rate.

The change in fuel efficiency was detrending for the effect of temperature and test day (using Equation 7). The resulting detrended change in fuel efficiency was still not significantly correlated with the change in ramp rate. Thus, ramp rate did not significantly impact the fuel efficiency.

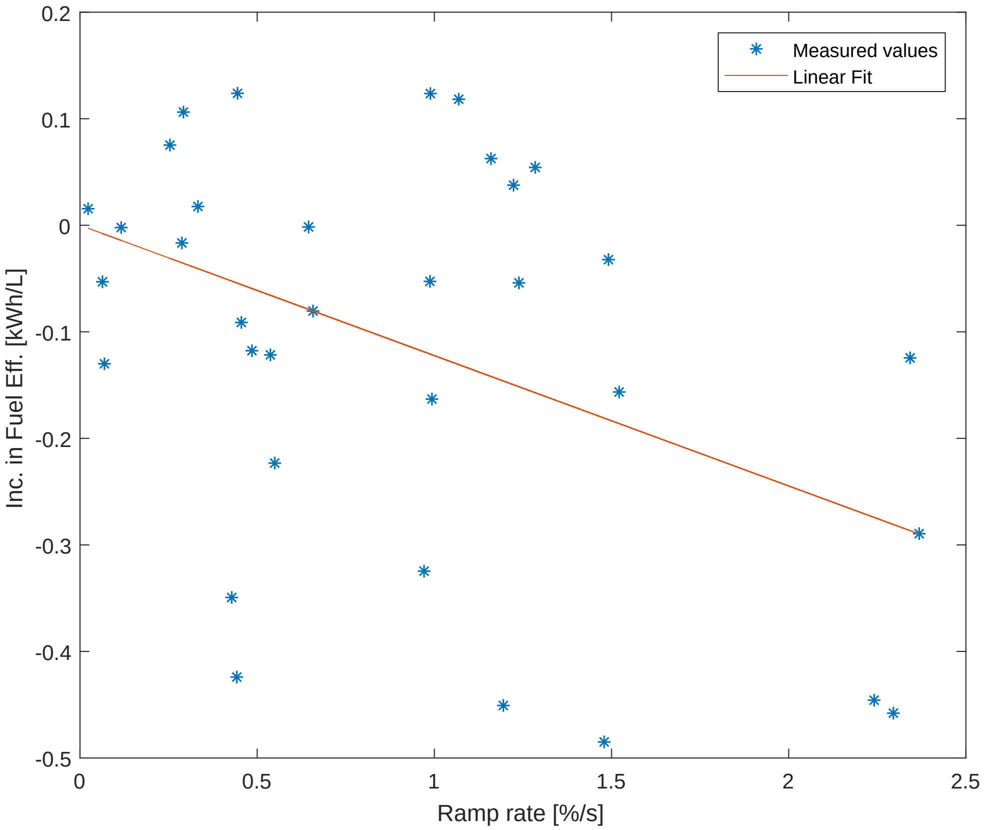

Figure 33: The increase in fuel efficiency plotted against the increase in ramp rate for all of the tests for the 190 kW generator. There is a significant fit between the two.

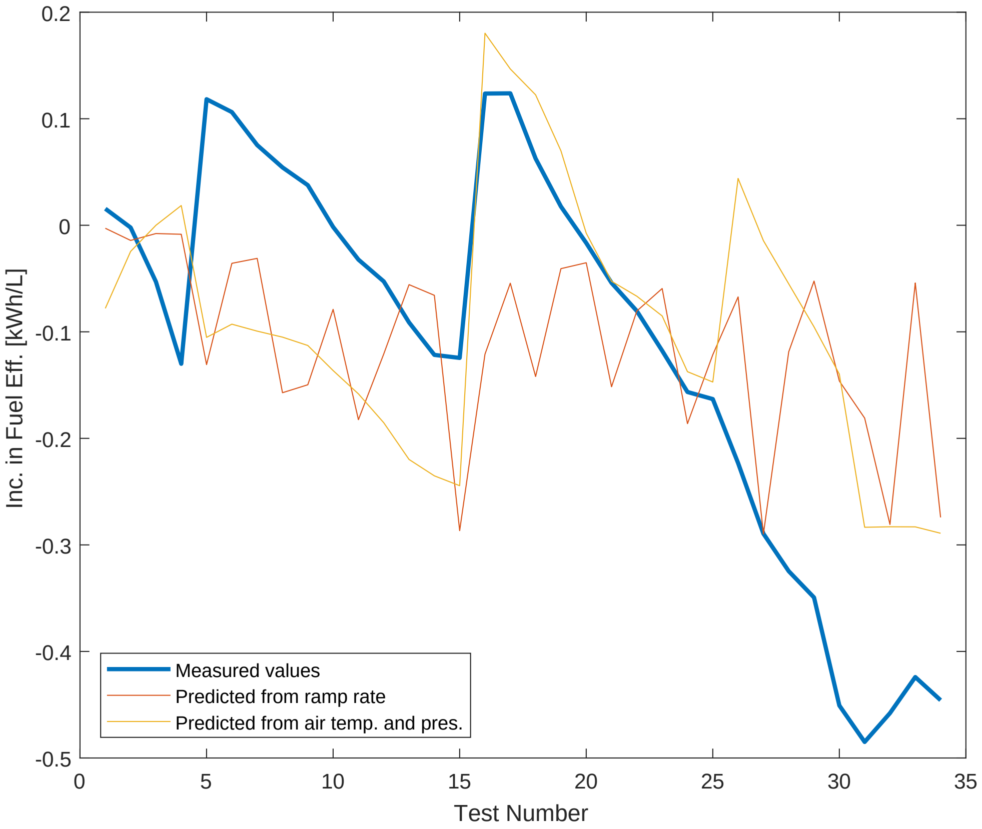

Figure 34: A comparison of different fits for the change in fuel efficiency for all of the 190 kW generator tests.

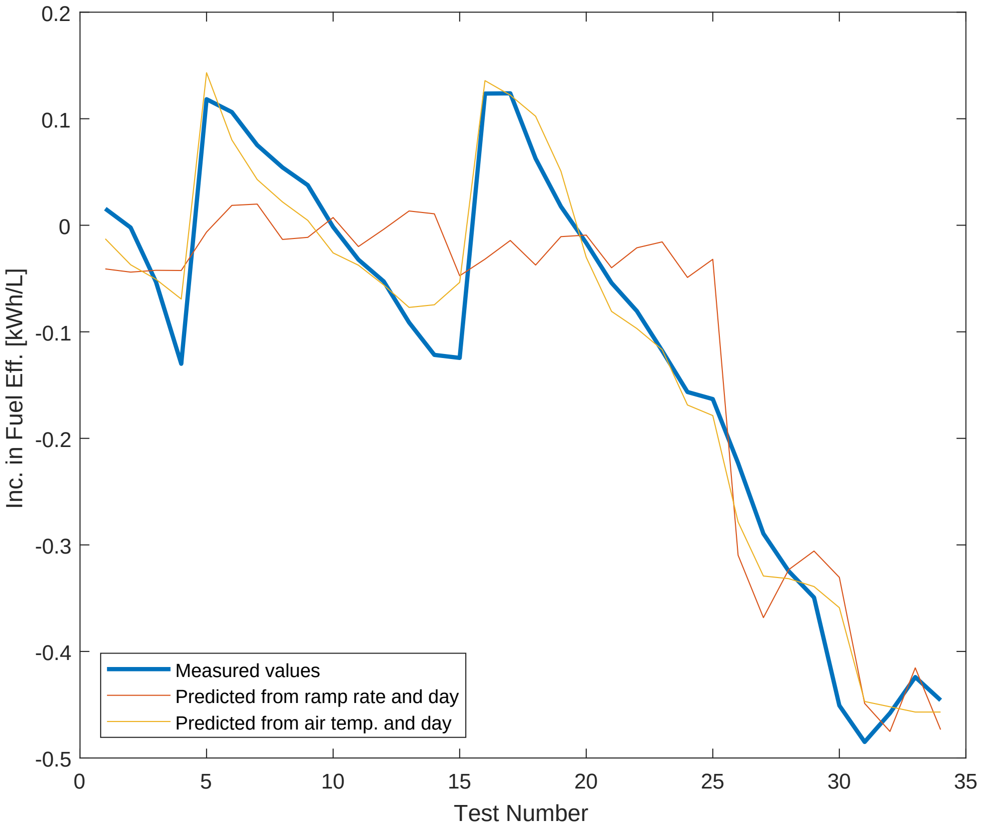

Figure 35: A comparison of different fits for the change in fuel efficiency for all of the 190 kW generator tests including with a different offset of each day.

Summary: Dynamic Loading Tests

The first row in Table 11 shows the deviation between the average fuel efficiency of the dynamic tests and the expected efficiency from the measured fuel efficiency curve. The deviation from the expected fuel efficiency was tested for correlations with different possible predictors, including ramp rate, ramp amplitude, ambient temperature and ambient pressure. The resulting deviations from the best empirical fits are shown in the second row. The third row shows which predictors yielded the best fit to the deviations from steady state fuel efficiency. 'ΔT' stands for the increase in temperature and 'A_{dayx}' for factors that represent which day the test occurred on. These test showed that the ramp rate did not have any significant effect on fuel efficiency. Air temperature had a very significant effect on fuel efficiency, and sometimes that effect seemed to change from day to day.

Table 11: The mean absolute deviation (MAD) and root mean squared deviation (RMSD) of dynamic tests from the expected fuel efficiency from the measured fuel curve.

Description	**Units**	**457 kW**		**320 kW**		**190 kW**	
		RMSD	MAD	RMSD	MAD	RMSD	MAD
Ramp test deviation	kWh/L	0.038	0.04	0.027	0.035	0.19	0.16
Ramp test fit deviation	kWh/L	0.0012	0.0009	0.015	0.011	0.037	0.027
Ramp test fit predictors		ΔT		$\Delta T + A_{dayx}$ $+ \Delta T \cdot A_{dayx}$		$\Delta T + A_{dayx}$	
Percent of variability explained by fit (R^2 value)	%	90		85		96	

Figure 36 shows the mean absolute deviations (MAD) from Table 11. There was a significant amount of deviation in the measured efficiency of the dynamic tests from the expected efficiency from the fuel curves for the different diesel generators. Four possible explanations for the deviation from the measured steady state fuel curve were tested: the ramp rate, ramp amplitude, change in ambient temperature, change in ambient pressure and the day the test was performed. The fits greatly reduced the amount of unexplained deviations in fuel efficiency.

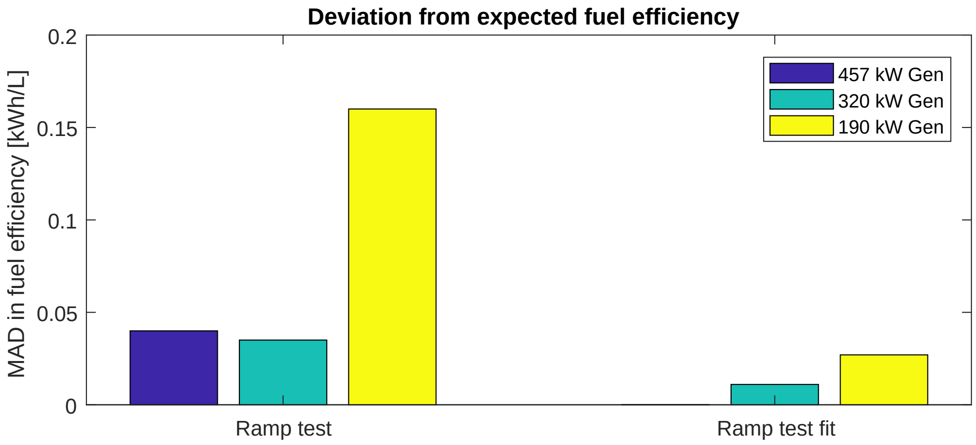

Figure 36: The mean average deviation (MAD) of the average fuel efficiency measured in each test compared to the expected fuel efficiency is show in the first set of bars. The second set of bars shows the remaining deviation after accounting for the deviation predicted by the fit. In other words, the remaining unexplained deviation. The MAD for the fitted values of the 457 generator is too low to be seen on this graph.

The deviation in the 457 kW generator's fuel efficiency from the expected efficiency from the fuel curve was well correlated with the change in ambient temperature and had no correlation with the ramp rate. The fit with temperature reduced the standard deviation from the steady state (root mean squared error) by 90% . The empirical fit showed a 0.01 kWh/L reduction in fuel efficiency for every 1°C increase in ambient temperature.

The deviation in fuel efficiency from the measured fuel curve for the 320 kW and 190 kW diesel generators seemed to be correlated with temperature as well as some other variable. This other variable could be modeled by taking into account the day on which the the test took place. For the 190 kW generator, a different offset was applied to the fit with air temperature for each day. For the 320 kW generator, a different offset and a different slope was applied to the fit with air temperature for each day. These fits were able to explain 90% and 85% of the deviation from the measured steady state efficiency respectively.

The cause for this apparent change in efficiency from day to day is not known. A diesel generator is not a linear system, since it has an active controller. Thus, there is a limit to the quality of a linear fit that can be achieved to predict its fuel efficiency. The EPA Tier (emissions) rating and possibly size of the generators likely played a role in how predictable their fuel efficiency was. The 457 kW diesel generator, Tier 2, had very little variability in fuel efficiency other than a trend that was very closely correlated with temperature. The 320 kW diesel generator was smaller and Tier 3 (a higher emissions rating). It had more variability in its efficiency which could not be predicted as well with just several variables. The 190 kW diesel generator was the smallest and had the highest emission rating (Tier 4). It had several times the variability in fuel efficiency that the other generators had. Much of this could be explained with temperature and some other daily effect. However, the remaining unexplained variability in fuel efficiency is still higher than the other generators.

6 Conclusion and Outlook

The fuel efficiency of a diesel generator has been measured to be highly variable, even at a constant loading. Among the three generators tested there was a correlation between the generator size, EPA emmisions Tier rating, and the variability in the fuel efficiency. The smaller generators with the higher emissions ratings also had a higher variability in fuel efficiency. Over the half hour tests, the short term variability in fuel efficiency was averaged out.

The dynamic loading tests showed no measurable correlation between the ramp rate of the loading and the generator fuel efficiency. If there is an effect, it is small and has been concealed by other effects which have a larger effect on fuel efficiency. These parameters include air temperature and air pressure. There also appeared to be a long term change in fuel efficiency over time. The cause for this is unknown.

While energy storage systems clearly can add significant value to medium and high penetration renewable energy microgrids, reduction in fuel utilization by smoothing the load on diesel generators is not a value proposition. This does not, however, preclude other valuable services that energy storage systems may provide resulting in improved (economic) operation of diesel generators. These tests did not look into the effect of dynamic loading on the maintenance costs, longevity and emissions of diesel engines. If they are negatively impacted by dynamic loading, then there would be a value proposition for smoothing the loading on the diesel generators with energy storage. This should be the focus of future papers.

A Data Acquisition System Description

Data from over 1000 channels is permanently logged when the laboratory is in operation. This data ranges from basic electrical measurements to all available diesel generator data, and independent fuel consumption measurements. All data is stored in daily files, one per channel, in netCDF format, and can quickly be retrieved and searched for relevant events on the fly.

Meters used for general data acquisition from all energy sources and sinks are either Electro Industries Shark 100 B and T, or Elkor WattsOn. All meters communicate via Modbus TCP. The meters provide data at a rate of about 5 S/s (samples/second). In addition to the standard utility-grade meters, an Elspec GS4300 BlackBox power quality analyzer is permanently installed on the feeder to the 480 VAC load bank. This meter provides permanent logging of voltage and current waveforms at 1024 S/cycle (samples/60 Hz cycle) and 512 S/cycle respectively.

Diesel fuel flow is measured with two Krall flow meters, one on the fuel supply line and one on the fuel return line. Fuel temperature is meaured at each meter and is used to calculate the mass flow of fuel. The Krall flow meters have a high measurement precision of 0.1%. Table 12 shows the model, serial number, software edition and calibration record for each of the components in the fuel flow measurement system.

Table 12: The model, serial numbers and calibrations for the components of the Krall fuel flow meter.

Component	**Model**	**Serial Number**	**Software Edition**	**Calibration**
Control, metering unit and display module	BEM-500	385061	3.002	-
Volumeter A Fuel supply flow transducer	OME20	385057	-	14W00823
Volumeter B Fuel return flow transducer	OME20	385058	-	14W00824

The laboratory LAN is managed by a Netgear FSV318G router. Additional ports are made available via several switches. A WAN connection can be made available via an eWON Cozy router and eWONs VPN software. Time keeping for data acquisition and control is provided by a Tekron NTP server. Data acquisition is driven by a PC with Fedora Linux OS and data is routed to a Buffalo TerraStation, striped and mirrored RAID, network attached storage drive with four physical hard drives.

B Lab Single Line

Figure 37 shows the single line of the PSI lab.

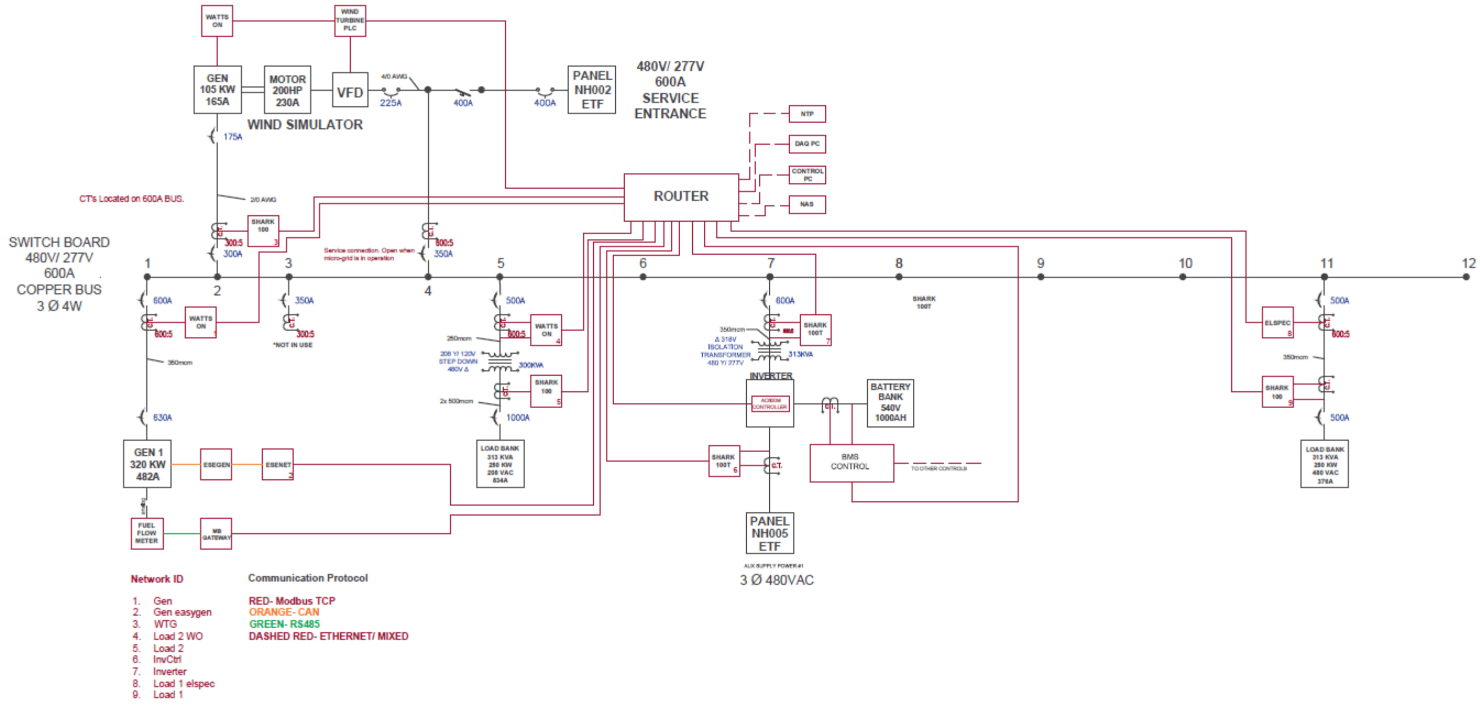

Figure 37: PSI Lab single line.