
Markham H2 CHP CMS-2-211258

Enbridge Gas Inc

2025-11-27

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Version 0.2

This project was supported by the financial contribution of the Independent Electricity System Operator.

[The report must be [AODA](#) compliant]

Table of Contents

1. Executive Summary	3
1.1 Objectives	3
1.2 Outcomes	3
1.3 Key Schedule Changes	4
2. Introduction and Goal	5
2.1 Introduction	5
2.2 Goal	5
3. Approach/Methodology and Assumptions	6
3.1 2025 Hydrogen Innovation Fund (HIF)	6
3.1.1 Summary and Objectives	6
3.1.2 Data Collection	7
3.1.3 Performance Analysis	8
3.1.3.1 Energy Tests	8
3.1.4 Energy Test Charts	9
3.1.4.1 Operating Reserve Tests	12
3.1.5 Operating Reserve Test Charts	13
3.1.5.1 Capacity Tests	15
3.1.6 Capacity Test Charts	16
3.1.6.1 Ramping Tests	19
3.1.7 Ramping Test Charts	20
3.1.7.1 Regulation Tests	24
3.1.8 Regulation Test Charts	26
3.2 International Performance Measurement and Verification Protocol (IPMVP)	28
3.2.1 The Process	28
3.2.1.1 Planning the Project	28
3.2.1.2 Installing the Project	30
3.2.1.3 Maintaining the Project	30

3.2.2	IPMVP Options	30
3.2.3	Annual Savings	30
4.	Results and Analysis	31
4.1	Summary of Load Displacement and Efficiency Results	31
4.2	Electrical Load Displacement	33
4.3	Fuel Consumption	34
4.4	Thermal Load Displacement	37
4.5	Operating Cycle Efficiencies	40
4.6	Ramp Rates	43
4.6.1	Cold Weather Ramp Rates	43
4.6.2	Hot Weather Ramp Rates	45
5.	Discussion	48
6.	Economic/Technical Impact, and Risk Assessments	49
6.1	Technical Inputs	49
6.2	Annual Technical Results	50
6.3	Financial Inputs	50
6.4	Financial Results	50
7.	Conclusion and Recommendations	51
8.	Lessons Learned	52
8.1	Engine Knock	52
8.2	Engine Trips During Grid Events	52
8.3	Power Reduction Due to High Exhaust Temperature	52
8.4	Natural Gas Regulator Failure	53
9.	Next Steps	54

1. Executive Summary

The Markham H₂ CHP Project (CMS-2-211258, Project Nos. 13704 & 13873) was executed by CEM Projects in collaboration with Enbridge Gas Distribution, 2G Energy, and Stolk Construction. The project installed and commissioned a hydrogen-compatible Combined Heat and Power (CHP) system at the Enbridge Technology and Operations Centre (TOC) in Markham, Ontario, integrating it with the existing Power-to-Gas (PtG) electrolyzer and hydrogen blending station.



Installed system in fully operational state.

1.1 Objectives

- Demonstrate reliable CHP operation on natural gas and hydrogen blends up to 100%.
- Reduce facility CO₂ emissions by substituting hydrogen for natural gas.
- Provide on-site electrical generation to offset grid consumption and recover waste heat for building use.
- Satisfy regulatory requirements under the IESO Hydrogen Innovation Fund (HIF).

1.2 Outcomes

- CHP unit mechanically and electrically integrated with the TOC facility & hydrogen supply.
- Achieved substantial completion on December 13, 2023; regulatory IESO testing rescheduled due to electrolyzer outage (Q1 2025) and warm weather testing requirements (Q2 2025).
- Total project budget of \$3,509,960, with the Independent Electricity System Operator (IESO) contributing up to a maximum of \$1,787,480.
- Lessons learned captured for future hydrogen CHP deployments, including early sensor configuration verification, robust grid disturbance handling, and pre-testing automation tools.

1.3 Key Schedule Changes

- An electrolyzer outage in Q1 2025, which impacted hydrogen blend testing.
- Warm weather requirements specified by the IESO HIF workbook, which deferred final regulation testing until late Q2/Q3 2025.
- Load bank sourcing and additional gas valve installation also caused minor adjustments to the testing schedule.

2. Introduction and Goal

2.1 Introduction

The CHP installed at the Enbridge's TOC Building in Markham can use emissions-free hydrogen to provide heat and power for the 120,000-square-foot facility, which is home to approximately 197 Enbridge employees.

The engine is supplied with hydrogen fuel from the existing Power-to-Gas (PtG) electrolyzer and hydrogen blending station and supplied with natural gas from the TOC Building gas main. The CHP reduces grid electrical consumption of TOC Building and reduces TOC Building natural gas consumption used in heating boilers.

The expected GHG reduction when the system is running on 100% hydrogen is about 133 tonnes of CO₂e annually, or the equivalent of removing approximately 28 passenger vehicles from the road each year.

The CHP maximum NO_x emissions certified by the CHP vendor is 0.26 g/kWh.



Installed system in fully operational state

2.2 Goal

The goal of the project is to demonstrate the feasibility of installing and operating a hydrogen fueled CHP system.

The system can operate effectively with a minimum blend ratio of 25% to 75% hydrogen to natural gas at full output and can operate on up to 100% pure hydrogen. The project's aim is to run the system on 100% Enbridge Gas-supplied hydrogen.

The CHP is designed to operate with a CHP efficiency of 80% HHV; maximum electrical efficiency of 37.7%, and maximum thermal efficiency of 42.3%.

3. Approach/Methodology and Assumptions

3.1 2025 Hydrogen Innovation Fund (HIF)

3.1.1 Summary and Objectives

HIF testing involved five (5) different types of tests listed and summarized as follows:

- Energy Tests (10 Test Runs) – demonstrate ability to follow a 5-min fluctuating dispatch signal as closely as possible at a constant H2 blending ratio. The generator needed to achieve the target operating range by the end of the interval.
- Operating Reserve Tests (5 Test Runs) – demonstrate the capability of the generator to ramp from minimum load to target electrical output within 10 minutes of receiving an activation notice and hold the load for 60 minutes at a constant H2 blending ratio.
- Capacity Tests (6 Test Runs) - demonstrate sustained delivery of target electrical output for 4 hours at a constant H2 blending ratio.
- Ramping Tests (8 Test Runs) - demonstrate max ramp-up and ramp-down rates from 0-100% and 100-0% operating range of the resource.
- Regulation Tests (5 Test Runs) - demonstrate ability to follow a rapidly fluctuating dispatch signal as closely as possible at a constant H2 blending ratio.

Refer to Appendix A for the HIF testing spreadsheet which shows all the testing results.

The intent of the HIF testing for the project is to support the IESO efforts in developing a baseline for H2 fueled power generation. The HIF testing did not have specific performance targets to reach but was more a demonstration of the capabilities of the CHP when operating with various hydrogen fuel blends.

Originally, the intent was to test the engine across a fully modulating range of H2 blends (i.e. the ability to blend continuously from 0% H2 up to 100% H2). However, after further discussion with 2G, as 2G developed the CHP's ability to operate with H2 blends, there were some operational limits which needed to be accommodated.

Once started with 100% natural gas, the engine could not begin to blend in hydrogen. Instead, if the intent was to operate with a blend of hydrogen and natural gas, the engine needed to be started with 100% hydrogen and then blend in natural gas.

The engine could not modulate fully between 0% hydrogen to 100% hydrogen. The H2 blend range is nominally limited to between 50% H2 up to 100% H2, but can go as low as approx. 25% depending on the operating point, and is dynamically controlled using the interface. All HIF tests were completed within this blend range.

The HIF agreement includes contingencies to avoid the Class A Global Adjustment (GA) peak hours. The electrolyser is shut down when peak loads are projected to minimize power consumption. The engine is run on stored hydrogen fuel during these potential GA peak events. If there is insufficient stored hydrogen to maintain H₂ fuel operation, the engine may be restarted to operate on natural gas to continue the Class A GA peak load avoidance.

3.1.2 Data Collection

The completed HIF spreadsheet was provided to IESO at an earlier date under separate cover. The results of the tests are based on a further analysis of the HIF test data reported (see Appendix A for the updated spreadsheet).

For each test, a data sample interval was assigned.

The following datapoints were taken directly from the 2G Engine controller:

- Target Electrical Production (kW) - Program Setpoint
- Actual Electrical Production (kW) - Bachmann, GSP 274, Accuracy +/-0.08%
- Total Site Electrical Load (kW) - AccuEnergy, Accuvim II, Accuracy +/-0.1%
- Hydrogen Gas Consumption (Nm³/hr) - Rosemount, Coriolis, CMFS025M, Accuracy +/-0.05%
- Natural Gas Consumptions (Nm³/hr) - E+H, T-mass, F300 6F3B40, Accuracy +/- 1%

The combustion energy in the hydrogen gas is calculated using the flow rate of hydrogen gas in Nm³/hr and a higher heating value of 3.4 kWh/Nm³.

The combustion energy in the natural gas is calculated using the flow rate of natural gas Nm³/hr and a higher heating value of 10.75 kWh/Nm³.

The following datapoints were taken from the facilities Building Automation System (Siemens BAS)

- Facility's heating system water temperature before the heat exchanger (TIT-0201)
 - (E+H, RTD Sensor, TH13-8A21X2A3S1AK, Accuracy Class B of IEC 60751)
- Facility's heating system water temperature after the heat exchanger (TIT-0202)
 - (E+H, RTD Sensor, TH13-8A21X2A3S1AK, Accuracy Class B of IEC 60751)
- Facility's heating system water flow rate through the heat exchanger (FIT-0201)
 - (E+H, PC Promag P300, 5P3B50, Accuracy +/- 0.7%)

The quantity of heat recovery is calculated based on a composition of 32% ethylene glycol and 68% water. The density of the water-glycol mixture is 8.49 lb/gal and the specific heat capacity of the solution is 0.94 Btu/lb.F

The HIF terminology, test numbering, and test descriptions are based on the HIF test plan spreadsheets prepared and provided by the IESO.

3.1.3 Performance Analysis

3.1.3.1 Energy Tests

Test Goal:

- The ten (10) energy tests had a sample interval of 5 minutes. The goal of the energy test was to achieve the target electrical production by the end of the sample period.

Test Design:

- Each test was designed to evaluate the engine's ability to follow a target electrical load while varying either the target load, or by varying the fuel blend (ratio of hydrogen fuel to natural gas fuel).

Test Results:

- The engine was able to meet the target electrical production for each test within 1% of the target for each of the tests. See summary table below. Charts for the first six (6) run tests have been included on the following page. Refer to Appendix A for all the data and charts. The Test Description in the chart below is based on the IESO Test Descriptions.

Test No.	H2 Blend Level (%)	Test Modifier Description	Average Deviation (Actual-Target (kW))	Standard Deviation (kW)	Average Deviation (Actual-Target)/Target (%)	Standard Deviation (%)
0	0	Low Operating Range (50% to 75% load)	0.51	0.16	0.7%	0.2%
00	0	High Operating Range (75% to 100% load)	0.40	0.19	0.4%	0.2%
1	Vary from 100 to 65 to 100	Minimum Continuous Load (50%)	0.47	0.32	0.8%	0.5%
2	Vary from 100 to 50 to 100	Maximum Continuous Load (100%)	0.17	0.92	0.1%	0.8%
3	65	Low Operating Range (50% to 75% load)	0.39	0.34	0.6%	0.5%
4	50	High Operating Range (75% to 100% load)	0.56	0.48	0.7%	0.6%
5	75	Low Operating Range (50% to 75% load)	0.51	0.52	0.8%	0.9%
6	75	High Operating Range (75% to 100% load)	0.38	0.74	0.5%	0.9%
7	100	Low Operating Range (50% to 75% load)	0.43	0.68	0.7%	1.0%
8	100	High Operating Range (75% to 100% load)	0.26	0.91	0.3%	1.0%

Table 1 | Performance Analysis Energy Test Results

3.1.4 Energy Test Charts

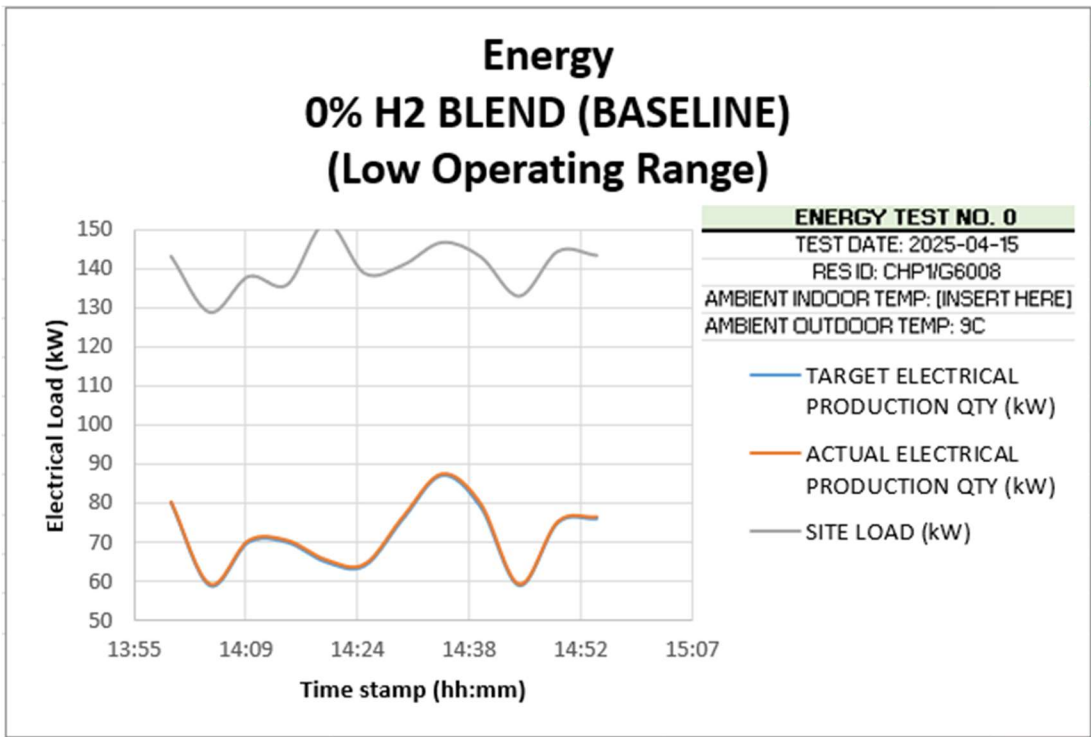


Figure 1 | Energy – 0% H2 Blend (Baseline) Low Operating Range

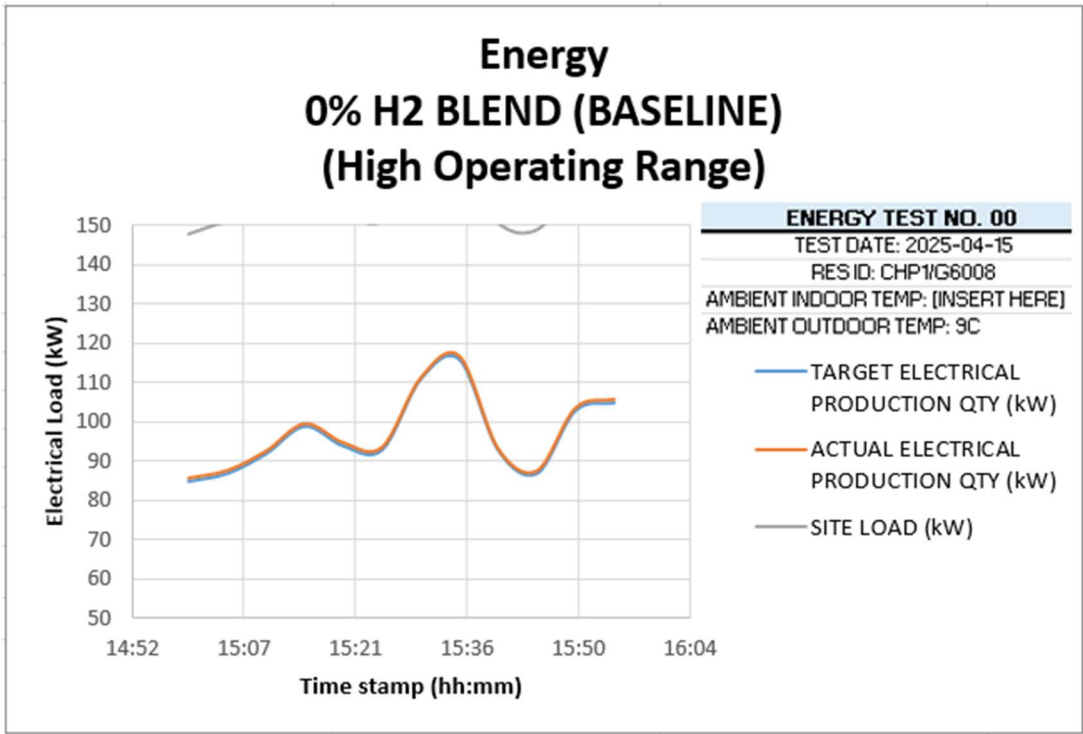


Figure 22 | Energy – 0% H2 Blend (Baseline) High Operating Range

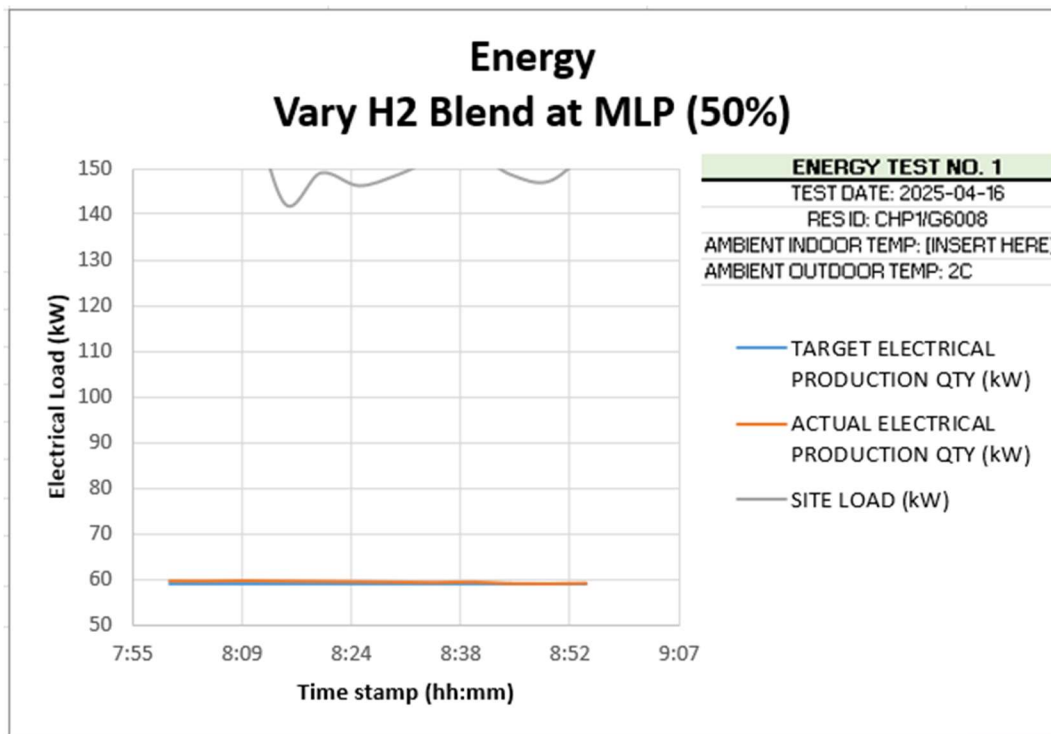


Figure 33 | Energy – Vary H2 Blend at MLP (50%)

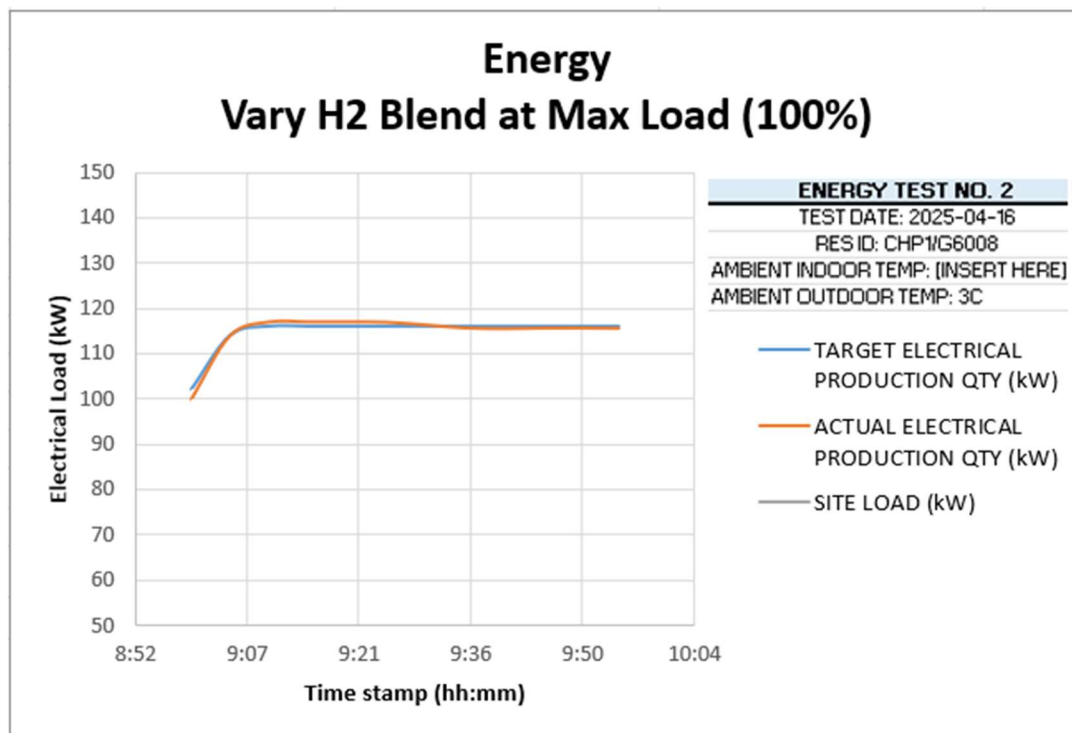


Figure 44 | Energy – Vary H2 Blend at Max Load (100%)

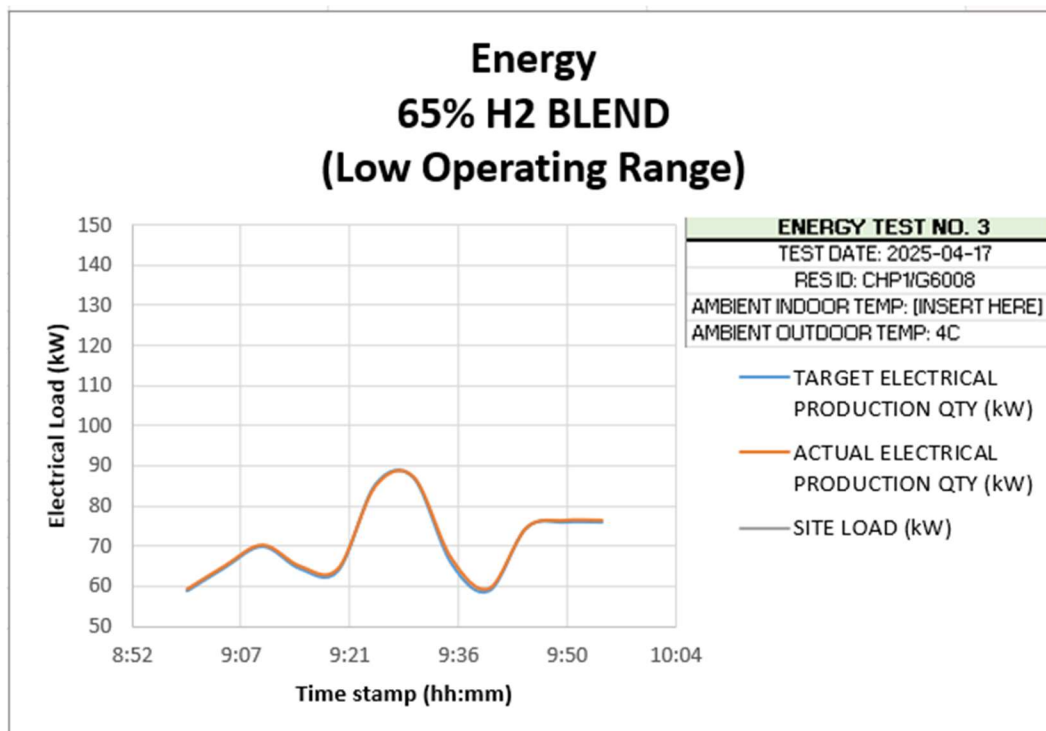


Figure 556 | Energy – 65% H2 Blend (Low Operating Range)

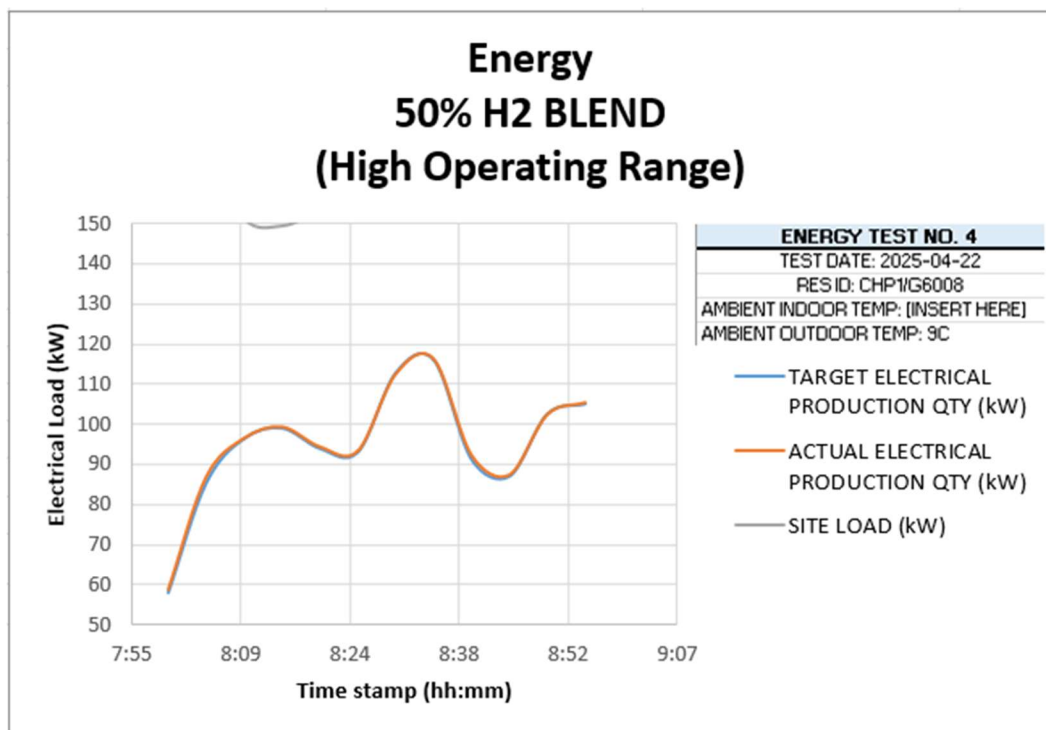


Figure 67 | Energy – 50% H2 Blend (High Operating Range)

3.1.4.1 Operating Reserve Tests

Test Goal:

- The five (5) operating reserve tests had a sample interval of 1 minute. The goal of the operating reserve test was to ramp to the target electrical production within 10 minutes of receiving and activation notice and hold that rate for 60 minutes at a constant H2 blending ratio.

Test Design:

- Each test was designed to evaluate the engine's ability to react to a call for power generation as if the CHP system is a demand response generation facility.

Test Results:

- In each case, the time from receiving the ramp notice to achieving the target electrical production was within 10 minutes. The engine was able to maintain the target electrical production for each test within 0.5% of the target. The test with the slowest time to respond was the 100% H2 blend. See summary table below:

Charts for each of the run tests have been included on the following page. Refer to Appendix A for all the data and charts. The Test Description in the chart below is based on the IESO Test Descriptions.

Test No.	H2 Blend Level (%)	Test Modifier Description	Time to Target (min)	Average Deviation (actual-Target (kW))	Standard Deviation (kW)	Average Deviation (Actual-Target)/Target (%)	Standard Deviation (%)
0	0	0 kW to 105 kW	5	0.45	0.20	0.5%	0.3%
1	65	0 kW to 105 kW	4	0.36	0.69	0.3%	0.8%
2	75	0 kW to 105 kW	4	0.33	0.86	0.3%	1.0%
3	85	0 kW to 105 kW	4	0.33	0.93	0.3%	0.9%
4	100	0 kW to 105 kW	8	0.37	1.12	0.4%	1.4%

Table 2 | Operating Reserve Tests Results

3.1.5 Operating Reserve Test Charts

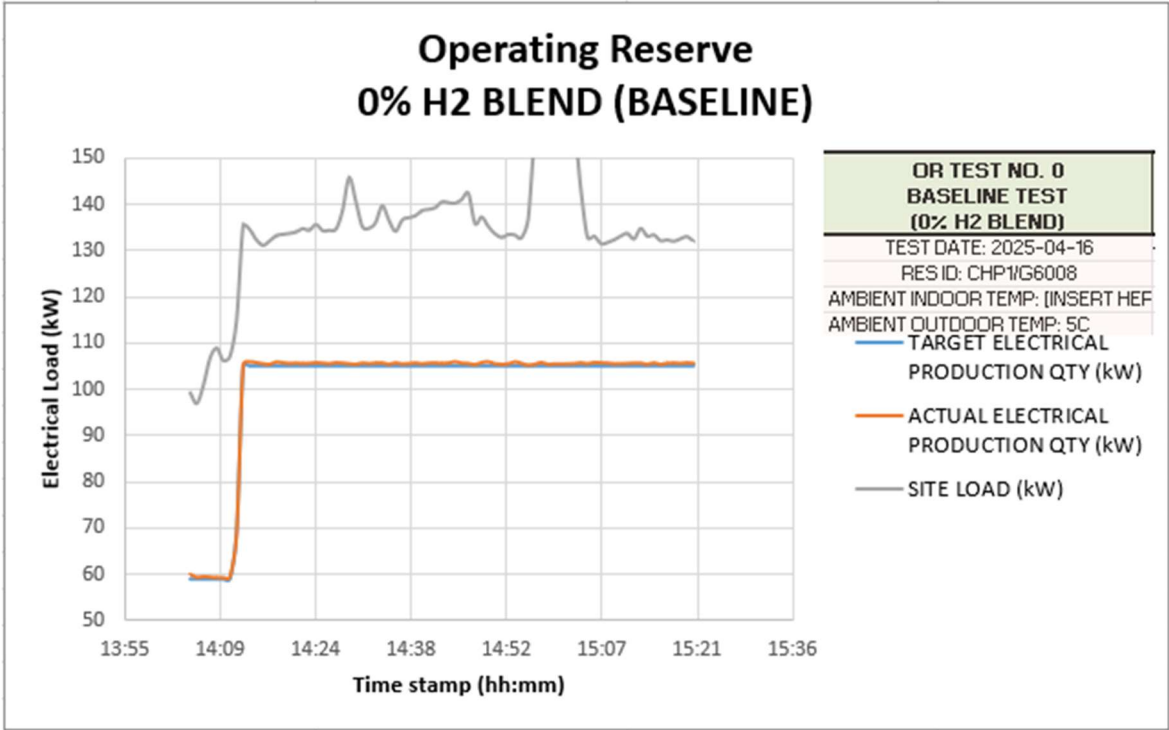


Figure 7 | Operating Reserve – 0% H2 Blend Baseline

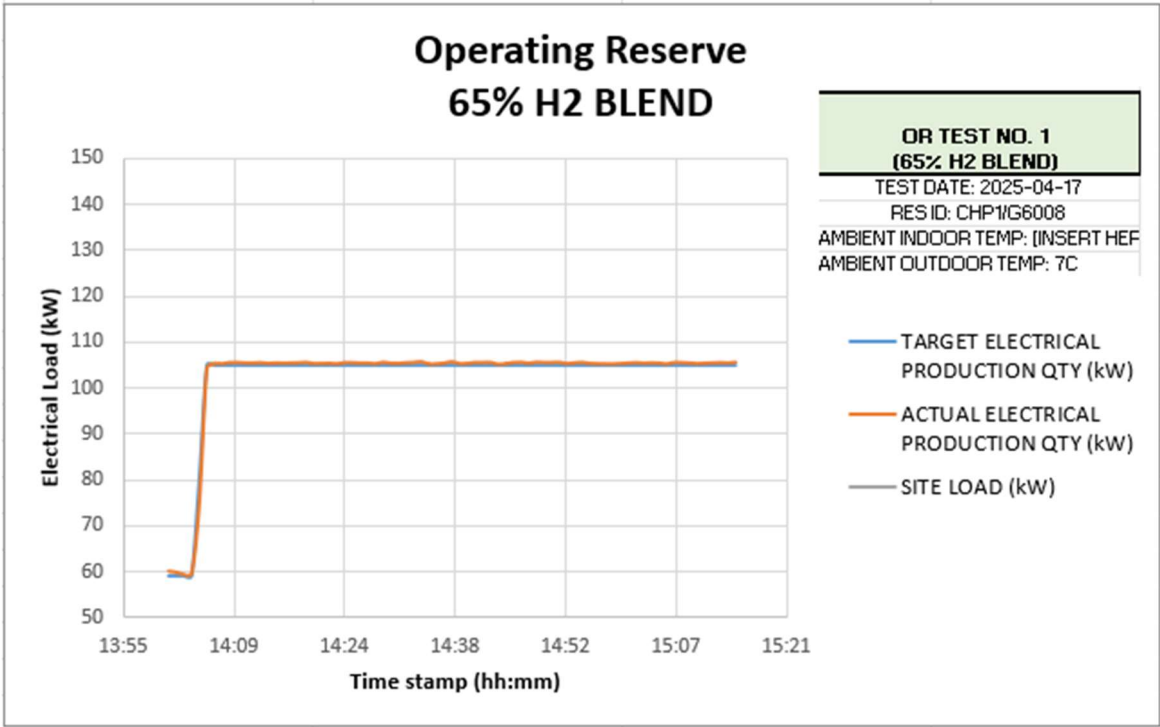


Figure 8 | Operating Reserve – 65% H2 Blend

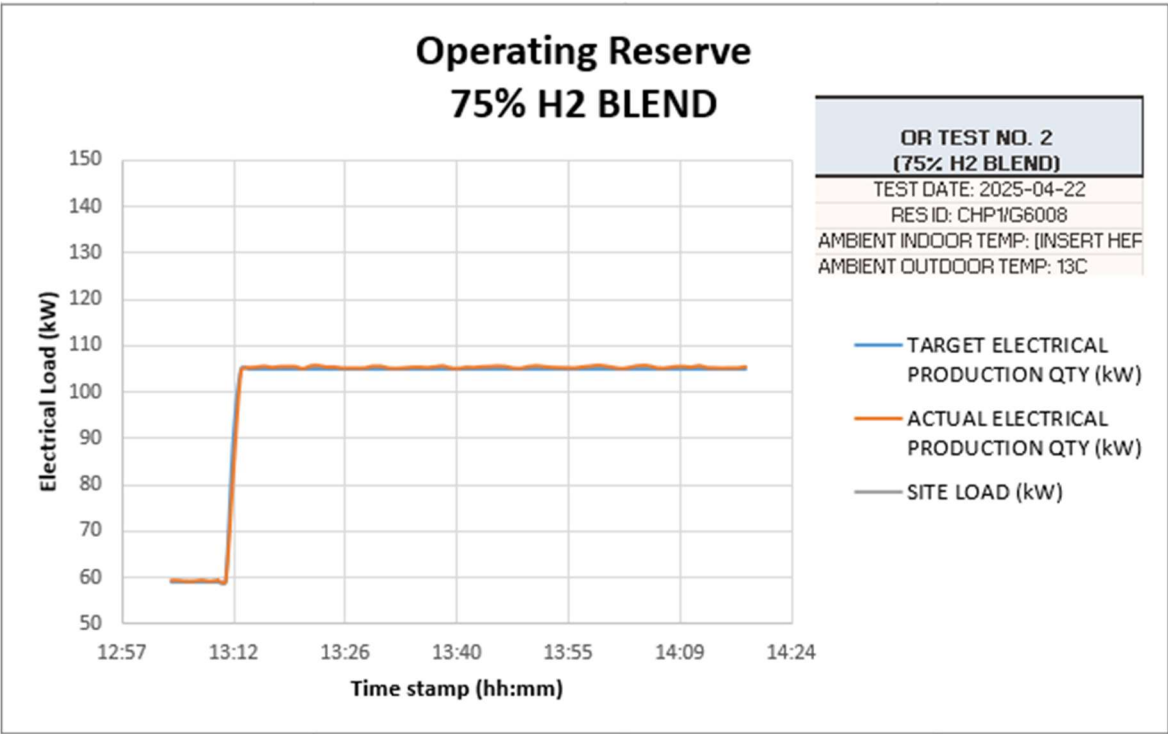


Figure 9 | Operating Reserve – 75% H2 Blend

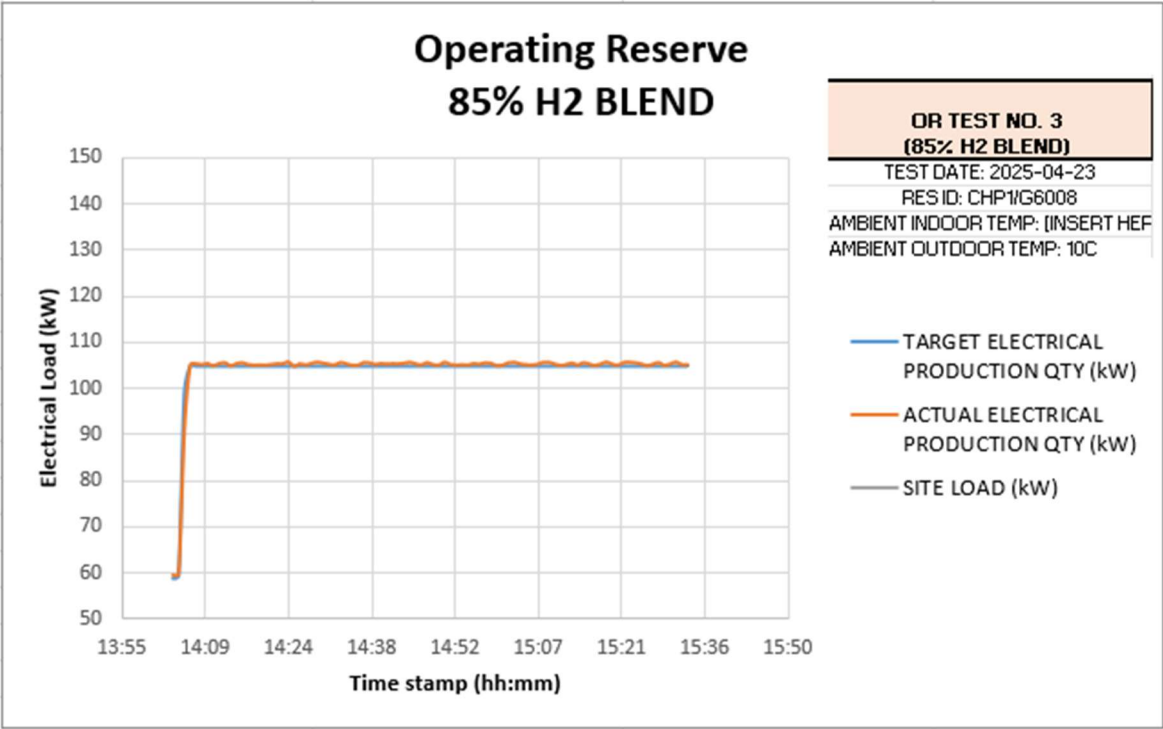


Figure 80 | Operating Reserve – 85% H2 Blend

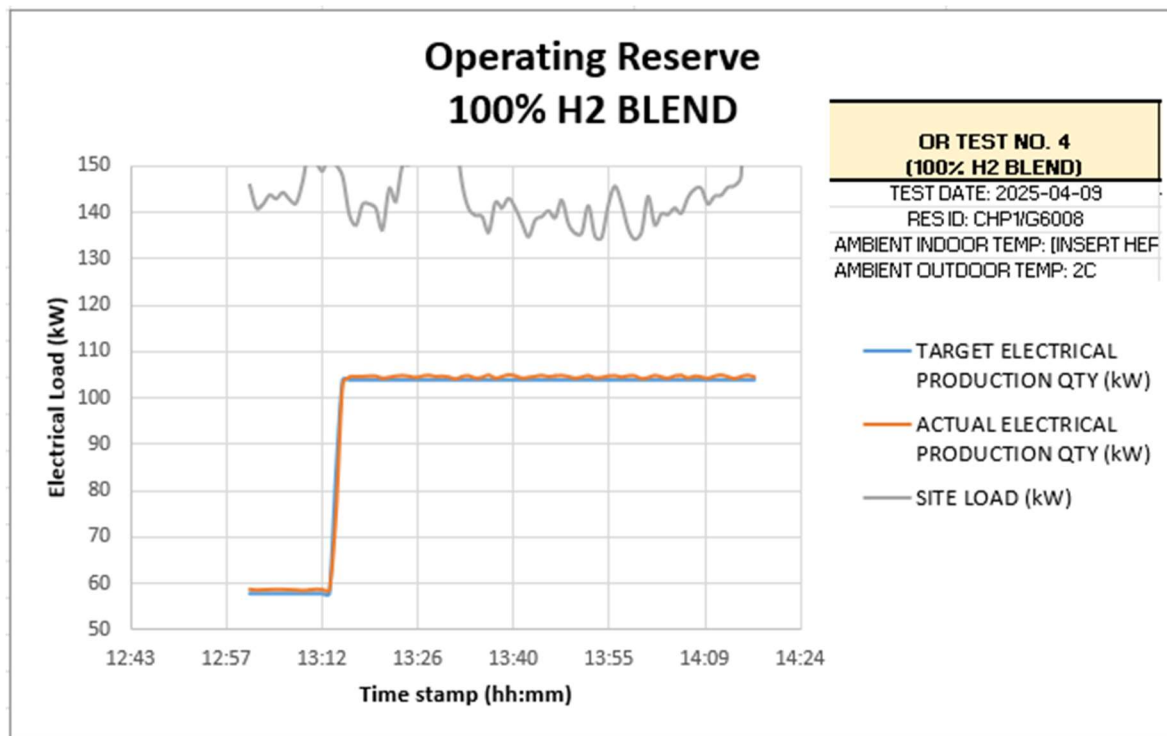


Figure 91 | Operating Reserve – 100% H2 Blend

3.1.5.1 Capacity Tests

Test Goal:

- The six (6) capacity tests had a sample interval of 5 minutes. The goal of the capacity test was to sustain the electrical output for 4 hours at a constant H2 blending ratio.

Test Design:

- Each test was designed to evaluate the engine's ability to maintain a continuous output for extended durations and to demonstrate the engine's ability to maintain the setpoint electrical load while operating.

Test Results:

- The engine was largely able to maintain the 4-hour run tests but did have some trip (and/or power reduction) occurrences (i.e. high exhaust temperature, knocking, faulty gas sensor). Additional engine tuning was able to improve the reliability of the engine. See summary table below:
- Test 0 tripped a few times due to high exhaust temperatures and high differential cooling water temperatures.
- Test 2 reduced power production a few times due to engine knocking.
- Test 4 tripped due to a false gas sensor alarm and trip.

Charts for each of the run tests have been included on the following page. Refer to Appendix A for all the data and charts. The Test Description in the chart below is based on the IESO Test Descriptions.

Test No.	H2 Blend Level (%)	Test Modifier Description	Average Deviation (actual-Target (kW))	Standard Deviation (kW)	Average Deviation (Actual-Target)/Target (%)	Standard Deviation (%)
0	0	Hot Weather (25°C)	-5.63	28.63	-4.9%	24.7%
00	0	Cold Weather (8°C)	0.44	0.58	0.4%	0.5%
1	50	Cold Weather (4°C)	0.44	0.80	0.4%	0.7%
2	65	Cold Weather (5°C)	0.12	6.99	0.1%	6.0%
3	80	Cold Weather (9°C)	0.43	0.54	0.4%	0.5%
4	100	Cold Weather (8°C)	0.44	0.65	0.4%	0.6%

Table 3 | Capacity Tests Results

3.1.6 Capacity Test Charts

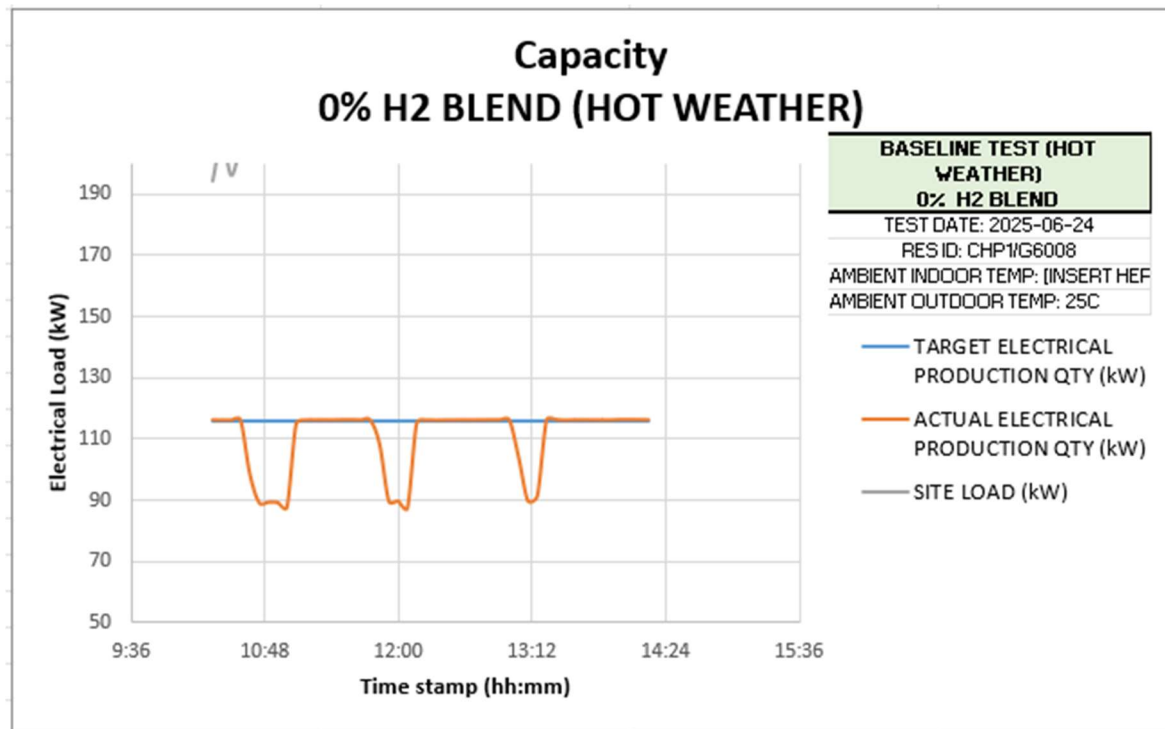


Figure 102 | Capacity – 0% H2 Blend (Hot Weather)

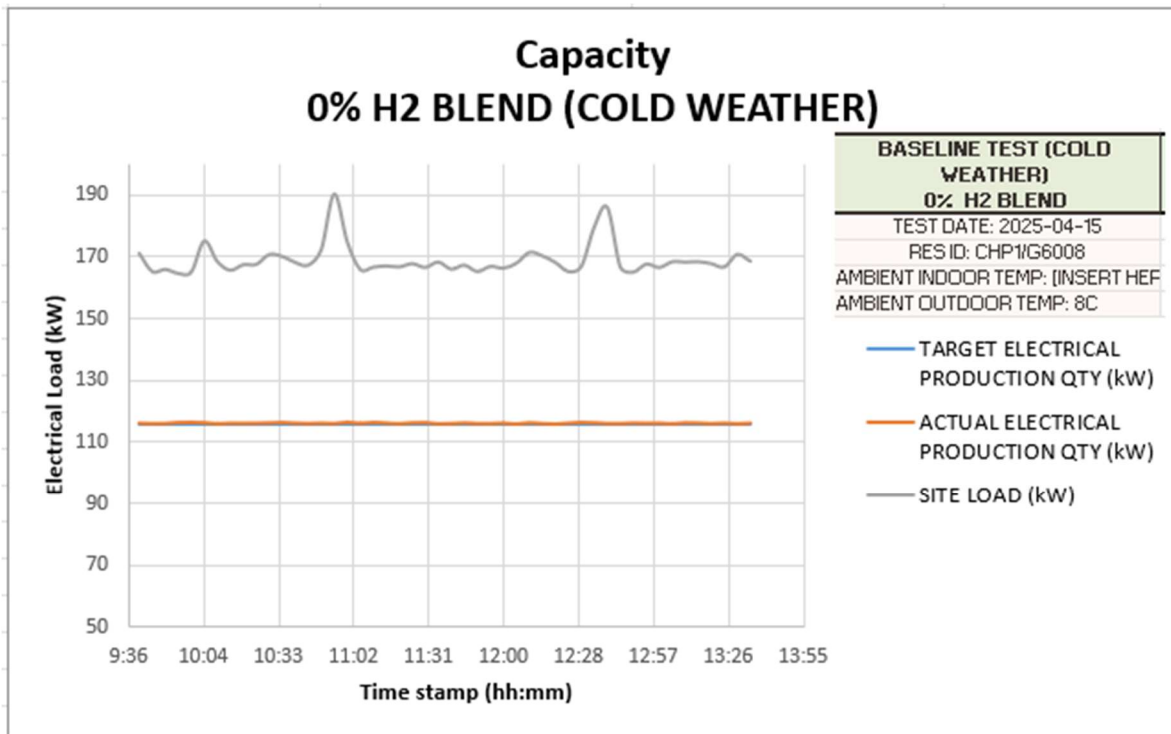


Figure 113 | Capacity – 0% H2 Blend (Cold Weather)

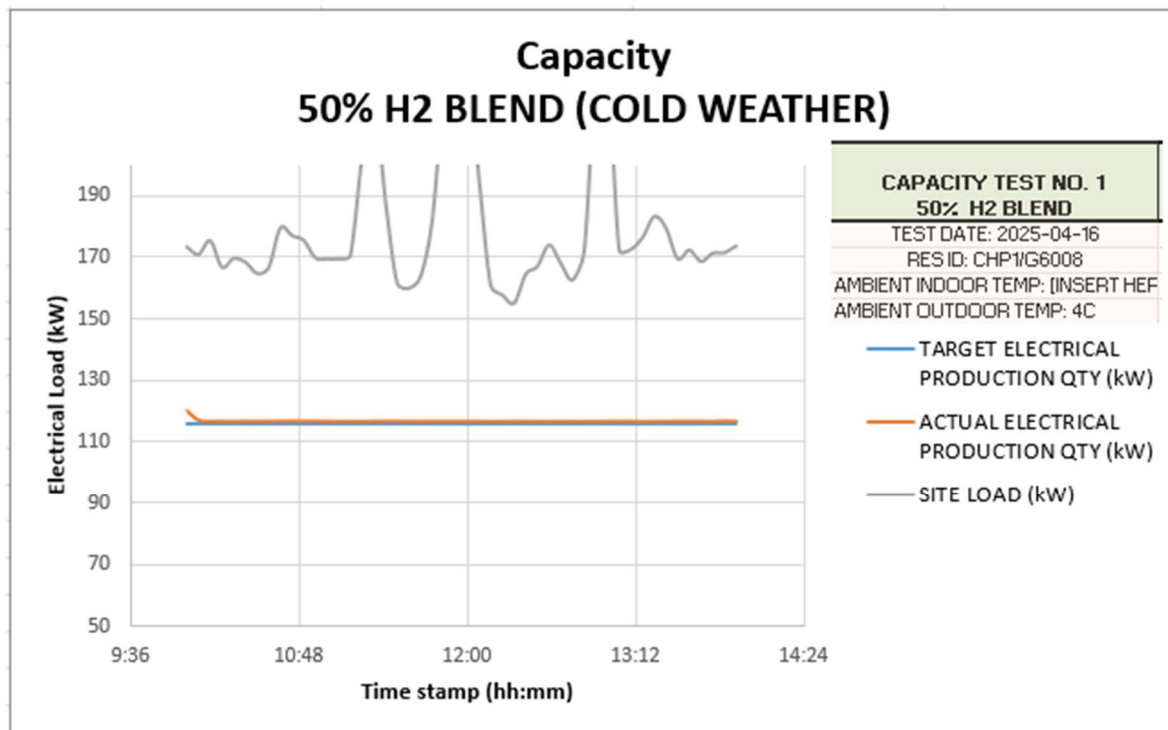


Figure 124 | Capacity – 50% H2 Blend (Cold Weather)

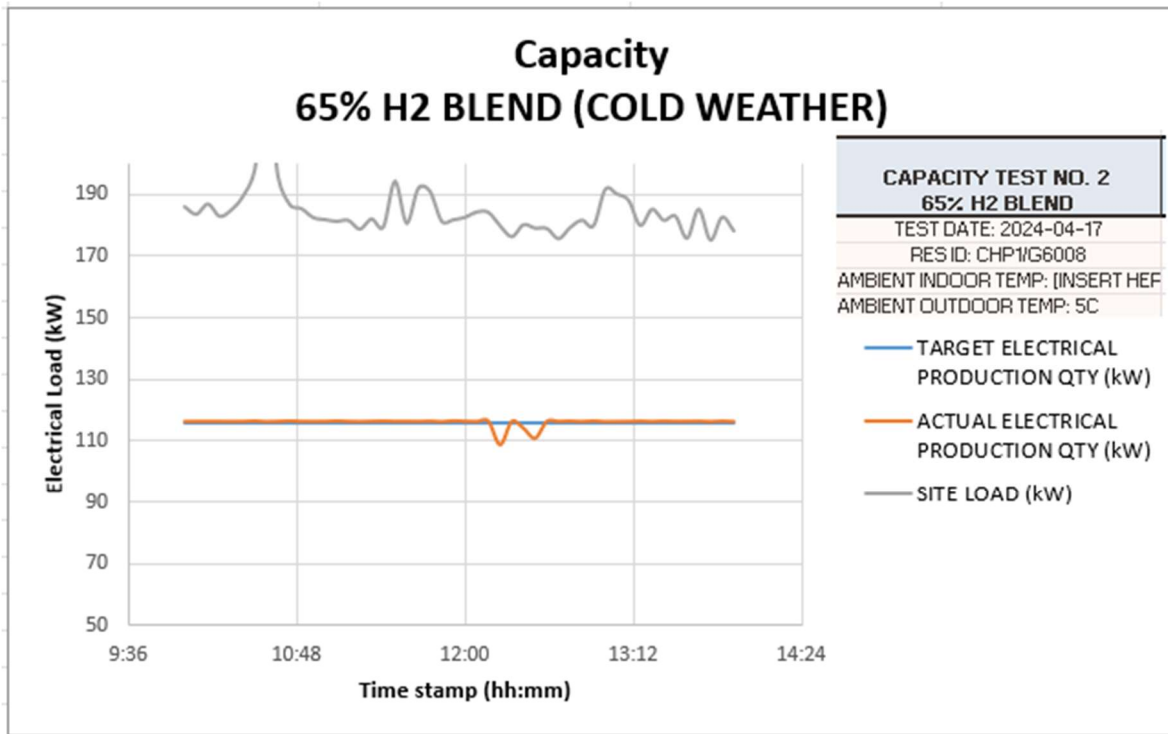


Figure 135 | Capacity – 65% H2 Blend (Cold Weather)

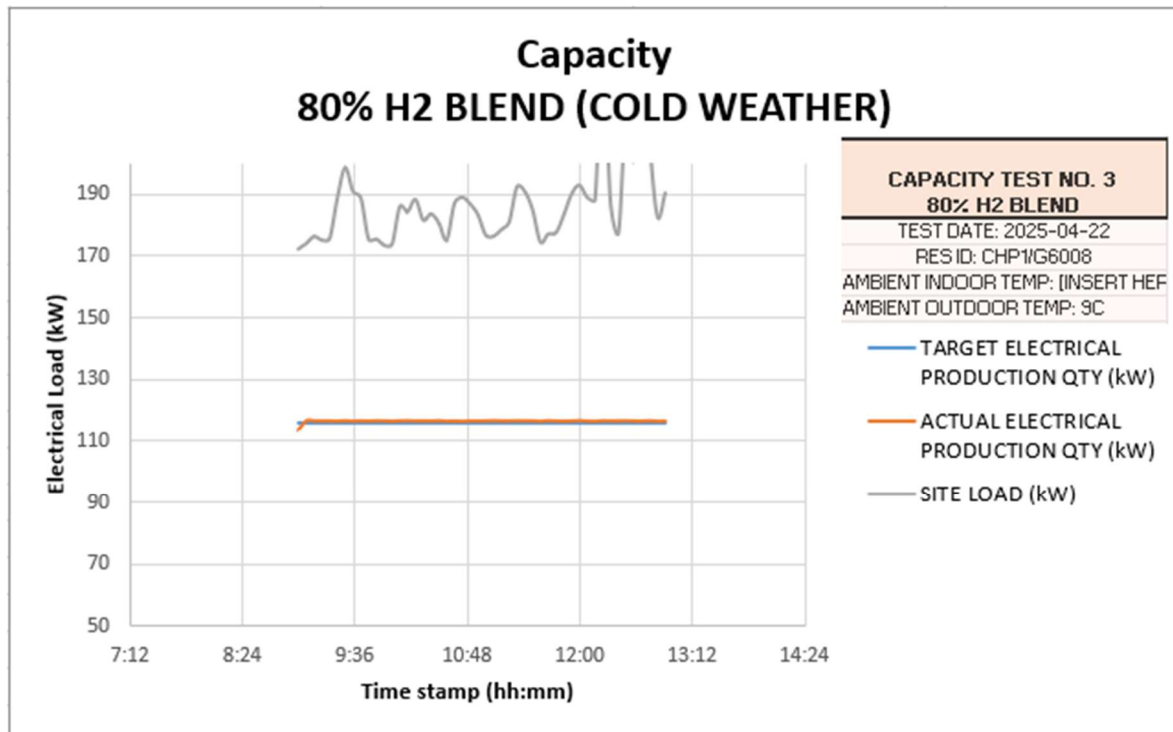


Figure 146 | Capacity – 80% H2 Blend (Cold Weather)

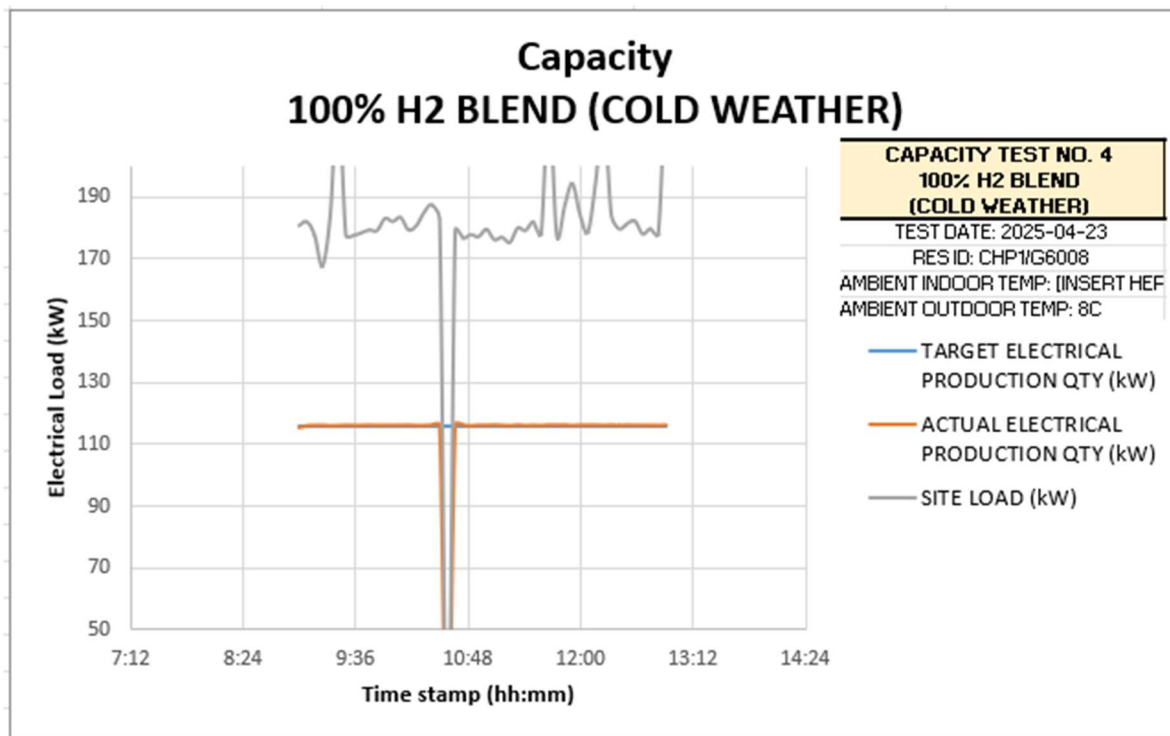


Figure 157 | Capacity – 100% H2 Blend (Cold Weather)

3.1.6.1 Ramping Tests

Test Goal

- The eight (8) ramping tests had a sample interval of 1 second. The goal of the ramping test was to demonstrate the maximum ramp-up and ramp-down rates from 0% to 100% and from 100% to 0%.

Test Design:

- Each test was designed to evaluate the engine's performance with aggressive ramp rates for hot start vs cold start conditions and at 0% H2 vs 100% H2.
- (Cold starts are when the engine is cool and requires a warm-up operating period. Hot starts are when the engine is sufficiently warm to allow ramp up immediately after start-up.

Test Results

- Operating with 0% H2;
- On cold start the engine was able to ramp up from 0% to 100% from within about 7.25 minutes.
- On hot start the engine was able to ramp up from 0% to 100% from within about 1.2 minutes.
- Operating with 100% H2;
- On cold start the engine was able to ramp up from 0% to 100% from within about 11.75 minutes.

- On hot start the engine was able to ramp up from 0% to 100% from within about 2.5 minutes.
- The engine has a better ramp response when operating on natural gas. See summary table below:

Charts for each of the run tests have been included below. Refer to Appendix A for all the data and charts. The Test Description in the chart below is based on the IESO Test Descriptions.

Test No.	H2 Blend Level (%)	Test Modifier Description	Time to 100% (mm:ss)	Average Deviation (actual-Target (kW))	Standard Deviation (kW)	Average Deviation (Actual-Target)/Target (%)	Standard Deviation (%)
0	0	Cold Start	6:45	0.21	1.96	-0.4%	6.0%
00	0	Hot Start	0:30	3.22	11.04	0.7%	1.7%
1	0	Cold Start	7:12	0.47	2.20	-0.1%	8.9%
2	0	Hot Start	1:10	-0.03	3.25	-2.0%	12.0%
3	100	Cold Start	9:28	0.53	6.59	19.2%	152.2%
4	100	Hot Start	2:14	0.45	8.51	25.9%	163.2%
5	100	Cold Start	11:42	0.44	6.55	19.2%	157.3%
6	100	Hot Start	2:40	-2.69	5.82	-4.8%	11.0%

Table 4 | Ramping Tests Results

3.1.7 Ramping Test Charts

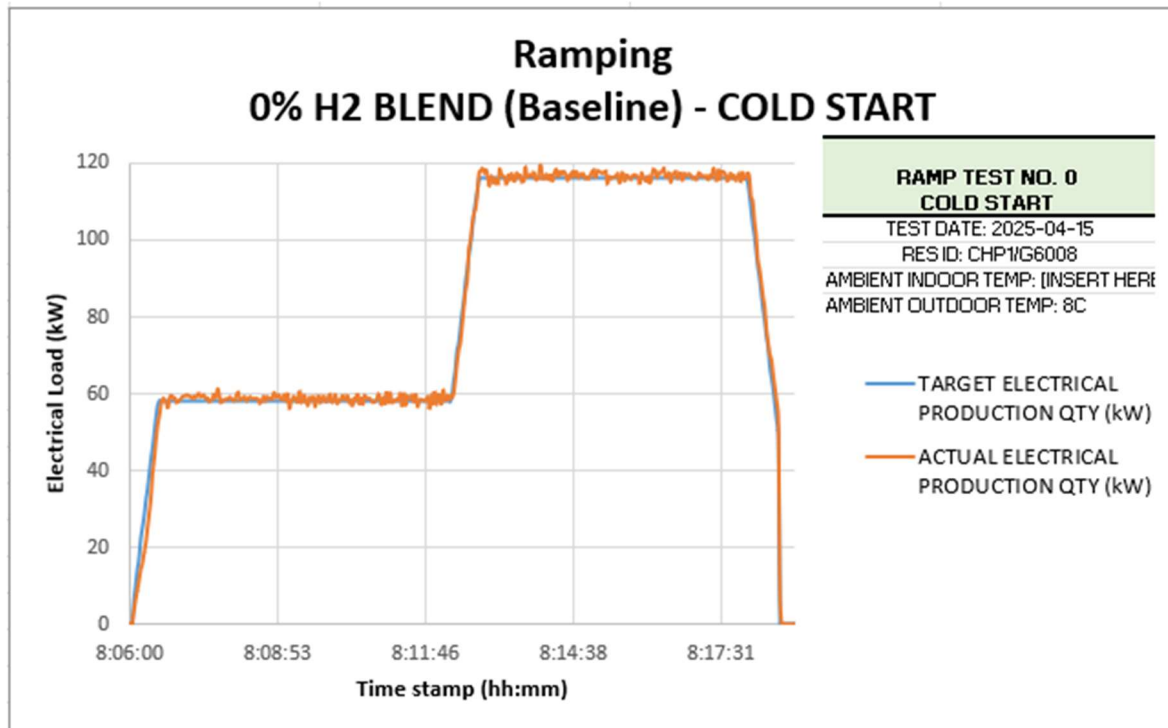


Figure 168 | Ramping – 0% H2 Blend (Baseline) Cold Start

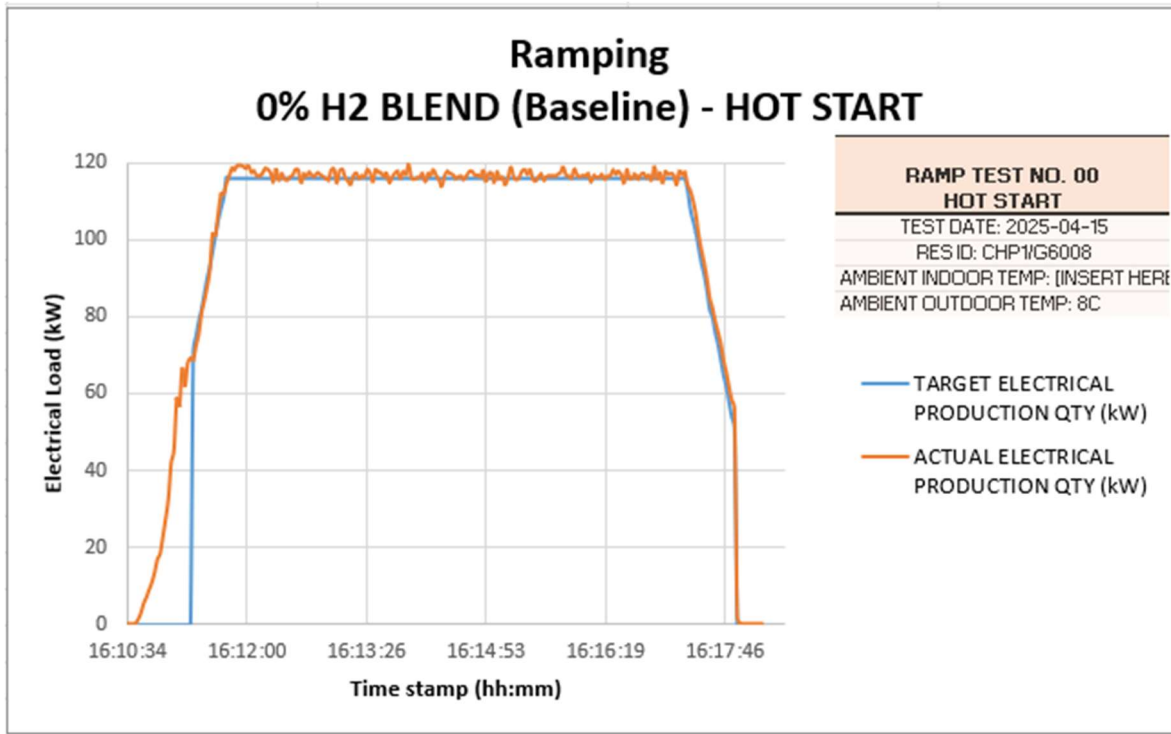


Figure 179 | Ramping – 0% H2 Blend (Baseline) Hot Start

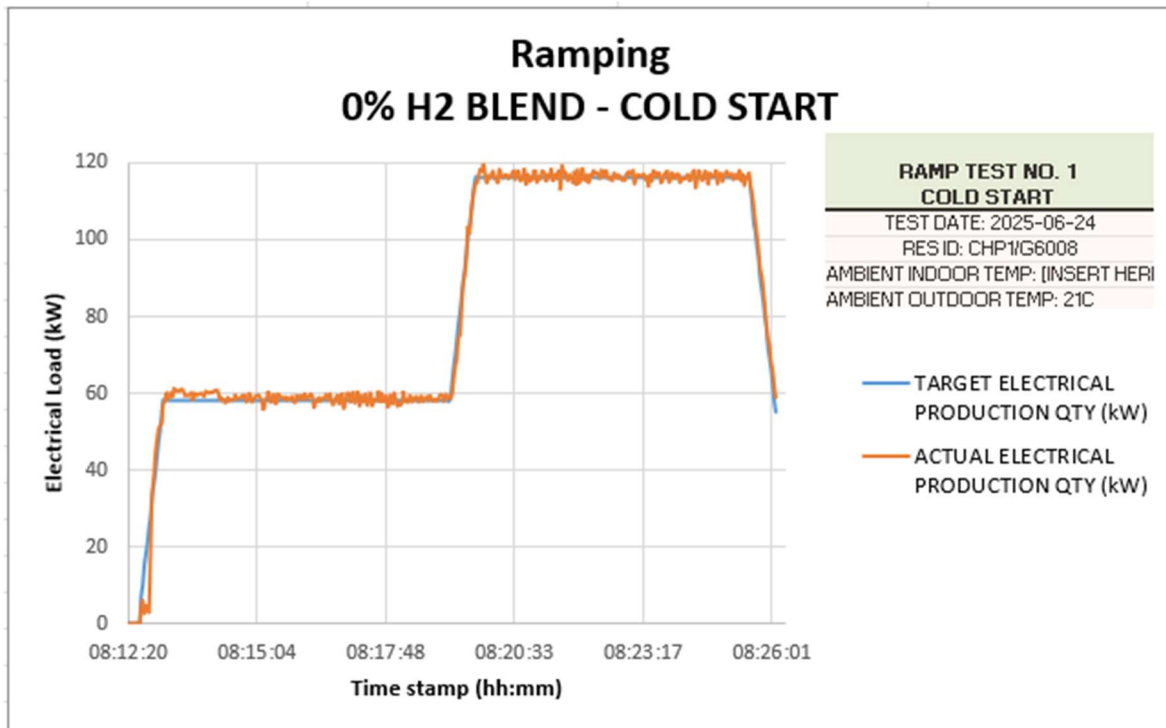


Figure 20 | Ramping – 0% H2 Blend Cold Start

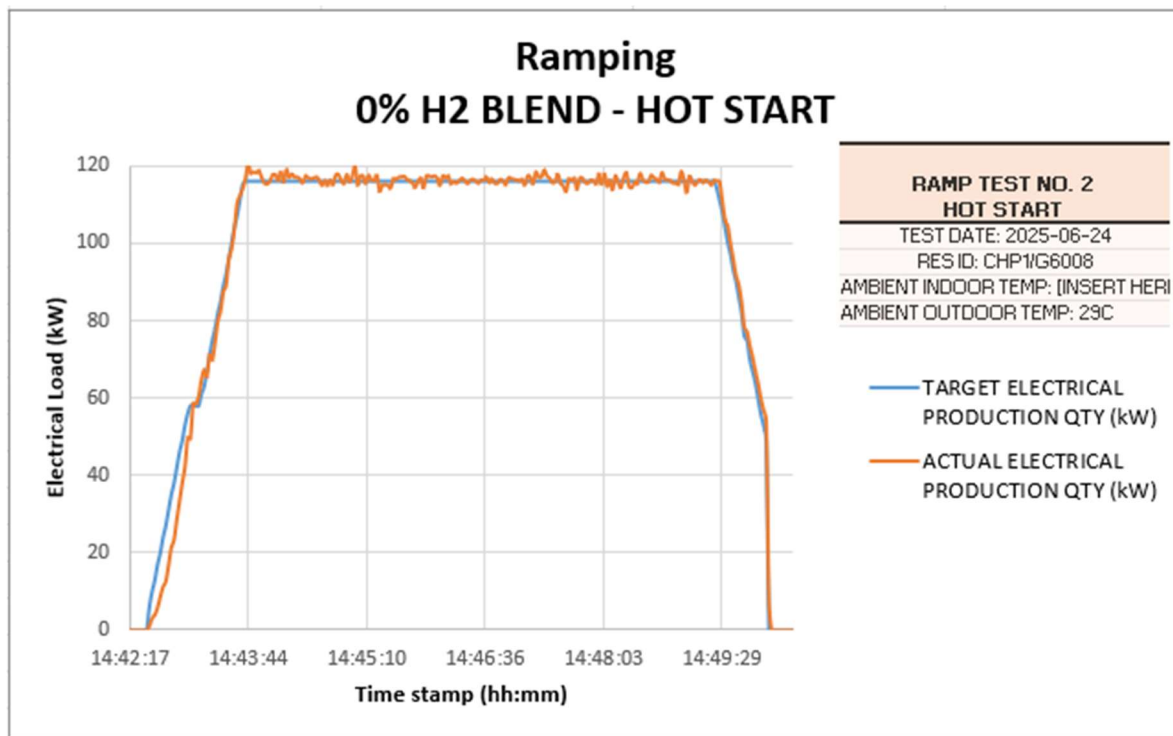


Figure 21 | Ramping – 0% H2 Blend Hot Start

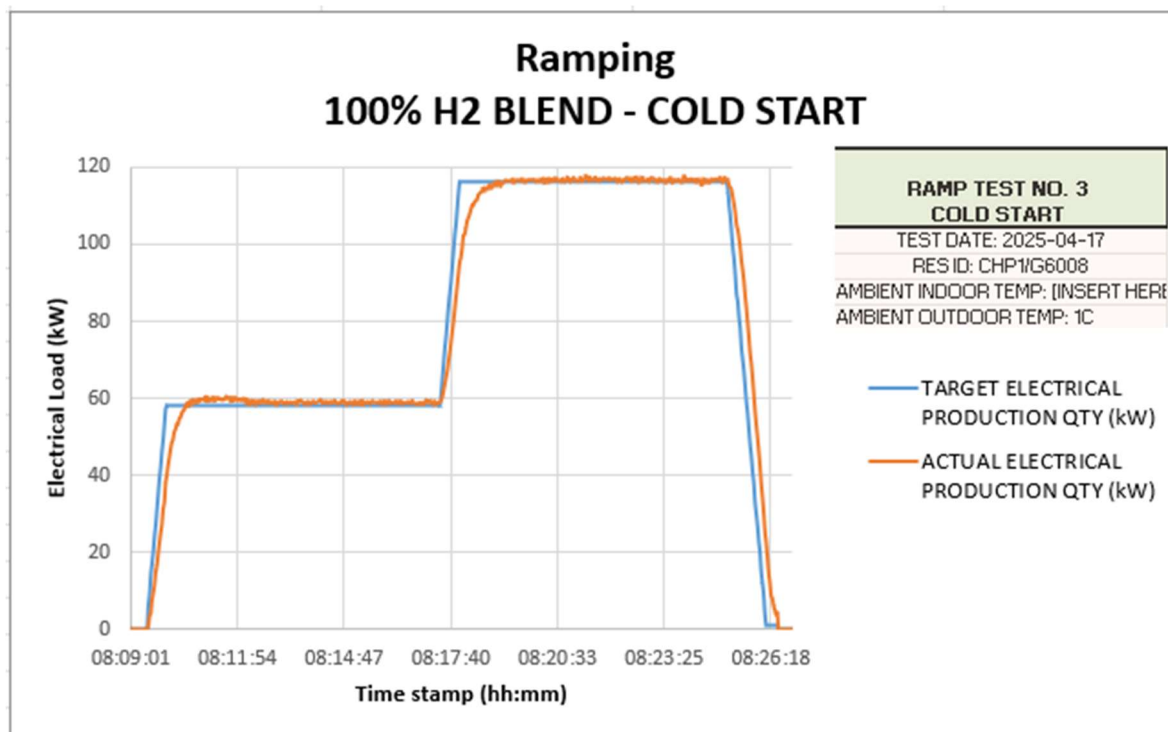


Figure 22 | Ramping – 100% H2 Blend – Cold Start

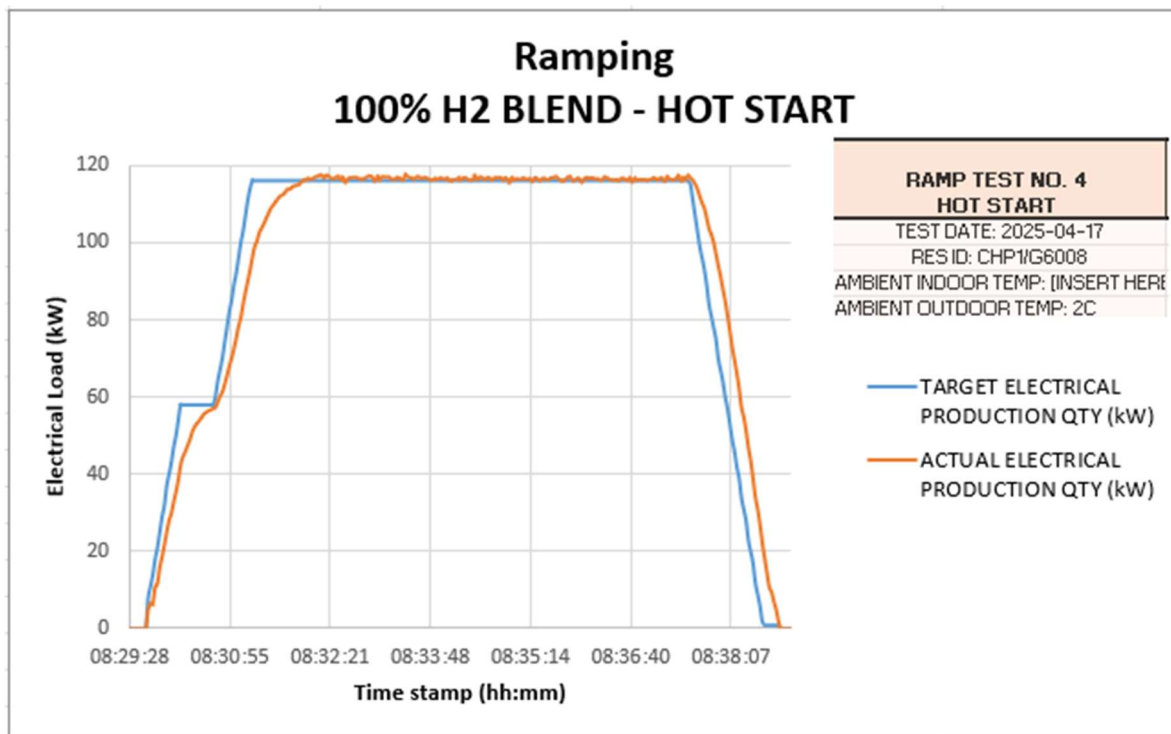


Figure 23 | Ramping – 100% H2 Blend – Hot Start

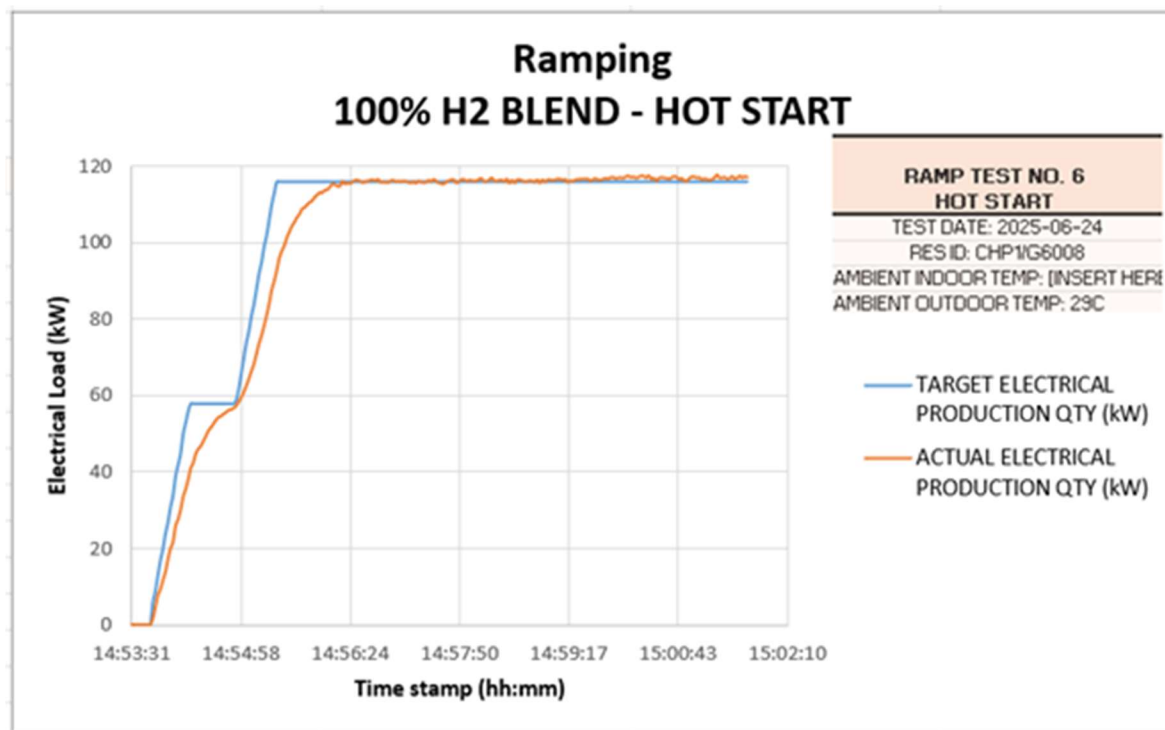


Figure 24 | Ramping – 100% H2 Blend – Hot Start

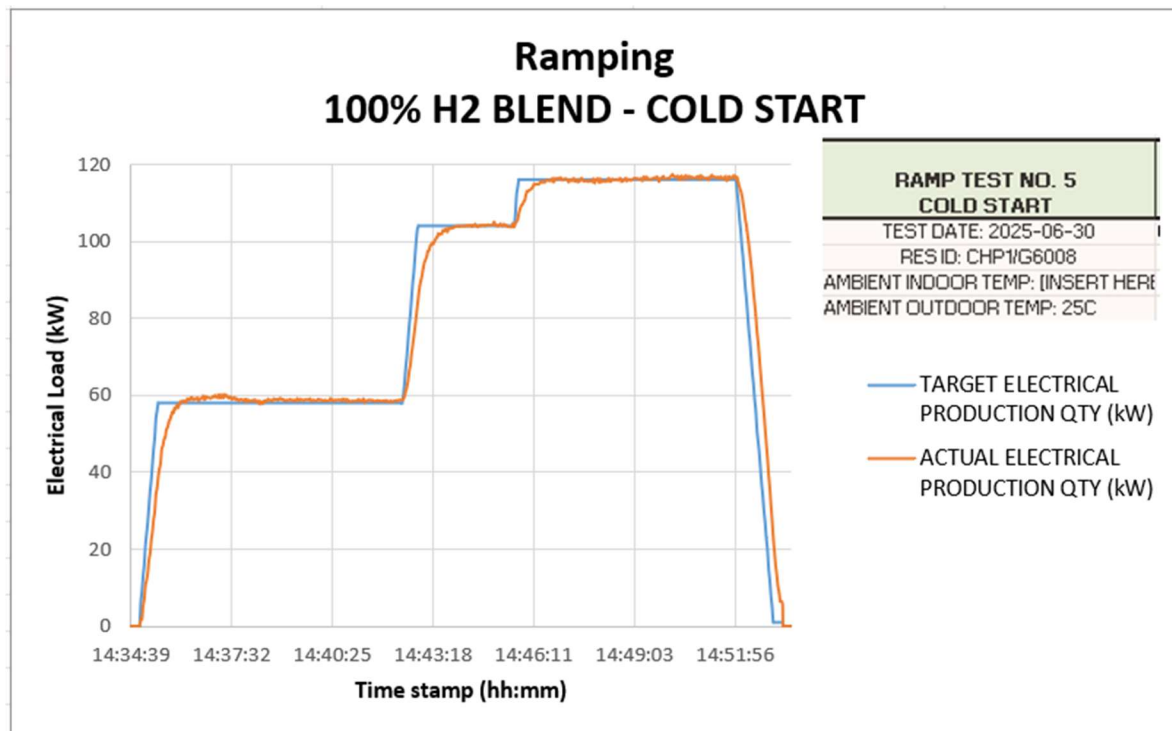


Figure 25 | Ramping – 100% H2 Blend – Cold Start

3.1.7.1 Regulation Tests

Test Goal

- The five (5) regulation tests had a sample interval of 4 seconds. The goal of the regulation test was to sustain a rapidly fluctuating dispatch signal as closely as possible. Each test maintained a constant H2 blending ratio.

Test Design

- Each test was designed to evaluate the engine's ability to follow a constantly fluctuating electrical load setpoint.

Test Results

- The engine did not perform incredibly well during the regulation test for the 0% H2 and the 100% H2 blends. The actual production varied an average of +/-9% from the target.
- However, with H2 blends between 65% and 85%, the engine was able to more closely follow the target electrical load. The actual power production varied an average of +/-1% from the target.
- See summary table below.

Charts for each of the run tests have been included below. Refer to Appendix A for all the data and charts. The Test Description in the chart below is based on the IESO Test Descriptions.

Test No.	H2 Blend Level (%)	Test Modifier Description	Average Deviation (actual-Target (kW))	Standard Deviation (kW)	Average Deviation (Actual-Target)/Target (%)	Standard Deviation (%)
0	0	-	-7.60	11.89	-8.5%	13.6%
1	65	-	-1.46	11.45	-0.9%	13.9%
2	75	-	-1.39	9.57	-1.1%	11.2%
3	85	-	-1.45	12.17	-0.7%	14.9%
4	100	-	3.80	11.13	5.7%	13.8%

Table 5 | Regulation Tests Results

3.1.8 Regulation Test Charts

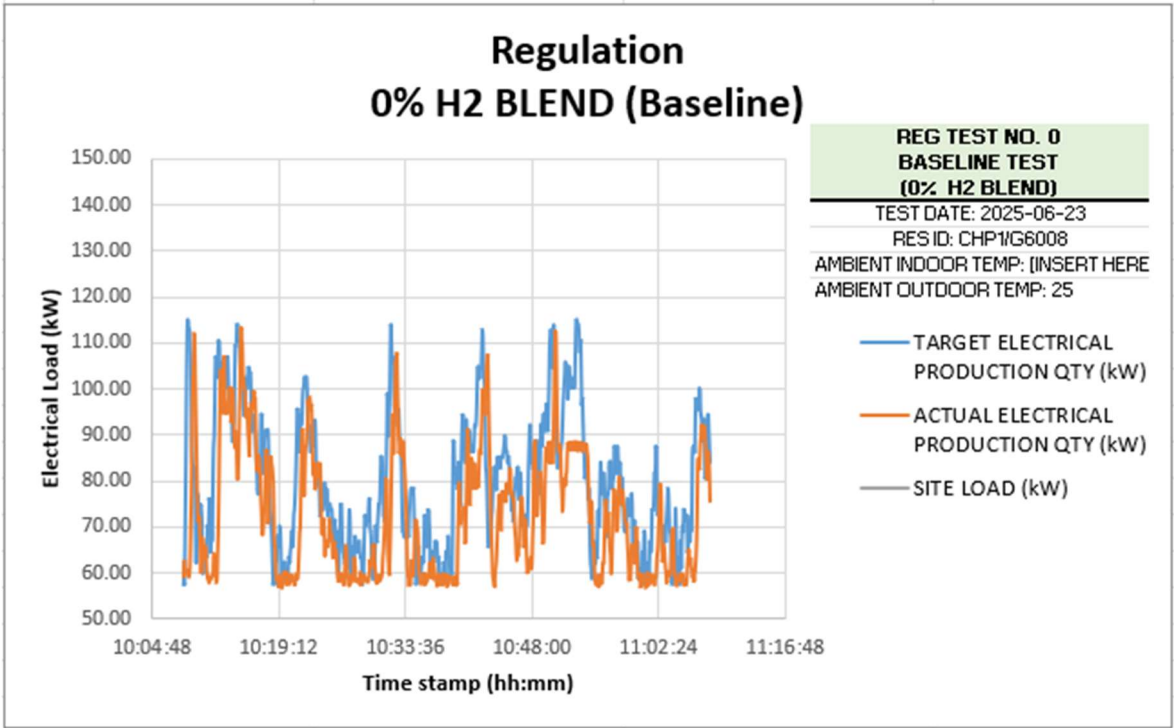


Figure 26 | Regulation – 0% H2 Blend (Baseline)

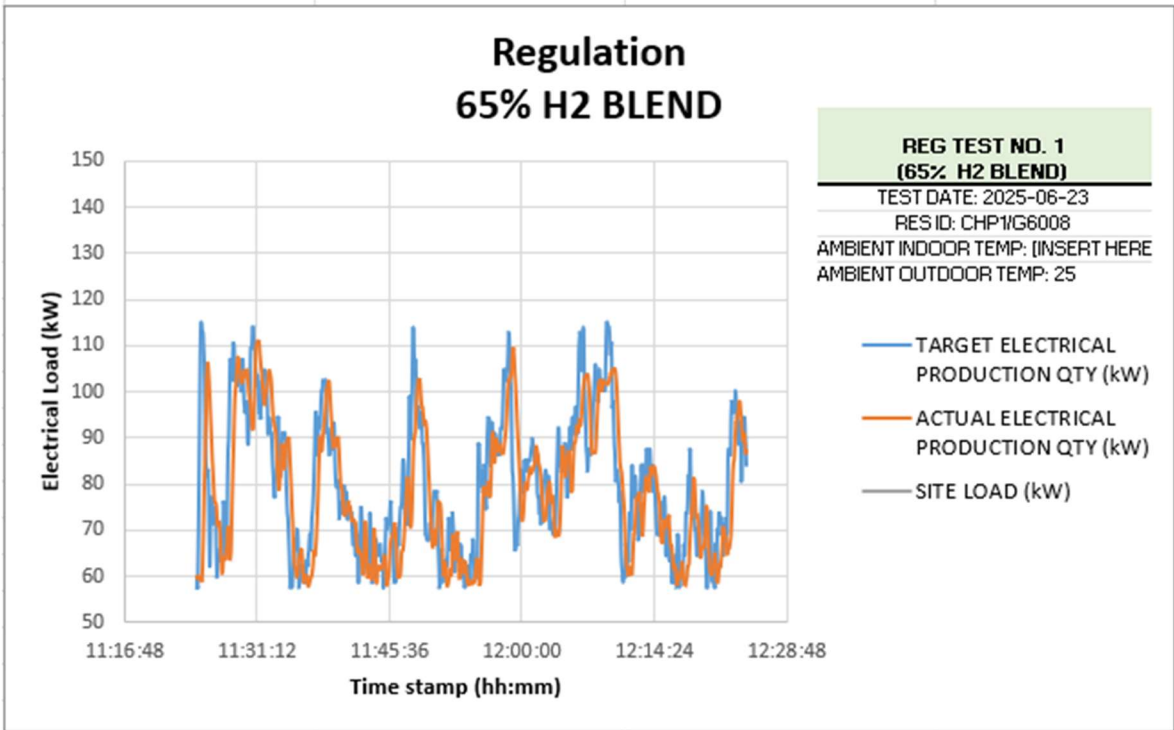


Figure 27 | Regulation – 65% H2 Blend

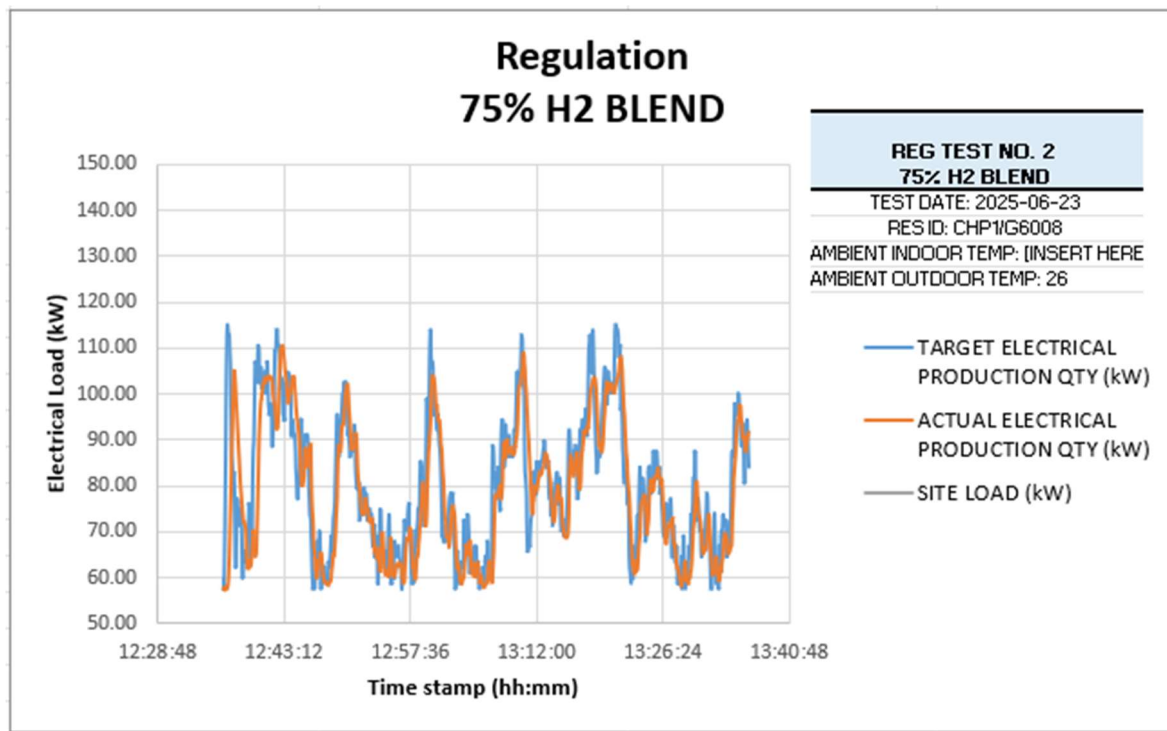


Figure 28 | Regulation – 75% H2 Blend

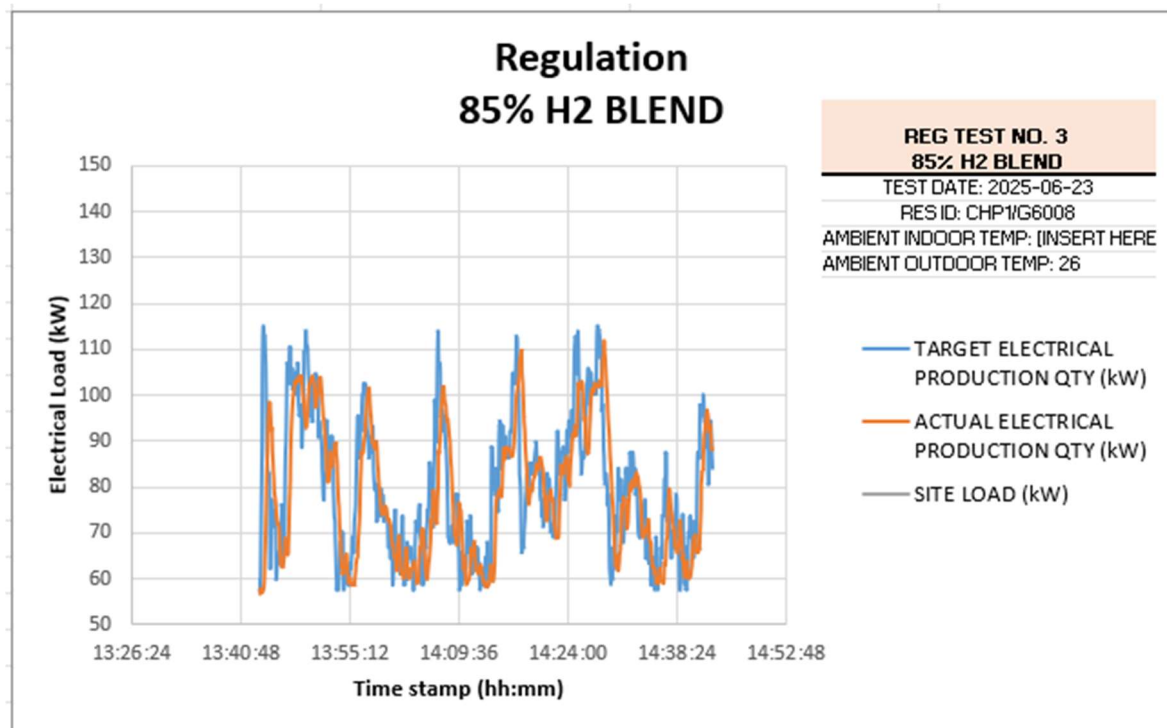


Figure 29 | Regulation – 85% H2 Blend

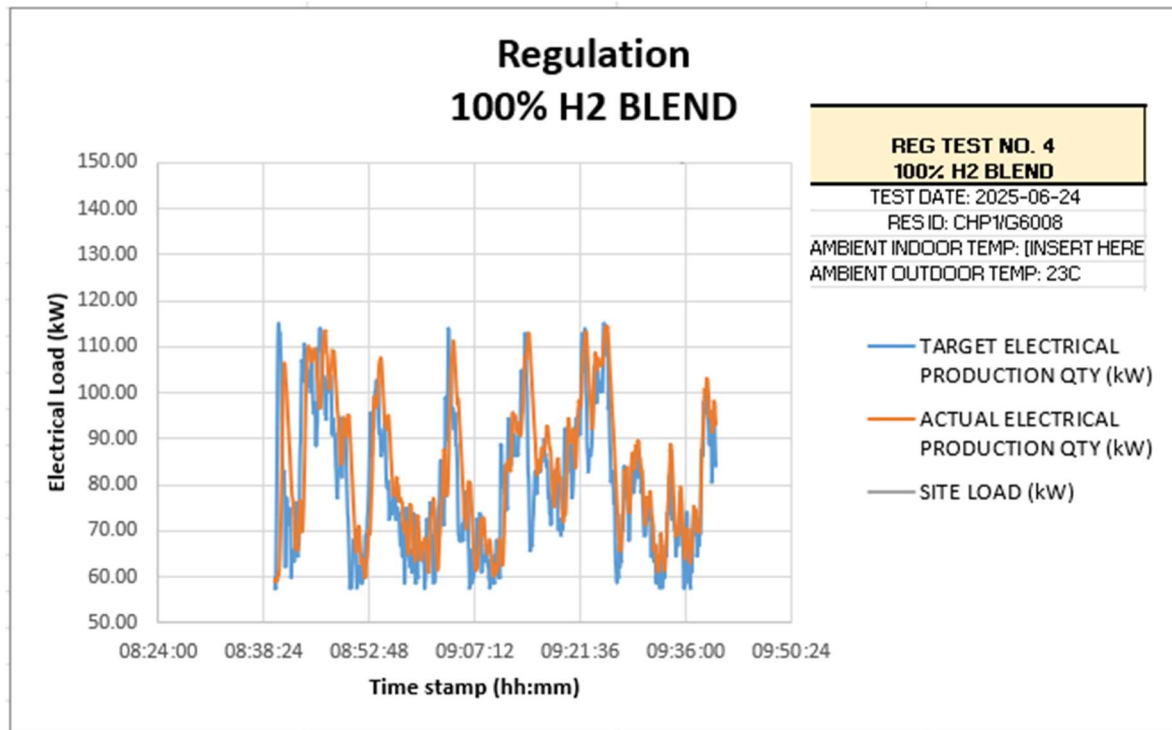


Figure 30 | Regulation – 100% H2 Blend

3.2 International Performance Measurement and Verification Protocol (IPMVP)

3.2.1 The Process

The IESO HIF Demonstration Framework, in conjunction with the IPMVP Measurement and Verification (M&V) methodology-Option B: Retrofit Isolation was used to measure, verify, and document the performance of the Hydrogen CHP system. System performance parameters were determined through field measurements of electricity, hydrogen, natural gas, and the hot water-glycol mixture, as well as relevant independent variables such as ambient temperature.

3.2.1.1 Planning the Project

Monthly whole facility measurement for natural gas consumption and electricity consumption for the TOC building was completed to determine the energy baseline for the TOC Building.

The monthly natural gas consumption was noticed to be highly dependent on the ambient temperature as natural gas is primarily used for space heating. Minimal natural gas is also used for domestic hot water heater for a negligible thermal baseload.

The hourly electricity consumption is highly dependent on building occupancy. There is moderate decrease in electrical load during evenings and a significant decrease in electrical load during weekends and holidays when the building is largely vacant.

The CHP system was sized to maximize the utilization of thermal energy from the CHP system to generate an optimized overall system efficiency. As a result, the system was sized based on the thermal load due to the seasonal nature of the building thermal load.

In 2015, the Baseline average electrical demand always exceeded 115 kW. By operating the CHP during workdays, all electrical power produced can be consumed within the TOC Building.

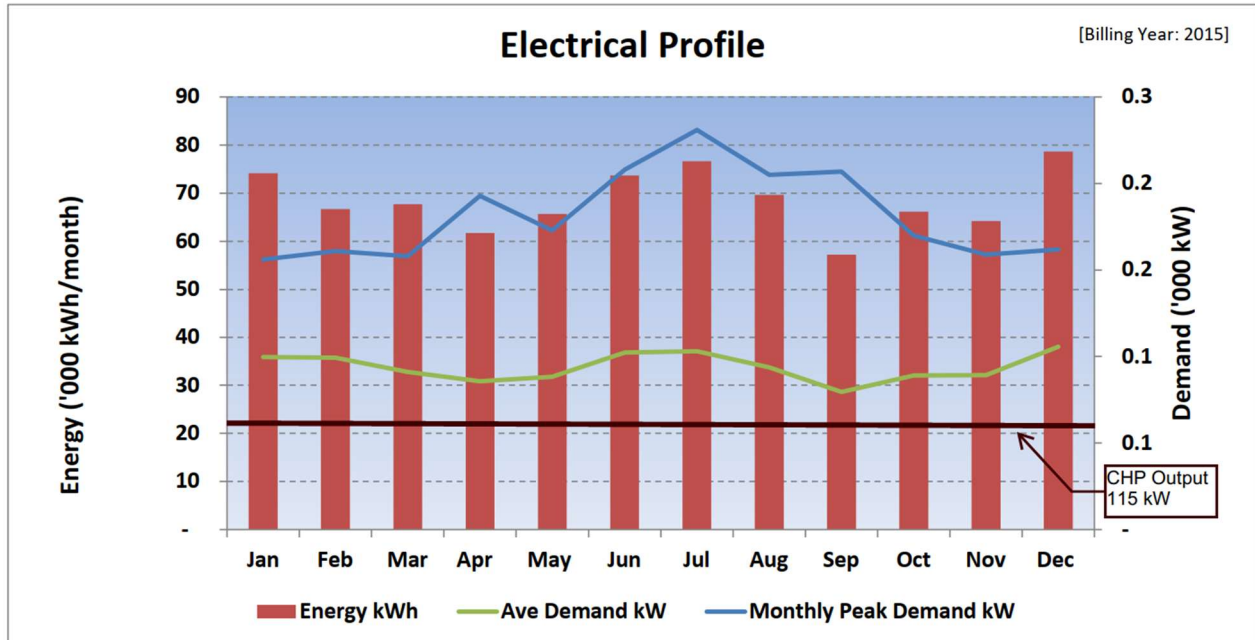


Figure 31 | Electrical Profile

The Baseline building thermal profile is indicated below. With the CHP sized for a maximum thermal output of 134 kWt, approximately 60% of the annual available heat from the CHP can be recovered.

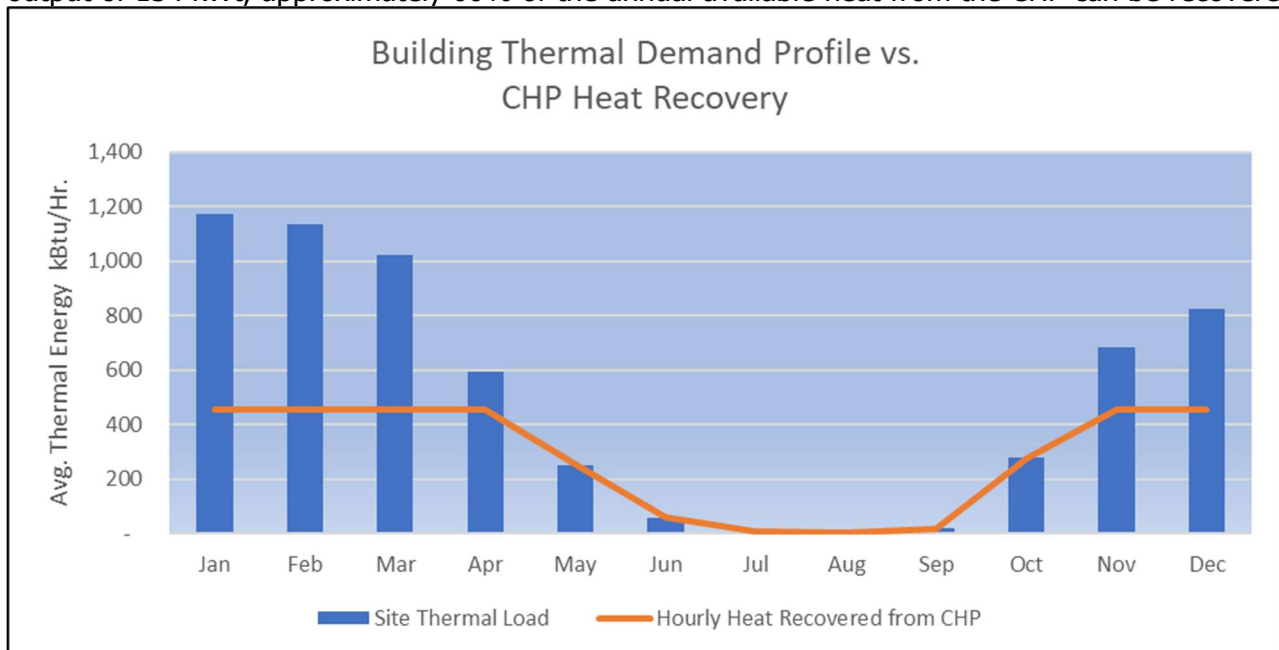


Figure 32 | Building Thermal Demand Profile vs. CHP Heat Recovery

3.2.1.2 Installing the Project

The CHP project went through engineering, construction, commissioning, and performance testing. The performance testing was completed according to the test plan for the HIF framework. (See Section 4.1 for HIF testing results.)

The building's electricity savings are equal to the measured net electricity generation of the CHP electric generator (gross power generation less any project auxiliary electrical loads).

The building's natural gas savings are equal to the measured heat recovery from the CHP (energy meter with flow and temperature measurements) and factored according to the efficiency of the existing boilers.

The CHP system's energy consumption is measured by a dedicated natural gas meter and a dedicated hydrogen fuel meter.

3.2.1.3 Maintaining the Project

Moving forward, it will be important to continue to measure and monitor the electrical generation, thermal heat recovery, and CHP fuel consumption to verify project performance.

3.2.2 IPMVP Options

The energy baseline was created using Option C: Whole Facility of the IPMVP options.

The energy savings are measured and calculated using Option B: Retrofit Isolation measuring all parameters.

3.2.3 Annual Savings

The CHP has not yet been operating for a full year, or even through its first winter. The HIF testing results indicate that the energy savings are in line with the original energy savings estimates. Evaluating the measurement data following a complete season of heat recovery is recommended to verify the estimated energy savings generated in the planning phase of the project.

4. Results and Analysis

4.1 Summary of Load Displacement and Efficiency Results

The CHP operation has been characterised based on the HIF testing completed. The following results could be further verified on an annual basis with the provision of annual operating data.

The during testing, actual fuel consumption is a little higher than the rated values, however there are some seasonal effects in fuel consumption where the fuel consumption is lower (increased efficiency) during colder ambient temperatures.

See comparison chart below comparing the results of the vendor's technical data versus the test results. The genset is capable of generating up to 160 kW of electricity when firing on 100% natural gas and 115 kW of electricity when firing with any H2 in the fuel blend. The rated data has been prorated to 115 kW for natural gas to provide a more direct comparison to H2 operation.

The electrical efficiency values are consistently lower than the rated values. The efficiency values are lower due to an increased fuel consumption from rated values.

Potential reasons for the increased relative fuel consumption are noted as:

- Deviations in real fuel HHV compared to assumed fuel HHV (10.75 kWh/Nm³ HHV). (Reported Enbridge fuel HHV deviations in 2024 was around +/-0.7%)
- Meter accuracies (+/- 1% for natural gas, +/-0.05% for hydrogen)
- Engine tuning or real engine performance not meeting rated design values

Parameter	Units	Datasheet Value 100% H2	Datasheet Value 0% H2 (at 115 kW)	Tested Value 100% H2	Tested Value 0% H2
Electrical Output Capacity	kW	115	115	116	116
Thermal Output Capacity	kW ¹	134	138	96	96
Fuel Consumption	kW (HHV) ²	361	343	396	377
Electrical Efficiency	% (HHV) ²	31.9	33.5	29.3	30.8
CHP Efficiency	% (HHV) ^{1,2}	68.9	74.4	53.5	56.2

Table 6 | Summary of Load Displacement Efficiency Results

Note 1 When testing the thermal capacity, the ambient temperature went as cold as +5°C. The heat recovery had not yet plateaued.

Presumably colder ambient temperatures would result in increased heat recovery. Additional cold weather testing would be required to confirm. In this system design the heat recovered is used to provide building heat, which in colder ambient conditions, would result in increased heat recovery. In other words, during the testing, the building could not take as much heat as the equipment could provide.

Note 2 The technical datasheets provide fuel consumption and efficiency ratings in lower heating values (LHV). The rated LHV values have been converted to higher heating values (HHV) at factors of 1.18 HHV/LHV for N2 and 1.11 HHV/LHV for natural gas.

4.2 Electrical Load Displacement

The engine is only dispatched from 7 am to 4 pm on weekdays. During evenings and weekends, the electrical load of the facility is too low to run the engine efficiently.

The electrical load at the facility varies significantly, but during the weekdays between 7 am and 4 pm, the facility load is consistently higher than the electrical capacity. As demonstrated during one of the capacity tests, the facility electrical load was around 170 kW (See chart below which illustrates the loads).

The engine can displace 100% of its 115 kW load capacity during weekday operating periods.

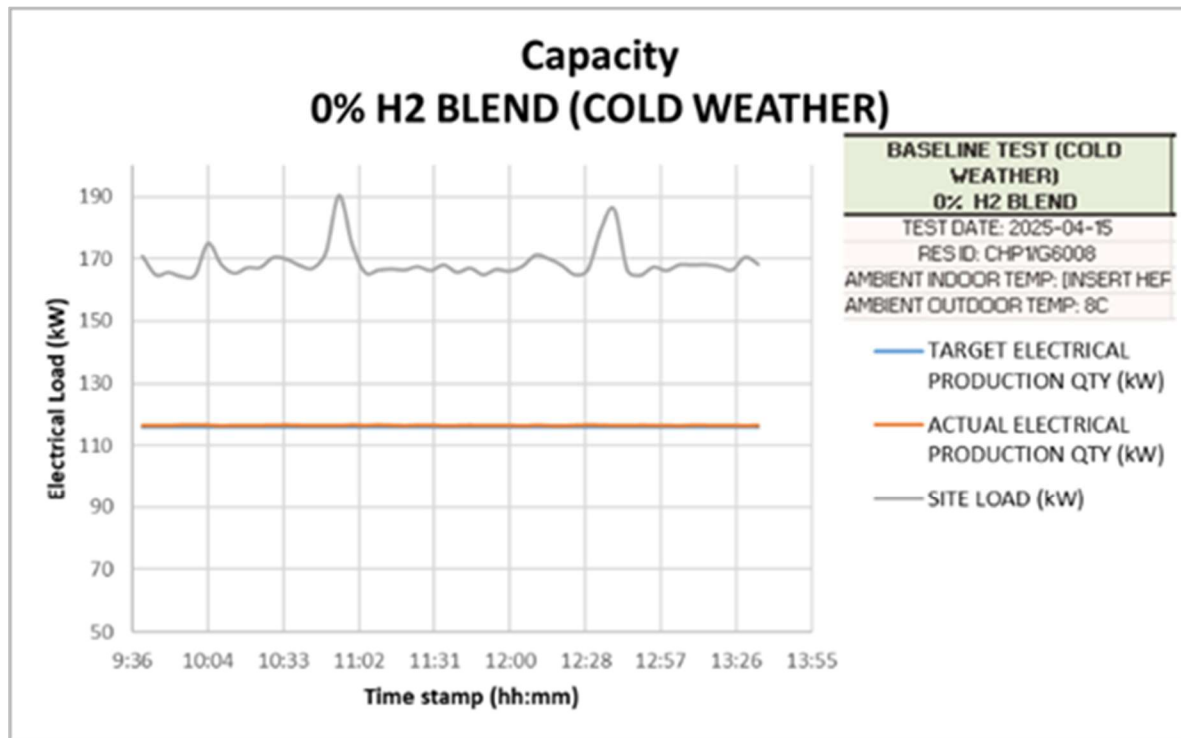


Figure 33 | Capacity – 0% H2 Blend (Cold Weather)

4.3 Fuel Consumption

The engine consumes natural gas or hydrogen according to the blend of fuel set at the CHP controller.

The H2 blend is nominally between 50% and 100% H2, but can go as low as approx. 25% depending on the operating point, and is dynamically controlled using the interface. If the engine is started on natural gas, the engine must continue to run on 100% natural gas until it is restarted. If the intent is to use various H2 blends for fuel, the engine must be started at 100% H2 and then natural gas can be blended into the fuel mix.

The measured fuel consumption at ~115 kW load is:

- With 100% H2: 396 kW (HHV).
- With 0% H2: 377 kW (HHV).

The rated fuel consumption at 115 kW load is:

- With 100% H2: 362 kW (HHV) (306 kW LHV x 1.18 HHV/LHV)
- With 0% H2: 340 kW (HHV) (306 kW LHV x 1.11 HHV/LHV)

Refer to the table and chart below for details. The average total fuel input is the sum of natural gas fuel energy and hydrogen fuel energy.

Test Plan	Test No.	H2 Blend Level (%)	Test Modifier Description	Ambient Temp. (°C)	Avg. Electrical Output kWe	Avg. Total Fuel Input kWt (HHV)
Energy	0	0	Low Operating Range (50% to 75% load)	9	72	259
Energy	00	0	High Operating Range (75% to 100% load)	9	97	325
Energy	1	Vary from 100 to 65 to 100	Minimum Continuous Load (50%)	2	59	227
Energy	2	Vary from 100 to 50 to 100	Maximum Continuous Load (100%)	3	115	379
Energy	3	65	Low Operating Range (50% to 75% load)	4	71	252
Energy	4	50	High Operating Range (75% to 100% load)	9	96	320
Energy	5	75	Low Operating Range (50% to 75% load)	7	69	254
Energy	6	75	High Operating Range (75% to 100% load)	14	94	319
Energy	7	100	Low Operating Range (50% to 75% load)	10	69	261
Energy	8	100	High Operating Range (75% to 100% load)	15	98	343

Test Plan	Test No.	H2 Blend Level (%)	Test Modifier Description	Ambient Temp. (°C)	Avg. Electrical Output kWe	Avg. Total Fuel Input kWt (HHV)
Operating Reserve	0	0	0 kW to 105 kW	5	101	331
Operating Reserve	1	65	0 kW to 105 kW	7	103	338
Operating Reserve	2	75	0 kW to 105 kW	13	100	337
Operating Reserve	3	85	0 kW to 105 kW	10	104	351
Operating Reserve	4	100	0 kW to 105 kW	2	96	340
Capacity	0	0	Hot Weather (25°C)	25	110	361
Capacity	00	0	Cold Weather (8°C)	8	116	377
Capacity	1	50	Cold Weather (4°C)	4	117	370
Capacity	2	65	Cold Weather (5°C)	5	116	376
Capacity	3	80	Cold Weather (9°C)	9	116	385
Capacity	4	100	Cold Weather (8°C)	8	116	396
Regulation	0	0	-	25	72	259
Regulation	1	65	-	25	79	273
Regulation	2	75	-	26	79	276
Regulation	3	85	-	26	79	279
Regulation	4	100	-	23	84	302
Average					93	195

Table 7 | Fuel Consumption Tests Results

The chart below illustrates the following:

- 100% hydrogen and blends containing hydrogen generally have a higher fuel consumption per unit power generated than 100% natural gas
- With lower power generation, the efficiency is less than the efficiency of the engine at 100% power generation
- For 100% hydrogen and blends containing hydrogen, generally have a lower efficiency than 100% natural gas

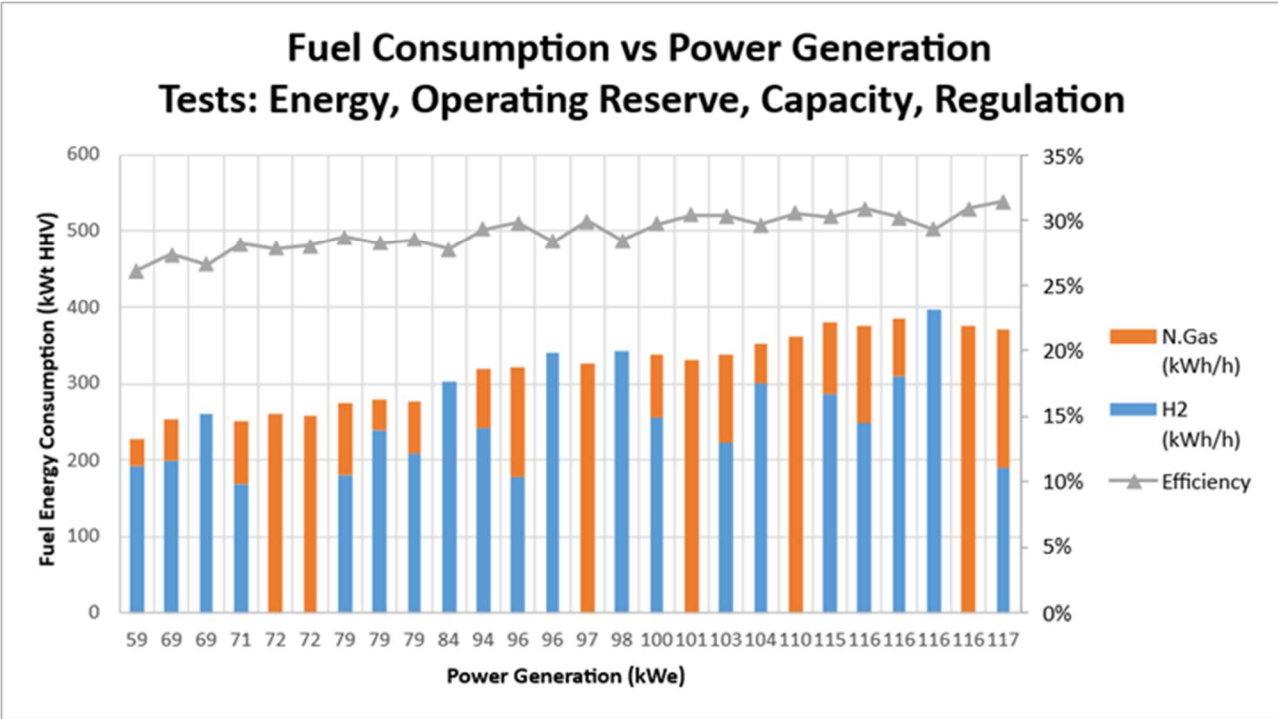


Figure 34 | Fuel Consumption vs Power Generation Tests: Energy, Operating Reserve, Capacity, Regulation

4.4 Thermal Load Displacement

The engine's cooling system uses an air-to-water heat exchanger (radiator) to reject any excess heat.

This cooling system is connected to the facility's building heating system by a water-glycol loop and heat exchanger. The hot cooling system pre-heats the building heating loop upstream of the boilers to reduce facility natural gas consumption.

The building heating system reduces the amount of heat the engine rejects to atmosphere and increases the engine's system efficiency. Any residual heat that the building load does not use is rejected by the engine's radiator.

The engine is rated to produce up to 134 kW of recoverable heat to the building.

The actual amount of heat recovery is dependent on the ambient temperature (and load on the building heating system). Based on the HIF testing at various ambient temperatures, the maximum heat recovery of 96 kWt occurred when the ambient temperature was 5°C. Colder temperatures are likely to increase the heat recovery. Once the ambient temperature is above 20°C, there is not enough building heating to take any more heat from the engine.

Based on Canadian Climate Normals for the Markham area, the average daily temperature is below 10°C for 5 months of the year, and below 20°C for 8 months of the year. Heat recovery is in use for about 66% of the year and 100% heat recovery is possible for about 42% of the year. The annual average heat recovery is estimated to be about 54% of the available amount.

Every kWh of heat recovery from the engine replaces 0.1 Nm³ of natural gas consumed by the building. (Based on 85% HHV boiler efficiency of the existing hot water boilers.)

See table and graph below for details. The ramping test cases skew the heat recovery results and have been excluded from the summary. The Test Description in the chart below is based on the IESO Test Descriptions.

Test Plan	Test No.	H2 Blend Level (%)	Test Modifier Description	Ambient Temp. (°C)	Average Heat Recovered (mmBtu/hr)	Average Heat Recovered (kWt)
Energy	0	0	Low Operating Range (50% to 75% load)	9	0.11	32
Energy	00	0	High Operating Range (75% to 100% load)	9	0.15	42
Energy	1	Vary from 100 to 65 to 100	Minimum Continuous Load (50%)	2	0.17	50
Energy	2	Vary from 100 to 50 to 100	Maximum Continuous Load (100%)	3	0.32	93
Energy	3	65	Low Operating Range (50% to 75% load)	4	0.27	78

Test Plan	Test No.	H2 Blend Level (%)	Test Modifier Description	Ambient Temp. (°C)	Average Heat Recovered (mmBtu/hr)	Average Heat Recovered (kWt)
Energy	4	50	High Operating Range (75% to 100% load)	9	0.15	45
Energy	5	75	Low Operating Range (50% to 75% load)	7	0.13	38
Energy	6	75	High Operating Range (75% to 100% load)	14	0.01	3
Energy	7	100	Low Operating Range (50% to 75% load)	10	0.01	2
Energy	8	100	High Operating Range (75% to 100% load)	15	0.01	2
Operating Reserve	0	0	0 kW to 105 kW	5	0.27	79
Operating Reserve	1	65	0 kW to 105 kW	7	0.23	67
Operating Reserve	2	75	0 kW to 105 kW	13	0.13	39
Operating Reserve	3	85	0 kW to 105 kW	10	0.01	3
Operating Reserve	4	100	0 kW to 105 kW	2	0.28	83
Capacity	0	0	Hot Weather (25°C)	25	-0.03	-9
Capacity	00	0	Cold Weather (8°C)	8	0.21	61
Capacity	1	50	Cold Weather (4°C)	4	0.30	88
Capacity	2	65	Cold Weather (5°C)	5	0.27	78
Capacity	3	80	Cold Weather (9°C)	9	0.19	57
Capacity	4	100	Cold Weather (8°C)	8	0.19	57
Regulation	0	0	-	25	0.01	3
Regulation	1	65	-	25	0.02	5

Test Plan	Test No.	H2 Blend Level (%)	Test Modifier Description	Ambient Temp. (°C)	Average Heat Recovered (mmBtu/hr)	Average Heat Recovered (kWt)
Regulation	2	75	-	26	0.01	4
Regulation	3	85	-	26	0.01	4
Regulation	4	100	-	23	0.04	12
Average					0.13	39

Table 8 | Thermal Load Displacement Tests Results

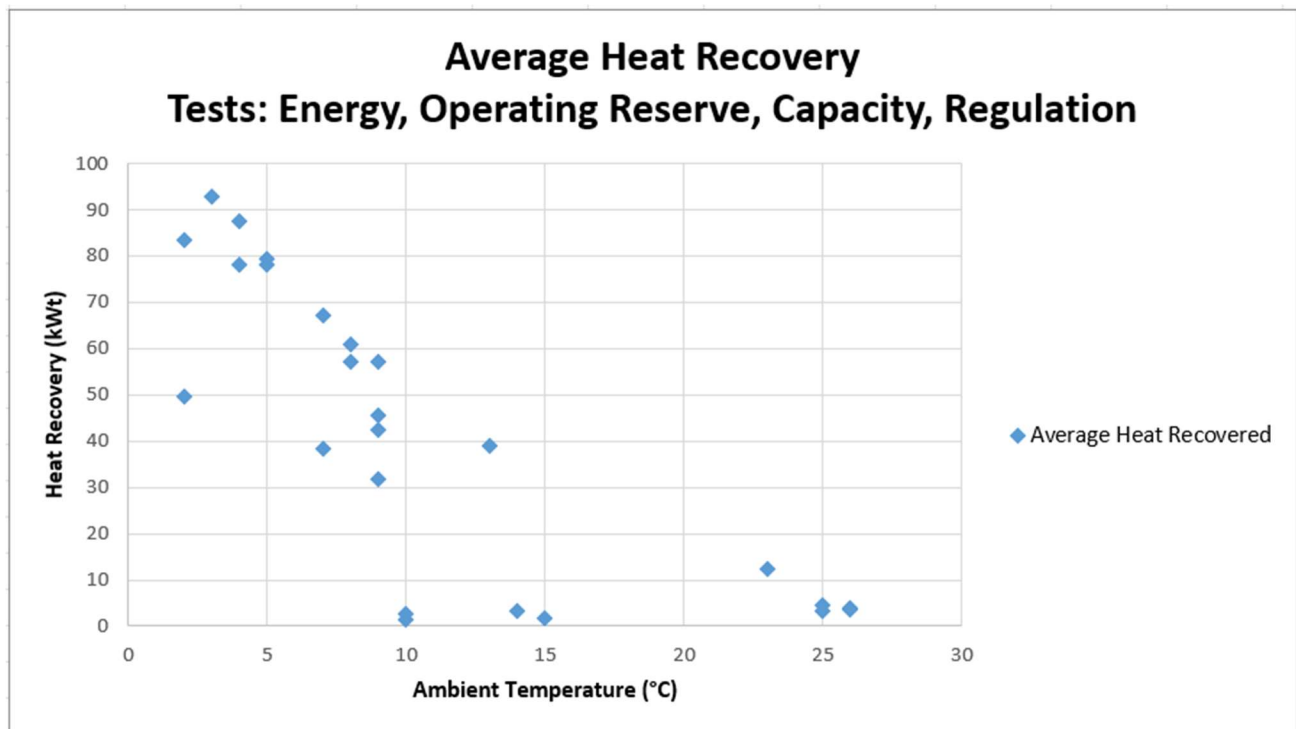


Figure 35 | Average Heat Recovery Tests: Energy, Operating Reserve, Capacity, Regulation

4.5 Operating Cycle Efficiencies

The electrical efficiency stays consistent across all the operating test at about 28% to 31% HHV.

The overall thermal efficiency is dependent on the ambient temperature (since it is used in the building heating system). The overall thermal efficiency varies from about 30% (with no heat recovery) to about 60% (with ambient temperature around 5°C).

See summary table and sample charts below. The ramping test cases skew the efficiency results and have been excluded from the summary.

Test Plan	Test No.	H2 Blend Level (%)	Test Modifier Description	Ambient Temp. (°C)	Average Electrical Efficiency (Electrical Load) / Fuel Input (%) HHV	Average CHP Efficiency (Elec. + Therm. Load) / Fuel Input (%) HHV
Energy	0	0	Low Operating Range (50% to 75% load)	9	28%	40%
Energy	00	0	High Operating Range (75% to 100% load)	9	30%	43%
Energy	1	Vary from 100 to 65 to 100	Minimum Continuous Load (50%)	2	26%	48%
Energy	2	Vary from 100 to 50 to 100	Maximum Continuous Load (100%)	3	30%	55%
Energy	3	65	Low Operating Range (50% to 75% load)	4	28%	59%
Energy	4	50	High Operating Range (75% to 100% load)	9	30%	43%
Energy	5	75	Low Operating Range (50% to 75% load)	7	27%	42%
Energy	6	75	High Operating Range (75% to 100% load)	14	29%	30%
Energy	7	100	Low Operating Range (50% to 75% load)	10	27%	27%
Energy	8	100	High Operating Range	15	28%	29%

Test Plan	Test No.	H2 Blend Level (%)	Test Modifier Description	Ambient Temp. (°C)	Average Electrical Efficiency (Electrical Load) / Fuel Input (%) HHV	Average CHP Efficiency (Elec. + Therm. Load) / Fuel Input (%) HHV
(75% to 100% load)						
Operating Reserve	0	0	0 kW to 105 kW	5	30%	54%
Operating Reserve	1	65	0 kW to 105 kW	7	30%	51%
Operating Reserve	2	75	0 kW to 105 kW	13	30%	42%
Operating Reserve	3	85	0 kW to 105 kW	10	30%	30%
Operating Reserve	4	100	0 kW to 105 kW	2	28%	53%
Capacity	0	0	Hot Weather (25°C)	25	30%	28%
Capacity	00	0	Cold Weather (8°C)	8	31%	47%
Capacity	1	50	Cold Weather (4°C)	4	31%	55%
Capacity	2	65	Cold Weather (5°C)	5	31%	52%
Capacity	3	80	Cold Weather (9°C)	9	30%	45%
Capacity	4	100	Cold Weather (8°C)	8	29%	44%
Regulation	0	0	-	25	28%	29%
Regulation	1	65	-	25	28%	30%
Regulation	2	75	-	26	28%	30%
Regulation	3	85	-	26	28%	29%
Regulation	4	100	-	23	28%	32%

Table 9 | Operating Cycle Efficiencies Tests Results

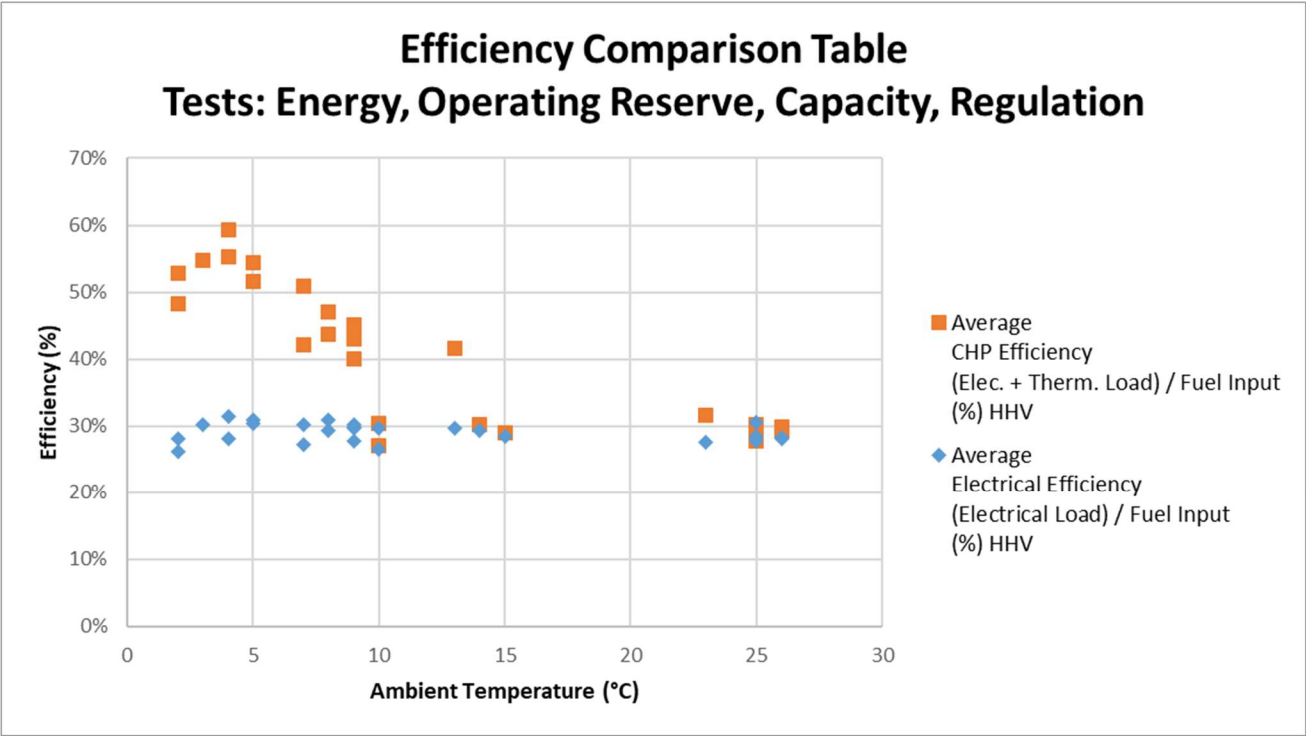


Figure 36 | Efficiency Comparison Table: Energy, Operating Reserve, Capacity, Regulation

4.6 Ramp Rates

Eight (8) ramp rate tests were conducted.

- Four (4) at cold weather (less than 15°C) and four (4) at hot weather (greater than 25°C).
- Of these tests, half were with 0% H2 blending and half were with 100% H2 blending
- Of these tests, half were starting from cold, and half were starting from hot.

The PLC would set an increasing target load at a pre-programmed ramp rate (0 – 100% load in 1 minute), and the engine would ramp up to meet that load.

On a cold-start, the engine would be brought from no load to 50% load, hold at 50% for about 5 minutes, then ramp to 100%.

On a hot-start, the engine would be brought from no load right up to 100% load.

At the end of each test the PLC would set a decreasing target load at a pre-programmed ramp-down rate, and the engine would ramp down to meet that load until the engine was at 50% load and then turn off.

Refer to charts below showing the ability of the engine to meet these ramp up rates.

As can be seen below, the engine follows the programmed ramp rate much better when operating with 0% H2 compared to operating with 100% H2. There does not appear to much change in the engine's ability to ramp up for hot weather vs cold weather.

4.6.1 Cold Weather Ramp Rates

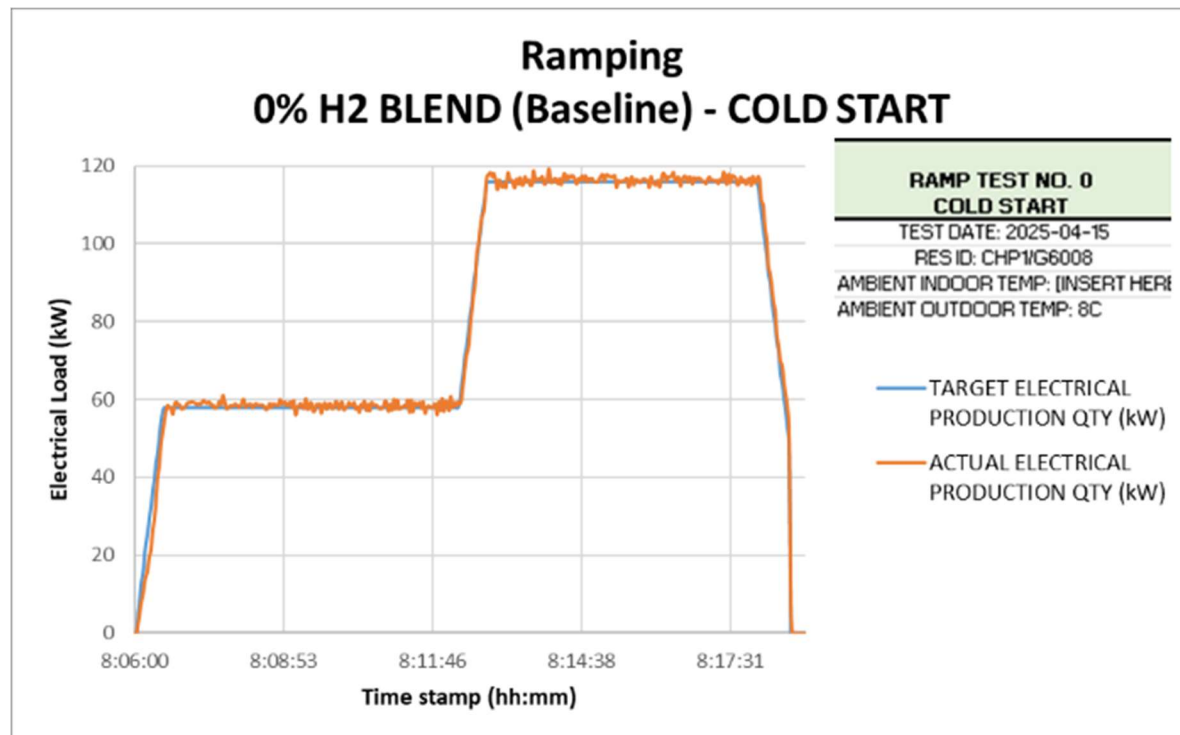


Figure 37 | Ramping – 0% H2 Blend (Baseline) Cold Start

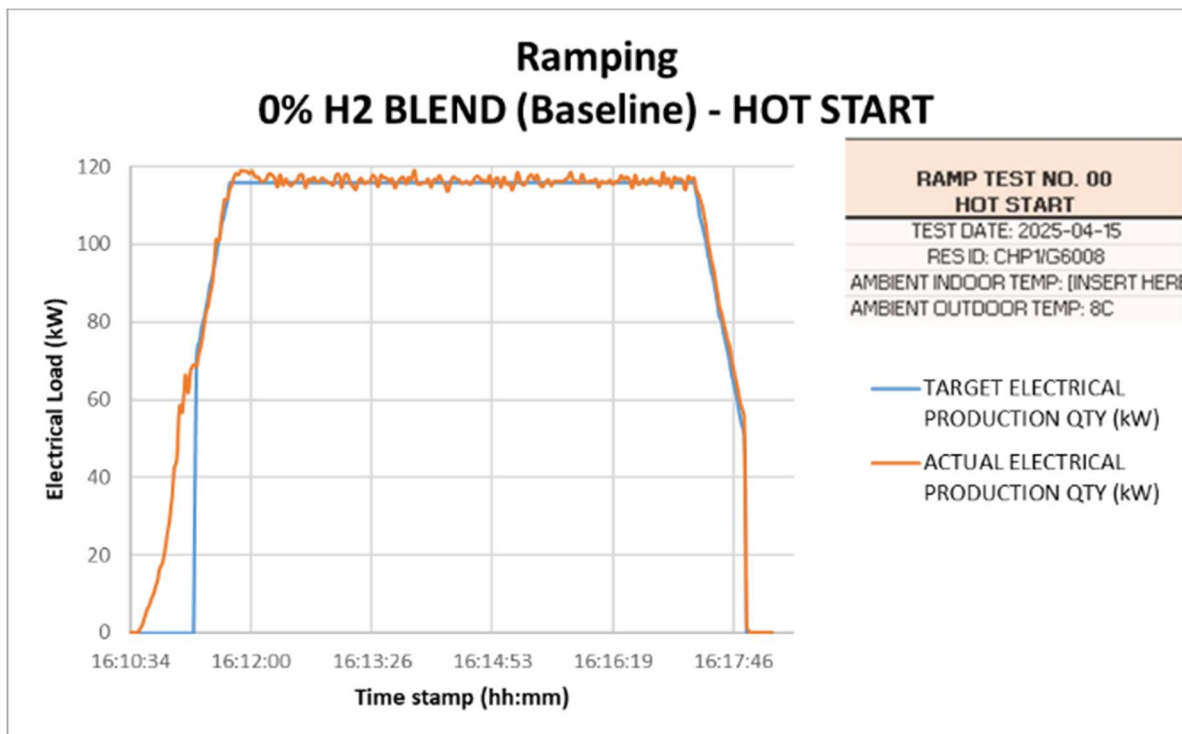


Figure 38 | Ramping – 0% H2 Blend (Baseline) Hot Start

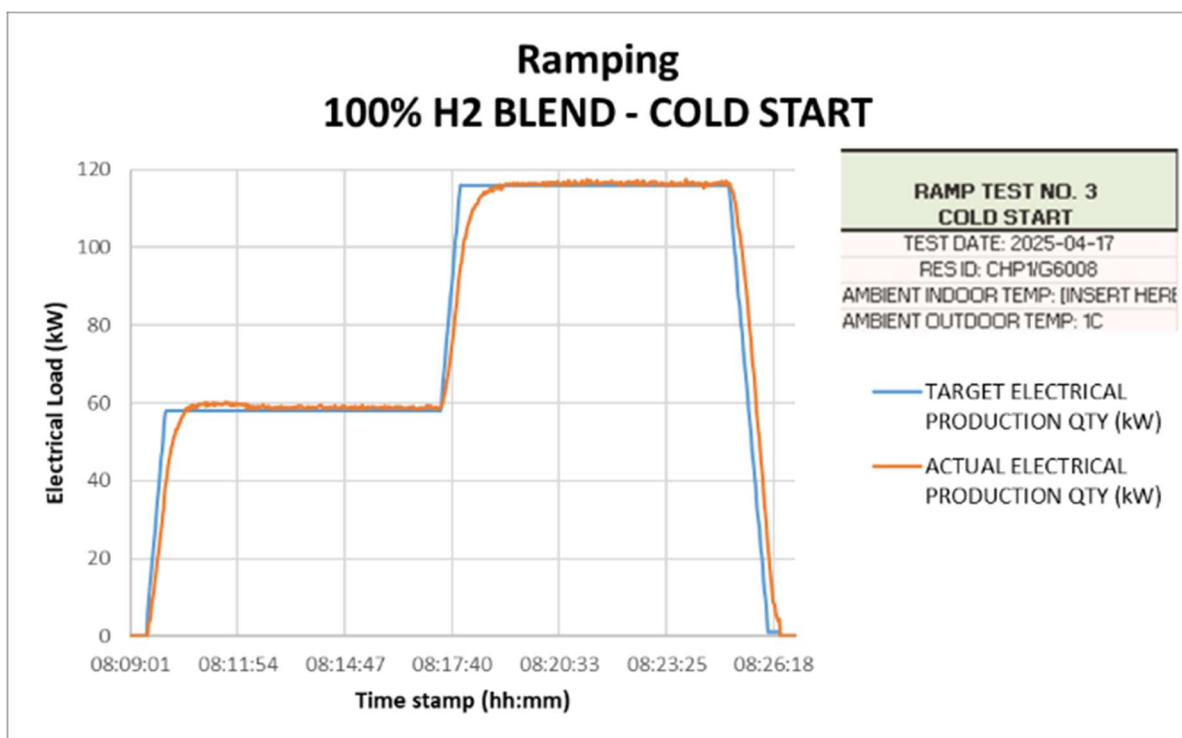


Figure 39 | Ramping – 100% H2 Blend – Cold Start

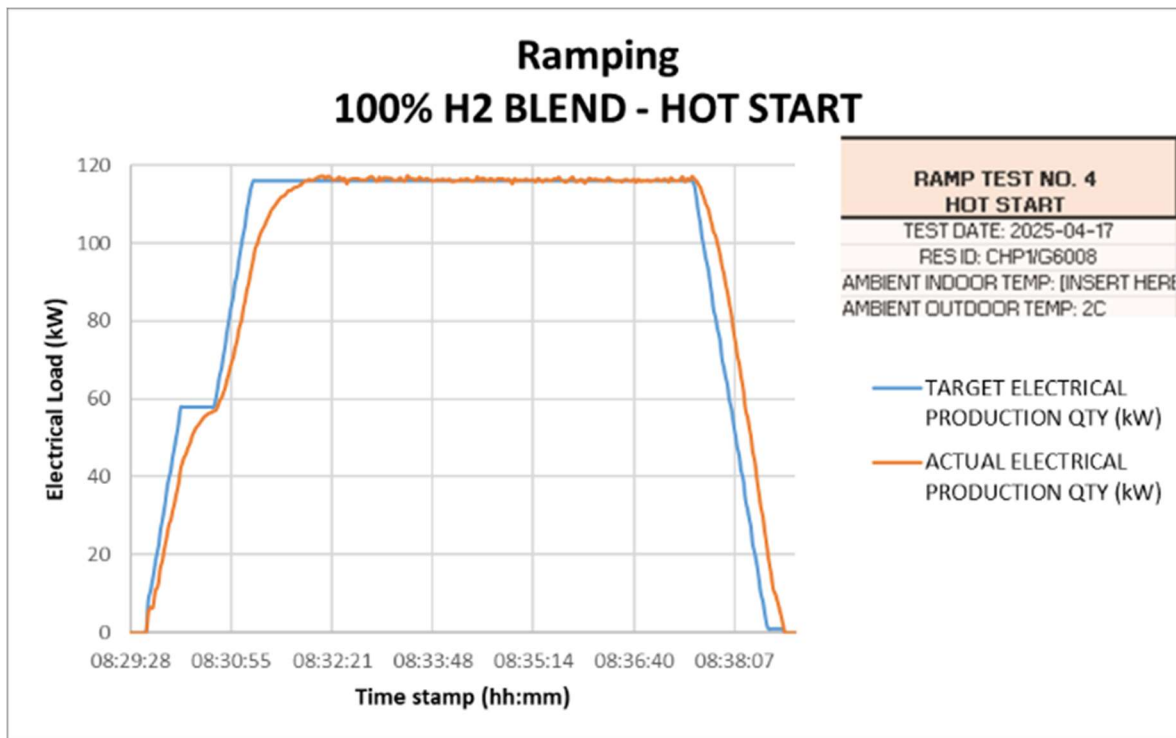


Figure 40 | Ramping – 100% H2 Blend – Hot Start

4.6.2 Hot Weather Ramp Rates

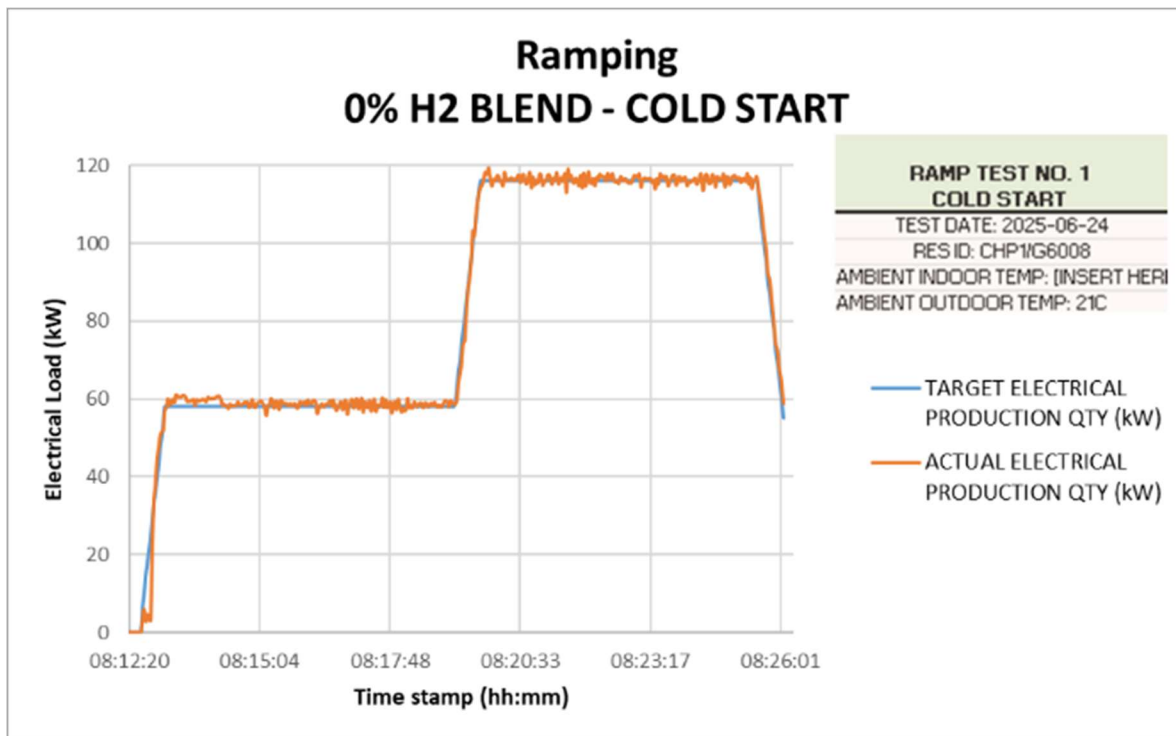


Figure 41 | Ramping – 0% H2 Blend – Cold Start

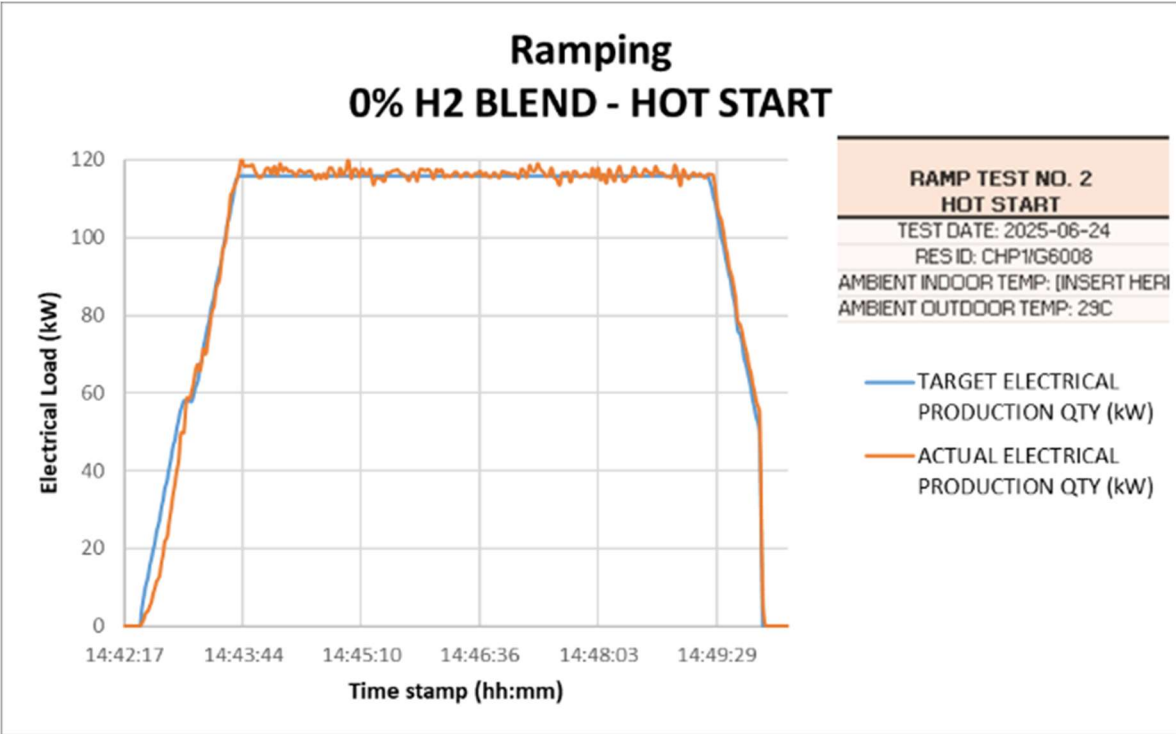


Figure 42 | Ramping – 0% H2 Blend – Hot Start

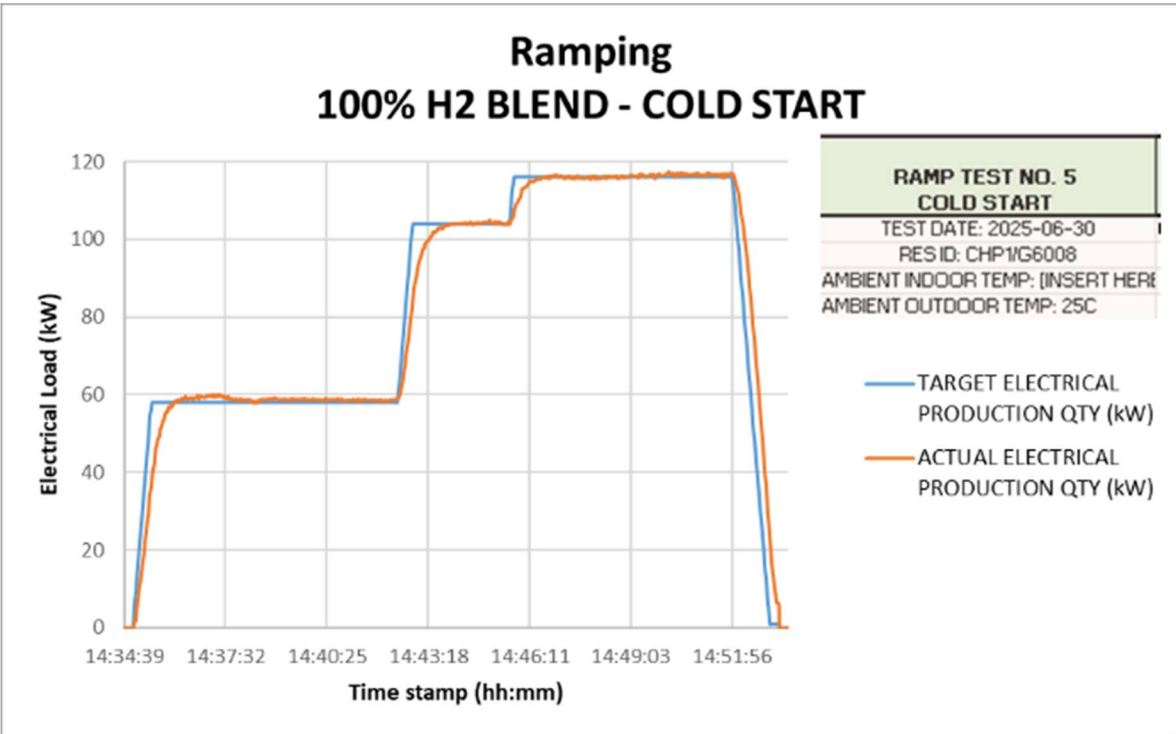


Figure 43 | Ramping – 100% H2 Blend – Cold Start

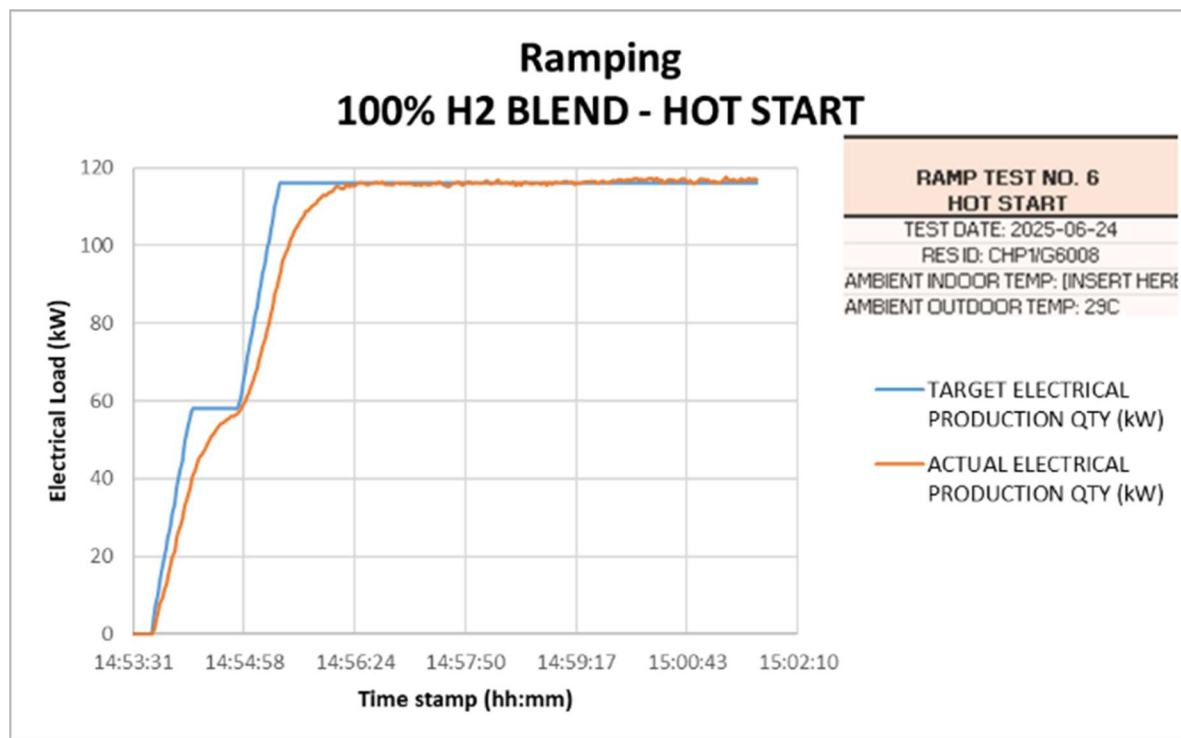


Figure 44 | Ramping – 100% H2 Blend – Hot Start

5. Discussion

While this project is small in scale, its implications are impressive. The system could consume approximately 78,000 kg of hydrogen annually, and the expected **GHG emissions reduction** when it's operating solely on hydrogen is approximately **133 tonnes of CO₂e**—that's roughly equivalent to removing 28 passenger vehicles off the road each year.

1. In the province of Ontario, alone, building heat is the second largest source of GHGs.
2. The hydrogen fuel is directly able to be burned in the engine directly replacing electrical and thermal energy otherwise generated by natural gas and/or other fossil fuels.
3. The project's aim is to run the system on 100% Enbridge Gas-supplied hydrogen within a year.
4. The engine was able to be dispatched and controlled similarly to other IESO connected generation assets. With a sufficient green hydrogen supply, the potential for natural gas emission reductions is significant as the technology is developed and scaled for larger engine powered generators.
5. CHP systems are extremely resilient as they operate independently of the main grid yet are complementary to it. They are also versatile and can be employed in a wide range of sizes, with demonstrated compatibility in different applications, fuel sources and technologies.

6. Economic/Technical Impact, and Risk Assessments

The hydrogen fueled CHP is a first-of-its-kind technology and was completed to demonstrate the technical feasibility and emission reduction potential of hydrogen fueled CHP. The project was not completed to demonstrate financial feasibility. As the technology develops and as the cost of hydrogen decreases (or cost of natural gas and carbon emissions increase), this technology will gain financial benefits.

Even though the financial return was not the intent of the project, a financial analysis was completed based on the final testing results. At today's hydrogen and natural gas market prices.

- The project does not generate any electrical savings when fueled with hydrogen.
- If the project ran on 100% natural gas, the annual cost savings would be about \$8,000/yr. Any fuel blend higher than 3% hydrogen results in negative annual savings.

A summary of the technical inputs and financial results are provided below. Refer to the life cycle cost analysis included in Appendix B for details.

6.1 Technical Inputs

Annual average CHP electrical output	116 kW
Maximum possible CHP thermal output	134 kW
Annual utilization of available CHP heat	54%
Full load fuel consumption for CHP	1.44 GJ/hr
Annual operating hours of the CHP	2,000 hrs ⁽¹⁾
Average efficiency of existing boilers	85% (HHV) ⁽²⁾
CO2 emission factor for natural gas	49 kg CO2/GJ
Heating value of natural gas	55 MJ/kg (HHV)
Annual blend	100% hydrogen fuel

Notes:

1 Based on 8 hrs/day, 5 days/week, 50 weeks/year

2 Assumed, not tested

6.2 Annual Technical Results

Annual total CHP electrical savings	232 MWh/yr
Annual total CHP thermal savings	521 GJ/yr
Annual total boiler natural gas savings	613 GJ/yr
Annual hydrogen consumption for CHP	2,877 GJ/yr (20,262 kg/yr)
Annual n. gas consumption for CHP	0 GJ/yr
Annual CO2 emission reduction	30,000 kg CO2/yr

6.3 Financial Inputs

Cost of purchased electricity	0.14 \$/kWh
Cost of natural gas	6.53 \$/GJ (\$0.25/Nm3)
Cost of hydrogen fuel	99 \$/GJ (\$14/kg)
Cost of maintenance reserve	0.02 \$/kWh (of generated power)
Total capital cost of project	\$3,574,960
Total grant funds	\$1,787,480

6.4 Financial Results

Annual electrical cost savings	\$33,000/yr
Annual boiler natural gas savings	\$4,000/yr
Annual carbon tax savings (on fuel)	\$2,000/yr
Annual cost of CHP hydrogen fuel	-\$284,000/yr
Annual cost of CHP natural gas fuel	-\$0/yr
Annual cost for CHP maintenance	-\$5,000/yr
Gross annual cost savings	-\$249,000/yr
Simple payback (before tax and escalation)	none
Actual payback (after tax and escalation)	none

7. Conclusion and Recommendations

The CHP system is operating as intended with 100% hydrogen and with various blends of natural gas. The electrical and heat recovery quantities are well in line with the estimated baseline energy savings.

While there were some project delays and challenges, the demonstration project has been able to achieve its goals.

The HIF tests consistently showed an engine operating efficiency lower than the rated values (see Table 6). Additional performance testing and metering verification could help identify why the engine is not meeting the rated performance metrics. In order to confirm the fuel consumption value, and/or improve the specific fuel consumption, efficiency testing could be done including fuel meter calibration and fuel composition verification. Discussions and potential re-tuning of the engine with the manufacturer could also help reduce the specific fuel consumption.

It is recommended to continue with measurement and verification of this project to complete the annual energy savings calculation. It's beneficial to continue to track the performance of the system in the long term and evaluate its capability to continue to respond to load swings and varying operational conditions.

Moving beyond the pilot and demonstration aspect of the project, developing larger and more effective H₂ fueled CHP projects looks technically feasible. With the right motivation and/or fuel market, similar projects could generate financial savings along with the environment benefits.

8. Lessons Learned

8.1 Engine Knock

Observation: Knock events were observed early in testing and again during the final days, flagged by 2G and resolved swiftly.

Root Cause:

- Load bank was not tied in through current transformers (CTs), affecting proper load detection (first instance).
- Knock sensor settings were not saved after replacement (second instance).

Resolution:

- Correct CT wiring to the load bank.
- Ensured proper sensor configuration and saved settings. Post-correction, the issue did not reoccur.

8.2 Engine Trips During Grid Events

Observation: A couple of trips occurred during warm weather testing. Sync issues were not directly observed but may have contributed.

Notable Instance:

- June 23rd – Reg Test #4: A grid blip caused protection relays to shut the engine down. The H2 plant tripped concurrently.

Root Cause:

- Likely caused by slight deviations in grid frequency or voltage, as mentioned during the CHP tour by the hydrogen systems operator.

Resolution:

- Confirmed functionality and settings are as required per Alectra and Hydro One and demonstrate the system is working as intended.

8.3 Power Reduction Due to High Exhaust Temperature

Observation: A couple of documented power reduction events occurred, not flagged by Enbridge but noted during capacity testing.

Notable Instance:

- June 24th – Capacity Test #0: High exhaust temperatures during natural gas operation led to power limitation.

Root Cause:

- Rich fuel mixture caused higher combustion temperatures.
- High differential in cooling water temperature further limited performance.

Resolution:

- Adjusted air/fuel parameters to reduce richness.
- Fine-tuned cooling system valve settings to improve response time and thermal regulation.

8.4 Natural Gas Regulator Failure

Observation: When commencing the natural gas testing, a high odor of gas was detected, and the system was shut down to investigate, finding a ruptured gas regulator.

Notable Instance:

- April 8th – Ramping Test 0: Ruptured regulator halted natural gas testing, hydrogen tests were rescheduled to keep testing going until the repair was completed on the natural gas system.

Root Cause:

- Uncertain, the system had no issues during TSSA testing and this was likely caused by diaphragm embrittlement during prolonged inactivity, leading to rupture when re-pressurized.

Recommendation:

- Prior to recommissioning either (natural gas or hydrogen) fuel system after long periods of inactivity, pressure test supply infrastructure to confirm integrity.

9. Next Steps

Next steps for this project include:

- Consider efficiency testing and engine re-tuning to validate and/or improve the operating efficiencies.
- Continue operating and maintaining the equipment. When operating on natural gas, the CHP system is able to generate financial savings with a good CHP efficiency during cold (<5°C weather). When operating on blends of hydrogen, the CHP system generates additional environmental benefits by displacing carbon equivalent emissions.
- Continue the M&V to verify seasonal efficiency and operating parameters.
- With the demonstration project validating this technology implementation, the next steps for the hydrogen fueled CHP market is to:
- Continue to scale up the project size and technology implementation
- Continue developing the hydrogen generation technologies to reduce the cost to make hydrogen.

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