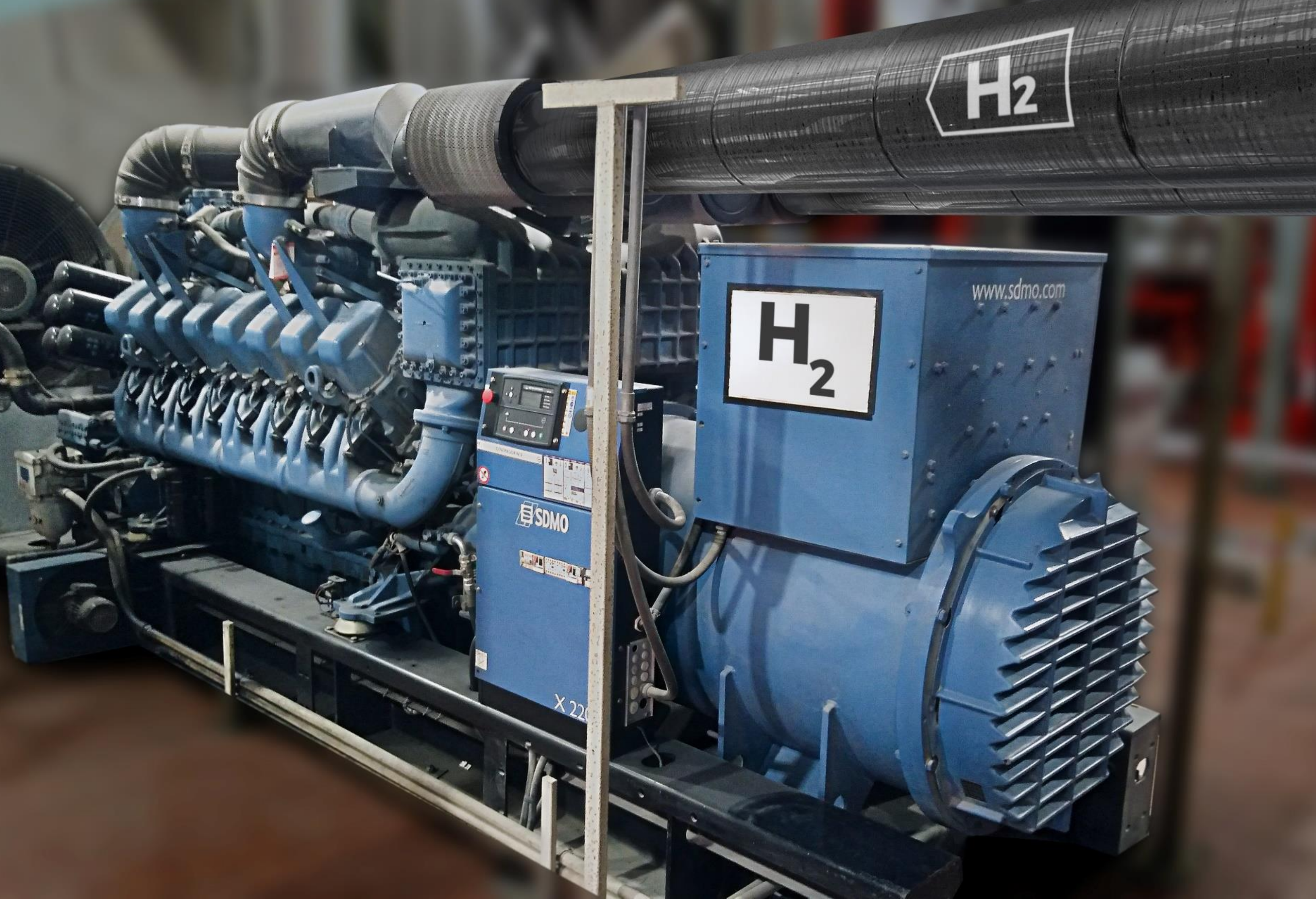

Hydrogen internal combustion engine dual fuel assessment

MTU 16V4000G23 - Peak Power Plant Generator

16 September, 2021

Programa de Energías Renovables y Eficiencia Energética en Chile

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Santiago, Chile; 16 of September, 2021

Contents

Acronyms and abbreviations

BMEP	Brake Mean Effective Pressure
CAN	Controller Area Network
CO_2	Carbon dioxide
ECU	Engine Control Unit
IP	Industrial Property
NO_x	Nitrogen oxides
OE	Original Equipment
OEM	Original Equipment Manufacturer
PID	Proportional, Integral and Derivative

1. Background

Peak Power Plants are small power plants generally fueled by diesel that run only when there is a high electricity demand. They bypass the conventional transmission system to deliver power directly to local distribution networks.

This study, commissioned by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) within the framework of its project "Decarbonisation of the Energy Sector in Chile", covers the estimation of hydrogen usage, diesel displacement, and CO_2 emissions savings for the conversion of an electric generator powered by the MTU G23 diesel engine to diesel-hydrogen combustion currently supplying electricity for one of the Cristalerías Chile factories. For this conversion, it was considered the MTU 16V4000G23 version as the most suitable of the engines that have been identified in the initial discussions. Further into the future, it may be possible to work with MTU directly and co-develop a dual-fuel application for much better hydrogen displacement figures. The problem with this approach is the timescales –several years of co-development are expected before the engine would be available.

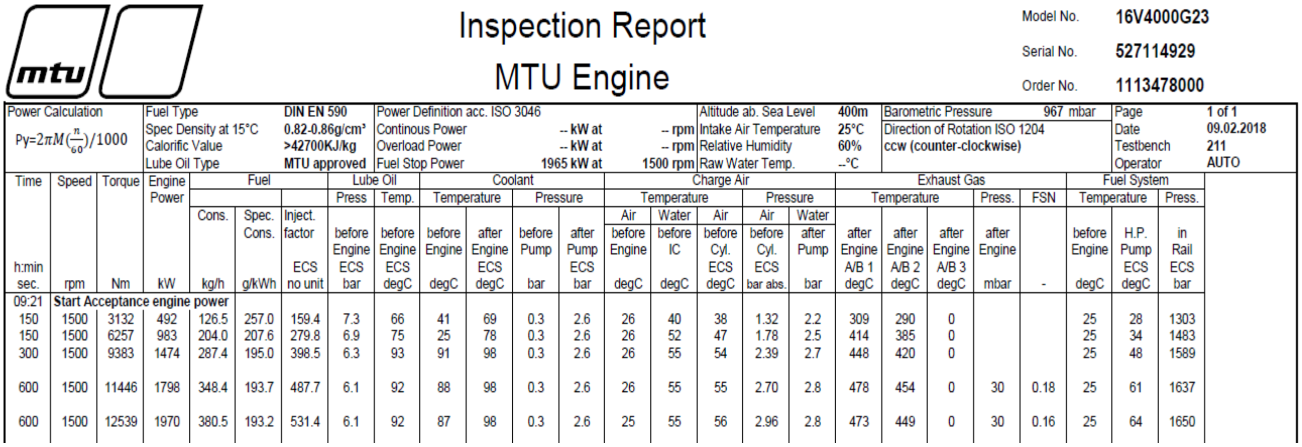
There is no information of anyone else doing dual fuel co-combustion on high speed diesel engines. However, an alternative approach could be to speak with the joint-venture company BeHydro about the latest dual fuel medium speed engine, if a medium speed engine solution is suitable.

2. Baseline data

All the assessment calculations were based on the data provided by the Chilean team, that was processed and compared to previous results from different engines converted by CMB.TECH.

2.1. BMEP

The inspection report information was used for the calculation of the MTU engine BMEP (Brake Mean Effective Pressure), an engine efficiency indicator chosen for this study comparisons.



Inspection Report
MTU Engine

Model No. 16V4000G23
Serial No. 527114929
Order No. 1113478000

Power Calculation	Fuel Type	DIN EN 590	Power Definition acc. ISO 3046			Altitude ab. Sea Level	400m	Barometric Pressure	967 mbar	Page	1 of 1
$Py=2\pi M(\frac{n}{60})/1000$	Spec Density at 15°C	0.82-0.86g/cm^3	Continous Power	-- kW at	-- rpm	Intake Air Temperature	25°C	Direction of Rotation ISO 1204		Date	09.02.2018
	Calorific Value	>42700KJ/kg	Overload Power	-- kW at	-- rpm	Relative Humidity	60%	ccw (counter-clockwise)		Testbench	211
	Lube Oil Type	MTU approved	Fuel Stop Power	1965 kW at	1500 rpm	Raw Water Temp.	--°C			Operator	AUTO

Time	Speed	Torque	Engine Power	Fuel			Lube Oil		Coolant				Charge Air					Exhaust Gas					Fuel System		
							Press	Temp.	Temperature		Pressure		Temperature			Pressure		Temperature			Press.	FSN	Temperature		Press.
				Cons.	Spec. Cons.	Inject. factor ECS	before Engine ECS	before Engine ECS	before Engine	after Engine ECS	before Pump	after Pump ECS	Air before Engine	Water before IC	Air before Cyl. ECS	Air before Cyl. ECS	Water after Pump	after Engine A/B 1	after Engine A/B 2	after Engine A/B 3	after Engine		before Engine	H.P. Pump ECS	in Rail ECS
h:min sec.	rpm	Nm	kW	kg/h	g/kWh	no unit	bar	degC	degC	degC	bar	bar	degC	degC	degC	bar abs.	bar	degC	degC	degC	mbar	-	degC	degC	bar
09:21	**Start Acceptance engine power**																								
150	1500	3132	492	126.5	257.0	159.4	7.3	66	41	69	0.3	2.6	26	40	38	1.32	2.2	309	290	0			25	28	1303
150	1500	6257	983	204.0	207.6	279.8	6.9	75	25	78	0.3	2.6	26	52	47	1.78	2.5	414	385	0			25	34	1483
300	1500	9383	1474	287.4	195.0	398.5	6.3	93	91	98	0.3	2.6	26	55	54	2.39	2.7	448	420	0			25	48	1589
600	1500	11446	1798	348.4	193.7	487.7	6.1	92	88	98	0.3	2.6	26	55	55	2.70	2.8	478	454	0	30	0.18	25	61	1637
600	1500	12539	1970	380.5	193.2	531.4	6.1	92	87	98	0.3	2.6	25	55	56	2.96	2.8	473	449	0	30	0.16	25	64	1650

Figure 1. Inspection report for MTU 16V4000G23 Engine

Table 1. Calculated BMEP from extracted data of MTU Engine parameters

Power Factor (%)	Torque (Nm)	Power (kW)	Diesel Consumption (kg/h)	BMEP (Bar)
25	3132	492	126.5	**5.16**
50	6257	983	204	**10.31**
75	9383	1474	287.4	**15.45**
100	12539	1970	380.5	**20.65**

The BMEP figures give means to an estimation of the MTU engine performance running in dual-fuel, based on the database collected by CMB.TECH along the years from other engines and applications.

2.2. Dual-Fuel conversion methods

There are two methods of conversion to enable an existing diesel engine to run in dual-fuel (Diesel-Hydrogen). What differs the two apart is the level of integration available from the OE (Original Equipment) engine management system. Neither of these two conversions involve internal modifications to the engine. They all add hydrogen into the air intake path via modification of some parts of the air intake, and that is controlled with a hydrogen ECU (Engine Control Unit)[1].

The first method is called **"Supervisory"**. This method requires minimum integration to the OE system and less engine calibration time. It works basically by monitoring key variables of the engine operation to deliver the correct amount of hydrogen. The benefit of its simplicity has a cost in terms of reduced diesel displacement numbers. The dual-fuel combustion delivers its full potential once the combustion is tuned for the dual fuel combustion via parameters like diesel injection timing, quantities, injection pressures etc. When operating on supervisory mode, all the combustion parameters remain at the original diesel-optimized values, this results in lower levels of diesel substitution.

The second method is called **"Full-Control"**. As the name implies, in this method not only the hydrogen but also the diesel delivery system needs to be calibrated by CMB.TECH's team. It demands a high level of integration to the OE system and more extensive calibration work. However, with both systems optimized the diesel substitution figures are substantially higher.

Both conversion options are covered by this study.

2.3. Daily usage

Daily usage was also calculated to estimate values for hydrogen supply, diesel, and CO_2 emissions savings for this particular application.

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[1] There is no power loss or change to the technical specification of the engine associated with the dual - fuel conversion.

The daily usage was based on the kW per hours plot provided, from 15 June 2021.

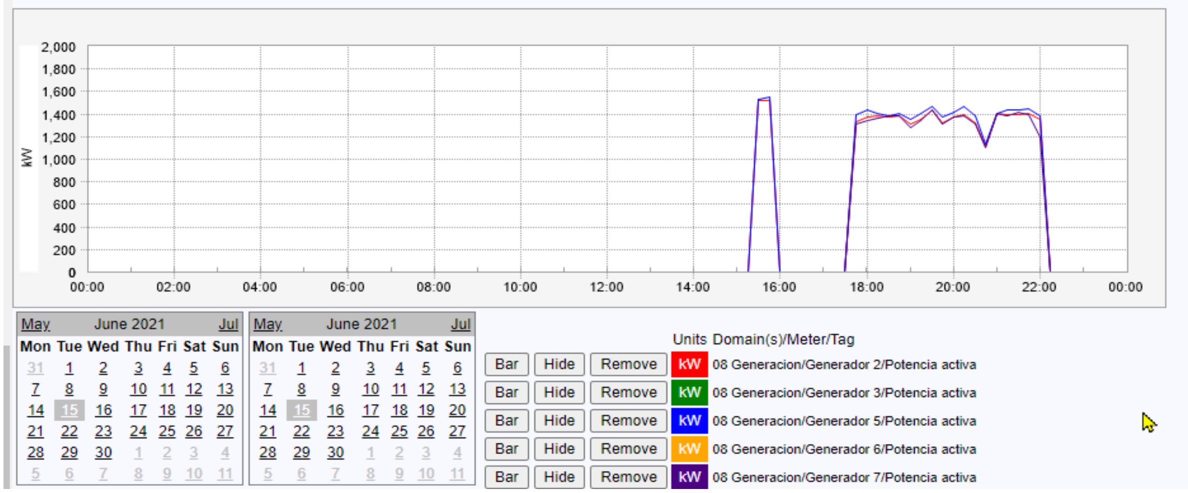

Figure 2. Engine running hours on June 15th, 2021

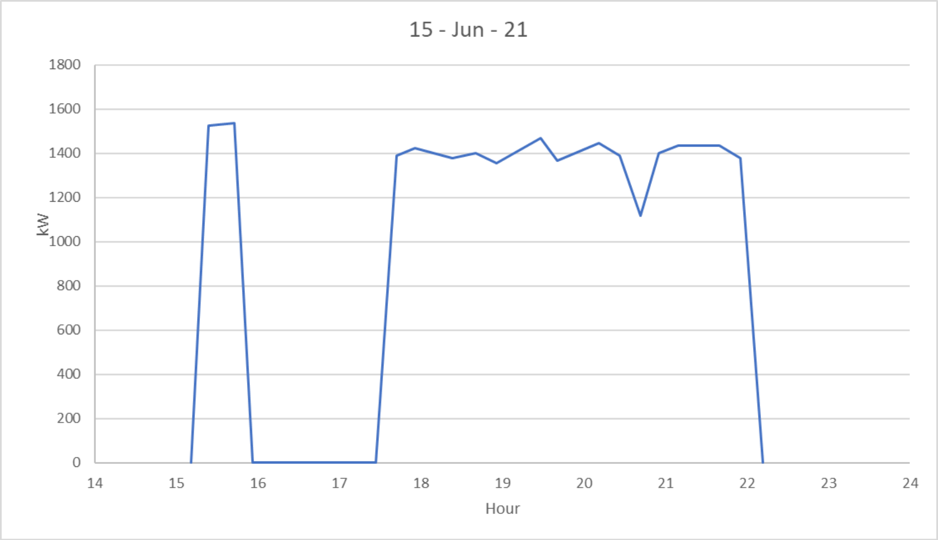

Figure 3. Power used per hour on June 15th, 2021

Table 2. Calculated average daily power and usage.

Average daily usage (h)	Average daily power (kW)
0.31	1531
4.22	1385

3. Supervisory method estimations

For the dual fuel co-combustion system, the hydrogen is supplied at 6-10 bar absolute, typically at a maximum of about 45°C, to the hydrogen injection system in the air intake. The purity of hydrogen is typically >99.95%, although such purity is not required by the engine, it is just what is commercially available in the UK. It is estimated that a purity of >98% would be required, depending on the constituents that make up the remaining 2%. For example, if the remaining 2% consisted of nitrogen, water, or carbon dioxide, there would be no measurable effect. If it contained for example carbon monoxide or methane, then they would add to the combustion process and release slightly more energy than the previously mentioned inert components but would be unlikely to change any of the emissions to a measurable extent.

The hydrogen injection quantities are controlled based on CAN messages read over the J1939 CAN bus communication available on this engine. Typically, these include engine speed, engine load, air temperature, boost/air pressure, fuel flow rate, and a range of other parameters that can be useful in reducing the additional hardware needed. There is no change to the OEM diesel-only calibration, or any change in the power capability of the engine, nor any real change in overall efficiency.

The diesel substitution level presents a strong correlation to BMEP values for hydrogen diesel co-combustion. With this knowledge, the MTU engine BMEP values were compared to results from other engines running on the **supervisory** method to obtain the estimated substitution values. Those percentages were used for the further calculations below.

Table 3. Estimated diesel substitution values on supervisory method.

Power Factor (%)	Torque (Nm)	Power (kW)	BMEP (Bar)	Diesel Consumption (kg/h)	Substitution (%)	Diesel Displaced (kg/h)	Hydrogen Equivalent (kg/h)	Hydrogen Loss (%)[2]	Hydrogen Total (kg/h)	CO_2 Savings (kg/h)
25	3132	492	5.16	126.5	**45.47**	57.52	20.42	5	21.44	180.68
50	6257	983	10.31	204.0	**17.33**	35.35	12.55	2	12.80	111.05
75	9383	1474	15.45	287.4	**14.89**	42.79	15.19	2.3	15.54	134.42
100	12539	1970	20.65	380.5	**9.80**	37.29	13.24	2.4	13.56	117.13

The hydrogen injection system is calibrated to always deliver the maximum displacement of diesel over the whole operating range of the enigne. At high loads, the displacement of diesel is limited by combustion knock, so a safe margin with temperature compensations is provided to ensure that knocking combustion never occur during use. At light loads, the OEM engine speed controller (known as a PID-controller as it has Proportional, Integral and Derivative components) limits the displacement. This is because the engine speed controller (the PID controller) cannot account for the change in torque produced by the hydrogen, and the control starts to become unstable if too much hydrogen is used. Given those limits, it can be estimate the hydrogen usage for any load profile.

Applying the results to the daily usage:

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[2] The hydrogen losses are the portion of the gas that is expelled through the exhaust pipes unburned. The values are also proportional to real measurements in similar applications.

Table 4. Average daily results for estimated hydrogen used on supervisory method.

Average Daily Usage (h)	Average Daily Power (h)	Diesel Cons (kg/h)	Diesel Daily Cons (kg)	Average Substitution (%)	Average Diesel Displaced (kg)	Hydrogen Equivalent (kg/h)	Hydrogen Loss (%)	Hydrogen Total (kg)	CO_2 Savings (kg)
0.31	1531	300.73	93.23	14.2	13.20	4.69	2.31	4.79	41.46
4.22	1392	273.47	1154.05	15.3	176.45	62.64	2.25	64.05	554.23

Table 5. Total daily usage on supervisory method

Total daily usage	
Diesel displacement (kg/day)	**189.66**
Hydrogen consumption (kg/day)	**68.85**
CO_2 Saving (kg/day)	**591.84**

4. Full-Control method estimations

The **full-control** system uses the same hydrogen injection system, with the same requirements for hydrogen delivery. The only change is the level of integration needed in order to optimize the dual fuel combustion. A range of diesel injection parameters, which would normally affect the diesel-only operation, have to be optimized. In this case, there is a new calibration required on the OEM ECU and a means of changing between diesel-only and dual fuel modes for optimized combustion in each mode. Again, there is no change in the power capability of the engine in either mode, but it is sometimes possible to bias slightly lower efficiency for better NO_x emissions in dual fuel mode.

As per the supervisory system, the BMEP values from the MTU engine were compared to the results from other applications using the **full-control** method. Presenting the following results:

Table 6. Estimated diesel substitution values on full-control method.

Power Factor (%)	Torque (Nm)	Power (kW)	BMEP (Bar)	Diesel Consumption (kg/h)	Diesel Substitution (%)	Diesel Displaced (kg/h)	Hydrogen Equivalent (kg/h)	Hydrogen Loss (%)	Hydrogen Total (kg/h)	CO_2 Savings (kg/h)
25	3132	492	5.158	126.5	**61.83**	78.22	27.77	5	29.16	245.70
50	6257	983	10.31	204	**51.58**	105.22	37.35	2	38.10	330.52
75	9383	1474	15.45	287.4	**34.41**	98.90	35.11	2.3	35.92	310.67
100	12539	1970	20.65	380.5	**23.26**	88.50	31.42	2.4	32.17	278.01

Applying the results to the daily usage:

Table 7. Average daily results for estimated hydrogen used on full-control method

Average Daily Usage (h)	Average Daily Power (h)	Diesel Cons (kg/h)	Diesel Daily Cons (kg)	Average Substitution (%)	Average Diesel Displaced (kg)	Hydrogen Equivalent (kg/h)	Hydrogen Loss (%)	Hydrogen Total (kg)	CO_2 Savings (kg)
0.31	1531	300.7	93.23	32.81	30.59	10.86	2.31	11.11	96.09
4.22	1392	273.5	1154.05	37.28	430.20	152.72	2.25	156.16	1351.34

Table 8. Total daily usage on full-control method

Summary of daily usage	
Diesel displacement (kg/day)	**460.79**
Hydrogen consumption (kg/day)	**167.27**
CO_2 saving (kg/day)	**1447.43**

5. Nitrogen oxides (NO_x) emissions in Dual-Fuel

5.1. NO_x formation

The NO_x is produced during fuel combustion by the reaction of nitrogen and oxygen. The main contributor to NO_x emissions is the thermal formation pathway. Higher flame temperatures lead to higher NO_x formation. Several variables can influence the combustion temperature on an internal combustion engine, a fact that makes NO_x emissions estimations (like the previous CO_2 savings estimations) impractical on many occasions.

5.2. Dual-Fuel NO_x emissions example

Since an engine's specific calculated prediction is impractical, the following data is from a previous engine converted by CMB.TECH running in Full-Control mode, as an example of the technology capability. Depending on engine load, up to 68.5% reduction could be achieved running at 1500 rpm.

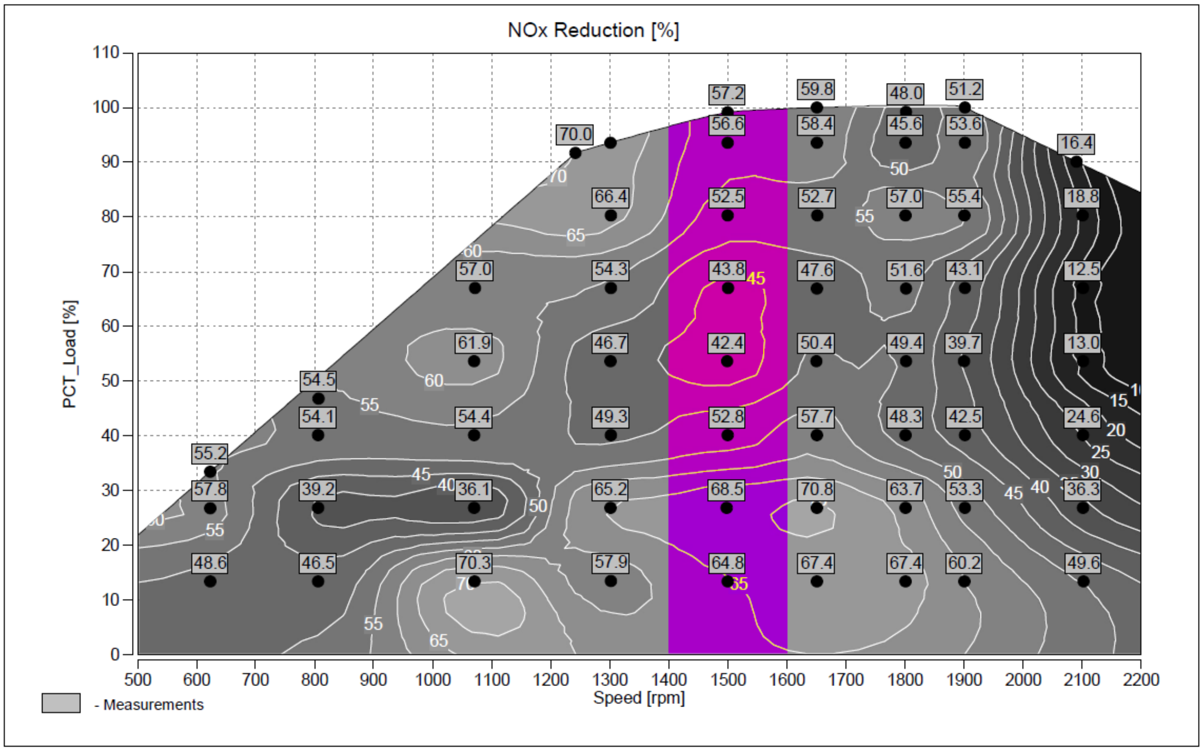

Figure 4. NO_x reduction percentage by varying speed with Full-Control Mode.

For the supervisory method, no changes in NO_x emissions are expected. The fact that the diesel injection parameters are not optimized may, at some points, lead to higher NO_x emissions. In this case, the hydrogen quantity is limited in the calibration to an amount that matches the NO_x emissions to the original diesel-only concentrations.

6. Conversion process

6.1. Supervisory convertion (High-level estimated: Time 4-6months/Cost £150.000)

System integration

Covers the connection between the MTU engine Original Equipment (OE) Engine Control Unit (ECU) and CMB's hydrogen Engine Control Unit, which is usually done via a Controller Area Network (CAN) bus. The hydrogen ECU is added to the original network to monitor the engine operating parameters. The information of what extent of data the OE ECU makes available over the network is required for this step.

Hydrogen delivery system engineering

Development of the hardware that delivers the hydrogen gas to the engine. It requires detailed information from the engine air charge system (information that can be acquired by reverse engineering physical parts). This reverse engineering is accounted for in the estimated costs, and a more detailed cost analysis would accompany a formal quotation with associated detailed delivery specifications etc. As no details of the engine (CAD/drawings, etc) were received, it was not possible to say which parts are to be dismantled. It would be necessary to see the CAD/drawings or the engine to determine how the hydrogen injection system could be adapted. It is not possible to determine how long this would take (weeks/months) until it is known what is being changed.

The intake geometry dictates the optimum injection points. Once the injection configuration is agreed, the supporting hardware can be engineered. Following is an example (still commercially sensitive, so no better image is available) of the product of this phase:

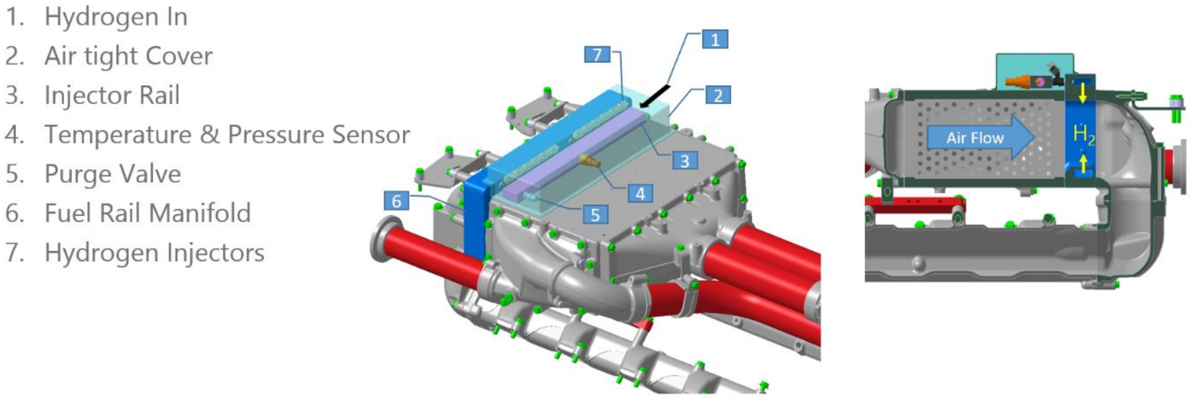

Figure 5. Example of an engine injection points.

Electrical harness engineering

The hydrogen injection system electrical wiring harness requires integration with the original engine harness. Detailed wiring diagrams from the engine are required to safely integrate the hydrogen system.

Engine calibration

This process will define the amount of hydrogen to be injected into the engine based on its operation points. It requires means of applying load to the engine to visit all speeds and loads that the engine will operate. As stated previously, the hydrogen injection is changed to suit the engine operation which is read from the various CAN J1939 messages.

Final testing

After the engine calibration work is done, a period of supervised running is required to make sure no problems will arise from extended periods of operation. After this phase, the engine is ready to be deployed for duty. For the supervisory system, the calibration is expected to take 2-4 weeks of operational testing, depending on usage profile and hydrogen availably.

Timing

The duration of this conversion is expected to be between four and six months. The main long-lead times, in CMB.TECH's experience, are the time taken to develop the hydrogen injection system on the engine – CAD package of components usually takes a long time. Once the CAD design has been agreed, rapid prototype parts confirm the package study. Wiring integration can also prove to be a timing challenge.

With the supervisory system, the calibration phase is expected to be completed on-site, testing the hydrogen displacement during the daily duty cycle. Therefore, multiple calibration trips to the site should be considered, alongside multiple trips for CAD/packaging confirmation and wiring integration.

6.2. Full Control convertion (High-level estimated: Time 12-18 months/Cost £1.5 million)

Converting the engine to full control mode requires the same hydrogen supply constraints and also requires the same steps identified for the supervisory system. The level of complexity, however, changes substantially for the "System Integration" and "Engine Calibration" phases.

For this type of conversion, CMB.TECH's team will require access to IP-sensitive information regarding the OE engine management software and calibration. The integration needs to go deep into the engine control software, and in some cases, software changes from the OE side are also necessary. That fact makes the engine manufacturer support essential to the project.

The engine calibration work complexity increases since major aspects of the diesel injection require modification for the diesel-hydrogen combustion optimization. The extent of these calibration changes typically requires that the engine to be at an engine test facility, on a test cell equipped with a dynamometer, and with extensive data recording peripherals. The shipping costs associated with such a requirement are not considered here.

Alternatively, in this case, if an engine can be scheduled to be “on-test” in a load sharing mode with another generator, it could be possible to complete this work on-site. However, this will result in a significantly longer timescale for the conversion work owing to the avialabiliy of the engine, the grid load, the hydrogen supply and emissions equipment (PEMS or equivalent) etc. Another factor which typically causes delays in the calibration process is the necessity to have the cooperation of the OEM and their commitment to deliver their changes as necessary in a timely manner.

Timing

The extended timing and increased cost for this conversion reflects the depth of integration needed between the OEM ECU and the hydrogen system, and the need for this to be done on a dyno test bench. Getting OEM approval can prove a lengthy task, and running large engines on a testbed is a lengthy and costly process.

7. Conclusions

The system is designed to use as much hydrogen as possible, and as efficiently as possible. Looking at the displacements for both modes, it would be better to use two engines at half load rather than one engine at full load, if hydrogen consumption and CO_2 savings are the goal.

It is outside the scope of this work to establish the hydrogen commercial supply and costings and project in the medium term what usage could be achieved. The calibration will be optimised to suit various conditions of temperate and pressure in the hydrogen supply, and that is what can take quite some time during the calibration process.

Operating in **supervisory** mode a single engine would require an estimated daily supply of 70*kg of hydrogen*, displacing around *190kg of diesel* fuel and saving over *590kg of* CO_2 emissions, per day. That translates on an average of *14.73%* less CO_2 emissions and diesel usage. The expected NO_x emissions would be the same as normal diesel operation.

Running in **full-control** mode a single engine would require an estimated daily supply *of 170kg of hydrogen*, displacing around *460kg of diesel* fuel and saving *1450kg of* CO_2 emissions, per day. That translates on an average of *35.05%* less CO_2 emissions and diesel usage. This conversion method also has the potential for NO_x emissions savings.

It is recommended to convert the MTU 16V4000G23 engine to the dual fuel supervisory system as previous experience has shown that hydrogen supply in the quantities needed is a big issue in using hydrogen as a fuel. It is also generally easier to do the supervisory system as there is no interaction with the OEM ECU and calibration, which simplifies the task greatly. Therefore, as a low-risk initial pilot conversion, the supervisory system offers the cheapest way to test out the dual fuel operation without impacting on the OEM calibration, and is a simple task to remove if there are operational issues with the hydrogen system.

Further, it is simpler, once the supervisory system is installed, to extend the project to the full control solution with the help of the OEM. It is suggested, if the conversion of the first engine to supervisory system is successful, to convert a second engine and operate the engines in more of a load-sharing capacity to increase the overall consumption of hydrogen - see table on page 5. Two engines at 50% load consuming 12-13kg/hr each, ~25kg/hr total, is better than one engine at 100% load consuming 13kg/hr. Converting the second engine would be much cheaper that the first, as the engineering and calibration costs are already covered by the first engine, so it is just down to additional hardware and some more testing.

No changes in the technical specifications of the converted genset are anticipated, which is why none have been included.

Currently, in the absence of information on engine layout and how hydrogen injection could be integrated into the engine air path, it is not possible to formulate plans and arrangements for auxiliary systems or necessary equipment.

For the handling of hydrogen, there is one golden rule: ventilation. Please ensure that hydrogen is always supplied in as open a manner as possible. It is such a buoyant gas, that the best thing to do in regards to safety is to allow it to escape upwards. The details of the hydrogen supply chain in this case are not known, so it is not possible to recommend, at this time, specific considerations for the safe handling of hydrogen.

Please note tha the hydrogen ECU has its own strategies in place to do leak detection, so it ensures the engine is always safe to operate on hydrogen when it is available, and operate safely on diesel when there is an hydrogen system fault. Work would be carried out on the existing facility to ensure those strategies are effectively integrated into the facility to ensure the safety of the facility as well as the engine.