Final report

1. Project details

Project title	Methanol as fuel for marine diesel engines
File no.	64019-0036
Name of the funding scheme	EUDP 2019-I
Project managing company / institution	Danish Technological Institute (DTI)
CVR number (central business register)	DK 5697 6116
Project partners	MAN Energy Solutions, Alfa Laval Aalborg, Nouryon Surface Chemistry, Nordic Green and Danish Technical University (DTU)
Submission date	January 28th 2022

2. Summary

- *English version*

Methanol is one of the most promising low carbon fuels available for future shipping. Methanol is abundant, clean burning and enables the lowest greenhouse impact of any liquid fuel. The consortium behind this project has developed a cost-effective methanol fuel system which can adapt to existing engines, based on engine tests and combustion modelling work. This report will move from an experimental 20 kW engine to a 220 kW engine and finally to a 2 MW ship engine as shown in Figure 1*.*

- *Danish version*

Metanol er et af de mest lovende biobrændstoffer til fremtidens skibsfart. Metanol findes i rigelige mængder, det brænder rent og muliggør det laveste CO2-aftryk af alle flydende brændstoffer. Konsortiet bag dette projekt har udviklet et omkostningseffektivt metanolsystem, som kan tilpasses eksisterende motorer, baseret på eksperimentel udvikling af et forvarmersystem samt brug af et kemisk additiv. I denne rapport arbejdes trinvist fra en 20 kW til en 220 kW motor og endelig til en 2 MW skibsmotor som vist i Figure 1*.*

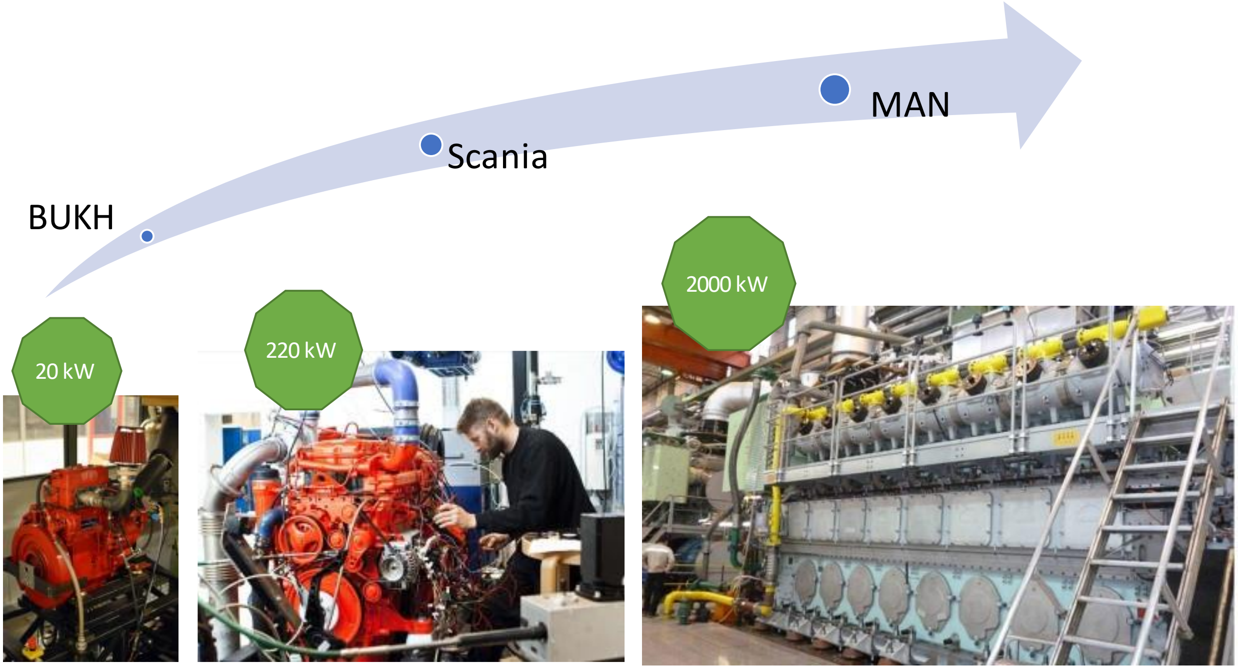

Figure 1 Overall concept of the project

3. Project objectives

- *What was the objective of the project?*

The main objective was to provide a cost-effective alternative to dual-fuel systems, such that the existing main fuel system could be used to inject methanol into the combustion chambers. In dual-fuel systems, either two separate nozzles or an advanced twin nozzle, which is not yet on the market, are required for each cylinder. If the original nozzle could be used for both diesel and methanol, then the cost of the system would drop significantly.

To separate the concept from dedicated MD95 engines, which are on the market, it was also a key objective to keep the compression ratio (CR) at standard levels below 18:1, whereas dedicated MD95 engines are at 28:1, so that pistons, rods etc. did not need changing. Furthermore, the use of chemical ignition enhancers was minimized to create an economically feasible marine engine concept.

Obviously, the original fuel system was not designed for methanol and the engine would not ignite if methanol were simply injected into the cylinders. To reduce development time and cost the project therefore used experimental data from a small engine to adapt a larger engine. It was important to know if the mathematical combustion models etc. were scalable so that cost could also be saved in future developments.

- *Which energy technology has been developed and demonstrated?*

Several engine and fuel system concepts were studied and evaluated during the project and the final concept is a result of extensive test and simulation work. A chemical additive, designed for ethanol burning was used to enhance ignition together with a chemical lubricant. Furthermore, the injection pumps were coated with a Diamond-Like-Carbon (DLC) surface to reduce wear and leakage flow.

Diesel, methanol, and additives were blended in different ratios to enable the engine to run at different load points. In some points, the engine would run on pure methanol, whereas start-up and full load operation required some amount of diesel fuel and additives.

Changeover between diesel and methanol was demonstrated successfully. Valves were fitted to automatically make the changeover.

A pre-heating system was installed both on the air intake and on the fuel side. The latter did not have the desired effect, but the air preheating had tremendous positive effect.

Stable running on methanol was obtained with compression ratios between 14:1 and 18:1 and a seamless transition to diesel and back to methanol was demonstrated.

4. Project implementation

- *How did the project evolve?*

Initial studies done at DTU had indicated that a diesel engine with a compression ratio of 18:1 should be able to run on methanol under certain conditions. The project therefore began with a parametric study on the 20 kW engine installed at DTU.

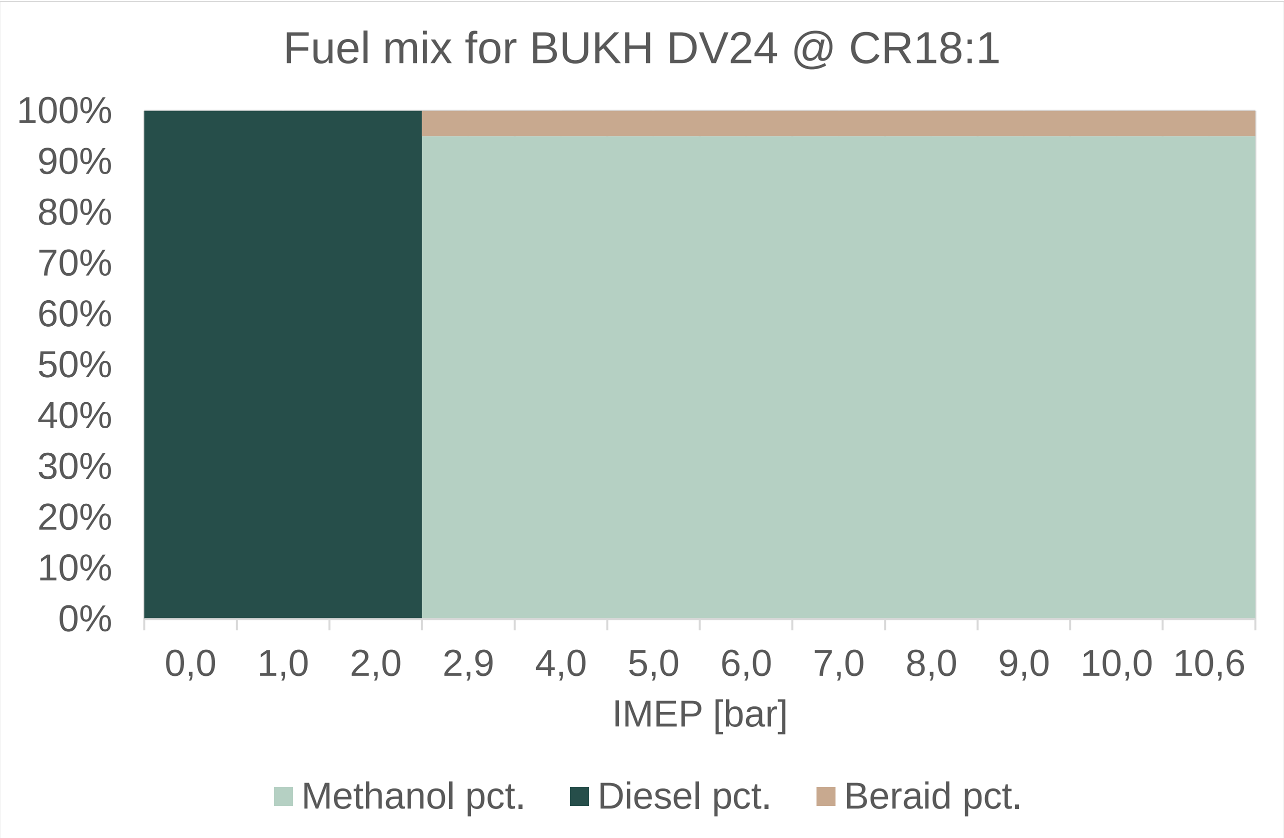

Figure 2 Load points and fuel mixtures used on the 20 kW engine

*This study indicated that preheated combustion air was beneficial for the ignition of methanol which is also in accordance with theory. However, the optimum injection timing was very early (45° BTDC) which would not be suitable for larger marine engines due to constraints in the injection control capabilities. The strategy was therefore adjusted to use later injection (10° BTDC) which would be more feasible for the larger engines. The engine was tested up to a IMEP of 10.6 bar (*Figure 2*), which corresponds to a brake torque of about 69 Nm. The results are presented in further detail in Appendix WP2.*

After satisfactory results had been reached on the 20 kW engine the next step was a 220 kW engine installed at DTI. The compression ratio was kept at standard 16:1 while other engine parameters were adjusted to mimic the settings of the smaller engine. Modelling work done at DTU supported the transfer of experience across engine sizes.

*Since the engine is turbocharged a significantly higher IMEP was reached. 22 bar corresponds to about 1461 Nm of torque (*Figure 3*).*

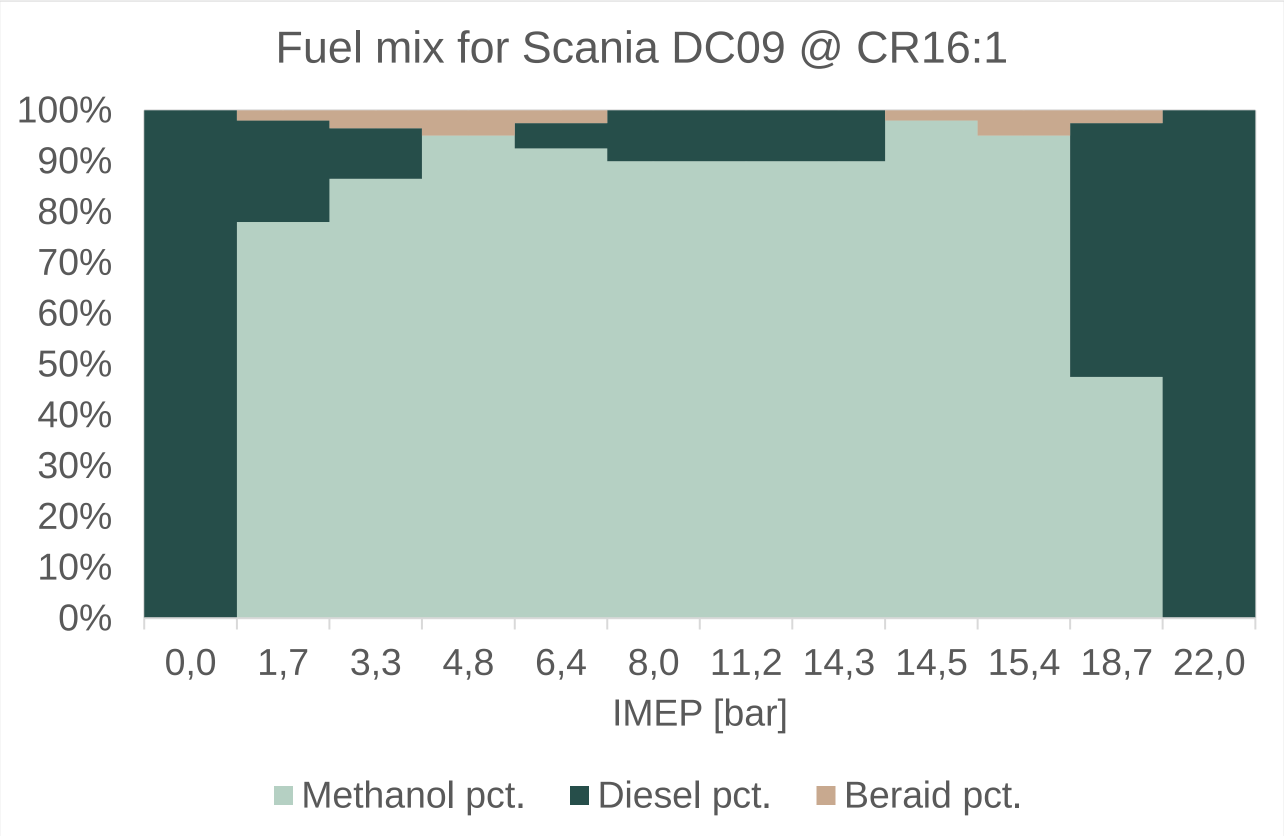

Figure 3 Load points and fuel mixtures used on the 220 kW engine

Extensive test work was done on the 220 kW engine which is described further in Appendix WP 3. This resulted in a number of possible engine and fuel booster concepts which could be transferred to the final stages of the project. An overview of the concepts evaluated along with the final concept is shown in Appendix WP1.

*Preparations for the final stage was done at Alfa Laval Aalborg (*Figure 4*) with the installation of a methanol storage and fuelling system which is described further in Appendix WP5.*

Figure 4 Filling the methanol tank at Alfa Laval Aalborg

The 2 MW test engine was prepared for the final trials by applying special coating to the injector pumps and modifying the fuel and air handling system. This is further described in Appendix WP4.

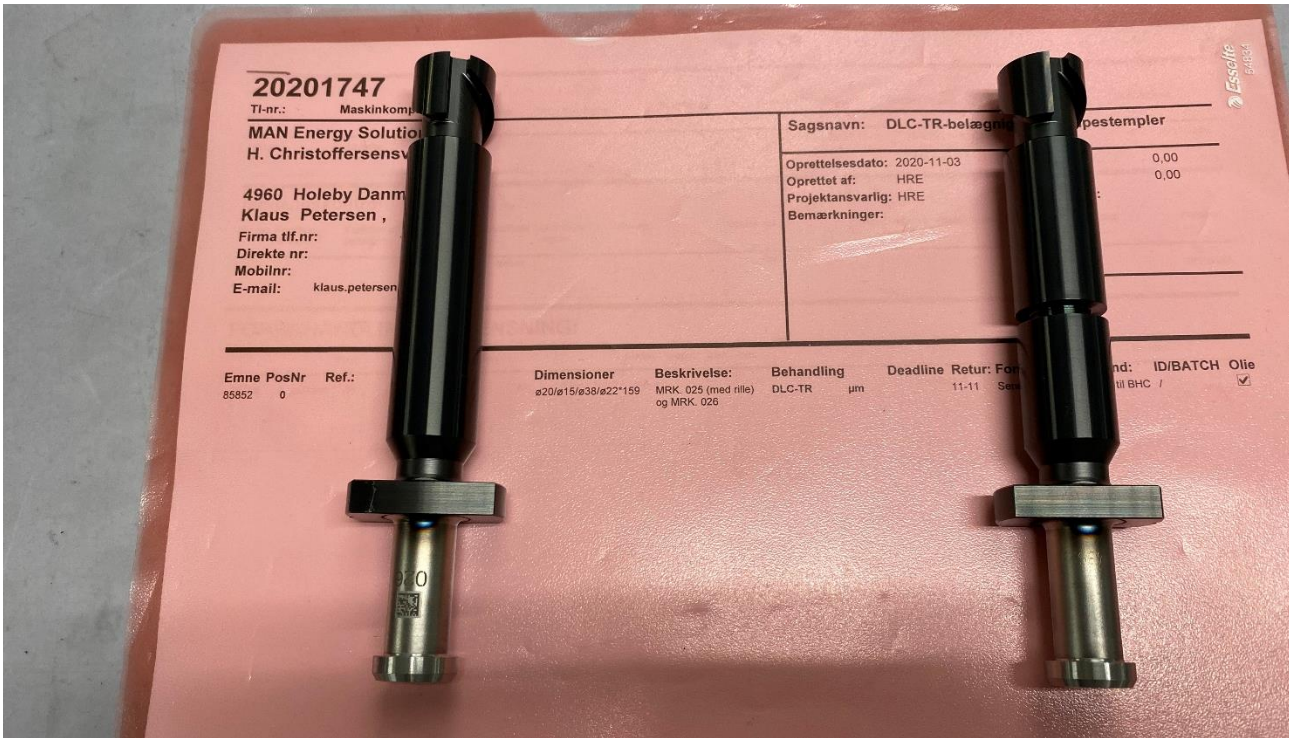

Figure 5 DLC (Diamond-Like Coating) on injector plungers for MAN L28 engine

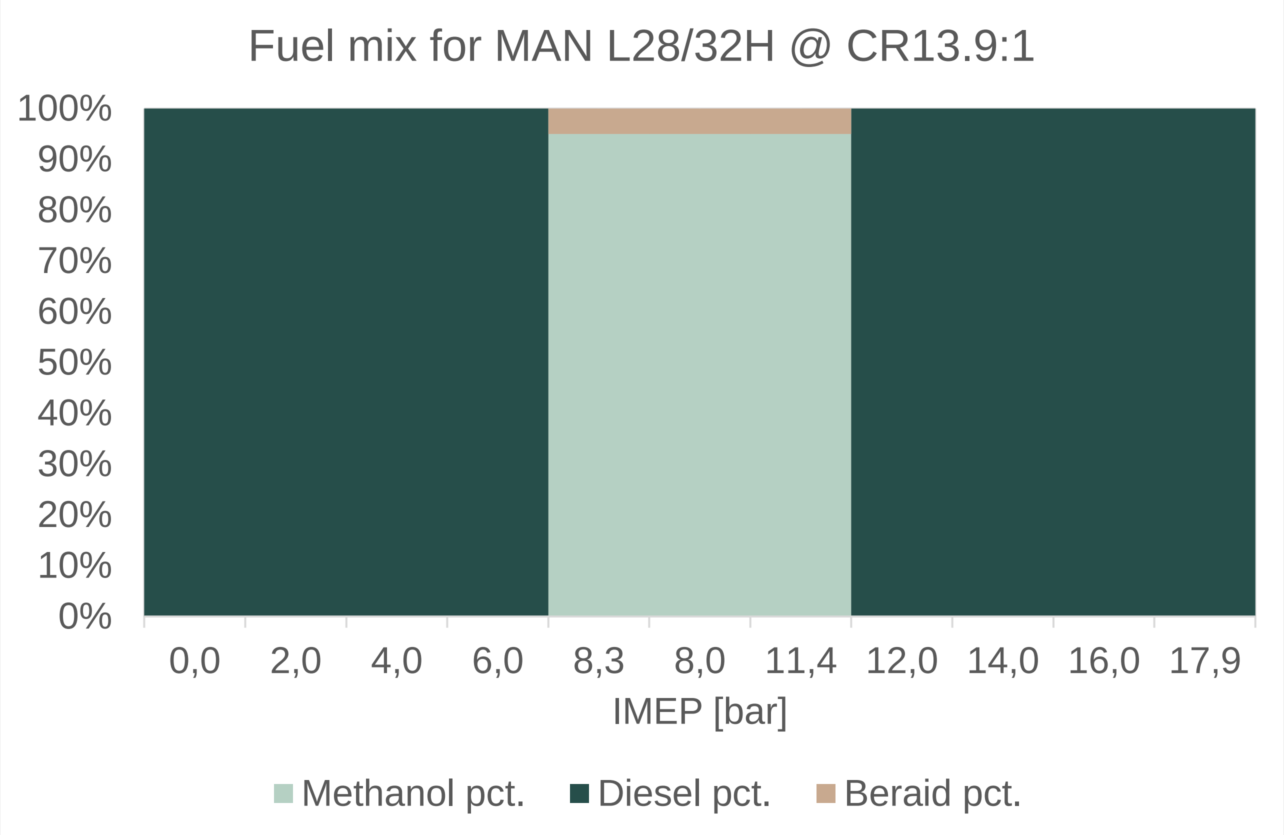

Figure 6 Load points and fuel mixtures used on the 2 MW engine

- *Describe the risks associated with conducting the project.*

There is always a financial risk involved when testing large engines because repairs can be very costly. Having the original engine manufacturer involved, however, reduced those risks.

Technical risks of failure were numerous. First, methanol does not ignite automatically in a diesel engine, so there would be a need to enhance the chemical reactions in the fuel and air mixture. Due to the extremely low viscosity of methanol the lubrication and leakage rate of fuel pumps was critical. These risks were mitigated by a combination of efforts involving chemical lubricants, DLC coating and intake air management.

In summary, the main technical challenges of the project were: Ignition, Start-up, Lubrication, Corrosion, Injection volume.

The scaling of results from a 20 kW to a 2 MW engine was also a big bet. The numerical combustion models available had not previously demonstrated such a jump. Excessive ignition delays might lead to knocking which would damage the engine. The injection volume needed was also a lot higher than the original engine specification.

- *Did the project implementation develop as foreseen and according to milestones agreed upon?*

Yes and No.

The initial studies of the 20 kW engine showed that injection timing needed to be pushed forward (timing advance) much more than what would be possible on the 2 MW engine. This called for an adjustment of test *strategy already from the beginning. After renewed tests it was shown that the engine could also operate on settings that would be possible on the larger engine.*

The work on the 220 kW engine was not without hurdles either. The main problem turned out to be the intake temperature which would only be sufficient when the turbo charger was spinning fast, which in turn required the engine to be working at a high load. Since it was not possible to obtain a high load from the start the turbo wouldn't spin fast enough and ignition would fail. After some weeks of testing, solutions to the problems were found and the engine performed quite well from then on.

When arriving at the 2 MW engine the team was well prepared from working with the two smaller engines and there were no major issues except a delay in municipal approval of the methanol tank installation. On the first test week the engine would occasionally misfire on individual cylinders, but this problem was solved with an innovative diesel-backup valve mounted on each cylinder. Misfiring is expected to occur on several random cylinders regardless injection system and ignition improver, when running methanol on multi-cylinder combustion engine, there will always be 1-2 cylinders performing/working less than other cylinders. These underperforming cylinders will misfire when running methanol. Especially during load reductions in a dynamic GenSet load.

- *Did the project experience problems not expected?*

The deliverance of a fuel booster system from Alfa Laval Spa. (Italy) failed due to corona issues. It was therefore necessary for Alfa Laval to design an alternative system which, after all, ended up working well.

5. Project results

- *Was the original objective of the project obtained? If not, explain which obstacles that caused it and which changes that were made to project plan to mitigate the obstacles.*

The project team unitedly feels that the project was a success. The goal was reached not by the first conception but by a steady improvement of the concept thanks to the problem-solving abilities of the team.

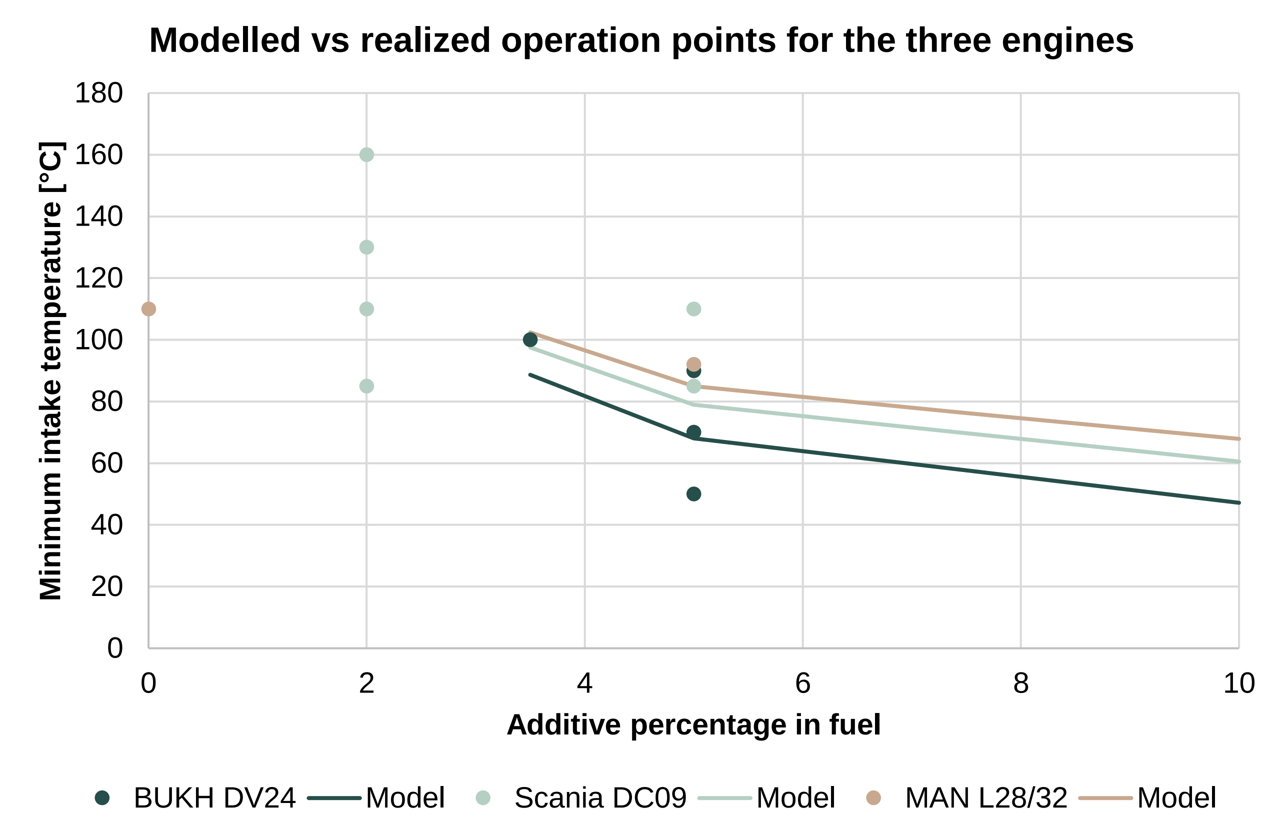

Figure 7 The test points of all three engines along with predicted operational limits

- *Describe the obtained technological results. Did the project produce results not expected?*

Running a 2MW marine engine on methanol with no physical modifications the engine internals except DLC coating of the fuel pump units is a rather significant result. Even though the engine did run on its maximum power setting, the fuel pumps could not deliver more than 55 % of nominal power due to the lower calorific value of methanol. However, emissions were low compared to diesel.

It was not expected that the engine would run entirely without ignition improver. However, in shorter periods, that was actually the case. This is better than expected. It needs to be investigated if the lubrication oil in combustion was acting as "pilot" or ignition improver.

Preheating of the fuel had very little effect, which was disappointing. It also turned out, that pre heated fuel would immediately cool off once it passes through the water-cooled cylinder heads. Some ideas as how to isolate or heat the fuel passages were developed but there was no time to do a practical installation of such a system. So, it remains for future work to try and feed fuel in the super-heated state to the injector nozzles. This would, in theory, enhance the ignition process significantly.

- *Describe the obtained commercial results. Did the project produce results not expected?*

The project results are highly commercially relevant. The short-term market is in retrofit conversion of the legacy L21/31-L23/32H-L27/38-L28/32H four-stroke engines from MAN.

The engine types L23/30H and L28/32H will have a limited power range of 35-55% load. Low-load limited to missing combustion pressure/temperature and high-load limited by fuel pump capacity. Fuel pumps can be *slightly enlarged but will require new roller and camshaft. Larger modification will require changes of gear box and frame. Changes of camshaft as retrofit is expected to be the commercial cost limit for retrofit.*

The engine types L21/31 and L27/38 are expected to have larger methanol potential:

Combustion pressure/temperature will comparably have lower limit of 25-30% for L21/31 and 30-35% for L27/38. Fuel pumps are much larger and can theoretically give 92-95% load.

Meaning these two engine types can easily fulfil the normal GenSet load of 40-80% load. Challenge is the dynamic GenSet load with load steps and load reductions. But in this project was developed solutions that secure electric power supply and if confirmation test is successful in Marts 2022 then it is expected to have a safe GenSet/Propulsion product for the market.

Market potential for L21/31 are 2600 engines, and L27/38 are 3000 engines, delivered end 2021

- *Target group and added value for users: Who should the solutions/technologies be sold to (target group)? Describe for each solutions/technology if several.*

The solution is to be offered for current ship owners and for shipbuilders. The added value is a significantly lower CO2-footprint and much lower particle emissions. The solution is relevant for ships from 1 to about 20 MW such as ferries and smaller freight vessels and for generator sets. Large ocean-going ships will prefer two strokes as main engines in the range of 20 - 90 MW and in average have 3xGenSet in the range of 0,5-3 MW.

- *Where and how have the project results been disseminated? Specify which conferences, journals, etc. where the project has been disseminated.*

The project has been presented in IEA-AMF Task 60 and will be included in the final report of this task, along with results from other participating countries Sweden, Switzerland, Korea, China, Finland, USA and Austria.

Alfa Laval sent out a press-release. A number of medias covered the case including;

1) Danish medias: Nordjyske and Energywatch. Nordjyske is a local/regional media and Energywatch is a national media focused on energy-news.

2) International shipping-medias: Riviera, Bunkerspot, Boating Business, Baltic Transport Journal etc.

3) International pricing-media: S&Pglobal Platts who is the world's biggest news-service within commodity-pricing.

4) International methanol-media: The story was brought in the weekly newsletter "Methanol Matters" on Friday the 12th of March 2021. "Methanol matters" is made by the global methanol branch-association Methanol Institute head-quartered in Washington DC.

6. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*

The technological results will be used by DTI and DTU for future research in sustainable marine fuels. Experiences from the project can be used both for ammonia, hydrogen, and other advanced fuels. It is expected that these results will lead to further R&D work performed both by DTU, DTI and the companies.

- *Describe how the obtained commercial results will be utilised in the future and by whom the results will be commercialised.*

The commercial results will be used by MAN-Holeby to offer a retrofit solution to existing four stroke marine engines in range of 0,5-3 MW whereas 90% are delivered as GenSet for electrical power supply onboard merchant vessels together with MAN B&W 2-stroke Main-Engine. The remaining 10% are delivered as 4-stroke propulsion Main-Engine in smaller vessel sizes and as Power Plant engines (e.g Greenland).

The tested L28/32H together with L23/30H seems to have too limited power range of 35-55% to be commercial attractive. But L21/31 and L27/38 can obtain a power range that can fulfil the normal GenSet load of 40-80% load. With the solutions developed during the project also able to fulfil the dynamic GenSet load and secure power supply.

Market potential for L21/31 are 2600 engines, and L27/38 are 3000 engines, delivered end 2021. Engine retrofit package is at current stage expected to cost 10-20.000 Euro per engine.

Several newbuilding vessel specifications contains currently methanol demand or methanol-ready demand for later conversion. With two proven methanol products that also can burn fuel and biofuel this is expected to significantly improve market shares in all markets. Most of the larger GenSet suppliers are expecting to have a methanol product in 2024-25.

- *Did the project so far lead to increased turnover, exports, employment and additional private investments? Do the project partners expect that the project results in increased turnover, exports, employment and additional private investments?*

The project did not commercialise within the time frame available for this report. However, there is a great demand worldwide for sustainable marine fuel solutions, so the partners are expecting big growth opportunities. Methanol seems the prime candidate fuel followed by ammonia which is still in the developing stage.

- *Describe the competitive situation in the market you expect to enter.*

The market for medium sized marine engines 2-10 MW is characterized by global competition. Physical engine production no longer takes place on Danish soil but a significant amount of know-how and IPR is still maintained within the country.

Several different fuels are on the agenda, and no winning candidate can be pointed out at this stage. Methanol ranks high along with ammonia, hydrogen, biogas but are closely challenged by synthetic biofuels, hydrothermally liquefied biomass etc. Even nuclear propulsion is on the agenda for very large ships.

MAN-Holeby deliver 90% of their engines as GenSet for merchant vessels together with MAN B&W 2-stroke Main-Engine. The remaining 10% are delivered as 4-stroke propulsion Main-Engine in smaller vessel sizes and as Power Plant engines (e.g Greenland).

Container vessels are normally 4-5 GenSet in power range 2-5 MW. Other vessel types are normally 3 GenSet in power range 0,5-2 MW.

- *Are there competing solutions on the market? Specify who the main competitors are and describe their solutions.*

There are several competing technologies for combustion of methanol. These are high compression M95 engines, spark ignited engines and dual fuel engines. Also, fuel cells for methanol are a viable competitor. High compression engines (Scandinaos) are available up to 440 kW which is somewhat below the segment we're addressing with this project. Spark ignited methanol engines are only available for trucks (Geely) up to 300 *kW but larger natural gas engines (Bergen/Rolls Royce) could probably be adapted for methanol although it is not on the market currently.*

The prevalent competing technology remains the dual fuel engine. These are available in both four and two stroke versions from 6 - 16 MW. However, they are somewhat more costly than the standard diesel versions. The project cost for the Wärtsilä 4-engine Stena Germanica dual fuel conversion in 2015 has been reported at 450,000 EURO per MW in total about 10.8 million EURO. The number would come down for future conversion projects probably to about 350,000 EURO per MW. For new builds the on-cost for methanol engines and tanks should be even lower since it can be planned from the start. Still, the cost of dual fuel engines is high compared with the concept used in this project. The main advantage of dual fuel engines is that they don't require chemical additives for ignition.

Wärtsilä have recently announced newbuilding order for W32 methanol engine for delivery in 2023. Wärtsilä have a minor market share for GenSet for merchant vessels.

HHI-Himsen have got the GenSet order for Maersk container vessel for delivery in 2023-24. HHI-Himsen is a major GenSet supplier for Korean orders.

Major Chinese GenSet suppliers are MAN-Holeby, Daihatsu and Yanmar. None of these have official announced a GenSet product for methanol. The first methanol GenSet product for China is expected to get significant GenSet market share in Chinese ship building

- *Describe entry or sales barriers and how these are expected to be overcome.*

A major part of the cost of methanol ship conversions is on the vessel and tank systems. Exchanging or upgrading the engines is only a small part of the problem. Shipowners would also need to take into account that methanol is still not available in every port and the cost of methanol is higher than that of marine diesel.

Methanol produced from natural gas and other fossil fuel have worse climate influence than using fossil diesel. Green and blue methanol require significant investment in Carbon Capture and Renewable Energy.

*If a solution with chemical additive is chosen, the cost of the additive adds significantly to the cost of operation, as shown in the figure below. When used in the prescribed dose at 5% the additive almost doubles the cost of the fuel (*Figure 8*).*

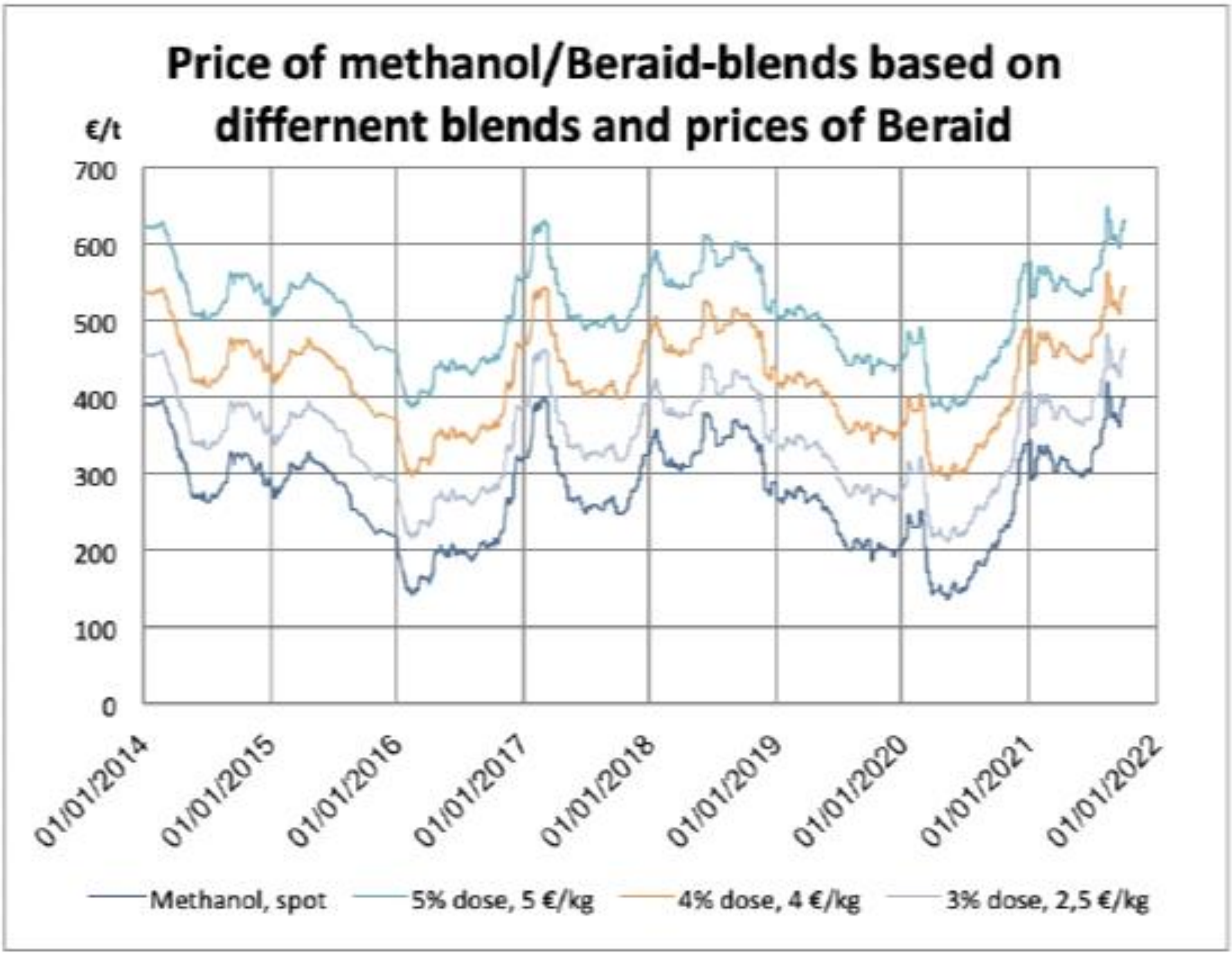

Figure 8 The dosage of chemical additives is a critical economic factor

The cost of the additive is the reason why this project has aimed to minimize the use of additive. The project has successfully reduced the consumption of additive from the usually prescribed 5% to less than 2%, and even 0%, depending on the operation state of the engine.

*The experiments performed has shown that in-cylinder temperature management can act as a substitute for additives (*Figure 7*).*

As alternative to high concentrations of Beraid in the methanol, a cost-effective alternative to improve the ignition could be to heat the inlet air. Increasing the inlet air temperature has been observed to have a very similar effect in terms of lowering ignition delay and increasing the reactivity of methanol. Figure 9 *compares the effects of inlet air heating and Beraid concentration on the combustion process, under equal operating conditions in the Scania engine. It is found here that increasing inlet temperature from 80 °C to 120 °C has the same effect as increasing the Beraid concentration from 3.5 to 10 %. In addition, the inlet temperature can potentially be adjusted faster than the Beraid concentration in the fuel supply, in situations where changes in engine load changes the requirement for additive.*

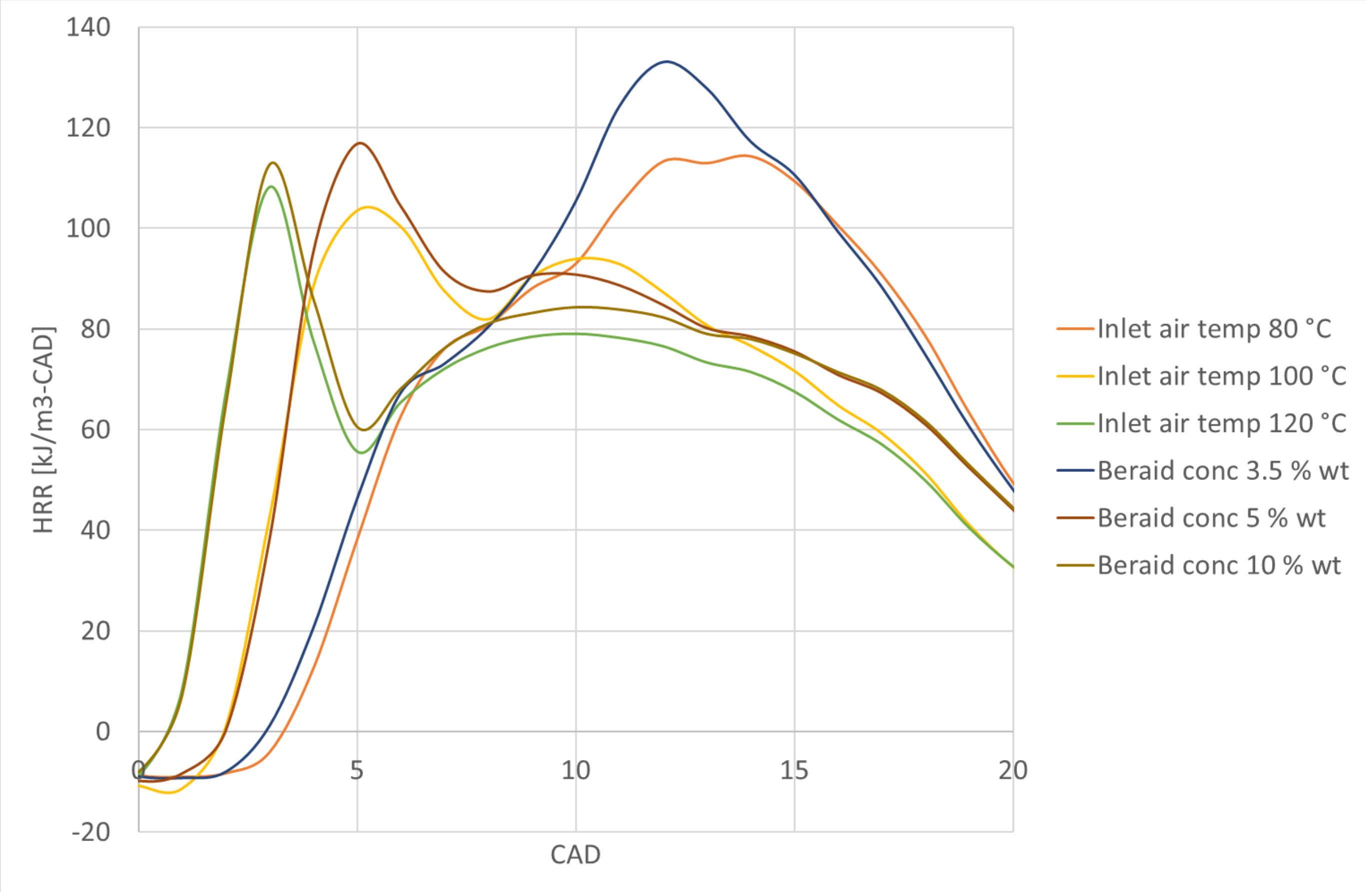

Figure 9: Comparison of changes to heat release rate, by changes in inlet temperature and concentration of Beraid show how in-cylinder temperature management can be used to reduce the need for additives thereby creating a more economical engine concept.

- *How does the project results contribute to realise energy policy objectives?*

The project results contribute to Danish and global energy policies by enabling the use of e-fuels in marine shipping.

- *If Ph.D.'s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities.*

Ph.D. student Chong Chen from DTU was attached to the project and during his internship with DTI he mapped the heat release rates and other parameters related to the Scania engine. His work will result in a numerical model of spray combustion of methanol with additives in diesel engines.

M.Sc candidate Thomas Berg Thomsen was also attached to the project and during his master thesis he mapped parameters related to the Bukh engine. He has since moved on to work as a research assistant at DTU.

7. Project conclusion and perspective

- *State the conclusions made in the project.*

It is possible to run a diesel engine with a compression ratio as low as 14:1 on methanol with little or no chemical additive once the engine is up to speed and turbos are delivering sufficient intake air temperature. Preheating the fuel has little or no effect as long as it is in the liquid state. Results have been shown to be scalable from 20 to 2000 kW engines. However, it is pivotal that experimental engines run on their own power and are not assisted by external power. A real turbo charger shall be included in the experiments because the turbo and the engine are highly mutually dependent. Methanol engines as investigated in this project are subject to random misfire in individual cylinders which has been addressed with a close coupled diesel boost valve on each cylinder. Emissions are generally low compared with diesel as shown in the table below.

Table 1 Emissions measured on MAN L28/32 engine

		Diesel	**Methanol**	**Reduction**
NO	ppm	1200	600	50%
NO2	ppm	50	20	60%
NOx	ppm	1250	620	50%
THC	ppm	50	40	20%
CO	ppm	170	150	12%
PM	mg/Nm3	25	12	52%

- *What are the next steps for the developed technology?*

New engine line-up. There is a new engine model already in production which has a higher compression ratio than the experimental engine used in this project. The new engine, due to the raised compression ratio, is assumed to handle methanol combustion even better than the old model. This should be investigated and clarified right away and will be pursued by MAN.

Supercritical injection with hot cylinder heads. Super critical methanol would in theory have a much higher reactivity and diffusivity and thus better ignition ability than sub critical as used today. Furthermore, super critical fluids have no heat of evaporation, so ignition delay will be shortened. This could eliminate the need for chemical ignition enhancers all together. The temperature needed for supercritical state is 240˚C at 81 bar. This requires the cylinder head to be heated or uncooled to avoid rapid cooling of the fuel when passing through the cylinder head. The supercritical methanol will be compressible, and viscosity as well as density will be low which will put some extra requirements on the injector pumps and valves. However, since supercritical fluids are widely used in the refrigeration sector it does not seem like an impossible task to handle such fluids. Development of a test rig for diesel-type combustion of supercritical methanol should be addressed. DTI and DTU will investigate the possibility to look further into this.

Glow plugs with sufficient life span for marine application. A glow plug would no doubt enhance ignition at low loads and temperatures. However, there are no such plugs on the market with a sufficient life span expectancy.

The plugs would need to be ceramic type or use other resistant materials to provide enough durability for heavy duty marine engines. Development of such glow plugs should be addressed.

- *Put into perspective how the project results may influence future development*

The project has shown that diesel-methanol engines do not need high compression or even pilot fuel if the temperature of the intake air is controlled sufficiently. The need for chemical ignition enhancers can be significantly reduced with the right control strategy. Thus, it can be economically feasible to convert existing engine models to methanol. Future developments might include pre-heating the intake air with steam or hot exhaust through a heat exchanger to enable more stable low load running with lower turbo pressure. The use of internal EGR by valve overlap would be another way to achieve similar benefits. A smooth changeover between diesel and methanol has been demonstrated in this project. A next step could be an intelligent control algorithm which doses diesel for each individual cylinder based on early signs of misfire.

The positive development in methanol engines will spark further development in tank and booster systems as well as refueling systems, safety, and handling procedures for methanol on ships. It could also help accelerate investments in Power-to-X technologies since it creates a future market for e-methanol.

8. Appendices

- WP 1 – Overview of engine concepts and parametric studies
- WP 2 - Test report on BUKH engine
- WP 3 - Test report on Scania engine
- WP 4 - Test report on MAN engine
- WP 5 – Fuel formulation and handling