Final Report

GreenPilot – Pilot Boat with Minimal Environmental Impact

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SWEDISH MARITIME ADMINISTRATION

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METHANOL INSTITUTE

Swedish Maritime Technology Forum

"GreenPilot is an exciting hands-on technical development project with high set up goals to advance the environmental profile of workboats and smaller ships.

SMTF is proud to be Project Lead of GreenPilot and excited to contribute to the development of a methanol fuel engine system for this segment."

ScandiNAOS

"Making use of the possibilities of domestic production of fossil free methanol and using this fuel for the transport industry is a prerequisite to reach the target goal of lowering greenhouse gases.

In this regard shipping has an important role as a platform for development and applied demonstrations - applications highly relevant for land transport as well."

SSPA

"SSPA is committed to developing sustainable solutions for shipping. The GreenPilot project objective of demonstrating bio-methanol as a low emissions, low environmental impact fuel is a great initiative for developing solutions for smaller ships and SSPA is excited to be part of the project team."

Swedish Transport Administration

"Through our participation in the GreenPilot project we contribute to the development of tomorrows technical solutions and to future fuels."

Swedish Maritime Administration

"Swedish Maritime Administrations vision is safe fairway in a sustainable future through maritime partnership. This vision trigged the startup of the GreenPilot project. To be able to run our engines on a renewable fuel is the first step towards our goal of having climate neutral pilot boats. With the GreenPilot project SMA aspires to be a first mover, allowing others a prepared fairway for the implementation of a greener fuel

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Preface

Contributing to a sustainable mode of transport

GreenPilot was initiated by the Swedish Maritime Administration (SMA) sharing their vision of a pilot boat with zero environmental impact. SMA wanted to make a significant reduction of the carbon footprint in the smaller engine segment with the use of a pilot boat. When the Swedish Transport Administration (STA) got on board the impact of the vision resounded even stronger. Sweden has a coastline of 2400 km that is maintained and serviced by vessels from SMA and STA, which collectively have a responsibility for service and maintenance of the waterways as well as for waterborne commuters and passengers.

Different fuels and powertrain solutions were discussed before taking the joint decision to go ahead with a pilot demonstration of bio-methanol as a possible way to reduce the environmental impact of near shore and inland shipping.

With the results in hand, GreenPilot has successfully shown that is has contributed greatly towards fulfilling the vision on which it was initiated. Adding to this, with its triple-helix (research, industry, and government) foundation at heart, the project has also managed to convert an innovation into a commodity, opening up for a new market in the smaller engine segment.

While the environmental achievement is the true benefit of GreenPilot, Sweden has gained yet another marine methanol success story and an even sharper competitive edge in the field of sustainable marine propulsion.

/Swedish Maritime Technology Forum,

Project Owner of GreenPilot

This report is a summary of the results from the GreenPilot project. The work included the following main components:

- Conversion work of engines to methanol operation
- Adaptation of on-board systems
- Hazard Identification study
- Field tests
- Environmental performance assessment

The report also describes the dissemination activities carried out during the project.

The GreenPilot project consortium consists of Swedish Maritime Technology Forum at RISE, ScandiNAOS, SSPA Sweden, Swedish Transport Administration, and the Swedish Maritime Administration.

Acknowledgements

The GreenPilot project is co-funded by the Swedish Transport Administration, Swedish Maritime Administration, and the Methanol Institute.

Executive summary

The GreenPilot project was carried out to demonstrate the emissions reductions and environmental performance improvements that could be achieved by converting a small vessel to run on methanol fuel. Reducing emissions is a priority for all vessel sizes, as emissions regulations are becoming stricter and concern about greenhouse gases and global warming continues to grow. Within Sweden, the government has announced its ambition to convert all state-owned vessels to fossil-free operation and is investigating 2030 and 2045 as possible deadlines. Methanol produced from renewable feedstock is a possible solution for some of the vessels.

By physically converting a Swedish pilot boat to run on methanol, the project demonstrated he feasibility of methanol as a fuel solution for small vessels. Work included converting and testing three different engines to run on methanol, two of which were installed and operated on the converted pilot boat. Emissions measurements showed good reductions as compared to conventional fuel oil. Fossil-free methanol produced from pulp mill black liquor in a Swedish pilot plant was used in some of the laboratory and on board tests. The project also investigated other solutions for reducing environmental impacts of the pilot boats, including the use of solar cells, batteries, and fuel cells.

Pilot Boat Conversion

Swedish pilot boat “729 SE”, which was made available to the project by the Swedish Maritime Administration, was converted for methanol operation on one of two engines. The conversion work had two main components:

1) Conversion of an engine to methanol operation
2) Adaptation of on-board systems, primarily fuel supply and safety

The main conversion work included the following:

- replacement of the port side engine with a methanol engine
- installation of two new methanol fuel tanks
- new gas tight tank room with A60 fire insulation
- fuel supply system installation, including a gas tight box containing fuel pumps and filters and double walled fuel piping in the engine room
- nitrogen system for methanol tank blanketing
- pressurized tank ventilation system
- tank room ventilation
- gas detection system
- installed new automation system
- upgraded fire suppression system.

The design for the conversion work was based on the existing provisional rules and guidelines for low flashpoint liquid fuels, including the IMO’s work on the IGF Code for ships using low flashpoint liquid fuels (2016 version, “*Draft Technical Provisions for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel”)*, and the provisional rules published by the classification societies LR and DNV GL. Special consideration was given to the methanol properties that are significantly different from diesel fuels, and normal risk mitigation practices were used to ensure an equivalent level of safety for the design. Some of the requirements for larger vessels were found to be not practical or reasonable for smaller vessels. These included airlocks, ventilation of double walled piping, and automatic purging of methanol pipes. Tank inertion with nitrogen gas was included in the pilot boat conversion, but it was considered that conventional atmospheric fuel tanks would have provided enough safety. For this solution the P/V valve used with inerted tanks could have been replaced with a flame arrestor.

Hazard Identification study

To identify any potential safety issues and minimize risks, a preliminary hazard identification study was carried out on the design. A hazard review meeting was held together with a classification society prior to testing, after most of the design work had been completed. Any issues and items identified by the studies were assessed in detail and addressed prior to carrying out the final conversion. The vessel was considered a demonstration platform only, and thus formal approval and certification were not carried out. The vessel was operated safely during the tests with no spills or accidents involving the methanol system.

Engine Conversion

Two engines, a Weichai and a Scania SI, were converted to run on methanol using spark-ignited port fuel injection (low pressure) technology. These were both installed and tested on the pilot boat. The engines were also tested in an engine dynamometer. Main conversion work on the engine included changes to the fuel system, spark plugs, fuel injectors on the inlet manifold, smaller turbo charger, and the engine control unit. Diesel-like performance was shown, with high efficiencies ranging from 37-40%. There was no SO_x and extremely low PM emissions. NO_x formation was reduced and the test emissions complied with existing and upcoming IMO and EU (Inland Waterway Euro V) regulations. The Weichai engine was run for about 150 hours on board the pilot boat and about 40 hours in dyno. Key internal components were inspected after the testing, with no indication of additional wear found. Valves, valve seats, exhaust system and cylinder liners were all clean. No soot or other types of sediment were present

A third engine, using compression ignition based on the Scania ED95 concept, was converted and tested in a laboratory with good results.

Environmental Performance

The main focus of the environmental performance assessment was comparing air emissions on a fuel life cycle basis. The fuel life cycle comparison includes emissions both from fuel production, "well to tank", and fuel combustion on board, "tank to propeller". Comparisons of methanol with marine gas oil (MGO) showed significant emissions reductions for NOx, SOx, and particulate matter (PM). Tank to propeller emissions were 99% lower. Regarding greenhouse gas emissions (GHG), fuel life cycle emissions in the range of 90% were achieved when methanol produced from pulp mill black liquor was used. This was the type used in most of the pilot testing. For methanol produced from natural gas (fossil fuel), greenhouse gas emissions were similar to those for MGO.

Sound measurements were also taken on board the pilot boat, and the methanol engine was found to have reduced noise emissions compared to the MGO engine, particularly for lower engine loads.

Assessment of other measures to improve environmental performance

Other measures to improve environmental performance of the pilot boat included improved energy management, use of solar panels, electrification, and fuel cells. Four solar panels were installed on the roof of the pilot boat cabin and used to charge the batteries on the vessel. With good weather conditions and optimum integration with the battery chargers it was estimated that 3-4 kW of power per day could be provided, which was still insufficient to keep the on board batteries charged without shore connection. Full electrification of the vessel was analysed and it was concluded that battery operation is not well-suited to high speed operation of the pilot boat. The required propulsion power is too high for current electric solutions to work well. Investigated fuel cell solutions were found to be similar to batteries in terms of low power output relative to the required system weight. Fuel cells and batteries were also were found to have a very high system cost with small benefit for a high speed boat.

Conclusions and Main Findings

The GreenPilot project has demonstrated that it is feasible to convert a pilot boat to methanol operation using available technology. Spark ignited engines with port injected methanol were found to have engine efficiency similar to diesel engines. Emissions reductions were substantial compared to conventional fuel oil. There is no sulphur in methanol, and NOx emissions were reduced so the engine can fulfil tier 3 and with a simple 3-way catalyst, Euro 6 emission levels can be reached. Particulate emissions from combustion were 99% lower than those from conventional fuel oil. Greenhouse gas emissions can be reduced significantly if methanol from fossil-free feedstock is used. The results and findings from the work are considered to be applicable for many other types of smaller vessels, which could achieve similar emissions reductions from using methanol fuel.

1 Introduction

The GreenPilot project was initiated to show the environmental impact reductions that could be achieved for smaller vessels with the use of methanol as a fuel. This was demonstrated through conversion and test operation of a pilot boat. The results and findings from the work are considered to be useful for many other types of smaller vessels, such as those trafficking inland waterways and archipelago areas, as well as smaller ships operating in coastal waters.

The two-year GreenPilot project started in 2016 and was carried out by a consortium of Swedish partners. The conversion object for the project was a 12.6 metre long pilot boat that was made available to the project by the Swedish Maritime Administration. The project showed the benefits of methanol for small vessels through a practical on-board application.

1.1 Background

Emissions from shipping, like those from all transport operations, have been of increasing concern due to impacts on the environment and the growing problem of climate change. Regulations have been developed on the international, European, and regional (emission control area) levels. To date these have primarily dealt with SO_x and NO_x emissions, but discussions on reducing CO_2 and particulate emissions are now underway. The International Maritime Organization (IMO) adopted a climate strategy in 2018, with a stated ambition to achieve a 50% reduction in GHG emissions from shipping by 2050, as compared to 2008 levels. Within cities and densely populated urban areas worldwide, air pollution can reach levels that are directly harmful for human health. Emissions of SOx, NOx, and particulate matter are of specific concern in these areas, in addition to the global impact of greenhouse gas emissions. The number of emission control areas worldwide continues to grow - theYangtze River Delta in China is an example of a new area, which now requires the use of 0.5% sulphur content fuel by October 2018. The allowable level of SOx in fuels in all international waters is being reduced from 3.5% to 0.5% in 2020, as the result of an IMO decision.

In Sweden, the government has directed the Swedish Transport Administration to carry out an analysis of how operation of state-owned vessels, including road ferries and pilot boats, could be fossil-free. Targets of 2030 and 2045 are being investigated (Swedish Government, 2018). Many vessels in the national fleet are of a smaller size, as they are not operating in international waters. Internationally, there are many smaller vessels operating in the densely populated areas where there are air pollution concerns.

Options for reducing emissions include exhaust gas after treatment or switching to a compliant fuel. Modern diesel engines such as those used in many smaller vessels generate significant NOx emissions due to the high combustion temperature and pressure. Further, the combustion of oil-based fuels generates particulate matter (PM), a component of which is black carbon (BC). BC emissions are harmful to human health impacts and are also a strong climate forcer (Lack et al., 2015). Efficient diesel combustion with oil-based fuels will always produce some harmful emissions. To fulfil upcoming requirements, aftertreatment systems for exhaust gas cleaning will need to be fitted. For a diesel engine the technology exists to reduce the emissions to very low levels, however the required equipment includes active particle filter (APF) to reduce the PM and selective catalytic reduction (SCR) to reduce the NOx emissions. These are complex systems that are similar in cost and volume to the actual engine itself and they require consumables and maintenance during operation. Alcohol fuels such as methanol and ethanol burn cleanly with very low particulate emissions. Methane (as LNG or biogas) also results in very low particulate matter emissions when combusted.

Fuels that may be produced from fossil-free feedstocks and thus contribute to reduced CO_2 emissions include:

- HVO (Hydrotreated Vegetable Oils): HVO is the easiest option for replacing fossil diesel with a fossil free alternative, as it is essentially a "drop-in" fuel. It can be blended with ordinary diesel fuel and can therefore easily be introduced to the market. The fuel feedstock can include animal fats such as slaughterhouse waste, tall oil, and residual products from palmoil production. The oils or fats have undergone hydrotreatment and refining and are stable during storage. The potential feedstock is limited and there is significant demand from the land transport industry for blending to meet renewable fuel directives. HVO will mainly affect the lifecycle CO_2 emissions and the SO_x emissions. There are some mixed results on whether NOx will be reduced (Bohl et al., 2018) as compared to fossil diesel. Researchers have shown reductions of PM and BC emissions as compared to fossil diesel (Bohl et al, 2018).
- FAME: Fatty acid methyl esters (FAME), also referred to as bio-diesels, can be produced from vegetable oils, used oil (such as from deep-frying), or animal oils. FAME that is produced in Sweden uses rapeseed oil as a feedstock, and is also referred to as RME. Producing FAME requires smaller infrastructure investments than HVO production, but the product is less stable. FAMEs have exhibited problems with stability during transport and storage, as they tends to oxidize and degrade during long term storage (6 to 10 months) (Hsieh and Felby, 2017). The stability is affected by oxidation, microbial growth and water contamination (Rashed et al., 2015). Emissions wise FAME produces more NOx during combustion compared to fossil diesel or HVO. (2017/18:RFR13
- Biogas: Biogas (primarily methane) can be used either as compressed biogas CBG or liquefied to LBG (the designations corresponds to CNG and LNG but with renewable gas). The main practical difference between CBG and LBG is the much higher complexity of the fuel storage and handling system for LBG as the fuel is cryogenic and is stored at -163 °C. The advantage is the higher energy density (in terms of volume). The main drawback with CBG is the low energy density of the fuel and pressurised storage system. LBG is a better alternative in terms of energy density but require a more complex gas preparation and vaporisation unit. Adaptation of systems that are being developed for use on trucks, such as the new Volvo FH LNG, might be an option in the future. Production of LBG is expensive and requires significant investments in production and storage facilities as the biogas feedstock needs to be cooled to -163 °C and kept at that temperature to remain liquid. An aspect of using biogas as fuel is that methane is a powerful greenhouse gas. General figures indicate a conservative estimate is that about 3% of the gas can be expected to slip through the engine uncombusted. Methane has a global warming potential 86 times more powerful than CO_2 (over a 20 year timespan).
- Ethanol: Ethanol, a colourless flammable liquid, is the most widely used biofuel in the world (Sucden, 2015). It is used primarily in blended fuels (E85) in spark-ignited engines in automotive transport, but has also been used in heavy duty engines in buses and trucks. In the diesel engine application an ignition improver is blended into the fuel – in Sweden it is referred to as ED95. It does not contain sulphur and particulate emissions are very low. It has not been tested as a ship fuel, probably due to its higher cost as compared to methanol, but is expected to perform in a similar manner.
- Methanol: Methanol is the simplest of alcohols, with one carbon atom, and the chemical formula (CH_3OH). Similar to ethanol, it is clean-burning and does not contain sulphur. Although most of the methanol on the market today is produced from natural gas, it can be produced from many renewable feedstocks, including forest residues, pulp mill black liquor, and municipal waste. It can also be produced as an

"electrofuel", which is essentially chemical energy storage for electricity where hydrogen from electrolysis of water is combined with carbon dioxide to form methanol. The advantage of methanol as compared to other electrofuels is that it is easy to store and transport, and it has a higher energy density compared to compressed hydrogen or batteries. The large quantity of methanol already available in combination with the relative ease of sustainable production is one major advantage of methanol.

1.1.1 Why methanol

Methanol was selected for testing within the GreenPilot project due to the very good potential for low emissions, and the potential to be produced from renewable feedstocks within Sweden. Project consortium members have been involved in previous projects which lead to testing and implementation of methanol in large vessels, including the Stena Germanica and the Waterfront shipping chemical tankers. For smaller vessels, a spark ignited port fuel injected methanol engines should have similar engine efficiency as a diesel engine and will have very clean exhaust out of the engine. The combustion generates in principle no PM, and very low NOx. With an inexpensive three-way catalyst as after treatment, a super low level of NOx can be achieved.

Fossil-free methanol was obtained for testing from the LTU Green Fuels pilot plant in Piteå. This demonstration plant has operated for over 11000 hours, successfully producing gas from black liquor for further conversion to methanol or DME (Landälv, 2017). The plant has the capability of producing 5.5 – 6 tonnes of methanol per day, but is currently being maintained in a moth-balled state awaiting new projects and funding (Granberg, 2018). Fossil-free methanol is also available in European market. Carbon Recycling International in Iceland has an annual production of 4 000 tons of methanol from recycled CO_2.

1.1.2 Past projects in Sweden using methanol as a marine fuel

Previous projects carried out within Sweden that focussed on the use of methanol as a marine fuel include the EffShip Project, SPIRETH, the Stena Germanica conversion, and the SUMMETH project. EffShip, "Efficient Shipping with Low Emissions", identified the potential of methanol as a marine fuel. This was further investigated for large engines in the SPIRETH project. Results from the methanol engine testing within SPIRETH lead to the conversion of methanol engines on the Stena Germanica, shown in Figure 1. The SUMMETH project was carried out to assess the feasibility of methanol in smaller engines and vessels. A case study of a road ferry conversion, using the Swedish road ferry Jupiter (shown in Figure 1), was carried out within SUMMETH.

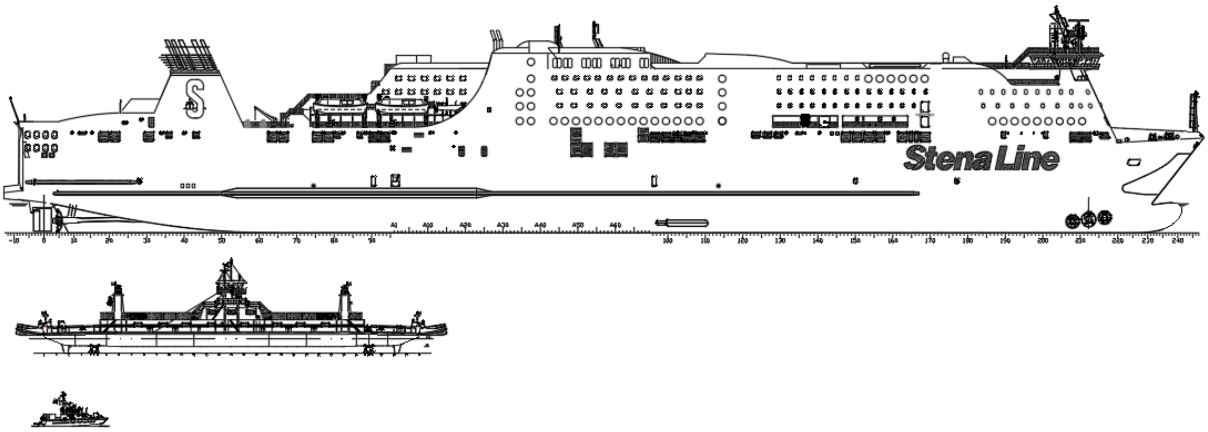


Figure 1-1: Size comparison between methanol projects. Stena Germanica, on top, has been approved for methanol according to LR rules and SOLAS. The Jupiter road ferry, used for the case study design, is shown in the centre. The pilot boat converted in the GreenPiot project is shown at the bottom of the figure.

Engine testing and development work within SUMMETH served as input to the GreenPilot project. The GreenPilot project is testing the application of methanol on an even smaller vessel – a 12.6 metre pilot boat shown in Figure 1.

1.1.3 Swedish pilot boat fleet performance and sustainability goals

The purpose of the Swedish pilot service is to assist with navigation and provide pilotage for vessels within Swedish territorial waters. The Swedish Transport Agency mandates pilotage for specific areas within Swedish waters. The Swedish pilot boat fleet consisted of 72 pilot boats in 2017, which carried out 33481 pilot services during the year (Sjöfartsverket, 2018).

Table 1-1: Summary statistics for the Swedish Pilot Boat Fleet and services for the years 2014 to 2017.

	2014	2015	2016	2017
Number of pilot boats	74	72	72	72
Piloting Services (number)	32661	32339	32669	33481
Fuel consumption total (m3)	2960	3072	3063	3100
Fuel Consumption pilot services only (m3)	2891	2939	2997	3022
Fuel consumption other uses (m3)	69	133	66	78

(Data summarised from Sjöfartsverket (2018); Borg (2018); Sjöfartsverket (2017b); and Sjöfartsverket (2016))

Total fuel consumed by the pilot boat service in 2017 was 3100 m^3, as shown in Table 1. Currently, all the fuel used by the pilot boats is low sulphur gasoil equivalent to marine gasoil (MGO). The Swedish Maritime Administration has set a goal of reducing the fuel consumption per pilot transport by 10% as compared to the 2016 level (Sjöfartsverket, 2018). Work to achieve this includes successively replacing engines on the older pilot boats with more efficient engines, technical improvements, and changes to work methods (Sjöfartsverket, 2018). Other environmental measures include using geothermal heat pump systems while the pilot boats are at the quay. The Swedish Maritime Administration is also part of the GreenPilot project to investigate the potential of green methanol to reduce emissions from pilot boats.

1.2 Objectives

The overall goal of the GreenPilot project was to reduce the environmental impact of a pilot boat through operation on methanol fuel. The specific objectives for achieving this goal included:

- Evaluating various methanol combustion concepts through laboratory testing, to select the best engine concept for the pilot boat installation
- Installing an adapted engine and fuel system on board a pilot boat
- Identifying relevant and applicable rules for the design and installation, and using the experience from the project to contribute to further regulatory development
- Reducing the emissions of CO_2, SO_x, NO_x, PM and BC from the pilot boat operation
- Reducing energy consumption of the pilot boat while at quayside
- Recommending improvements that could be made to other ship systems that have a negative impact on the environment.

1.3 Scope

The scope of the work included the following:

Adaptation of a suitable pilot boat: An appropriate pilot boat was identified for conversion to methanol operation. Adaption work included replacing the existing engine with a new engine that had been modified within the project to run on methanol. Relevant auxiliary systems such as bunkering, fuel storage and piping, gas and fire detection system, and fire suppression systems were replaced or adapted to be compatible with methanol operation.

Analysis, evaluation, and development of proposals for applicable rules and regulations for methanol fuel installations on smaller vessels: Currently, there are no rules in force for the use of low flashpoint liquid fuels on smaller ships. The project was to identify applicable solutions and rules to ensure that the current safety levels of the pilot boat operation are maintained or improved where appropriate. The project results could potentially serve as a platform for development of official regulations and classification society rules.

Engine Adaptation: A number of methanol engine concepts deemed possible for implementation on the pilot boat were analysed and the most applicable selected for installation. The engine was physically adapted and tested before on board installation. Results from laboratory tests carried out in similar projects such as SUMMETH were utilized for evaluation and engine adaption/calibration.

System for distribution of methanol: A system and procedure for bunkering methanol to the pilot boat was to be developed. Fossil-free methanol produced in Sweden was also to be tested within the project.

Modification of other ship systems to reduce environmental impact: Other ship systems, separate from the engine, were to be analysed to identify their environmental impact. Possible methods for reducing these impacts were to be investigated and implemented where possible. Electrification and fuel cells were part of this additional investigation.

2 Methanol conversion of pilot boat

The physical conversion of the 12.6 metre long Swedish Maritime Administration pilot boat, Pilot 729SE, was based on the existing provisional rules and guidelines for low flashpoint liquid fuels, including the *Draft Technical Provisions for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel* contained in the IMO's IGF Code Part A-2 (2016), and the provisional rules published by the classification societies LR and DNV GL. The aim was to achieve a safe and reliable design, giving special consideration to the methanol properties that are significantly different from diesel fuels and using normal risk mitigation practices to ensure an equivalent level of safety.

The first part of this chapter highlights the properties of methanol that were considered in the physical design and operational procedures. This is followed by a brief overview of the regulatory framework relevant for the pilot boat. The main part of the chapter thereafter describes the conversion work done to the boat that allows for safe operation on methanol.

2.1 Methanol properties considered for ship safety and design

From a safety perspective methanol offers some new challenges. In comparison to diesel fuels, the flashpoint is low, which means that methanol is easily ignited by a spark or open flame. The lower flashpoint is the largest difference in terms of safety and as a result all equipment used in areas where methanol leaks can be expected needs to be safe for use in potentially explosive atmospheres (EX-class equipment). There are also advantages with methanol from a fire safety perspective - the heat release is lower, no smoke is produced from methanol combustion, and methanol fires can be extinguished with water.

As methanol is a liquid, conventional fuel tanks are used for storage. Potential spills will also behave like a liquid and conventional fire suppression methods are used. Methanol is also soluble in water and is not harmful to the aquatic environment if spilled.

2.1.1 Fire considerations for methanol

By using the flashpoint, vapour pressure and flammability range a corresponding temperature where a flammable atmosphere can occur inside a closed tank can be calculated. The table below illustrates that for methanol, a combustible air/fuel mixture can form inside a closed tank when the temperature is between 11 and 41 °C. This is a major reason why tank inertion is required by the IGF code when using methanol. The image below also shows the heat radiations from pool fires of 50 m^2 and 4 m^2 respectively for pure methanol and a gasoline-methanol mixture. The heat radiation from the pure methanol fire is significantly less, which makes a potential fire easier to approach during suppression.

	Vapor pressure @20°C [kPa]	Flamability range [vol%]	Flashpoint [°C]	Translated temperature range [°C]
Methanol	12.3	6 – 36	11	11 – 41
Diesel	0.05	1 – 6	>56	60 – 150
Gasoline	40 – 100	1.4 – 7.6	<-40	-43 – 10

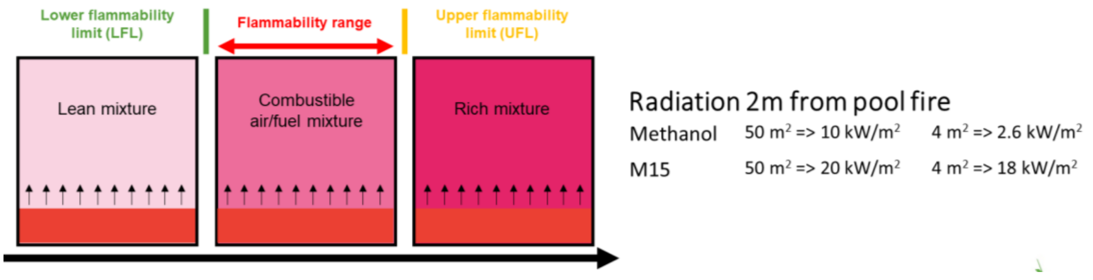
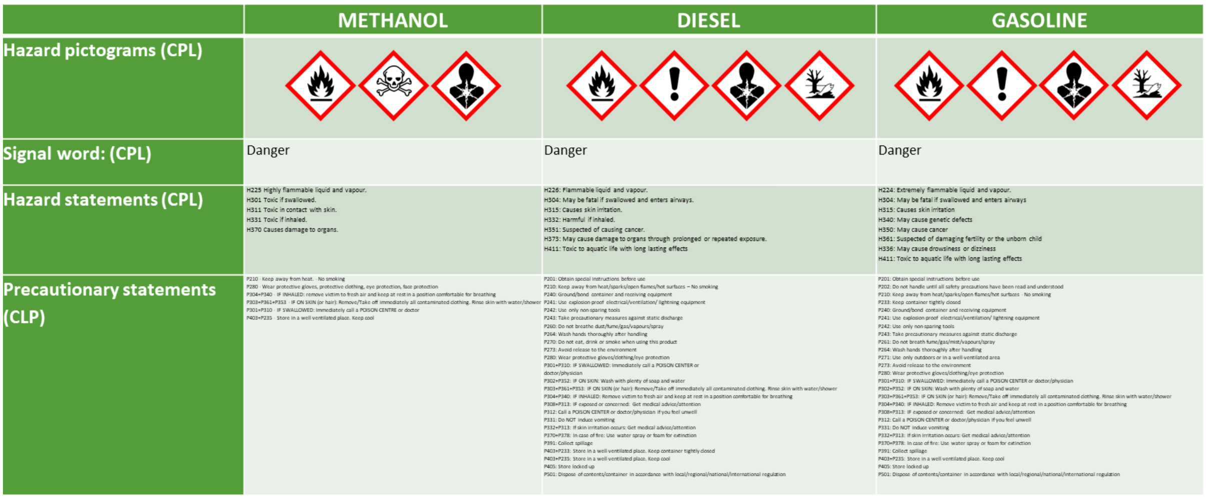


Figure 2-1: Flammability and fire characteristics summary of methanol compared to diesel and gasoline. Numbers and figures adapted from SP Rapport 2017:22 (Evegren, 2017).

2.1.2 Toxicity

As methanol is toxic precautions during handling are necessary. During work with methanol and methanol fuel equipment eye protection should be used and exposure to the skin avoided. If ingested, immediate medical attention should be sought. Compared to diesel and gasoline methanol is more toxic by some measures (classified as toxic in contrast to harmful) but it is not carcinogenic. It is also classified as highly flammable in contrast to flammable (diesel) and extremely flammable (gasoline).

From an environmental perspective methanol is soluble in water and quickly biodegrades with no lasting effects on the environment. Because of this methanol can, in contrast to petroleum products, be stored in double bottom tanks in a ship without a double barrier towards the sea.



	METHANOL	DIESEL	GASOLINE
Hazard pictograms (CPL)			
Signal word: (CPL)	Danger	Danger	Danger
Hazard statements (CPL)	H225 Highly flammable liquid and vapour. H301 Toxic if swallowed. H311 Toxic in contact with skin. H331 Toxic if inhaled. H370 Causes damage to organs.	H226: Flammable liquid and vapour. H304: May be fatal if swallowed and enters airways. H315: Causes skin irritation. H332: Harmful if inhaled. H351: Suspected of causing cancer. H373: May cause damage to organs through prolonged or repeated exposure. H411: Toxic to aquatic life with long lasting effects	H224: Extremely flammable liquid and vapour. H304: May be fatal if swallowed and enters airways H315: Causes skin irritation H340: May cause genetic defects H350: May cause cancer H361: Suspected of damaging fertility or the unborn child H336: May cause drowsiness or dizziness H411: Toxic to aquatic life with long lasting effects
Precautionary statements (CLP)	P210 · Keep away from heat. · No smoking P280 · Wear protective gloves, protective clothing, eye protection, face protection P304+P340 · IF INHALED: remove victim to fresh air and keep at rest in a position comfortable for breathing P303+P361+P353 · IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower P301+P310 · IF SWALLOWED: Immediately call a POISON CENTRE or doctor P403+P235 · Store in a well ventilated place. Keep cool	P201: Obtain special instructions before use P210: Keep away from heat/sparks/open flames/hot surfaces – No smoking P240: Ground/bond container and receiving equipment P241: Use explosion proof electrical/ventilation/ lightning equipment P242: Use only non sparing tools P243: Take precautionary measures against static discharge P260: Do not breathe dust/fume/gas/vapours/spray P264: Wash hands thoroughly after handling P270: Do not eat, drink or smoke when using this product P273: Avoid release to the environment P280: Wear protective gloves/clothing/eye protection P301+P310: IF SWALLOWED: Immediately call a POISON CENTER or doctor/physician P302+P352: IF ON SKIN: Wash with plenty of soap and water P303+P361+P353: IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower P304+P340: IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing P308+P313: IF exposed or concerned: Get medical advice/attention P312: Call a POISON CENTER or doctor/physician if you feel unwell P331: Do NOT induce vomiting P332+P313: If skin irritation occurs: Get medical advice/attention P370+P378: In case of fire: Use water spray or foam for extinction P391: Collect spillage P403+P233: Store in a well ventilated place. Keep container tightly closed P403+P235: Store in a well ventilated place. Keep cool P405: Store locked up P501: Dispose of contents/container in accordance with local/regional/national/international regulation	P201: Obtain special instructions before use P202: Do not handle until all safety precautions have been read and understood P210: Keep away from heat/sparks/open flames/hot surfaces · No smoking P233: Keep container tightly closed P240: Ground/bond container and receiving equipment P241: Use explosion proof electrical/ventilation/ lightning equipment P242: Use only non sparing tools P243: Take precautionary measures against static discharge P261: Do not breath fume/gas/mist/vapours/spray P264: Wash hands thoroughly after handling P271: Use only outdoors or in a well ventilated area P273: Avoid release to the environment P280: Wear protective gloves/clothing/eye protection P301+P310: IF SWALLOWED: Immediately call a POISON CENTER or doctor/physician P302+P352: IF ON SKIN: Wash with plenty of soap and water P303+P361+P353: IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower P304+P340: IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing P308+P313: IF exposed or concerned: Get medical advice/attention P312: Call a POISON CENTER or doctor/physician if you feel unwell P331: Do NOT induce vomiting P332+P313: If skin irritation occurs: Get medical advice/attention P370+P378: In case of fire: Use water spray or foam for extinction P391: Collect spillage P403+P235: Store in a well ventilated place. Keep cool P405: Store locked up P501: Dispose of contents/container in accordance with local/regional/national/international regulation

Figure 2-2: Comparison of CPL hazards for methanol, diesel and gasoline according to European Regulation (EC) No 1272/2008. A readable format of the table can be found in Appendix I.

2.1.3 Energy content

Methanol has a lower energy density than petroleum products, thus requiring larger fuel tanks to achieve the same range. For pilot boats operating in close proximity to a bunker station the effects on operability should be minimal. For comparison Table 2-1 list the specific energy for the comparable fuels as well as other potential fuels and also a battery alternative,

Table 2-1: Energy density comparison between different potential fuels and energy carriers.

	Specific energy [MJ/kg]	Energy density [MJ/l]
Methanol	19.7	15.6
Ethanol	26.4	20.9
Diesel	48	35.8
Gasoline	46.4	26
LNG	53.6	22.2
Natural gas	55.5	0.0364
Hydrogen (700 bar)	142	9.17
Lithium-ion 26650 battery	0.53-0.65	

2.2 Design philosophy and regulatory framework for pilot boat conversion

For conversions the usual approach is to look at the regulations applied when the boat was originally constructed. For Pilot 729SE that was the NBS Y 90 (Nordic Boat Standard for working boats), which is no longer relevant. Comprehensive design documentation for the original construction was not available. As methanol is a rather new unconventional fuel the approach has instead been to look at the currently available regulations and the requirements that would be applicable for a newbuilding.

The statutes determined to be most relevant are TSFS 2014:1 for machinery and electrical installations. The statutes have a requirement on minimum fuel flashpoint of 43 °C, analogue to the SOLAS requirement for 60 °C. TSFS 2014:1 also include an alternative design route where risk analysis is to be used to find design solutions outside of the requirements in the statutes, similar to the alternative design route according to SOLAS (regulation 17).

The approval body in Sweden is the Swedish Transport Agency (TS) while the operator and owner of the Swedish pilot boats is the Swedish Maritime Administrator (SMA).

The aim of the project was to have the methanol systems fully approved by the authorities. A number of meetings to discuss the design and on-board arrangements were conducted but it was concluded that it would not be possible to arrange a formal approval process without a formal request from SMA. During the project new statutes also entered in to force, the TSFS 2017:26[1] for ships in national traffic. The new rules do not have any requirements specifying a minimum fuel flashpoint and are a function-based set of regulations with few formal requirements. A short passage in the rules mention that the use of low flashpoint fuels requires special considerations.

The conclusion was that continuation of the tests for GreenPilot was acceptable without formal approval of the vessel. Formal approval or a documented “approval in principle” was however not possible to obtain due to administrative reasons.

As the GreenPilot project could continue as a development project without formal approval such documentation was not sought further.

In terms of safety the design and construction were carried out with the aim of having a system that would be to the satisfaction of the approval body. The approach that was used to ensure conformity to the regulations was to conduct risk analysis work and to base the design on the rules that are available. In terms of available regulations the IMO were working on rules for low flashpoint liquid fuels (IGF-code part B) and classification societies DNV-GL and Lloyds Register have both published rules for use of methanol. The IMO committee working on methanol rules completed their work on the *draft interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel* during September 2018; this latest version of the guidelines has not been considered in the scope of the GreenPilot project.

The guidelines described above, however, are not directly applicable for the pilot boat because they apply to classed ships and ships in international traffic. For vessels in national traffic there are no equivalent rules which in turn led to the decision to use the class rules as reference for the design.

The general principles of the class rules govern the design of the methanol systems but some requirements are not applicable for smaller vessels such as the pilot boat due to space limitations and limitations on installed systems. Examples of this are requirements on airlocks, double walled piping ventilation, automatic purging of methanol pipes, etc.

[1] Transportstyrelsens föreskrifter och allmänna råd om fartyg i nationell sjöfart

The requirements for risk assessment according to the class rules and for alternative design according to 2014:1 were also somewhat scaled down compared to what would have been performed on a large ship.

2.3 Arrangement and design

2.3.1 Pilot 729SE General

Table 2-2: Pilot 729 SE main particulars

Name	Pilot 729SE	
Year built:	1996	
Yard:	Smögens plåt och svets	
L_{OA}	12.6	m
L_{PP}	11.1	m
$Breath_{moulded}$	4.16	m
$Depth_{moulded}$	1.05	m
Draught	0.7	m
Class	NBS Y 90	
Hull material	Aluminium	
Superstructure	Composite	
Lightship	11	ton
GT/NT	20/6	
DWT	1.5	ton
Max speed	32	kn

The vessel is constructed with an aluminium hull and composite cabin. The cabin rests in a recess in the hull. The space between the hull and cabin is drained towards the side of the vessel and a rubber seal is fitted along the deck to prevent water entering from above.

The engine compartment is located to the aft, providing good access to the engines for a conversion project. A hatch is located aft of the cabin for access to the engine compartment from deck. Two engines are fitted in parallel, powering the two waterjets. Both engines are equipped with a generator for charging the starter batteries and consumption batteries respectively. The engine compartment also holds the electrical switchboard, fire pump and a diesel boiler (no longer in service).

Forward of a watertight bulkhead, below the cabin, is the location for the fuel tanks and batteries. Goosenecks to the deck provide ventilation for the space.

The forepeak is accessible from deck and used as storage for some emergency and lifesaving equipment.

The engine room is protected by a CO_2 total flooding systems. The manual release point and CO_2 bottles are located inside a cabinet aft on deck. The cabinet also holds the ventilation fans for the engine room and manual fire dampers. When the cabinet is open an alarm is sounded in the machinery room.

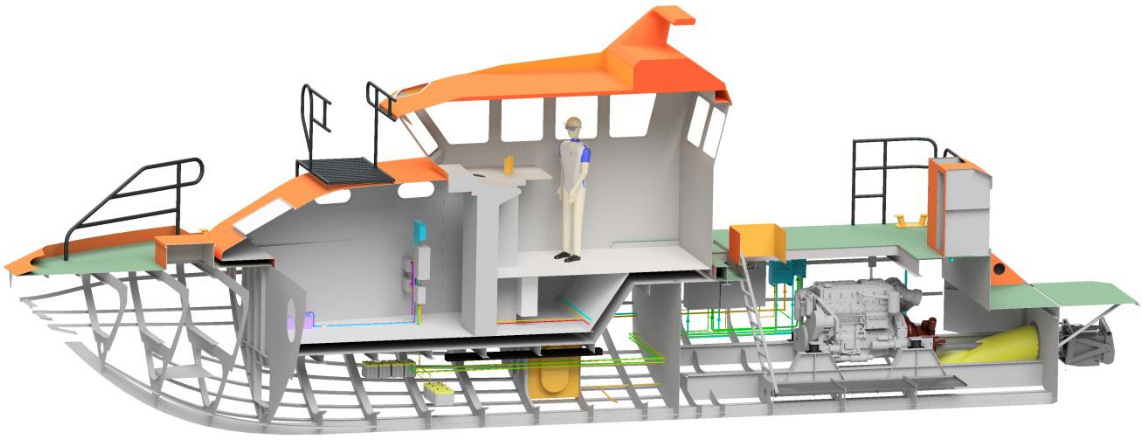


Figure 2-3: Half section view of the pilot boat before conversion.

A door from aft deck leads in to the cabin. The top part is dominated by the steering position, all navigation equipment and alarm panels. Half a stair down in the forward part is a small galley, table and a door to the toilet. A fuse box, mostly for the navigation equipment, is also located here. Behind the small stairway is an entry to the electrical compartment located below the steering position.

2.4 Methanol conversion

The basics of the methanol conversion included changing the port side engine to a methanol engine, installing a new fuel delivery system for that engine, and installing new methanol fuel tanks. Auxiliary systems work included new control systems, methanol vapour detection and upgraded fire detection and suppression systems. The original engine speed control system was kept intact and used also for the methanol engine.

One diesel engine was retained for redundancy during testing of the methanol system. For usability of the boat two similar engines would be better but drivability of the vessel was also good with two different engines.

For the methanol engine, two different engines were used during the trials; one Weichai 12l engine, converted by Fitech, and one Scania 13l converted by ScandiNAOS. Both engines are spark ignited and port fuel injected with similar performance.

2.4.1 Methanol fuel tanks and tank room

The fuel tanks need to be installed in a separate compartment that is ventilated to the outside. The space between the diesel tanks and engine room was identified as the best alternative for a new tank room. The battery banks originally located there were moved forward of the diesel tanks and a new bolted hatch installed on the partial bulkhead to the aft of the diesel tanks. The new methanol tank room is insulated with A60 fire insulation on the forward and aft bulkhead and below the deck. A new bolted hatch was cut in the engine room bulkhead for installation of the fuel tanks.

A ventilation fan was installed in the compartment in case of methanol leakage from the tanks or during service. The ventilation fan is controlled from the steering position and is turned off during normal operation.

2.4.2 Fuel tanks

Two independent fuel tanks were installed in the new tank room, as pictured in Figure1. The fuel tanks are symmetrical and constructed of stainless steel (EN 1.4404). Each tank is fitted with remote operated fuel valves and nitrogen inertion. Fuel return lines from the engines are installed, but not in use. The tank ventilation from each tank was merged to a common ventilation pipe that extends up to the higher part of the cabin on port side.

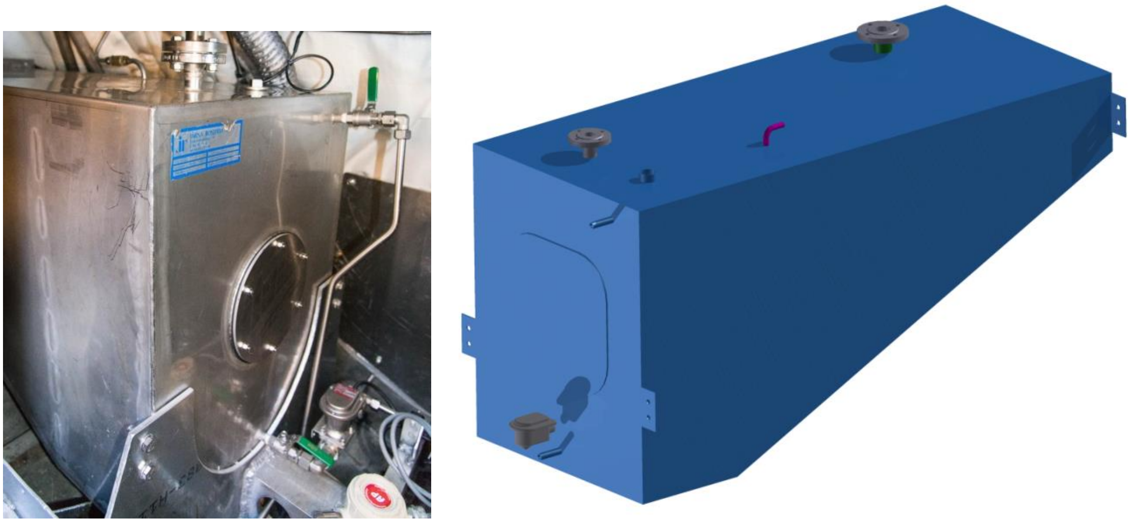


Figure 2-4: Port side fuel tank installed in the methanol tank room. The solenoid fuel valve and vapour detector are also visible in the image. To the right a model of the fuel tank I presented. Two tanks were installed, each with 440 l volume.

The tank capacity is 440 l for each tank. Level measuring is done with mechanical float level transmitter meters connected to the automation system.

2.4.3 Inert gas system

The methanol fuel tanks are inerted with nitrogen in line with the rules for larger ships. Nitrogen is stored in two pressure bottles in a cabinet on deck, as shown in Figure 5, with supply pipes to both tanks.

The nitrogen is used to supress oxygen content in the fuel tanks. A small overpressure of about 100 mbar is used to supress fuel vapours in the tanks and to ensure adequate nitrogen pressure. To sustain the overpressure a mechanical P/V valve is used on the end of the tank ventilation pipe. When the pressure of the tanks rises, as during bunkering, the spring loaded valve opens and exhausts nitrogen. The valve also opens if there is vacuum pressure in the tanks, e.g. if the nitrogen system fails and the methanol engine is running, to prevent damage to the tanks.

Figure 2-5: The nitrogen cabinet on deck. Two bottles are connected but one is in use.

The inertion pressure is controlled by an electrical pressure reducer located in the nitrogen cabinet on deck. The supply pipes enter the tank room from above and are not drawn through any other closed compartments on the vessel. This minimizes the risk of leakage in any compartment that could lead to oxygen starvation. If nitrogen is stored in a closed compartment that allows for entering there should be equipment to ensure sufficient oxygen content in the atmosphere before entering.

Figure 2-6: The P/V valve open during bunkering to exhaust nitrogen from the tanks. If the nitrogen system is unavailable during operations the P/V valve will also open to prevent vacuum pressure in the fuel system. The valve is fully mechanical.

Nitrogen inertion is a requirement in the LR rules for methanol, as shown in the text box below. There are also requirements for purging fuel pipes and bunker piping with nitrogen - for the pilot boat these parts of the class requirements were not implemented as the volumes are small.

LR provisional rules for classification of methanol fuelled ships (2016). Ch1 Sec6

6.8.1 Provisions shall be made for supply of nitrogen inert gas. This shall be either through on board generation of inert gas or through an inert gas storage system with provision for refilling from shore.

6.8.2 The inerting arrangements shall provide for:

a) inerting of all fuel piping during normal operation and emergency shutdown activation;
b) inerting of methanol-fuelled consumers;
c) atmospheric control (e.g.., double wall piping annulus and maintaining tank vapour spaces in an inert condition at all times);
d) fire protection systems

6.8.3 The inert gas system shall be able to maintain a pressure of at least 0.007 MPa gauge within the fuel storage tank(s) at all times. The inert gas system shall not raise the fuel storage pressure to more than the tank's relief-valve setting.

2.4.4 Fuel supply

Mounted on each fuel tank are solenoid fuel valves that allow for remote operation of the fuel supply. Normally these valves are closed when the engine is not running and they open upon starting the engine. The pipes from each tank merge to a common supply pipe, this allows for some overflow between the tanks when both valves are open.

The fuel pipes are single walled inside the tank room. Before penetrating the engine room bulkhead the supply pipe is double walled to prevent leakage in case of damage to the inner pipe. Double walled piping is required by the class rules and draft IGF code. The annular space is not ventilated on the pilot boat application but is used as a secondary boundary.

Fuel pumps and fuel filters are contained inside a steel box, referred to as the "pump chest", in the engine room. The pump chest will contain any potential leakage of the equipment and couplings in the box, thus no methanol vapours or liquid spills from a failed pump or filter can accumulate in the engine room. Piping inside the pump chest is single walled as the box is the secondary barrier. The pump chest is equipped with a methanol vapour detector that is monitored from the steering position and triggers an alarm when the vapour level reaches 15 % LEL.

No engine mounted fuel pumps are used on the engine. The fuel pumps in the pump chest supply fuel pressure for the common rail system where double walled fuel pipes go between the pump chest and engine, both supply and return. The pipes are essentially part of the common rail pressure system. The working pressure is about 4 bar, i.e. it is not a high pressure system.

Figure 2-7: Photo of the open pump chest, looking forward in the engine room. Piping and fuel filters are visible, with the intermediate catch tank visible along the vapour detector closest to the camera. Double walled pipes can been seen entering the pump chest furthest away from the camera, and entering the tank room below to the right of the pump chest.

A small intermediate catch tank is used in the fuel system, located inside the pump chest. The fuel pumps are controlled from the steering position together with controls for the fuel valves.

For a system with multiple engines, of the current design, each engine would be equipped with an independent pump chests to ensure redundancy and the possibility of shutting down the fuel supply to an individual engine in case of failure.

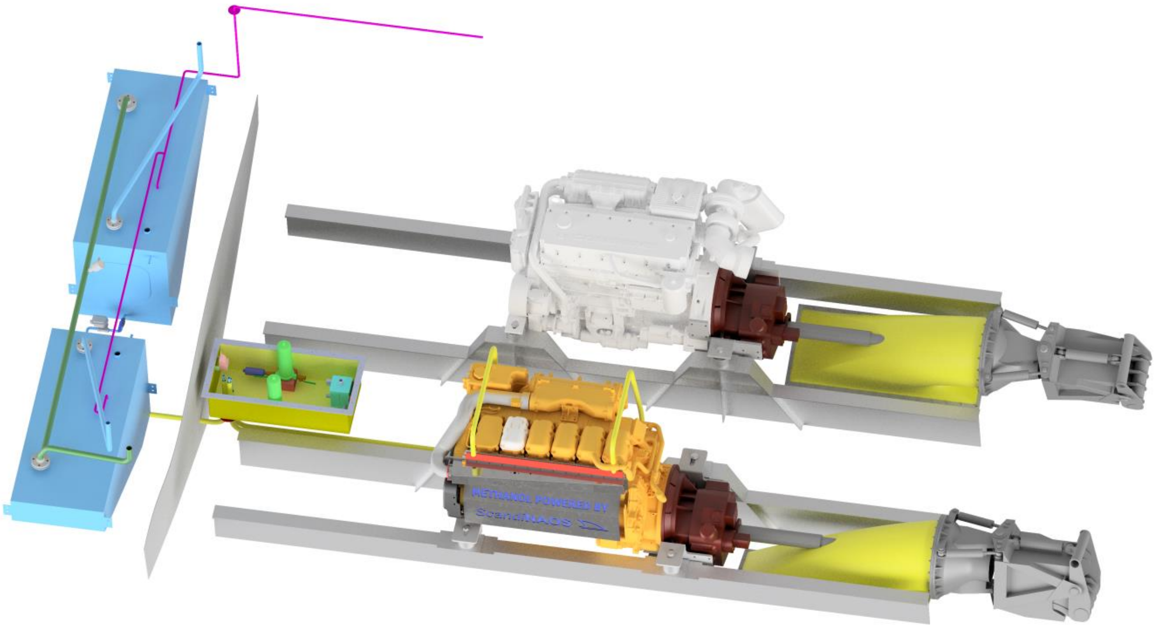


Figure 2-8: Render of the fuel system and engine installation. The methanol fuel tanks are located in a compartment forward of the engine room. In the engine room, the filters and fuel pumps are located inside the pump chest. Methanol fuel pipes go from the pump chest to and from the methanol engine on the port side.

The philosophy of the use of pump chests is to minimize the possibility of leakage and to control the possible leakage locations. Damage to the double walled fuel pipes that would cause leakage is highly unlikely; leakage from a damaged fuel pump or loose connection are much more probable and thus containing these areas inside the pump chest where leakage can be handled in a safe way greatly raises the safety and limits the risks.

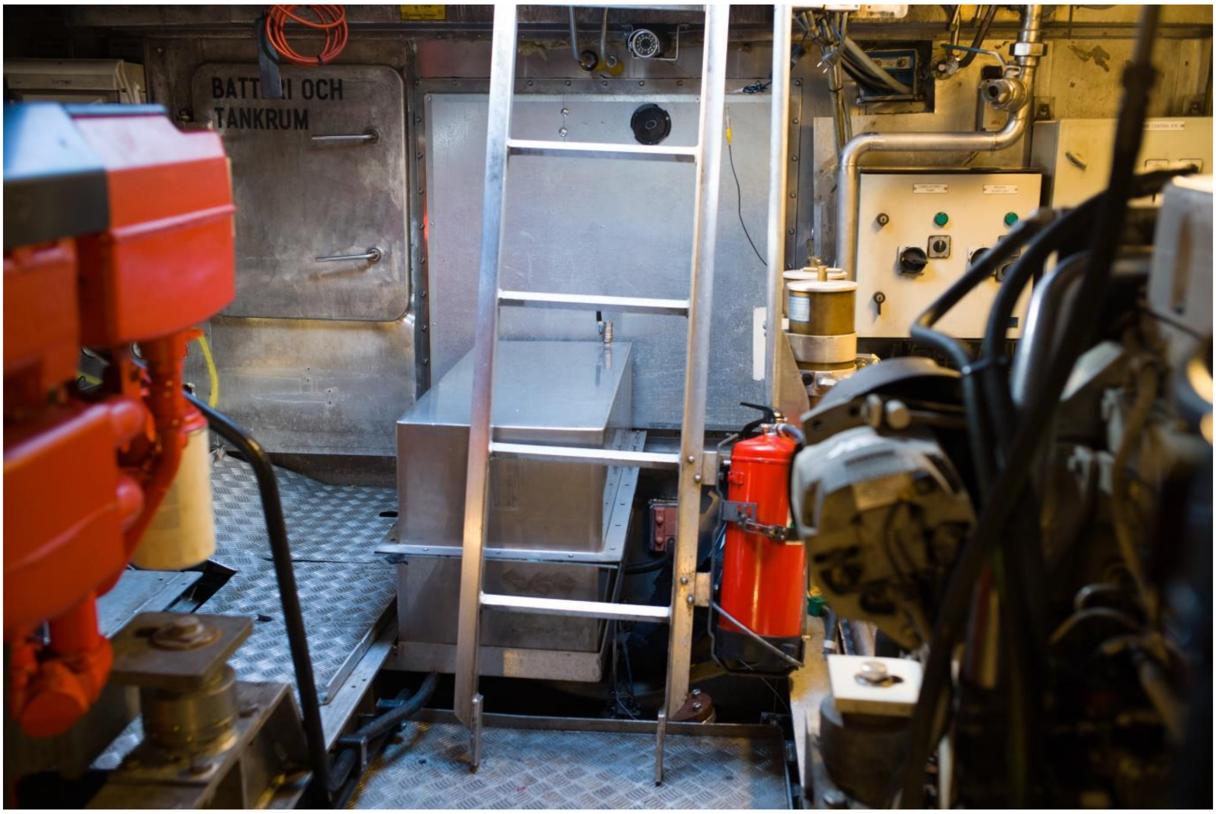


Figure 2-9: The closed pump chest.

The other area where leakage is more likely is on the engine and where the double walled pipes connect to the fuel rail. Suggestions of how to protect this area have been tried and evaluated but no protection is currently in use. During testing no incidents of leakage from the pipe connection or fuel injector connections to the fuel rail have been detected.

2.4.5 Automation and alarm

A new automation and alarm system was installed. The automation system was built around a programmable logic controller (PLC) situated in a new electrical cabinet in the engine room. The PLC monitors the methanol fuel level, tank pressure and all gas detectors as well as some diagnostic equipment such as fuel flow meter and torque meter on the output axle from the gearbox. The PLC also controls the fuel valves and fuel pumps.

A Human-Machine Interface Display (HMI) is installed along the navigational instruments in the cabin for monitoring of all parameters of the methanol system. All vapour detectors, fuel parameters and tank levels are visible there during operation.

PLC installation

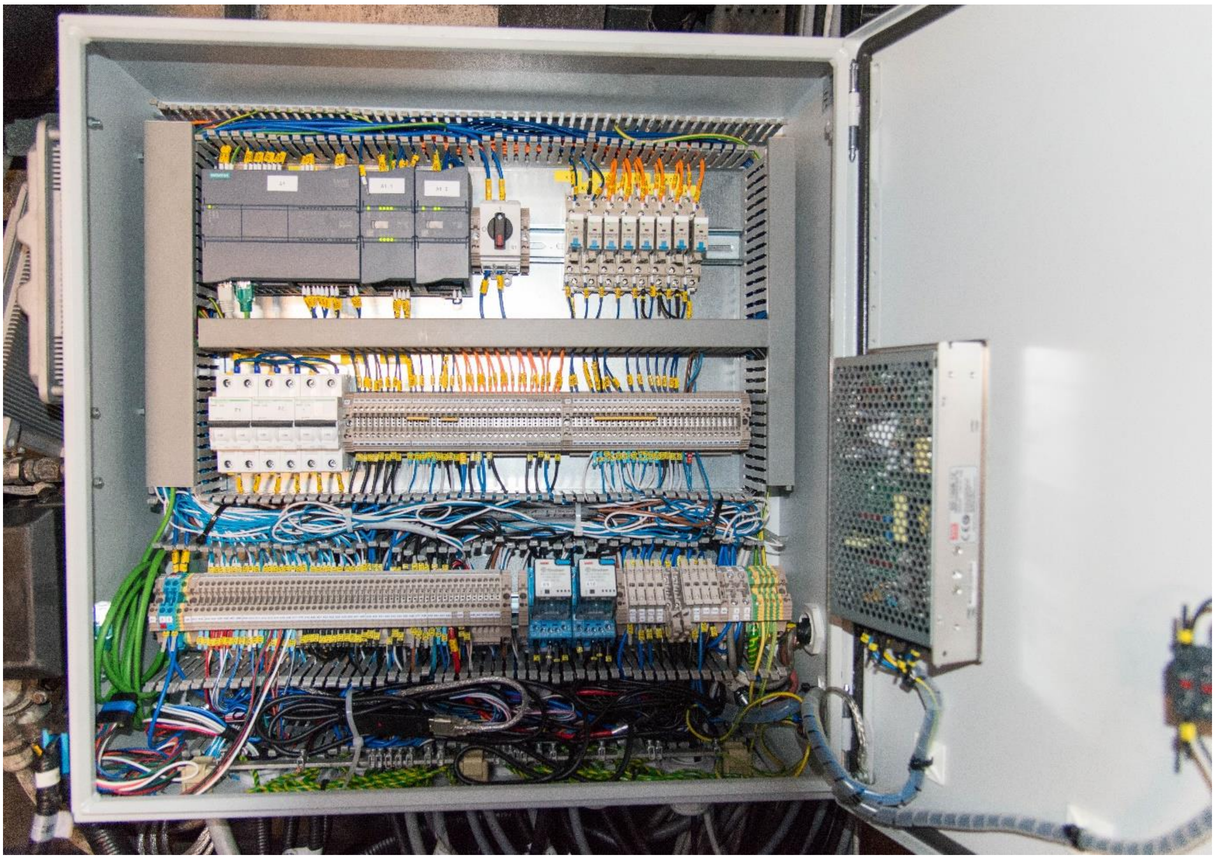


Figure 2-10: The PLC installation in the engine room. All the new sensors are connected to the cabinets. The methanol fuel pumps and fuel valves are also controlled by the PLC.

HMI panel

For control and monitoring of the methanol system a HMI-panel was installed in the cabin. All sensor data used by the PLC can be displayed on a number of different screens where a vessel overview and a performance monitor view are the most used. The HMI is also the interface to view the level in the methanol tanks and to view and acknowledge alarms from the system.

Figure 2-11: The HMI panel at the steering position.

Vapour detection

Vapour detectors are mounted in three locations on the vessel: low in the middle of the tank room, inside the pump chest and above the methanol engine. The sensors detect methanol vapours in air and output the concentration as %LEL from 0 to 100 continuously. The vapour detectors provide a 4-20 mA signal to the PLC and are powered by 24 VDC.

Figure 2-12: The gas detector in the methanol tank room. Also partly visible are the manual and solenoid master fuel valves for the methanol tanks.

Three detectors are installed for detection of leakage. During work on the fuel system before first start of the Scania engine a small leakage occurred at one fuel injector to fuel rail connection. This was immediately picked up by the detector above the engine.

2.4.6 Fire prevention and protection

As methanol does not produce any smoke during combustion the fire detection system must not rely exclusively on smoke detectors. The on board system has therefore been expanded with heat detectors in the tank room and engine room. The tank room detector is connected to a second spare loop on the detection system. No further modifications have been made to the detection system for methanol compatibility

Gas total flooding

The boat is equipped with a CO_2 fire suppression system that is manually operated from a gas cabinet on deck. In order to provide sufficient extinguishing power for a methanol fire the CO_2 gas concentration needs to be higher as compared to that used for a diesel fire (minimum 55% instead of 40%). The two bottles that are used for the system have been determined to be sufficient to supply the necessary concentration without upgrade and is thus retained in original form.

For the tank room a separate gas system is used with Inergen. A single unit with gas container and automatic heat-induced release valve is installed inside the compartment. The system is similar to units used for engine room protection in recreational crafts. The installation is considered safe as the tank room cannot be entered and there is no risk of oxygen deprivation. The tank room is gas and water tight towards the machinery room.

Fire extinguishers

The boat is equipped with portable fire extinguishers in the machinery room and cabin. All extinguishers are of powder type, which has been shown to have good effect on methanol fires. In terms of compatibility all common types work well with methanol but for foam extinguishers it is important to ensure that the foam agent is alcohol resistant. The type of extinguishers used should also be effective against diesel fires and electrical fires.

2.5 Engine conversions

Three engines have been converted to run on methanol in the project. Of these three engines two have been installed and tested in the pilot boat. The two engines tested on board were built with the same combustion concept with spark ignition. The third engine is compression ignition.

Spark ignited engines

Two engines have been converted to run on 100% methanol. One is a Weichai, originally CNG powered, and the other a Scania, originally diesel powered. Both engines have been modified to run as spark ignited (SI) with port fuel injection (PFI). Both are six-cylinder engines with total cylinder volume of 12L (Weichai) and 13L (Scania).

PFI is a well-known technology used in many applications; among these are the majority of gasoline and gas engines. The fuel is injected before the inlet valves via electrically controlled fuel injectors, which lets the fuel enter the cylinders together with the air.

One advantage of using PFI onboard ships, compared to other common injection methods, is the low fuel pressure needed, normally 3-5 bar. The fuel pressure impacts the complexity of fuel pumps, injectors, fuel pipes and fire safety. PFI will also provide good fuel-air mixture before ignition, this minimizes the risk for droplets of fuel and contributes to desired combustion properties, as well as clean exhausts.

The physical properties of methanol make it suitable for different types of combustion. PFI-SI engines belong to the most promising combustion concepts. Methanol has a high octane rating, high heat of vaporization and high oxygen content. The high octane rating and cooling effect make methanol less susceptible to knock (uncontrolled pre-ignition) and it is therefore a well-suited fuel for spark ignition. The reduced knock tendencies of methanol can be utilized with an increase in compression, leading to higher efficiency and higher power output.

Methanol is less likely to form soot emissions because it is a simple molecule with one carbon atom, and it contains oxygen. The cooling effect from fuel vaporization will reduce emissions of NO_x.

Spark ignited engines can run stoichiometric with a three-way catalyst or lean burn with an oxidation catalyst that reduces emissions.

Methanol is a single-component fuel (one type of molecule) with a specific vapor pressure and boiling point; this is not the case for gasoline, diesel and most gas fuels where variations in the chemical composition require higher tolerance and therefore less optimized engines.

In a cold engine it can be difficult to vaporize enough fuel to reach an ignitable mixture. Potentially this could make low-temperature cold starts difficult.

2.5.1 WeiChai – FiTech

The originally CNG powered Weichai engine was converted to run on methanol. The concept and calibration of the methanol engine were done by FiTech in Chongqing, China. FiTech supplied the engine, methanol components and software. The physical conversion of the engine used in the pilot boat was done in Sweden.

The engine is port fuel injected and spark ignited. It produces an output power of 313 kW at 2200 RPM and maximum torque of 1530 Nm at 1500 RPM.

Originally the CNG concept relied on SI-single point fuel injection. The combustion concept, cylinder heads, spark plugs, and compression ratio is original. Added is throttle air control, port fuel injectors, modified inlet manifold and an engine control unit calibrated for this engine. See Figure 2-13.

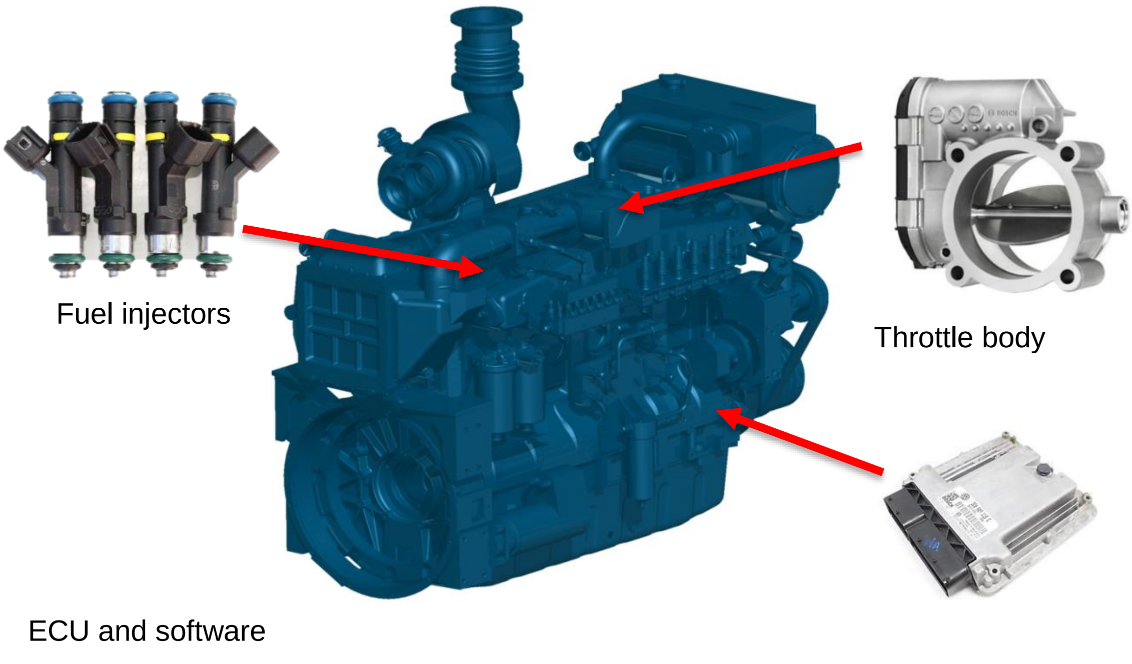


Figure 2-13: Weichai engine with modifications made for the GreenPilot Project

2.5.2 Scania SI

A six-cylinder Scania diesel engine has been converted to run on methanol, relying on SI-PFI technology. Many of the components are similar and well suited for both concepts. The conversion was mainly related to systems for air and fuel supply, ignition and engine control. See Figure 2-14:, which shows new components.

Diesel injectors were replaced by spark plugs, the inlet manifold was custom made to fit fuel injectors, pistons were replaced with lower compression (compared to diesel) versions, and the engine control unit was calibrated for this specific engine.

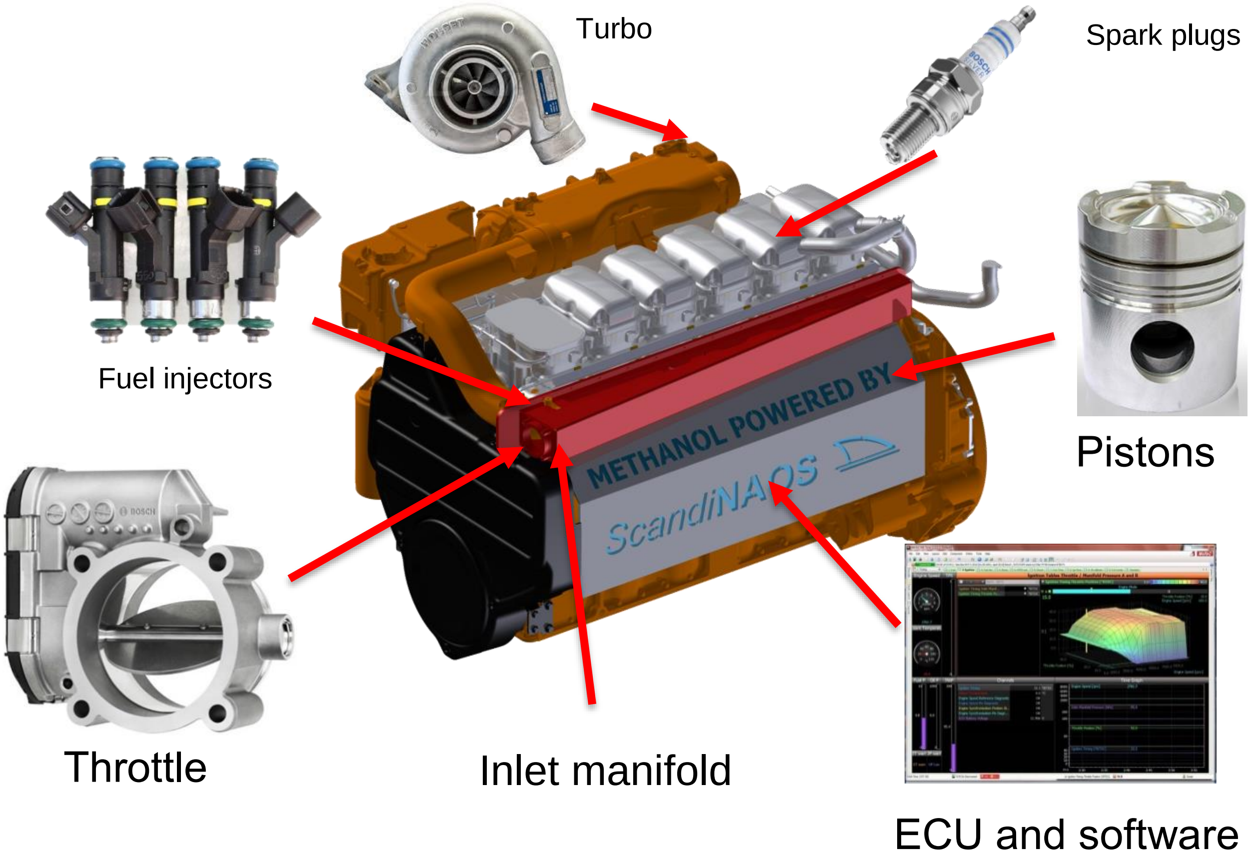


Figure 2-14: Scania engine with components added for the GreenPilot project conversion

2.5.3 Scania MD95

The third engine converted was a compression ignition engine based on the Scania ED95 concept. The engine is basically a conventional diesel engine but equipped with larger fuel injectors and high compression pistons. The fuel used is methanol blended with an ignition improver. The ignition improver, together with the higher compression ratio, allows for the fuel blend to self-ignite in the cylinder. The ignition improver is required because pure methanol has poor self-ignition characteristics.

In contrast to the port ignited engine the MD95 engine has a high-pressure common rail fuel system with a mechanically driven engine mounted fuel pump.

2.6 Bunkering

On each side of the boat there are bunkering connections that are connected to the corresponding tank. By opening the fuel valves on the tanks there will be some overflow from one tank to the other but not enough to allow bunkering on only one side.

The bunker connections used are of the dry-disconnect type that prevents any leakage of fuel during bunkering. These minimize the risk of spillage and also prevent the crew from coming in to contact with methanol. When the hose and boat are disconnected both sides will be sealed.

The bunkering arrangement on land can be either from a stationary tank or a portable one. During testing a portable option was used that allowed for easy movement of the bunker station. The setup is very simplistic with an IBC (intermediate bulk container) tank and portable electrical pump. The pump is powered by 230 VAC either from a shore connection or from the boat.

Remote, wire controlled, control of the pump is used where the operator needs to continually press the button during fuel transfer.

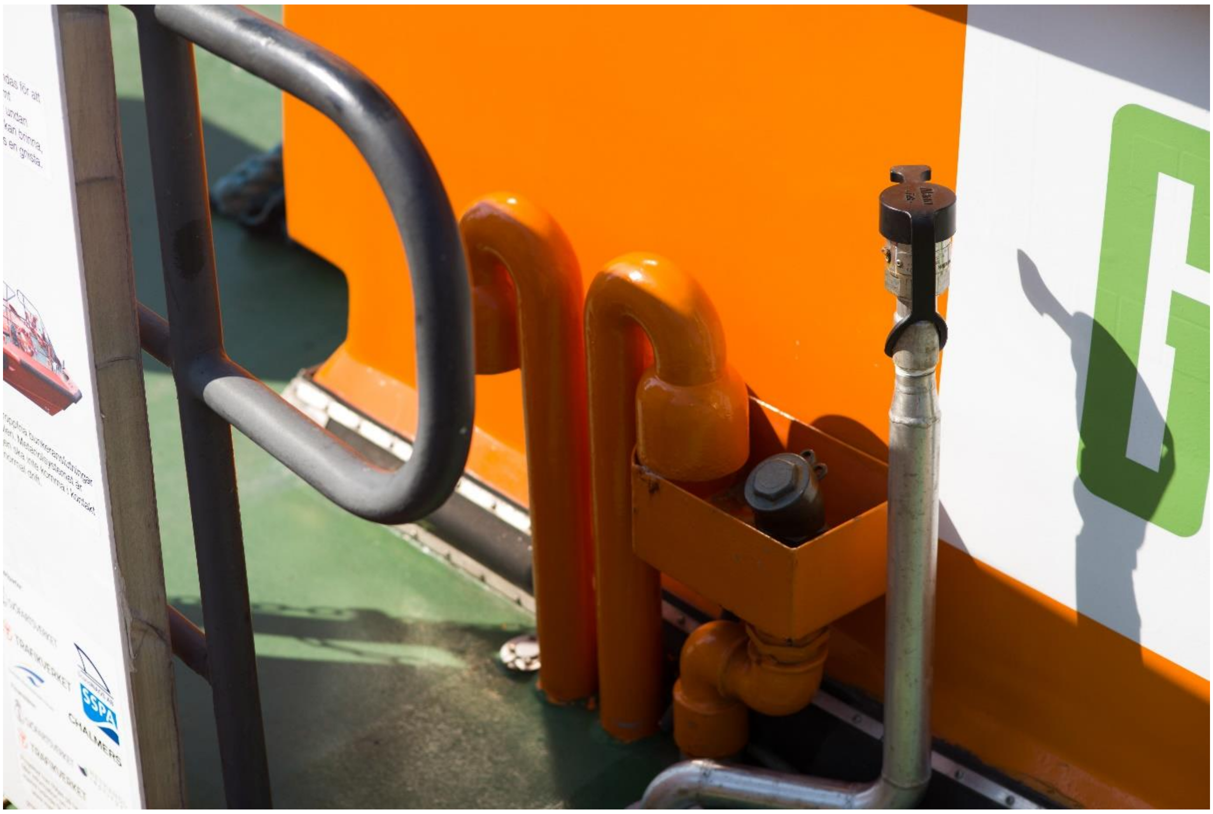


Figure 2-15: The bunker connection for methanol forward of the diesel bunker pipe.

During bunkering the immediate area around the portable tank and bunker manifolds are considered hazardous and all electrical equipment used inside shall be EX-classed.

Safety equipment such as goggles and gloves are advised during bunkering.

A checklist has been developed for bunkering to ensure safe operation. The checklist is attached as an Appendix VII.

2.7 Economic Analysis

The cost of the Swedish pilot operation is about 500 MSEK per year. The fuel cost is roughly 12 million MSEK. The cost of renewable fuel is about twice as expensive compared to fossil fuel. Total change over to renewable fuel would increase the total Swedish pilot operation with 12 MSEK or 2.4%.

For a new building the additional cost for a methanol operated pilot boat compared to a conventional diesel operated pilot boat is estimated to be approx. SEK 800 000. This includes adaptation of the standard engines, additional structural insulation, gas detection, double walled piping, nitrogen tank blanketing and a control and monitoring system that also covers methanol specific systems.

For an existing pilot boat, the conversion should be scheduled when the boat is due for engine change. The estimated additional cost to also make a methanol conversion in relation to a scheduled engine change is approx. SEK 1 000 000 – 1 300 000. The higher cost compared to new building is due to structural works related to modification of fuel tank, tank rooms, ventilation, replacement of existing piping and insulation.

3 Hazard Identification and Safety Assessment

Work carried out to assess the safety of the methanol system installed on board pilot boat 729, to minimise risks during testing of the system, and to identify potential safety issues, included the following:

- Preliminary Hazard Identification sessions carried out by Lloyds Register in Copenhagen
- Hazard review meeting with project team members and the Swedish Transport Agency
- Preparation of a Hazardous Area Plan for pilot boat 729
- Review of previous accident and incident data for Swedish pilot boats.

These are described in more detail in the following sub-sections.

3.1 Hazard Identification

A preliminary hazard identification study was conducted for the GreenPilot methanol conversion design prior to the actual conversion of the vessel. At the time of the hazard identification workshops the design of the systems was to a large degree completed, which allowed for a practical review and evaluation of the proposed design to find areas for improvement. This section is mainly a description of the formal preliminary hazard identification study done together with Lloyds Register (LR) in Copenhagen. During the design phase informal hazard and safety assessment discussions were an integral part of the work, and were conducted as part of evaluation of different design proposals based on previous experience of methanol systems design for the Stena Scanrail (SPIRETH project) and Stena Germanica conversion project.

The aim of the risk analysis was to ensure that the proposed design would be at least as safe as a conventional design. The rules referred to for the requirements were the LR Provision Rules for the Classification of Methanol Fuelled Ships. The pilot boat is not subject to class rules and is significantly smaller than classed ships – this has a large impact on which requirements are feasible. Although not all class rules could be applied, they were used as the basis of the study.

The preliminary hazard identification study was arranged as a workshop at the LR offices in Copenhagen and was attended by experts from LR and the design team from ScandiNAOS. All of the methanol and auxiliary systems were reviewed together with a basic operational profile for the boat where general risks with methanol use were addressed. The workshop was conducted during two separate occasions where some of the remarks from the first day were addressed before the second session took place.

In order to systematically work through the design a number of nodes were used to encourage discussions around the different systems. The nodes are presented in Table 3-1.

Table 3-1: Preliminary HAZID Study Nodes.

Nodes	
Equipment and Location	Methanol tank room and fire insulation
	General arrangement
	Methanol pump chest
	Methanol piping
Operational modes	Sailing, normal operation
	Sailing, heavy weather

	Sailing, methanol systems not working
	Bunkering
Failures	Methanol leakage in tank, pipe or valves
	Fire

3.1.1 Conclusions and comments

The hazard identification work resulted in a Hazid Study report from LR where the GreenPilot boat methanol system was reviewed. The full report is attached as Appendix VI. The key items identified in the study report are discussed below.

Location of the p/v valve for the methanol tank should be carefully considered.

During the design process the proposed location of the P/V (pressure/vacuum) valve was changed a number of times. The first suggestion was a mast on aft deck, inspired by the requirements in the rules, that would be separate from the cabin. This solution offered the best possibility to be in line with the rules but introduced a large risk of being damaged, especially during operation in heavy weather when receiving or leaving a pilot on another ship.

The final solution was to arrange the valve on port side of the cabin, forward of the bunker manifold.

During normal operation the valve will remain closed. During bunkering it will ventilate nitrogen from the fuel tanks. In case of failure of the nitrogen system a vacuum pressure inside the tanks will build until the valve opens at which time air will be allowed in to the tanks to restore atmospheric pressure.

Ventilation and ex safe requirements for the pump chest need to be further considered.

Ventilation of the pump chest is another area where the design has iterated during the process. The final decision was to have no active ventilation of the pump chest. Instead two valves are fitted to the box in order to drain any possible methanol leakage.

Ventilation requirement in the methanol tank room to be confirmed.

The tank room is equipped with an in-line fan for extraction of air from the tank room. Air is drawn from a low point in the middle of the room and exhausted on starboard side of the vessel. The fan can be turned on from the control panel in the cabin. During normal operation the fan is not running and the pipe allows for some natural ventilation of the compartment.

If the methanol detector inside the tank room indicates methanol vapours the fan is used to ventilate the compartment. The fan is spark resistant according to recreational craft ISO-standards.

Bunkering operations need to be further considered.

A bunkering checklist has been developed and is attached in the report as an appendix.

The missing double block and bleed arrangement to be further considered.

Double block and bleed is not a requirement for methanol installations. The concept is used for LNG and gaseous fuels where fuel can be trapped between two closed valves and create high pressures when evaporating. This is not relevant for fuels that are liquid at ambient temperature and pressure.

The outer pipes of the methanol double pipes to be further considered, as they are not ventilated or pressurized.

Double walled pipes are used in order to minimize the risk of methanol leakage. The annular space is not ventilated but open towards the pump chest. In case of leakage of the inner pipe methanol will be drained to the pump chest where the methanol detector will indicate leakage. The pump chest is considered safe and leakage will not result in an immediate danger.

All existing installations need to be included in the modification drawings, as pipes and cables passing through the methanol tank room were not shown on the current drawings.

The issue relates to the arrangement of the tank room between the engine compartment and the cabin. As the tank room is located forward of the engine compartment all cables and pipes pass right through the compartment. This includes communication interfaces as well as electrical power cables. All cables are of fire retardant material and no connections or joints are located inside the tank room. The cables are not cause for any foreseeable risk but would preferably be routed differently if the possibility existed.

3.2 Hazard review meeting prior to sea trials

After conversion work was completed on the vessel, a meeting and on-board review was carried out prior to sea trials. As the vessel was a demonstration platform only and the engine had not been adapted for commercial use, the full system did not undergo formal approval and certification for the pilot testing.

The meeting attendees included the ScandiNAOS design team, a representative from project partner SSPA, a Swedish Transport Agency representative, and a Swedish Maritime Administration representative. The meeting took place on 20170406 at ScandiNAOS offices and included a visit on board the pilot boat to review the installed system. The latest version of the design was presented and the key items identified in the Preliminary Hazard Identification Study report as described above were reviewed. Items discussed included the location of the p/v valve, location of detectors (heat, smoke, and methanol detectors), ventilation, and the pump chest, among other issues.

3.3 Hazardous area plan

A hazardous area plan is used to identify areas where flammable liquids, vapours or gas can be expected to exist, and to restrict access and ignition sources as appropriate for the level of hazard. A hazardous area plan for the pilot boat was developed according to the general principles from the LR rules for methanol fuelled ships. The hazardous areas definition and the prescribed hazardous zones around points such as ventilation outlets is one of the class rules which is the least suitable for use on smaller vessels. It is neither possible nor reasonable to use the large safety zones prescribed in the rules and it is important to remember that the rules were developed for ship applications where the methanol fuel tanks alone are many times larger than a smaller boat. Thus, the possible worst case scenario of flammable vapour volume will also be very different.

The general idea of hazardous area classification is, however, is still relevant to smaller vessels. The class rules and IGF code define the areas similarly. The DNV-GL rules have a good definition as quoted in Table 3-2.

Table 3-2: DNV-GL Hazardous Area Definition

DNV-GL Rules for classification - Part 6 Chapter 2 Section 6	
Part 6 Additional class notations	
Section 6 Low flashpoint liquid fuelled engines - LFL FUELLED	
Hazardous areas is an area in which an explosive gas atmosphere is or may be expected to be present, in quantities such as to require special precautions for the construction, installation and use of electrical apparatus. Hazardous areas are divided into Zone 0, 1 and 2 as defined below and according to the area classification specified in [5.2].	
Zone 0 =	Area in which an explosive gas atmosphere is present continuously or is present for long periods.
Zone 1 =	Area in which an explosive gas atmosphere is likely to occur in normal operation.
Zone 2 =	Area in which an explosive gas atmosphere is not likely to occur in normal operation and, if it does occur, is likely to do so only infrequently and will exist for a short period only.
Guidance note: The definition of hazardous area is only related to the risk of explosion. In this context, health, safety and environmental issues, i.e. toxicity, is not considered.	

The class rules define areas that are to be classified as hazardous. The inside of the fuel tank is Zone 0 and the methanol pump room (also tank room and pump chest) is classified as Zone 1. Deviations from the regulations are necessary on open deck as the rules define a radius around ventilation openings and the tank P/V valve which is not suitable for smaller vessels.

The illustration below in Figure 3-1shows the hazardous zones identified for the pilot boat. During normal operation the areas on deck as well as the air in the pump room will not contain any traces of methanol. During bunkering the P/V valve will open but as the methanol fuel tanks are inerted with nitrogen the ventilated gas from the tanks will not be flammable.

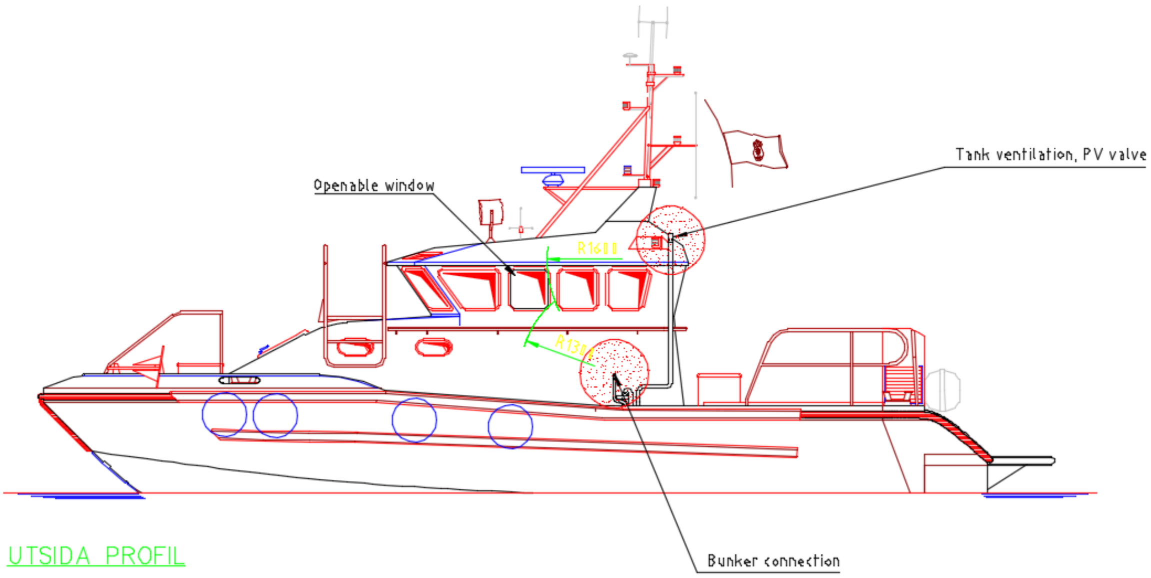


Figure 3-1: Part of the Hazardous area plan, SNP15091-707, showing port side of the pilot boat. The circles indicate hazardous areas of zone 2. The full Hazardous area plan for the pilot boat is attached as an appendix.

3.4 Previous accidents and incidents

A review of data from the Swedish Sea Accident (SOS) database (SOS: "SJöOlyckssytem") was carried out to identify any types of accidents or incidents with pilot boats that may result in different consequences for a methanol fueled vessel as compared to one operating on conventional fuel oil. SOS is a national casualty database that contains information on accidents and incidents involving Swedish flagged vessels in all waters, and vessels of all flags in Swedish territorial water. Reportable accidents to this database include events that may have resulted in personal injury or death, ship damage, or escape of harmful substance (spill). Three categories are used to describe the severity of the event: serious accident, minor accident, and incident.

Data on accidents and incidents involving Swedish pilot boats over the 10-year period from 2007 to the end of 2016 was obtained from the SOS database and is summarized in Figure 3-2.

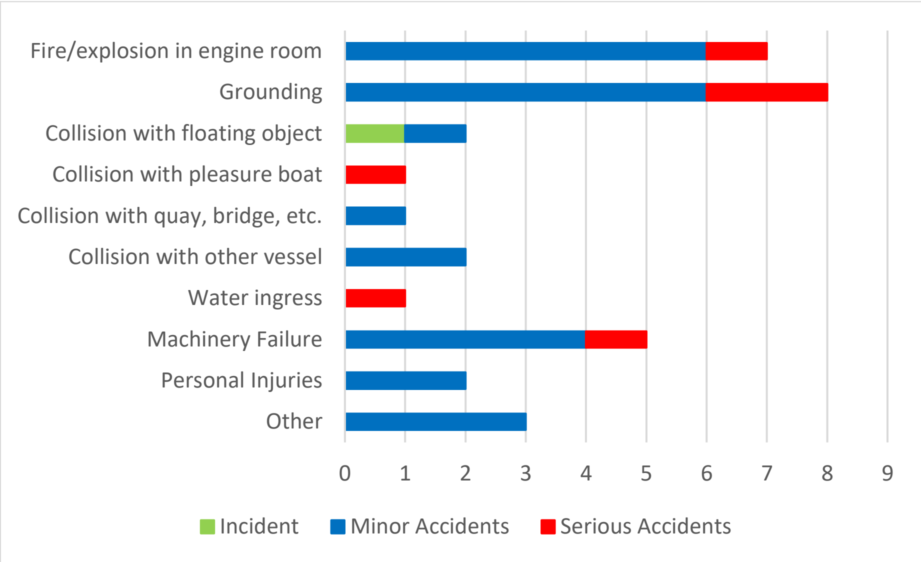


Figure 3-2: Accidents and incidents involving Swedish Pilot Boats – 20070101 to 20161231 (Data from the SOS database)

There were six serious accidents involving Swedish pilot boats during the ten-year period assessed. Only one of the serious accidents was caused by fire/explosion in the engine room, and this was described to be caused by a fuel oil filter leakage and spray of fuel oil onto a hot surface. The two serious grounding accidents resulted in the pilot boat being completely or partly out of the water after hitting small islands or rock outcrops. Both of these cases were attributed to human error. Although there was hull damage, there was no leakage from the fuel tanks in either case. None of the other serious accidents or incidents resulted in leakage from the fuel tanks.

4 Performance Testing and Field Tests

The pilot boat has been subjected to several field tests in order to evaluate the performance before and after the conversion. The Weichai engine has also undergone further tests on land for more controlled emission measurements and performance evaluation analysis.

Instrumentation has been installed on board for measurement of output torque to the water jet, combined with continuous measurement of the fuel consumption and engine speed, the power and efficiency can be monitored continuously from the steering position during operation.

4.1 Baseline performance evaluation

The goal of the first field test was to evaluate the performance of the two originally installed diesel engines in order to have a benchmark for comparison of the methanol engines. By monitoring engine power and vessel speed a propeller curve was plotted that was used for mapping and calibration of the methanol engines.

4.1.1 Execution

The test was completed in the outlet of the river Göta älv, Gothenburg in October 2016. The test was done starting from low speed and increasing to full speed followed by a mirror run going back to low speed. The current was normal, considered low and the water was calm. Wind was below 5 m/s NW.

The test was static, which means that the engine rpm, load and speed of the boat were stabilised before data was recorded. Since the steady speed resistance of the boat will set the limit for required torque at each rpm, the recorded data describes the engine characteristics, torque, power and brake specific fuel consumption (BSFC) at part load.

The result of the test was a propeller curve with required torque (and power) to engine speed, as shown in Figure 4-1. Maximum torque and power to engine speed was calculated and plotted with dashed lines.

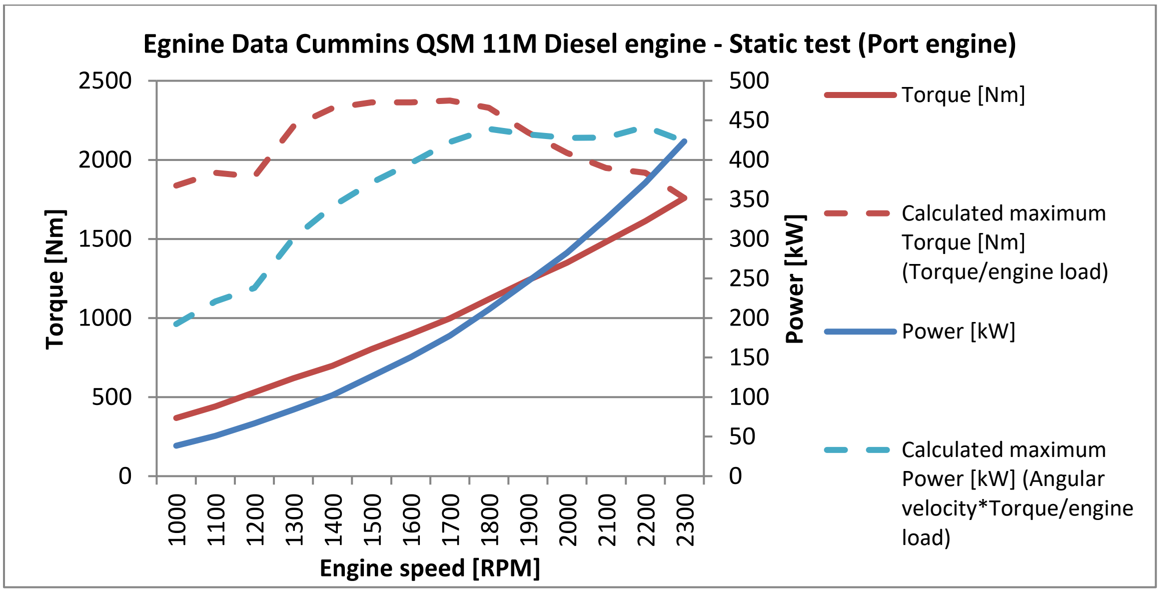


Figure 4-1: Propeller curve generated with test data collected from the baseline testing.

The fuel consumption was also monitored and the fuel consumption to boat speed plotted, as shown in Figure 4-2. The fuel consumption was measured as volumetric flow.

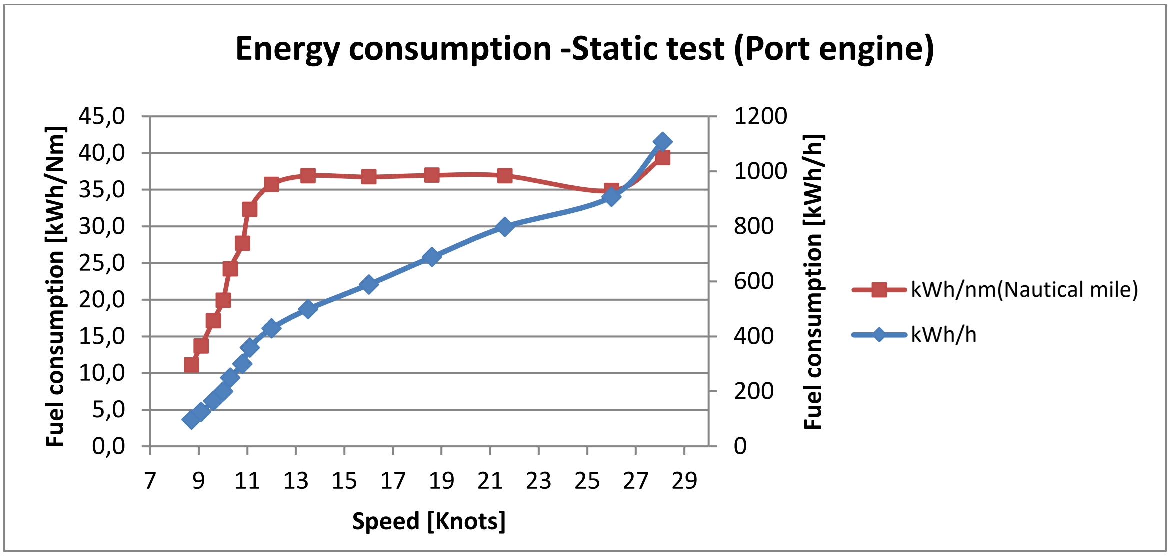


Figure 4-2: Energy consumption, converted to energy, for the port side engine. The required power is independent of engine installation. The volumetric fuel consumption is dependent on engine efficiency and energy content in the fuel.

4.2 Weichai engine

Emission and performance testing of the Weichai engine has been done both as bench testing on land and installed in the pilot boat. Testing on land provides more options and easier access to emission monitoring equipment as well as the ability to control engine load and speed over the full range of the engine. Testing the engine installed in the pilot boat on the other hand provides real world emission levels but the engine speed and load is limited to points along the propeller curve and environmental variables such as air temperature and cooling can not be controlled.

In real driving conditions the efficiency of the engine varies between 33 % to 38 %, depending on engine speed. Figure 4-3 shows the efficiency at various speeds and loads of the engine as well as maximum torque as measured during bench testing. The propeller curve is superimposed on the figure.

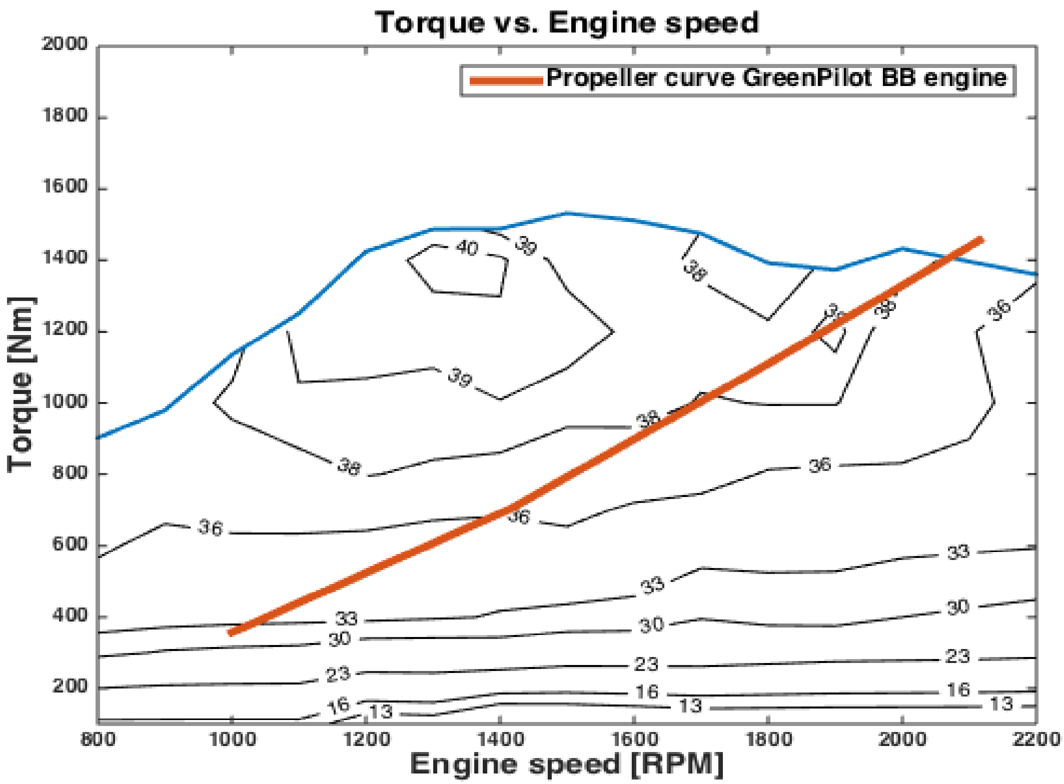


Figure 4-3: Efficiency of the Weichai engine for different engine speed and torque. The red line is the port side (BB) propeller curve of the pilot boat. The blue line is the maximum torque. Installed in the pilot boat the maximum speed of the engine is limited to approximately 2100 rpm as the engine does not have enough torque to follow the propeller line above that speed.

Results from both bench testing and real driving provided encouraging results.

4.2.1 Compliance with IMO NOx requirements

For dyno testing it can be concluded that the engine fulfils IMO NOx code of maximum 1,96g/kWh. The emission standards provide alternative load combinations for the manufacturer to choose from. Independent on which load combination that is selected the engine fulfilled the requirements. The IMO -accepted load combination with lowest NOx emission was “option C” with emission factor of 1,34g/kWh. The real driving proved the low emission factors. The lowest emission factor in real driving condition was “option A” of 2,07g/kWh.

4.2.2 Compliance with Emission standards for inland waterways vessels and European recreational crafts

The European standards regulates emissions of CO, HC, NOx, PM and PN. In the dyno test, NOx and CO was measured. In the real driving test NOx, CO, PM and PN was measured. This lack of HC means that the compliance cannot be fully guaranteed.

The engine fully complies with today’s standard for inland waterways (2007) and the standard for recreational crafts (2013).

The engine also fully complies with upcoming standard for inland waterways, stage V (2020). NOx emissions are, according to EU regulations, calculated to 1,77g/kWh, the regulation limit is 1,8g/kWh. CO emission of 2,21g/kWh (table 7.7) is below the limit of 3,5g/kWh. Particulate mass of 7,53E-05 g/kWh (table 7,9) is below the limit of 0.02 g/kWh. HC is not measured and cannot be verified.

The upcoming regulations for stage V non-road engines can be fulfilled with respect to CO, PM and PN, but not for NOx emissions which is limited to 0,4 g/kWh.

The engine is configured for high efficiency and not primarily for low emissions. There is still a possibility to further decrees the NOx emissions, with the drawback of slightly higher fuel consumption. The engine does not use any after treatment systems such as 3-way catalyst or SCR (selective catalyst reduction). With the implementation of such a system there are great possibilities to further reduce the emissions.

4.2.3 PM measurements

Over all the concentrations of PM was very low in the exhaust gases during the real driving tests. This was the case for both the mass and number concentrations. The measured EF (emission factor) for particle mass was much lower than current legislation for comparable engines. The EF for particle mass was also lower than the upcoming regulations for inland waterways in 2020. Currently there are no regulations regarding particle number emissions for marine engines. However, these emissions are regulated in the upcoming regulations for European Inland Waterways (2020) and for recreational crafts. The calculated EF-particle numbers are well below these standards for a majority of the load. The results are similar to those obtained with engine testing performed by Lund University in the SUMMETH project (Tunér et al., 2018).

The table below shows the resulting emission levels for the on board testing of the Weichai engine.

Table 4-1. Emission levels for the Weichai engine according to EU Stage V and IMO Tier 3 calculation. The results are from the on board tests of the engine. Results for HC and CO are after an oxidation catalyst. E3 is the emission test cycle used.

	EU Stage V, E3 [g/kWh]	IMO Tier III, E3 [g/kWh]	EU Stage V limits	IMO Tier III limits
Nox	1.8	1.3	1.8	1.96
Pm	0.000	-	0.015	-
HC	0.16	-	0.19	-
CO	0.4	-	3.5	-

The Weichai engine has approximately 150 running hours onboard and additionally 40 hours in dyno. During the testing the boat travelled successfully to Oslo for the Nor-Shipping 2017 convention where it was on display in the harbour.

Inspections on vital internal components have been done and no indication of additional wear could be identified. Valves, valve seats, exhaust system and cylinder liners were all clean. No soot or other types of sediment were present.

4.3 Scania SI engine

Emission and performance testing of the Scania SI engine similar in scope as for the Weichai engine were originally planned but it was concluded that such testing would not be representative without further work on the engine calibration in an engine testing facility with the ability to better control the load independent of engine speed. Initial tests provided results similar to the Weichai engine with regard to efficiency and NOx emissions whereas hydrocarbons have not been measured.

Cold starting problems have in some cases occurred. In winter time there have been problems with starting the engine without an engine heater. With the engine heater switched on and the engine temperature at about 25 °C, starts even when the outside temperature was -15 °C were not an issue.

4.4 Scania MD95 Engine

Results from the testing of the MD95 engine also look promising. The work carried out has been done to ensure good combustion on different loads and speeds without exceeding the physical limitations of the engine, i.e. mainly maximum cylinder pressure. Exhaust gas temperatures that is a limitation for the spark ignited engines were not a limitation on any load point. NOx levels have been encouraging and are on an early stage very close to the Tier III limits. The results indicate that Tier III should be possible with some optimisation of the injection timing but more time is required for actual measurements.

The characteristics of the engine power and torque are also very good with high torque and power. Compared to the spark ignited engines the torque is much higher at part load and the maximum power is also higher.

At the time of the project end comparative emission factors have not been compiled but the results indicated during testing position the MD95 as the most promising engine for further development work.

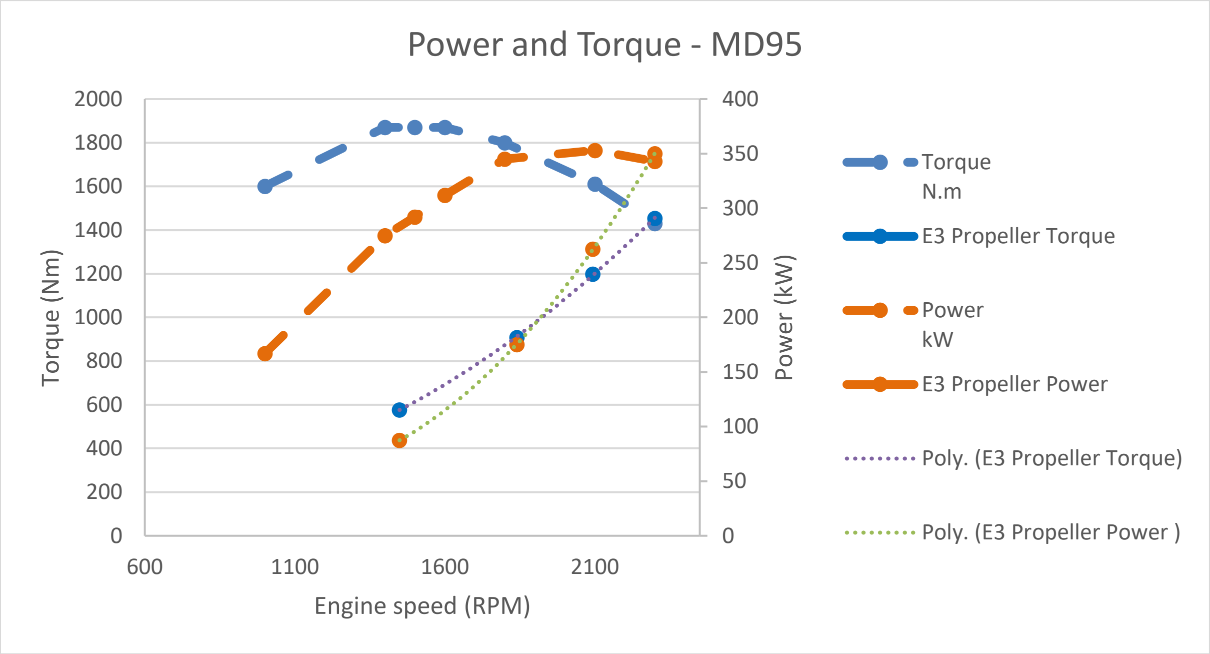


Figure 4-4: Power and torque for the Scania MD95 engine. …

5 Environmental Performance Assessment

5.1 Introduction

This chapter describes the work carried out to assess the environmental performance improvement resulting from the pilot boat conversion within the GreenPilot project. The overall objective of the GreenPilot project was to demonstrate that use of methanol as a fuel can reduce the environmental impact and improve the competitiveness of smaller vessels. Ships can have many different types of impacts on the environment, through release of harmful air emissions, discharges to water, introduction of invasive species, and underwater noise. Poulsen et al. (2018) state that "environmental performance refers to any aspect of a ship's environmental footprint". They consider that an improvement in environmental performance occurs whenever any part of the environmental footprint, such as a specific emission, is reduced. For the GreenPilot project, the main focus was on assessing air emissions reductions. Reductions of noise emissions were also assessed, through on-board measurements from the perspective of work place environment. Aspects of environmental performance that were compared for methanol operation of a pilot boat with operation on conventional fuels are shown in Figure 5-1.

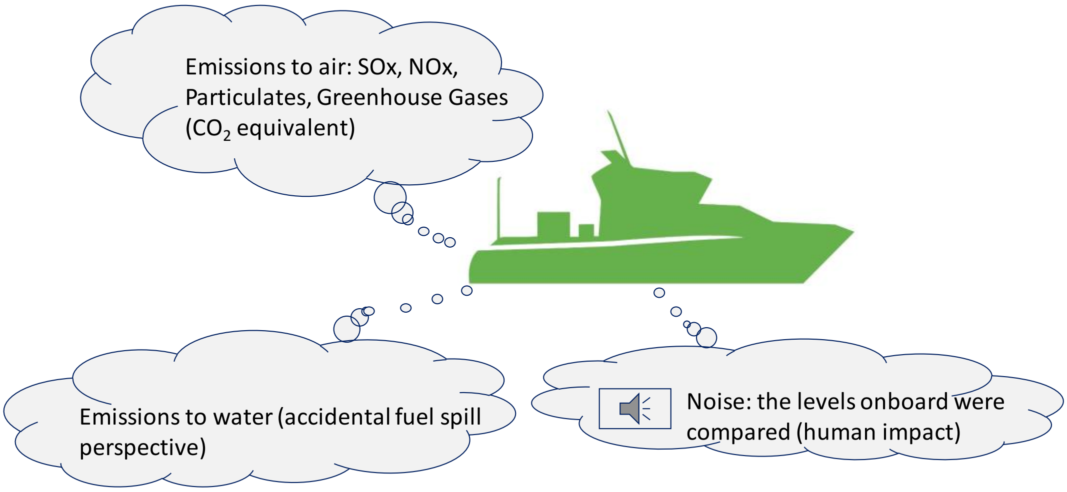


Figure 5-1. Environmental performance aspects of methanol fuel compared with conventional diesel oil fuel for pilot boat operation

5.2 GreenPilot Environmental Performance Assessment Objectives

The overall objective of the GreenPilot project was to demonstrate that use of methanol as a fuel can reduce the environmental impact and improve the competitiveness of smaller vessels. This was done by converting a pilot boat to methanol operation. The environmental performance assessment work compared operation of the converted pilot boat with that of the conventional vessel operation and included the following:

- Estimation of the reduction of emissions to air from operation on renewable methanol as compared to the current operation on conventional MGO fuel. This was done from a fuel life cycle perspective.
- Comparison of noise emissions from methanol engines with those from conventional engine operation.

5.3 Emissions – Fuel life cycle comparison

The air emissions assessment took a fuel life cycle approach, and included the fuel life cycle components "well to tank" and "tank to propeller" for methanol (with a focus on that produced from renewable feedstock) and the conventional MGO fuel used in the baseline case. The fuel currently used by the Swedish Maritime Administration for pilot boats is "Eldningsolja 1 kvalitet E10" (summertime) and "E32" (wintertime) (SMA, personal communication), which is equivalent to marine gas oil (MGO). The sulphur content is 0.05%. The methanol tested in the pilot boat included renewable methanol purchased from LTU Green Fuels pilot plant in Piteå, Sweden. The facility orignially used black liquor, a residual product from the adjacent pulp and paper mill, as the main feedstock for gasification. In 2015, pyrolysis oil, a liquid produced from residual forest biomass, was used in combination with the black liquor as a feedstock for the process to increase production. Conventional methanol produced from natural gas feedstock was also used as fuel for the GreenPilot project testing.

5.3.1 Fuel Life Cycle Approach

A Life Cycle Assessment (LCA) study assesses the environmental impact of a specific product or activity "from the cradle to the grave". Although some LCAs can be very detailed, assessing the whole life of a process or product, others may take a more streamlined approach, setting limits on the detail of the information collected, or the types of environmental impacts to be addressed (Environmental Resource Management, 2002). The GreenPilot project assessment took a more focussed approach, as the intent was to compare the operation of the pilot boat on different fuels. The study concentrated primarily on fuel production and use for propulsion on board a pilot boat, the "well to propeller" chain, as shown in Figure 5-2.

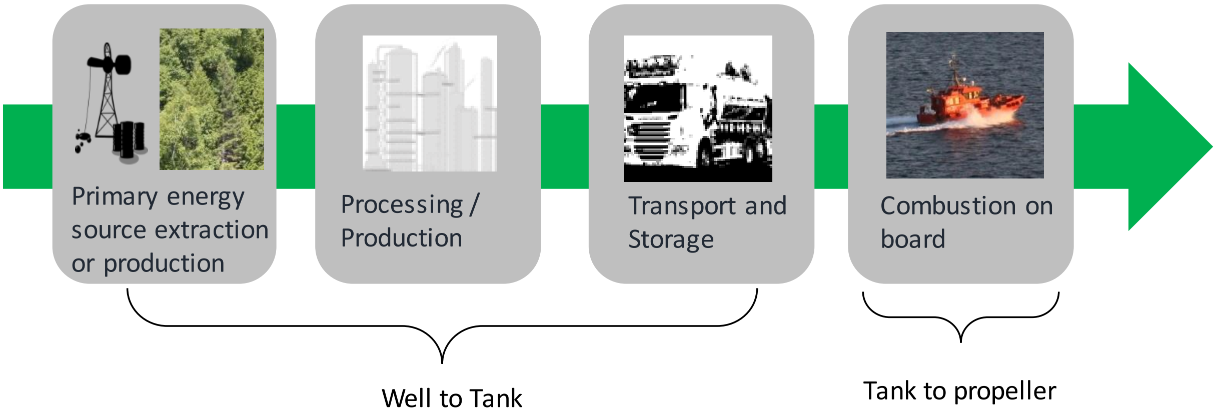


Figure 5-2. Simplified Well to Propeller" chain for fuel use on board a vessel

Total Fuel Cycle Analysis (TFCA), which is considered a sub-set of LCA, was developed as alternative fuels were being investigated and compared. The TFCA methodology has been applied to shipping in several studies in recent years, as more interest has developed in alternative fuels as a way of improving environmental performance of shipping. Some examples of TFCA studies include a study by Corbett et al. (2014) that evaluated extraction, processing, distribution, and use of fuels in three case study vessels, and a comparison of alternative and conventional marine fuels by Brynolf (2014).

5.3.2 Fuel Life Cycle Scope and Method

Scope

System Boundary: The impacts resulting from fuel supply and use by the Swedish pilot boat fleet over a one-year period were assessed. Fuel production and supply was considered to include raw material extraction, production, transportation, storage, and bunkering. Fuel use included combustion of the fuel in pilot boat engines.

Functional Unit: The functional unit was considered to be fuel use during one year of operation of the Swedish Maritime Administration pilot boat fleet. This fleet carried out 33,481 operations during 2017, the baseline year used for the study, and used 3100 m^3 of fuel, as shown in Table 1. The fleet currently uses an MGO equivalent fuel, as described previously. The fuel consumption was converted to an energy requirement, and the amount of methanol required to provide the energy for one year's worth of operation was estimated. For both the case of MGO fuel and the case of methanol fuel, the transport work was assumed to be the same. Thus total impacts per year of operation were compared.

Data Sources

Existing life cycle inventory data was used for the extraction and processing portion of the "well to tank" fuel life cycle chain, while distribution data was adapted for the case of pilot boats in Sweden. Data for the marine gas oil and methanol produced from natural gas was based on environmental flows for well to tank reported in "Fuels in the Baltic Sea after SECA" (Trafikanalys report by Andersson et al., 2016). For renewable methanol produced from black liquor, data was sourced from the well to tank data presented in the "JEC Well-to-wheels analysis" (Edwards et al., 2014). As the JEC study was for automotive fuels in the European context, the data were adjusted for use in the marine context. This involved adjustments to the final transport and distribution steps. The production pathways and data adjustments made for the specific fuels in the study are described in the results section.

For tank to propeller emissions data, sources were as follows:

- Marine Gas Oil: Emissions data for the Cummins basic engine model QSM11-M was used (Cummins Inc., 2010). Pilot Boat 729 had two Cummins engines on board prior to the GreenPilot project. The port side engine remained for redundancy during the test period, while a methanol engine was installed on the starboard side. ISO 8178 E3 test cycle data was used for NOx and PM. CO_2 was calculated for the E3 cycle using performance curve data to estimate the weighted brake specific fuel consumption (BFSC), and using a specific CO_2 emission of 3.2 kg CO_2/kg diesel fuel.
- Methanol: Measurement data from the testing carried out on the converted Weichai engine that was installed on board the converted GreenPilot vessel (Pilot Boat 729) was used. This data was collected as described in Molander (2017). For NO_x and CO_2, data from dynamometer testing using the E3 test cycle was used. For PM, data from on-board measurements was used from various load point to calculate an emission factor for E3 under real driving conditions (Molander, 2017).

For vessel fuel use, annual data as obtained from the Swedish Maritime Administration was used.

5.3.3 Well to Tank Emissions Results

"Well to tank" air emissions for fuel production and distribution were estimated as described below for MGO, methanol produced from natural gas, and methanol produced from black liquor.

MGO

The environmental flows used for fuel production for MGO (0.1% S) were as reported in Andersson et al. (2016) and Brynolf (2014). The data for fuel production from this source was stated to be from the ELCD core database. The feedstock for production of MGO is crude oil, which is extracted from an underground reservoir (on land or off shore). The crude is then conditioned or stabilized as required for shipping and transported to a refinery, where it is processed. The finished fuel is transported to the user. Sweden has refineries in Lysekil, Göteborg, and Nynäshamn. An average transport distance of 100 NM by tanker vessel to port depots and 50 km by tanker truck was assumed for distribution of fuel to pilot boat stations.

The fuel used by the Swedish pilot boat fleets (Eldningsölja) was assumed to have the same production flows as MGO. A simplified pathway for the fuel production and supply chain is shown in Figure 5-3.

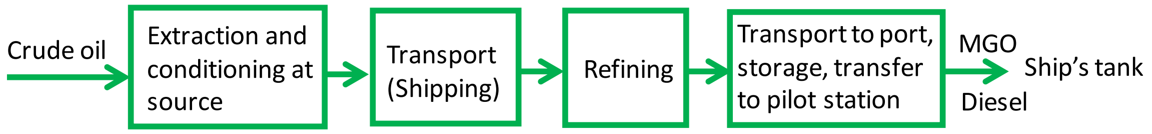


Figure 5-3. MGO Simplified Pathway for Production and Transport

<u>Methanol produced from natural gas</u>

Steam reformation of fossil natural gas is the most common and lowest cost production method of fossil methanol that is available in Europe. The environmental flows for production of methanol were from Brynolf (2014), which assumed production of methanol in Norway from Norwegian natural gas, and transport of the methanol by chemical tanker. For the GreenPilot study, the same production environmental flows were used but sea transport was increased to an average distance of 900 NM, to cover small vessel users further away from production facilities, and a road transport leg of 100 km was added for transport of the methanol by tanker truck to pilot boat stations.

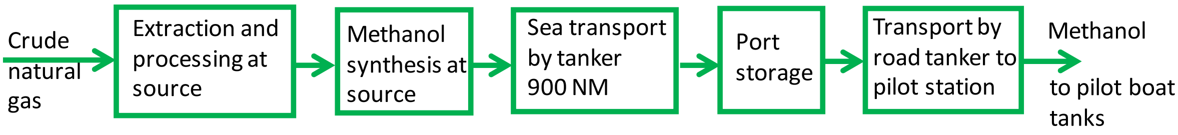


Figure 5-4. Simplified pathway for production of methanol from natural gas

<u>Methanol produced from black liquor (via wood waste)</u>

Methanol from waste wood can be produced via black liquor, which is a by-product of the process at mills to turn wood into pulp for making paper. Extensive work on producing methanol from black liquor has been carried out in Sweden, and a pilot plant in Piteå that produces methanol and DME via this method has successfully operated for about 11,000 hours (Landälv, 2017). Södra Cell AB's pulp mill in Mönsterås is being adapted to produce 5000 tonnes of methanol per year from raw methanol that is a by-product of the pulp production. This facility is expected to be completed in 2019 (Jacobsson, 2017). "Well to tank" data for methanol produced from black liquor was obtained from the JEC - Joint Research Centre-EUCAR-CONCAWE collaboration study "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context" (Edwards, 2014). Ahlgren and Eriksson's 2013 review of fuel LCA data sources stated that this reference is appropriate for use when comparing fossil fuels with biofuels. Edwards (2014) used data from the Swedish technical study by Ekbom (2003) which describes the same process tested at pilot scale at Piteå. The simplified pathway for productions as adapted from Edwards for the GreenPilot study is shown in Figure 5-5. An average road transport distance of 400 km was assumed.

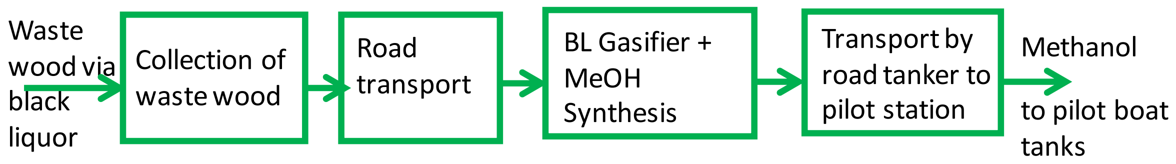


Figure 5-5. Simplified pathway for production of methanol from forest residues.

A summary of the well to tank emissions of GHG, SO_2, NO_x, and particulates for methanol produced from natural gas and black liquor, as used in the pilot boat analysis, is shown in Table 5-1. MGO is also shown as the comparison fuel.

Table 5-1. The well to tank (WTT) (raw materials aquisition, fuel production, and transport to vessel) emissions for MJ of fuel produced.

Fuels	CO_2 g/MJ	CH_4 g/MJ	N_2O g/MJ	GHGs g CO_2e/MJ	NOx g/MJ	SOx g/MJ	PM10 g/MJ
Diesel (MGO values)[1]	7,2	0,078	0,00018	9,5	0,023	0,041	0,00110
Methanol from natural gas[1]	21,1	0,011	0,00034	21,5	0,061	0,004	0,00079
Methanol black liquor[2]	2,4	0,010	0,00832	4,9	-	-	-

1 Data for production from Brynolf (2014) Environmental assessment of present and future marine fuels. Doctoral Dissertation. Chalmers University of Technology, with transport emissions estimated for supply to pilot boats; 2 Production data from Edwards, R., Larivé, J.-F., Rickeard, D., and W. Weindorf. 2014. Well-to-wheels analysis of future automotive fuels and powertrains in the European Context, Well-To-Tank (WTT) report, Version 4a, transport emissions estimated for supply to pilot boats.. Emissions from transport of the fuel by truck to the vessel were estimated using NTM Calc. 4.0 baseline data.

5.3.4 Tank to Propeller Results

Tank to propeller emissions from combustion of methanol were measured in an engine laboratory and on board Pilot Boat 729. For the MGO engine, values from Cummins were used for all parameters except CH_4, which was from Cooper and Gustafsson (2004) for a high speed marine engine. Emissions per MJ of MGO and methanol are summarized in Table 5-2.

Table 5-2. Emissions per MJ fuel combusted for MGO and methanol. 1 from Cummins (2010) and Cooper and Gustafsson (2004) for CH4; 2 Molander, 2017 (measurements taken during the GreenPilot project).

Fuel and Engine	CO_2 g/MJ	CH_4 g/MJ	GHGs g CO_2e/MJ	NOx g/MJ	SOx g/MJ	PM g/MJ
MGO, 0.05% S, High Speed Marine Diesel Engine (Cummins)[1]	74,7	0,00046	74,7	0,518	0,023	0,01240
Methanol, Spark ignited, port fuel injection engine (Weichai)[2]	68,5	0,00000	68,5	0,178	0,000	2,8E-06

As shown in Table 5-2, the NO_x and PM emissions from the methanol-fuelled combustion engine are significantly lower than the reference engine using MGO fuel. The SO_x emissions from the methanol engine are zero, as the fuel does not contain sulphur.

5.3.5 Well to Propeller Impact Summary

The emissions associated with fuel production and use over a one year period were estimated using the annual fuel consumption of the Swedish Maritime Administration's pilot boat fleet. As shown previously in Table 1, the fleet used 3100 m^3 of MGO equivalent fuel in 2017. The energy requirement associated with this fuel use was calculated to be 111 169 gigajoules. Emissions were calculated for methanol to provide the energy required – noting that it has a lower energy content than MGO so more fuel must be combusted to provide the same energy. The total estimated annual emissions in terms of GHG are shown in Figure 5-6.

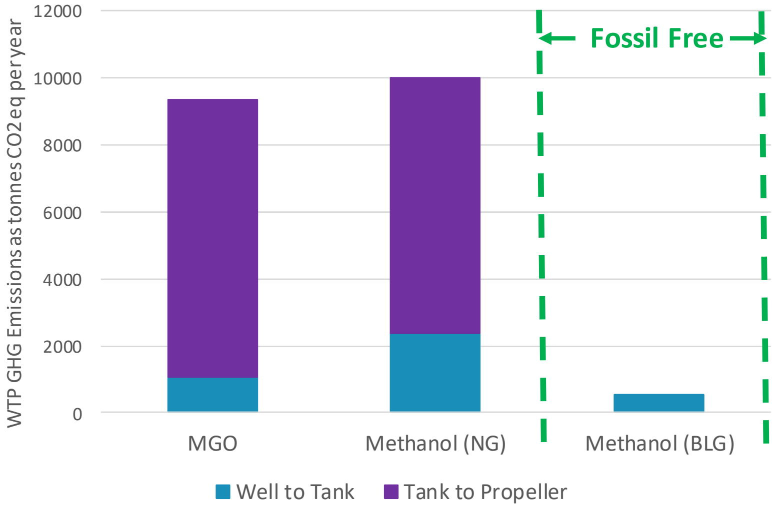


Figure 5-6. Annual emissions of GHG for pilot boat fleet as estimated for MGO (base case) and methanol produced from natural gas and from black liquor

The emissions from fuel oil and methanol produced from natural gas (fossil feedstock) are in the same range, with the methanol having slightly lower emissions during combustion but higher emissions associated with the "well to tank" portion of the life cycle.

Emissions of carbon dioxide from combustion of methanol produced from renewable feedstock (wood residue and black liquor gasification) are considered to be zero. This is consistent with the EU Renewable Energy Directive (2009/28/EC) rules for calculating the greenhouse gas impact of biofuels. The amount of CO_2 released during combustion is considered equivalent to that captured by the plant during growth (Brynolf, 2014). There are some emissions attributed to production due to the use of fossil fuels for some parts of the process, such as for transporting feedstock to the gasification facility.

The total annual emissions of NO_x and SO_x for the MGO base case and for the case of using methanol produced from natural gas are shown in Figure 5-7. Data on NO_x and SO_x emissions associated with production and transport ("well to tank") of methanol from pulp mill black liquor were not available. Emissions during the "tank to propeller" phase would be the same as for methanol produced from natural gas.

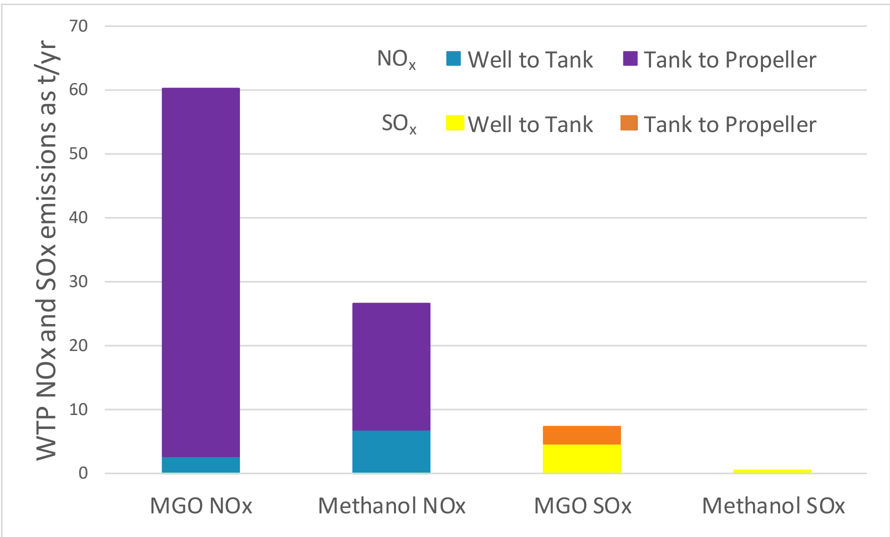


Figure 5-7. Annual emissions of NOx and SOx for the pilot boat fleet as estimated for MGO (base case) and methanol produced from natural gas

The life cycle emissions of both NO_x and SO_x are significantly lower for methanol than for MGO. For NO_x, the emissions due to fuel combustion ("tank to propeller") are higher than the "well to tank" phase. For SOx, there are small emissions during combustion of MGO due to the small sulphur content in the fuel (0.05% sulphur), and no emissions during combustion of methanol.

The total annual emissions of particulate matter for the MGO base case and for the case of using methanol produced from natural gas are shown in Figure 5-8.

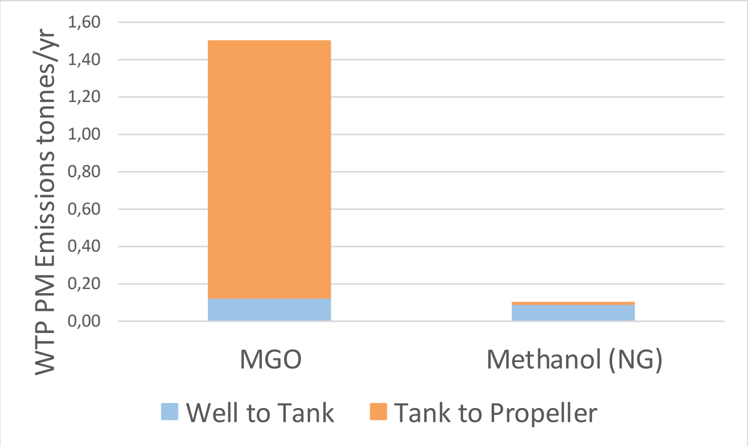


Figure 5-8. Annual emissions of particulate matter for the pilot boat fleet as estimated for MGO (base case) and methanol produced from natural gas

Particle emissions during the "tank to propeller" phase are more than 99% lower than those for MGO. Emissions for the "well to tank" phase are similar for both fuels.

5.4 Sound Measurements

Sound measurements were taken onboard the pilot boat in the engine room and the cabin to compare noise levels from the Weichai methanol engine operation with the conventional diesel fuel engine operation (Cummins engine). The background noise levels were measured prior to starting the engines. For the testing, the boat was moored to the quayside and the gear was engaged with the waterjet thrust pointing straight down. Only one engine was operated and measured at a time. The difference was noted to be greatest at 850 rpm, corresponding to slow driving. In the engine room, the difference exceeded 7 Db for db (A), and more than 6 Db for db (C), as shown in Figure 5-9 and Figure 5-10. The difference was much less in the cabin, which is isolated against sound, as indicated in Figure 5-11 and Figure 5-12. The difference was also less when noise from the turbo charters was intensified at higher engine speed.

Sound level measurements for the MD95 engine has not been done but the engine is not expected to produce lower sounds than the diesel engine. The lower sound levels only applies to the spark ignited engines.

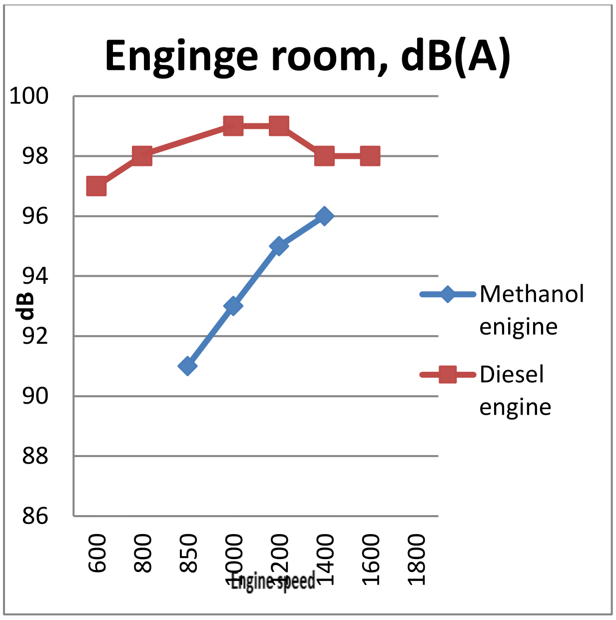


Figure 5-9: Sound levels in the engine loom

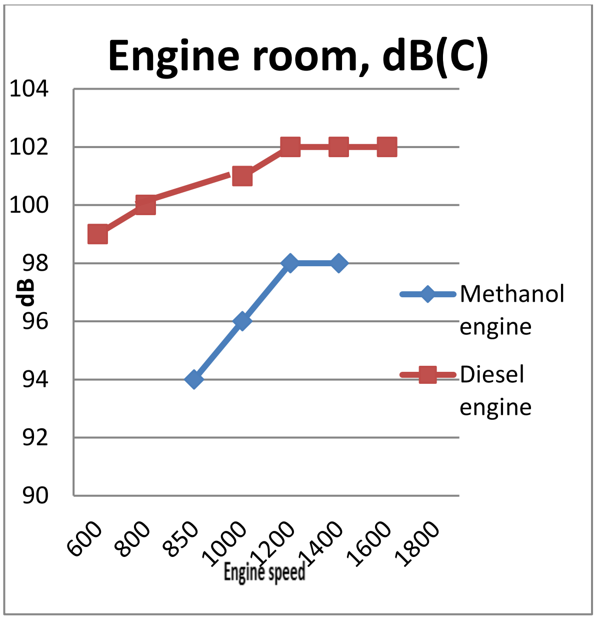


Figure 5-10: Sound levels in the engine room

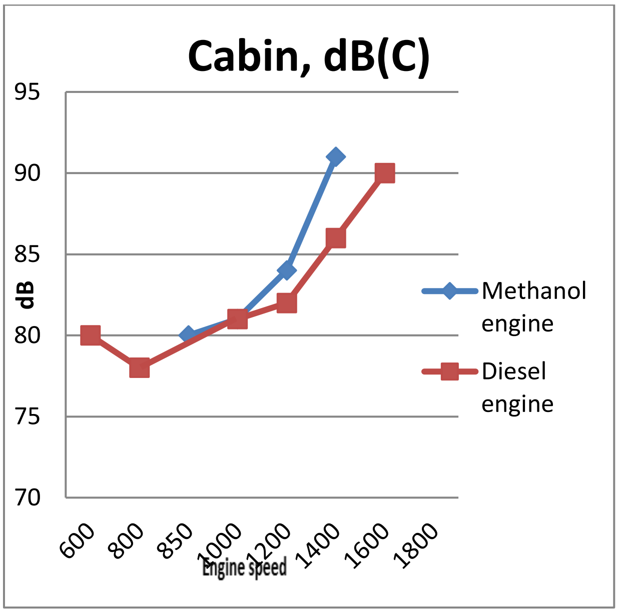


Figure 5-11: Sound levels in the cabin

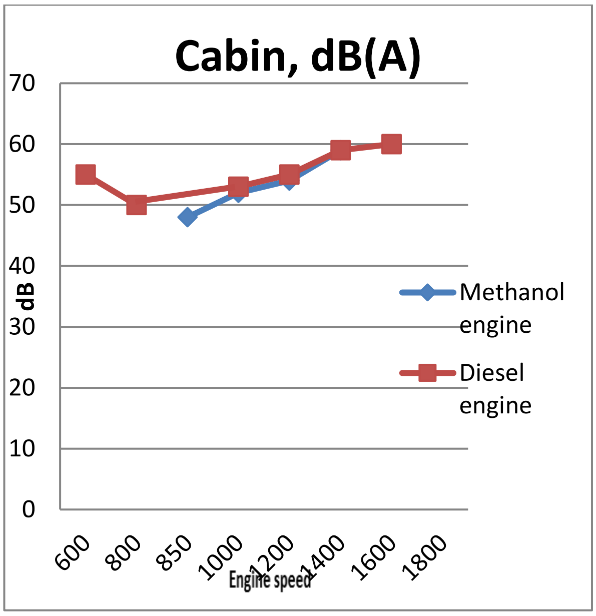


Figure 5-12: Sound levels in the cabin

6 Modification of other ship systems to reduce environmental impact

In addition to the conversion to methanol, other methods to lower the environmental impact of the pilot boat have been assessed. The work was mainly focused on lowering the energy consumption. Further work with hull paints and trials with more environmentally friendly lubricants and fluids were initially considered but ended up outside the scope of the project.

6.1 Electric energy management and consumption

Even without change of fuel the emissions can be reduced by consuming less overall energy. For a particular boat, the operational pattern has a huge impact on fuel consumption where a small reduction of speed can result in a large reduction of consumed energy.

A smaller but still important part is the electricity consumed on board, both at sea and when at port in standby mode. For a large ship, changing lights to low energy lighting and installing motion detectors for activation of lights can be used to lower the energy consumption. For a pilot boat these types of measures will have little to no impact on the overall energy consumption.

To investigate the overall energy use of pilot boats in general and the GreenPilot boat in particular, the electrical consumption was monitored. The overall consumption has mainly been monitored by measuring how much energy that has been used by the shore connection and the consumption on some of the larger consumers on board. The final estimation is based on combining the data from both approaches. The investigation was conducted during the summer months, for winter conditions the consumption is estimated based on the summer results and the installed equipment.

When connected to shore, the largest consumers by far are the engine heaters, making up about two thirds of the electrical consumption even during summer time. During winter the engine heaters will consume even more power. There is also an electrical heater installed for cabin heating. For the project boat this was disconnected due to pipe interference issues with the methanol system, but it would need to be in operation for regular use of the boat. The consumption of the cabin heater has therefore been used for the winter condition. The electrical cabin heater and engine heaters can only be in operation when connected to shore power.

Other consumers that are always operational are radio equipment, maintenance chargers for the battery banks and alarm systems.

The time at port is estimated to 14 hours per day. During winter higher power is required to keep the engines warm and the cabin heater is active. The winter period is estimated to be four months.

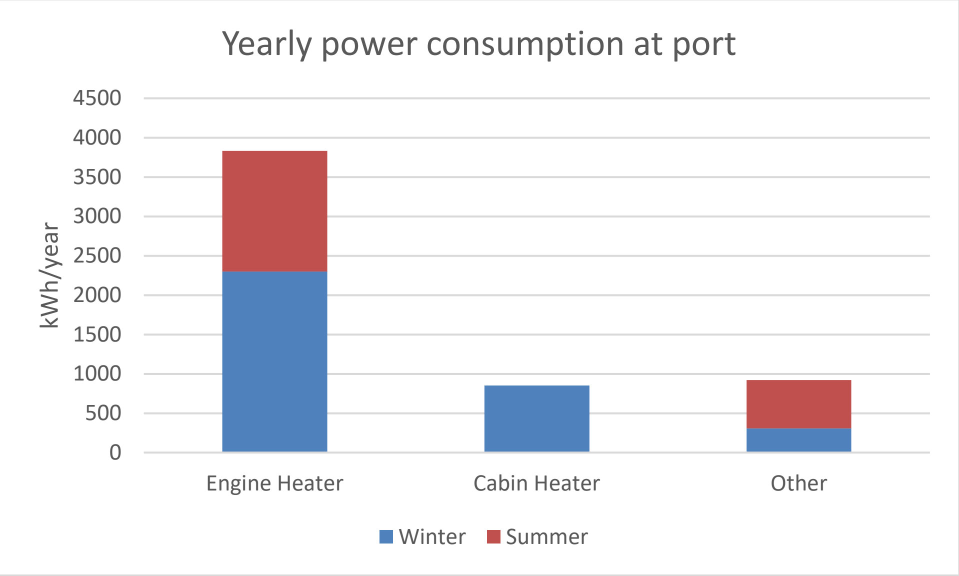


Figure 6-1. Electrical consumption from the shore connection. The estimation is based on 10 hour daily operating time, i.e. 14 hours in port. The winter season is estimated to 4 months. The total consumption is just above 5.6 MWh. The "Other "category includes maintenance charging of the battery banks, power for radio equipment and alarm systems.

The main electrical consumers on board are presented in the diagram below. These consumers are mainly used when the boat is running, with exception of the methanol systems which are always on. Note that the much higher electrical consumption of the methanol engine compared to the diesel engine is mainly a result of the electrically powered fuel pumps while the fuel pump for the diesel engine is mechanically powered by the engine.

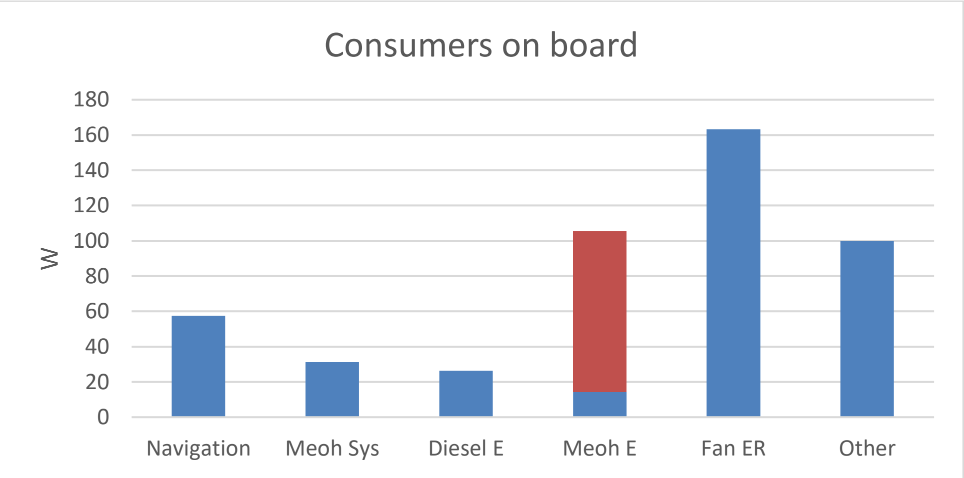


Figure 6-2. Electrical consumers on board. Note that the higher electrical consumption for the methanol engine is related to the electrical fuel pumps while the fuel pump for the diesel engine is mechanically driven.

6.2 Solar panels

The electrical systems on board are powered from two main battery banks; starting batteries and consumption batteries. The starting batteries power the engine control electronics, methanol control systems and the start motors. The consumption batteries provide power to the other on board consumers. Each engine is equipped with a generator that charges one of the battery banks. When at port the batteries are charged from the grid through a shore connection.

The batteries have enough energy storage to power the boat during about two day at port. In this operational mode the communication equipment and alarms are on with most of the other systems shut down.

In order for the pilot boat to be more energy efficient solar panels have been installed. The solar panels provide additional charge to the batteries during all operation modes. When at port solar panels will supplement the shore connection with charging the batteries.

A total of four solar panels were installed on the cabin roof. Two 90W in series and two 45W in series, both connected to a control unit in the engine compartment. During a cloudy but bright day the solar panels manage to charge the batteries with about 1.5 A continuously which is not enough to keep the batteries from discharging over time. During optimal conditions the panels should be able to charge about 180W, or 7.5 A.

In practice the solar panels only make a small contribution, about 1 kWh per day. Better integration with the battery chargers could probably increase charging from the solar panels to at least 3-4 kWh/day but it would still not be enough to keep the batteries on board charged without shore connection, even without activation of the engine heaters.

Figure 6-3. Illustration of the solar panels mounted on the cabin roof.

7 Electrification

Electrification is becoming a viable and more and more familiar alternative for land transport. Electrification has the benefit of having no end of pipe emissions and low sound, thus it is suitable for vehicles/vessels that operate close to population centres and sensitive environments. Marine applications include some road ferries where fast charging apparatus is installed on both sides of the route. There is also the Norwegian tour ship "Vision of the Fjords" that has the capacity to be powered by batteries during short times when cruising in sensitive maritime areas.

A brief evaluation of electrification concepts for GreenPilot has been performed. The characteristics of the boat are found not to be the best suited for electrification. The hull does not work at its best at low speed and water jet propulsion generally has low efficiency at slow speed. A redesign of the propulsion system was not considered in the electrical evaluation but would most likely be beneficial, especially for low speed which is where electrification would work best.

7.1 Power Requirements

Propulsion is the dominating power consumer, for evaluation of energy and power requirements the auxiliary systems such as navigation equipment, lights, etc .are not considered at this time.

In diesel configuration the two installed engines can produce approximately 800 kW with 2 x 600 l fuel capacity. The average output during normal operation is about 85% of the installed power and the fuel consumption is approximately 220 g/kWh at 24 knots. This gives an endurance of 6 hours and 20 minutes and a range of 150 NM.

For pure methanol operation, 2x 1000 l methanol tanks could be installed. The endurance would be 5 hours and the range 120 NM, at 24 knots.

Looking at the propulsion power measured on GreenPilot it can be determined that for the boat to move at 6-7 knots the load on each engine needs to be about 30 kW, 60 kW total power output. For electric propulsion the best application would be at low speed, e.g. within harbour areas. At low speed the resistance is low, thus less energy is required and the lower energy density in batteries is a smaller drawback.

7.2 Batteries as energy storage

Using batteries as energy storage offers easy energy management possibilities and very good power delivery potential. Charging the batteries is easy and straightforward while at port, although the charging time is considerably slower than bunkering liquid fuel. The main drawback with batteries is the relatively low energy density. Charging time is not considered at this stage.

A drawback for battery powered boats is also that there are no operations where power can be regenerated, compared with road transport some power can be regenerated during deceleration which will add to the longevity of the charge. The resistance when moving through water is also high, especially for a fast moving boat.

Reliable information on batteries suitable for use in the pilot boat is sparse but some information available from commercially available batteries has been compiled.

For the evaluation two different batteries are compared. Torqeedo manufacture a battery for marine applications, mainly to be used with outboard engines on smaller boats. Combining many such battery packs might be problematic in practice but offers a benchmark in terms or space and weight requirements.

The other battery used in the comparison is a Tesla Model S battery. Detailed data is not available from the manufacturer in the same sense as for the Torqeedo but data is available from third party analysis of the battery itself. Similar to the Torqeedo direct installation of a Tesla battery is probably not possible but comparing the two alternatives should provide data to better understand the requirements and possibilities with battery power.

Torqueedo battery

The Torqeedo battery POWER 26-104 is a commercially available marine battery of LiNMC type. The capacity is 2.685 kWh and it comes in a 24.3 kg, 32 litre package (Torqeedo, 2018).

The energy density is 110 Wh/kg and power density 185 W/kg.

In general batteries for marine applications seem to have lower energy density compared to car batteries as the batteries are required to handle lower charge levels for longer times compared to a car that is charged more often.

Figure 7-1. Torquedo Power 26-104 battery.

In terms of packaging the Torqeedo is intended to be used with smaller outboard engines and the packaging is not optimized for large battery banks like the one suggested for the pilot boat. Better solutions are likely to exist. For a large battery bank cooling systems would likely be needed but should provide no difficulty for a marine application with ample supply of cold water.

Tesla Model S battery

The model S battery consists of 16 modules each consisting of individual lithium-ion cells and is rated at 85 kWh.

The energy density is 140 Wh/kg (Enipedia, 2018) and the power density 516 W/kg. Data on the volume of the installation is not readily available but as the Tesla battery is built in with the frame rather than delivered as a separate unit this figure might be misleading. The Tesla battery packs are liquid cooled allowing for higher power delivery than a Torqueedo unit.

Figure 7-2. Tesla Model S battery. The battery cells and cooling are built in to the chassis.

7.2.1 Comparison and application

A comparison of the two alternatives, shown in Table 7-1, shows significant differences. A conservative assumption is that a marine battery could be expected to perform somewhere between the two alternatives.

Table 7-1. Battery comparison between Torqeedo and Tesla batteries.

		Torqeedo	Tesla
Energy	kWh	2.7	85
Energy density	[Wh/kg]	110	140
Power density	[W/kg]	185	516
Volume	[l]	32	-
Price	[SEK]	31 900	210 000
Price per kWh	[SEK/kWh]	11 880	2 475

Looking at the performance data from the pilot boat it is concluded that 60 kW is the required power output in order to achieve 6 kn speed. With an operating time of minimum 2 hours, i.e. 2x 6 NM (10 km), the minimum required battery capacity is 120 kWh.

Table 7-2. Comparison between 120 kWh battery packs for the Pilot boat.

		Torqeedo	Tesla
Energy	[kWh]	120	120

Weight	[kg]	1090	857
Volume	[m3]	1.4	
Price	[1000x SEK]	1 426	297

For higher speeds the energy requirements are significantly higher. In order for the boat to travel at mach speed of 24 kn the power requirement is approximately 680 kW. The table below is a relative comparison between the two batteries, the original diesel installation, and a full methanol installation.

Table 7-3. Comparison between battery packs, diesel and methanol propulsion.

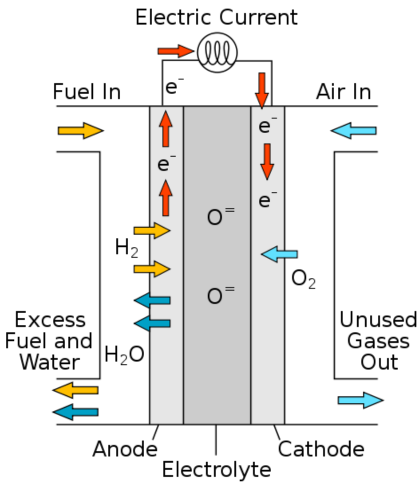
		Diesel	Methanol	Torqeedo	Tesla
Installed power	kW	800	800	800	800
Average engine load	%	0,85	0,85	0,85	0.85
Average utilized power	kW	680	680	680	680
Specific fuel consumption	g/kWh	220	472	-	
Power to weight	kWh/kg	4.5	2.1		
Specific weight of battery	kWh/kg	-	-	0.11	0.14
Endurance	h	6.4	5	2	2
Fuel volume	l	1200	2000	16 100	
Fuel weight	kg	960	1600	13 700[2]	10 800[3]
Stored energy	MWh	11,4	8,8	1.36	1.36
Fuel consumption per hour	kg/h	150	321	-	-
	l/h	187	401	-	-
Endurance	h	6,4	5,0	2	2
Speed	knots	24	24	24	24
Range	NM	154	120	48	48

The calculation for high speed requirements indicated that batteries are not well suited to this type of operation. The power consumption compared to the low power density is too low for a large battery bank to be transported on the boat. Even if the endurance is only one third of the time compared to diesel operation the battery weight becomes more than 10 tonnes for the best alternative. This should be compared to the current total displacement of the ship which is approximately 15 tonnes.

7.3 Fuel cell

Fuel cells come in different types but regardless of type the basic working principle is the same where electricity is generated by combining hydrogen and oxygen to water. The principle is illustrated below. Hydrogen enters the fuel cell along the anode where electrons are released from the hydrogen molecules. The electrons can't pass through the electrolyte and are channelled through a conductor to the cathode side of the fuel cell to react with oxygen to create oxygen ions. Oxygen ions in turn move through the electrolyte to react with hydrogen to form water. The power outtake from the fuel cell is generated by the electron flow that creates the electrical current.

[2] This assumes that the efficiency of conversion of electric energy to mechanical energy is 90%



Anode reaction:

$$2H_2 + 4H_2O \rightarrow 4H_3O^+ + 4e^-$$

Cathode reaction:

$$0_2 + 4H_3O^+ + 4e^- \rightarrow 6H_2O$$

Total reaction:

$$2H_2 + O_2 \rightarrow 2H_2O$$

Figure 7-3. Basic working principle for a fuel cell. Hydrogen and oxygen is combined.

The main difference between types of fuel cells is the electrolyte. The most common type of fuel cell in commercial operations today is the PEM (or PEMFC). PEM stands for Proton Exchange Membrane (previously Polymer Electrolyte Membrane). PEM cells operate with moderate temperature and have a short start up time.

SOFC are (Solid Oxide Fuel Cell) are also common but suffer from long start up time, up to ten minutes. The SOFC also operates at high temperature, 1000 °C is not uncommon for the electrolyte layer.

Several other types of fuel cells exist with varying degree of maturity and future prospects. As of today, PEM seems to be the best alternative. Special types of PEM fuel cells can also be run directly on methanol, forming the subcategory Direct Methanol Fuel Cells (DMFC).

Indirect use of other fuels is more common. In this case the other fuel is used to generate hydrogen in a reformer. For carbon-based fuels CO_2 will be a product from the reformer. The reformer also requires some energy which lowers the overall efficiency.

A disadvantage with fuel cells is low load operation; for efficient use of the cell it needs to operate on full load as much as possible. The most obvious way to achieve this is to combine the fuel cell with a battery pack. When high power is required both fuel cell and batteries will power the vessel. During times with lower load the excess power from the fuel cell will instead charge the batteries.

7.3.1 Fuel cell for Green Pilot

A short evaluation of the possibilities of using fuel cells for GreenPilot has been conducted. The aim of the evaluation is mainly to determine what a fuel cell installation could look like for the pilot boat and what kind of performance that could be delivered.

For the purpose of the evaluation one particular fuel cell has been investigated. The fuel cell is a 5 kW unit manufactured by the Danish company Serenergy. The fuel cell is a High temperature PEM with an inbuilt reformer, fuelled by methanol.

The HT-PEM unit with methanol reformer was chosen in part because of availability but it is also seen as the best alternative. In comparison a direct methanol fuel cell offers the advantage of not needing a reformer but have lower efficiency (28 %). The low temperature PEM is also an alternative but requires higher purity of the reformed product and thus has lower efficiency (33 %) and combined products have not been found. Fuel cells that run on hydrogen have not been considered.

Two pilot installations on board of ships have also been done, one for propulsion of a battery-electric tour ferry[3] and the other as auxiliary electrical power for a ropax-ship[4]. The fuel cell is also used commercially, mostly for powering remote telecommunications masts and similar infrastructure with constant but relatively low power demand. The unit is available with marine approval.

In terms of efficiency the unit converts about 45% of the energy to electricity, with the possibility of recovering some heat from the exhausts.

The proposed solution for any fuel cell powered vehicle is to use it together with a battery pack where the fuel cell is used as a range extender. This mitigates some of the weak points of the fuel cell and in particular fuel cells with reformers which have a relatively slow load response time. By having a hybrid solution, batteries can be used to balance the load and allow for faster load transients.

Table 7-4. Technical data for the H3 5000.

Modular H3 5000

Serenergy		
Power	5	kW
Voltage	48	V
Fuel mix	60%	MEOH
Fuel cons	0,85	L/kWh
Height	266	mm
Width	483	mm
Width OA	520	mm
Length	702	mm
Length OA	767	mm
Weight	75	kg
Price	30 000 €/unit	

The fuel used is a mixture of 60 % methanol and 40 % water. Water is commonly used in fuel cells to dilute the fuel source to avoid poisoning the catalyst in the reactor. The technical data of the Serenergy H3 5000 is presented above.

By looking at the propulsion power measured on GreenPilot it can be determined that for the boat to move at 6-7 kn the load on each engine needs to be about 30 kW. A conversion to electric propulsion would likely involve an upgrade to the propulsion system as well which would probably lower the required power somewhat. Nevertheless, by simply looking at the current water jet installation 60 kW power would be required from the fuel cells to provide enough capacity to move at reasonable speed purely powered from the fuel cells.

The methanol tanks are similar to those used for a combustion engine installation.

As for the batteries a reasonable requirement is that the fuel cells should be able to deliver enough power for the vessel to move at 6 kn. For higher power output plug-in power from batteries could be used. As established 60 kW would be needed.

60 kW power would be equivalent to 6 H3 modules representing a cost of approximately 360 000 € and 450 kg. Additional equipment includes a fuel preparation unit, water tank and cooling systems.

[3] MS innogy

[4] Viking Lines MS Mariella

7.3.2 Battery Fuel cell hybrid

By benefiting from the advantages of batteries and fuel cells a hybrid system looks like the most promising. Batteries have high power output but can only hold a limited charge. Fuel cells on the other hand have lower power output but the fuel has relatively high energy density which means they are well suited for longevity.

By looking at a small installation with 60 kW and comparing how the weight increases with increasing running time it can be noted that the weight of the fuel cell installation is almost entirely dependent on the weight of the actual fuel cell with relatively small additional weight penalty for carrying more fuel. Batteries on the other hand have a higher penalty for longevity but also an initial lower weight. By combining 30 kW of fuel cells with a 30 kW battery the result is in the middle.

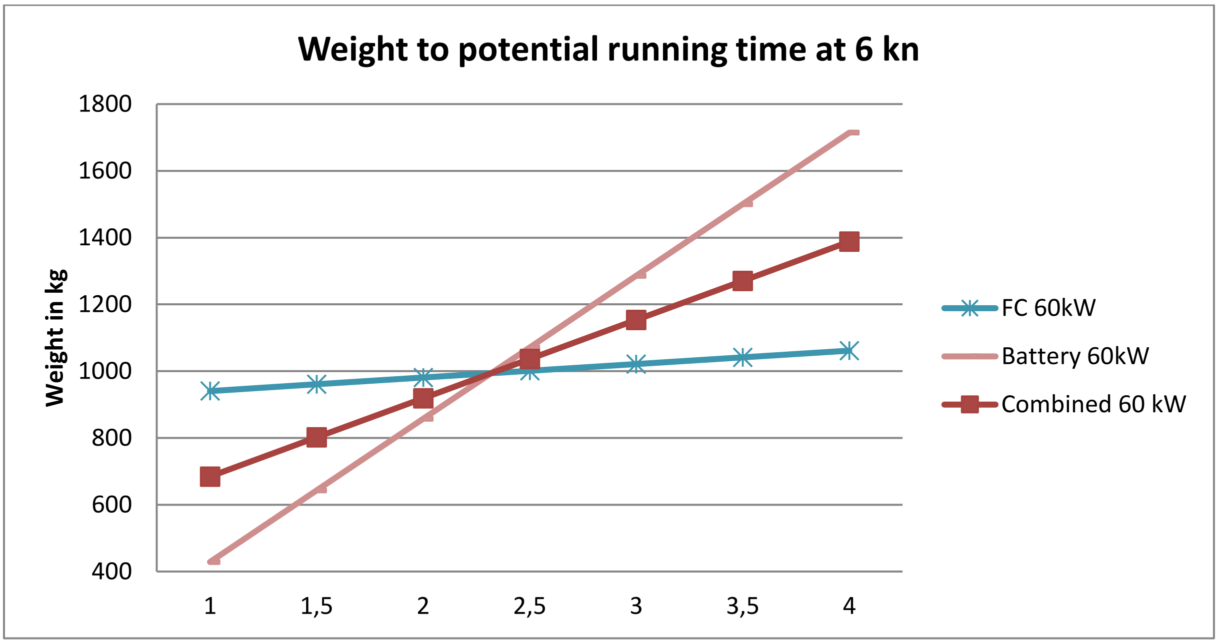


Figure 7-4. Weight to running time in hours assuming constant 60 kW power. For the fuel cell only the weight of methanol is added to provide longer running time while the other part of the system rem. ains the same. For battery and hybrid systems higher weight penalties in the form of batteries add to the weight.

By looking at the power curves from the pilot boat it is also indicated that for the boat to travel at 16 kn 100 kW of power is required (2x50 kW). By combining a 60 kW fuel cell with a 80 kWh battery bank continual running on 6 kn combined with two hour operation on 16 kn would be possible. As with the other graphs the weight of the batteries and fuel cells is plotted below. 2 hours operation on 6 kn plus 2 hours on 16 kn would in such a case result in just above 1600 kg weight for fuel, batteries and fuel cells.

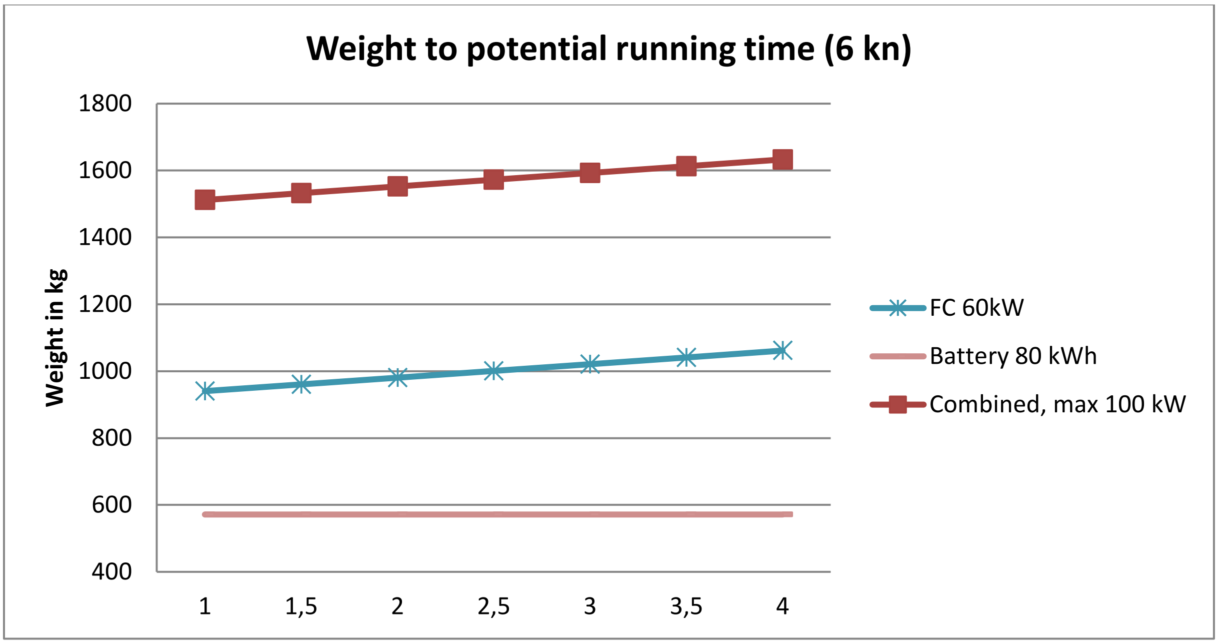


Figure 7-5.

7.4 Conclusion

Battery solutions are attractive as they offer good drivability, comfort and absence of local emissions. For a vessel the size of the pilot boat the required propulsion power is too high for an electric solution to work well. As of today the battery technology does not provide high enough energy density batteries to sustain the vessel with high enough speed and longevity,

The fuel cell solution is similar to batteries in terms of low power output relative to the required system weight. Fuel cells and batteries also come at a very high system cost with small benefit for a high speed boat.

8 Project Communication and Dissemination Activities

The work carried out in GreenPilot has been widely communicated both in Sweden and internationally. The marine methanol community has followed the development of the project, resulting in numerous invitations for international presentations and a high level of international visitors at the end-of-project seminar. Engines from the project have been on display at two national events and at two international shipping exhibitions under the Swedish flag in the Swedish national pavilion. Shipping exhibitions were identified as an effective way to demonstrate the close proximity of the project results to market and to reach new international contacts. Exposure has predominantly been given in the context of marine fuels and propulsion, but the project has also been communicated in the general context of sustainable transport and green technology.

The GreenPilot consortia recognized at an early stage in the project's planning phase the potential, however uncertain, for GreenPilot to lead to yet another marine methanol success story following the work carried out on Stena Germanica in the larger engine segment. Communicating GreenPilot and its high innovation level benefited from the hands-on nature of the project, the technical novelty of the conversion, the high profile financiers and the potential for high commercial value in the smaller engine segment. Dissemination activities have hence targeted a wide variety of audiences focusing on, but not limited to, the maritime industry. "External" stakeholders include policy makers, biofuel producers, the methanol value chain as well as the general public. A full outline of the project as well as the final report is accessible via the homepage www.greenpilot.se. The webpage has generated contacts with journalists and people curious to learn more about the technical details of the project. It was decided that the homepage will be maintained beyond the final date of the project as the GreenPilot consortia will continue building on the knowledge achieved in GreenPilot and carry it into other projects.

In summary the dissemination of GreenPilot has contributed to Sweden's cutting edge profile in areas of green and sustainable propulsion in general and methanol propulsion in particular.

A selection of communication activities throughout the project, shown in Table 9-1, shows the spread and reach of GreenPilot.

Table 9-1: Selection of GreenPilot Communication Activities

What	When	Event/Media	Where
Project Kick-off	June 2016	Seminar	Gothenburg, Sweden
Mid-Project Update	June 2017	Seminar	Gothenburg, Sweden
End of Project Seminar	May 2018	Seminar	Gothenburg, Sweden
International Shipping Exhibition	June 2017	Nor-Shipping	Lilleström, Norway
National Exhibition on Climate	November 2017	Klimatforum	Stockholm, Sweden
International Shipping Exhibition	September 2018	SMM	Hamburg, Germany
Donsö Shipping Meeting	September 2017	DSM	Donsö Island, Sweden
Articles			
	June 2016	Sjöfartstidningen	Sweden
	August 2016	Sjövägen	Sweden
	June 2017	Skärgårdsredaren	Sweden
	July 2017	Svenskt Båtägande	Sweden
	July 2017	Svenska Dagbladet	Sweden

	October 2017	Proffessional Mariner Magazine	USA
	October 2018	Marine Proffessionals IMarEST	UK
Pressrelease SMM	September 2018	My News Desk:	
		Fire News	USA
		Broadly Boats News - Firetrench	UK
		Industry Europe	UK
		All About Shipping	UK
		Bunker Index	UK
Panel Debate	April 2017	Ekotransport Conference	Stockholm, Sweden
Presentations	June 2016	Almedalen	Visby, Sweden
	September 2016	India's Leap Into Methanol Economy	New Dehli, India
	October 2016	Making Marine Applications Greener	Reykjavik, Iceland
	January 2017	TRANSPORTFORUM	Linköping, Sweden
	June 2017	Marine Fuel Beyond LNG - Methanol as an Alternative?	Elsfleth, Germany
	June 2017	IMPCA Methanol Conference	Hamburg, Germany
	October 2017	Meeting with India's Minister of Transport	New Delhi, India
	March 2018	MAN & Methanol Institute Workshop	Copenhagen, Denmark
	June 2018	Swedish Transport Administration's Research and Innovation Day - Shipping 2018	Stockholm, Sweden
	October 2018	Maritime Cluster Norddeutschland	Hamburg, Germany
Visits to the Pilot Boat	April 2017	"Billion Miles" representative from Singapore	Gothenburg, Sweden
	April 2017	Swedish CIMAC Members	Gothenburg, Sweden
	February 2018	Delegation from Port of Hamburg	Gothenburg, Sweden

9 Discussion and Conclusions

Pilot Boat 729 was successfully converted to methanol operation and tested at sea with good overall results. On-board emissions testing showed very low particulate emissions and significant NOx reductions. For the two engines tested on board the vessel, diesel-like performance was shown, with engine efficiencies ranging from 37-40%. Another positive experience was the lower sound from the engines. The spark ignited methanol engines have a significantly lower sound level which improves the working environment onboard. The sound is also at higher frequency which makes sound insulation easier.

9.1 Lessons learned / recommendations for further improvements

During the testing no issues with material incompatibility were noted and no issues with the engines arose. The Weichai engine has been partly dissembled after use to inspect the cylinders and valves for wear. No excessive wear was noted, but the testing time was also limited and further long term evaluation of methanol use is necessary.

For the test vessel using one diesel engine and one methanol engine did not adversely affect the manoeuvrability, to a large extent due to the use of water jets. The main issue on board during testing was that there was some difficulty when engaging and disengaging the gear. This is in part an engine optimization problem but also a result of using the existing hardware that was installed for diesel engines. Equipment for gasoline engines generally engages the gear in a smoother manner to prevent the engine from stalling.

9.1.1 Tank metering

The fuel tanks were equipped with floating point resistance gauges. These have not worked as well as expected, exhibiting slow response and low measuring resolution. This has been a problem in particular during bunkering where there has been uncertainty about the available space in the tanks.

For future projects a different type of tank measurement is advised. A secondary high-high meter is also advised with possibility to connect the alarm to bunker shutoff functionality.

As the bunker tanks are located above the on board fuel tanks and no air can enter the hose or bunker manifold, the system works as a siphon during bunkering; shutdown of the transfer pump does not stop methanol transfer. An automatic shutdown therefore needs some additional equipment to be effective. There are a number of possible solutions:

1. Remote operated shutoff valves on each bunker line
2. Remote operated shutoff line on the bunker station (with boat-shore communication interface)
3. Vacuum valve on bunker line

Each proposal has pros and cons. On board shutoff valves have some advantages such as fast response and additional safety during service of the bunker connection. The solution is on the other hand expensive and the serviceability of the actual valve may be limited due to lack of surrounding space.

Equipment located on the actual bunker station is likely preferred but for a portable solution it would complicate the system and would not work that well for the current setup. For a permanent or semi-permanent bunker station a remote shutoff valve would likely be the best solution.

Remote shutoff for the bunkering would also allow for faster bunkering while maintaining safe operation.

9.1.2 PV valve spray protection

The tank ventilation exits high on port side of the cabin. A high location was determined to be the best solution in order to allow for easy dilution of possible fuel vapours exhausted through the ventilation. The high location was also preferred in order to somewhat protect the valve from the sea in heavy weather.

The location itself could be retained for the tank ventilation outlet but it should be equipped with a spray hood to direct any methanol overflow from the tanks. The hood would also work as extra weather protection.

In case of overflow the hood would stop fuel from being dispersed to the sides and instead direct a more controlled flow downwards. An important task is also to collect small airborne droplets that would be easier to inhale for the crew.

Spray protection on the ventilation outlet is advised regardless of whether tank inertion is used or not.

9.1.3 Tank inertion

The fuel tanks in the pilot boat are inerted with nitrogen. Inertion is a requirement in the draft IGF technical provisions for methyl/ethyl alcohol and in the classification rules for low flashpoint fuels. For transportation of methanol this is not a requirement of the IGC code but has become common practice for many of the large tankers; both to improve safety and to keep the methanol pure. For road transportation and storage facilities inertion is not used.

For a small boat inertion is not practical due mainly to space requirements but also auxiliary system requirements. These obstacles are easier to overcome on large ships where the large quantities of fuel will also motivate the additional safety. For smaller ships and vessels there should be some crossover point where inertion no longer provides additional safety but instead overcomplicates the system design with the risk of introducing new hazards.

GreenPilot is designed with a nitrogen inertion system that works but it can be questioned if it should be required. Conventional atmospheric fuel tanks should provide enough safety.

In the case of using atmospheric fuel tanks the P/V valve on the tank ventilation should be exchanged with a flame arrestor to prevent any flame from propagating down the ventilation pipe.

For the bunker manifold the dry disconnect coupling would prevent any flame to propagate through the bunker pipes as the connection is always closed when disconnected. During connection and disconnection the two parts outer casing will engage before the connection opens, thus any build-up of static electricity would discharge before any methanol could be ignited.

9.2 Environmental Performance Improvements

A comparison of estimated annual emissions of the pilot boat fleet for MGO and methanol for GHGs, NO_x, SO_x, and particulate matter showed that significant emissions reductions could be achieved with the adoption of methanol fuel. For greenhouse gas emissions, reductions in the range of 90% could be achieved with the use of renewable methanol produced from pulp mill black liquor. For methanol produced from natural gas, a fossil feedstock, greenhouse gas emissions are similar to those from MGO fuel.

NO_x emissions were much lower from combustion of methanol during the “tank to propeller” phase than they were from combustion of MGO. There are no SO_x emissions from methanol combustion, and very small emissions during the “well to tank” portion of the fuel life cycle.

Particle emissions were significantly reduced with methanol combustion as compared to MGO.

9.3 Potential small vessel market for methanol fuel

The GreenPilot project successfully demonstrated that a small vessel can be converted to run on methanol fuel, with significantly reduced emissions as compared to conventional petroleum fuel. Vessels operating in areas with stricter emissions requirements, or those with operators that have a strong incentive to reduce their emissions due to corporate or government strategic goals, are likely first adopters of methanol fuel.

9.3.1 Inland waterway vessels

Inland waterway vessels are an example where stricter emissions regulations are coming into force soon. The EU Stage V emission limits, applicable to non-road mobile machinery including inland waterway vessel engines, comes in to force on 1 January 2019 for engines with net power less than 300 kW, and on 1 January 2020 for those with net power of 300 kW or higher. These regulations require significant reductions of hydrocarbons (HC), NO_x, and Particulate Matter (PM). The standards will be applicable to both newbuilds and any conversions done after the applicable date.

To fulfil the new Stage V emission limits most diesel engines will have to use after-treatment systems such as particle filters, oxidation catalysts and selective catalytic reduction (SCR) system with urea (e,g, AdBlue, a liquid solution of urea). The cost of the after-treatment systems needed for a diesel engine will be in the same range as the base engine itself. The systems are voluminous and might be difficult to fit in an engine room and will generate running costs for consumables and maintenance.

A methanol-fuelled engine can fulfil the toughest requirements for PM and NO_x with a simple and inexpensive passive 3-way catalyst, and thus could be a very cost (and space) competitive alternative. There are about 200 – 300 new inland waterway vessels delivered within EU annually. These will be good candidates for methanol operation.

India has allocated money to improve the utilization of inland waterways, and there is incentive to use a fuel that can be produced nationally and that has low emissions. The government has proposed using methanol as a fuel for inland waterway vessels (Economic Times, 2018). A program for renewing the fleet with 500 vessels has been decided (ref).

China has a similar interest in shifting cargo from road to inland waterways and to operate the inland waterway vessel on clean burning fuel.

9.3.2 Renewable methanol for meeting CO_2 reduction targets

Some governments and corporations are already setting targets for reducing their CO_2 emissions ahead of any regulations. The Swedish government, for example, is currently investigating alternatives for converting all state vessels to fossil-free operations. All of the fossil-free fuels currently cost more than conventional options, but methanol has the potential to be competitive within this segment. This could be particularly true where there is local production of fossil free methanol. The following operations are considered to be premium candidates for use of renewable methanol:

- Operations under direct or indirect government control (national or municipal levels)
  - Pilot boat operation
  - Road ferries
  - Ice breakers
  - Coat guards
  - Waterborne public transportation
  - Harbour crafts (tugs, fire department)

    - Search and rescue operation
- Operations where the customers are environmentally conscious
    - Passenger and cruise operation, particularly in environmental sensitive areas
- Pleasure craft

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Appendix I – Methanol Safety Sheet

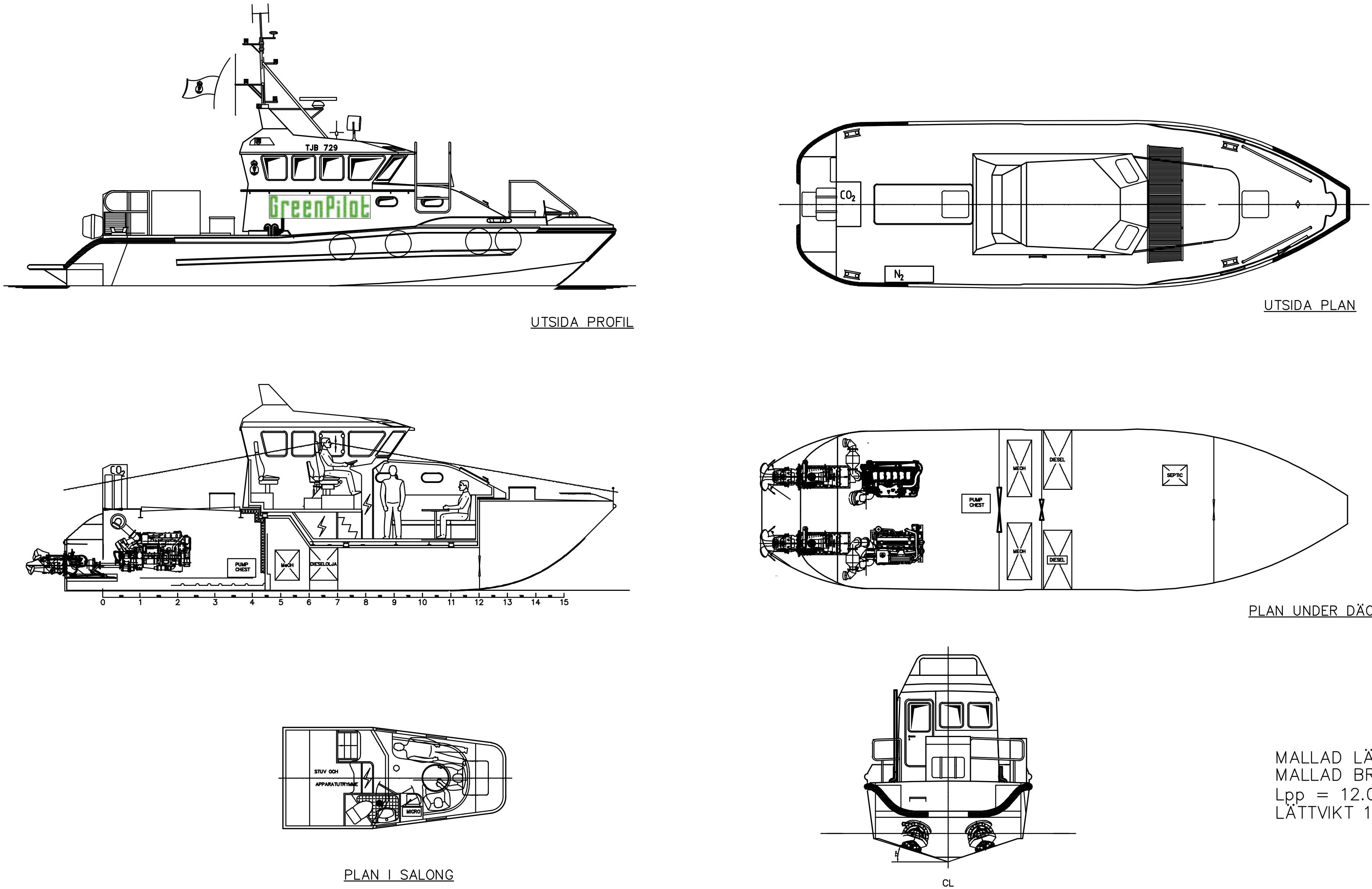
SAFETY DATA SHEETS

Product	Gasoline MK1 93.5, 95, 96, 98 (CAS 86290-81-5)	Diesel (CAS 68334-30-5)	Methanol
Source	St1 Refinery AB	St1 Refinery AB	Methanex Europe S.A
Appearance:	Pale yellow, clear liquid	Clear liquid, colourless, yellow or green	Clear
Odour:	Characteristic	Characteristic	Alcohol odour
Odour threshold:	-	-	4,2 - 5960 ppm
pH:	Not applicable	Not applicable	Not applicable
Melting point/freezing point:	< -60 °C	< -10 °C	-97,8°C
Initial boiling point and boiling range:	25 - 205°C	160 - 370°C	64,7°C
Flash point:	< -40 °C	>56 °C	11°C
Evaporation rate:	-	-	-
Flammability (solid, gas)	-	-	Highly flammable liquid and vapour
Upper/lower flammability or explosive limits:	1 – 8 vol %	0,6 – 7,5 vol %	5,5 - 36,5 vol %
Vapour pressure:	45 - 95 kPa @ 37,8 °C	<0,5 kPa @ 37,8 °C	12,8 kPa @ 20°C
Relative vapour density @ 20oC:	-	.	1.1
Relative density:	720 - 775 kg/m3	820 - 860 kg/m3	791 – 793 kg/m3
Solubility(ies):	Low solubility	Not solubility	Miscible with water
Auto-ignition temperature:	> 250°C	> 225°C	464°C
Kinematics Viscosity, 40°C	< 1 mm2/s	1 - 5 mm2/s	
Explosive properties:	Not considered to be explosive	Not considered to be explosive	Vapours may form explosive mixture with air.
Oxidising properties:	Not considered to oxidise	Not considered to oxidise	Not oxidising.
Hazard pictograms (CPL)			
Signal word: (CPL)	Danger	Danger	Danger
Hazard statements (CPL)	H224: Extremely flammable liquid and vapour. H304: May be fatal if swallowed and enters airways H315: Causes skin irritation H340: May cause genetic defects H350: May cause cancer H361: Suspected of damaging fertility or the unborn child H336: May cause drowsiness or dizziness H411: Toxic to aquatic life with long lasting effects	H226: Flammable liquid and vapour. H304: May be fatal if swallowed and enters airways. H315: Causes skin irritation. H332: Harmful if inhaled. H351: Suspected of causing cancer. H373: May cause damage to organs through prolonged or repeated exposure. H411: Toxic to aquatic life with long lasting effects	H225 Highly flammable liquid and vapour. H301 Toxic if swallowed. H311 Toxic in contact with skin. H331 Toxic if inhaled. H370 Causes damage to organs.
Precautionary statements (CLP)	P201: Obtain special instructions before use P202: Do not handle until all safety precautions have been read and understood P210: Keep away from heat/sparks/open flames/hot	P201: Obtain special instructions before use P210: Keep away from heat/sparks/open flames/hot surfaces – No smoking P240: Ground/bond container and receiving equipment	P210 - Keep away from heat. - No smoking P280 - Wear protective gloves, protective clothing, eye protection, face protection P304+P340 - IF INHALED: remove victim to fresh air and keep at rest

	surfaces - No smoking P233: Keep container tightly closed P240: Ground/bond container and receiving equipment P241: Use explosion-proof electrical/ventilation/ lightning equipment P242: Use only non-sparing tools P243: Take precautionary measures against static discharge P261: Do not breath fume/gas/mist/vapours/spray P264: Wash hands thoroughly after handling P271: Use only outdoors or in a well-ventilated area P273: Avoid release to the environment P280: Wear protective gloves/clothing/eye protection P301+P310: IF SWALLOWED: Immediately call a POISON CENTER or doctor/physician P302+P352: IF ON SKIN: Wash with plenty of soap and water P303+P361+P353: IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower P304+P340: IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing P308+P313: IF exposed or concerned: Get medical advice/attention P312: Call a POISON CENTER or doctor/physician if you feel unwell P331: Do NOT induce vomiting P332+P313: If skin irritation occurs: Get medical advice/attention P370+P378: In case of fire: Use water spray or foam for extinction P391: Collect spillage P403+P235: Store in a well-ventilated place. Keep cool P405: Store locked up P501: Dispose of contents/container in accordance with local/regional/national/internationa l regulation	P241: Use explosion-proof electrical/ventilation/ lightning equipment P242: Use only non-sparing tools P243: Take precautionary measures against static discharge P260: Do not breathe dust/fume/gas/vapours/spray P264: Wash hands thoroughly after handling P270: Do not eat, drink or smoke when using this product P273: Avoid release to the environment P280: Wear protective gloves/clothing/eye protection P301+P310: IF SWALLOWED: Immediately call a POISON CENTER or doctor/physician P302+P352: IF ON SKIN: Wash with plenty of soap and water P303+P361+P353: IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower P304+P340: IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing P308+P313: IF exposed or concerned: Get medical advice/attention P312: Call a POISON CENTER or doctor/physician if you feel unwell P331: Do NOT induce vomiting P332+P313: If skin irritation occurs: Get medical advice/attention P370+P378: In case of fire: Use water spray or foam for extinction P391: Collect spillage P403+P233: Store in a well-ventilated place. Keep container tightly closed P403+P235: Store in a well-ventilated place. Keep cool P405: Store locked up P501: Dispose of contents/container in accordance with local/regional/national/internationa l regulation	in a position comfortable for breathing P303+P361+P353 - IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse skin with water/shower P301+P310 - IF SWALLOWED: Immediately call a POISON CENTRE or doctor P403+P235 - Store in a well-ventilated place. Keep cool

Appendix II - SNP15091-100 General Arrangement

ISSUE	DESCRIPTION	DATE	DRWN	DATE	CHKD
A	FOR LR PRE-HAZID	2016-06-20	JB		
B	FOR RISK ASSESSMENT	2016-10-28	JB		
C	AS BUILT	2017-01-07	JB		



MALLAD LÄNGD = 13.5 m
MALLAD BREDD = 4.16 m
Lpp = 12.08 m
LÄTTVIKT 12.4 ton

ScandiNAOS AB
Adolf Edelsvärds gata 11 7
414 41 Göteborg
Sweden

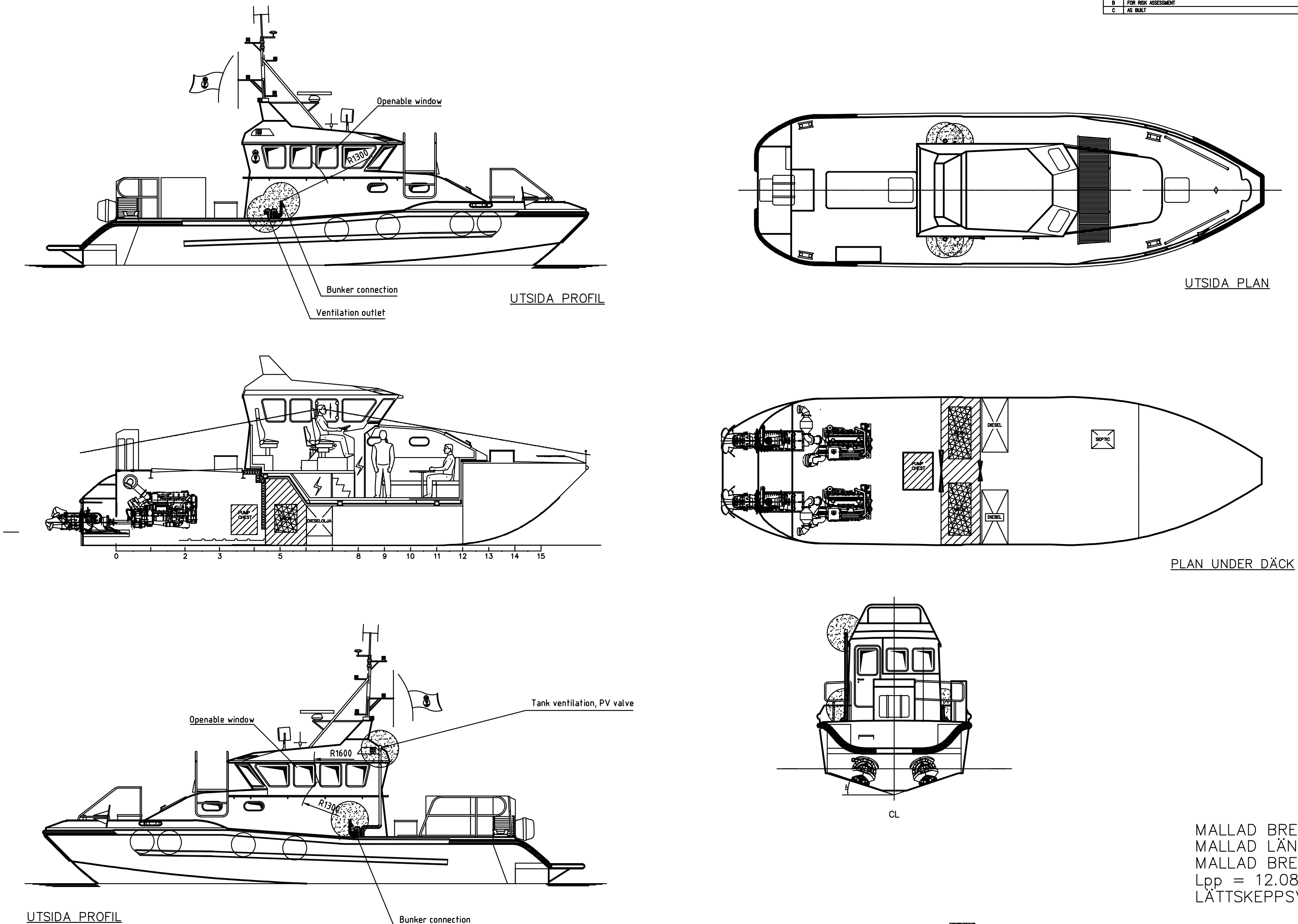
Project number	SNP15091	
Owner		
Class	–	
PREP. BY: JB	DATE: 2016-04-12	
CHECK. BY	DATE	
SCALE: 1:50	Size: A1	SH.S: 1 of 1
DRAW. N°	SNP15091-100	

GREEN PILOT
METHANOL CONVERSION
GENERAL ARRANGEMENT

SNP100

Appendix III - SNP15091-707 Hazardous area plan

ISSUE	DESCRIPTION	DATE	DRWN	DATE	CHKD
A	FOR LR PRE-HAZID	2016-06-20	JB		
B	FOR RISK ASSESSMENT	2016-11-09	JB		
C	AS BUILT	2017-03-20	JB		



MALLAD BREDD = 4.16 m
MALLAD LÄNGD = 13.5 m
MALLAD BREDD = 4.16 m
Lpp = 12.08 m
LÄTTSKEPPSVIKT 12.4 ton

HAZARDOUS AREA ZONE 0

HAZARDOUS AREA ZONE 1

HAZARDOUS AREA ZONE 2

ScandiNAOS AB

Adolf Edelsvärds gata 11 7
414 51 Göteborg
Sweden

Project number SNP15091

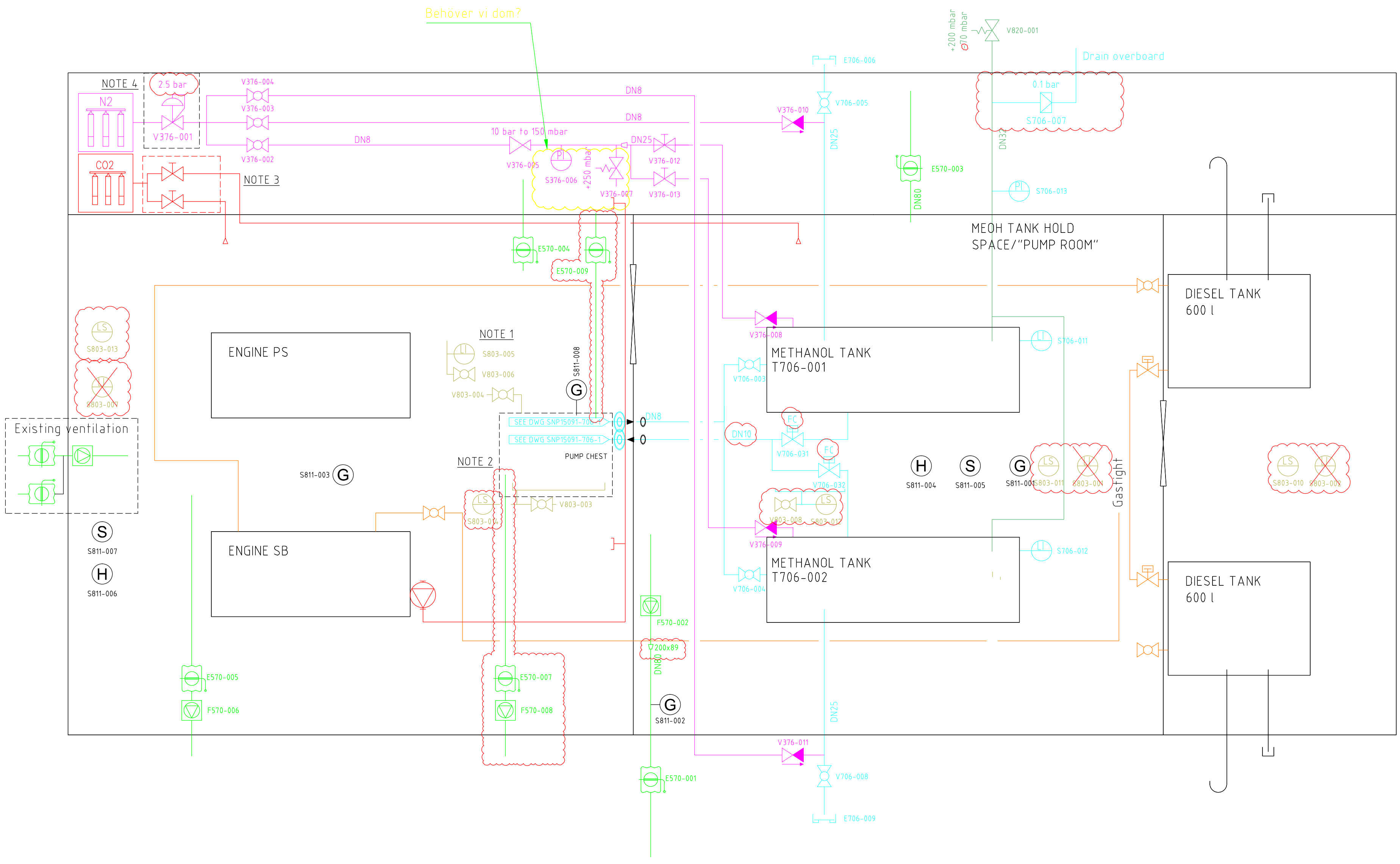
GREEN PILOT
METHANOL CONVERSION
HAZARDOUS AREA PLAN

JB
2016-03-30
1:50
A1
1 of 2
SNP15091-707

SNP100

Appendix IV - SNP15091-780 System coordination diagram

ISSUE	DESCRIPTION	DATE	DRWN	DATE	CHKD
A	FOR LR PRE-HAZID	2016-06-20	JB		
B	WIP		JB		



NOTES

1. Location and number of sensors for the annular space to be determined
2. Pump Chest to be gas tight.
3. See separate documentation for CO2 control valves
4. See separate documentation for detail design.

Latest eq.
376-013
570-009
706-014
803-014
811-008
820-002

METHANOL FUEL SYSTEM
METHANOL DRAIN SYSTEM
NITROGEN SYSTEM
TANK VENTILATION AND OVERFLOW
VENTILATION

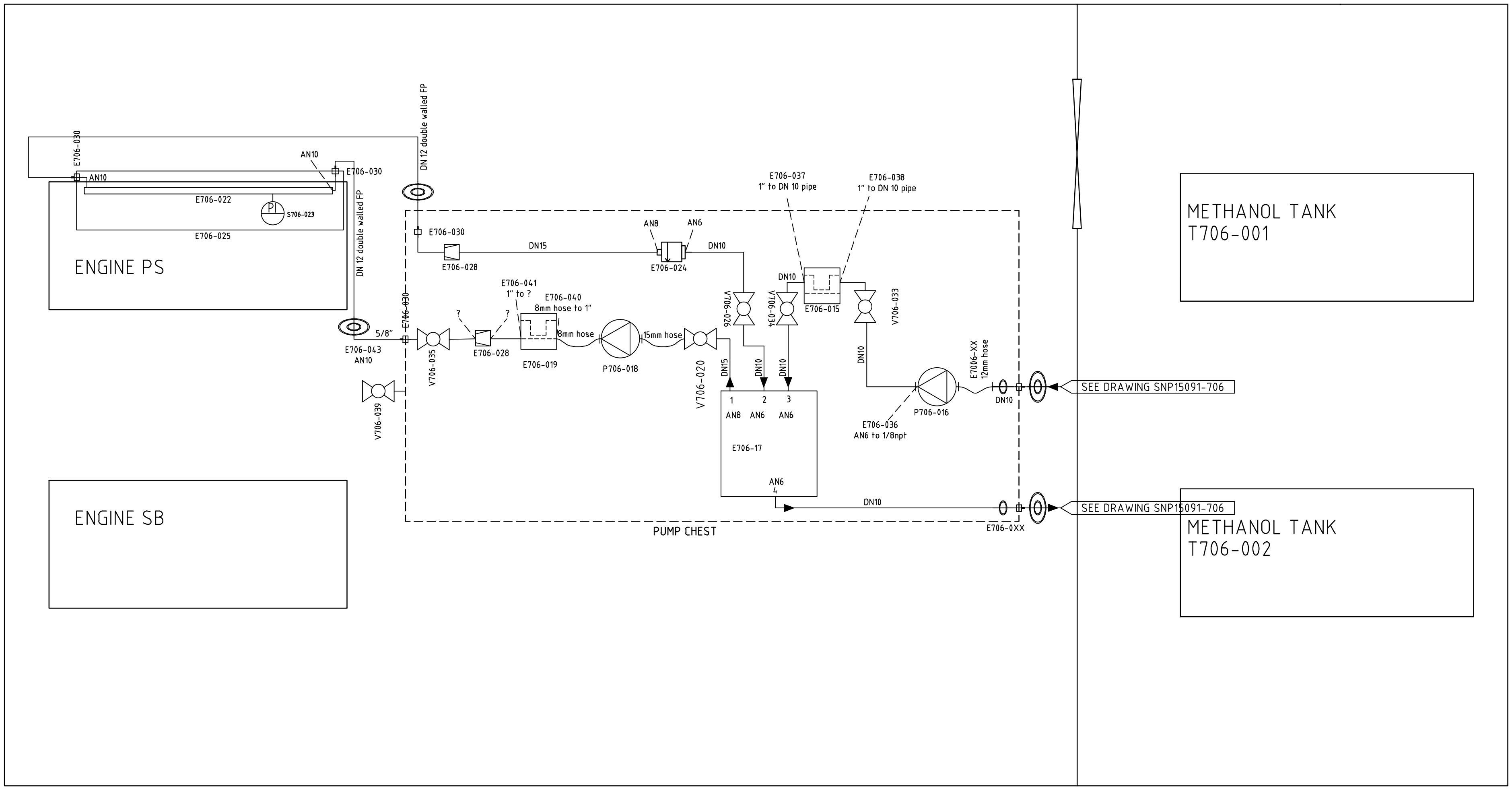
ScandiNAOS AB
Adolf Edelsvärds gata 11 7
414 41 Göteborg
Sweden

GREEN PILOT
METHANOL CONVERSION
SYSTEM COORDINATION DIAGRAM

Project number	SNP15091
OWNER	
Class	-
PREP. BY	JB
DATE	2016-02-11
CHECK. BY	
SCALE	NTS
Size	A2
SH.S	1 of 1
DRAW. N°	SNP15091-780

SNP100

ISSUE	DESCRIPTION	DATE	DRWN	DATE	CHKD
A	FOR RISK ASSESSMENT	2016-11-28	JB		

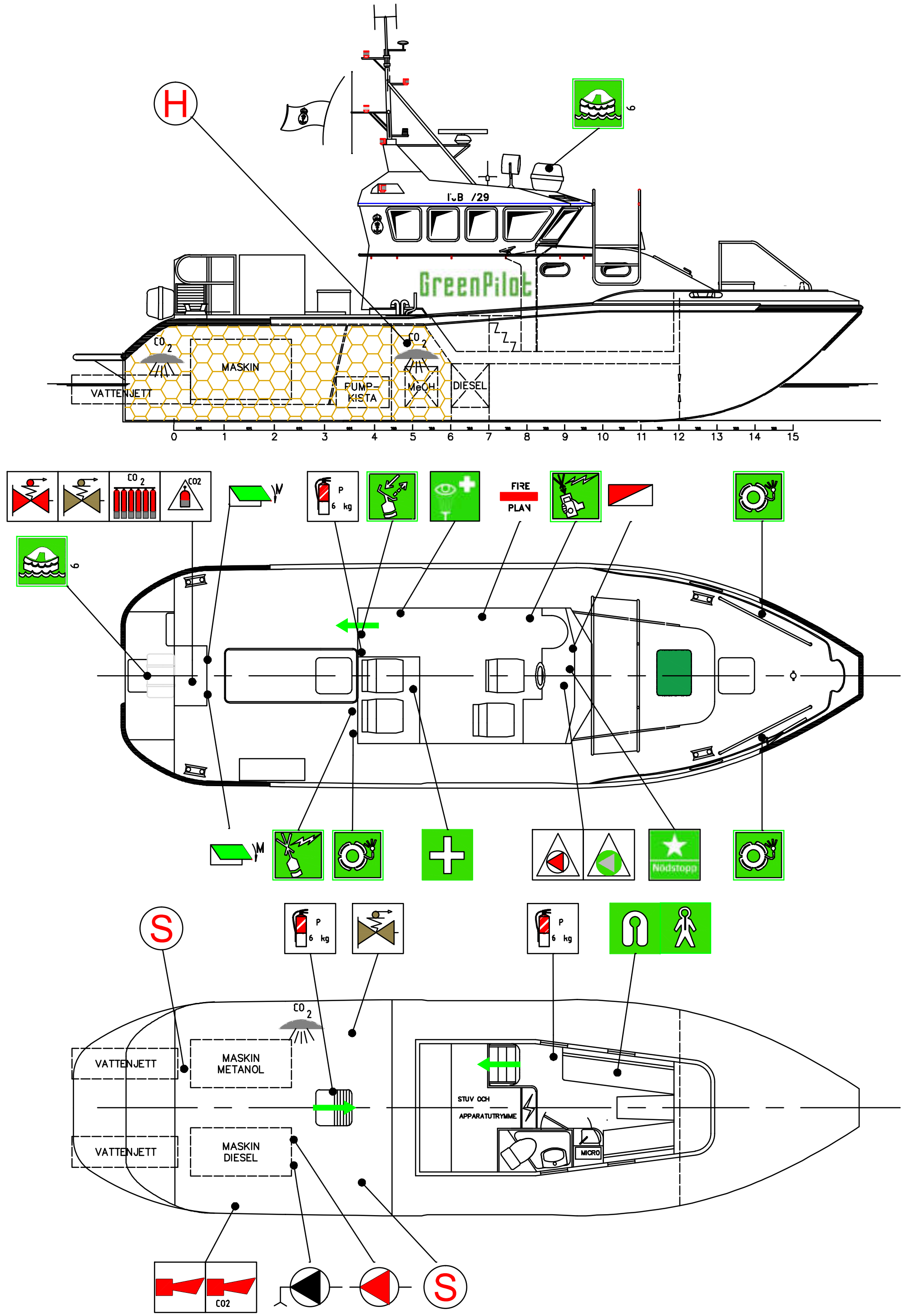


1" to1/2"
E706-042

AN10 to AN8
E706-044

ScandiNAOS AB Adolf Edelsvärds gata 11 7 414 41 Göteborg Sweden Phone +46 31 694361 e-mail: info@scandinaos.com web site www.scandinaos.com	Existing law protects ScandiNAOS AB right of possession of this drawing. The drawing must not be published, copied, reproduced, manufactured or exploited in any other way without the permission of ScandiNAOS AB.	Project number SNP15091 OWNER Class –
Cad file: SNP100	GREEN PILOT METHANOL CONVERSION METHANOL FUEL SYSTEM	PREP. BY / DATE 2016-02-11 CHECK. BY / DATE SCALE NTS / Size A3 / SH.S 1 of 1 DRAW. N° SNP15091-706-1

Appendix V - SNP15091 - Safety Plan



FIRE P. AN	1	SÄKERHETSPLAN	Nödstopp	2	NÖDSTOPP MASKIN
		NÖDUTGÅNG		1	NÖDSTOPP DIESEL
		UTRYMNINGSVÄG		1	NÖDSTOPP METANOL
	3	LIVBOJ MED LJUS		2	STÄNGNING MASKINRUMSVENTILATION
	1	LIVVÄSTAR (7 st)		1	START BRANDPUMP
9	2	LIVFLOTTE 6 PERSONER		1	START LÄNSPUMP
	1	EPIRB		1	BRANDLARMSPANEL
	1	SART		1	BRANDLARM TYFON
	1	BÄRBAR RADIO	P 6 kg	3	BÄRBAR PULVERBRANDSLÄCKARE 6 kg
	1	FÖRSTA HJÄLPEN		1	MELLANSKUM MUNSTYCKE
	1	ÖGONDUSCH	CO 2	1	CO2-FLASKOR
		ÖVERLEVNADSDRÄKT	CO2	1	UTLÖSNING CO2 MASKINRUM
			CO2	1	CO2-LARM SIGNAL
				1	CO2-LARM LJUS
			CO 2		OMRÅDE SKYDDAT AV CO2
			S	2	RÖKDETEKTOR
			H	1	VÄRMEDETEKTOR
				1	BRANDPUMP
				1	LÄNSPUMP

GreenPilot

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Project number	SNP15091
OWNER	
Class	–
PREP. BY	JB
DATE	2017-05-16
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SH.S	1 of 1
DRAW. N°	SNP15091–

SNP100

GREEN PILOT
SÄKERHETSPLAN

Appendix VI – LR Preliminary HAZID Study

Lloyd's Register Marine

Working together
for a safer world

Report

Preliminary HAZID Study for the methanol conversion of Green Pilot

Report for:
ScandiNAOS AB

Reference:
CPN 1600521

Reporting date:
11 January 2017

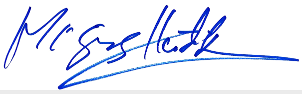
Report by:
Christian Kämmerer

Report summary

Lloyd's Register EMEA's Copenhagen Technical Support Office (CTSO) facilitated a preliminary Hazard Identification (HAZID) Study for the Green Pilot vessel methanol conversion.

The objective of the HAZID Study is to compare the proposed design with the existing rules for methanol, and analyse the design to identify any reasonably and foreseeable hazards.

The proposed design and safeguards were considered, and a list of findings and recommendations are compiled throughout the workshop and listed in section 4.

Written by:	Approved by :
Christian Kämmerer, M.Sc.	Mogens Heidtmann
Signature:	Signature:
	
Designation:	Designation:
Senior Specialist	Lead Technical Specialist
Date of approval:	
13 January 2017	

Rev. No.	Date	Compiled By	Verified By	Approved By	Reason for Revision
0	11-01-2017	C. Kämmerer	M. Heidtmann	M. Heidtmann	Final report

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1. Introduction

1.1 Background

ScandiNAOS is the designer for the conversion of one of the engines of the Green Pilot vessel to methanol operation.

As the vessel has two independent main engines, the methanol system is not considered essential service.

Lloyd's Register (LR) has been commissioned by ScandiNAOS to conduct a preliminary Hazard Identification (HAZID) study for the proposed methanol installation on the Green Pilot.

1.2 Objectives

The objectives of the preliminary HAZID are:

– to compare the proposed methanol system design with the existing methanol rules

– to identify potential hazards and the proposed safeguards & control measures

2. System Description

2.1 Methanol installation

The Green Pilot is a Swedish pilot boat which is being converted to run one of its two engines on methanol. The other engine will continue to use the existing diesel fuel system.

Two 500 L methanol tanks are being installed midship in a separate methanol tank room in front of the engine room. The methanol tanks are inerted by a Nitrogen system which is located on the aft deck. In the current design an air pipe with a high velocity head is located low on the portside of the main deck next to the pilot ladder. The engine- and methanol tank room are protected by a CO2 firefighting system which is also located on the aft deck.

Double walled pipes will transfer the methanol fuel to a pump chest in the engine room which will deliver the fuel to the portside engine at 4-8 bars at a flow of about 5 L/min.

A new portside engine will be installed to purely run on methanol. A Chinese made and certified gas engine will be converted to burn methanol in a Otto process (with spark plugs).

Vessel name:	PILOT 729 SE
Length (pp):	12,08 m
Lightweight:	12,4 t
Speed:	34 knots

Figure 1 – Picture of the Green Pilot.

3. Preliminary HAZID Study

A preliminary HAZID Study is a methodical ‘creative brainstorming’ technique used to identify hazards and operational issues associated with a design or process at an early stage.

3.1 Study Methodology

A Structured Checklist technique shall be used based upon LR experience with guidance from the following sources:

BS ISO 31000: 2009, Risk Management – Principles and Guidelines

BS ISO 31010: 2010, Risk Management – Risk Assessment Techniques

The HAZID node, operation conditions and failure modes used to initiate and encourage discussions are shown in

Table 1. For each node, possible causes and consequences were discussed. These prompts were based upon previous experience (and were not considered an exhaustive list) but indicative of the types of hazards that were thought to be applicable for such a design.

Risk mitigation and reduction measures were discussed, with a focus on elimination of the risk through an inherently safer design. All items discussed are listed in the worksheet.

3.2 Study Assumptions

A number of assumptions are generally made when completing a HAZID Study of this type. For this project these included:

- The installation and general layout are in line with the drawings and documentation provided.
- Where relevant, reference was made to existing rules during the meeting. It was taken into consideration that the vessel does not have to comply with the existing methanol rules, as it is below SOLAS and MARPOL minimum sizes (< 400 GT).
- As the vessel has two independent engines, and only one is using methanol, the methanol installation is not considered as essential service for the vessel. The pilot vessel will always be able to manoeuvre with the second diesel engine. So the methanol system for this conversion is only looked at from a safety point of view and what impact it can have on the rest of the vessel.
- All equipment and materials are suitable for the operating conditions & environment.

3.3 Preliminary HAZID Nodes

The following nodes were suggested to encourage free discussion during the preliminary HAZID Study, which may prompt the requirement for additional deviations during the workshop.

Equipment & Location	Methanol tank room and fire insulation
	General arrangement
	Methanol pump chest
	Methanol piping
Operation modes	Sailing, normal operations
	Sailing in heavy weather
	Sailing, methanol system not working
	Bunkering
Failures	Methanol leakage in tank, pipes or valves
	Fire

Table 1 – Preliminary HAZID Study Nodes.

3.4 Sessions and Timings

1. Workshop - 22.06.2016 **Lloyd's Register office, Hellerup**		
10:00	12:00	Discussion
12:00	13:15	Lunch
13:15	14:15	Summary

2. Workshop - 16.11.2016 **Lloyd's Register office, Hellerup**		
10:15	13:15	Discussion
13:15	13:45	Lunch
13:45	14:00	Summary

Table 2 – Agenda of workshops and time spent.

3.5 Team Members and Attendance

Participants – 1. Workshop		
Name	**Company**	**Role & Title**
Christian Kämmerer	Lloyd's Register	Facilitator Risk and Methanol Senior Specialist
Paul Herbert	Lloyd's Register	Subject Matter Expert Mechanical Engineer, piping
Jacob Plum	Lloyd's Register	Subject Matter Expert Electrical Engineer
Mogens Heidtman	Lloyd's Register	Subject Matter Expert Fire and safety
Bengt Ramne	ScandiNAOS AB	Naval Architect
Joakim Bomanson	ScandiNAOS AB	Naval Architect
Patrik Molander	ScandiNAOS AB	Naval Architect

Participants – 2. Workshop		
Name	**Company**	**Role & Title**
Christian Kämmerer	Lloyd's Register	Facilitator Risk and Methanol Senior Specialist
Paul Herbert	Lloyd's Register	Subject Matter Expert Mechanical Engineer, piping
Jacob Plum	Lloyd's Register	Subject Matter Expert Electrical Engineer
Bengt Ramne	ScandiNAOS AB	Naval Architect
Joakim Bomanson	ScandiNAOS AB	Naval Architect
Patrik Molander	ScandiNAOS AB	Naval Architect

Table 3 – Team members and attendence.

3.6 Preliminary HAZID Study

Two workshops took place in the office of Lloyd's Register (Hellerup, Denmark) on the 22nd June and the 16th November 2016.

The workshops were facilitated by a Risk Specialist and involved relevant stakeholders and Subject Matter Experts (SMEs) as shown in section 3.5.

3.7 Worksheet

The discussions and results from the two HAZID workshops are detailed in the following worksheet. The comments from both sessions have been combined, and all final comments are with reference to the latest drawings as referred to in the Appendix.

No.	Item		Action
1.1	Pipes passing through methanol tank room	It was mentioned during the discussions that several pipes and cables pass through the methanol tank room. This could not be seen on the drawings which were available during the workshops. This is only acceptable if the fire integrity of the methanol tank room is kept intact. So either pipes and cables are insulated, or more likely are not routed through this compartment at all.	
1.2	Air pipe P/V valve	The current location of the air pipe for the methanol tank is located on the main deck, portside, at frame #9 along the superstructure. The top of the pipe is equipped with a P/V valve which controls the over and under pressure in the tank in order to keep any methanol or nitrogen gasses inside the tank under normal conditions. During an emergency the valve will open and release any gasses or vapours at high velocity in order to disperse them as fast as possible. A location on a dedicated mast on the aft end of the vessel was discussed, but there was concern about the mast head hitting the hull of other vessels during heavy seas and manoeuvring. A location on top of the wheel house was also discussed, but a lot of electrical equipment is located there, so this might pose an ignition hazard to any methanol vapour. As any methanol vapour being dispersed by the P/V valve is both flammable and toxic, so the final location of the P/V valve must be carefully considered during a future HAZOP.	

1.3	Methanol Bunkering	The methanol tanks are equipped with a level gauge with an high level alarm which activates a buzzer on the bridge. It is expected that bunkering will be either by truck or from a 1 m3 tank on a trailer. It is recommended that the bunkering connection is grounded (common grounding point). The bunkering operation will either be by a pump with automatic connection to the high level alarm, or by push button operation of the pump which needs to be pressed continuously to work. The filling flow is estimated to be 50 L/min. The methanol tanks have no dedicated overflow, so any methanol will exit through the air pipe which is only visible from one side of the vessel.	
1.4	Methanol tank level gauge	In principle (following the class rules), if the level gauge/alarm is controlled by a PLC, it needs to be type approved, and the software would need to be approved too, if there is no hardwired backup.	
1.5	Nitrogen system	The nitrogen production unit is located on the aft deck and a pipe runs on the deck and leads directly into the methanol tank room. This is the shortest and simplest way to connect the nitrogen system and as most of the piping is on open deck, any leakage will not accumulate in a closed space.	
1.6	CO2 system	Both engine room and the methanol tank room are protected by a CO2 system located on the aft deck. Adequate CO2 capacity for methanol fires is to be confirmed by calculations.	
1.7	Smoke detector in methanol tank room	It was discussed if a smoke detector would be required in the methanol tank room. A heat detector is already planned, and the question is if a methanol fire will develop enough smoke for a smoke detector to function properly.	LR (Mogens Heidtman) to confirm if smoke detector is needed.
1.8	Bilge pump in methanol tank room	The methanol tank room has a manually operated bilge pump which is located in a recess on the side of the vessel. Any content is pumped direct overboard. It was discussed in the first workshop if in the case of a methanol leak in the tank room, the room should just be closed off and kept closed until the vessel returns to port. This is something which could be taken up in a future HAZOP.	
1.9	Fire insulation	The methanol tank room is A60 fire insulated towards the engine room and the superstructure.	

1.10	Insulation of aluminium hull	The normal requirements for aluminium vessels is to have A60 insulation of the entire engine room down to 300 mm below the lightest waterline in order to ensure the structural integrity of the hull in case of a fire in the engine room. As the vessel is not currently covered by the normal rules, this is not currently complied with. This is one of the points which need to be discussed further with the authorising administration.	
1.11	Cofferdam between methanol tank room and accommodation	The gap between the aluminium hull and the composite superstructure was considered as being equivalent to a cofferdam, so only the hull needs to be A60 insulated.	
1.12	Ventilation in methanol tank room	The ventilation fan needs to be of a safe type. It was discussed if a non-safe fan could be used if calculation of the LOL level in the methanol tank room showed that it would not reach an unsafe level.	
2.1	Location of emergency batteries	The emergency battery pack will be moved from the methanol tank room to the diesel tank room. Natural ventilation is provided (similar to the existing arrangement for the batteries) and a new access hatch on the forward bulkhead will be installed so that the compartment can be accessed without passing through the methanol tank room.	
2.2	Accumulation of methanol between superstructure and hull	The composite superstructure is mounted on top of the aluminium hull, inside a cavity. The small space between the two parts of the ship is rubber sealed, but not completely water tight. So it is advised to develop a safe working procedure in the event of a methanol spill or leak or any other occasion where this space is drained or accessed.	
3.1	Methanol pump chest	Pump chest insulated to A0, similar to cold box for LNG.	
3.2	Methanol pump in pump chest	It is difficult to find an "ex safe" fuel pump. Designer proposes to calculate the amount of methanol which could accumulate in the pump chest to determine if it would lead to an unsafe situation.	
3.3	High ventilation in pump chest	A possible way to not use "ex safe" equipment in the pump would be to install high flow ventilation.	LR (Jacob Plum) to confirm if pump chest can have "unsafe" equipment if installed with high flow ventilation.

3.4	Ventilation in pump chest	It was discussed that the ventilation from the pump chest could be merged with the ventilation from the methanol tank room. This needs to be further considered with regards to air ducts routing etc.	
3.5	Double pipe level switch in pump chest	Level switch in the pump chest installed, as it is the lowest point between tank and pump chest.	
4.1	Double pipes not ventilated or pressurized	The double pipes in the methanol system are not pressurized or ventilated, but are monitored for leakage by level switches in the outer pipes. This was discussed and given that the pressure is only 4-8 bar and the flow is about 5 L/min this was found to be acceptable.	
4.2	No block and bleed	There is no double block and bleed installation in the methanol system. Given the low flow and pressure (see above), this was considered to be acceptable. Operation during leak or failure scenarios to be confirmed in a future HAZOP.	
4.3	Double pipe level switch	Level switch in low point of double pipe installed between engine and pump chest.	
4.4	Valves for methanol	Solenoid valves are acceptable for fail to close valves.	

4. Conclusions and Recommendations

It was noted during the HAZID Study that a substantial number of issues had already been addressed at the conceptual design stage of this project based on ScandiNAOS's experience with earlier methanol projects (STENA GERMANICA).

At the same time, only limited information about all the vessels systems was available at the time of the workshop (see drawings list in the Appendix), including info about the engines methanol system.

It was often discussed which existing methanol rules can be used for such a small vessel. The risk of methanol was often compared to the risk of using gasoline on other vessels of similar size.

The following key items were identified during the HAZID workshops:

- Location of the p/v valve for the methanol tank should be carefully considered.
- Ventilation and ex safe requirements for the pump chest need to be further considered.
- Ventilation requirement in the methanol tank room to be confirmed.
- Bunkering operations need to be further considered.
- The missing double block and bleed arrangement to be further considered.
- The outer pipes of the methanol double pipes to be further considered, as they are not ventilated or pressurized.
- All existing installations need to be included in the modification drawings, as pipes and cables passing through the methanol tank room were not shown on the current drawings.

5. Appendix

5.1 Drawings & Documents

Title	Number & Revision	Date
General Arrangement	SNP15091-100_B	28.10.2016
Pipe Arrangement	SNP15091-105_A	01.11.2016
Methanol fuel system	SNP15091-706-1_A	28.11.2016
Hazardous area plan	SNP15091-707_B	09.11.2016
System coordination diagram	SNP15091-780_B	01.11.2016
Structural fire protection	SNP15091-810_A	28.10.2016
"Hazardous area classification for small methanol applications"	SNP15091-2	18.04.2016
"Preliminary design details"	SNP15091-101-1	12.04.2016

5.2 Rules

"Provisional Rules for the classification of methanol fuelled ships"
January 2016, Lloyd's Register

"Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuel"
July 2016, Lloyd's Register

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Appendix VII – Bunker checklist

METHANOL BUNKERING SAFETY CHECKLIST

Plats	Datum
Starttid	Sluttid
Fartyg	

Ögonskydd måste användas

Skyddshandskar måste användas

Brandfarlig vara hanteras

Volym att bunkra

Bunker id	Volym av tank 98%	Bränslevolym i tankar	Tillgänglig volym i tankar	Volym i tank på land	Tänkt volym att bunkra	Faktisk bunkrad volym	Kvarvarande volym i tank ombord
BB Tank	430 liter						
SB Tank	430 liter						

Förberedelser

Check	OP	Remarks
1. Upprätta säkerhetszon runt bunkringsfordon		
2. Arrangera pump och spänningsmatning till bunkring		
3. Säkerställ pump och slang är i gott skick samt alla kopplingar säkrade		

Anslutning av slang

Check	OP	Remarks
4. Kontrollera att inga larm är aktiva ombord och att ventiler samt bränslepumpar är stängda.		
5. Stäng av hyttventilation		
6. Kontrollera hur mycket bränsle som ska bunkras och notera på checklista		
7. Anslut jordkabel mellan båt och bunkringsstation		

Bunkering

Check	OP	Remarks
8. Starta bunkring		
9. Övervaka kontinuerligt att bunkrad volym överensstämmer mellan tank i land och bränslemätning ombord.		Avbryt vid skillnad
10. Stoppa bunkring när önskad volym är överförd		

Frånkoppling

Check	OP	Remarks
11. Koppla från bunkerslang		
12. Koppla från jordkabel		
13. Gör notering i loggbok och på checklista		