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A Pre-Combustion Carbon Capture System Applied to a Modern LNG Carrier

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Abstract

At the end of 2022, Rotoboost, Wärtsilä and ABS agreed to investigate the use of a pre-combustion carbon capture solution from Rotoboost applied in a ship design of a newbuild LNG carrier. The goal of this work is to find technically and economically feasible solutions on how to upgrade a modern LNG carrier design to reduce its overall carbon footprint and allow for compliance with carbon emission regulations throughout the ship's lifetime. Since regulations are not fully in place, the carbon reduction goal set for the project has been assumed based on the trajectory line extended from the CII regulation in place today.

It has been found that Rotoboost's solution is one of the most promising technical solutions capable of reducing carbon by nearly 100%, also reducing the carbon footprint of the ship to the agreed upon level. The technology is still under development and is based on a liquid catalyst that is decomposing NG into Hydrogen and solid carbon. Rotoboost has completed the first pilot test in their factory with very promising results, so the next step is to implement it in a new LNG carrier design to gather operational experience. The solution from Rotoboost will need to be integrated with a gas fuel supply system onboard, some of the NG will need to be diverted to the Rotoboost system, where the NG is decomposed.

After the decomposition, the hydrogen goes through a cleaning process, where the hydrogen will then be returned and blended into the NG flow and injected as a fuel into the onboard gensets.

The engine investigated is of the type W34DF and is developed by Wärtsilä. The engine system needs to be upgraded to be able to use hydrogen or the fuel blends with higher hydrogen content.

The solid carbon from the process is a powder that will need to be stored onboard in dedicated tanks. Once the vessel docks, the solid carbon will need to be offloaded in port, where it can be upgraded to graphene or graphite and used in many products, like in batteries, fuel cells and steelmaking. All equipment and materials are expected to be recirculated. This paper will describe in detail the impact that the Rotoboost system is going to have on operational costs and will provide a technical feasibility study developed for the full system, a description of the system and the results of the risk assessment.

Introduction

Designing an LNG carrier to carry and use hydrogen as a fuel contains some significant challenges. Storage of hydrogen either in a liquid or as compressed hydrogen occupies a substantial volume onboard the LNG carrier that will impact on the amount of LNG it can carry. Using the pre-combustion carbon capture technology from Rotoboost to decompose the NG into Hydrogen and solid carbon seems to be an attractive solution. This technology requires engine technologies that can operate on hydrogen, or a blend of Hydrogen and Methane. Wärtsilä is available with its W50DF-H/W46DF-H that can operate on hydrogen or eventually using a mixture of hydrogen and LNG.

An additional benefit of increased hydrogen content among natural gas fuel is the reduction of methane (CH4) slip from combustion. The combustion characteristics (wider flammability range and a faster heat release) of hydrogen also help the methane to combust more efficiently in the engine.

Carbon being segregated as solid carbon/graphite, requires much smaller onboard storage volume & weight in ambient conditions compared to temperature controlled and pressurized CO2 regardless of the post combustion CCS type.

The 174 kcum LNG Carrier

DFDE propulsion has been widely used by LNG carriers over the course of the last decade. However, the introduction of two-stroke dual fuel mechanical propulsion has shaken up the segment and today the 2-stroke dominate in LNG carriers. With the need to reduce CO2 and GHG emission and since the 2-stroke engine designers are not yet available with hydrogen engine solution, this gives Wärtsilä an opportunity to re-enter this market again as a leader in development of engine that can operate on pure hydrogen or a blend of hydrogen and methane.

For this study we are not targeting a 100% carbon reduction, which however is doable with the decomposer. Designing a system to compose 100% of the NG into hydrogen and solid carbon requires higher energy amount per ton, and a bigger decomposer unit, than a solution with smaller composing percentage.

The decomposer system is sized to run at its optimum, lowest total cost (CAPEX + OPEX) per captured ton of carbon, Rotoboost has investigated the process and concluded that the lowest cost per ton of Carbon, is found when decomposing 80% (mol%/mol%) of the NG into Hydrogen and solid carbon, at this optimum 20% of the NG is therefore not decomposed and will be delivered in a mixture with Hydrogen to feed the engine.

Please see figures 1 and 2 that illustrating the mass flow and gas composition.

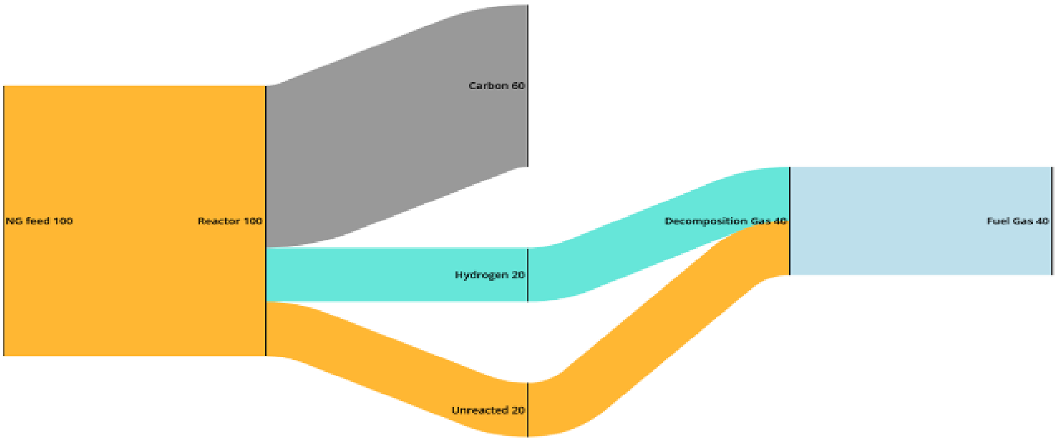


Figure 1. Decomposer mass flow diagram

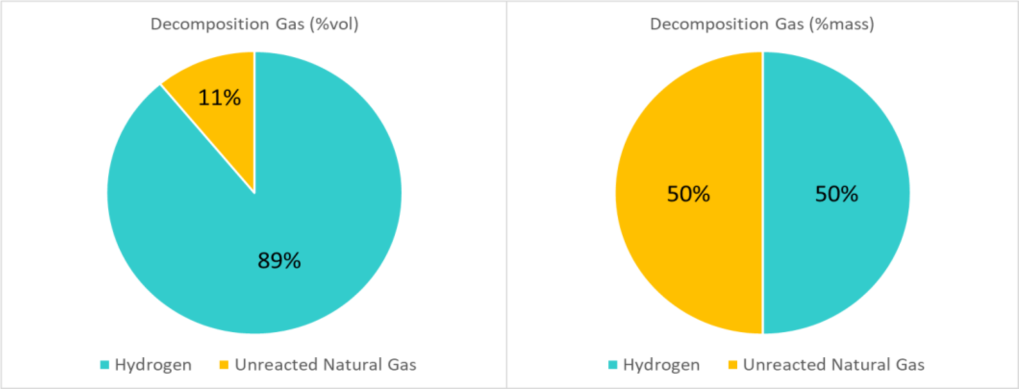
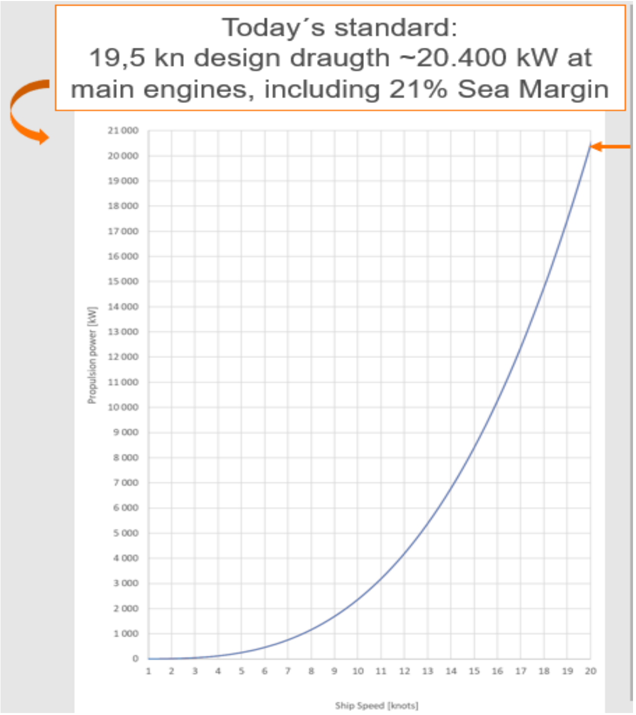


Figure 2. Decomposition gas composition

The baseline for this study is an LNG carrier with twin propeller and a propulsion power requirement at design speed. The Auxiliary power will depend on the configuration of the natural gas supply system. The power for offloading power is the dominating power and that is in the range of 6-8 MW & a load of 2-3 MW during seagoing condition. For a DFDE configuration, offloading of LNG and propulsion do not take place at the same time. So, the installed power will be sized from propulsion power plus the aux. power i.e. hotel load, required power from fuel and gas supply system supplying NG to the decomposer unit and DFDE engine system.

For this example, we have been using the speed power curve shown in figure 3. The design speed is 19.5 knots, requiring an el. DFDE Power of 20.5 MW.



Today´s standard:
19,5 kn design draugth ~20.400 kW at main engines, including 21% Sea Margin

Figure 3 Typical speed power curve for a 174kcum LNG carrier

During normal operation the ship speed is 18.5 knots in laden and 16. 5 knots in ballast condition. The DFDE el. propulsion power is found to 15905 kW with a seagoing Aux. Power requirement of 3110 kW at 18.5 knots, this to cover all aux. power requirement onboard the ship incl. pumps, BOG compressors and the el. Power requirement to run the accommodation. At 16.6 knots propulsion power requirement is found to 11680 kW, with a total el power requirement of 2300 kW at seagoing conditions.

The above baseline ‘typical round-trip sailing’ case requires 19015 kW (laden) / 13980 kW (ballast) total power production which equals natural gas consumption 65.7 (laden) / 48.3 (ballast) MT/day (LHV 50 MJ/kg). When this fuel is replaced with Decomposition gas (LHV 85 MJ/kg) which has 50%mass fraction of Hydrogen (LHV 120 MJ/kg), it correlates to Decomposition gas consumption of 38.6 (laden) / 28.4 (ballast) MT/day, of which 19.3 (laden) / 14.2 (ballast) MT/day is hydrogen, for identical power production.

The production of this amount of decomposition gas requires 96.6 (laden) / 71.0 (ballast) MT/day of natural gas as feedstock into Decomposer reactor (including the NG fraction which does not decompose) and additional up to 17.4 (laden) / 12.8 (ballast) MT/day of NG for heating and internal consumption, giving total NG consumption to be 114.0 (laden) / 83.9 (ballast) MT/day. By-product solid carbon production at this capacity is 57.9 (laden) / 42.6 (ballast) MT/day or approx. 30 (laden) / 22 (ballast) m3/day. Electricity consumption of this size Decomposer system is approx. 200kW.

The energy balance of decomposition system is shown as fig. 4. In the above ‘typical round-trip sailing’ case the total CO2 emissions from vessel would drop in average from 157 tons/day to 87.7 tons/day, or -44%, without considering any heat recovery. Approx 10% of total consumed NG energy can be recovered as heat, which equals -50% reduction in CO2 emissions. Above numbers are also considering the increased CO2 emissions from Decomposition reactor energy consumptions.

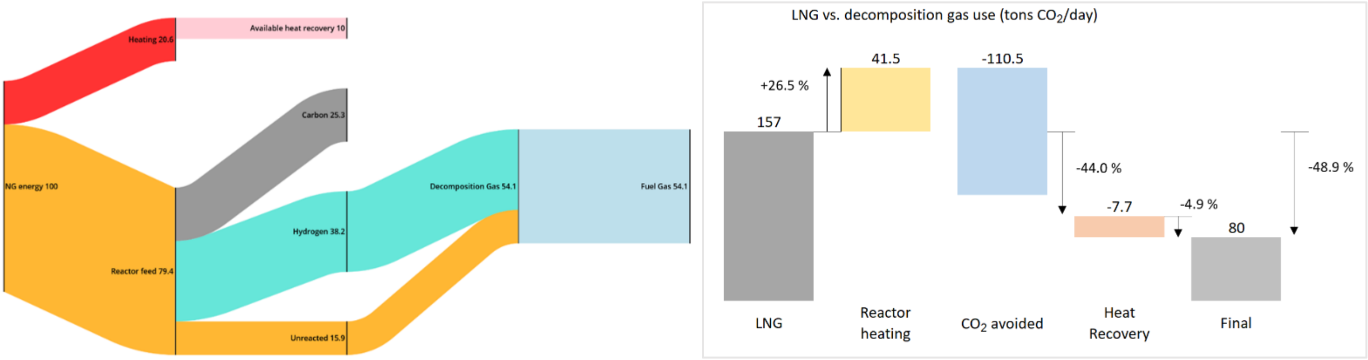


Figure 4. Decomposer energy balance diagram and carbon capture rate for the full gas and propulsion system

Naturally, also Boil-off Gas can be used to feed Decomposer and dimensioning Decomposer system capacity to handle full BOG amount from the LNG carrier. Today a BOR of 0.08% LNG volume/day, is typical and considered as being sufficient design criteria for the decomposer system, delivering a 80/20 H2/NG mol% mixture to the DFDE engine system.

DFDE Engine Configuration

The engine configuration of the DFDE can be arranged in many ways.

The general setup is comprising of the fuel supply system as shown in the pictures below figure 5 & 6. Note that engine sizing and the general lay-out of the tank system is just added for illustrative purpose. In this illustration the Tank Connection Space is placed after the LNG tank, where the LNG is evaporated and pressurized to the desired pressure.

The fuel gas is going directly to the gas valve unit (GVU), that is controlling the final pressure for the engines and contains also filters and safety valves. Part of the gas can also go to the gas decomposing unit and returned to the inlet of the GVU, this requires however that the gas in the NG by-pass is being regulated with a pressure reduction valve. Depending on the setup of the gas decomposing unit and depending on gas pressure requirement for the engine. A gas compressor for the H2 return pipe from the decomposer unit can be applied instead to increase the pressure and to secure the NG and H2 can be mixed, before the blend reach the engine.

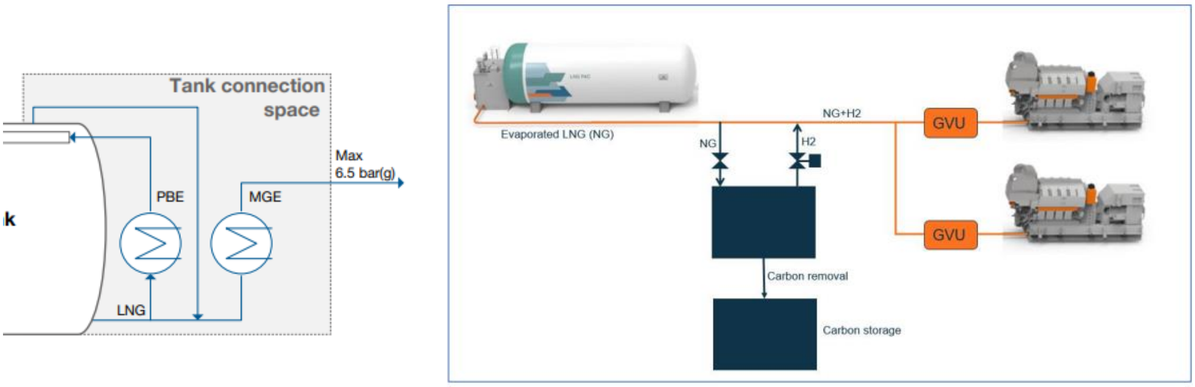


Figure 5: Figure illustrating the natural gas flow going from the tank system to the engine system, with a decomposer unit added, to decompose NG into a blend of Hydrogen and NG

For the LNG carrier Wärtsilä is proposing the DFDE engine set-up shown in figure 6 below, comprising 2 x 8L46TS DF and 2 x 6L46TS DF

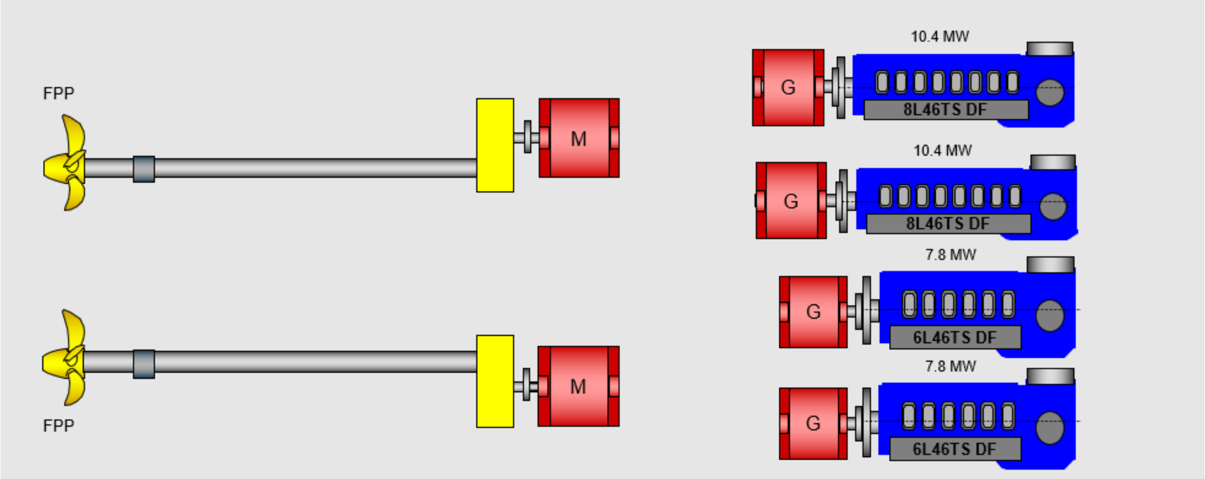


Figure 6: DFDE engine lay-out proposal from Wärtsilä, comprising 2 x 8L46TS DF and 2 x 6L46TS DF and with an installed engine capacity of 36.4 MW.

Today operation on hydrogen or a blend of hydrogen and NG is not yet in Wartsila's plan. But as described in the paragraph, it has been demonstrated that a blend can be used in the smaller engines, so when the interest hits the market this engine type L46TS DF can be upgraded as well.

The Hydrogen Fuelled Engine

The idea of blending hydrogen into natural gas has been initiated at first from the stationary engine power plants. The increasing energy production with wind and solar can sometimes result in overproduction of electricity. In this situation it would be beneficial to produce hydrogen and store it until the energy is needed. The produced hydrogen can then be added to the natural gas grid and be used as part of the fuel in the engine power plants. For this reason, Wärtsilä tested and verified the operation on natural gas/hydrogen blends already back in 2015.

The engine testing was carried out on both a pure gas engine (Wärtsilä 34SG) and in a dual fuel engine (Wärtsilä 34DF). For this carbon capture marine solution study, the dual fuel

Wärtsilä L46TS DF is the best choice as it is a well-known concept for the marine industry and especially in the LNG carriers. This engine type is relatively new, it offers a very high engine efficiency and a high power output. For this study we are assuming the same performance for the L46TS DF as has been verified for the smaller engine size, if the engine is going to be upgraded to use blend of H2/NG the performance is expected to be significant improved compared to the 34DF.

The dual fuel engine is a multiple fuel engine that can operate on both gaseous fuels as on liquid fuel. The fuel systems are divided so that the engine can easily switch between different fuel modes when requested or required. There are also possibilities to operate the engine on both gas and liquid fuel simultaneously i.e. fuel sharing.

The engine operates in gas mode according to the otto combustion principle and in liquid fuel mode according to the diesel combustion principle. In gas mode the ignition is handled by a micro pilot diesel injection.

The dual fuel lean burn gas engine is by nature compliant with the IMO Tier III NOx regulations, thanks to the lean burn otto engine concept that provides fast combustion leading to high efficiency, together with a rather low combustion temperature, which provides both low NOx emissions as well as low thermal loading on the engine components. The medium speed dual fuel engine provides fast loading characteristics that makes it suitable for most of the marine applications. As the engine is also equipped with a liquid fuel system, the fuel modes can be switched without delay, which makes the engine concept both robust and safe.

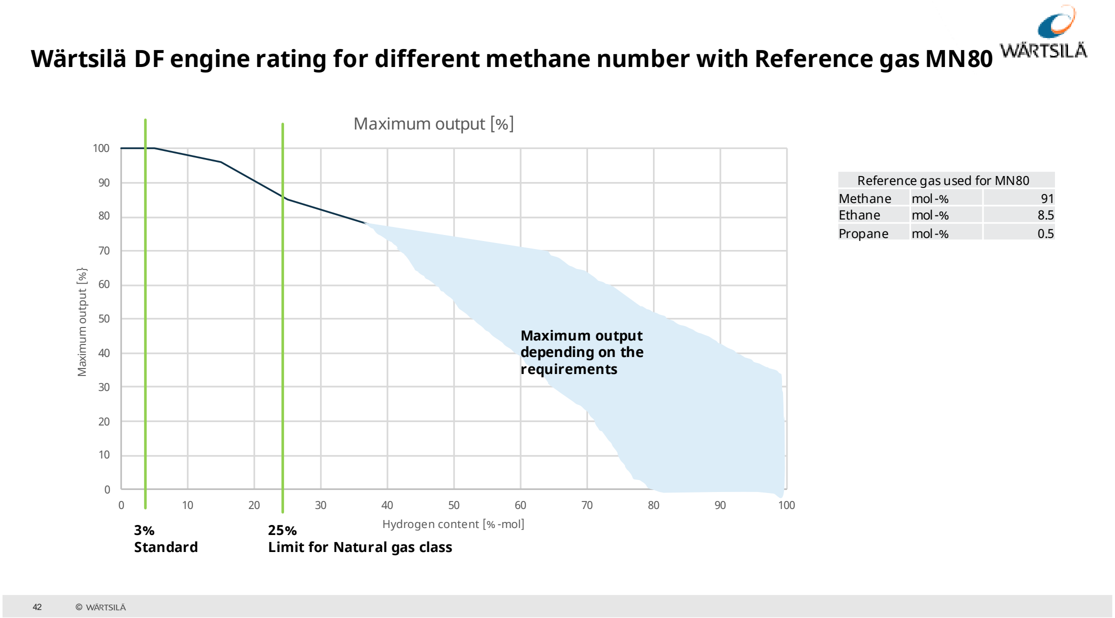
The low-pressure gas system is providing a safe and easy to install fuel system for the vessel. The low-pressure gas system also requires minimal external power to operate.

The medium speed dual fuel engine can operate both as a constant speed engine and as a variable speed engine depending on the application. The engine efficiency can be kept high on a wide range of the operating field.

The engine and the auxiliary systems will be designed according to the hydrogen/natural gas blending ratio as shown here below:

- Hydrogen < 3% vol
    - Standard LNG setup without modifications
- Hydrogen 3% vol – 25% vol

  - Engine mechanical setup according to natural gas operation
  - Blending control needed and information about the ratio to be given to the engine control system.
  - Engine automation for combustion control
  - Maximum allowed output according to the methane number derating curve.
- Hydrogen >25% vol
  - Engine setup according to hydrogen operation
  - Blending control needed and information about the ratio to be given to the engine control system.
  - Safety system setup according to hydrogen operation
  - Engine automation for combustion control
  - Maximum allowed output according to the methane number derating curve.



Wärtsilä DF engine rating for different methane number with Reference gas MN80

Reference gas used for MN80		
Methane	mol-%	91
Ethane	mol-%	8.5
Propane	mol-%	0.5

Figure 7: This engine performance is applied to the engine L46TS DF. When the engine is using a 80/20 blend, note that at 100% load the output is reduced to 50% engine load.

Hydrogen blending into natural gas makes the heat release faster and the combustion becomes more complete. This benefit is expected to result in less methane slip. The higher combustion temperature due to an improved heat release may however result a higher NOx. Table 1 shows the results from performance test done with 15%-vol hydrogen.

Table 1: Performance test results using a H2/NG blend

Engine performance comparison with 15%-vol hydrogen blending into natural gas compared to pure natural gas operation		
	Without combustion tuning	With combustion tuning
NOx	110%	as reference
Max cylinder pressures	20%	10%
Unburnt fuel	-15%	-15%
Combustion duration	-30%	-30%
Engine efficiency	+ 1%-unit	as reference

Working Principle of the TDC System from Rotoboost

In the TDC concept developed and tested by Rotoboost, methane (CH4) is broken down into H2 gas and solid carbon via a thermo-catalytic decomposition process (TCD) using heat energy and catalysts to lower the temperature requirement. The hydrogen produced is in the form of gas blend of H2 (89%vol) and unreacted CH4 (11%vol) called decomposition gas. Utilizing this gas blend as fuel in engine reduces CO2 emission since the carbon has been removed from fuel before combustion (pre-combustion carbon capture). Additionally, the system produces solid carbon with a significant market value. The produced carbon is either fullerenes (= an extremely stable circular carbon molecule that typically consist of 60 carbon atoms), single walled nanotubes or graphene depending on running conditions of the TDC unit. It can also be turned in to hard carbon, which is suitable for large scale energy storage in sodium ion battery applications.

Process Description

The conversion of methane into hydrogen gas and solid carbon is conducted via thermo-catalytic decomposition process (TCD, also referred to as methane pyrolysis with catalyst). In this process the methane molecule (and other hydrocarbon molecules) decomposes into hydrogen and carbon consuming heat energy. The hydrogen is released as H2 gas and carbon is in solid form.

$$CH_4 \rightarrow 2\ H_2 + C$$

This reaction is possible to achieve the heat energy alone, but the introduction of catalyst material lowers the required temperature significantly and thus making the process much less energy consuming.

As first step the system removes sulphur components away from the natural gas in a sweetening unit. Then feed gas is preheated in a heat exchange arrangement (internal heat recovery) before being introduced into decomposition reactor.

The catalyst forms a vital part of the process due to its impact on process efficiency and economics. In this project a special molten (liquid) metal catalyst is used in the reactor. The novel liquid metal catalyst has high heat capacity and it ensures homogenous heat supply to each methane molecule. When the methane molecule is split into hydrogen and carbon, the hydrogen gas escapes the liquid molten media and the carbon particles floats on the surface due to the difference between the carbon and the molten liquid density. These characteristics allow removal of both produced hydrogen gas and solid carbon during operation without significant catalyst losses.

The required reaction heat can be produced using different methods but onboard a marine vessel the preferred methods are 1) combustion of a small side-stream of the natural gas, 2) combustion of a fraction of the produced hydrogen rich decomposition gas.

Heating the reactor by combusting natural gas or hydrogen rich decomposition gas generates some CO2 emissions, while still much less than without the H2 generation system.

Decomposition process contains heat exchange arrangements to reduce the total heat energy consumption by utilizing available heat from product streams through heat recovery. Decomposition process also contain further arrangements for separating and collecting all solid carbon particles from the process to make decomposition gas particle-free.

The technology could work on various marine vessel types. And a HAZID has previously been completed for three vessel types and evaluated: Product Carrier, Ferry and a Very Large Crude Carrier (VLCC). The system arrangement on an LNG carrier will need to be tailored to fit into the specific LNGC vessel; system can be packaged into separate enclosures on deck or as a ‘back-bag installation’ depending on available space in vessel general arrangement.

Installing Decomposer system on a side stream of the main natural gas fuel feed is also a viable alternative: part of the fuel feed is treated in an Decomposer system to remove carbon and the produced hydrogen rich natural gas blend, called decomposition gas, is returned to vessels' Fuel Gas Supply Systems (FGSS) and mixed with vapourised natural gas to form a fuel gas blend with increased hydrogen content, but with smaller hydrogen fraction than directly from Decomposer.

By treating full fuel stream in the Decomposer system and utilizing (partial) NG combustion as a source for required reaction heat for the decomposition process, the CO2 emissions from propulsion are reduced significantly compared to natural gas fuelled engine operation. When the excess heat from the Decomposer is recovered for steam and/or hot water production, the energy efficiency is further improved and total CO2 emissions from vessel can be reduced up to -50%. CO2 reduction levels even beyond -50% are possible when using hydrogen-rich Decomposition gas as reactor heating fuel.

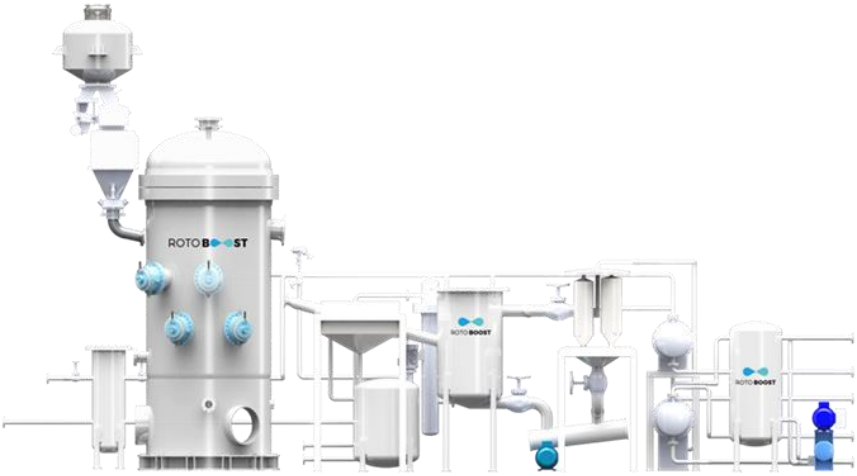


Figure 8 shows a general outline of TCD system arrangement for marine

Process Integration Onboard

The Decomposer system is connected and added downstream the LNG carriers fuel gas supply system as a gas consumer to receive the Boil off gas or the vaporized natural gas. The produced decomposition gas (mixture of hydrogen and unreacted natural gas) is then delivered further downstream to the FGSS's Gas Valve Unit for utilizing as fuel gas for the engine system. The system is prepared so the decomposition gas can be mixed with vaporized natural gas in the GVU before being delivered to the engine as fuel gas. This preparation is done to reduce hydrogen content when smaller hydrogen fraction is enough for reaching desired decarbonisation effect. As the engine technology and controls are still under development for higher hydrogen fractions, normal LNG FGSS still takes priority and needs to be fully operational if the Decomposer system fails during operation.

Rotoboost TCD system itself has very low electricity consumption since the energy required by the chemical reactions can be provided with small fraction of NG combustion. In addition, the excess heat can be recovered by the LNG carrier with conventional exhaust gas boilers to produce steam/hot water, which further improve the economics.

System Layout for the 174 kcum LNG Carrier

When the TCD system is located on the deck of the LNG carrier near the existing BOG compressor, the gas piping length and complexity is reduced. However, the system weight will be subjected on the deck and the deck needs additional reinforcement. Also the Decomposer system compartment with hot components inside is better not to be located directly on LNG tank top and therefore shall be installed at elevated position but considering bridge visibility requirements. The space below Decomposer system can be utilized for solid carbon onboard storage.

Required footprint area for Decomposer system is roughly approx. 100 m2 per each 10 000 kgH2 produced per day when equipment is installed on same level. The system arrangement onboard can have part of the equipment at different levels when available height allows and this reduce the required footprint in GA. The reactors are the tallest single equipment with up to 5 m height (including maintenance space). For the baseline case above, the system basic footprint is approx. 200 m2 and it can be arranged within approx. 150 m2 footprint when 5 m height is available for full area.

If the TCD system is located at the aft of the vessel the retrofit of such a system is simpler as no reinforcement needs to be welded on a tank top, but rather the back. Also, the height of the system will not be an issue as the system will always be lower than the stack even if arranged on several floors. Also, the arrangement of the TCD exhaust gas piping can be arranged at the same funnel as the engine exhaust. Common waste heat recovery can be considered. The H2 delivery piping to engine will also be shortened, however the compressed gas pipes from the BOG compressor will be longer. The system is also subjected to more vibration at the aft compared to the tank top.

Onboard carbon storage depends on required autonomy time. One convenient location for carbon storage is below the Decomposer system. The weight of equipment incl. the carbon storage is concentrated in mass on a small area, the deck structure will need to be reinforced, but the installation would be easier and only small area of vessel is influenced with the new system. Carbon storage on LNG Carrier could be dimensioned for 30 day round-trip to allow only single centralized carbon unloading location at gas loading terminal, which would make the operations quite convenient. The collection of the solid carbon in tanks with a 80/20 blend does not increase the overall weight of the vessel during sailing. See figures 8 and 9 as reference.

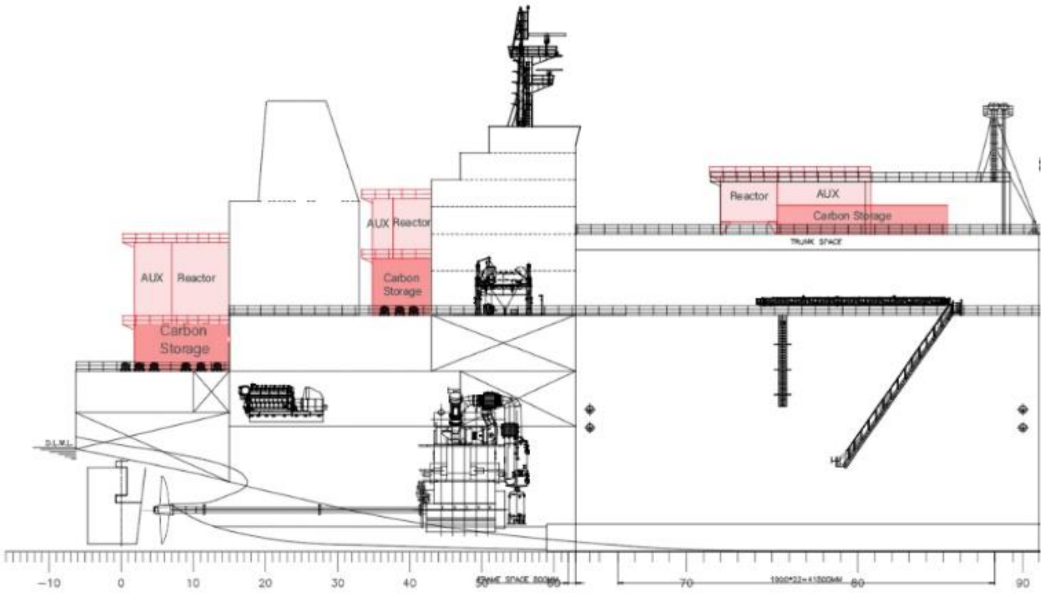


Figure 8 Three alternative system locations onboard LNG Carrier

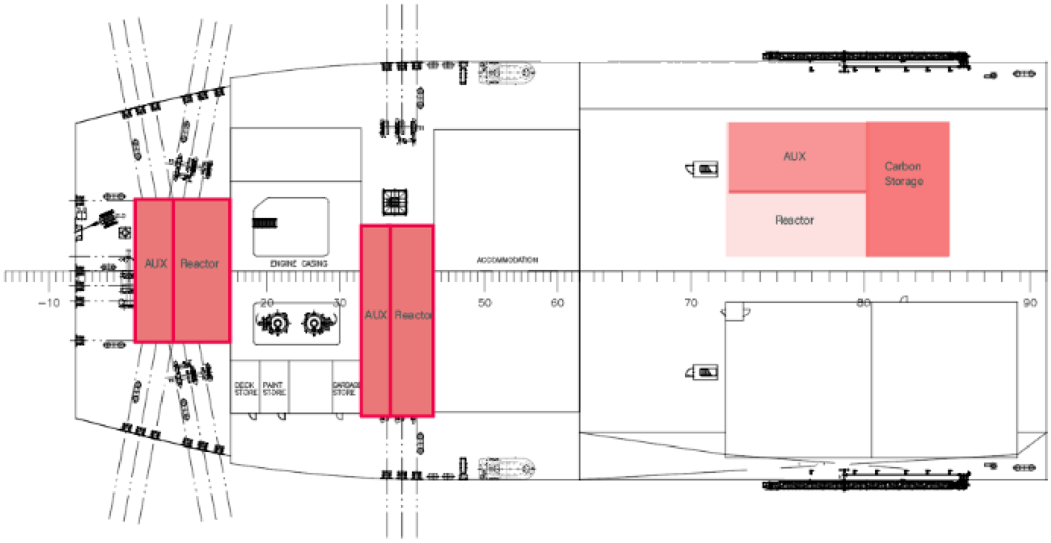


Figure 9 Three alternative system locations onboard LNG Carrier

Other alternative locations onboard can be found too for both Decomposer equipment and onboard carbon storage on different vessels, but generally a location relatively close to engine is preferred.

Sizing of Fuel Gas Supply System

An LNG carrier using Low pressure engines is today typically equipped with 2 x Boil Off Gas compressors to handle the gas fuel supply going to the engines, often it is a 6-stage cryogenic compressor from Cryostar that is being used feeding the 2-stroke engines with natural gas at a pressure of 7-15 bar. For the DFDE solution, the supply pressure is reduced to 7 bar, so the same compressors and the same compressor configuration can be used also for the DFDE system.

When a decomposer unit is built into between the compressors and the gas valve unit as illustrated in figure 5. All the equipment downstream the decomposer unit will have be modified to be able to handle hydrogen, as the product gas downstream the decomposer will contain hydrogen. So the following is needs to be considered:

- Material compatibility with hydrogen, the components such as valves, pipe material, sensors, sealings may not be suitable and need to be upgraded.
- Volumetric fuel gas feed flow changes (volumetric energy content of decomposition gas is smaller than natural gas; approx. 13 MJ/Nm3 vs. 37 MJ/Nm3 of NG)
- Gas detection sensors has to be upgraded to also detect H2

In addition, the upstream gas compressors capacity, the heat exchangers, the piping system has to be upgraded to accommodate the higher gas flow required when the decomposer are in operation. The turndown ratio of the compressors need to be adjusted as well to operate with increased flow capacity when H2 is produced, considering the different gas flows at Decomposition gas operation vs. NG operation.

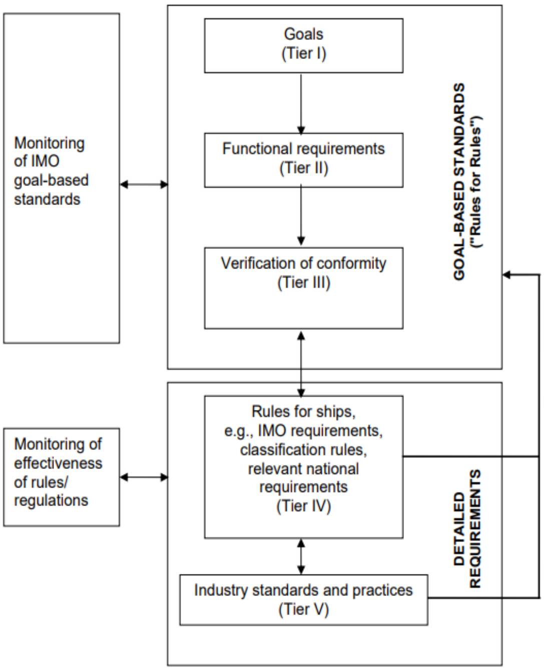
The gas pressure is provided by upstream BOG compressor and this pressure only needs to be increased slightly to overcome a small pressure loss in the decomposer system, the DFDE engine system needs same supply pressure for the 80/20 blend as for the 100 % natural gas. For practical control reasons a small buffer tank should be considered and implemented downstream the decomposer system.

In case only part of the fuel gas is decomposition gas (decomposition gas as drop-in fuel), mixing with natural gas should be done prior to feeding the fuel blend into engine or at the engine depending on engine maker exact set up. This requires a pressure reduction valve in by pass pipe section.

Classification Process

The International Maritime Organization (IMO) addresses gas carriers under the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). This Code does not however include hydrogen as an allowed product. In addition, the Code only addresses liquefied gases. It does not cover the transport of gaseous hydrogen under pressure. As a result of the above, as there are no international codes for the use of hydrogen as a fuel onboard LNG carrier, and for decomposing LNG into solid carbon and hydrogen, a goal-based approach under ***IMO MSc.1/Circ.1394*** shall be followed, considering alternative design and compliance.

Figure 10 IMO Goal Based Standards Framework



A formal document must be submitted by the flag state for IMO consideration. In this process, the flag state typically relies heavily on input from the classification society, designer, shipyard, and owner to provide necessary documentation.

The first step in this process is to perform a preliminary Hazard Identification (HAZID) study, which is performed when the ship design has reached a sufficient level of detail to identify the high-level risks applicable during construction and operations. This HAZID supports the new design process and follows established risk assessment methodologies to satisfy the IMO IGC Code intent.

For a partly hydrogen fuelled vessel equipped with the decomposer system, a HAZID was completed in 2022, and subsequent design and engineering has been performed in accordance with the risk register derived from the HAZID.

To design, build and class such an LNG carrier with a TDC system from Rotoboost, ABS has developed the following publications:

- ABS Guidance Notes on Review and Approval of Novel Concepts
- ABS Guidance Notes on Qualifying New Technologies
- ABS Guide for Vessels Intended to operate on hydrogen using ICE
- ABS Guide for Carbon capture

As part of these requirements, a What-if/HAZID must be in addition be completed.

Considering the proposed design of the gaseous hydrogen fuelled engine, and the absence of an international standard addressing the pre-combustion CCS, such design is a novel concept, ABS has however recently launched its own guideline for hydrogen fuelled vessels and a guideline for post combustion carbon capture, those guidelines cannot be used directly, but it was used to some extend as guidance for some aspect in the approval process. This process incl. the guidelines available, allowed the design to be reviewed and an ABS Approval in Principle (AIP) was thereafter issued to Rotoboost covering the TDC system.

For a successful approval process for Noval system, it requires that all parties involved understand the system in detail. When the process was developed to evaluate the safety aspect, ABS therefore adopted the following evaluation methodology / steps to arrive at a level where all aspect are understood and evaluated:

1. Develop an understanding of the concept. For complex systems this requires several mutual meetings before full understanding is achieved.
2. Identify the novel aspects of the proposed design.
3. Identify the hazards and safety concerns arising from the concept, and from the specific novel features.
4. Identify existing marine and offshore requirements and standards and conduct a gap analysis.
5. Use the gap analysis to identify those areas of the design for which no relevant standards currently exist.
6. Apply first principles and risk methodology for identification of risks

Novel Concepts Review Process

A novel concepts review must be able to contribute to the development of a novel project without requiring extensive information, at least for the initial stages of the project.

Figure 11 illustrates the review processes employed for this project, involving increasingly detailed information as the project matures. It provides a general overview showing that as more engineering, testing, and/or risk assessments needs to be conducted for the concept, the level of confidence increases as the concept performance approaches the required performance limits. The performance limits may include required reliability, function, safety and strength.

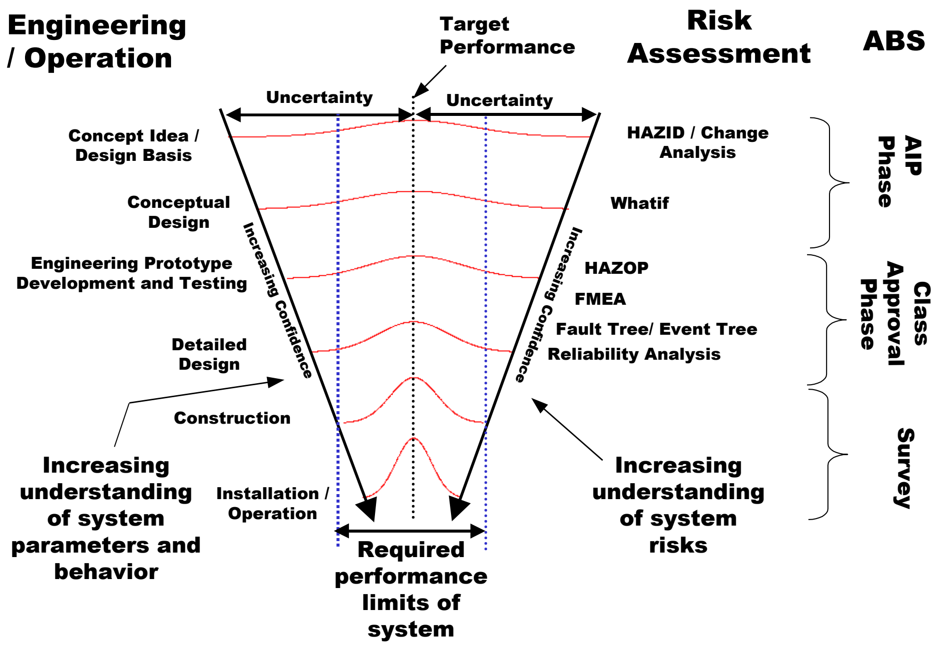


Figure 11: Novel Concept Review Process

Some of the typical risk techniques and engineering steps that would be expected during the development of a new concept are shown along the concept evolution route. As more engineering and/or testing is conducted a better understanding of the system parameters and behavior occurs. Note that the knowledge being gained during the concept development does not stop at the end of detailed design. Particularly with novel concepts, it is important that information continues to be gathered during construction, and during implementation into ship design and during operation.

During the concept evolution, risk assessments will be conducted to identify risks related with the concept, and that effective mitigation measures can be put in place. The risk assessments are arranged in general order of complexity and required concept development stages. However, there are instances where more detailed risk assessment techniques are conducted during earlier stages of the concept development.

At the far-right side of the Figure 11 above, the general classification/certification phases are listed. It is important to note that this is a generalized figure of the concept evolution and there may be overlap between specific engineering step progression as well as different timing of the application of the risk assessment techniques.

The conceptual design of the TDC system applied in ship designs was assessed by ABS following the above steps and procedures. A HAZID risk assessment was conducted implementing the system into several ships designs, and all significant risks were identified and documented. The ABS review followed the principles of the IMO IGC code; the IGF Code and the several other ABS Guides.

After careful evaluation, Approval in Principle was granted in 2022 by ABS for the proposed designs of the TDC system. A number of risks were identified that required further study and testing and are further summarized below. Those have all been addressed by Rotoboost during their developments during 2022

Hydrogen and Decomposer Safety

The IMO IGC Code addresses safety related to liquified gases, and not methane being decomposed to methane and solid carbon, for the hydrogen thereafter to be delivered to an engine in compressed gaseous condition. Therefore, and from a first principle approach, the hydrogen thermodynamic properties and its inherent risks were duly considered.

The following risk were identified and evaluated for safety, considering the compressed hydrogen supplied to the engine at 15 bars or lower:

- Material – susceptibility for H2 embrittlement
- Potential for leak - smallest atom size
- Wide flammability range: 4 - 75%
- Detonation, missile effect
- Gas dispersion, fire and explosion
- Clean burning, no flame visibility
- Stored energy in buffer volume (compressed gas)

In total 203 recommendation was found during the safety evaluation, and all related to the TDC was thereafter solved by Rotoboost.

Highlighting the unique features of the design then as examples such as tanks to store the solid carbon generated safety concerns, certain issues related to explosion in the TDC reactor and solidification of materials at critical locations, external fires & explosion of carbon powder were also identified as high risk and it led to increased focus on some of aspect shown here below:

- Pressure relief system in the TDC reactor
- Fire protection
- Dirt in and composition of the NG

Safety Approach for LNG Carrier

Previous workshop identified the hazards related to the handling of NG delivering pressurized hydrogen mixed with NG to hydrogen fuelled engine in marine vessels, determined the potential consequences of each identified hazard, identified existing safeguard(s) which will provide prevention, control and/or mitigation to the identified hazard, and proposed recommendations to further reduce the risk of the identified hazard if needed.

Most of the identified risks during previous workshop were related to necessary safety arrangements with low-flashpoint fuel gas (hydrogen) which topic is in principle level already well covered by IGF code and practical level arrangements need to be specified for each system installation location and arrangement. Material compatibility in hydrogen influenced equipment need to be confirmed (also for the fuel gas supply system). And marine engine design and controls need to be further developed to ensure good performance especially considering the high hydrogen fraction in fuel gas.

As for any new concept, and as the design progresses, the risks identified in the HAZID register must be addressed through the continued design development.

Total Cost of Ownership and Commercialisation

The Market for Solid Carbon

At the moment for the larger pilot systems at industrial gas flows and systems the generated carbon is either nano balls (fullerenes), single walled nanotubes or graphene. All of these have their own attractive after markets. For example, single walled nanotubes can be used as raw material for lithium-ion batteries in large scale and in smaller scale as catalyst raw material.

They are also useful in large scale energy storage, which will be more required in land-based installations due to the zero-carbon energy transition.

Graphene has excellent properties due to its strength and can be used mixed in with paint, concrete and steel. If mixed in with steel they can increase the strength multiple times, by up to 100 times even if added in high enough percentages. So even though it is not a novel material, but if produced in bulk it can be benefit several large-scale applications where graphene was previously considered unaffordable at its USD50-250/kg price tag. Also graphene batteries have multiple benefits over traditional lithium ion batteries such as shorted charging time and high energy storage capacity, but the cost of graphene has been a limiting factor.

Fullerenes are also very specialised materials and are 100 x stronger than steel while being one sixth of its weight. With the energy transition some of the most advanced use scenarios for fullerenes are using them in solar cells or more conventionally in electronic applications. They can also be used for conductors, superconductors, and a wide range of medical applications. Typically, fullerenes have been USD25-100/ g, but with this process they are a by-product of an economical decarbonising process making them available for a wide application of beneficial uses that were previously not possible.

There is an increasing demand for these super materials with the net zero energy transition, however their cost has been a limiting factor. For this particulate vessel we would be generating over 60 tons of these materials daily let alone for a fleet, making these materials more widely available at an affordable cost.

Operational Cost

Due to the high-grade carbon being generated, the shipowner would be able to break even for the installation in approximately 4 years depending on the LNG cost, which means that the system is negative in OPEX. Rotoboost is willing to buy back the carbon from the LNG carrier.

Capex Cost

Depending on the system size and needed capacity, the practical cost for the prefabricated and assembled system module is between 7-15 million USD for an LNG carrier

Conclusion

Using the TDC turning NG into hydrogen and carbon. The 'inevitable penalty' of Rotoboost solution come from increased NG consumption (since the carbon fraction is left uncombusted) while total GHG emissions from vessel are being reduced. This economical burden is minimized with additional revenue from carbon sales, making Rotoboost pre-combustion CCS unique and very economical to use compared to more conventional CCS. Using bio/e-LNG as fuel might even make the vessel carbon negative.

The flexibility in operating with different fuel with a dynamic operation profile is highly prioritized in today's development of the marine engine. The use of both liquid fuels and NG in operation will be still important for years to come. It has been shown by Wärtsilä that the engine system can be designed to operate on a blend of hydrogen and natural gas. It has been shown that blending in hydrogen has a good impact on the combustion and the methane slip. NOx emissions need to be further controlled when hydrogen is introduced to the engines. For the engine system as it is proposed today the DF engine reduces its power output down to 35%, if the fuel is NG fuel is turned into 100% hydrogen. With an 80/20 blend as investigated in this paper, the output is reduced to 50%. Upgrading the propulsion system to fit the bigger engine type the L46TS DF in a DFDE configuration, will require new development from Wärtsilä. Hydrogen fuel is new to the marine engine industry, and the performance is not yet at the level where it is supposed to be for a fully developed engine system. In the future we should expect that engines can be designed to be further optimized for pure hydrogen operation, which will give a significant higher power output with improved engine efficiency compared to what has been used in this study.

Next step in the project would be to bring in an owner and shipyard which is interesting in optimizing this LNG carrier solution further for a commercial LNG carrier project. The risk will have to be evaluated once more when the final design of the LNG carrier is available with the decomposer unit incorporated.

The TDC system can be designed to any carbon capture rate, even a capture rate of 100%. This will however further increase the cost both capex and the fuel penalty. A higher capture rate will result in a higher capacity a fuel gas supply system. In this study BOR of 0.08% shows feasible in this study, but if the capture rate increases it might show to be better to have a higher BOR. This could reduce the need for insulation, potentially there could be some capex savings on the LNG tank system.

The solid carbon produces in the TDC comes from fossil LNG, today we see a significant market potential for solid carbon but the solid carbon has to be upscaled into nano balls (fullerenes), single walled nanotubes or graphene that all has a higher market value. The use for these material are many, even though the carbon arrives from fossil fuels we assume that materials goes into a circular carbon economy, creating a closed-loop system where the carbon is be reused again and again. This carbon can play a crucial role in building up a new carbon neutral society that we now are targeting for 2050.