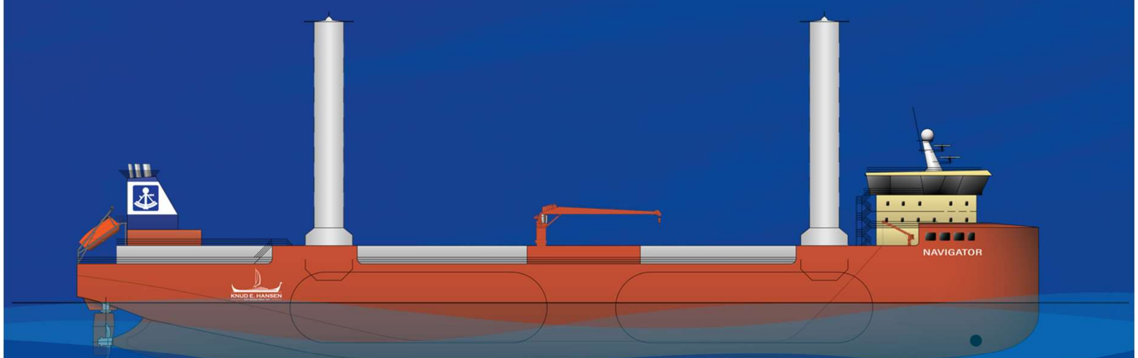
Carbon Capture & Storage

Conceptual Design of CO2 carriers

Dan-Unity CO2 – November 2025



DAN-UNITY CO₂

seapeak

DEN DANSKE MARITIME FOND

NAVIGATOR GAS

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Preface

The initiative for this report was taken back in 2019, when Ultragas, later Navigator Gas, wanted to investigate whether CO_2 could be handled and transported by the existing fleet, thus sowing the seeds of a cross-industry collaboration between Ultragas, Evergas and EPIC Kosan.

A joint venture between Ultragas and Evergas was formed called Dan-Unity CO_2, whose purpose was to build competencies in the handling and transport of captured CO_2 as cargo.

When it became clear that existing tonnage could not satisfactorily handle CO2 as cargo, it was therefore quite natural to develop a new CO_2 carrier ship design and not least enter a dialogue with the CO_2 capture chain (CCS) including emitters, transporters and not least the CO_2 storage about what the design should be able to do.

It was clear that CCS would be a significant part of various countries' climate goals, not least in Europe, and that in this connection there would be a need for transport from emitter to storage both by land and sea. This could take place with larger or smaller quantities and at varying distances but would be a continuous process so that a CO_2 carrier would be a kind of sailing pipeline, as LNG transport arose 30-35 years ago.

This report is made possible under the Danish Maritime Fund's grant scheme, which aims to provide financial support for initiatives that contribute to promoting Danish shipping and maritime industry. The project was carried out in the period spring 2021 to spring 2025 in collaboration between Ultragas (later Navigator Gas) and Evergas (later Seapeak).

Our work has been publicly presented on several occasions:

- *CO_2 – Seaborne Transport – from an owner's perspective*; Danish SNAME (Skibsteknisk Selskabs Fond) – Copenhagen 23 January 2023 by C. Manniche
- *CO_2 Shipping & Terminals Conference 2023 - CO2 carrier design*; London 27 June 2023 by C. Manniche
- *CCS – Owner's perspective - part II;* Danish SNAME (Skibsteknisk Selskabs Fond) – Copenhagen 4 November 2024 by C. Manniche
- *CO_2 Shipping & Terminals Conference 2024 – In panel debate*; London 18 June 2024 by C. Manniche

A big thank you and recognition of the Danish Maritime Fund's purpose and work to make this project possible and to support Blue Denmark.

The project group consisted of:

Mihir Navalkar – Seapeak

Ajay Arora – Seapeak

Carsten Manniche – Navigator Gas (author)

Gentofte 18th November 2025

Background & Purpose

The project involved the preparation of several CO_2 tank designs, associated piping systems and related cargo equipment for onboard storage and handling of a CO_2 cargo volume for several ship sizes.

Dan-Unity CO_2 wanted to clarify the technical challenges and, not least, get an overview of potential showstoppers as well as their solutions and costs to develop an actual newbuilding specification in time.

The background for the project is to understand and handle any challenges in the CCS chain and ensure that future designs live up to the requirements of a given CCS chain. In addition, there will be a due focus on the final price per ton of CO_2 stored and the contribution of shipping to this, as well as the CO_2 footprint of the transport part. A 16,000 m^3 CO_2 MP carrier was developed for the ARA to Iceland route.

Summary

In the start-up phase of the project, there was a somewhat narrow focus on optimizing the ship design as a "stand alone" design, partly due to a lack of understanding of the needs of the upstream and downstream CCS chain. This resulted in a prioritization of transport in the low-pressure area (LP) close to the triple point (transition from three-phase to two-phase), which meant that the tanks could be made larger and thus keep the ship's newbuilding price down.

However, it became clear that it was necessary to design the ship to the needs of the CCS chain, especially in terms of energy requirements for handling and cooling, but also to keep CAPEX down. Furthermore, it became clear that the CCS chains were not the same and that the ship's design had to be tailored to it, which made CAPEX and partly OPEX larger, but the total cost of final storage per ton of CO_2 smaller.

The need to cooperate with the various CCS chain links, in particular upstream, i.e. the emitters (cement plants, power plants, etc.), became evident, when the Norwegian project Northern Light saw the light of day. Here, the focus was on smaller vessels of size 7,500 m^3 in the medium pressure (MP) range, which quickly became the standard for a CO2 carrier, especially in the smaller segments. Therefore, the focus of the project also changed towards MP.

The project ended up developing several designs of different sizes and pressure ranges in collaboration with German/Japanese TGE Marine, where the size of 16,000 m^3 CO_2 MP was the subject of a more detailed design development by the Danish ship consulting firm Knud E. Hansen, which is explained in detail in this report.

Deliverable

<u>Designs – LP:</u>

Sizes: 7,500 m^3, 12,500 m^3, 12,500 m^3 shuttle, 14,000 m^3, 21,000 m^3, 22,000 m^3 & 56,000 m^3

Approval in Principle (AiP) by ABS for 12,500 m^3 and 22,000 m^3 early in the project phase.

<u>Designs – MP:</u>

Sizes: 16,000 m^3 & 24,000 m^3

<u>Detailed design – MP:</u>

Size: 16,000 m^3

<u>Documents and drawings for all designs:</u>

- Cargo tank Outline Specification
- Cargo Tank drawing
- FEED study report
- General Arrangement Plan
- General Outline specification
- Cargo Handling System
- Outline Specification for cargo system
- Pipe Routing Analysis
- Pressure built-up – time calculation

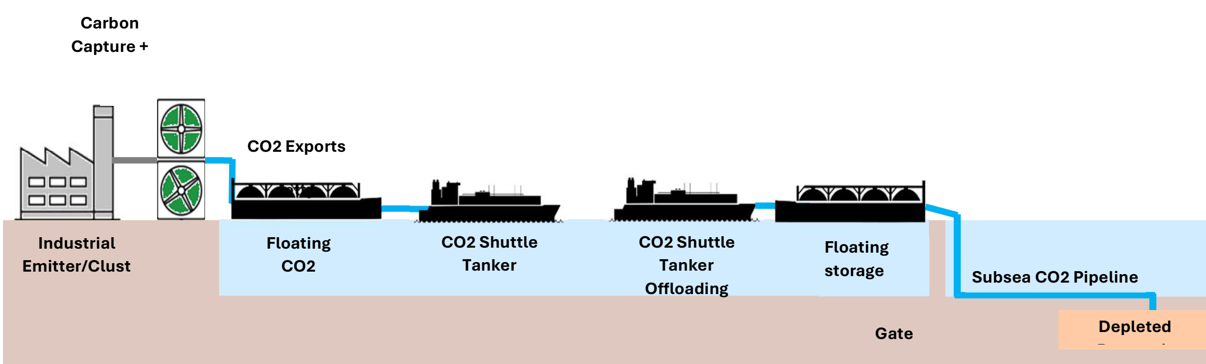
- Approval in Principle – 12,500 m^3 & 22,000 m^3 LP

<u>Further documents and drawings for 16,000 m^3 MP:</u>

- Lines Plan
- Lightweight Calculation
- Speed & Power
- Propulsion Report
- EEDI Calculations
- CFD Analysis
- Emission Reduction Report
- Intact Stability
- Damaged Stability

Conclusion

CCS is expected to be a cornerstone in the transition away from fossil fuels, and here transport by ship plays an important role. Transport by ship can take place between emitters for storage, both off- and on-shore, possibly as shown in the figure below.



Source: Navigator Gas

The project is based on previous Navigator Gas studies of a conversion of an LPG carrier for the transport of CO_2, which turned out not to be possible due to the almost twice as high density compared to ordinary LPG cargoes.

Therefore, Evergas (later Seapeak) and Ultragas (later Navigator Gas) chose to investigate the possibilities of designing a suitable size CO_2 carrier for the emerging market. As an example of a market, the focus was on ARA for Iceland (the Carbfix project) with a low-pressure design of varying sizes, as low-pressure would be most optimal for the ship design alone.

However, it became clear that the emitters primarily focused on medium pressure driven by the Northern Light project, so it was decided to detail design a medium pressure design of 16,000 m^3 for the Carbfix project.

The size of the CO_2 carrier follows a multiple of the largest CO2 cylindrical tanks that can be built for that pressure and is highly dependent on available material, which is preferably manufactured for the lighter LPG loads. The 16,000 m^3 CO_2 described below is based on four 4,000 m^3 cylindrical tanks, as the maximum capacity of the medium-pressure tanks at the time of writing is precisely 4,000 m^3. Currently, the maximum tank size for low pressure is 7,000 m^3 and therefore the design below is a multiple of this size.

In popular terms, it can be said that the cargo tanks are designed in line with the CCS chain's quantity requirements and that the ship is designed around the tanks, however, with respect for maximum draught, speed and consumption, maneuverability and so on.

It is expected that the maximum tank sizes will increase as dedicated materials and class rules are developed. However, the heat treatment requirements of the completed tanks may be a limiting factor for the tank manufacturer.

In collaboration with ECA Engineering, a CCS model chain has been created, where the emitter's need for transport volumes can be varied and the ship size/pressure can be optimized based on several inputs such as distance, quantity, OPEX, CAPEX, speed, CO_2 footprint and much more. The model is available as an app and can be used by anyone by contacting the project group or directly to ECA Engineering.

Methanol has been chosen as the fuel, as it is expected to be possible in the long term to bunker green methanol based on captured CO_2 in Iceland. This will provide a not insignificant advantage in the context of the EU ETS/EUAs as well as FuelEU Maritime for the route between Iceland and ARA. The methanol is placed in tanks amidships because of the weight balance, but also because of leak stability requirements for separation of the cargo holds.

The Wind Assisting Propulsion System (WAPS) has been studied in detail for four Flettner rotors, but a more in-depth study needs to be carried out, especially regarding their mutual interaction. In addition, they have achieved savings and thus payback hampered by the advantage of the consumption of green methanol in connection with the calculation of EUAs and FuelEU Maritime, but of course also depending on the price of the methanol. However, the ship is shown with four Flettner rotors.

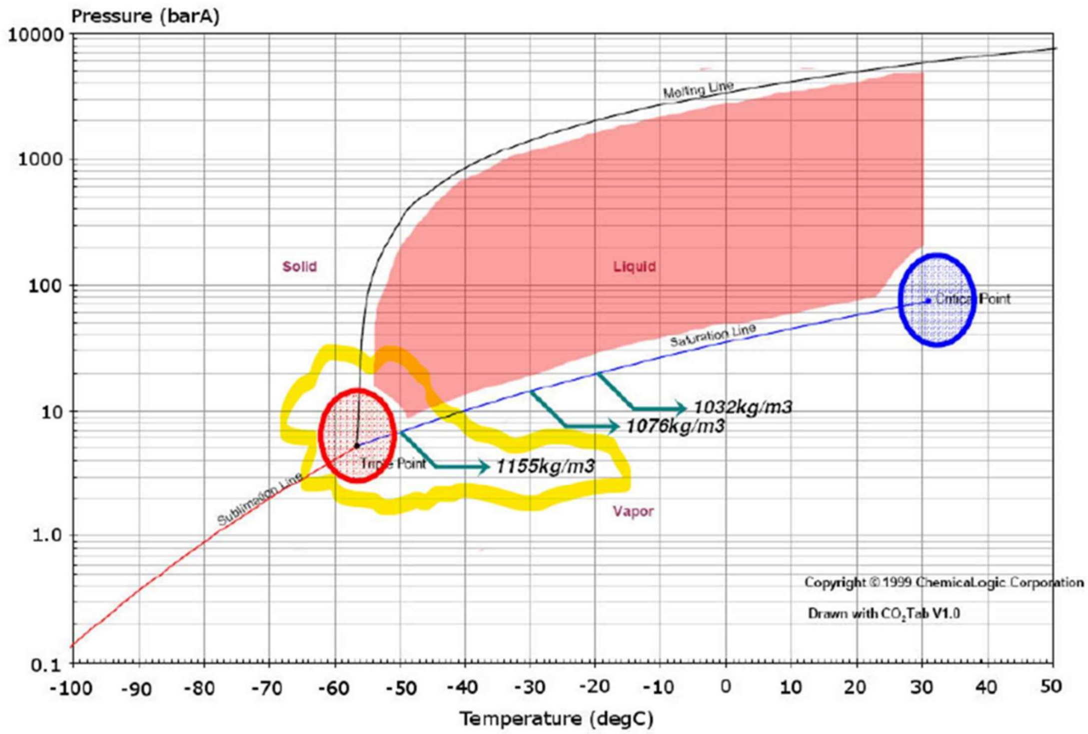
The ship's accommodation has been moved to the front of the ship to provide a better balance and optimize trim. The position of the accommodation at the front during operations in the North Sea and the Atlantic can be discussed, and especially the accelerations at sea in relation to the welfare of the crew, must be examined in detail.

The ship's speed is relatively high and depends on the final rotation and frequency of calls, but also on the necessary engine power for operation in the waters between ARA and Iceland.

CO_2 tanks – pressure, design & material

CO_2, as cargo, is far heavier than normal cargoes such as ammonia, LPG, butadine and propane for LPG carriers both under low and medium pressure +/- 1100 kg/m^3 (see Fig. 1), where ammonia is approx. 680 kg/m^3. This is one of the reasons why transport in the existing LPG carrier would result in significant modifications such as the installation of extra shutters in the tanks due to sloshing from partially loaded CO_2 as well as general reinforcements.

In addition, CO_2 will fall under IGC, which primarily covers the more volatile and lighter loads. So the combination of heavier loads and for the lower temperature at LP means that the current designs and not least the tank material are not optimal for transporting CO_2.



ChemiLogic Cooperation

Fig. 1 Phase diagram for clean CO_2

Low pressure – low pressure (LP)

Transport at low pressure is just above the triple point (see fig. 1) and takes place at temperatures between approx. -55 C° to approx. -40 C°, pressures between approx. 5.8-10 bar and with a density of approx. 1170-1120 kg/m^3.

The advantage of low pressure is that the tanks can be designed larger (larger diameter) and thus fewer in number. Limiting factors are the maximum diameter of the tank, maximum plate thickness as well as minimum temperature for material testing (-70 C°) for testing of the maximum plate thickness as well as the tank builder's facilities, not least the requirement for heat post-treatment of the tank after assembly.

The risk of low-pressure tanks is the formation of dry ice (which does not expand), so a certain kind of safety margin to the triple point is necessary also to be able to handle the influence of any impurities on the distance to the triple point. However, the influence of impurities will not be dealt with in this report but will have a significant impact on the CCS chain, not least during the handling of vapor return from loading of tanks land- and ship-based.

In addition, the greater pressure, which is somewhat above normal, on the tank foundation, the saddles, must also be assessed, but it is expected to be able to handle due to the experience with LPG tanks of varying formats.

Medium pressure – mid pressure (MP)

Transport at medium pressure has a larger margin to the triple point (see fig. 1) and takes place at temperatures between approx. -33 C° to approx. -21 C°, pressures between approx. 14-19 bar and with a density of approx. 1070-1040 kg/m^3.

The advantage of medium pressure is that the tanks and associated systems have a larger margin to the triple point and thus the risk of dry ice build-up, but due to the relatively higher pressure, it is only possible to build with a smaller diameter and thus more tanks for the same load volume.

Medium pressure has long been in focus for projects with transport in smaller ships and on shorter distances such as for Northern Light, while it is expected that the focus on low pressure and thus larger ships will increase especially for projects in Asia, but also for projects outside the EU, e.g. to Iceland.

During our conversations with upstream emitters, the question was what pressure we, as shipowners, wanted to receive the CO_2 in. This has opened a debate about what the emitter expected the most optimal pressure and temperature would be for the emitter's capture, transport and intermediate storage until loaded into the ship, which has not always been clear to the emitter.

In our opinion, the CO_2 tanks on board the ship can advantageously be built in an area from low to medium pressure, which favors and optimizes the upstream cost of capture, transport (preferably pipes) and not least storage on the quay. So, tank pressure and temperature do not have to be either low pressure or medium pressure but can also be a level in between.

The transport of CO_2 under high pressure, which takes place at temperatures above +5 C°, pressures above 40 bar and with a density of approximately 900 kg/m^3 or less, is not covered in this report. However, it can be mentioned that especially in the case of final storage in the subsoil on land, as on water, CO_2 can be advantageously received at high pressure, as it must be pressurized before pumping down (with temperature increase as a result) in the subsoil at +200 bar pressure.

Impurities

It is not the purpose of this report to describe and deal with the effect of impurities in CO_2, but since impurities can have a greater impact on the CCS chain, we will briefly explain our considerations.

Impurities have an impact on the thermodynamic, physical and chemical values of the CO_2 flow. However, it is uncertain to what extent the influence is, but there is no doubt that especially for LP, the type and level of impurities will pose a risk. Since the number of impurities can be relatively large, their influence on each other and not least the location of the triple point/phase unknown and with many variables, research and standardization work are ongoing in the area. The uncertainty about the consequences of the content of impurities means that current CCS projects such as Northern Light work with a CO_2 specification of high purity, which is understandable, but which is also expected to have a negative effect on the cost per stored CO_2.

It should also be mentioned that there is usually a small residual load left in the tanks, so-called *heel* after unloading, which will contain a greater level of impurities. The amounts of impurities will increase after several load/unload cycles, which will eventually create a relationship beyond the design values of the tank. Therefore, we have found that the handling of vapor return is extremely important for the CCS chain's functionality and not just for the ship.

Impurities can hardly be avoided in captured CO_2 and since there is currently no actual standard for the level of impurities, the CO_2 tanks are designed for pure CO_2.

Lately, it has been the norm to use the Northern Light specification for impurities, but other project-defined specifications are also in play. There is a need for an actual common standard, but also that one standard can have an adverse influence on the CCS chain depending on the source of the captured CO_2 and the final transport, storage and storage method.

Our tank design is intended for pure CO_2, but we have included the following composition of impurities in our considerations of their effect on tank design see Fig 2.

Component	Concentration, ppm (mol)
Water, H_2O	≤ 30
Oxygen, O_2	≤ 10
Sulphur oxides, SOx	≤ 10
Nitric oxide/Nitrogen dioxide, NOx	≤ 10
Hydrogen sulphide, H_2S	≤ 9
Carbon monoxide, CO	≤ 100
Amine	≤ 10
Ammonia, NH_3	≤ 10
Hydrogen, H_2	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Mercury, Hg	≤ 0.03
Cadmium, Cd Thallium, Tl	≤ 0.03 (sum)

Source: TGE Marine

Fig. 2 Composition of impurities of captured CO_2

Since CO_2 usually comes from combustion or cement production, several gases with a low boiling point such as nitrogen, oxygen, methane and argon will be present in the captured CO_2 which must be handled along the CCS chain. The effect of these gases on the cargo tank design will mainly be a higher pressure. As an example, nitrogen can be used, which will increase the pressure significantly even at relatively small amounts – see Figure 3 below.

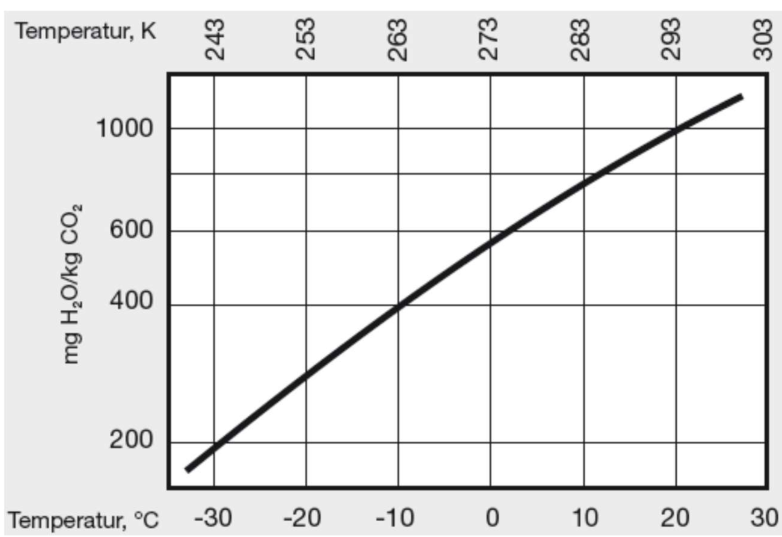
Boiling pressure at -55 °C	
% mole N_2 in liquid	Pressure bar a
0,0	5,5
0,1	6,3
0,2	7,1
0,3	7,9
0,4	8,6
0,5	9,4
1,0	13,2
1,5	16,9
2,0	20,6

Source: TGE Marine

Fig. 3 Boiling point pressure of CO_2/N_2 mix

As can be seen, a tank with MARVS of 7.5 barg will be able to handle an N_2 content of up to approximately 0.2% mol in the liquid before the safety valves will lift and the vapors will be vented.

Free water will also be a by-product of capture of CO_2, which is not wanted in the CCS chain due to the risk of a rapid reaction of corrosion and which must therefore be removed, which can happen in several ways in the chain. It will be necessary to remove water even before land-based transport and storage, but there is uncertainty at what level. The solubility of water in CO2 depends on temperature and pressure, as well as the content of gases such as oxygen, nitrogen and methane, which will significantly reduce solubility. The water content of pure CO2 is about 80 ppm (mass) and 200 ppm (mole) at -50 C°.



Source: TGE Marine

Fig. 4 Solubility of water in pure CO2

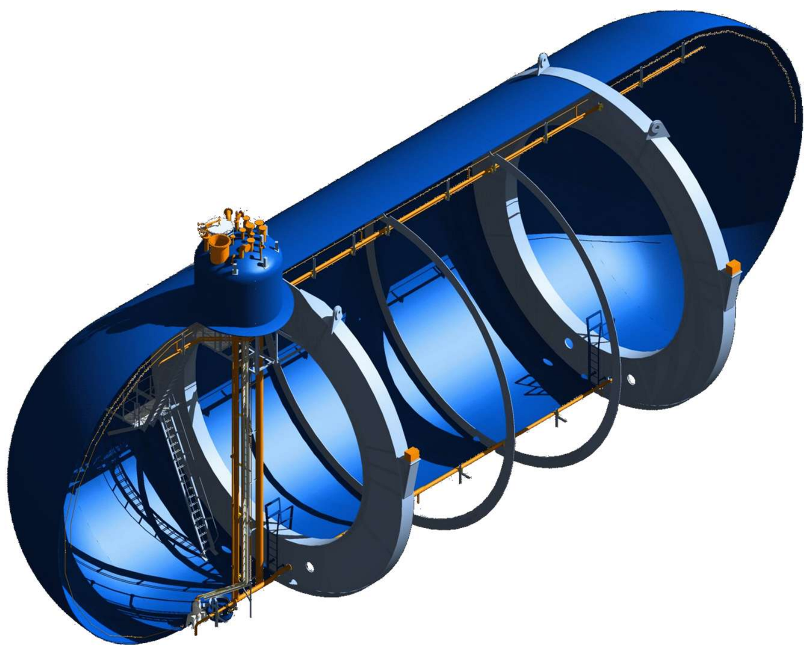
However, as can be seen from the specification used (fig.4), the requirement for the < 30 ppm mole in the captured CO_2 may be met depending on the content of impurities, as there is some margin to the 200 ppm mole at a temperature of -50 C°.

Tank Design

Gases under low and medium pressure are usually transported in so-called type A, B, C or membrane tanks, each of which has its advantages.

Since CO_2 must be transported in liquid form at a minimum of approximately 5.3 bar, it is currently only type C tanks that are relevant.

They are available as cylinder, bi-lope or tri-lope tanks see Fig. 5-7. Bi- and tri-lope tanks are primarily bilt to be able to fill the ship's volume for lighter cargoes, whereas CO_2 tanks have more need for buoyancy due to the higher density/weight of CO_2 than space in the hold.



Source: TGE Marine

Fig 5 Cylinder cargo tank type C

Source: TGE Marine

Fig 6 Bi-lope cargo tank type C

Source: AC-INOX

Fig 7 Tri-lope cargo tank type C

Since CO_2 is almost twice as heavy as ammonia, only the cylindrical type C tank is relevant for transporting CO_2. Our calculations also show that bilope tanks will consist of 15% more steel than cylindrical tanks, not least because of the heavy design of the center shutter.

However, the tanks will generally be heavier due to the stronger structure, but otherwise not be as significantly different from normal LPG/ammonia type C tanks. However, the relatively low temperature and high pressures, both for LP and MP, will have an impact on the construction of the tanks, as experience has shown.

Especially the heat treatment of the tanks after welding has proven to be a challenge for production, so it is recommended that the design and thus the size of the tanks consider where the tanks are to be built and their production facilities.

The design of the CO_2 cargo tanks is important for the design of the ship, as the ship as such is designed around the tanks with the required capacity. So, the design of the tanks has an indirect impact on the ship's hull propulsion performance as well as the CO_2 footprint of the transport part.

At the beginning of the project, calculations of the maximum load capacity for the LP tanks were approximately 3,000-3,500 m^3/tank but ended up at approximately 6,250 m^3/tank using the normal materials available (5% nickel low temperature steel). This meant that we decided to include a 12,500 m^3 ship design in our study.

It is expected that in line with the development of materials, more geared towards the transport of CO_2 under lower temperature and higher pressure/density than LPG/ammonia loads, the maximum capacity of low-pressure tanks will increase to over 10,000 m^3 per tank in the coming years. This, of course, will have a positive effect on the final cost of storing captured CO_2.

For MP tanks, the maximum tank capacity ended up at 4,000 m^3 for this project, but here too it is expected that the maximum capacity will be increased in line with the development of tank material for CO_2.

Tank design – LP

As previously described, the most cost-effective tank design and thus ship design for the transport of captured CO_2 LP.

Therefore, we initially chose to focus on LP in the sizes 7,500 m^3, 9,500 m^3 (later increased to 12,500 m^3), 22,000 m^3 and 50,000 m^3. As the LP tank sizes were increased from the original 5,500 m^3 to 6,250 m^3, a 22,000 m^3 design would be changed to 25,000 m^3, but along the way it became possible to increase the LP tank size further to 7,000 m^3 per tank through detailed and direct calculations.

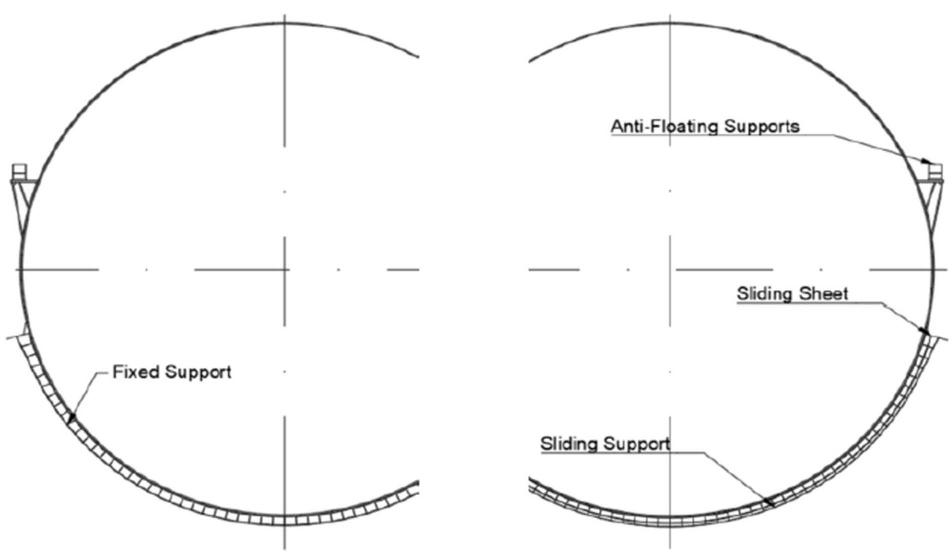
This meant that additional ship designs were examined for a 2, 3 (in a row) and 8 (in pairs) tank version, respectively, i.e. in 14,000 m^3, 21,000 m^3 and 56,000 m^3.

At the time of writing, it appears that LP tanks with the right materials can be increased to over 10,000 m^3, which will have an impact on the chosen sizes for this study.

However, we chose to focus on the above sizes with a view to the following markets: 7,500 m^3 for intra-Europe, 14,000 m^3 for intra-Europe + Western Mediterranean, 21,000 m^3 for Europe for Iceland and finally 56,000 m^3 for international operations. In particular, the 21,000 m^3 was tailor-made for Iceland and the Carbfix storage project and 7,500 m^3 and 12,500 m^3 were also made in a shuttle solution with bow unloading to buoy intended for the Greensand project.

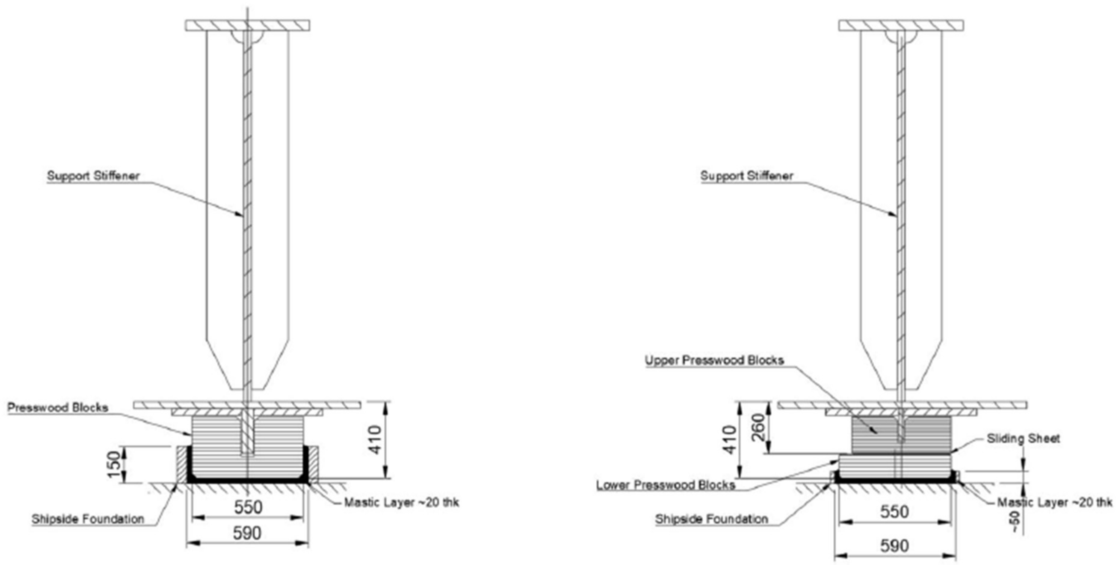
After several optimizations of the maximum tank size, we ended up at 7,000 m^3 per LP tank with the following data:

Tank type:		Cylindrical, horizontal
Type of heads:		Hemispherical (fore and aft)
Diameter:	[mm]	16000 mm
Length:	[mm]	41000 mm
Distance of supports:	[mm]	20300 mm
Capacity per tank:	[m^3]	7000 m^3 (excl. dome)
Design internal pressure	[bar(g)]	8.3
Design external pressure	[bar(g)]	0.3
Design density of CO2	[kg/m^3]	1172
Min. design temperature	[°C]	-55
Max. design temperature	[°C]	+45
Design life	[years]	20
Type of insulation:		PU Spray foam with mechanical protection cover
Nominal thickness:		300 mm
Overall thermal conductivity (approx.):		0.095 W/m^2K
Nominal heat ingress:		21 kW per tank at max. design temperature
Insulation surface:		2194 m^3 per tank
Thickness of cylindrical shell:		40 ... 50 mm
Thickness of hemispherical heads:		20 ... 30 mm
Approximate installation weight:		900 t per tank



Source: TGE Marine

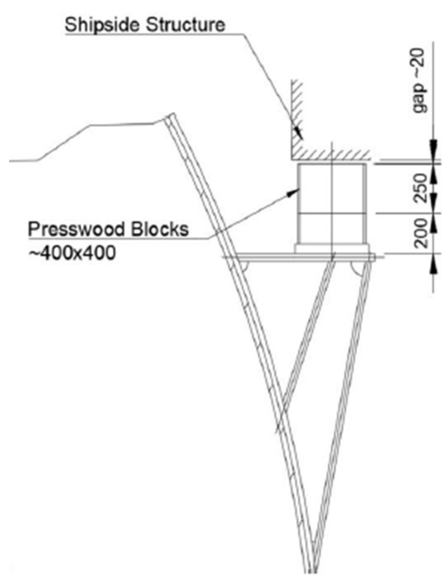
Fig 7a Typical cross-section of a cylindrical C-type tank



Source: TGE Marine

Fig 8 Typical saddle constructions: fixed saddle support on the left and selectable on the right.

The 7,000 m^3 is a large and heavy tank, but the saddle pressure was acceptable after further calculations made by TGE Marine, which will have to be verified in a future study. It should also be noted that for simple reasons it is not possible to load two saddles with a third, as it will only be two saddles that carry at a time. For information, a special pressed wood composite is used for weight transfer, as the composite material has not proven to be suitable so far.



Source: TGE Marine

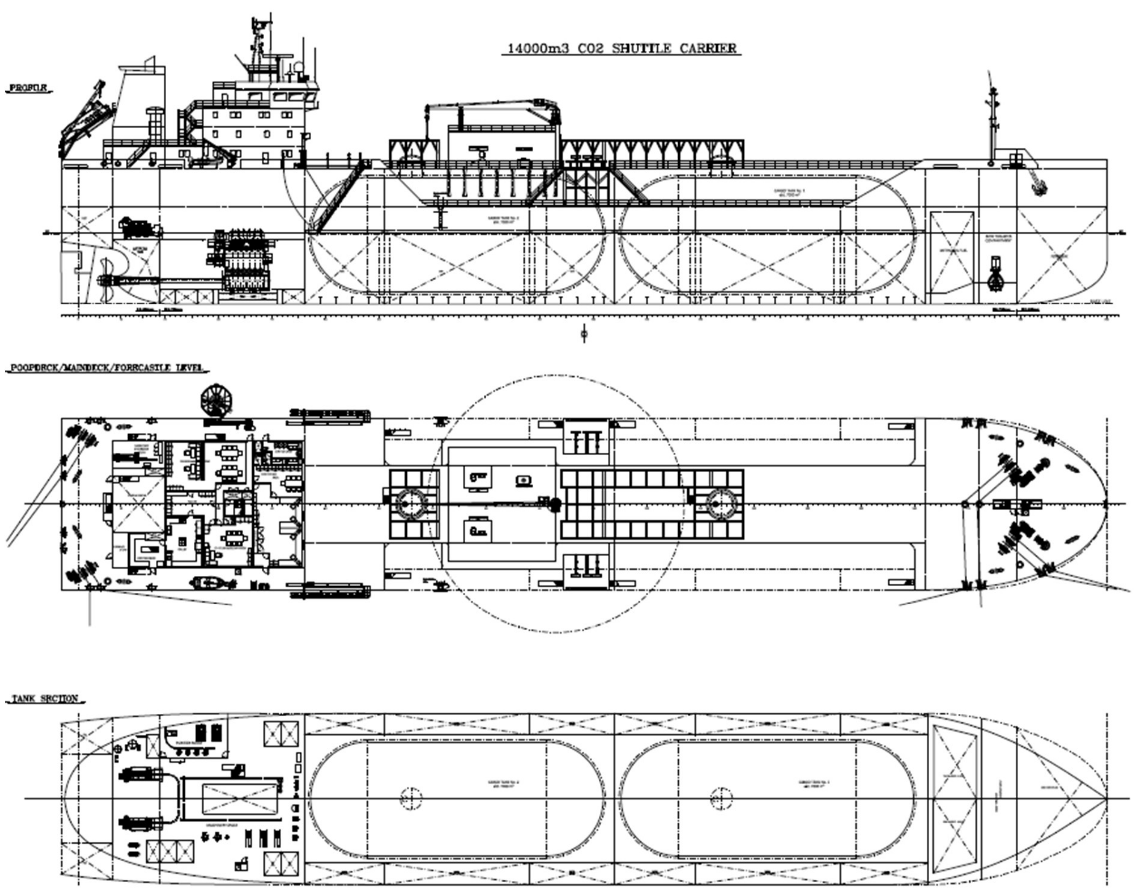
Fig 9 Typical anti-floating stopper

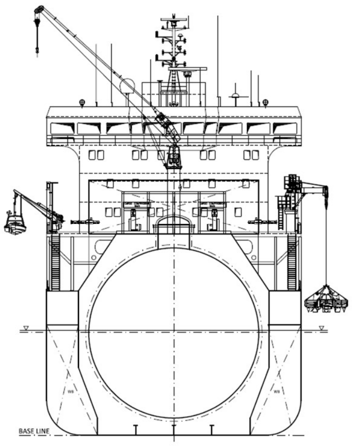
The tank is also established with so-called anti-floating measures that prevent the tank from a vertical movement so that a loosely standing tank does not shoot through the weather deck if the cargo hold is filled by accident.

The above tank designs are based on a 14,000 m^3 vessel with the following dimensions:

Scantling length L_0	[m]	144.15
Greatest moulded breadth B	[m]	24.00
Draught T	[m]	9.90
Speed v	[kn]	13.50
Block coefficient cB	[-]	0.752
Longitudinal distance x	[m]	25
Transversal distance y	[m]	0
Vertical distance z	[m]	-0.2

As previously mentioned, the ship was designed around the 2 x 7,000 m^3 tanks and the first round of the design spiral produced the following ship:





Principal particulars

Length over all	**abt.**	**146.80**	**m**
Length between perpendiculars		**144.15**	**m**
Breadth moulded		**24.00**	**m**
Depth to maindeck		**13.60**	**m**
Cargo tank capacity (100 %)	**abt.**	**14 000**	**m^3**
Draught (design)	**abt.**	**9.70**	**m**
Corresp. deadweight all told		**18 200**	**t**
Draught (scantl.)	**abt.**	**9.90**	**m**
Corresp. deadweight all told		**18 600**	**t**
Service speed at design draught	**abt.**	**13.50**	**kn**

Additional material for 7,500 m^3, 12,500 m^3, 21,000 m^3, 22,000 m^3 and 56,000 m^3 can be studied in Appendix A.

Tank design – MP

MP tanks were not originally part of our studies, as the focus was on optimising the ship design from a cost perspective, but as several projects in the EU, including not least Northern Light, focused on transport at MP, we chose to investigate this possibility as well.

TGE Marine investigated the possibilities of increasing the maximum 2,500 m^3 per MP tank, which proved possible first to the 3,750 m^3 as for the Northern Light vessels and later to a maximum of 4,000 m^3. It was not least the acceptance of the increased load on the saddles that made the tanks' capacity greater, as the length of the tank increased to over 40 m. However, it is necessary to verify the increased saddle load by a detailed calculation with an appropriate safety margin, which is extremely important as it has an impact on the capacity of the tank and thus the size of the ship.

It is expected over time that the maximum capacity per tank will increase to over 5,000 m^3, especially when more tailor-made material is on the market. However, it also depends on the resistance of the saddles as mentioned.

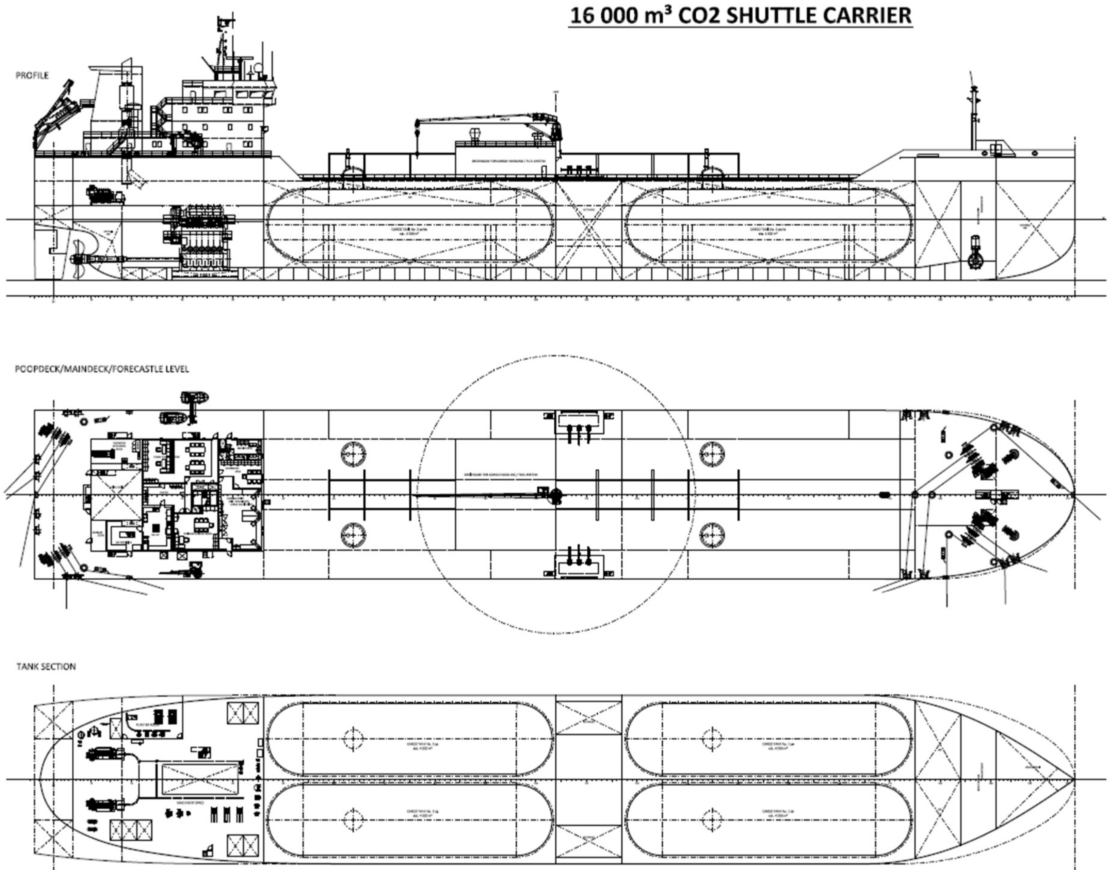
The material for the 4,000 m^3 tanks used is the available P690QL2 and vessel sizes a multiple of 4,000 m^3 cylindrical tanks, i.e. 16,000 m^3 (pair) and 24,000 m^3 (pair).

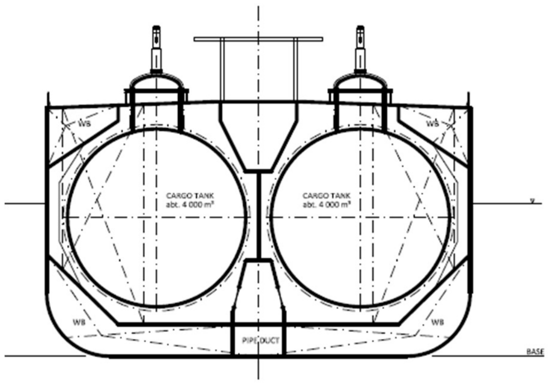
Tank type:		Cylindrical, horizontal
Type of heads:		Hemispherical (fore and aft)
Diameter:	[mm]	11200 mm
Length:	[mm]	45000 mm
Distance of supports:	[mm]	25600 mm
Capacity per tank:	[m^3]	4000 m^3 (excl. dome)
Design internal pressure	[bar(g)]	19.0
Design external pressure	[bar(g)]	0.3
Design density of CO_2	[kg/m^3]	1100
Min. design temperature	[°C]	-35
Max. design temperature	[°C]	+45
Design life	[years]	20

Type of insulation:	PU Spray foam with mechanical protection cover
Nominal thickness:	250 mm
Overall thermal conductivity (approx.):	0.115 W/m^2K
Nominal heat ingress:	16 kW per tank at max. design temperature
Insulation surface:	1704 m^3 per tank
Thickness of cylindrical shell:	40 ... 50 mm
Thickness of hemispherical heads:	20 ... 25 mm
Approximate installation weight:	653 t per tank

As can be seen from the above, the maximum plate thickness is 50 mm due to the high pressure, while the diameter is reduced compared to the LP tanks. We chose to focus on 16,000 m^3, as the nascent CCS market, not least in the UK, pointed towards larger ships than Northern Light. However, 16,000 m^3 was perhaps just below the optimal for Iceland and the Carbfix project due to OPEX including fuel consumption.

16 000 m^3 CO2 SHUTTLE CARRIER





Principal particulars

Length over all	**abt.**	**164.80**	**m**
Length between perpendiculars		**161.70**	**m**
Breadth moulded		**26.60**	**m**
Depth to maindeck		**15.60**	**m**
Cargo tank capacity (100 %)	**abt.**	**16 000**	**m^3**
Draught (design)	**abt.**	**9.30**	**m**
Corresp. deadweight all told		**20 500**	**t**
Draught (scantl.)	**abt.**	**9.60**	**m**
Corresp. deadweight all told		**21 700**	**t**
Service speed at design draught	**abt.**	**15.50**	**kn**

As can be seen from the figure above, the holds are separated by fuel tanks/voids, which is necessary due to the ship being specified to be able to survive a one-compartment damage to a cargo hold and adjacent compartments. Perhaps a bit of a tough requirement, but since the ship is single-hull in one piece of the vertical side and the cargo is almost twice as heavy as normal gas cargoes, we chose to make increased demands for survival for safety reasons. The requirement makes the ship longer and thus more expensive, but without knowing how much more expensive.

Additional material for 24,000 m^3 MP can be studied in Appendix B.

Tank material

Cargo tank size is a function of the diameter, maximum pressure and plate thickness and the material composition. The higher the material strength, the thicker the plate thickness and the greater the pressure, which however has a negative impact on the impact toughness under the low design and test temperatures. The low impact toughness test temperature makes the design process complicated as direct calculation/approval may be necessary; a process that takes time.

The use of high-strength steel and thus a larger diameter also has an impact on the fatigue life of the material, which must be considered when designing the tank in detail.

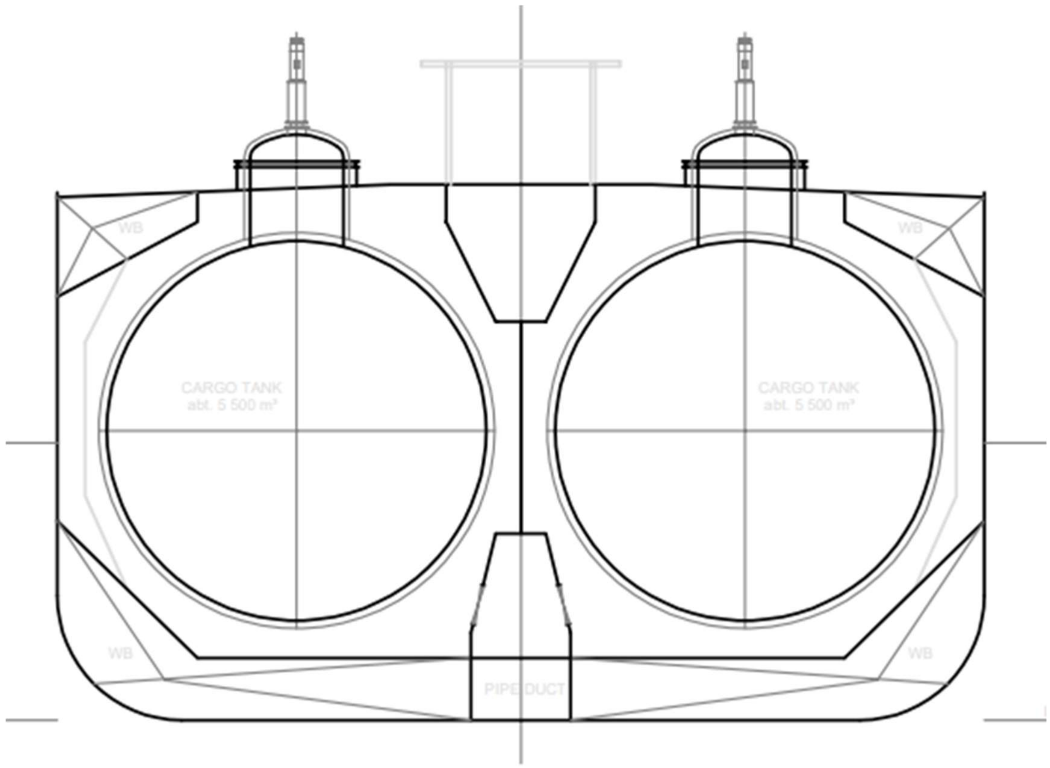
It is possible to build CO_2 tanks from material with a composition that is not mentioned in the IGC, which several steel mills are in the process of.

The Austrian company Voelstalpine has in recent years been working on the development of materials designed for CO_2 MP tanks, which will replace the previous so-called 5% nickel 690 MPa (yield) material with a design temperature of only -10 C°. The product F550 TMCP Toughcore, approved by Class, has a design temperature down to -40 C° and can be supplied in thicknesses up to 60 mm. F550 (Mpa) TMCP Toughcore has a low nickel content of <1% and possibly cheaper to manufacture than normal 5% nickel steel.

Voelstalpine is working on developing a material more aimed at LP tanks called F460+ TMCP Toughcore but has not received the final Class approvals. However, this is expected shortly. Asian steel mills also work on materials better aimed at CO_2 MP & LP tanks, so it is expected that the construction of the tanks will come down significantly in price in the future.

As previously mentioned, the project's focus was initially focused on LP tanks, where the collaboration with TGE Marine developed into bigger LP tanks, which also applied to MP tanks.

The development in size for MP tanks was from 2,500 m^3 to 4,000 m^3 per tank, which also developed the size of the ship as it was a multiple of the maximum tank size. That is, 7,500 m^3 design initially consisted of 3 x 2,500 m^3 tanks and later consisted of 2 x 3,750 m^3 tanks. Likewise, the final 16,000 m^3 design consisted of 4 x 4,000 m^3 tanks (pairs) as shown in principle in Figure 10 below.



Source: Dan-Unity CO2

Fig. 10 Typical arrangement of two cylindrical CO_2 tanks in pairs

The development for LP tanks started with 3,750 m^3 and ended in 7,000 m^3 tanks, which will possibly be increased with the new materials, as mentioned earlier. However, attention must be paid to the increased load on the saddle foundation.

Pressure build-up

The pressure build-up as a function of time was examined for pure CO_2 for LP and MP, even though impurities will change in the calculations. However, it was estimated that the impurities, as mentioned earlier, did not have a major impact on the holding time, but that a time margin should be built in for safety's sake.

For the LP tanks (-55 C°), the critical pressure for pure CO_2 was set at 4.18 barg as the lower limit and 7.5 barg for the safety valves, while for the MP tanks (-35 C°) the critical pressure for pure CO_2 was set at 11 barg as the lower limit and 19 barg for the safety valves. The maximum fill limits were set as follows – see Fig. 11.

MARVS [barg]	max. laoding limit [%]	approx. Mass
7,5	94,3	7,500m³: 8 kt; 12,500m³: 14 kt; 22,000 m³: 24 kt; 50,000 m³: 56 kt;
8,3	93,4	14,000m³: 15 kt; 21,000m³: 23 kt; 56,000 m³: 61,5 kt;
19	91,2	16,000 m³: 16000 t; 24,000 m³: 24 kt

Fig. 11 Maximum tank filling values

The tank strength calculations have not considered sloshing at the lower fillings, as it is not expected to have an impact, but it must be assessed more carefully in the final design.

bar a	°C
5,2	-56,5
6,0	-53,1
7,0	-49,4
8,0	-46,0
9,0	-42,9
12,0	**-35,1**
20,0	**-19,5**

Fig. 12 Vapour pressure values for calculating the pressure build-up

The ambient temperature for the calculations was 32 C° for lake water, maximum air temperature of 45 C° with an average temperature of 25 C°.

Cargo Tank Data						**14,000 m³**	
				12,500 m³		**21,000 m³**	**16,000 m³**
			7,500 m³	**50,000 m³**	22,000 m³	**56,000 m³**	**24,000 m³**
Tank volume	V	m³	3750	6250	5500	7000	**4000**
Tank surface	A	m²	1513	1967	2112	2194	**1699**
Tank weight	m	t	555	790	745	920	**585**
k value of insulation	k	W/m²/K	0,131	0,100	0,121	0,095	**0,114**
MARVS	-	bar g	7,5	7,5	7,5	8,3	**19**
No. of tanks	-	-	2	**2 / 8**	4	**2 / 3 / 8**	**4 / 6**

Fig. 13 Cargo tank data - overview

The insulation of the tanks fluctuated between 250-300 mm PU foam depending on tank size and the overall long holding time was striking – see Fig. 14. The figure below shows the holding time for a 3,750 m^3, which is the shortest time of all.

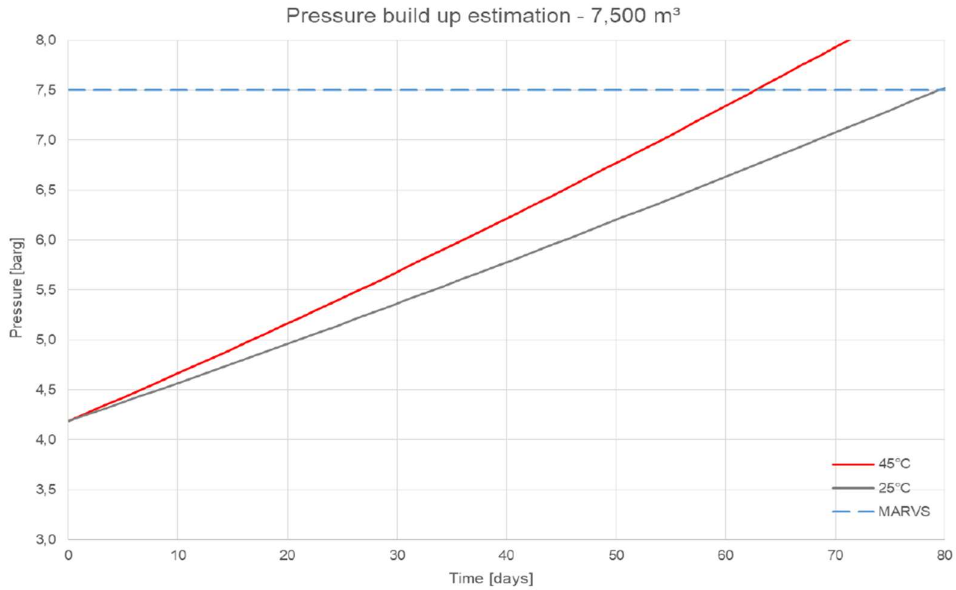


Fig. 14 Cargo tank pressure build-up as a function of time for a 3,750 m^3. MARVS at 7.5 barg

The expected long holding time meant that the project team decided not to install a refrigeration system due to the relatively short EU routes (3-7 days) and that the ships were not designed as combi carriers for cargo other than CO_2.

Ship design – MP

Due to the development of MP CCS projects around Europe, not least for Northern Light, it was natural to investigate a MP design and the choice fell on 16,000 m^3 (two cargo tank pairs) and 24,000 m^3 (three cargo tank pairs), where the result from the first round in the design circle can be studied above and in Appendix B below.

The 16,000 m^3 design is with 4 x 4,000 m^3 cylindrical tanks in pairs based on TGE Marine outline and chosen as the size for a more detailed study in collaboration with the ship consultant company Knud E. Hansen (KEH).

The task for KEH consisted of the development of the hull design as well as an optimization of hull performance and associated propulsion system with full focus on alternative green propulsion means for a route between ARA and the Carbfix storage project at Straumsvik, Iceland.

Due to the operation in the North Atlantic, the foreship will be designed with greater strength (steel weight), less flare (slamming) and a focus on bottom silting. In addition, the focus was on the stern, as twin propulsion could be an advantage for speed and consumption.

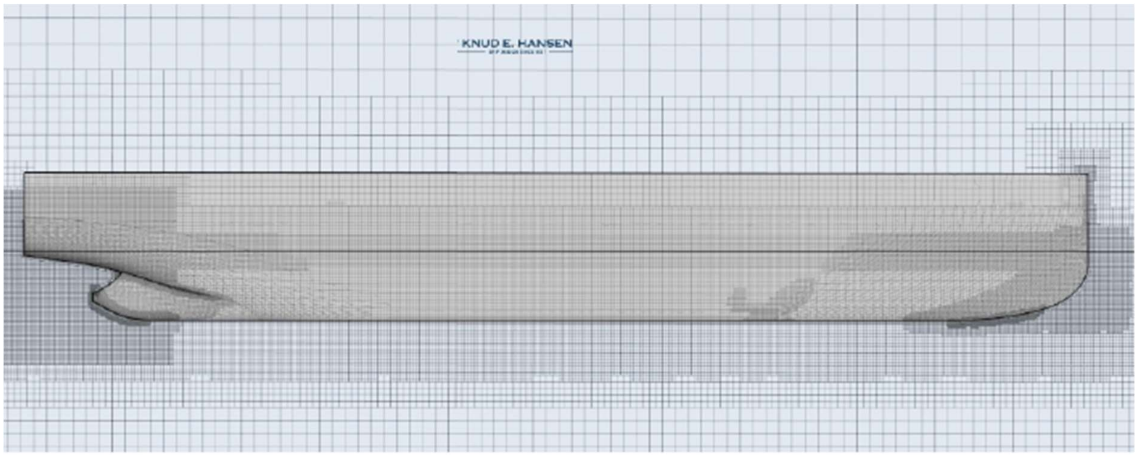
The design process itself consisted of two phases with milestones:

- Phase 1: Two hull shape optimizations of speed/consumption for single and twin skeg
- Milestone: Choice of hull shape
- Phase 2: study of different propulsion methods
- Milestone: Choice of propulsion

The actual content can be studied in Appendix E below.

It became clear relatively quickly that the twin skeg design did not have the original expected advantage, so the single skeg was chosen as the final aft design. Earlier in the project, a pod solution was not chosen due to the area of operation and the relatively long route.

Friction – single & twin skeg



Source: KEH

To calculate speed & power, an empirical model was first used, which was later replaced by an actual CFD model. The hull lines were developed in NAPA and imported into CAESES for hydrostatic calculations and general optimization - hull dimensions are shown in Fig. 15.

Item	Symbol	Quantity	Unit
Length between perpendiculars	LBP	161.7	*[m]*
Breadth	B	26.6	*[m]*
Draught, design	T_d	9.30	*[m]*
Block coefficient design	Cb_d	0.75	*[-]*

Source: KEH

Fig. 15 Baseline design

The speed & power optimization is calculated without appendages and rudders. Roughness for appendage was set to 150my.

The result of the two stern ships was judged on wave movements at a wave height of 1.5 m and 4.0 m and a speed of 15.5 knots as well as EEDI speeds and the result is shown in the tables below.

Table 3: Results rel. resistance design draught single skeg.

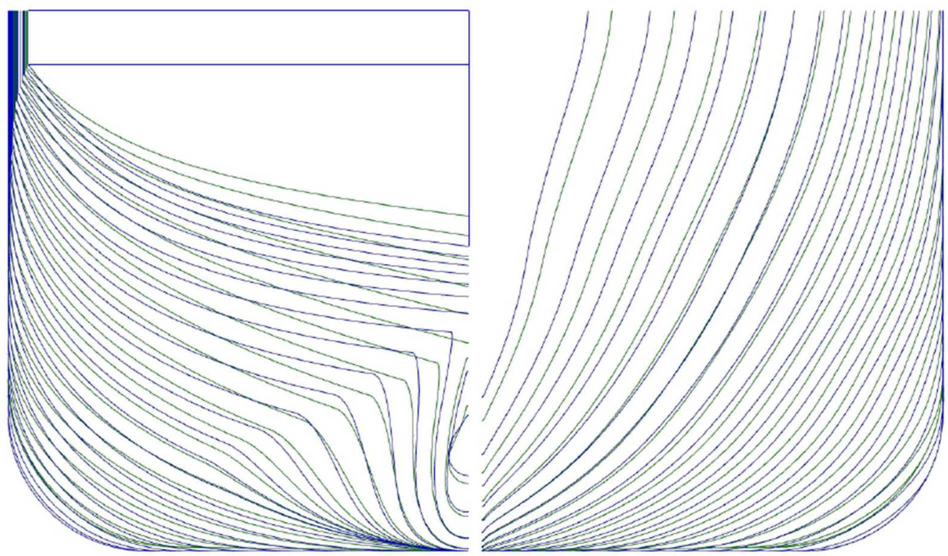
vs	Rel. Dif.
[kn]	[%]
9.5	-5.01%
11.5	-5.91%
13.5	-5.82%
15.5	-5.13%
17.5	-6.47%

Table 4: Results rel. resistance design draught best designs single vs twin skeg.

vs	Rel. Dif.
[kn]	[%]
9.5	-8.74%
11.5	-9.13%
13.5	-8.80%
15.5	-8.56%
17.5	-1.76%

Table 3 shows the reduction of optimized hull shape resistance with single skeg compared to base design, where Table 4 shows the comparison of the drag reduction between single and twin skegs.

Table 4 shows that the single skeg hull performs better, which was perhaps to be expected as twin skeg is often advantageous for larger and faster ships. After this, the single skeg hull was chosen with an approximately 5-6% lower resistance than the baseline design.



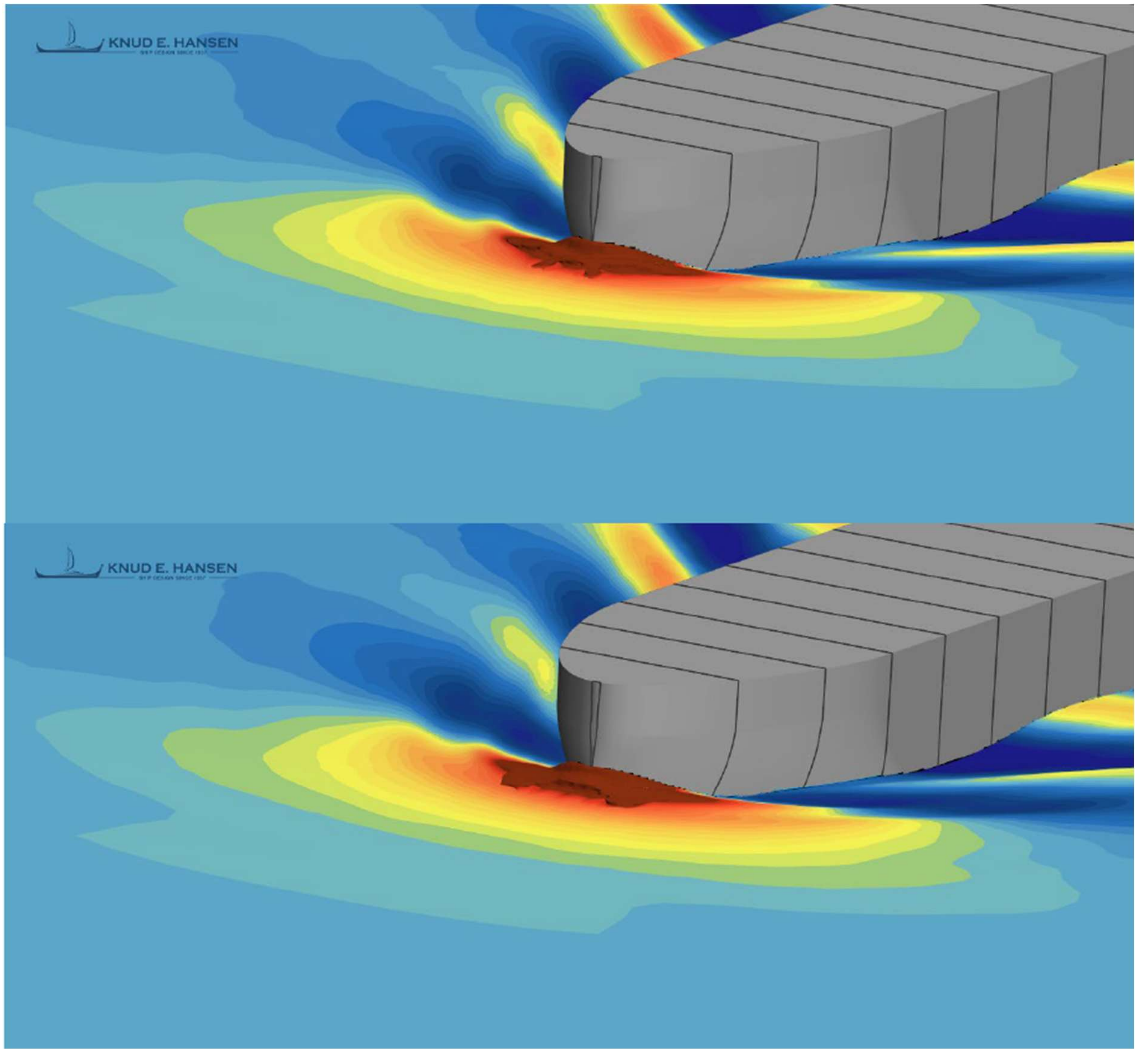
Source: KEH

Fig. 16 Baseline design in blue and optimized version in green

The difference between the baseline design and the optimized design is as the table below, where the LCB was moved slightly forward, which can be seen on the wave system.

Hull ID	B	LPP	T	DISP	LWL	WSA	LCB
	[m]	[m]	[m]	[m³]	[m]	[m²]	[m]
Baseline	26.6	161.7	9.30	30002.4	164.8	5911.56	81
Optimized				30000.2	162.3	5819.85	81.74

However, it was clear that the foreship of the optimized single skeg design could be further optimized, which was done during the optimization of speed & power.



Source: KEH

Fig. 17 Wave system – baseline at the top and optimized hull at the bottom

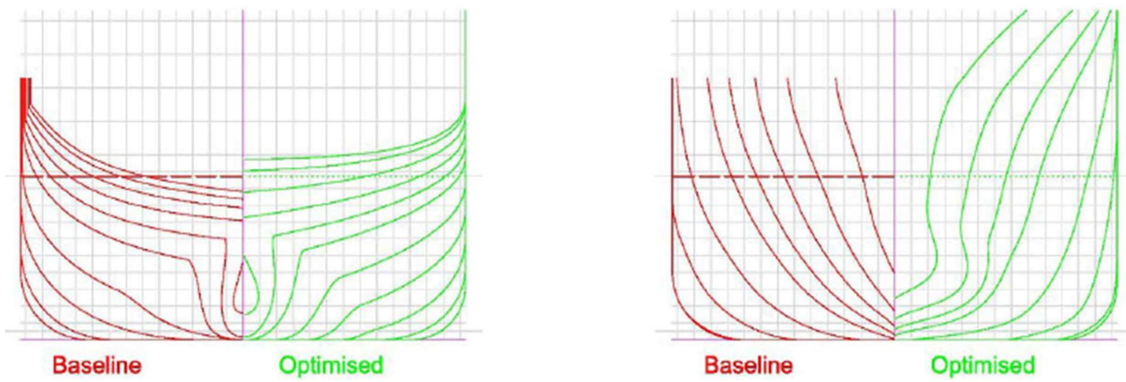
Speed & Consumption – single skeg

Speed & power estimation was calculated by Hydrocomp NavCad and for the optimized single skeg design described above, however, with appendages and wind resistance included.

Several optimized hull types were developed and the below shows the relatively large improvement, especially for the higher speeds between the optimized hull *HULL02_002* and the further development *of HULL11* – see table below.

	HULL02_002	HULL11
vs	Rel. Dif.	Rel. Dif.
[kn]	[%]	[%]
9.5	-5.01%	-2.85%
11.5	-5.91%	-5.19%
13.5	-5.82%	-11.16%
15.5	-5.13%	-12.90%
17.5	-6.47%	-12.05%

At the design speed of 15.5 knots, the further improvement is a whopping 12.9%. This may also show the conservatism of the original empirical starting point. The result is due to a raising of the aft lines (less wet surface and better release of the water after the propeller) as well as the addition of a built-in bulb and a better interaction between the fore and aft ships.



Source: KEH

Fig. 17 Baseline design in red and optimized version in green

However, the improvements could have been slightly better, but consideration was given to minimizing double-curved cladding plates – *HULL23*.

For the speed and power calculation, the main engine MAN 5G60ME-C10.5-LGIM-EGRBP with MCR of 9771 kW at 94 rpm and a shaft generator of 700 kW was chosen, as well as a 4-blade fix pitch propeller developed in cooperation with Everllence. More on this later.

The design parameter was as follows:

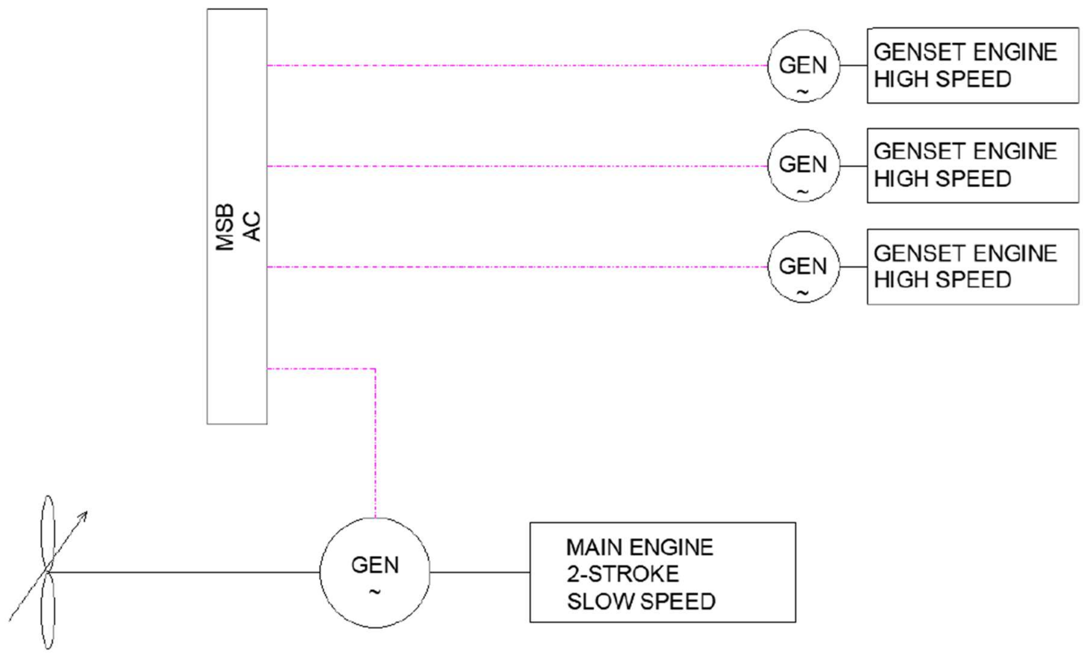
- Design speed 15.5 knots with 15% Sea Margin
- Design speed 14.5 knots with 55% Sea Margin
- The following conditions are considered for the design speed points:
- Design draught (9.7m) on even keel,
- 90% MCR on main engine,
- 700kW on PTO,
- Deep water,
- Calm weather (BF0) with no wind, waves or current,
- Salt water 1.025t/m3 at 15 deg C, and
- Clean bottom and appendages.

The speed & power curves and tables can be seen in Appendix F.

Propulsion

The propulsion system was optimized for the 4-5 days round trip between ARA and Iceland in an area that requires sufficient power in reserve. Since the design speed is relatively high and thus power installed, we have chosen not to calculate the minimum power according to IMO guidelines to be able to maneuver in rough weather, as it is not expected to be a problem.

Several drives, such as diesel-electric and direct drives, have been investigated, but the choice fell on a conventional and direct drive as shown in Figure 18 based on a slow-moving 2-stroke engine.



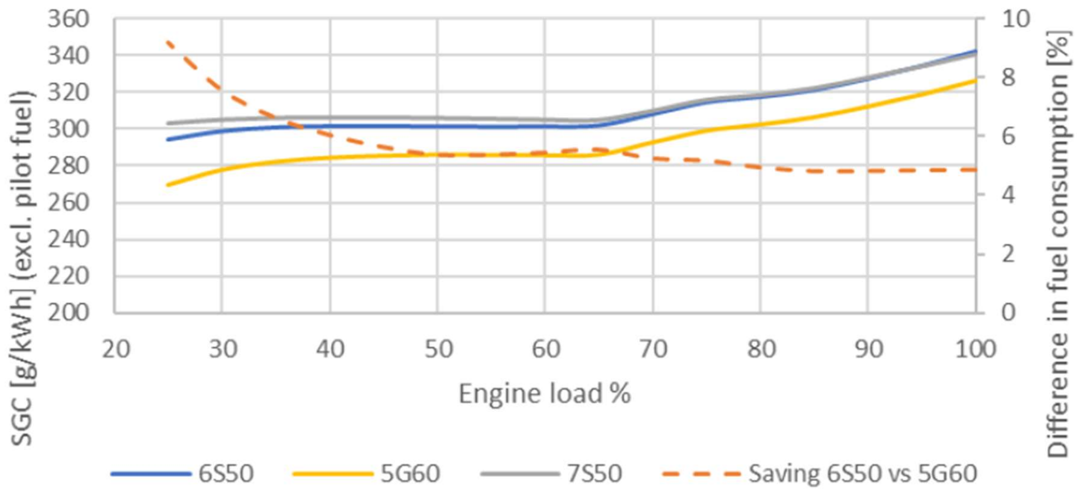
Source: KEH

Fig. 18 Direct drive was chosen with three auxiliary motors as well as a shaft generator

In addition, the power take-out (PTO) via a shaft generator with an electrical output of approximately 700 kWe@90%MCR (approximately 800 kWm) is installed to minimize consumption on the 4-stroke auxiliary engines due to their slightly lower fuel economy. Both the main engine and the auxiliary engines will be powered by methanol.

The following main engines (dual fuel) and turbocharger (t/c) were examined:

- 5G60ME-C10.5-LGIM-EGRBP, SMCR: 9.771 kW@94 rpm + MAN TCT40-ML
- 6S50ME-C9.6-LGIM-EGRBP, SMCR: 9.771 kW@108 rpm + MAN TCT40-ML
- 7S50ME-C10.5-LGIM-EGRBP, SMCR: 9.771 kW@94 rpm + MAN TCT40-ML



Source: KEH

Fig. 19 Comparison of three sizes of main engines – methanol – from Everllence

Based on the comparison, the somewhat larger engine in bore was chosen 5G60ME-C10.5-LGIM-EGRBP, but in a de-rated version to improve efficiency and with one less cylinder.

When choosing a 5-cylinder engine for a 4-blade propeller, the propulsion system and the hull beam must be examined for any harmful vibrations/resonance, which has not been done here.

Neither the shaft generator nor auxiliary engines are specifically chosen other than their performance. In a future and more detailed study, the electrical balance will be prepared and here it will be assessed whether CO_2 should be able to be cooled, as it will have a greater impact on the electrical balance. However, with the current cargo tank's degree of insulation, it should not be necessary to cool the cargo for 4-8 days of travel and cargo handling, but it should be investigated.

The propeller – the four blade – is a CPP due to the installation of WAPS but may need to be changed to an FPP if WAPS is not installed. The design of CPP has been verified by Everllence, Frederikshavn.

Energy optimization

As mentioned earlier, various commercial models showed that a CO_2 carrier and thus the CCS chain is economically affected more by OPEX, not least by the fuel costs than for the newbuilding price.

Therefore, we have focused on improving energy efficiency by studying several different efficiency improvement measures, an excerpt of which can be studied in the following. However, most have not been studied in detail for this ship, but more based on experience from previous installations and projects.

- Anti-fouling paint
- CO_2 for cooling the accommodation
- Variable Frequency Drive (VFD)
- Hull lines

- Wind Assisted Propulsion System (WAPS)
- Propeller and Rudder
- Air Lubrication
- Fuel and route optimization/performance system

The ship is intended to run on methanol, and it is debatable whether this is the best solution, as the choice of fuel also depends on the outcome of the IMO MEPC GFIs in 2026, the adaptation of FuelEU Maritime with future GFIs and access to the various green fuels. However, the choice is based on access to (green) methanol in Iceland. See the influence of GFI's, FuelEU Maritime & EU ETS in chapter *Rules & Regulation: IMO GFI's, FuelEU & EU ETS*.

The choice of fuel for propulsion will have an impact on the payback for the energy optimisations due to the large variance in price per tonne and in particular for the price per MJ.

In the following, we will briefly go through the above-mentioned energy optimization possibilities based on our own experiences and input from the company Njord.

Anti-fouling paint

The development in silicone-based anti-fouling over the last 10 years has been great and today there are several products on the market. The advantage of silicone-based anti-fouling is less roughness and better resistance to fouling during idling achieved by a significantly lower content of biocides. As an example, Navigator Gas has applied silicone-based anti fouling for the last 6-7 years with good improvements up to 8-10% on average on consumption over a docking period.

Therefore, the hull will be applied with silicone-based anti fouling with an expected additional price of approximately. USD 50-80k/ship.

CO2 for cooling the accommodation

As something new, it should be investigated whether liquid CO_2 can be used to cool the accommodation, but with due respect to the disadvantages of CO_2 during a leak in the aircon system. As far as is known, CO_2 as a refrigerant in ships has not been tested in recent years.

Variable Frequency Control (VFD)

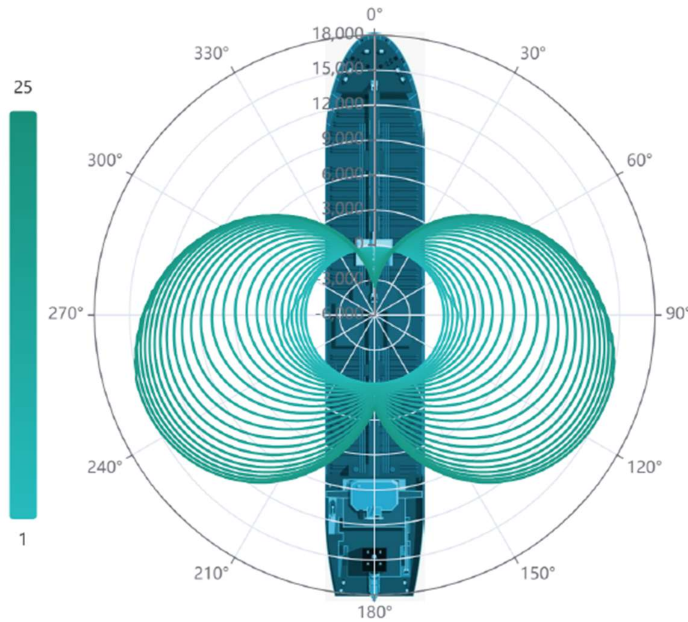
There are several consumers, such as different pumps, engine room fans, etc., that can be advantageously optimized by a so-called VFD – Variable Frequency Drive – which regulates according to the pump demand and not 0 or 100% as standard.

Hull lines

As mentioned earlier, the current hull lines can be further optimized, although to a lesser extent. The focus will be on the foreship's lines for operation in the North Atlantic as well as the inflow to the stern. A further 3-5% better performance will be the goal.

Wind Assisted Propulsion System (WAPS)

As the vessel is designed to operate from ARA to Iceland, it was decided to investigate the possibility of optimizing performance when installing WAPS due to the prevailing wind expected to be westerly and in from transverse directions. Calculations show that the optimal wind direction for several WAPS technologies is in from the stern of the transverse and significantly decreasing with headwinds and tailwinds.



Source: Norsepower

Fig. 20 Trust from the Flettner rotor principle as a function of wind strength and direction

Two WAPS technologies were investigated, Norsepower (Flettner Rotor) and BAR Technologies (suction wings) for the following route round trip – see Fig. 21.

Source: Norsepower

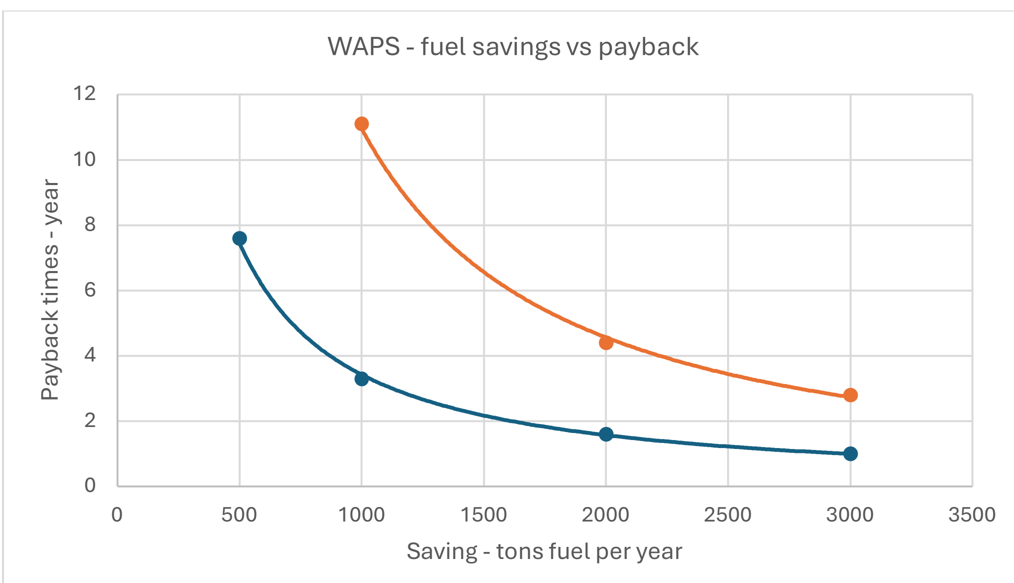
Fig. 21 Route – Amsterdam to Straumsvik round trip

The comparison of BAR and Norsepower fell out in favor of Norsepower (Flettner) Rotor Sails and will be reviewed briefly in the following.

The starting point for the study of the effect of Norsepower rotors was the following:

- 4 x Flettner rotors: 35 m x 5 m (H x D)
- $Length_{overall}$: 163,0 m
- $Beam_{moulded}$: 26,6 m
- $Draft_{design}$: 9,7 m
- $Draft_{ballast}$: 6,0 m
- $CAPEX_{total}$: USD 4,56 mill
- $OPEX_{year}$ USD 0,05 mill
- Rotor efficiency: 70%
- At Sea: 70%
- $Speed_{laden}$: 15,5 knots
- $Speed_{ballast}$: 15,5 knots
- $Voyages_{annual}$: 20 rejser
- Est fuel $consump_{voyage}$ 56 mt/dag – metanol + pilot (MGO)
- Est fuel $consump_{annual}$ 11.000 mt – metanol + pilot (MGO)
- Est fuel $consump_{voyage}$ 26,3 mt/dag – MGO
- Est fuel $consump_{annual}$ 5.200 mt – MGO
- Fuel $price_{methanol}$ 800 USD/mt
- Fuel $price_{MGO}$ 650 USD/mt

The expected payback scenarios for WAPS on the route in question are calculated as follows and at an 8% interest rate:



Source: Navigator Gas

Fig. 22 Payback estimates as a function of fuel savings in tonnes per year – ex emission benefits. Orange curve: MGO & blue curve: methanol

As can be seen from Fig. 22, the fuel savings must be at least 10% on average for WAPS, which few people do not even expect on this advantageous route. This means that it is the lower emission costs from the EU ETS (EUA's), FuelEU Maritime and the upcoming IMO GFI's that will bear the investment in WAPS.

The impact of the various emission control programmes can be studied under the chapter *Rules & Regulation: IMO GFI's, FuelEU & EU ETS*. Furthermore, it can be mentioned that EEDI phase III cannot be met by MGO alone, which can be studied under *EEDI phase 1-3 results*.

However, we decided to continue with four Norsepower (Flettner) Rotor Sails of the above size on the ship, but it should be mentioned that especially the mutual rotor effect as well as the effect on the ship's course stability and heeling must be investigated more closely.

In particular, the interdependencies of four rotors, accommodation and equipment on decks can have a negative impact of up to 20% reduction in savings, according to Navigator Gas' previous studies. It is expected that the result of the above studies can reduce the number of rotors to two.

Propellers and Rudder

The propeller is a CPP with a built-in control system, possibly supplied by Danish Frugal, of pitch/rpm and optimization of blade design to an average speed of about 14 knots.

This may seem like a relatively high speed for a smaller ship and not least for a cargo of CO_2 of low value, but since the ship is part of a CCS chain, the time for transport is an important parameter.

However, the speed must be matched with the requirements for the CCS chain both in terms of time, route optimization and what rates and quantities the final storage requires, but also about the CO_2 footprint of the journey, especially if the fuel is MGO.

The rudder can have a minor impact on the ship's performance and there are several variants that are optimized for the ship, speed, manoeuvrability and route. The rudder system chosen is a so-called gate rudder, which has proven effective, but which is also a relatively new and untested design for larger ships. Therefore, it will require deeper investigation and, not least, the expectation of a larger CAPEX due to the shipyards' lack of experience with the installation.

Source: Wärtsilä

Fig. 23 Gate Rudder

According to Wärtsilä, gate rudders have advantages such as better fuel performance, manoeuvrability, and lower noise and vibration levels.

Air lubrication - hull

Air Lubrication Systems (ALS) have been tested and to some extent built especially for cruise ships, but also for a small number of merchant ships, especially ships with a larger block coefficient, as a relatively large flat area/flat bottom is necessary.

CO_2 carriers built for Northern Light are installed with ALS and we wanted to investigate this for our double the size of the vessel.

ALS can be popularly described as air lubrication that replaces water with air, which in theory makes sense, but can be a challenge in practice. There are several variants, but the most common is an installation in the flat bottom of the ship, which pumps a kind of air curtain out of the hull via openings in the hull (either as openings in the hull or in a basin in the flat bottom).

The air replaces the water and thus reduces friction due to a lower density of air in relation to water. There are advantages and disadvantages associated with this, and one of the challenges is to hold the air curtain so that it does not blow up along the side and avoid affecting the efficiency of the propeller if the air curtain continues into the propeller. In addition, the buoyancy of the ship will certainly be reduced due to the difference in the density of water and air.

Njord assisted us in the study, as they had previously done a study with the Alfa Laval OceanGlide air lubrication system (hereinafter referred to as OceanGlide) on a slightly larger ship than ours.

Oceanglide was developed in 2014 and was intended to create an even and dynamic layer of air in the ship's flat bottom. OceanGlide consists of compressors that supply air through wing-shaped air distribution bands that are attached to the bottom of the ship. The air distribution bands generate small, uniform air bubbles that fuse together to form an even layer of air. The amount of air injected by an air distribution belt is adjusted by a control system to optimize the performance of the air supply under the given load and sail conditions.

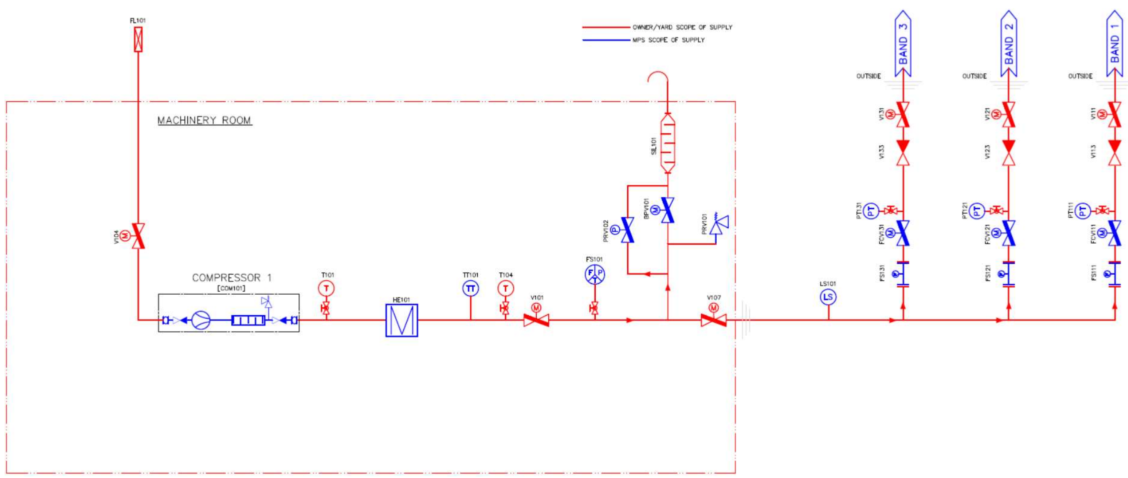
The installation covers the flat bottom by dividing the hull into sections, so that each part of the air layer can be controlled and optimized.

System configuration utility

The location of the air distribution bands is determined by the area of the flat bottom, as well as the location of the compressors and the need for electrical wiring and/or ventilation.

The vessel's operating profile is input to the compressor dimensioning, because draught and higher speeds require more air volume in the system. The typical dimensions of an air distribution tape are 60mm (H) x 600-800mm (W) x the width of the vessel's flat bottom and are designed to be installed without extensive hull modifications.

The piping and instrumentation diagram – see Fig. 24 – represents a typical configuration for an installation with three air distribution belts.



Source: AlfaLaval

Fig. 24 Typical piping and equipment for ALS

Air is supplied to each air distribution belt through a single pass-through from the ballast tank, supplied by screw compressors.

The control system controls the airflow to each of the air distribution bands via a combination of pressure sensors, flow control valves and proprietary inlets in the oscillators.

Calculations of the potential net savings under optimal conditions were a 6% reduction in power on the axle, i.e. approximately 2-3% on fuel consumption, which in our case could not be covered by a payback calculation, so we chose not to pursue it further.

Since OceanGlide and other systems can be retrofitted, it cannot be ruled out to take it up later, especially if the operation profile of the ship becomes more favorable for an ALS system.

Fuel and route optimization/performance system

A fuel and route optimization/performance system will be installed on board to optimize the sailing as well as collect system data from different consumers to minimize fuel consumption as much as possible.

This has proven to be an advantage especially when training the crews to increase their understanding of the importance of this, especially as the ship is part of a CCS chain. In addition, it is possible to actively follow real-life data as well as support decisions regarding hull cleaning etc.

However, it is not expected that a trim optimization will be of any significant advantage if the ship is in regular service between ARA and Iceland loaded with CO_2, as the hull is optimized for the draft 50/50 ballast and loaded. However, trim optimization will certainly be an advantage if the ship sails on longer routes or changes cargo.

It will also be necessary to be able to demonstrate and report the ship's fuel consumption and emissions to be able to document the ship's CO_2 footprint in the CCS chain. This footprint is expected to be one of the success parameters for a given CCS chain, as requirements for a limited footprint could be set by a possible CCS project support measure.

Other initiatives

There are several other options for optimizing energy consumption such as VFD controlled pumps and fans, economizers on the auxiliary machinery exhaust, LED lights, electric pre-heaters instead of an oil-fired boiler, onboard carbon capture in the case of using HFO/MGO and so on.

However, these initiatives are not discussed here but should be part of a detailed study further down the design spiral.

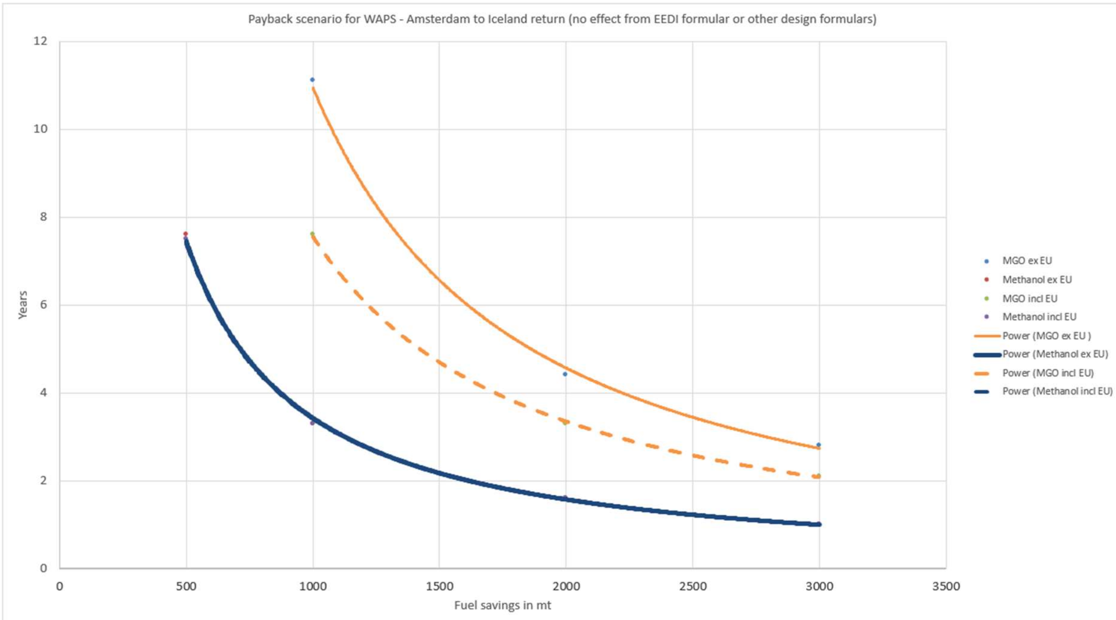
Rules & Regulation: IMO GFI's, FuelEU & EU ETS

As the reader may be aware, there are several different maritime and emission reduction initiatives running and coming in the near future.

Without going into detail about the measures, the European FuelEU Maritime is a well-to-wake initiative to appreciate a shift away from fossil fuels. In addition, the EU ETS is a tank-to-wake emissions trading system, where the upcoming IMO GFI is the UN's global tool for limiting GHG emissions. All three programmes have integrated a charge for non-compliance with the maximum emission limits, where the installation of WAPS results in a reduction both in the calculation of the ship's maximum emission limit and in the reduction of emissions discharged.

In the following, we have simulated the expected benefit of installing four Norsepower Rotor Sails for FuelEU and EU ETS applicable to the route between ARA and Iceland as well as the emission requirements in 2030.

We have not included the IMO GFI, as it has not been finally adopted at the time of writing and that the price for tier I & II has not been set.



Source: Navigator Gas

Fig. 25 Payback estimates as a function of fuel savings in tons per year – including emission benefits. Orange curve: MGO ex emission benefits, dotted orange curve: MGO including emission benefits & blue curve: methanol ex emissions benefits (including emission benefits are almost the same with ex emission benefits)

As can be seen from the above figure 25, the benefit of fuel savings is of course affected by the fuel price, and since the price for MGO and (blue) methanol with similar energy content is currently approximately 1:2.5, the payback time for WAPS installation will of course be shorter for methanol compared to MGO.

The benefit of the fuel savings in terms of the emission cost (from the EU ETS & FuelEU Maritime) is significant for MGO as a fuel compared to methanol, where the benefit of the savings from the EU ETS is offset by the reduction of the surplus from FuelEU Maritime. However, this is route specific, but for ARA to Iceland, it does not appear that the reduction in emissions will mean an advantage for methanol.

However, it must be said that the design advantage of having WAPS installed is not included here, and that it should be calculated before the decision on whether WAPS should be installed is made.

Fuel review

The 16,000 m^3 MP CO_2 carrier will operate in an EU area with a high focus on GHG emissions and is expected to meet requirements for CO_2 emissions footprint from the CCS chain's responsible party. As mentioned, the CO_2 carrier is designed for ARA-Iceland return, i.e. intra EU ETS system, but in and out of FuelEU Maritime as Iceland is not a member of the EEA.

In addition, the requirement for the ships' Energy Efficiency Design Index (EEDI), which since its implementation in 2015 has been 30% stricter, which will have a negative effect on the ship's speed and consumption when using fossil fuels.

There are therefore several good reasons to compare different fuel types for current and future requirements, so that the ship can operate sensibly and competitively over its 25-year lifetime.

Iceland is one of the pioneers when it comes to the production of green methanol based on hydropower and thermal energy as well as captured CO_2, possibly imported by ship. It was therefore obvious to use this opportunity to bunker green methanol in Iceland for at least a round trip to ARA, but it should be mentioned that the supply of green methanol as fuel at another area of operation must be studied in detail.

We chose to focus on green methanol as a fuel but also considered biofuel B100 as a possible alternative.

Methanol veras MGO and B100 biofuel

As mentioned earlier, it would be possible to bunker green methanol in Iceland in the long term but chose to compare the use of green methanol versus MGO on the ARA Island route.

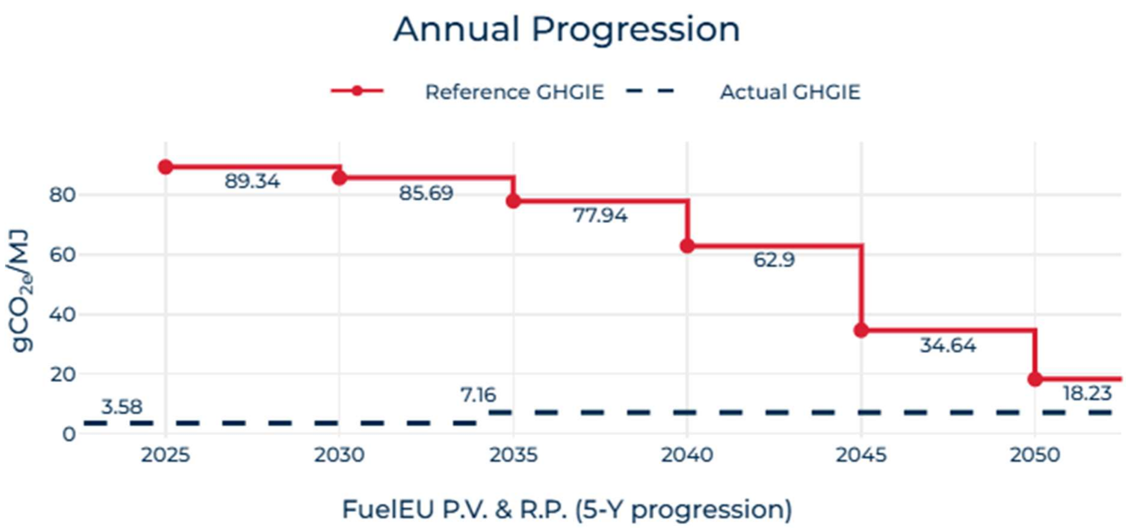
Input for calculation and comparison between green methanol and MGO for the EU ETS and FuelEU Maritime:

- Distance ARA - Island: 1200 miles each way
- $Speed_{laden}$: 15,5 knots
- $Speed_{ballast}$: 15,5 knots
- $Voyages_{annual}$: 20 voyages
- Est fuel $consump_{voyage}$ 56 mt/day – methanol + 5% pilot (Biofuel B100)
- Est fuel $consump_{year}$ 11.000 mt – methanol + 5% pilot (est 260 mt Biofuel B100)
- Est fuel $consump_{voyage}$ 29,9 mt/day – Biofuel B100
- Est fuel $consump_{year}$ 5.900 mt – Biofuel B100
- Est fuel $consump_{voyage}$ 26,3 mt/day – MGO
- Est fuel $consump_{year}$ 5.200 mt – MGO
- Fuel $price_{methanol}$: 800 USD/mt
- Fuel $price_{Biofuel\ B100}$: 750 USD/mt
- Fuel $price_{MGO}$: 650 USD/mt
- Biofuel $B100_{LCV}$: 37 MJ/kg (RED-II)
- Biofuel $B100_{GHG}$: 22 gCO_{2e}/MJ
- $Methanol_{GHG}$: 4.4 gCO_{2e}/MJ (source: Methanol Institute)
- FuelEU $Maritime_{penalty}$: EUR 640/tCO_{2e}
- $CO2_{Correction\ factor\ -\ MGO}$: 3.206 (TtW)
- $CO2_{Correction\ factor\ –\ B100}$: 0 (TtW)
- $CO2_{Correction\ factor\ –\ Metanol}$: 0 (TtW)
- No WAPS installed

As mentioned, the not insignificant advantage in the rules of installing WAPS is not included, which would be a point for further investigation.

However, we chose not to include the power from WAPS due to the obvious advantage of being able to bunker green methanol in Iceland but chose to show the CO_2 carrier with Flettner rotor for later assessment.

FuelEU Maritime has developed an increasing requirement for maximum GHG emissions per MJ, while the EU ETS is constant until 2030, when a revision of the performance will be carried out. It should be noted that the EU ETS is a so-called Tank-to-Wake consideration, while FuelEU Maritime is Well-to-Wake, which means that, for example, black LNG has an advantage over HFO/MGO, so this will not be the case for FuelEU Maritime.



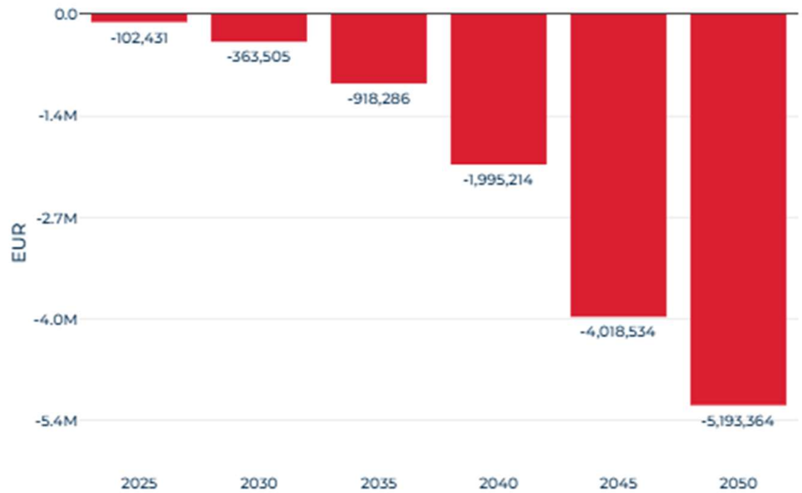
Source: ABS

Fig. 26 Maximum GHG per MJ emission requirement from date to 2050. The actual GHG emissions per MJ for green methanol are indicated by the dotted line

FuelEU Maritime – MGO

Marine Gas Oil (MGO) is today a well-known fuel that does not require any further introduction.

In EU SECA, fuels with a content above 0.1% sulphur are not allowed unless a so-called scrubber, which cleans the flue gas of sulphur, is installed. If a scrubber is installed, HFO with up to 3.5% sulphur can be burned, but we have chosen to ignore this solution in this study.



CB and FuelEU P.V./R.P. (5-Y progression)

	2025	2030	2035	2040	2045	2050
CO_2e [MT]	-158.8	-563.7	-1.4k	-3.1k	-6.2k	-8.1k
FuelEU [EUR]	-102.4k	-363.5k	-918.3k	-2.0M	-4.0M	-5.2M

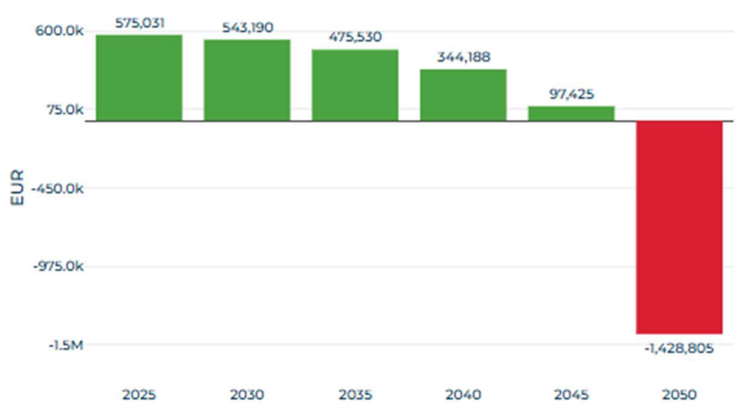
Source: ABS

Fig. 27 Development in annual CO_2 surplus/deficit from MGO as fuel

FuelEU Maritime – B100 biofuel:

Variations of biofuel are on the market today and many ships have experience with storage, handling and incineration, not least in EU waters.

Of course, it is unknown how demand and price develop over time, but biofuel is a clear candidate as a transition fuel between fossil and green fuels. Since LCV is slightly lower than MGO, the expected annual consumption in tons is slightly higher in comparison. The B100 biofuel used here is a so-called generation II biofuel.



CB and FuelEU P.V./R.P. (5-Y progression)

	2025	2030	2035	2040	2045	2050
CO_2e [MT]	7.2k	6.8k	5.9k	4.3k	1.2k	-573.2
FuelEU [EUR]	575.0k	543.2k	475.5k	344.2k	97.4k	-1.4M

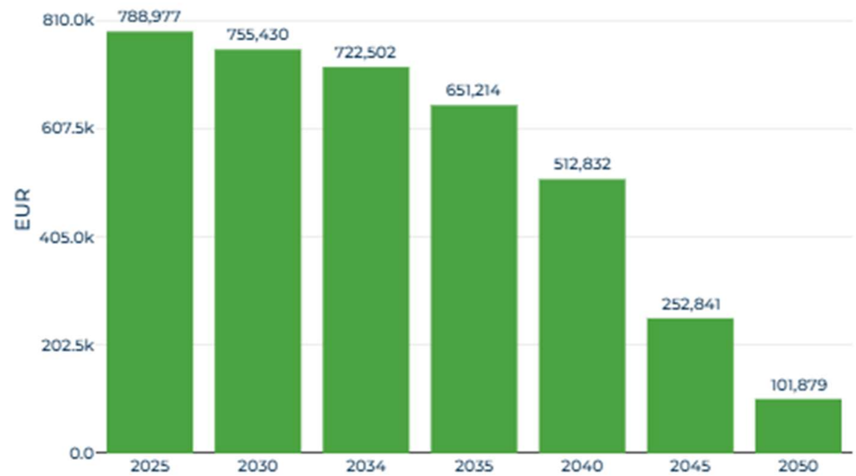
Source: ABS

Fig. 28 Development in annual CO2 surplus/deficit of B100 biofuel as fuel

FuelEU Maritime – green methanol

As previously mentioned, there is access to green methanol in Iceland, which will future proof the operation of the CO_2 carrier also after 2050 and create a not insignificant surplus of CO_2 equivalents, which can either be sold to the CCS chain, on the CO_2 exchange or pooled with other vessels.

Methanol has a lower LCV, so the consumption in tons is about 2-2.5 times greater than MGO and B100 biofuel. Methanol emits GHG, but since it is produced on captured CO2, and the manufacturing process is powered by hydropower or thermal energy, it is considered green.



CB and FuelEU P.V./R.P. (5-Y progression)

	2025	2030	2034	2035	2040	2045	2050
CO_2e [MT]	9.9k	9.4k	9.0k	8.1k	6.4k	3.2k	1.3k
FuelEU [EUR]	789.0k	755.4k	722.5k	651.2k	512.8k	252.8k	101.9k

Source: ABS

Fig. 29 Development in annual CO_2 surplus/deficit of green methanol as fuel

EU ETS (EUA)

The EU ETS value is calculated as *emitted CO_2 [mt] x EUR 80 x 50%* for journeys in and out of the EU, while intra-EU journeys are calculated as *emitted CO_2 [mt] x EUR 80*. Since Iceland is a member of the EU ETS, only intra-EU trips are counted, while stays in port are not included.

The EU ETS is calculated from Tank-to-Wake (TtW) where both B100 biofuel and green methanol are 0, whereas MGO has a correction factor of 3.206 converted to tonnes of CO_2.

So, for the GO, the annual ETS accounts in EUA's (or EUR as here) will be as follows:

5,200 mt MGO x 3,206 x EUR 80 = EUR 1.34 mill per ship/year

IMO GFI's

GFI's are not included here as mentioned earlier, as the proposal has not been adopted at the time of writing and that some form of adaptation of FuelEU Maritime is expected in that case the IMO finally adopts and ratifies GFI. When the final result is available both regarding the IMO's adoption and the EU's revision of FuelEU Maritime, the cost of the different fuels must be recalculated.

EEDI – preliminary calculations

EEDI is of course an important parameter for every ship design and therefore a preliminary check of EEDI was calculated for phases 2 & 3 for different fuels, of which the following is an excerpt. The calculations have been made in accordance with MEPC.254(67) and MEPC.308(73).

We have examined MGO, methanol, biofuel and LNG (grey) and followed guidelines MEPC.1/Circ.905 and MEPC.308(73). All fuels have been tested with and without WAPS.

Since the CO_2 carrier has installed a high powered main engine to be able to achieve the design speed of 15.5 knots in both ballast and loaded, EEDI phase 3 would not be able to be fulfilled with MGO.

In fact, the design speed would drop by about 2 knots to below 13.5 knots, which would have a relatively large impact on both the CCS chain's efficiency as well as CAPEX to maintain the required transport sequence.

But since we did not have knowledge of the full CCS chain, such as the transport of tons of captured CO_2 per year as well as the capacity of the storage and storage process, we chose to stick with the 15.5 knots.

We included LNG (grey) and biofuel as possible fuels just to understand the difference between MGO, methanol and LNG. The biofuel used is a 45% blend so as not to exceed any NOx requirements, but that B100 would certainly be a more suitable and contemporary alternative to methanol. See Appendix H for the calculation of Cf for B45 blend.

For the calculations, the following LCV and correction factors were used:

Fuel types	LCV (kJ/kg)	Cf
MDO/MGO	42,700	3.206
LFO	41,200	3.151
HFO	40,200	3.114
LNG	48,000	2.750
Propane	46,300	3.000
Butane	45,700	3.030
Methanol	19,900	1.375
Ethanol	26,800	1.913
MDO - 45% BIO	39.301	2.047

Source: KEH

Fig. 30 EEDI – LCV & CO_2 correction factors

The result of the preliminary EEDI calculations can be seen in Figure 31 below. It was clear, which was not unexpected, that MGO would not be a suitable fuel either for now or in the future in the envisaged area of operation and speed.

However, it was a bigger surprise that the improvement was not greater when installing WAPS.

The calculations showed the not unexpectedly large impact the different fuels had on EEDI, which was also the intention of the IMO when EEDI was discussed and adopted.

		Cf	3.206	Cf	1.375	Cf	2.047	Cf	2.75
Speed	EEDI	MDO		Methanol		BIO		LNG	
		Without	WAPS	Without	WAPS	Without	WAPS	Without	WAPS
13.4	Phase 2	13%	35%	34%	50%	44%	57%	46%	59%
	Phase 3	1%	25%	25%	43%	36%	51%	38%	53%
13.5	Phase 2	12%	33%	33%	49%	43%	56%	45%	58%
	Phase 3	-1%	24%	23%	42%	35%	50%	37%	52%
14	Phase 2	4%	25%	27%	43%	38%	51%	41%	53%
	Phase 3	-9%	14%	17%	35%	29%	44%	32%	46%
14.5	Phase 2	-5%	15%	21%	36%	33%	45%	35%	47%
	Phase 3	-19%	3%	9%	26%	23%	37%	26%	40%
15	Phase 2	-15%	4%	13%	27%	26%	38%	29%	40%
	Phase 3	-31%	-9%	0%	17%	15%	29%	19%	32%
15.58	Phase 2	-30%	-11%	2%	16%	16%	28%	20%	31%
	Phase 3	-48%	-27%	-12%	4%	5%	18%	9%	21%

Source: KEH

Fig. 31 EEDI – results of the preliminary calculations.

The calculations also showed that the design speed could be difficult to maintain even when using methanol and without WAPS, so it is necessary to get a more detailed description of LCA from the source both for the EEDI calculations, but also for the FuelEU Maritime calculations.

It was somewhat surprising that biofuel (B45 blend) had a somewhat more positive influence on EEDI than methanol, which should be verified by a continuation of this project.

LNG delivers the best EEDI result, but we do not believe it has the necessary futureproofing in the EU area, so we chose to ignore it.

Lightweight estimate

The lightweight estimate for the CO_2 carrier was estimated especially to get a better picture of the steel weight, as it would be expected to be somewhat larger than for normal LPG/c with a load density of approximately 0.68 tons/m^3 (ex VCM loads) compared to CO_2 of approximately 1.10 tons/m^3. In addition, the weight of the cargo tanks themselves and the impacts on the saddles were also somewhat greater.

The lightweight estimate included welding, hull curvature and a 4% margin and ended up at approx. 10,500 tonnes, which is estimated to be approximate. 750 tonnes higher than equivalent sizes of LPG/c. Of course, this must be carefully calculated by a more detailed study.

Weight groups	Notes		Group Weight	Center og gravity COG		
				LCG	TCG	VCG
					SB (-) PS (+)	
			t of 1000 kg	X (m)	Y (m)	Z (m)
Group 1000 - Cargo Handling and Access			2706	82.78	0.00	8.56
Group 2000 - Hull Structure	Included = 2% welding + 3 % rolling		5545	77.37	0.00	8.97
Group 3000 - Outfit and Equipment			263	45.07	0.00	10.85
Group 4000 - Accommodation			229	116.38	0.00	26.09
Group 5000 - Hull Systems			337	51.72	0.00	7.37
Group 6000 - Machinery Components			722	19.70	0.00	8.34
Group 7000 - Machinery Systems			47	22.54	0.00	8.32
Group 8000 - Electrical Systems & Autom.			243	41.18	0.00	12.65
Total light weight			**10092**	**72.75**	**0.00**	**9.29**
Margin	Percentage	4.0%	404			0.30
Rounding						
Total light weight including margin and roundings			**10495**	**72.75**	**0.00**	**9.59**

Source: KEH

Fig. 32 The lightweight calculation – the cargo tanks are included in group 1000

Stability – intact and leakage stability

Intact stability is calculated according to the 2008 Intact Stability Code via NAPA software and the following conditions are examined:

LCOND	TEXT	ARR	LGV	T m	TR m	HEEL deg
LC101	FULL LOAD DEPARTURE	A	D21	9.48	-0.13	0.0
LC102	FULL LOAD ARRIVAL	A	D21	9.46	-0.23	0.0
LC201	BALLAST DEPARTURE	A	D21	5.84	-1.25	0.0
LC202	BALLAST ARRIVAL	A	D21	5.59	-1.66	0.0
LC301	MINIMAL LOAD LOW BUNKERS	A	D21	4.41	-3.03	0.0

Loads and displacement:

LCOND	Cargo t	Bunker t	Ballast t	Deadweight t	Displacement t
LC101	17496.72	2350.61	100.00	20577.33	31072.33
LC102	17496.72	235.00	2321.94	20503.67	30998.67
LC201	0.00	2350.61	4306.12	7286.73	17781.73
LC202	0.00	235.00	5721.21	6406.21	16901.21
LC301	535.61	535.00	806.89	2327.50	12822.50

Stability info:

LCOND	DCRI	STAT	SIDE	GM m	MINGM m	GM Margin m
LC101	267.2.2.4	OK	PS	2.282	0.150	2.132
LC102	267.2.2.4	OK	PS	2.772	0.150	2.622
LC201	267.2.2.4	OK	PS	5.480	0.150	5.330
LC202	267.2.3.1	OK	PS	6.376	0.253	6.123
LC301	267.2.2.3	OK	PS	6.024	2.340	3.684

Source: KEH

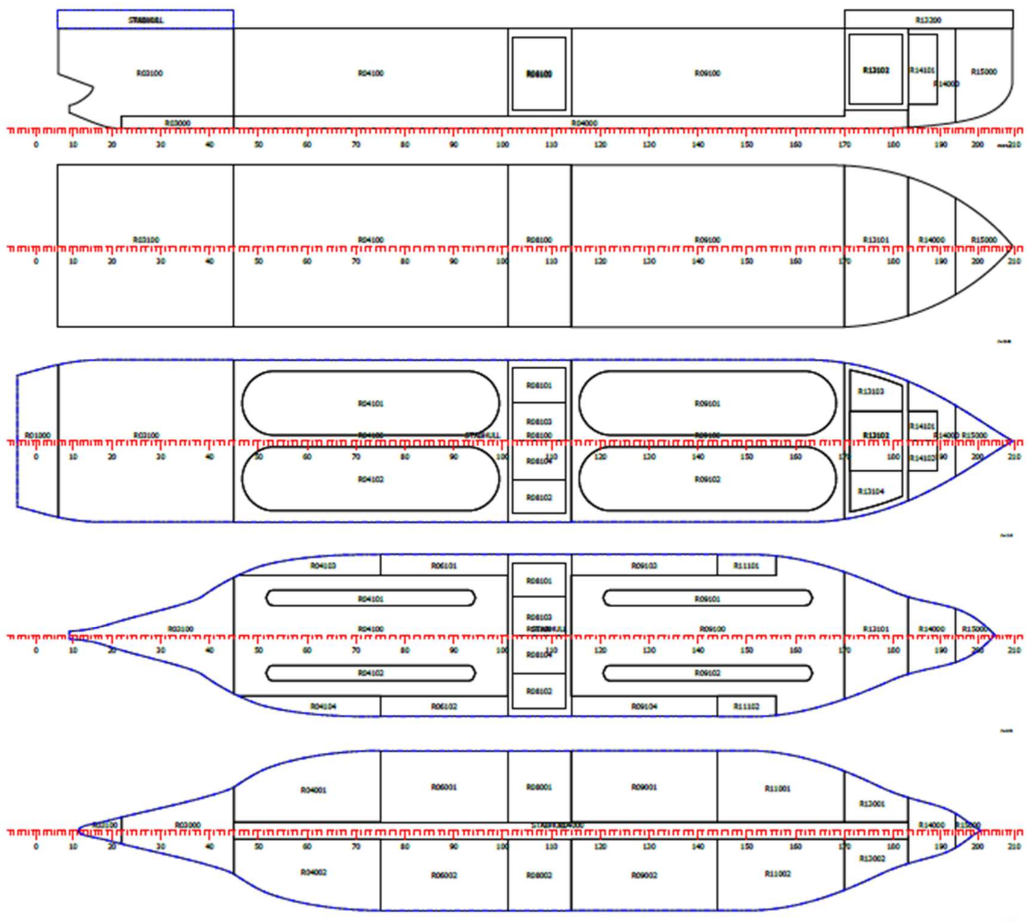
Fig. 33 Load conditions and intact stability check

It was not expected that the intact stability would cause problems, which the above result does not indicate either.

Leak stability was calculated according to the 2014 IGC *International Code for the Construction and Equipment of Ships carrying Liquefied Gasses in Bulk* and as a 3G type and via NAPA software. The model in NAPA was made for the hull up to 16.3 m above the baseline and the first floor of the accommodation. The deterministic method was used for one-room damage between the main shutters as well as relevant bottom damage.

During the calculations, it became clear that it would be advantageous to share the two cargo spaces with a batch of methanol tanks, not only in terms of trim, but also to meet leak stability requirements.

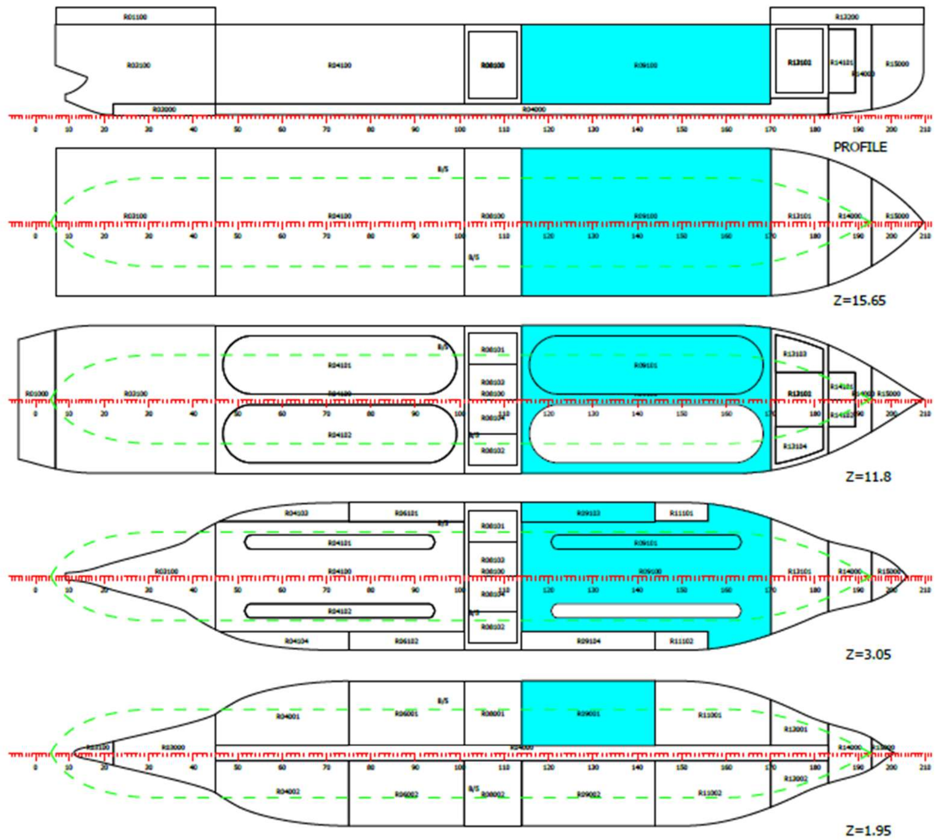
The final compartment division can be seen in Fig. 34 below.



Source: KEH

Fig. 34 Space division for leak stability calculations

As an example of a major damage where the ship survives, is shown in Fig. 35. It was clear that a two-compartment damage involving the center tanks as well as a cargo hold and associated bottom tanks would cause the design to fail, but the placement of the center tanks has added a better safety to the design.



STAGE	PHASES	COMP	DES	IPERM	VOL m3	XCG m	YCG m	ZCG m
1	3	R09101	CO2 TANK FWD PORT INCLUDING INSULATION	0.95	4457.5	110.00	6.20	8.90
1	3	R09100	CARGO TK HOLD FWD	0.95	7313.6	110.14	0.00	10.05
1	3	R09001	DB WB TK	0.95	521.7	99.60	6.85	1.03
1	3	R09103	WB TK	0.95	237.4	99.60	11.76	3.48

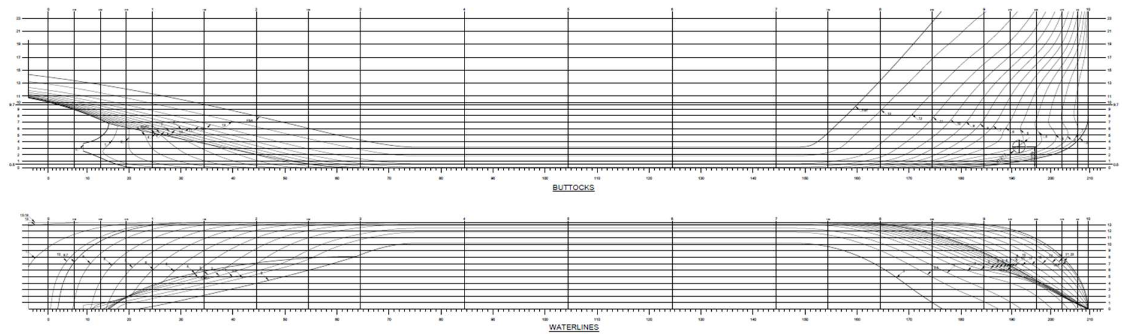
Source: KEH

Fig. 35 Typical one room injury with survival

Line drawing

The first versions of the lines were carried out with a focus on propulsion optimization, optimal trim and limitation of double-curved plates.

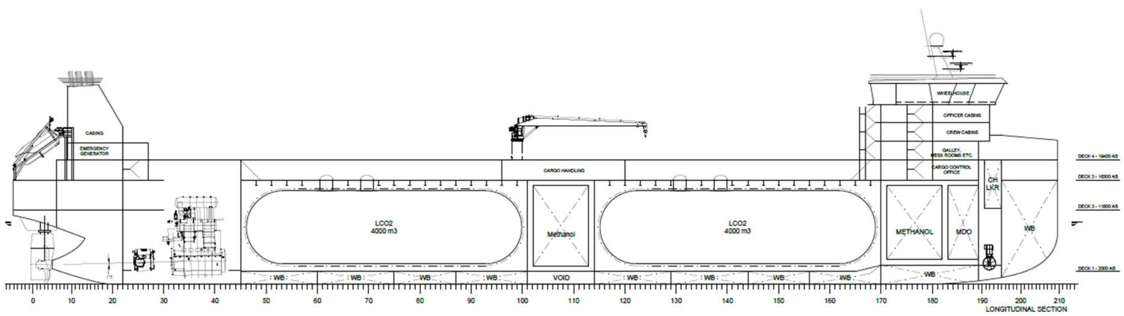
When continuing the design, focus should be placed on further optimisation of the hull shape, both in terms of propulsion optimisation, but not least crew welfare at the front of the ship. This could possibly be done by introducing greater buoyancy or a so-called Ulstein X-bow® to limit acceleration in rough seas.



Source: KEH

Fig. 36 Line drawing

Description of the CO_2 carrier

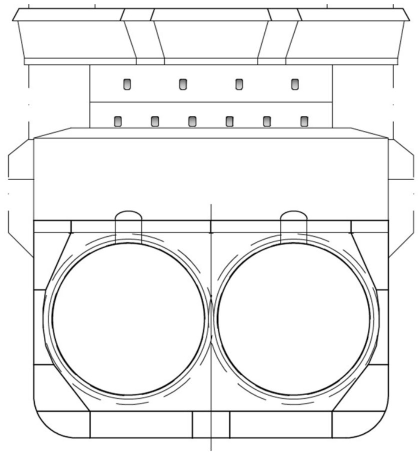


The final design for this study is with four separate CO_2 tanks, each with a 100% capacity of 4,000 m^3 installed in two cargo holds separated by methanol fuel tanks amidships.

The accommodation is located at the front of the ship to ensure a more balanced weight distribution during full load and not least in ballast, which can be a challenge due to the higher weight of the cargo. We consider the ship design as a so-called deadweight vessel and not, as is normal for LPG carriers, a volume vessel.

As the ship will sail 50/50 loaded/ballast, performance in ballast condition is just as important as under full load, so the goal of the design is to be able to sail as close as possible to even keel without much use of ballast, which meant that the accommodation was moved forward in the ship.

With an area of operations that includes the Atlantic Ocean and the North Sea, the comfort of the crew is important, especially in the expected major accelerations that are to be expected by moving the accommodation out into the bow. There are several ships in operation with the accommodation in front and a few have observed challenges with comfort in rough weather, so it must be ensured that this is taken care of, possibly with an acceleration-dampening foreship, e.g. as the Ulstein X-bow®.



The bridge is closed for comfort, and the lower rows of windows must be examined for strength against green sea impact.

A single propeller (CPP) with propeller boss cap fin (PBCF) is installed aft with a gate rudder to increase maneuverability as well as improve performance. Bow thruster is also installed.

The fuel tanks are located with four methanol tanks amidships, four under the accommodation and two MGO tanks also under the accommodation.

Day and service tanks are located in the engine room together with the methanol treatment system, which is located in a separate fire-insulated room.

Four Flettner rotor sails are placed in pairs, but as mentioned earlier, it must be carefully examined whether it makes sense, especially in terms of their influence on each other and not least the payback time. We are uncertain whether it makes sense to use WAPS, especially when using green methanol for propulsion, and if so, whether the payback is satisfactory, and whether two or four should be installed. So, it will be natural to investigate these scenarios in detail in the further design process.

The holds are separated by methanol tanks amidships, primarily due to the balance of the ship, but also because of the leakage stability, where the ship has difficulty surviving the necessary damage in the event of a one-room cargo space damage. It must be said that several published CO_2 carrier designs are shown without this separation of the cargo holds, but it has not been possible for us to meet the leak stability rules without the tanks amidships.

Pocket Plan:

For the presentation of the CO_2 carrier, a pocket plan was made – see appendix D – which can be used for newbuilding brokers or directly for shipyards in collaboration with Knud E. Hansen.

CCS chain and model

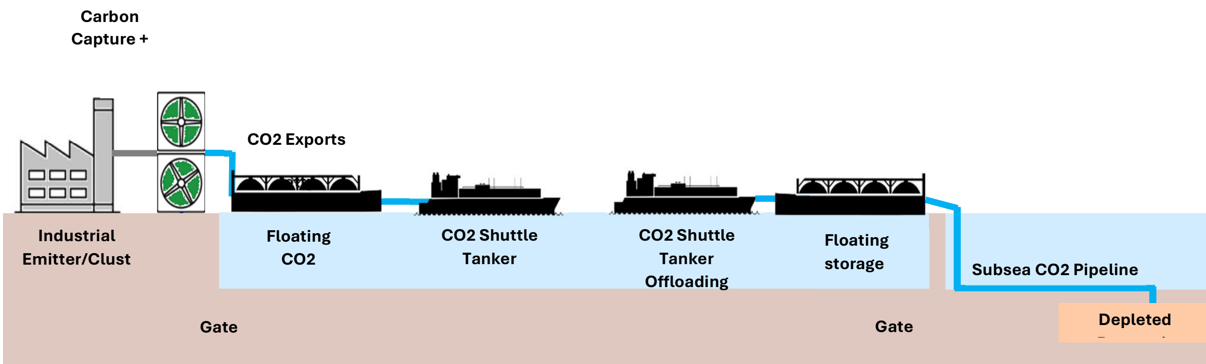


Fig. 37 Typical CCS chain

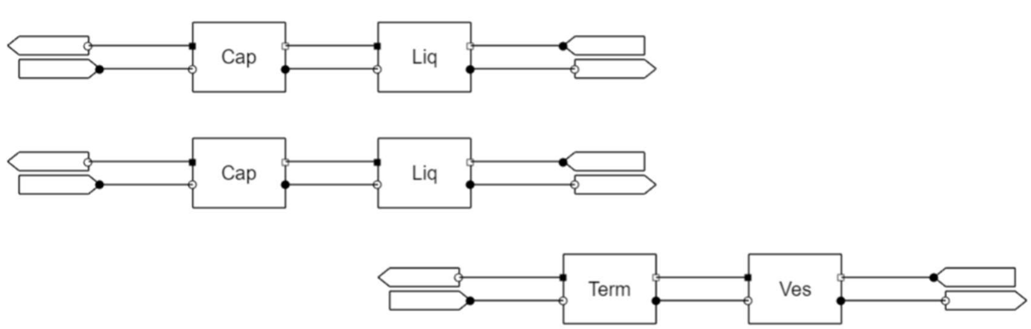
As mentioned earlier, it became clear that when developing a ship design, it would be necessary to know more about the CCS chain, both downstream and especially upstream, to optimize the CCS chain and not just the ship. We were often asked by the emitter what our requirements were for the delivered CO_2, where we just as often returned with a: what do you want and what is the most optimal for you?

Therefore, a model for simulation of the entire value chain for CCS was developed with the help of ECA Engineering.

The model is built using so-called object-oriented programming, which means that it can easily be configured to simulate different designs of value chains.

An example could be several emitters with different CO_2 qualities that are connected to one or more storage facilities and which, for example, share a tank system consisting of many individual tanks, which then finally fill one or more ships that sail on a regular service to one or more disposal sites.

Figure 38 shows an example where the software is configured to simulate two emitters, each with its own CO2 capture facility (*Cap*) and lead facility (*Liq*), and where both emitters deliver liquid CO_2 to a terminal (*Term*) that finally fills a ship (*Ves*) sailing to a landfill field.



Source: ECA Engineering

Fig. 38 Example of a CCS value chain that is configured using the software. The chart is displayed by clicking on "ccs chain model" in the software's graphical user interface (GUI).

Basically, the CCS value chain consists of well-known unit operations such as burners, motors, absorption towers, cooling towers, compressors, heat exchangers, nozzles, pumps and tanks, and in many cases the same unit operations can be used in several parts of the value chain.

For example, a gas turbine, cement burner and marine engine use the same class (super class) for calculation of combustion products and energy generation, as all fuels can be characterized based on a chemical settlement and the calorific value.

Likewise, for the simulation of a CO_2 terminal, the object uses the same class (super class) for the simulation of its pressurized and insulated tanks, just as the object of a ship is used to simulate its pressurized and cooled tanks.

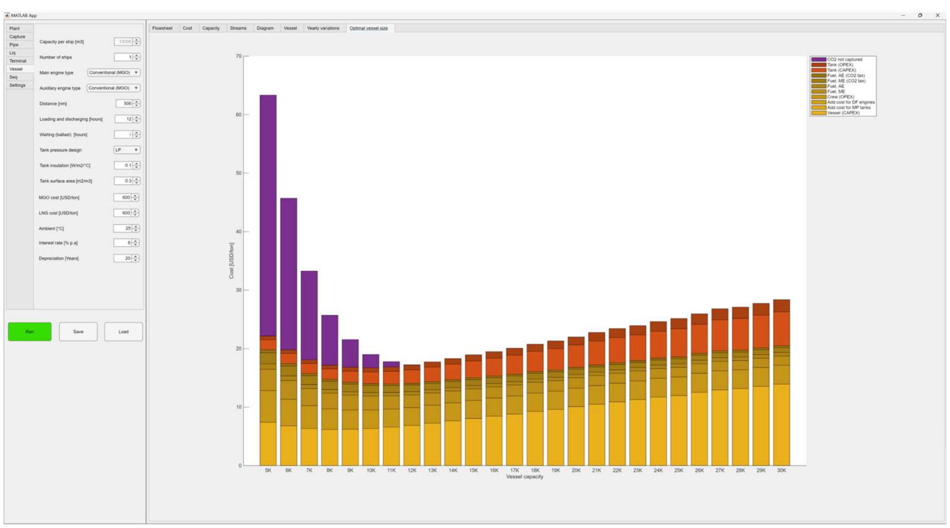
The above objects all need thermodynamic data for the currents that go in and out of the objects. The objects are therefore programmed to communicate with a so-called CapeOpen standard, whereby they can extract all necessary thermodynamic data from existing functions for calculating densities, enthalpies, and entropies such as a function of pressure, temperature, and composition.

This is particularly relevant for mixtures, as only small impurities such as N_2, O_2 or NOx have a major impact on the energy used to produce CO_2 and as the split between gas and liquid is strongly nonlinear. Furthermore, it is important to comply with standards defined for the final CO_2 (e.g. Northern Light).

The overall model is used to optimize the ship size for a case in collaboration with an emitter.

Figure 39 shows that a ship with a capacity of 12,000 m3 CO_2 will have the lowest total costs (OPEX including fuel plus depreciation on CAPEX).

The most important parameters for optimizing the ship size can be adjusted in the panel on the left of the figure and all have a very large impact on the optimal ship size that exists.



Source: ECA Engineering

Fig. 39 Optimization of vessel size in an emitter's CCS value chain. The Y-axis shows the total total cost, which is the sum of the depreciation of the investments and the operating costs. The X-axis shows ship sizes from 5,000 to 30,000 tons of CO_2 capacity. In the panel on the left, you *can select different numbers of ships and change the design pressure as well as a number of other relevant parameters.*

The above is shown as concrete examples, but the strength of the model is of course that another CCS chain can easily be configured, illustrated, simulated and optimized using the developed software.

The program is available via an app and can be tailored to the CCS chain in question that is to be investigated. It is possible to access the app by contacting ECA Engineering.

Abbreviations

AiP:	Approval in Principle
ALS:	Air Lubrication Systems
ARA:	Amsterdam-Rotterdam-Antwerp trading area
CAPEX:	Capital Expenditures
CCS:	Carbon Capture & Storage
CPP:	Controlable Pitch Propeller
EEA (EEA):	European Economic Area
EEDI:	Energy Efficiency Design Index
ETS:	Emission Trading Scheme
EUA:	European Union Allowance
EEA (EEA):	European Economic Area
FPP:	Fixed Pitch Propeller
GFI:	Greenhouse Gas Fuel Intensity
GHG:	Green House Gas
HFO:	Heavy Fuel Oil
IGC:	International Gas Code (2016 edition)
IMO:	International Maritime Organization (UN)
Class:	Classification societies such as ABS, DNV, Lloyd's and more
LCB:	Longitudinal Center of Bouyancy
GATE:	Light Emitting Diode
LCA:	Life Cycle Analasys
LCV:	Lower Calorific Value
LP:	Low pressure

MARVS: Maximum Allowable Relief Valve Setting

MGO: Marine Gas Oil

MP: Mid pressure

OPEX: Operational Expenditures

PBCF: Propeller Boss Cap Fin

PTO: Power-take-out (shaft generator)

RED II: Renewable Energy Directive II (European)

SECA: Sulphor Emission Controlled Area

TtW: Tank-to-Wake

VCM: Vinyl Chloride Monomer

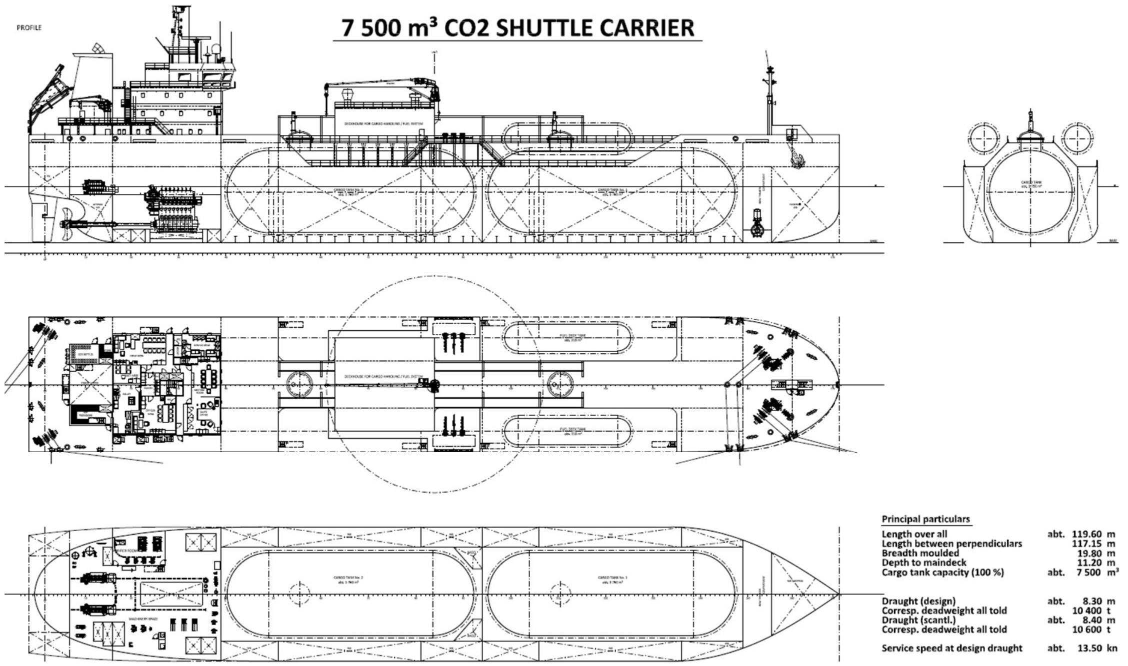
VFD: Variable Frequency Drive

WAPS: Wind Assisted Propulsion System

WtW: Well-to-Wake

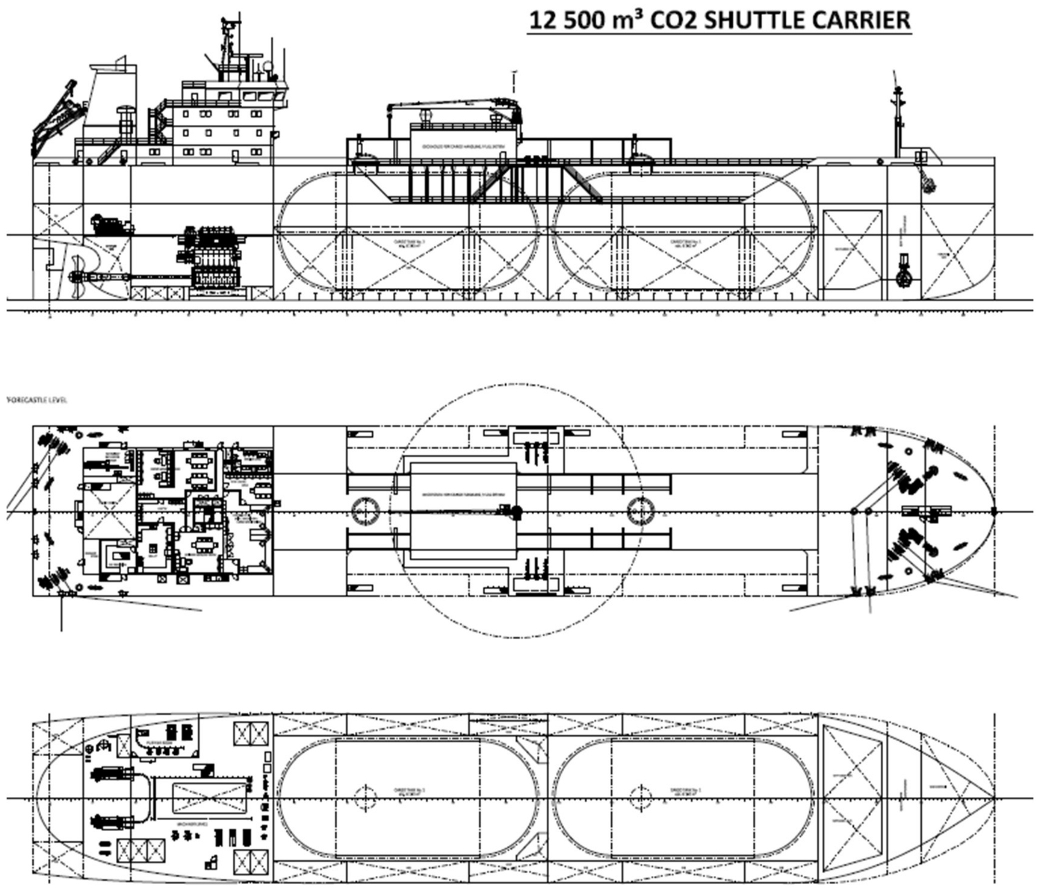
Appendix A – LP Ship Design

Appendix A – 7,500 m^3 LP CO_2 carrier



Source: TGE Marine

Appendix A – 12,500 m^3 LP CO2 carrier

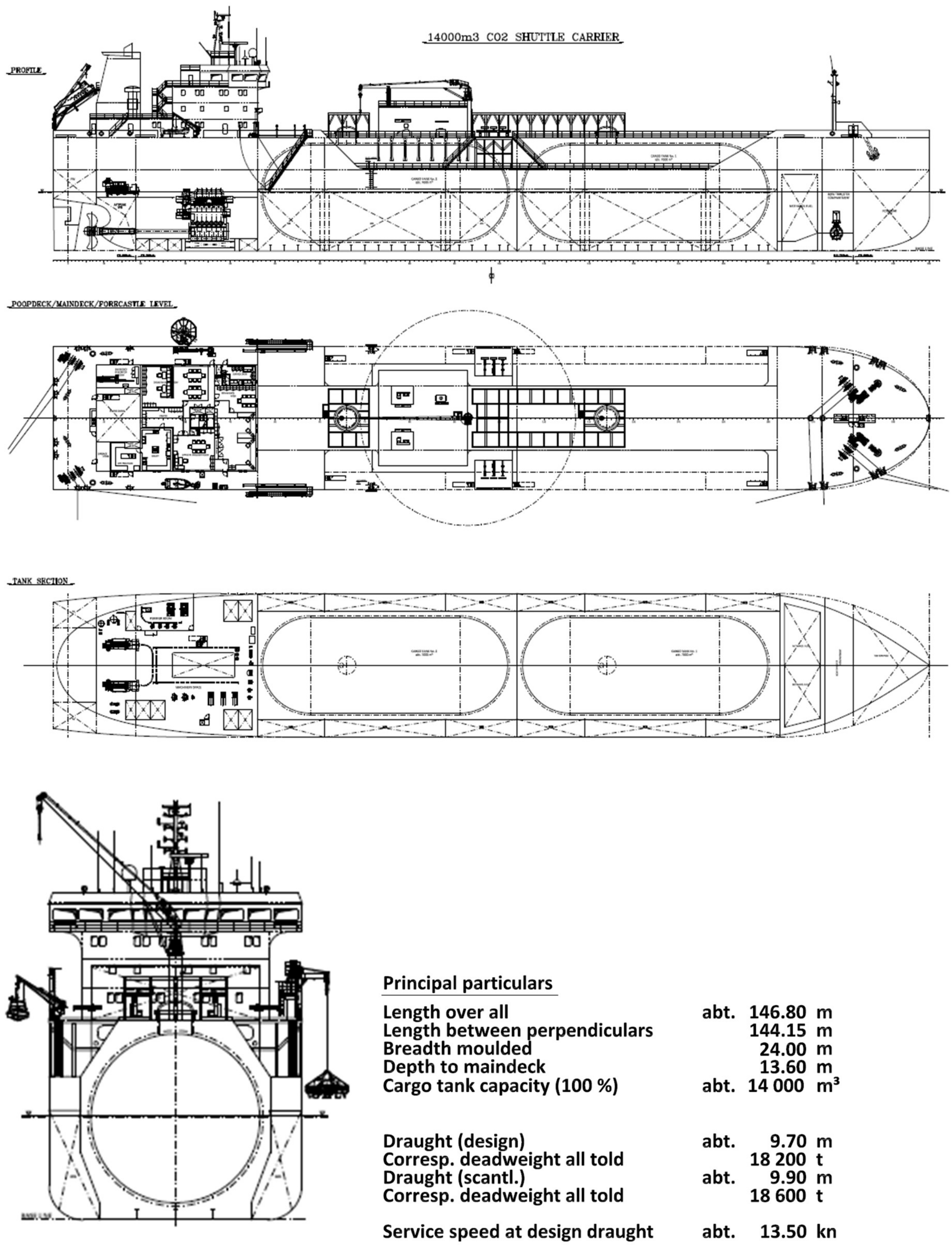


Source: TGE Marine

Source: TGE Marine

Fig 40 12,500 m^3 LP CO2 carrier

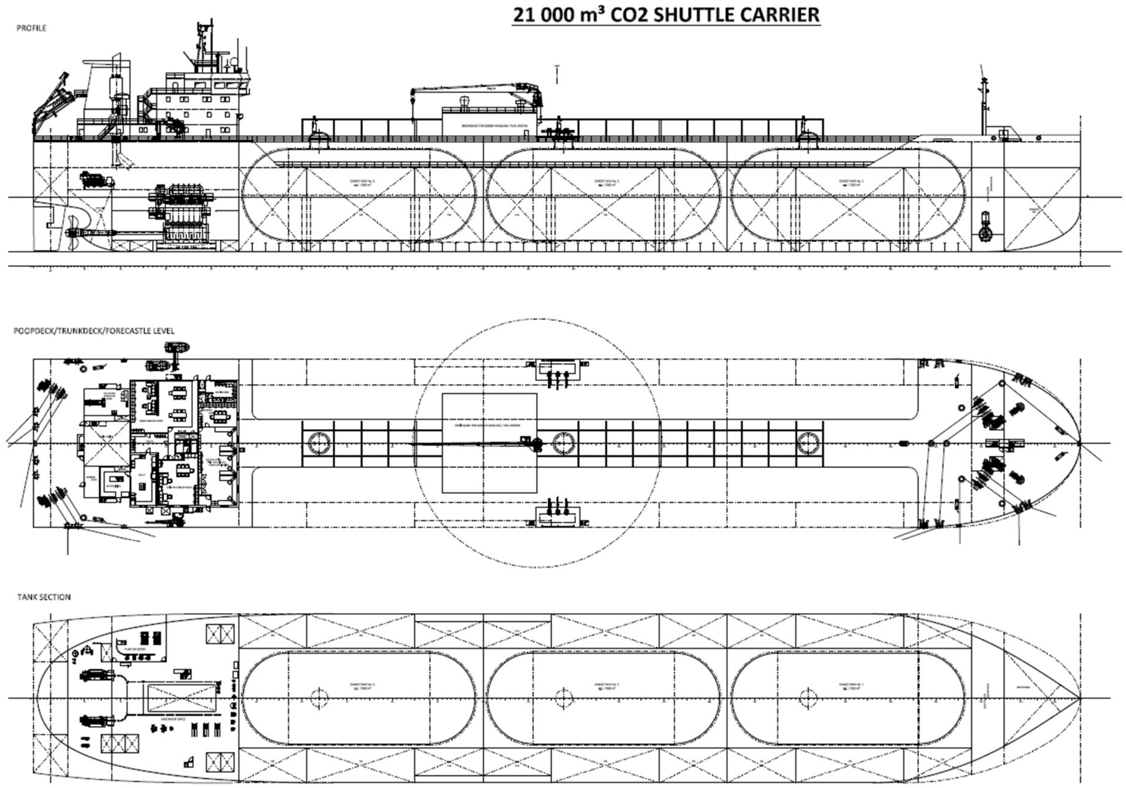
Appendix A – 14,000 m^3 LP CO2 carrier

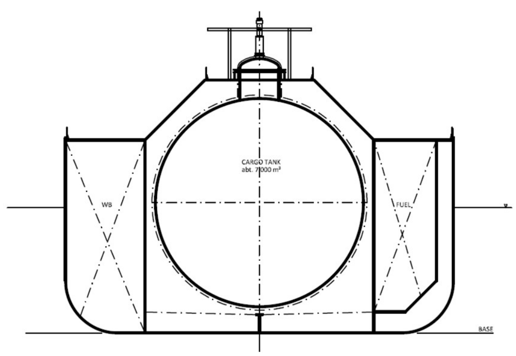


Source: TGE Marine

Fig 41 14,000 m^3 LP CO2 carrier

Appendix A – 21,000 m^3 LP CO2 carrier





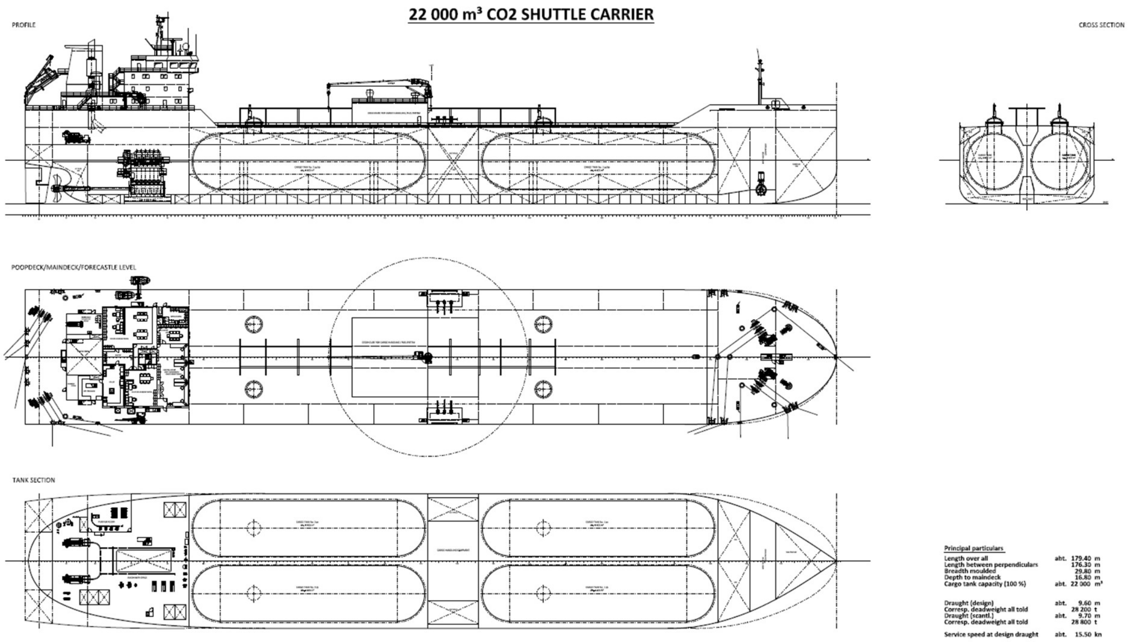
Principal particulars

Length over all	**abt.**	**185.00**	**m**
Length between perpendiculars		**181.90**	**m**
Breadth moulded		**29.80**	**m**
Depth to maindeck		**14.80**	**m**
Cargo tank capacity (100 %)	**abt.**	**21 000**	**m³**
Draught (design)	**abt.**	**9.20**	**m**
Corresp. deadweight all told		**27 600**	**t**
Draught (scantl.)	**abt.**	**9.30**	**m**
Corresp. deadweight all told		**28 200**	**t**
Service speed at design draught	**abt.**	**15.50**	**kn**

Source: TGE Marine

Fig 42 21,000 m^3 LP CO2 carrier

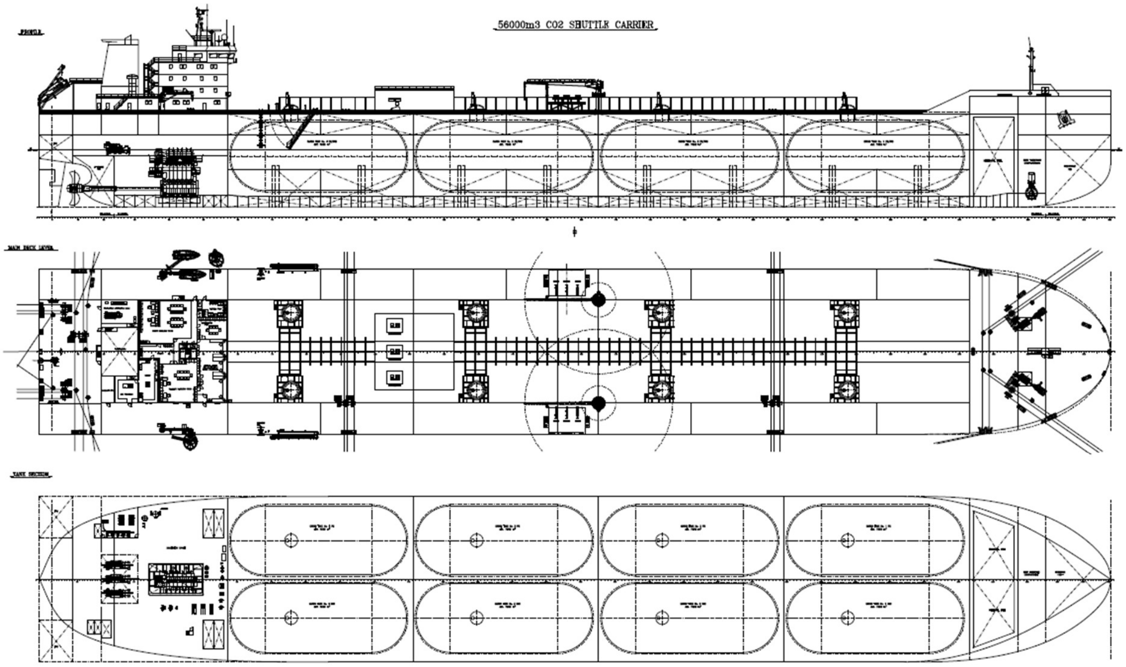
Appendix A – 22,000 m³ LP CO2 carrier

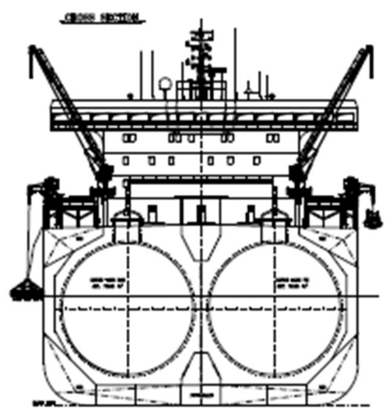


Source: TGE Marine

Fig 43   22,000 m³ LP CO2 carrier

Appendix A – 56,000 m^3 LP CO2 carrier





Principal particulars

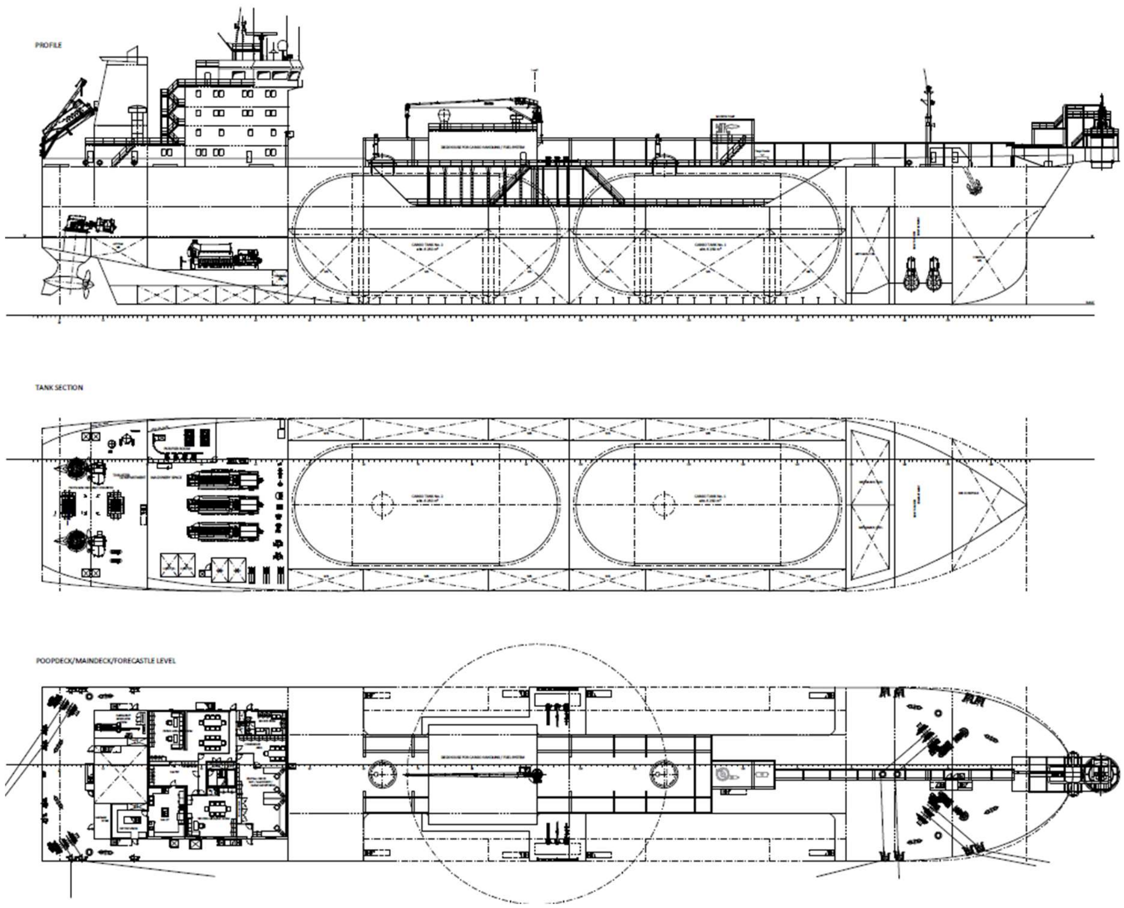
Length over all	**abt.**	**249.75**	**m**
Length between perpendiculars		**246.39**	**m**
Breadth moulded		**38.40**	**m**
Depth to maindeck		**21.60**	**m**
Cargo tank capacity (100 %)	**abt.**	**56 000**	**m^3**
Draught (design)	**abt.**	**13.10**	**m**
Corresp. deadweight all told		**69 600**	**t**
Draught (scantl.)	**abt.**	**13.30**	**m**
Corresp. deadweight all told		**71 000**	**t**
Service speed at design draught	**abt.**	**15.50**	**kn**

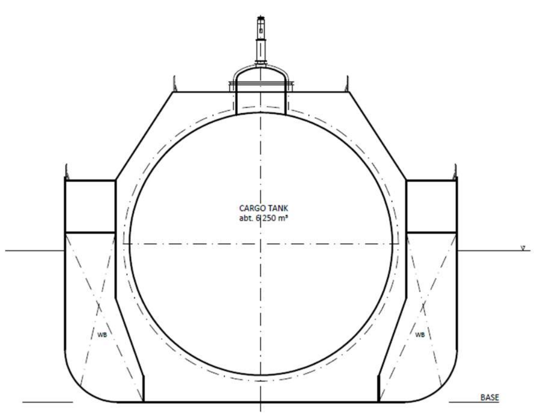
Source: TGE Marine

Fig 44 56,000 m^3 LP CO2 carrier

Appendix A – 12,500 m³ LP CO2 shuttle carrier for Greensand

12 500 m³ CO2 Carrier





Principal particulars

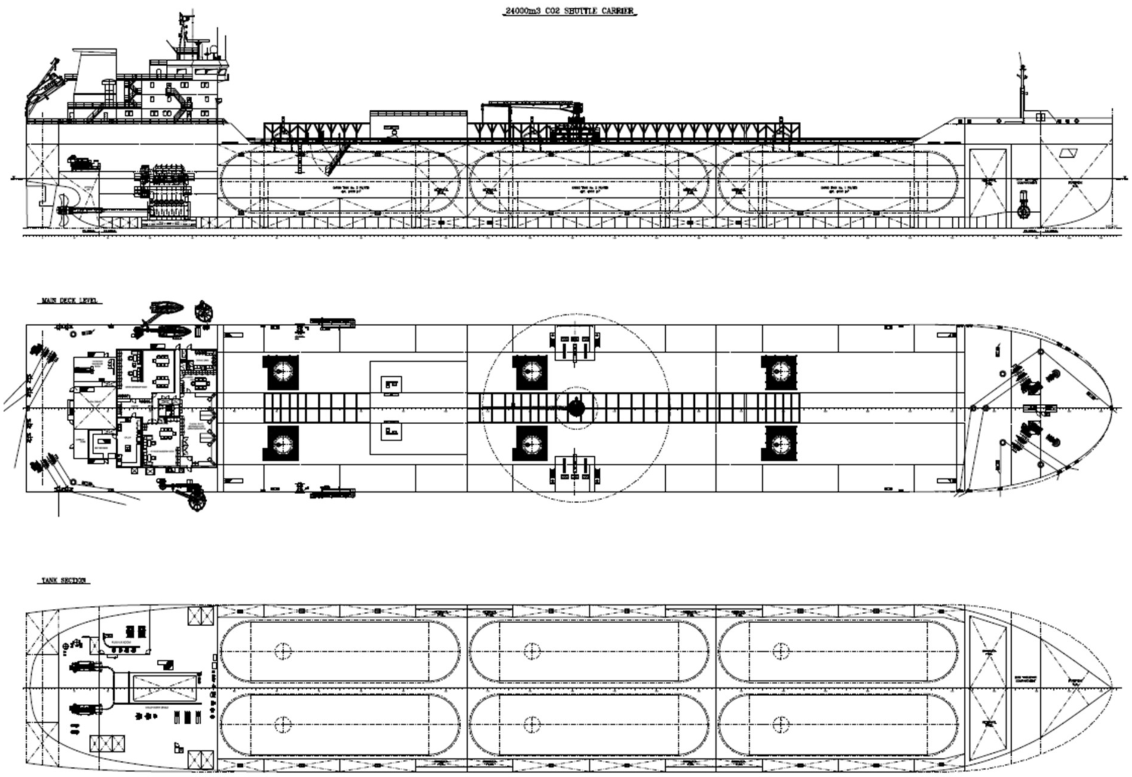
Length over all	**abt.**	**142.8**	**m**
Length over all (incl. turret)	**abt.**	**149.12**	**m**
Length between perpendiculars		**133.95**	**m**
Breadth moulded		**24.00**	**m**
Depth to maindeck		**13.60**	**m**
Cargo tank capacity (100 %)	**abt.**	**12 500**	**m³**
Draught (design)	**abt.**	**9.30**	**m**
Corresp. deadweight all told		**16 200**	**t**
Draught (scantl.)	**abt.**	**9.40**	**m**
Corresp. deadweight all told		**16 600**	**t**
Service speed at design draught	**abt.**	**13.50**	**kn**

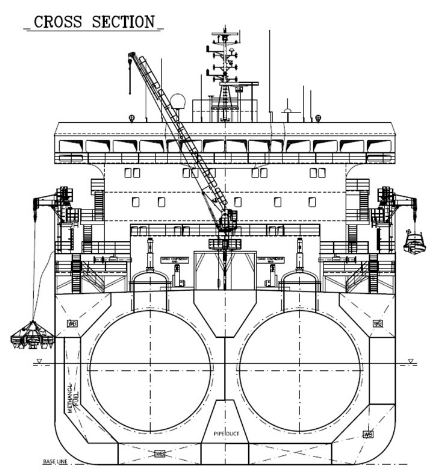
Source: TGE Marine

Fig 45 12,500 m³ LP CO2 carrier with turret off-loading; for Greensand project

Appendix B – MP ship design

Appendix B – 24,000 m³ LP CO2 carrier





Principal particulars

Length over all	abt.	205.70	m
Length between perpendiculars		202.70	m
Breadth moulded		31.60	m
Depth to maindeck		15.80	m
Cargo tank capacity (100 %)	abt.	24 000	m³
Draught (design)	abt.	9.20	m
Corresp. deadweight all told		31 500	t
Draught (scantl.)	abt.	9.40	m
Corresp. deadweight all told		32 500	t
Service speed at design draught	abt.	15.50	kn

Source: TGE Marine

Fig 46 24,000 m³ MP CO2 carrier – Iceland & Carbfix trade

Appendix C – Approval in Principle by ABS: 12,500 m^3 LP and 22,000 m^3 LP

APPROVAL IN PRINCIPLE | **ABS**

as requested by:

Dan-Unity CO2

Date of Issuance: 10 November 2021

Certificate Number: T2188705

ABS has reviewed the documentation as specified in the ABS letter dated 2 November 2021 (Task No. T2183451/489), 8 November 2021 (Task No. T2183450/489/632 and T2183467) and dated 3 November 2021 (Task No. T2183493) in accordance with the ABS 2017 *Guidance Notes on Review and Approval of Novel Concepts*, and considers that the conceptual engineering as proposed is feasible for the intended application, and the facilities as presented are, in principle, in compliance with the applicable requirements of the *ABS Rules for Building and Classing Steel Vessels 2021; International Convention for the Safety of Life at Sea (SOLAS 1974); IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).*

Facility: 12,500 cbm CO2 Carrier

Description: Approval in Principle of Cargo Tanks and Cargo Handling System

New Technology Maturity Level:

[Subsystem B – Concept Verification Stage]

To achieve final class approval of the subject design, the conditions and requirements as specified in the Approval Road Map [2 November 2021 (Task No. T2183451/489), 8 November 2021 (Task No. T2183450/489/632 and T2183467) and dated 3 November 2021 (Task No. T2183493)] must be satisfied.

Bin-Hong Wang
Director of Engineering, ABS

By:

Ya-Lin Li
Manager – Machinery, ABS

Note: This certificate evidences compliance with one or more of the Rules, Guides, standards or other criteria of American Bureau of Shipping or a statutory, industrial or manufacturer's standards and is issued solely for the use of the Bureau, its committees, its clients or other authorized entities. Any significant changes to the aforementioned product without ABS approval will result in this certificate becoming void. This certificate is governed by the terms and conditions in the ABS Rules.

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APPROVAL IN PRINCIPLE

ABS

as requested by:

Dan-Unity CO2

Date of Issuance: 10 November 2021

Certificate Number: T2188462

ABS has reviewed the documentation as specified in the ABS letter dated 2 November 2021 (Task No. T2183456/487), 8 November 2021 (Task No. T2183454/487/638 and T2183469) and dated 4 November 2021 (Task No. T2183488) in accordance with the ABS 2017 *Guidance Notes on Review and Approval of Novel Concepts*, and considers that the conceptual engineering as proposed is feasible for the intended application, and the facilities as presented are, in principle, in compliance with the applicable requirements of the *ABS Rules for Building and Classing Steel Vessels 2021; International Convention for the Safety of Life at Sea (SOLAS 1974); IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).*

Facility: 22,000 cbm CO2 Carrier

Description: Approval in Principle of Cargo Tanks and Cargo Handling System

New Technology Maturity Level:

[Subsystem B – Concept Verification Stage]

To achieve final class approval of the subject design, the conditions and requirements as specified in the Approval Road Map [2 November 2021 (Task No. T2183456/487), 8 November 2021 (Task No. T2183454/487/638 and T2183469) and dated 4 November 2021 (Task No. T2183488)] must be satisfied.

Bin-Hong Wang
Director of Engineering, ABS

By:

Ya-Lin Li
Manager – Machinery, ABS

Note: This certificate evidences compliance with one or more of the Rules, Guides, standards or other criteria of American Bureau of Shipping or a statutory, industrial or manufacturer's standards and is issued solely for the use of the Bureau, its committees, its clients or other authorized entities. Any significant changes to the aforementioned product without ABS approval will result in this certificate becoming void. This certificate is governed by the terms and conditions in the ABS Rules.

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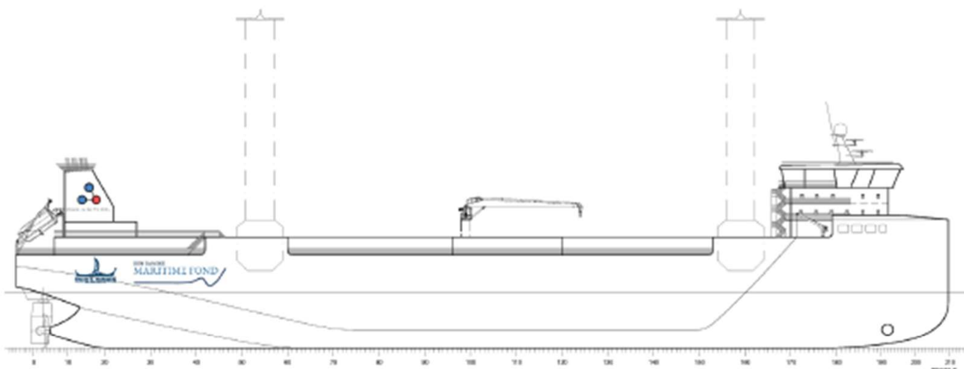
Appendix D – 16.000 MP design: Pocket Plan

KNUD E. HANSEN
SHIP DESIGN SINCE 1937

DAN-UNITY LCO2 CARRIER



The LCO2 tanker is designed to transport medium pressure LCO2 between ports. The design of the ship is tailored for the operation in the North Atlantic area. The design includes four times 4,000 m3 LCO2 tanks, given a total gross volume of 16,000 m3.

The ship is prepared for future fuels such as methanol and bio-diesel, but can also be delivered for bio-LNG, ammonia etc.

The ship is highly optimized in all details to lower energy consumption and features among others the following features:

- One long stroke slow running 2-stroke main engine,
- ORC units to transform waste heat into electrical power,
- 4 Flettner rotors to provide wind assistant propulsion,
- Air lubrication to lower hull friction,
- Gate rudder.

MAIN PARTICULARS	
Length o.a.	163.00 m
Length p.o	158.00 m
Breadth, moulded	26.60 m
Draught (design)	9.70 m
Depth to main	16.30 m

CAPACITY	
LCO2 tanks gross volume	16,000 m³
No. of LCO2 tanks	4 pcs
LCO2 tank design pressure	19 barg

SPEED	
Service speed	15.50 kn

MACHINERY & EQUIPMENT	
Diesel main engines	MAN-ES 5G60ME-C10.5-LGIM
Installed power	1 x 9,771 kW
Aux. power	3 x 1,200 KW

SCOPE OF WORK
General Arrangement
Stability calculations
CFD hull optimization
Energy saving strategy

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Appendix E – 16,000 MP design: scope of work

Deliverable	Scope of Work/Remarks
Requirement For Design	The requirements from client to be listed and agreed. One page with bullet points to be created. In general the outset will be the already provided GA from client; however this needs to be "taken over" by KEH and a proper general arrangement to be made as per KEH standards. As client has already performed initial development of the design the following to be informed as constrains for the optimization (not exhaustive): • Displacement and associated draughts

	- Draught from general arrangement supplied by Client or as agreed with Client at project start (below 10m but not a must) - Onboard cargo tanks and amount of contents - From material supplied by Client - Speed range - From general arrangement supplied by Client or as agreed at project start. Expected around 15.5 kn, but to be further evaluated when speed/power is available, see milestones. - Draught limitations in operation - As per table 1 - Draft limitations in operation - None considered - Possible SAL system is considered as an option for the project and with this also the necessary DP2 notation and thrusters. - Intended fuel - Methanol or ammonia considered. Ship should be able to carry both, however methanol space reservation could impact some particulars of the ship. - Route data for optimization - From Client: ARA (Antwerp-Rotterdam-Amsterdam) to Straumsvik in Iceland and return Table 1: Port restrictions in Iceland Straumsvik max: Quay 1: Mooring draft: max 12 m Loa: 180 m Bm: 27 m Quay 2: Mooring draft: max 10 m Loa: 200 m Bm: 30 m

A Hull development single boss hull	Summary sheet to be created. To be developed to a stage where comparing between the two hulls A and B is possible.
A.1 Single boss hull lines	2D line plan. One drawing to be delivered.
A.2 Single boss power prediction	Power prediction based on empirical approach and CFD. One summary power to be delivered.
A.3 Single boss stability	Evaluation of trim and stability.

	Does only include major tanks already located by client (cargo, fuel and ballast). One calculation to be delivered.
A.4 Propulsion concept	Outline of propulsion concept. One report to be delivered (1-3 pages).
A.5 EEDI calculation	One calculation to be delivered.
A.6 Lightweight and COG estimation	Estimation needed for hull development. One summary calculation to be delivered.
B Optimization of twin skeg	Summary sheet to be created. To be developed to a stage where comparing between the two hulls A and B is possible.
B.1 Twin skeg lines	2D line plan. One drawing to be delivered.
B.2 Twin skeg power prediction	Power prediction based on empirical approach and CFD. One summary power to be delivered.
B.3 Twin skeg stability	Evaluation of trim and stability. Does only include major tanks already located by client (cargo, fuel and ballast). One calculation to be delivered.
B.4 Propulsion concept	Outline of propulsion concept One report to be delivered (1-3 pages).
B.5 EEDI calculation	One calculation to be delivered.
B.6 Lightweight and COG estimation	One summary calculation to be delivered.
Milestone workshop	Meeting to summarize and decide upon A or B. Minor adjustments to be accommodated to be agreed.
Miletstone conclusion sheet	To settle the hull to optimize, A or B
Optimization meeting	As suggested by Client, Njord to comment on possible savings that could be introduced into the design. Time for delivery of data to Njord and meeting to be planned by KEH. Considered to be via TEAMS or a meeting of max one day at KEH office in Helsingør (DK).
C Selected hull final loop	The purpose is to finalize the selected hull.

C.1 Hull lines	Final loop for minor adjustments. One updated drawing to be delivered.
C.2 Power prediction	Power prediction update based on empirical approach and CFD. One updated summary calculation to be delivered. Ballast and design condition shall be included as 50/50% of time.
C.3 Stability	Evaluation of trim and stability as well as intact and damage stability. Based on the KEH updated general arrangement.
C.4 Propulsion concept	Outline of propulsion concept One updated report to be delivered. Will include major components as outline in conceptual stage. Will not be specified in details as this is subject to detailed design. Gensets will not be specified with power rating as this is subject to detailed design. Consumption for gensets, or aux power from shaft generators, will however be indicated for client calculation of Cii and EEOI. CAPEX and OPEX not included for propulsion concept.
C.5 EEDI	One updated calculation to be delivered.
C.6 General arrangement update	KEH to make a KEH general arrangement based on Clients general arrangement but a general arrangement that suits the stability and optimized hull lines. The number and capacity of cargo tanks to be as for the provided general arrangement from client. Tanks to be included in the GA (Not minor engine room tanks). If existing GA can be delivered in (DWG/DXF) tank etc. can be transferred. If not possible KEH can see if a PDF to CAD conversion is possible.
Light weight	Updated light weight. Tolerances as for a typical design at this stage.

Appendix F – 16,000 MP design: speed & performance

Hull version		HULL11 / HULL23	
Length betw. perpendiculars	Lpp	159.93	m
Waterline length	L	158.75	m
Breadth	B	26.60	m
Draught	T	9.70	m
Hull volume, bare hull	∇	31140	m^3
Wetted surface, bare hull	S	5929	m^2

PRELIMINARY

Notes:

- Propulsion efficiencies from manufacturer data
- Single screw, Dp = 6.1m, Z=4

Design Condition:

- Seawater of 1.025t/m^3 at 15 deg C
- Clean bottom, appendages and propeller
- Deep water
- Calm (BF0), with no wind, waves or current
- Even keel

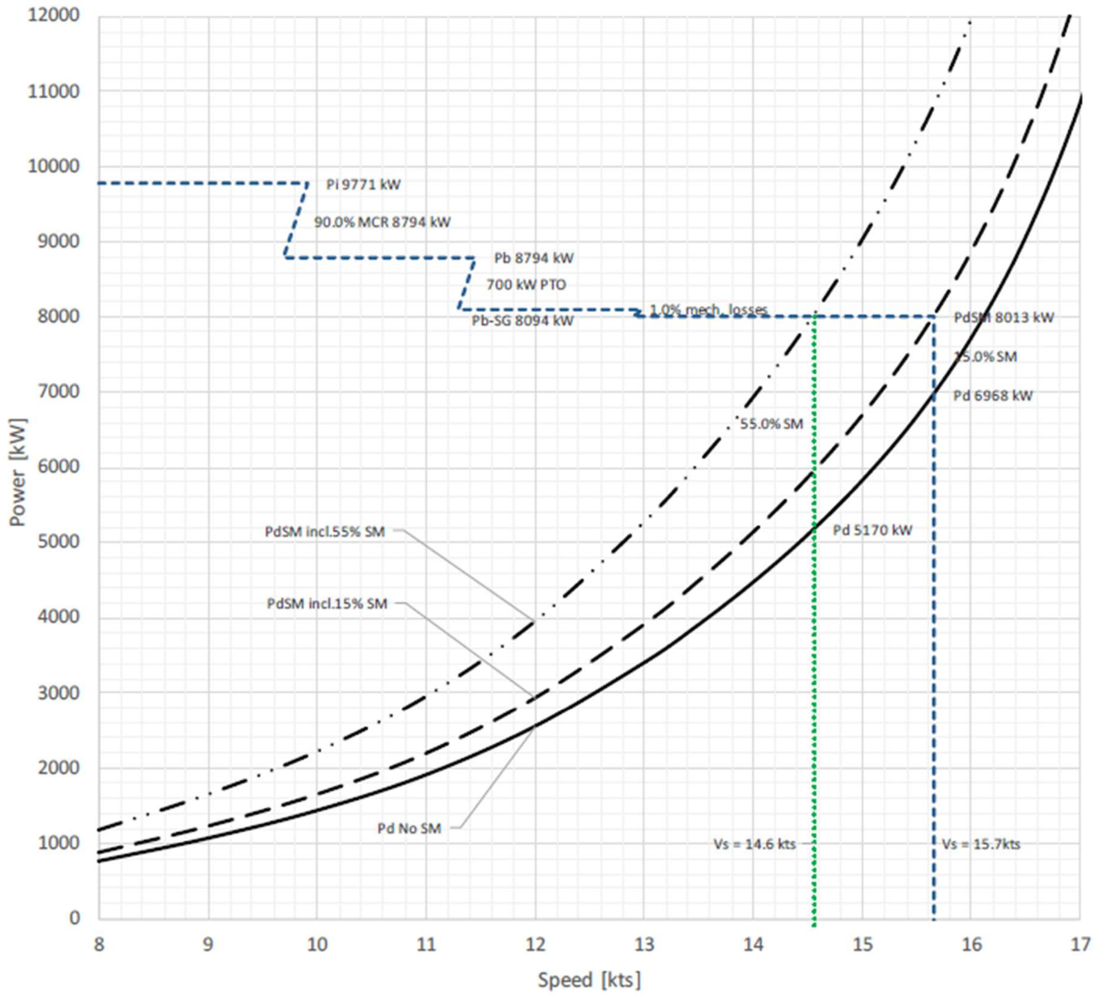
Main Engine:

5G60ME-C10.5-LGIM-EGRBP

Available delivered power including sea margin (PdSM*): 8013 kW

*Available PdSM based on below efficiencies / coefficients:

Diesel-Mechanical	SG 700 kW	MCR 90%	Shaft eff. 0.99	Gear eff. 1.00



Pi	Installed power
MCR	Maximum allowable engine load
Pb	Available brake power
Ps	Available shaft power
SM	Sea margin to account for wind, waves and current
PdSM	Available delivered power including sea margin
Pd	Available delivered power
Vs	Attainable ship speed

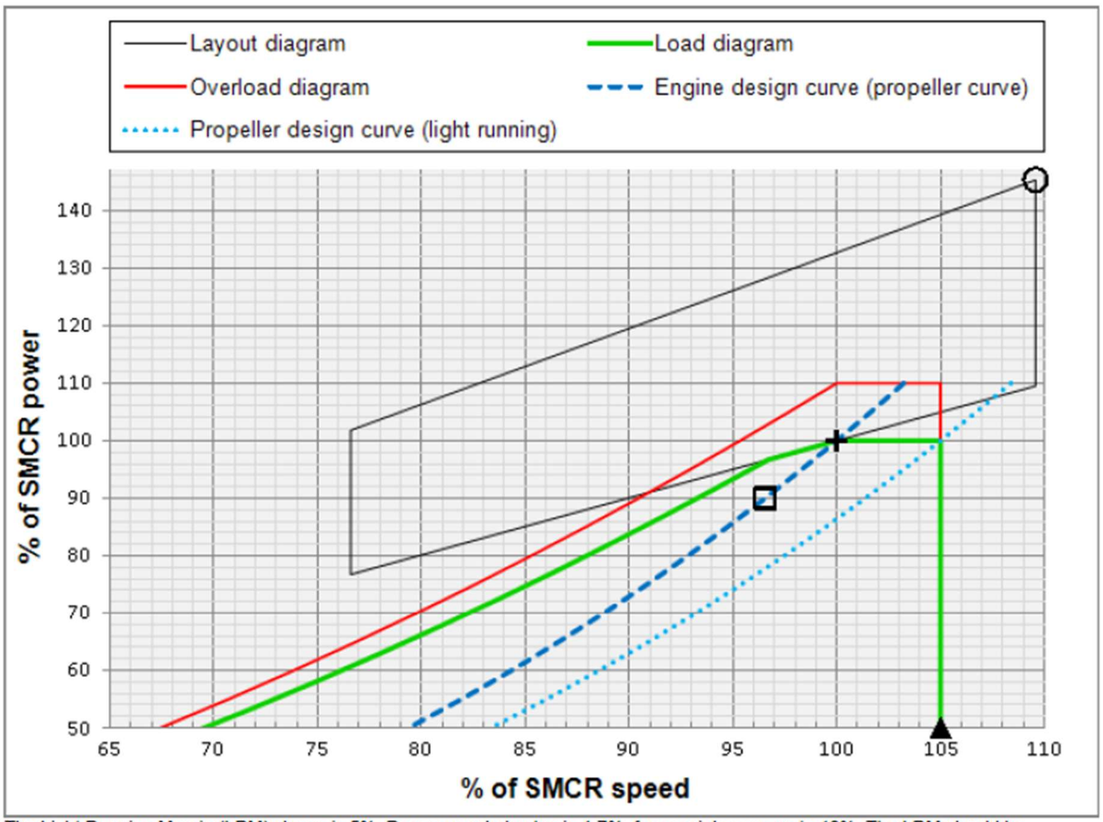
Table 3. Power prediction for 15% Sea Margin

Speed *[kts]*	Fn *[-]*	Pd *[kW]*	Pd_{SM} *[kW]*	Ps (EEDI) *[kW]*	PbSM *[kW]*	Pinst *[kW]*
8.0	0.104	758	871	765	880	1756
9.0	0.117	1062	1221	1073	1234	2149
10.0	0.130	1430	1644	1444	1661	2623
11.0	0.143	1903	2189	1922	2211	3234
12.0	0.156	2548	2930	2573	2959	4066
13.0	0.169	3398	3907	3432	3947	5163
13.5	0.176	3903	4489	3943	4534	5815
14.0	0.182	4466	5136	4511	5188	6542
14.5	0.189	5097	5862	5149	5921	7356
15.0	0.196	5817	6690	5876	6758	8286
15.5	0.202	6667	7667	6734	7744	9382
16.0	0.209	7711	8867	7788	8957	10730
16.5	0.215	9051	10409	9143	10514	12460
17.0	0.222	10840	12466	10949	12591	14768
17.5	0.228	13288	15281	13422	15436	17929

Appendix G - Engine type & layout:

MAN Energy Solutions

CEAS Engine Data report
5G60ME-C10.5-LGIM-EGRBP



The Light Running Margin (LRM) shown is 5%. Recommended value is 4-7%, for special cases up to 10%. The LRM should be evaluated for each ship project depending on for example: In-service increase of vessel resistance, ship manoeuvring requirements, additional engine load due to power take-out (PTO) and possible requirements related to a barred speed range (short passing time).

Point		Power kW	Speed r/min	MEP bar
+	SMCR: Specified Maximum Continuous Rating (68.8% of NMCR)	9,771	94.0	15.8
◻	NCR: Normal Continuous Rating (90.00% of SMCR)	8,794	94.0	14.2
	Maximum over load (110% of SMCR)	10,748	-	-
▲	Maximum speed limit (105% of SMCR)	-	98.7	-
O	L1, NMCR: Nominal Maximum Continuous Rating	14,200	103.0	21.0

Specified Main Engine and Other Parameters

Specified parameters	
Type of propeller	Controllable pitch propeller
Cooling system	Central water cooling system
Hydraulic control oil system	Common (system oil)
Hydraulic power supply	Mechanical
Cylinder oil lubricator type	Alpha lubricator
Fuel sulphur content for engine design	Low sulphur
Sulphur in fuel (Tier II)	max 0.5% sulphur
Sulphur in fuel (Tier III)	max 0.1% sulphur
NOx emission compliance	Tier II / Tier III
Pilot oil energy fraction	Nominal 5.0%

Turbocharger specifications	
Turbocharger efficiency	High efficiency
Exhaust gas bypass	With EGB
Number of turbochargers and make/type	1 x MAN TCT40-ML
Turbocharger lubricating	Common (system oil)
Exhaust gas scrubber for high sulphur	Not installed
Exhaust back pressure (Tier II)	30 mbar
Exhaust back pressure (Tier III)	30 mbar

Fuel Consumption and Gas Figures

	Tier II		Tier III	
SFOC	SMCR g/kWh	NCR g/kWh	SMCR g/kWh	NCR g/kWh
ISO	165.0	160.4	167.0	164.3
Tropical	166.7	162.1	168.8	166.0
Specified	163.0	158.5	165.0	162.3

SFOC: Specific Fuel Oil Consumption (LCV: 42,700 kJ/kg)

	Tier II		Tier III	
SPOC/SGC (Heat rate)	SMCR g/kWh (kJ/kWh)	NCR g/kWh (kJ/kWh)	SMCR g/kWh (kJ/kWh)	NCR g/kWh (kJ/kWh)
ISO	11.07/326.0 (6,960)	12.30/312.1 (6,737)	11.07/330.3 (7,045)	12.30/320.4 (6,901)
Tropical	11.07/329.7 (7,034)	12.30/315.7 (6,808)	11.07/334.0 (7,120)	12.30/324.0 (6,974)
Specified	11.07/321.8 (6,877)	12.30/308.1 (6,656)	11.07/326.0 (6,961)	12.30/316.2 (6,818)

SPOC: Specific Pilot Oil Consumption (LCV: 42,700 kJ/kg)
SGC: Specific Gas Consumption (LCV: 19,900 kJ/kg)

	Tier II		Tier III	
Exhaust gas amount	SMCR kg/s	NCR kg/s	SMCR kg/s	NCR kg/s
ISO	19.1	17.7	18.1	16.5
Tropical	17.3	16.0	17.0	15.5
Specified	19.6	18.2	18.3	16.7

	Tier II		Tier III	
Exhaust gas temperature	SMCR °C	NCR °C	SMCR °C	NCR °C
ISO	268	242	217	205
Tropical	316	288	261	247
Specified	241	217	194	182

	Tier II		Tier III	
Turbocharger air consumption	SMCR kg/s	NCR kg/s	SMCR kg/s	NCR kg/s
ISO	18.1	16.9	17.5	16.0
Tropical	16.6	15.5	16.6	15.2
Specified	18.7	17.4	17.7	16.2

ISO, tropical and specified conditions are listed in the References and tolerances section.

Expected lubricating oil consumption

Fuel sulphur	Cylinder oil consumption	Lubricating oil consumption
0.1%-0.5%	minimum 0.6 g/kWh	from negligible to 0.1 g/kWh

Capacities of Pumps and Coolers

Pump	Flow capacity m³/h	Pump head bar
Fuel oil circulation	5.3	6.0
Fuel oil supply	2.7	4.0
Jacket cooling water	80	3.0
Lubricating oil	280	4.2
Central fresh water	300	2.5
Sea water for central cooling	360	2.0

The pump heads stated are for guidance only, and depend on the actual pressure drop across coolers, filters, etc. in the systems. The capacities do not account for any components other than the engine itself.

Flow capacities of cooler(s) on engine	Central water flow m³/h
Total flow capacity for scavenge air- / EGR coolers(s)*),**)	200

*) This engine has 1 EGR string installed.
**) This engine can be ordered with Adaptive Cooling. It requires a custom made CEAS report and frequency drives for pumps in engine room.

Capacities of auxiliary heat exchangers		m³/h	Central water flow m³/h	Heat dissipation kW
Central cooler	Sea water flow	360	300	7,340
Jacket water cooler	Jacket water flow	80	100	1,420
Lubricating oil cooler	Oil flow	280	100	920

All flows are stated as minimum required flows.
The heat capacity of the central cooler (including 5% safety margin) is calculated as the sum of the 100% SMCR heat dissipation from all coolers in the worst case of each of the engine operational modes (fuel type, emission mode and ambient condition).
The heat capacity of the jacket water cooler and lubricating oil cooler (including 10% safety margin) is based on the highest heat dissipation of each of the engine operational modes (fuel type, emission mode and tropical condition).
Pertaining cooling water flow diagram, temperatures, viscosities and pressures for pumps and coolers, see “Engine Project Guide”.

Low Flashpoint Fuel Supply System

Low-Flashpoint Fuel Auxiliary Systems		
Supply pressure	bar(g)	13
System design pressure	bar(g)	16
Pulsation limit at valve train	bar	+0.5
Fuel temperature at engine inlet	°C	25-50
Particle size requirement at outlet of LFSS	µm	Max. 10
Max. fuel flow **)	kg/h	4,100
Minimum flow change rate requirement	[(kg/h)/s]	390
Fuel heat exchanger – heating capacity	kW	150
Fuel heat exchanger – cooling capacity	kW	80

**) At an LCV of 19,000 kJ/kg
Max. fuel flow should be carefully evaluated for specific project conditions.
The fuel heat exchanger heating capacity is based on maximum fuel flow from pump to be heated from -10°C to 50°C.
The fuel heat exchanger cooling capacity is based on maximum fuel flow from pump to be cooled from 65°C to 45°C.

Inert Gas System		
Medium		Nitrogen (N2)
Min. purging pressure	bar(g)	8
Leak test pressure	bar(g)	13
Engine nitrogen volume	liter	To be determined

Ventilation System*)		
Ventilation Fan		
Medium		Dry Air
Air intake quality		ISO 8573-1:2010 [7:4:X(50 mg/m³)]
Particle size		Class 7: max. 40 µm
Pressure dew point custom	°C	≤ +3
Oil content		Class X: max. 50 mg/m³
Ventilation air absolute pressure		Less than atmospheric
Ventilation air pressure drop**		To be determined
Engine ventilation volume	liter	To be determined
Engine friction coefficient**	m^{-4}	Not avail.
Fan flow volume**	Air changes per hour	30-45
Dry Air System		
Air intake quality		Ambient
Air supply quality		ISO 8573-1:2010 [7:4:X(50 mg/m³)]
Supply flow		Approx. 110% of fan flow

*) Refer to the separate documentation of "Low Flashpoint Fuel Ventilation System" for further information.
**) Refer to "LF ventilation system" for auxiliaries contained in the ventilation line. Total ventilation volume, fan flow and fan head must be calculated by the yard as instructed in the "Fan capacity guide".

Sealing oil system		
Medium		Low pressure hydraulic oil *)
Power consumption	kW	8.6
Oil consumption	l/24h	36.00

*) Supplied from engine.

Capacities of Auxiliary Systems

Air cooler cleaning unit	
Air cooler cleaning tank	0.30 m^3
Capacity of pump	1.0 m^3/h

Cylinder oil system	
Storage tanks, 2 x 90 days*)	2 x 23 m^3
Service tanks, 2 x 1 day*)	2 x 0.3 m^3

*) Based on average feed rate of 0.8 g/kWh.

Fuel oil system	
Distillate marine fuel service tank, 12 h	22.6 m^3
Residual marine fuel settling tanks, 2 x 12 h	2 x 21.2 m^3
Residual marine fuel service tank, 12 h/95 °C	21 m^3
Residual marine fuel separator, 98 °C	2,250 l/h
Distillate marine fuel oil circulation cooler	25 kW
Fuel oil pre-heater	77 kW

Lubricating oil system	
Storage tanks, 2 x 90 days	2 x 3.5 m^3
Separator, 90 °C	1,930 l/h
Recommended lubricating oil bottom tank*)	17 m^3

*) Based on an oil circulation rate between 15 and 18, above calculation is based on 16.5 times per hour.

Miscellaneous	
Jacket water expansion tank*)	10 %
Recommended engine room ventilation flow**)	32 m^3/s
Motor rating, auxiliary blowers	2 x 35 kW
EGR blower max power consumption***)	113 kWe

*) Jacket water expansion tank volume given in percent of the total jacket water volume.
**) This air flow is given as 200% of the main engine combustion air flow. Besides the combustion air flow (100%), it includes cooling air for main engine radiation heat (50%), an estimate of combustion air for gensets/boilers and cooling air for their radiation heat (25%) and an estimate of radiated heat from other equipment (25%). Please check with ISO 8861:1998(E) for details.
***) Powered by a variable frequency drive, so no margin for starting current is required. Number of EGR blowers must be informed by maker. Nominal power rating for EGR blower may differ significantly from this value.

Starting air system, 30 bar*)	
Receiver volume (6 starts)	2 x 3.0 m^3
Compressors (total)	180 m^3/h

*) Compressor capacity is based on ISO 1217 FAD. Starting air system capacities do not include air consumption for ventilation of double wall pipe or Tier III air consumers. An assessment is to be performed to determine whether the above needs to be increased.

Starting air system, 30 bar*)	
Receiver volume (6 starts)	2 x 3.0 m^3
Compressors (total)	180 m^3/h

*) Compressor capacity is based on ISO 1217 FAD. Starting air system capacities do not include air consumption for ventilation of double wall pipe or Tier III air consumers. An assessment is to be performed to determine whether the above needs to be increased.

Various drain tanks	
Stuffing box drain tank	0.30 m^3
Scavenge air drain tank	0.50 m^3

EGR Water Handling System 2 (WHS 2)	
Pump flows	
EGR treated water supply pump	2.0 m^3/h
NaOH dosing pump	4 l/h
Pump heads	
EGR treated water supply pump	10 bar
NaOH dosing pump	10 bar

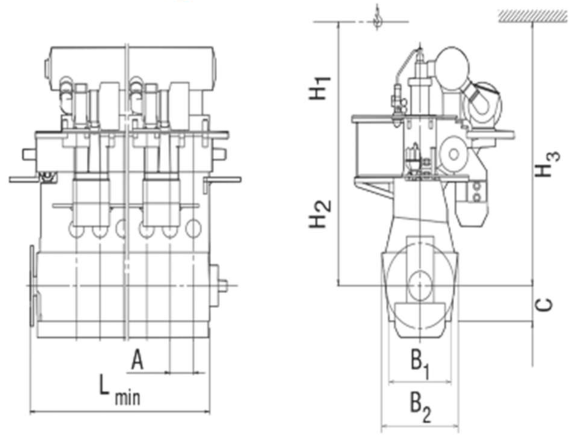
Engine Dimensions, Masses and Overhaul Heights

Dimensions	
A: Cylinder distance	1,080 mm
B1: Width of bedplate at foot flange	4,090 mm
B2: Width of bedplate at top flange	4,220 mm
C: Distance from foot to crankshaft	1,500 mm
L min: Minimum length of engine	7,390 mm

Overhaul heights	
H1: Normal lifting procedure	12,175 mm
H2: Reduced height lifting procedure	n.a. mm
H3: Tilted lifting with double jib crane	n.a. mm

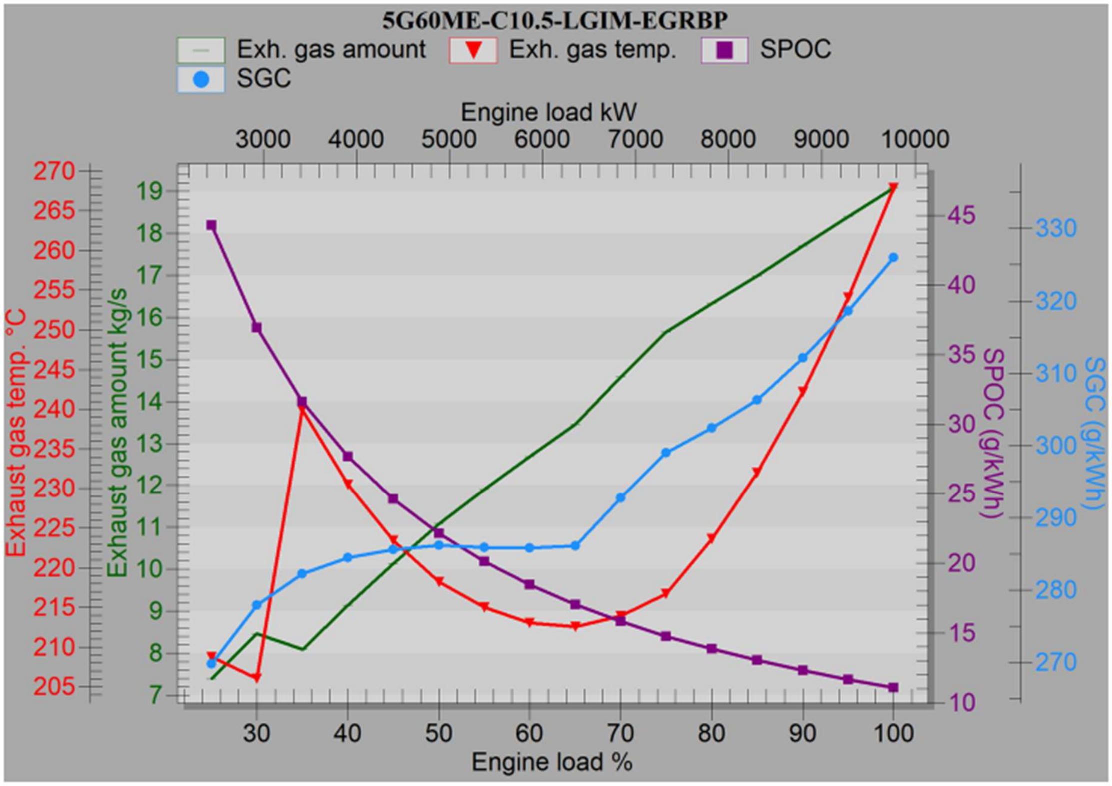
Crane capacities	
Normal lifting procedure	4.0 t
With electrical double jib crane	2 x 2.0 t

Masses	
Mass of main engine, dry	400 t
Added engine dry mass for EGRBP	14 t
Mass of water and oil in engine	4.0 t



The real engine length at crankshaft centreline level may be larger than the minimum length of the engine, as it depends on the vibration conditions of the main engine and shaft system, i.e. on whether a vibration damper and/or moment compensator needs to be installed.
Only EGRBP related components, that are mounted on the engine, are included in the above added mass.
Indicated values are for guidance only and are not binding.

Fuel Consumption and Exhaust Gas Data
Low Flashpoint Fuel, Tier II mode



ISO ambient conditions (ambient air: 25 °C, scavenge air coolant: 25 °C)

Load % SMCR	Power kW	Speed r/min	SPOC g/kWh	SGC g/kWh	Heat rate kJ/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	11.07	326.0	6,960	19.1	268	2,250
95	9,282	94.0	11.66	318.6	6,838	18.4	254	1,890
90	8,794	94.0	12.30	312.1	6,737	17.7	242	1,580
85	8,305	94.0	13.03	306.3	6,651	17.0	232	1,320
80	7,817	94.0	13.84	302.4	6,609	16.3	224	1,110
75	7,328	94.0	14.77	299.0	6,580	15.6	217	940
70	6,840	94.0	15.82	292.7	6,501	14.6	214	840
65	6,351	94.0	17.04	286.1	6,421	13.5	213	760
60	5,863	94.0	18.46	285.8	6,475	12.7	213	740
55	5,374	94.0	20.14	285.9	6,549	11.9	215	730
50	4,886	94.0	22.15	286.1	6,640	11.1	218	730
45	4,397	94.0	24.61	285.5	6,733	10.1	223	750
40	3,908	94.0	27.69	284.4	6,843	9.1	231	780
35	3,420	94.0	31.64	282.2	6,967	8.1	240	810
30	2,931	94.0	36.92	277.9	7,106	8.5	206	420
25	2,443	94.0	44.29	269.7	7,259	7.4	209	400

Fuel Consumption and Exhaust Gas Data
Low Flashpoint Fuel, Tier II mode

Tropical ambient conditions (ambient air: 45 °C, scavenge air coolant: 36 °C)

Load % SMCR	Power kW	Speed r/min	SPOC g/kWh	SGC g/kWh	Heat rate kJ/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	11.07	329.7	7,034	17.3	316	3,000
95	9,282	94.0	11.66	322.2	6,910	16.6	301	2,660
90	8,794	94.0	12.30	315.7	6,808	16.0	288	2,360
85	8,305	94.0	13.03	309.8	6,722	15.3	277	2,080
80	7,817	94.0	13.84	305.9	6,679	14.7	268	1,860
75	7,328	94.0	14.77	302.5	6,650	14.1	261	1,660
70	6,840	94.0	15.82	296.2	6,570	13.1	258	1,510
65	6,351	94.0	17.04	289.5	6,489	12.1	256	1,390
60	5,863	94.0	18.46	289.2	6,544	11.4	256	1,320
55	5,374	94.0	20.14	289.4	6,618	10.7	258	1,280
50	4,886	94.0	22.15	289.7	6,710	10.0	261	1,250
45	4,397	94.0	24.61	289.1	6,805	9.1	266	1,220
40	3,908	94.0	27.69	288.1	6,915	8.2	273	1,200
35	3,420	94.0	31.64	285.9	7,041	8.6	240	840
30	2,931	94.0	36.92	281.6	7,181	7.6	243	790
25	2,443	94.0	44.29	273.6	7,336	6.7	243	710

Specified ambient conditions (ambient air: 10 °C, scavenge air coolant: 10 °C)

Load % SMCR	Power kW	Speed r/min	SPOC g/kWh	SGC g/kWh	Heat rate kJ/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	11.07	321.8	6,877	19.6	241	1,700
95	9,282	94.0	11.66	314.5	6,756	18.9	228	1,350
90	8,794	94.0	12.30	308.1	6,656	18.2	217	1,060
85	8,305	94.0	13.03	302.3	6,571	17.5	207	820
80	7,817	94.0	13.84	298.4	6,530	16.8	199	630
75	7,328	94.0	14.77	295.0	6,501	16.1	192	470
70	6,840	94.0	15.82	288.8	6,423	15.0	190	390
65	6,351	94.0	17.04	282.3	6,344	13.8	188	330
60	5,863	94.0	18.46	281.9	6,398	13.0	189	320
55	5,374	94.0	20.14	281.9	6,470	12.2	191	330
50	4,886	94.0	22.15	282.1	6,560	11.4	194	360
45	4,397	94.0	24.61	281.5	6,653	10.4	199	410
40	3,908	94.0	27.69	280.3	6,760	9.4	205	460
35	3,420	94.0	31.64	278.0	6,883	8.3	214	520
30	2,931	94.0	36.92	273.6	7,021	8.8	180	0
25	2,443	94.0	44.29	265.4	7,172	7.7	182	0

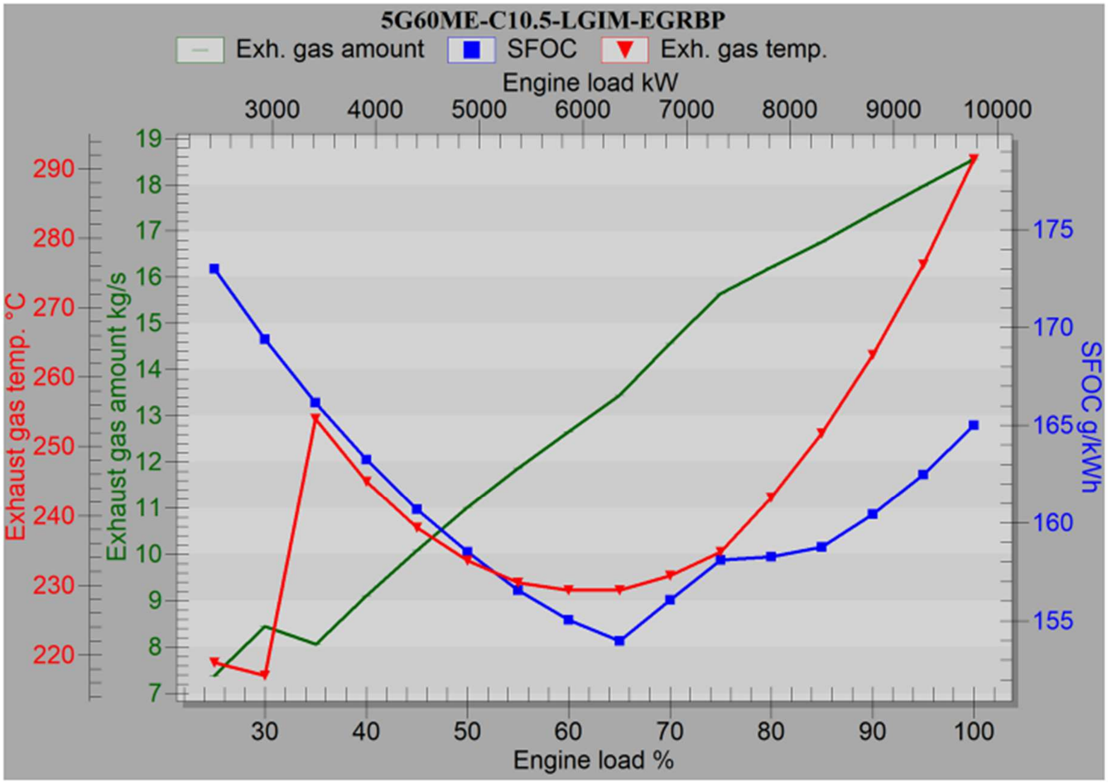
Comments / details

SPOC: Specific Pilot Oil Consumption (LCV: 42,700 kJ/kg)
SGC: Specific Gas Consumption (LCV: 19,900 kJ/kg)
Loads below 50% are associated with larger tolerances.

*) Mixed exhaust gas temperature after turbocharger.
**) Guiding steam production capacity at 7.0 bar(a) with variable pinch point temperature, matched to 15°C at 85% load in Tier II and ISO. Contact boiler maker for actual steam production.

Heat rate is the guaranteed value. Calculating the heat rate from SPOC and SGC can, in some cases, be inaccurate, due to rounding.

Fuel Consumption and Exhaust Gas Data
Fuel Oil, Tier II mode



ISO ambient conditions (ambient air: 25 °C, scavenge air coolant: 25 °C)

Load % SMCR	Power kW	Speed r/min	SFOC g/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	165.0	18.5	291	2,680
95	9,282	94.0	162.5	18.0	276	2,330
90	8,794	94.0	160.4	17.4	263	2,000
85	8,305	94.0	158.8	16.8	252	1,720
80	7,817	94.0	158.3	16.2	243	1,490
75	7,328	94.0	158.1	15.6	235	1,290
70	6,840	94.0	156.0	14.6	231	1,160
65	6,351	94.0	154.0	13.4	229	1,050
60	5,863	94.0	155.0	12.7	229	1,000
55	5,374	94.0	156.6	11.9	230	970
50	4,886	94.0	158.5	11.0	234	950
45	4,397	94.0	160.7	10.1	238	950
40	3,908	94.0	163.2	9.1	245	960
35	3,420	94.0	166.2	8.1	254	960
30	2,931	94.0	169.4	8.4	217	560
25	2,443	94.0	173.0	7.4	219	510

Fuel Consumption and Exhaust Gas Data
Fuel Oil, Tier II mode

Tropical ambient conditions (ambient air: 45 °C, scavenge air coolant: 36 °C)

Load % SMCR	Power kW	Speed r/min	SFOC g/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	166.7	16.7	344	3,430
95	9,282	94.0	164.2	16.2	328	3,090
90	8,794	94.0	162.1	15.7	314	2,780
85	8,305	94.0	160.4	15.1	301	2,500
80	7,817	94.0	159.9	14.6	291	2,260
75	7,328	94.0	159.8	14.1	283	2,050
70	6,840	94.0	157.7	13.1	279	1,870
65	6,351	94.0	155.6	12.1	276	1,710
60	5,863	94.0	156.7	11.4	276	1,620
55	5,374	94.0	158.2	10.6	277	1,550
50	4,886	94.0	160.2	9.9	279	1,490
45	4,397	94.0	162.4	9.1	284	1,440
40	3,908	94.0	165.0	8.2	290	1,390
35	3,420	94.0	167.9	8.5	254	1,010
30	2,931	94.0	171.2	7.6	256	930
25	2,443	94.0	174.8	6.7	255	830

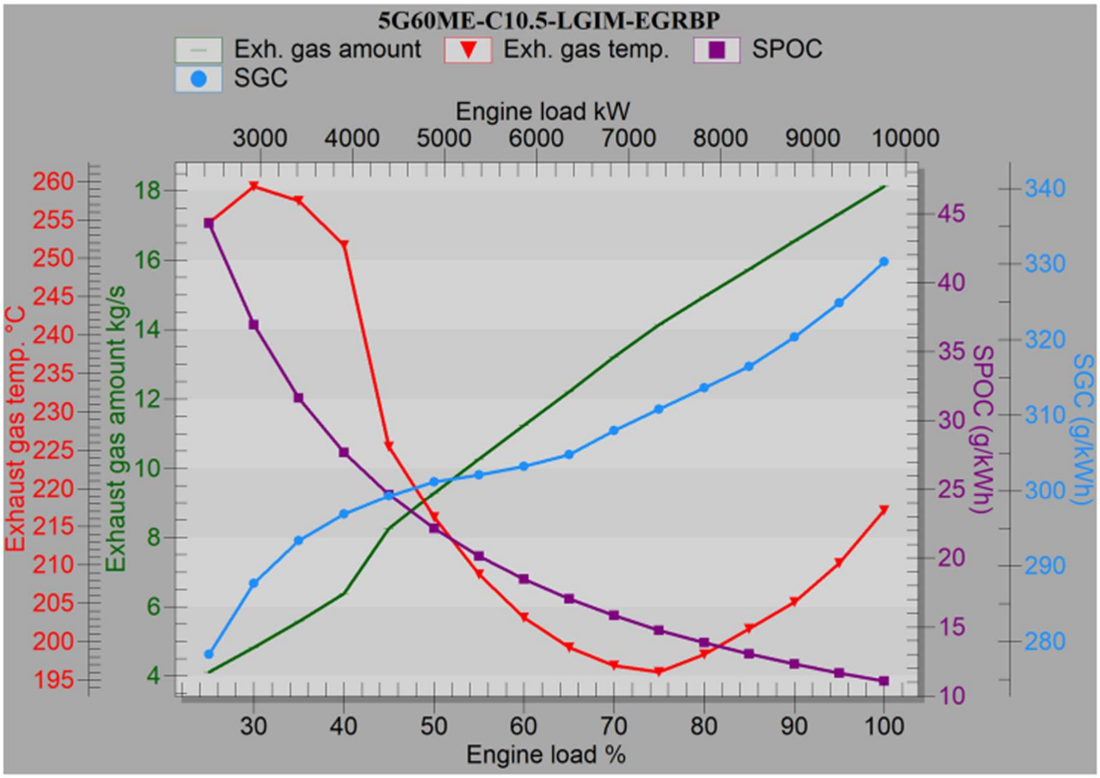
Specified ambient conditions (ambient air: 10 °C, scavenge air coolant: 10 °C)

Load % SMCR	Power kW	Speed r/min	SFOC g/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	163.0	19.1	263	2,140
95	9,282	94.0	160.5	18.5	248	1,780
90	8,794	94.0	158.5	17.9	236	1,460
85	8,305	94.0	156.9	17.2	225	1,200
80	7,817	94.0	156.4	16.7	216	980
75	7,328	94.0	156.2	16.1	209	810
70	6,840	94.0	154.2	15.0	206	700
65	6,351	94.0	152.1	13.8	204	620
60	5,863	94.0	153.2	13.0	204	590
55	5,374	94.0	154.7	12.2	205	580
50	4,886	94.0	156.6	11.3	207	580
45	4,397	94.0	158.8	10.4	212	600
40	3,908	94.0	161.3	9.4	219	640
35	3,420	94.0	164.2	8.3	227	670
30	2,931	94.0	167.4	8.8	190	210
25	2,443	94.0	170.9	7.7	191	190

Comments / details:
SFOC: Specific Fuel Oil Consumption (LCV: 42,700 kJ/kg)
Loads below 50% are associated with larger tolerances.

*) Mixed exhaust gas temperature after turbocharger.
**) Guiding steam production capacity at 7.0 bar(a) with variable pinch point temperature, matched to 15°C at 85% load in Tier II and ISO. Contact boiler maker for actual steam production.

Fuel Consumption and Exhaust Gas Data
Low Flashpoint Fuel, Tier III mode



ISO ambient conditions (ambient air: 25 °C, scavenge air coolant: 25 °C)

Load % SMCR	Power kW	Speed r/min	SPOC g/kWh	SGC g/kWh	Heat rate kJ/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	11.07	330.3	7,045	18.1	217	1,070
95	9,282	94.0	11.66	324.9	6,963	17.3	210	890
90	8,794	94.0	12.30	320.4	6,901	16.5	205	750
85	8,305	94.0	13.03	316.5	6,854	15.7	202	650
80	7,817	94.0	13.84	313.7	6,833	14.9	198	560
75	7,328	94.0	14.77	310.8	6,815	14.1	196	490
70	6,840	94.0	15.82	308.0	6,804	13.2	197	480
65	6,351	94.0	17.04	304.8	6,793	12.2	199	480
60	5,863	94.0	18.46	303.2	6,823	11.2	203	510
55	5,374	94.0	20.14	302.1	6,872	10.3	209	550
50	4,886	94.0	22.15	301.2	6,939	9.3	216	600
45	4,397	94.0	24.61	299.3	7,007	8.3	225	650
40	3,908	94.0	27.69	296.9	7,090	6.4	252	760
35	3,420	94.0	31.64	293.4	7,189	5.6	258	720
30	2,931	94.0	36.92	287.7	7,302	4.8	259	630
25	2,443	94.0	44.29	278.3	7,430	4.1	255	500

Fuel Consumption and Exhaust Gas Data
Low Flashpoint Fuel, Tier III mode

Tropical ambient conditions (ambient air: 45 °C, scavenge air coolant: 36 °C)

Load % SMCR	Power kW	Speed r/min	SPOC g/kWh	SGC g/kWh	Heat rate kJ/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	11.07	334.0	7,120	17.0	261	1,920
95	9,282	94.0	11.66	328.6	7,036	16.3	253	1,700
90	8,794	94.0	12.30	324.0	6,974	15.5	247	1,520
85	8,305	94.0	13.03	320.1	6,927	14.8	243	1,390
80	7,817	94.0	13.84	317.3	6,905	14.1	238	1,250
75	7,328	94.0	14.77	314.4	6,887	13.3	235	1,140
70	6,840	94.0	15.82	311.6	6,876	12.5	236	1,090
65	6,351	94.0	17.04	308.4	6,865	11.6	237	1,050
60	5,863	94.0	18.46	306.9	6,895	10.7	241	1,040
55	5,374	94.0	20.14	305.8	6,945	9.8	246	1,030
50	4,886	94.0	22.15	304.8	7,012	9.0	252	1,030
45	4,397	94.0	24.61	303.0	7,081	8.0	261	1,030
40	3,908	94.0	27.69	300.6	7,165	6.5	274	990
35	3,420	94.0	31.64	297.2	7,265	5.7	279	920
30	2,931	94.0	36.92	291.6	7,380	5.0	280	810
25	2,443	94.0	44.29	282.3	7,508	4.3	275	670

Specified ambient conditions (ambient air: 10 °C, scavenge air coolant: 10 °C)

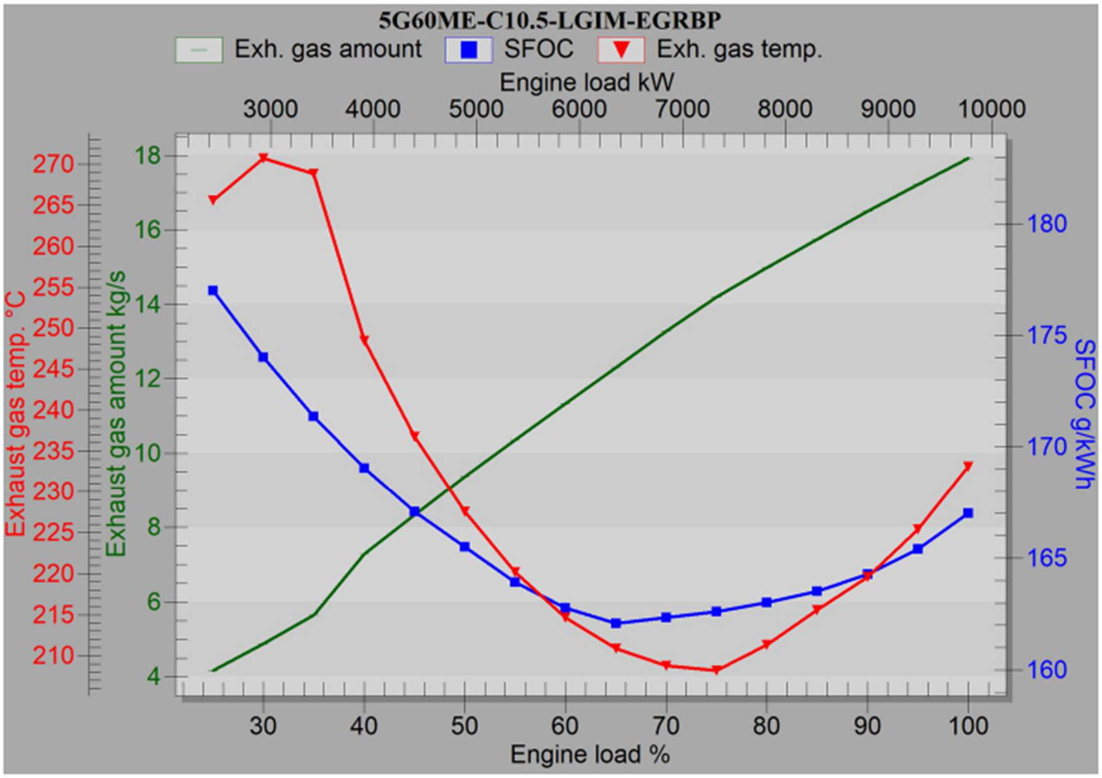
Load % SMCR	Power kW	Speed r/min	SPOC g/kWh	SGC g/kWh	Heat rate kJ/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	11.07	326.0	6,961	18.3	194	560
95	9,282	94.0	11.66	320.7	6,879	17.5	187	390
90	8,794	94.0	12.30	316.2	6,818	16.7	182	260
85	8,305	94.0	13.03	312.3	6,772	15.9	179	160
80	7,817	94.0	13.84	309.5	6,751	15.1	176	0
75	7,328	94.0	14.77	306.7	6,733	14.2	174	0
70	6,840	94.0	15.82	303.9	6,723	13.3	175	0
65	6,351	94.0	17.04	300.7	6,711	12.3	177	0
60	5,863	94.0	18.46	299.1	6,741	11.3	181	110
55	5,374	94.0	20.14	298.0	6,789	10.3	187	210
50	4,886	94.0	22.15	297.0	6,856	9.3	194	300
45	4,397	94.0	24.61	295.1	6,923	8.3	204	380
40	3,908	94.0	27.69	292.6	7,005	6.3	231	550
35	3,420	94.0	31.64	289.0	7,103	5.5	236	520
30	2,931	94.0	36.92	283.3	7,215	4.8	236	450
25	2,443	94.0	44.29	273.8	7,341	4.1	230	320

Comments / details
SPOC: Specific Pilot Oil Consumption (LCV: 42,700 kJ/kg)
SGC: Specific Gas Consumption (LCV: 19,900 kJ/kg)
Loads below 50% are associated with larger tolerances.

*) Mixed exhaust gas temperature after turbocharger.
**) Guiding steam production capacity at 7.0 bar(a) with variable pinch point temperature, matched to 15°C at 85% load in Tier II and ISO. Contact boiler maker for actual steam production.

Heat rate is the guaranteed value. Calculating the heat rate from SPOC and SGC can, in some cases, be inaccurate, due to rounding.

Fuel Consumption and Exhaust Gas Data
Fuel Oil, Tier III mode



ISO ambient conditions (ambient air: 25 °C, scavenge air coolant: 25 °C)

Load % SMCR	Power kW	Speed r/min	SFOC g/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	167.0	17.9	233	1,400
95	9,282	94.0	165.4	17.2	225	1,200
90	8,794	94.0	164.3	16.5	220	1,040
85	8,305	94.0	163.5	15.7	216	930
80	7,817	94.0	163.0	15.0	211	810
75	7,328	94.0	162.6	14.2	208	720
70	6,840	94.0	162.3	13.3	209	690
65	6,351	94.0	162.1	12.3	211	680
60	5,863	94.0	162.8	11.3	215	690
55	5,374	94.0	163.9	10.4	220	720
50	4,886	94.0	165.5	9.4	228	760
45	4,397	94.0	167.1	8.3	237	790
40	3,908	94.0	169.0	7.3	248	820
35	3,420	94.0	171.4	5.7	269	820
30	2,931	94.0	174.0	4.9	271	730
25	2,443	94.0	177.0	4.2	266	580

Fuel Consumption and Exhaust Gas Data
Fuel Oil, Tier III mode

Tropical ambient conditions (ambient air: 45 °C, scavenge air coolant: 36 °C)

Load % SMCR	Power kW	Speed r/min	SFOC g/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	168.8	16.7	281	2,290
95	9,282	94.0	167.1	16.1	272	2,060
90	8,794	94.0	166.0	15.4	265	1,870
85	8,305	94.0	165.2	14.8	260	1,710
80	7,817	94.0	164.7	14.1	255	1,550
75	7,328	94.0	164.3	13.3	251	1,410
70	6,840	94.0	164.1	12.5	251	1,340
65	6,351	94.0	163.8	11.6	252	1,280
60	5,863	94.0	164.5	10.8	255	1,250
55	5,374	94.0	165.7	9.9	260	1,230
50	4,886	94.0	167.3	9.0	267	1,220
45	4,397	94.0	168.9	8.0	275	1,200
40	3,908	94.0	170.8	7.1	286	1,180
35	3,420	94.0	173.2	5.8	293	1,040
30	2,931	94.0	175.9	5.0	294	930
25	2,443	94.0	178.9	4.3	288	760

Specified ambient conditions (ambient air: 10 °C, scavenge air coolant: 10 °C)

Load % SMCR	Power kW	Speed r/min	SFOC g/kWh	Exh. gas kg/s	Exh. gas*) °C	Steam**) kg/h
100	9,771	94.0	165.0	18.1	208	870
95	9,282	94.0	163.4	17.4	201	690
90	8,794	94.0	162.3	16.7	196	560
85	8,305	94.0	161.6	15.9	192	460
80	7,817	94.0	161.1	15.1	188	350
75	7,328	94.0	160.7	14.3	185	270
70	6,840	94.0	160.4	13.4	186	270
65	6,351	94.0	160.1	12.4	188	290
60	5,863	94.0	160.8	11.4	192	330
55	5,374	94.0	162.0	10.4	197	390
50	4,886	94.0	163.5	9.4	205	450
45	4,397	94.0	165.1	8.4	214	510
40	3,908	94.0	167.0	6.4	241	660
35	3,420	94.0	169.3	5.6	246	620
30	2,931	94.0	171.9	4.9	247	540
25	2,443	94.0	174.9	4.1	240	400

Comments / details

SFOC: Specific Fuel Oil Consumption (LCV: 42,700 kJ/kg)
Loads below 50% are associated with larger tolerances.

*) Mixed exhaust gas temperature after turbocharger.
**) Guiding steam production capacity at 7.0 bar(a) with variable pinch point temperature, matched to 15°C at 85% load in Tier II and ISO. Contact boiler maker for actual steam production.

Tables of Capacities - Tier II, Low Flashpoint Fuel

1	Engine load (% SMCR)	4	Scavenge air receiver temp. (°C)	7	Jacket water heat diss. (kW) +10/-15%
2	T/C air consumption (kg/s) +/-5%	5	Scavenge air heat diss. (kW)	8	Lubricating oil heat diss. (kW) +/-10%
3	Scavenge air pressure (bara)	6	EGR heat dissipation (kW)	9	Condensed water (non-EGR) (t/24h)

Loads below 50% are associated with larger tolerances.

ISO ambient conditions (ambient air: 25.0 °C, scavenge air coolant: 25.0 °C)

1	2	3	4	5	6	7	8	9
100	18.1	3.51	37	2,700	0	1,240	800	0.0
95	17.5	3.37	36	2,490	0	1,190	760	0.0
90	16.9	3.23	35	2,300	0	1,140	720	0.0
85	16.2	3.09	34	2,110	0	1,090	690	0.0
80	15.6	2.97	34	1,950	0	1,040	650	0.0
75	15.0	2.84	33	1,790	0	990	620	0.0
70	14.0	2.64	32	1,540	0	940	580	0.0
65	12.9	2.44	30	1,300	0	890	550	0.0
60	12.2	2.31	30	1,150	0	830	520	0.0
55	11.4	2.19	29	1,010	0	780	490	0.0
50	10.7	2.06	29	870	0	730	460	0.0
45	9.8	1.92	28	720	0	680	440	0.0
40	8.8	1.78	27	580	0	630	410	0.0
35	7.8	1.64	27	440	0	580	380	0.0
30	8.2	1.67	35	430	0	530	360	0.0
25	7.2	1.52	35	310	0	480	330	0.0

Tropical ambient conditions (ambient air: 45.0 °C, scavenge air coolant: 36.0 °C)

1	2	3	4	5	6	7	8	9
100	16.6	3.28	46	2,620	0	1,260	810	27.8
95	16.1	3.15	45	2,420	0	1,200	770	26.7
90	15.5	3.02	44	2,230	0	1,150	730	25.5
85	14.9	2.88	44	2,050	0	1,100	690	24.2
80	14.3	2.77	43	1,890	0	1,050	660	23.1
75	13.7	2.65	42	1,730	0	1,000	620	21.8
70	12.8	2.47	41	1,500	0	950	590	19.8
65	11.8	2.28	40	1,260	0	890	560	17.5
60	11.1	2.17	40	1,120	0	840	530	16.0
55	10.4	2.06	39	980	0	790	500	14.5
50	9.7	1.94	39	850	0	740	470	12.9
45	8.9	1.82	38	710	0	690	440	11.1
40	8.0	1.69	38	570	0	640	410	9.2
35	8.4	1.72	46	570	0	580	390	9.7
30	7.5	1.58	46	440	0	530	360	7.7
25	6.6	1.46	45	320	0	480	340	5.8

Specified ambient conditions (ambient air: 10.0 °C, scavenge air coolant: 10.0 °C)

1	2	3	4	5	6	7	8	9
100	18.7	3.53	23	2,640	0	1,230	790	1.2
95	18.1	3.39	22	2,440	0	1,180	750	1.1
90	17.4	3.25	21	2,250	0	1,130	720	1.1
85	16.7	3.10	20	2,070	0	1,080	680	1.0
80	16.1	2.98	19	1,910	0	1,030	640	0.9
75	15.4	2.85	18	1,750	0	980	610	0.9
70	14.4	2.65	17	1,510	0	920	580	0.7
65	13.3	2.44	16	1,270	0	870	540	0.5
60	12.5	2.31	15	1,120	0	820	510	0.4
55	11.8	2.19	14	980	0	770	490	0.3
50	11.0	2.06	14	850	0	720	460	0.2
45	10.0	1.93	13	700	0	670	430	0.1
40	9.1	1.79	12	560	0	620	400	0.0
35	8.0	1.64	12	430	0	570	380	0.0
30	8.5	1.68	20	430	0	520	350	0.0
25	7.5	1.53	20	310	0	470	330	0.0

Tables of Capacities - Tier III, Low Flashpoint Fuel

1	Engine load (% SMCR)	4	Scavenge air receiver temp. (°C)	7	Jacket water heat diss. (kW) +10/-15%
2	T/C air consumption (kg/s) +/-5%	5	Scavenge air heat diss. (kW)	8	Lubricating oil heat diss. (kW) +/-10%
3	Scavenge air pressure (bara)	6	EGR heat dissipation (kW)	9	Condensed water (non-EGR) (t/24h)

Loads below 50% are associated with larger tolerances.

ISO ambient conditions (ambient air: 25.0 °C, scavenge air coolant: 25.0 °C)

1	2	3	4	5	6	7	8	9
100	17.5	3.51	34	2,000	2,910	1,260	810	0.0
95	16.7	3.33	34	1,820	2,790	1,210	770	0.0
90	16.0	3.15	34	1,650	2,670	1,150	730	0.0
85	15.2	2.98	34	1,490	2,550	1,100	690	0.0
80	14.5	2.80	33	1,250	2,560	1,050	660	0.0
75	13.7	2.63	33	1,030	2,520	1,000	620	0.0
70	12.8	2.46	33	910	2,340	950	590	0.0
65	11.9	2.29	33	790	2,140	900	560	0.0
60	10.9	2.13	33	670	1,960	840	530	0.0
55	10.0	1.98	32	570	1,780	790	500	0.0
50	9.0	1.83	32	470	1,610	740	470	0.0
45	8.0	1.68	31	350	1,450	690	440	0.0
40	6.2	1.49	41	250	1,490	640	410	0.0
35	5.4	1.38	40	170	1,330	590	390	0.0
30	4.7	1.29	39	110	1,160	530	360	0.0
25	4.0	1.22	39	70	1,000	480	340	0.0

Tropical ambient conditions (ambient air: 45.0 °C, scavenge air coolant: 36.0 °C)

1	2	3	4	5	6	7	8	9
100	16.6	3.39	43	2,100	2,560	1,270	820	32.9
95	15.9	3.22	43	1,920	2,450	1,220	780	31.4
90	15.2	3.06	43	1,750	2,340	1,170	740	29.9
85	14.5	2.89	43	1,580	2,230	1,110	700	28.2
80	13.8	2.72	42	1,340	2,280	1,060	670	25.8
75	13.1	2.56	42	1,120	2,270	1,010	630	23.3
70	12.2	2.40	42	1,000	2,090	960	600	21.3
65	11.4	2.24	42	870	1,910	910	560	19.2
60	10.5	2.10	42	760	1,730	850	530	17.1
55	9.6	1.96	41	650	1,570	800	500	15.0
50	8.8	1.82	41	550	1,400	750	470	12.9
45	7.8	1.67	41	420	1,260	700	450	10.3
40	6.4	1.51	48	340	1,330	640	420	9.4
35	5.6	1.40	48	250	1,180	590	390	7.1
30	4.9	1.31	48	180	1,040	540	370	5.2
25	4.2	1.23	47	120	900	490	340	3.6

Specified ambient conditions (ambient air: 10.0 °C, scavenge air coolant: 10.0 °C)

1	2	3	4	5	6	7	8	9
100	17.7	3.47	19	1,900	3,050	1,240	800	2.6
95	17.0	3.29	19	1,720	2,920	1,190	760	2.4
90	16.2	3.11	19	1,560	2,800	1,140	720	2.2
85	15.4	2.94	19	1,400	2,670	1,090	690	2.0
80	14.6	2.76	19	1,170	2,670	1,040	650	1.8
75	13.9	2.59	19	970	2,620	990	620	1.5
70	12.9	2.42	18	850	2,430	940	580	1.3
65	12.0	2.26	18	730	2,240	890	550	0.9
60	11.0	2.10	18	630	2,050	830	520	0.6
55	10.0	1.95	18	530	1,870	780	490	0.4
50	9.1	1.81	17	430	1,690	730	460	0.1
45	8.0	1.66	16	320	1,520	680	440	0.0
40	6.1	1.47	26	230	1,600	630	410	0.0
35	5.4	1.37	26	160	1,420	580	380	0.0
30	4.6	1.28	25	100	1,250	530	360	0.0
25	4.0	1.21	24	60	1,080	480	330	0.0

Tables of EGR consumption - Tier III Fuel Oil

1	Engine load (% SMCR)	3	Freshwater consumption (l/h)	5	Sludge accumulation (l/h)
2	Power, EGR blower (kWe)	4	Processwater bleed off (l/h)	6	NaOH consumption (l/h)

EGR blower power consumption has a tolerance of 20%.
Based on 0.1% fuel sulphur content. Sludge accumulation based on 7% dry matter. Fresh water consumption accounts for water added to the EGR process. WTS water consumption is not included (to be informed by maker).
NaOH consumption is based on a 50% NaOH solution. Minimum tolerance is +0.5 l/MWh.

1	2	3	4	5	6
ISO ambient conditions (ambient air: 25.0 °C, scavenge air coolant: 25.0 °C)					
100	44	0	560	1.7	2.9
95	49	0	540	1.7	2.8
90	53	0	520	1.6	2.8
85	57	0	500	1.6	2.7
80	58	0	500	1.6	2.7
75	58	0	500	1.6	2.7
70	59	0	460	1.5	2.5
65	59	0	420	1.3	2.4
60	58	0	380	1.2	2.2
55	55	0	350	1.1	2.0
50	52	0	310	1.0	1.8
45	45	0	280	0.8	1.7
40	37	0	250	0.7	1.5
35	65	0	220	0.7	1.5
30	50	0	190	0.6	1.4
25	38	0	170	0.5	1.2
Tropical ambient conditions (ambient air: 45.0 °C, scavenge air coolant: 36.0 °C)					
100	30	0	520	1.4	2.5
95	32	0	500	1.4	2.4
90	35	0	490	1.4	2.4
85	37	0	470	1.3	2.3
80	39	0	480	1.4	2.4
75	39	0	480	1.4	2.4
70	40	0	440	1.3	2.2
65	39	0	410	1.2	2.0
60	38	0	380	1.0	1.9
55	36	0	350	0.9	1.7
50	33	0	310	0.8	1.5
45	29	0	290	0.7	1.4
40	24	0	260	0.6	1.2
35	38	0	260	0.6	1.3
30	29	0	240	0.5	1.2
25	22	0	210	0.4	1.0
Specified ambient conditions (ambient air: 10.0 °C, scavenge air coolant: 10.0 °C)					
100	49	0	610	1.8	3.0
95	53	0	590	1.8	3.0
90	58	0	570	1.7	2.9
85	62	0	560	1.6	2.8
80	63	0	560	1.7	2.8
75	61	0	560	1.6	2.8
70	63	0	520	1.5	2.6
65	62	0	490	1.4	2.5
60	61	0	450	1.3	2.3
55	58	0	420	1.1	2.1
50	54	0	380	1.0	1.9
45	46	0	350	0.9	1.7
40	87	0	340	0.9	1.8
35	69	0	310	0.7	1.6
30	53	0	280	0.6	1.4
25	41	0	240	0.5	1.2

Tables of EGR consumption - Tier III Low Flashpoint Fuel

1	Engine load (% SMCR)	3	Freshwater consumption (l/h)	5	Sludge accumulation (l/h)
2	Power, EGR blower (kWe)	4	Processwater bleed off (l/h)	6	NaOH consumption (l/h)

EGR blower power consumption has a tolerance of 20%.
Based on 0.1% fuel sulphur content. Sludge accumulation based on 7% dry matter. Fresh water consumption accounts for water added to the EGR process. WTS water consumption is not included (to be informed by maker).
NaOH consumption is based on a 50% NaOH solution. Minimum tolerance is +0.5 l/MWh.

ISO ambient conditions (ambient air: 25.0 °C, scavenge air coolant: 25.0 °C)

1	2	3	4	5	6
100	49	0	1,130	1.8	1.6
95	53	0	1,080	1.7	1.6
90	57	0	1,040	1.7	1.6
85	61	0	990	1.6	1.5
80	63	0	990	1.6	1.6
75	62	0	980	1.6	1.6
70	63	0	910	1.5	1.5
65	62	0	830	1.4	1.4
60	61	0	760	1.3	1.3
55	58	0	680	1.1	1.2
50	54	0	610	1.0	1.1
45	46	0	540	0.9	1.0
40	85	0	510	0.9	1.0
35	67	0	450	0.7	0.9
30	51	0	380	0.6	0.8
25	39	0	320	0.5	0.8

Tropical ambient conditions (ambient air: 45.0 °C, scavenge air coolant: 36.0 °C)

1	2	3	4	5	6
100	33	0	1,010	1.5	1.4
95	35	0	970	1.5	1.4
90	37	0	930	1.4	1.3
85	40	0	890	1.4	1.3
80	42	0	910	1.4	1.4
75	42	0	910	1.4	1.4
70	42	0	840	1.3	1.3
65	41	0	770	1.2	1.2
60	40	0	700	1.1	1.1
55	38	0	640	1.0	1.0
50	35	0	570	0.8	0.9
45	30	0	510	0.7	0.8
40	49	0	520	0.7	0.9
35	39	0	460	0.6	0.8
30	30	0	400	0.5	0.7
25	23	0	350	0.4	0.6

Specified ambient conditions (ambient air: 10.0 °C, scavenge air coolant: 10.0 °C)

1	2	3	4	5	6
100	54	0	1,200	1.9	1.7
95	58	0	1,160	1.8	1.7
90	63	0	1,120	1.8	1.7
85	67	0	1,070	1.7	1.6
80	68	0	1,070	1.7	1.7
75	66	0	1,060	1.7	1.6
70	67	0	990	1.6	1.6
65	66	0	910	1.4	1.4
60	64	0	830	1.3	1.3
55	61	0	760	1.2	1.2
50	56	0	690	1.0	1.1
45	48	0	620	0.9	1.0
40	90	0	620	0.9	1.1
35	70	0	540	0.8	1.0
30	54	0	470	0.6	0.9
25	42	0	400	0.5	0.8

Typical Noise and Vibration Levels

SMCR

Octave band centre freq. in Hz	31.5	63	125	250	500	1k	2k	4k	8k	Avg.	Avg.	Max.
	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB(lin)	dB(A)	dB(A)
A) Exhaust gas noise	121.4	116.0	108.2	103.5	101.9	97.7	86.8	76.9	68.4	122.8	103.0	-
B) Spatial noise, standard NR	97.5	96.5	97.3	96.8	97.0	98.3	98.8	93.8	85.7	106.3	103.7	108.9
C) Spatial noise, additional NR	97.5	95.6	94.9	95.1	95.1	96.4	96.7	89.1	82.0	104.6	101.4	105.7
D) Structure borne vibrations	75.6	73.6	70.7	68.9	66.6	61.0	54.7	46.5	40.0	-	-	-

NCR (90.00% of SMCR)

Octave band centre freq. in Hz	31.5	63	125	250	500	1k	2k	4k	8k	Avg.	Avg.	Max.
	dB	dB	dB	dB	dB	dB	dB	dB	dB	dB(lin)	dB(A)	dB(A)
A) Exhaust gas noise	120.5	115.1	107.3	102.6	101.0	96.8	85.9	76.0	67.5	121.9	102.1	-
B) Spatial noise, standard NR	97.1	96.0	96.9	96.3	96.4	97.4	97.5	92.2	84.9	105.5	102.6	107.3
C) Spatial noise, additional NR	97.0	95.2	94.5	94.6	94.5	95.5	95.4	87.6	81.2	103.9	100.3	104.1
D) Structure borne vibrations	75.2	73.1	70.3	68.4	66.2	60.5	54.3	46.1	39.5	-	-	-

A) Sound pressure levels from exhaust gas system ($2x10^{-5}$ Pa).
The expected sound pressure level at 1 metre from the edge of the exhaust gas pipe opening at an angle of 30 degrees to the direction of the gas flow and valid for a normal exhaust gas system - but without a boiler and silencer.

B) Airborne sound pressure levels - with standard noise reduction (NR) countermeasures ($2x10^{-5}$ Pa).
Expected mean sound pressure octave spectrum levels, i.e. the average spatial noise values at a distance of 1 metre from the engine. Prescribed measuring surface area is 376.0 m^2.

C) Air-borne sound pressure levels - with additional noise reduction (NR) countermeasures ($2x10^{-5}$ Pa).
Expected mean sound pressure octave spectrum levels, i.e. the average spatial noise values at a distance of 1 metre from the engine. Prescribed measuring surface area is 376.0 m^2.

Additional noise reduction countermeasures, e.g.:
Extra good turbocharger air intake silencer(s)
External sound insulation of scavenge air receiver
External sound insulation of scavenge air cooler(s).

Supplementary reduction of 0.0 dB is needed.

Other additional noise reduction countermeasures are also available. The noise figures given are in accordance with the CIMAC recommendations for measurements of the overall noise for reciprocating engines. The average levels will, depending on the actual engine room configuration, be 1-5 dB higher when the engine is installed in the engine room.

D) Structure borne vibration levels ($5x10^{-8}$ Pa).
Expected mean velocity octave spectrum levels at the engine base plate as installed on board the ship. Based on an average engine foundation of a ship, and may only be used as a rough estimate as the velocity levels will depend on the actual foundation used. If the vibration velocity levels are referred to 10^{-9} m/s instead of $5x10^{-8}$ m/s, the calculated dB figures will be 34.0 dB higher than above stated.

Reference Data

Ambient condition	Scavenge air coolant temp.*) °C	Ambient air temp. °C	Rel. air humidity %	Barometric pressure mbar
ISO**)	25	25	30	1,000
Tropical	36	45	60	1,000
Specified	10	10	60	1,000

*) With a central cooling system, the sea water will be 4 ºC lower than these temperatures.
**) Refers to ISO 3046-1 2002(E) and ISO 15550:2016(E).

Tolerances	
Specific Fuel Oil Consumption (SFOC) tolerance at SMCR	+/- 5%
Specific Gas Consumption (SGC) tolerance at SMCR	+/- 5%
Specific Pilot Oil Consumption (SPOC) tolerance at SMCR	+/- 25%
Exhaust gas amount tolerance	+/- 5%
Exhaust gas temperature tolerance	+/- 15°C

Guarantee point	
Guarantee point (same as NCR)	90.00% of SMCR
Guarantee point SFOC tolerance	5%

Guarantee figures for low flashpoint fuel engines are given for heat rate, which has the same tolerance as SFOC guarantees.
Heat rate is calculated as follows:

Heat rate [kJ/kWh] = SGC [g/kWh] x LCV_{SGC} [kJ/g] + SPOC [g/kWh] x LCV_{SPOC} [kJ/g]

Values for EEDI	
Engine type	5G60ME-C10.5-LGIM-EGRBP
SMCR power	9,771 kW
SMCR RPM	94.0 r/min
Ambient condition	ISO
Reference LCV of pilot oil	42,700 kJ/kg
Reference LCV of fuel gas	19,900 kJ/kg
Low Flashpoint Fuel mode	
SGC at SMCR	326.0 g/kWh
SGC at 75% SMCR	299.0 g/kWh
SGC at 75% SMCR incl. 1.34% tolerance*)	**303.0 g/kWh**
SPOC at SMCR	11.07 g/kWh
SPOC at 75% SMCR	14.77 g/kWh
SPOC at 75% SMCR incl. 50% tolerance*)	**22.15 g/kWh**
Heat rate at 75% SMCR incl. 6% tolerance	**6974 kJ/kWh**

*) The SGC and SPOC with tolerance have been calculated so they correspond to adding a 6% tolerance to the heat rate.

CEAS ID for Design Specification Order (DSO)
e6e3a0a7-4104-4447-8977-e75ac52ec56f

This ID must be used by an MAN-ES licensee when creating a DSO.

Appendix H – calculation of the CO_2 correction factor for B45 blend

■ Example Calculation 1:

For an unblended biofuel certified by the above PoS sample:

・Lower Calorific Value (LCV) [MJ/g] = 809,930 [MJ] / 21.890 × 10^6 [g] = 0.037 [MJ/g]

・GHG Intensity [gCO2eq/MJ] = 14.9 [gCO2eq/MJ] (< 33 [gCO2eq/MJ])

・Cf [gCO2eq/g] = 14.9 × 0.037 = 0.551 [gCO2eq/g]

■ Example Calculation 2:

For 75MT of blended biofuel (a blend of 21.890MT of the biofuel from Example 1 and 53.110MT of VLSFO):

・Energy of biofuel [MJ] = 0.037 [MJ/gFuel] × 21.890 × 10^6 [g] = 809,930 [MJ]

・Energy of VLSFO [MJ] = 0.041 [MJ/gFuel] × 53.110 × 10^6 [g] = 2,177,510 [MJ]

(In the case that LCV and Cf of LFO are used for VLSFO.)

・Ratio of energy between biofuel and VLSFO = 809,930 / (809,930 + 2,177,510) : 2,177,510 / (809,930 + 2,177,510) = 0.271 : 0.729

・Blend Cf [gCO2eq/g] = 0.271 × 0.551 + 0.729 × 3.151 = 2.446 [gCO2eq/g]

	Lower Calorific Value [MJ/g]	Fuel Weight [g]	Energy Amount [MJ]	Ratio of Energy	Cf [gCO2eq/g]	Blend Cf (Weighted Average based on Energy) [gCO2eq/g]
FAME	0.037	21.890×10^6	809,930	0.271	0.551	0.149
VLSFO	0.041	53.110×10^6	2,177,510	0.729	3.151	2.297
Total		75.000×10^6	2,987,440	1.000		**2.446**