RESEARCH REPORT

METHANOL FEASIBILITY STUDY

GMM 2.0 WP-3 Veerhaven Pusher

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TABLE OF CONTENTS

1 Introduction ... 7
2 Base case ... 8
  2.1 Reference Vessel ... 8
  2.2 Conventional design ... 8
  2.3 Operational Profile ... 9
  2.4 Power Generation ... 10
  2.5 System Efficiency ... 10
  2.6 Energy Storage ... 11
    2.6.1 Fuel Storage Capacity ... 11
    2.6.2 Autonomy ... 11
    2.6.3 Capacity evaluation ... 12
  2.7 Weight and volume ... 12
    2.7.1 Steel weight ... 12
    2.7.2 Power generation ... 13
    2.7.3 Other ... 14
    2.7.4 LSW ... 14
    2.7.5 Displacement ... 15
    2.7.6 DWT ... 15
  2.8 Harmful Emissions ... 15
3 Methanol-direct propulsion ... 18
  3.1 Power generation ... 18
  3.2 System efficiency ... 18
  3.3 Energy storage ... 19
  3.4 LSW & DWT ... 20
  3.5 Emissions ... 22
4 Methanol-hybrid propulsion ... 24
  4.1 Power Generation ... 24
  4.2 System Efficiency ... 24
  4.3 Energy Storage ... 27
  4.4 LSW & DWT ... 29
  4.5 Emissions ... 30
5 Case comparison ... 32
  5.1 Energy Storage ... 32

5.2 Efficiencies 32
5.3 LSW & DWT 33
5.4 Harmful Emissions 34
5.5 Engine running hours 34
5.6 Conclusion 35
6 Initial methanol design 36
6.1 General arrangement 36
6.2 Tank capacities 36
6.3 Additional systems 36
6.4 Renders 37
7 Conclusion & Recommendations 39
7.1 Conclusion 39
7.2 Recommendations 39
8 Bibliography 40
9 References 40

LIST OF TABLES

Table 2-1: Main particulars reference vessel 8
Table 2-2: Main particulars conventional vessel 9
Table 2-3: Operational profile pusher 9
Table 2-4: Power generation pusher 10
Table 2-5 efficiencies operations 11
Table 2-6: Energy consumption 12
Table 2-7: Steel weight estimation 13
Table 2-8: Power generation weight estimation (B=15 m) 13
Table 2-9: Power generation weight estimation (B=20 m) 14
Table 2-10: Lightship weight estimation 14
Table 2-11: Displacement estimation 15
Table 2-12: Deadweight estimation 15
Table 2-13 Emissions conventional case upstream 16
Table 2-14 Emissions conventional case downstream 17
Table 3-1 Power generation methanol-direct 18
Table 3-2 System efficiency methanol-direct 19
Table 3-3: Energy consumption methanol direct operation 20
Table 3-4 Total required capacity methanol direct operation 20
Table 3-5 Power generation methanol-direct 21
Table 3-6 LSW methanol-direct 21
Table 3-7 Deadweight methanol direct 21
Table 3-8 Displacement methanol direct 22
Table 3-9 Emissions properties methanol and MGO 22
Table 3-10 Relative emissions methanol-direct case 23
Table 3-11 Absolute emissions methanol-direct case 23
Table 4-1: Power generation methanol-hybrid case 24
Table 4-2 System efficiency methanol-hybrid 25
Table 4-3 Calculation brake power 26
Table 4-4: Calculation energy consumption methanol-hybrid case 28
Table 4-5 Required fuel capacity methanol-hybrid operation 28
Table 4-6 Overview power generation methanol-hybrid case 29
Table 4-7 LSW estimation methanol-hybrid case 29
Table 4-8 Overview DWT methanol-hybrid case 29
Table 4-9 Displacement methanol-hybrid 30
Table 4-10 Relative emissions methanol-hybrid 30
Table 4-11 Absolute emissions methanol-hybrid 31
Table 5-1 Minimum required fuel capacities 32
Table 5-2 Overview SFC's and efficiencies 32
Table 5-3 Overall efficiencies 33
Table 5-4 Comparison energy consumption 33
Table 5-5 Comparison LSW and DWT 33
Table 5-6 Comparison emissions 34
Table 5-7 Engine running hours comparison 34
Table 5-8 Conclusion comparison towards conventional case 35
Table 6-1 Gross tank volumes 36

TABLE OF FIGURES

Figure 2-1 3D perspective view conventional design 8
Figure 2-2 Side & front view conventional design 9
Figure 2-3 MGO SFC for up & downstream conventional case 10
Figure 2-4: System efficiency conventional vessel 11
Figure 2-5: Section plan pusher 13
Figure 3-1 Methanol SFC for up & downstream methanol-direct case 19
Figure 4-1 Methanol SFC for up & downstream methanol-hybrid case 25
Figure 4-2 Overview configuration 27
Figure 6-1 Render inside starboard 37
Figure 6-2 Render inside front 38

1 INTRODUCTION

In the Green Maritime Methanol 2.0 consortium methanol as marine fuel is further investigated for various ship types and sizes including a pusher. Much is unknown about the technical and economic impact of using methanol on a pusher tug boat. Therefore, the purpose of this document is to identify the consequences of methanol fuel implementation in a river-sailing pusher. A preliminary general arrangement of the methanol fueled vessel will be delivered and compared to the conventional base case driven on MGO with focus on The fuel capacities and efficiencies. In addition a comparison has been made between a methanol-direct propulsion system and a methanol-hybrid propulsion. At the end a conclusion will be provided with recommendations identifying topics for further research. The project will run together with Veerhaven and MARIN.

2 BASE CASE

In this chapter the conventional vessel is described. The operational profile, power generation, system efficiency, energy storage, weight, volume, and emissions of the conventional vessel are defined in this chapter. The conventional vessel will be used as a base case to compare the methanol version of the vessel with.

A existing vessel is used as reference. Because of low water levels in the rivers future vessels require a smaller draft. To reduce the draft, the width of the reference vessel is scaled to 20 meters. The upscaled reference vessel will act as the conventional vessel in this research.

2.1 Reference Vessel

The conventional vessel is based on the reference vessel Veerhaven IV with 3 propellers and a width of 15 meters. The Veerhaven IV is scaled up to a width of 20 meters. The main particulars of the Veerhaven IV are shown in Table 2-1.

Main particulars		
L_{oa}	[m]	40.00
L_{pp}	[m]	-
B_{mld}	[m]	15.00
D	[m]	2.75
T_{summer}	[m]	1.75
LSW	[t]	650
Displacement	[t]	879

Table 2-1: Main particulars reference vessel

2.2 Conventional design

Figure 2-1 shows a 3D perspective view of the conventional vessel. Figure 2-2 shows the side and front view of the conventional vessel.

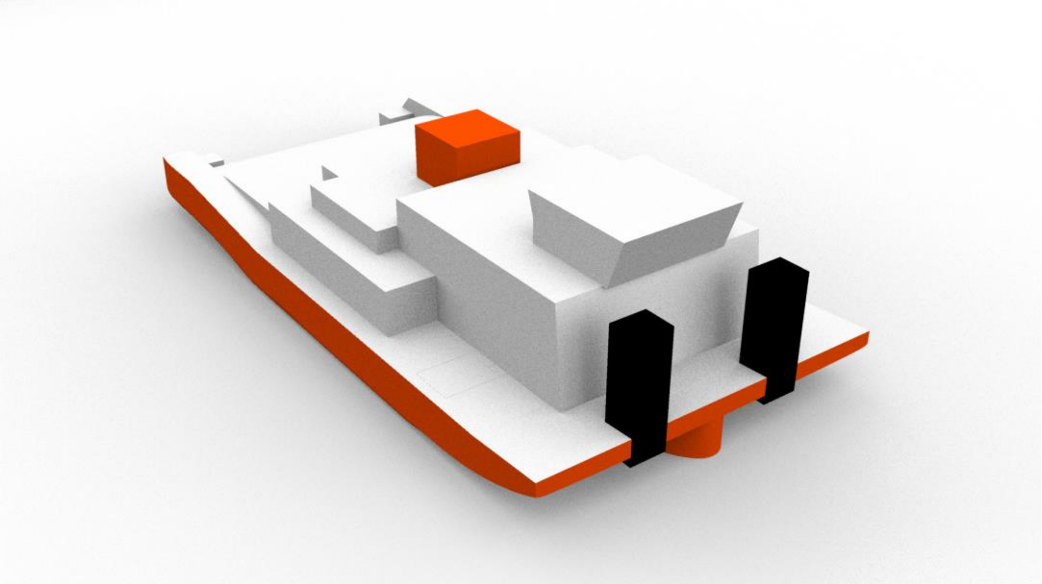

Figure 2-1 3D perspective view conventional design

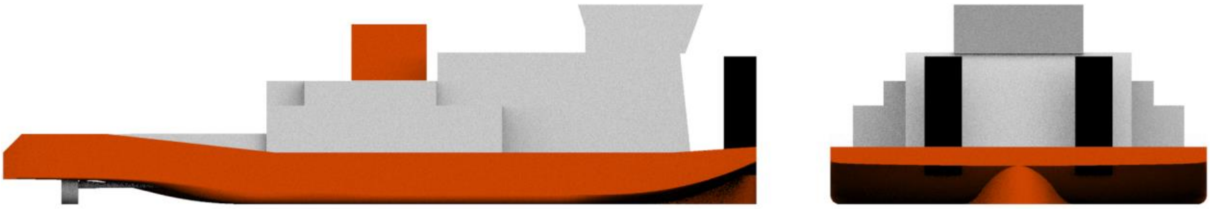

Figure 2-2 Side & front view conventional design

The conventional vessel has a width of 20 meters, contains 4 main engines and 4 propellers. The main particulars of the vessel are shown in Table 2-2.

Main particulars		
L_{oa}	[m]	40.00
L_{pp}	[m]	-
B_{mld}	[m]	20.00
D	[m]	2.75
T_{summer}	[m]	1.60

Table 2-2: Main particulars conventional vessel

2.3 Operational Profile

Veerhaven operates a fleet of push boats transporting coal and ore along a fixed route on the Rhine between Rotterdam and Duisburg of roughly 230 km. The vessel sails upstream with 6 loaded barges when the water level is above 750 cm at Lobith and 233 cm at Ruhrort. When water levels are lower a convoy of 4 barges is used. The cargo capacity depends on the water depth. During the return trip the barges are empty. The ship sails two roundtrips before it has to bunker and the ship bunker during sailing. The range of the ship is 920 km (2x2x230). The average speed, time and power are shown in Table 2-3 (Marin, 2022).

Operational Profile	**Unit**	**Upstream**	**Downstream**
Average speed over ground	[km/h]	7.9	17.3
Average voyage time	[h]	28.8	13.1
Average brake power	[kW]	2800	1300

Table 2-3: Operational profile pusher

2.4 Power Generation

The diesel-direct ship design has 4 ABC 6DZC main engines with a total power of 3816 kW. The ship also has 2 Scania DS-12-70 M auxiliary engines with Stamford generators and 1 Sisu diesel 49 DTAG with a Stamford generator. General information about the power generation is shown in Table 2-4.

Component	Quantity	Type	Ne [rpm]	Pb [kW]	Pb total [kW]	Weight [ton]	Total weight [ton]
Main engines	4	ABC 6DZC-720-166 [CI-ICE]	720	954	3816	10.6	42.5
Auxiliary engines	2	Scania DS-12-70 M [CI-ICE]	1500	211	422	2.6	5.1
Harbour engine	1	Sisu Diesel 49 DTAG [CI-ICE]	1500	95	95	1.1	1.1

Table 2-4: Power generation pusher

2.5 System Efficiency

On average the vessel uses 73% MCR to sails upstream and 34% MCR to sail downstream. Upstream the vessel will generate a respective 2800 kW brake power, downstream the vessel will generate a respective 1300 kW brake power.

The systems efficiency is dependent on the operational usage of the vessel. Because the efficiency of the engine is not stated by the engine manufacturer, the efficiency has been approached with an analytic model delivered by MARIN. With this model the BSFC can be obtained to further investigate the influences of different loads. See Figure 2-3 for the engine-diagrams regarding the operating points during up & downstream sailing.

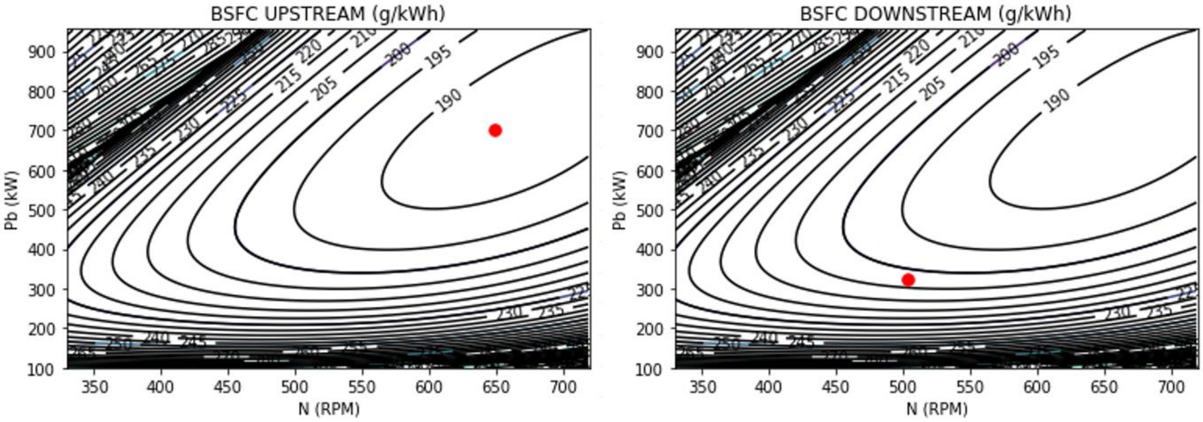

Figure 2-3 MGO SFC for up & downstream conventional case

The efficiencies during the different operations are described in Table 2-5.

Condition	BSFC [g/kWh]	Efficiency	GB efficiency	Combined efficiency
Upstream theoretical	190	0.44	0.97	0.43
Upstream practice	199	0.42	0.97	0.41
Downstream theoretical	205	0.41	0.97	0.40
Downstream practice	227	0.37	0.97	0.36

Table 2-5 efficiencies operations

According to Veerhaven, the efficiency is lower in practice. Therefore, the efficiency of the engine while sailing upstream will be lowered with 2%, and the efficiency of the engine while sailing downstream will be lowered with 4%. That makes the engine efficiency while sailing upstream 42% and downstream 37%.

See Figure 2-4 for an overview the propulsion train regarding output and efficiencies. The gearbox efficiency is based on the MARIN report and will remain the same for up and downstream sailing.

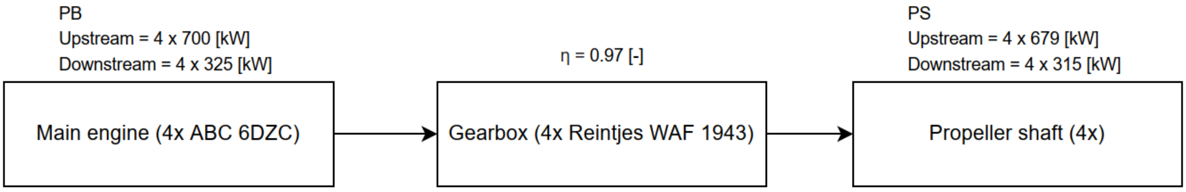

Figure 2-4: System efficiency conventional vessel

2.6 Energy Storage

2.6.1 Fuel Storage Capacity

Based on the tank plan of the reference vessel, the MGO storage capacity of the ship is approximately 152 m^3.

2.6.2 Autonomy

Upstream, the ship sails fully loaded for 28.8 hours at an average power of 2800 kW. This requires 80640 kWh of energy. With an efficiency of 42.4%, the total upstream energy consumption is 190309 kWh. Divided by an energy density of 11.86 kWh/kg. The upstream MGO consumption is 16.0 ton.

While sailing downstream, the ship is empty. The trip downstream takes 13.1 hours with an average engine power of 1300 kW. This results in a total energy usage of 17030 kWh. With an efficiency of 37.1%, the total downstream energy consumption becomes 45870 kWh. Divided by an energy density of 11.86 kWh/kg of MGO, the downstream energy consumption is 3.9 ton MGO.

The total fuel consumption sailing upstream and downstream is 19.9 ton. With an density of 860 kg/m^3 is the volume of the fuel consumed during a round trip is 23.2 m^3. The ship has to sail 2 round trips without bunkering. In the calculation a margin of 10% is taken into account. That makes the total volume of fuel including margin 50.9 m^3, the total weight is 43.8 ton. When the filling level factor and steel factor are applied, the total gross volume is 52.5 m^3. An overview of the calculated values is shown in Table 2-6.

Calculation steps	Unit	Upstream	Downstream
Average voyage time	[h]	28.8	13.1
Average brake power	[kW]	2800	1300
Mechanical energy out	[kWh]	80640	17030
MCR	[%]	73	34
SFC	[g/kwh]	190	205
Efficiency	[%]	44.4	41.1
Corrected efficiency	[%]	42.4	37.1
Chemical energy in	[kWh]	109309	45870
Fuel consumption	[ton]	16.0	3.9
Round trips	[-]	2	2
Margin	[%]	10	10
Required capacity	[ton]	35.3	8.5
Total required capacity	[ton]	43.8	
Total required capacity	[m^3]	50.9	
Filling level	[-]	0.98	
Steel factor	[-]	0.99	
Gross volume 3D model	[m^3]	52.5	

Table 2-6: Energy consumption

2.6.3 Capacity evaluation

A comparison of the current capacity (152m^3) with the required capacity (52.5m^3) shows that the capacity of the vessel is approximately 2.9 times as big as necessary for the required range. For the conventional vessel the capacity will be kept at 152 m^3 as base.

2.7 Weight and volume

The LSW of the conventional base vessel (B=20m) is estimated with preliminary calculations using the reference vessel (B=15m). The light ship weight is divided in 3 categories consisting of; steel weight, power generation, and other weight.

2.7.1 Steel weight

The steel weight of the reference vessel has been provided by the yard (Thyssenkrupp Veerhaven, 2022), separated in two main parts namely the hull + fixed deckhouse (blue) and the flexible deckhouse (green). These parts are shown in Figure 2-5.

The volume of the hull and deckhouse parts has been calculated for both the reference vessel and the conventional vessel. The known weights of the hull and deckhouse parts of the reference vessel have been linear scaled up based on the volume obtained in the 3D model. The weights and volumes are shown in Table 2-7.

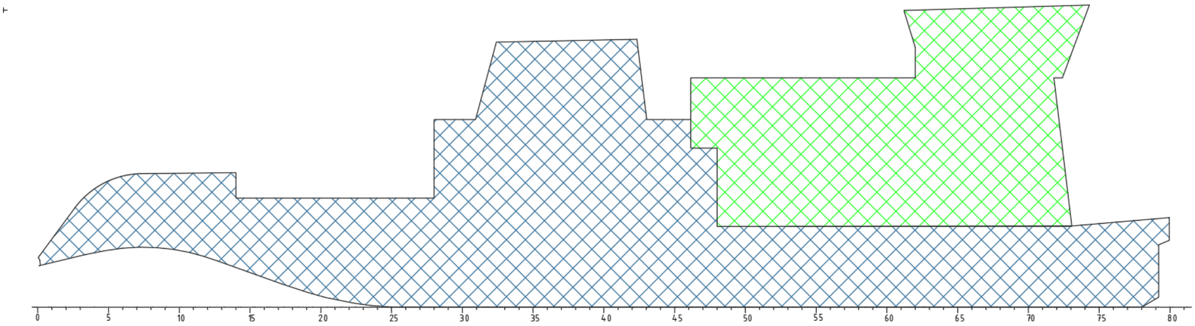

Figure 2-5: Section plan pusher

Component	Reference vessel B=15m	Conventional vessel B=20m
Volume hull + deckhouse fixed [m^3]	2063	*2784
Volume deckhouse flexible [m^3]	838	838
Weight hull + deckhouse fixed [ton]	270	**364
Weight deckhouse flexible [ton]	90	90
Total steel weight [ton]	360	454

Table 2-7: Steel weight estimation

*Volume of hull derived from 3D (Rhino) model and volume of fixed deckhouse is linear scaled with the breadth of 15 meter to 20 meter.
**Weight of hull and fixed deckhouse is linear scaled with weight volume ratio derived from reference vessel and applied for conventional vessel.

2.7.2 Power generation

The weight of the power generation system is determined for both vessels and shown in Table 2-8 and Table 2-9.

Reference vessel B=15m

Component	Quantity	Weight per component [ton]	Total weight [ton]
Main Engine	3	11.00	33.00
Gearbox	3	4.46	13.38
Auxiliary generator set	2	2.55	5.10
Harbour generator set	1	1.10	1.10
Electric systems	1	2.20	2.20
Shafts	3	2.50	7.50
Total			62.3

Table 2-8: Power generation weight estimation (B=15 m)

Conventional vessel B=20m

Component	Quantity	Weight per component [ton]	Total weight [ton]
Main Engine	4	10.6	42.5
Gearbox	4	4.5	17.8
Auxiliary generator set	2	2.6	5.1
Harbour generator set	1	1.1	1.1
Electric systems	1	2.2	2.2
Shafts	4	2.5	10.0
DPF	4	2.2	8,8
SCR system	4	0.9	3.6
Total			91.1

Table 2-9: Power generation weight estimation (B=20 m)

The conventional case has a SCR system because the ship has to comply to the IMO tier III. The reference ship is an existing ship and doesn't have a SCR system.

2.7.3 Other

The other weight is derived from the LSW of the B=15m vessel. The other weight is the total LSW minus the steel weight and the power generation. The other weight is considered constant for both vessels because that weight consists parts that do not change on the B=20m vessel. Table 2-10 shows that the other weight is 228 ton for both vessel.

2.7.4 LSW

In Table 2-10 is the total lightship weight estimated based on the lightship weight of the reference vessel. The steel weight of the reference vessel is 360 ton and the power generation is 62 ton. The total LSW is 650 ton. That means that there is another weight of 228 ton. This weight stays the same for the conventional vessel.

Lightship weight estimation	Reference vessel B=15m [ton]	Conventional vessel B=20m [ton]
Steel weight	360	454
Power generation	62	91
Other	228	228
Total LSW	650	773

Table 2-10: Lightship weight estimation

2.7.5 Displacement

The maximum displacement of the conventional vessel is 935 ton at a draft of 1.6 m obtained from the Rhino model. The LSW is 773 ton and that makes the deadweight is 163 ton. An overview of the displacement of both ships is shown in Table 2-11.

Component	Reference vessel B-15m, T=1.75m [ton]	Conventional vessel B-20m, T=1.6m [ton]
LSW	650	773
Deadweight	79	162
Total Displacement	729	935

Table 2-11: Displacement estimation

2.7.6 DWT

In Table 2-12, the deadweight of the reference vessel is obtained from the minimal storage (Thyssenkrupp Veerhaven, n.d.) and other deadweight derived from the displacement of the conventional vessel. The minimum fuel deadweight of the conventional vessel is based on the range that is demanded for the new design.

Component	Reference vessel B=15m [ton]	Conventional vessel B=20m [ton]
Lube oil	7.0	9.0
Fresh water	15.0	15.0
Circulation tank	15.0	15.0
Required MGO	30.0	43.8
Urea*	-	2.5
Margin	12.0	76.2
Total deadweight	79.0	161.5

Table 2-12: Deadweight estimation

* The conventional design has an urea storage tank to supply the SCR system to comply to the IMO tier III. The size of the urea tank is approximately 6% of the MGO capacity.

2.8 Harmful Emissions

In this section, the emissions will be shown. The carbon dioxide equivalent, or CO2 equivalent, abbreviated as CO2eq, is a metric measure used to compare the emissions from various greenhouse gases on the basis of their 100 year Global-Warming Potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential over a 100 years.

Emission properties

In Table 2-13, the properties of the different kind of emissions are shown.

Emission type			Fuel based emissions [g/g-fuel]
GHG	WTT	CO2-eq	0.74400
	TTP	CO2	3.20600
		CH4	0.00005
		N2O	0.00018
		BC	0.00004
	WTP	Total CO2-eq	-
Air pollution		SOx	0.00137
		NOx*	
		PM10	0.00090
		PM2.5	0.00083
		CO	0.00259
		NMVOC	0.00240

Table 2-13 Emissions conventional case upstream

Non-methane volatile organic compounds (NMVOCs) are a collection of organic compounds that differ widely in their chemical composition but display similar behavior in the atmosphere. NMVOCs contribute to the formation of ground level (tropospheric) ozone. In addition, certain NMVOC species or species groups such as benzene and 1,3 butadiene are hazardous to human health.

Relative and Absolute emissions

In Table 2-14, the relative and absolute emissions for the conventional vessel sailing on MGO during upstream and downstream operation are shown.

Emission type	Emissions [g/kWh] Upstream	CO2-eq [g/kWh] Upstream	Emissions [ton/year] Upstream	Emissions [g/kWh] Downstream	CO2-eq [g/kWh] Downstream	Emissions [ton/year] Downstream
CO2-eq	148.047	148.0		168.970	169.0	
CO2	637.954	638.0		728.116	728.1	
CH4	0.010	0.3		0.011	0.3	
N2O	0.036	9.5		0.041	10.8	
BC	0.008	7.2		0.009	8.2	
CO2-eq total		802.9	12367.0		916.4	2980.8
SOx	0.273		4.199	0.311		1.012
NOx*	2.600		40.046	2.600		8.457
PM10	0.179		2.758	0.204		0.665
PM2.5	0.165		2.544	0.189		0.613
CO	0.515		7.938	0.588		1.913
NMVOC	0.478		7.356	0.545		1.773

Table 2-14 Emissions conventional case downstream

*SCR is applied to reduce NOx emissions. Compliant with ECA and IMO Tier III regulations.

3 METHANOL-DIRECT PROPULSION

Two different methanol cases will be observed and further looked into. This case is a methanol-direct design. The efficiency, energy storage, and emissions will be analysed. The main particulars are the same as the conventional design and are shown in Table 2-2. Also, the operational profile as described in section 2.3 stays the same.

3.1 Power generation

The ship has 4 ABC 6DZD main engines with a total power of 3816 kW. The ship also has 2 Scania DS-12-70 M auxiliary engines with Stamford generators, and 1 Sisu diesel 49 DTAG with a Stamford generator. General information about the power generation is shown in Table 3-1.

Component	**Quantity**	**Type**	**Ne [rpm]**	**Pb [kW]**	**Pb total [kW]**	**Weight [ton]**	**Total weight [ton]**
Main engines	4	ABC 6DZD-720-166[1] [CI-ICE]	720	954	3816	10.7	42.9
Auxiliary engines	2	Scania DS-12-70 M [CI-ICE]	1500	211	422	2.6	5.1
Harbour engine	1	Sisu Diesel 49 DTAG [CI-ICE]	1500	95	95	1.1	1.1

Table 3-1 Power generation methanol-direct

3.2 System efficiency

The vessel sails upstream average on 73% MCR, and downstream at 34% MCR. Upstream the vessel will generate a respective 2800 kW brake power, downstream the vessel will generate a respective 1300 kW brake power.

The systems efficiency is dependent on the operational usage of the vessel. Because the efficiency of the engine is not stated by the engine manufacturer, the efficiency has been approached with an analytic model delivered by MARIN. With this model the Brake-Specific Fuel Consumption (BSFC) at multiple operational points can be determined. Figure 3-1 shows the engine-diagrams with the operating points during up- and downstream sailing. Table 3-2 shows the specific fuel consumption and system efficiency of the methanol direct case during multiple operational conditions

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[1] Engine rating not available in supplier specifications, based on reduction of MEP from 18.1bar to 16.6bar

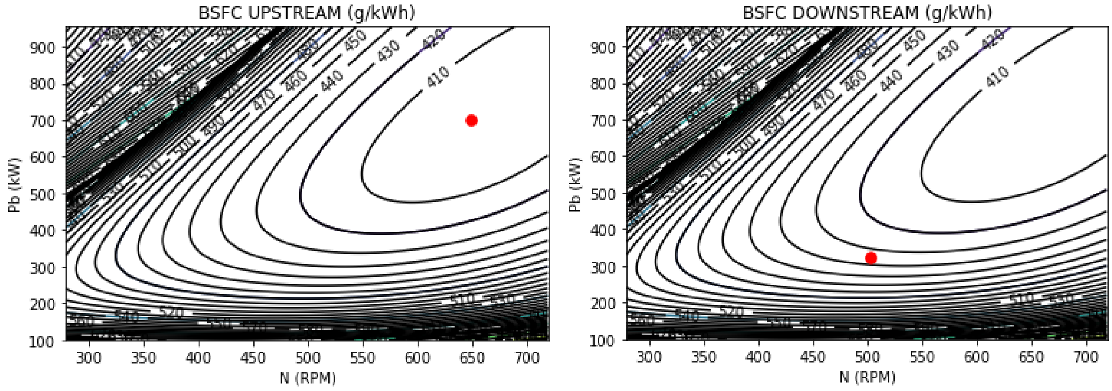

Figure 3-1 Methanol SFC for up & downstream methanol-direct case

The BSFC is for methanol only. Pilot fuel is not taken into account.

Condition	**BSFC [g/kWh]**		**Engine efficiency [-]**	**Gearbox efficiency [-]**	**Combined efficiency [-]**
	Methanol	**MGO**			
Upstream theoretical	351.3	26.3	0.44	0.97	0.43
Upstream Practice	367.9	27.5	0.42	0.97	0.41
Downstream theoretical	308.9	61.1	0.41	0.97	0.40
Downstream Practice	342.1	67.6	0.37	0.97	0.36

Table 3-2 System efficiency methanol-direct

According to Veerhaven, the efficiency is lower in practice. Therefore, the efficiency of the engine during upstream sailing will be lowered with 2%, and the efficiency of the engine during downstream sailing will lowered with 4%. That makes the engine efficiency during upstream sailing 42% and downstream 37%.

3.3 Energy storage

In this paragraph the required fuel storage capacity and available fuel storage capacity are evaluated. Furthermore, the total autonomy of the methanol-direct vessel is determined.

Capacity:

The required methanol storage is calculated based on the demanded range of two journeys back and forth from Rotterdam to Duisburg. The required methanol capacity is 98.8 m3 or 78.1 ton.

Autonomy:

Section 2.6.2 describes which autonomy is required for the new design. During methanol operation a pilot fuel is used to promote the ignition of methanol, which is harder to ignite than MGO. The pilot fuel is MGO, and provides 10% of the energy used during combustion at 100% MCR.

For upstream operation a MCR of 73% is set. This results in SFC of 367.9 g/kWh for methanol, and 27.5 g/kWh for MGO. This results in a pilot fuel percentage of 14% in terms of energy. The MGO delivers a fixed absolute quantity of power. Therefore, when the overall power output of the engine is lower, the percentage of MGO is higher. These SFC's result in a fuel consumption of 28.3 ton for methanol, and 2.1 ton of MGO for one journey. A margin of 10% is required for the fuel capacities. Table 3-3 gives an overview of the results.

For downstream operation a much lower MCR of 34% is set. This results in SFC of 342.1 g/kWh for methanol and 67.6 g/kWh for MGO. The pilot fuel percentage is 30% in terms of energy. These SFC's result in a fuel consumption of 5.8 ton for methanol and 1.2 ton of MGO for one journey. A margin of 10% is required for the fuel capacities. Table 3-3 gives an overview of the results.

Calculation steps	Unit	Upstream		Downstream	
		Methanol	MGO	Methanol	MGO
Average voyage time	[h]	28.8		13.1	
Average brake power	[kW]	2800		1300	
Mechanical energy out	[kWh]	80640		17030	
Efficiency	[%]	42.4		37.1	
Chemical energy in	[kWh]	190309		45870	
Fuel consumption 1 trip	[ton]	29.7	2.2	5.8	1.2
Fuel consumption 1 trip	[m^3]	37.6	2.6	7.4	1.3
Round trips	[-]	2	2	2	2
Margin	[%]	10	10	10	10
Total required capacity	[ton]	65.3	4.9	12.8	2.5
Total required capacity	[m^3]	82.6	5.7	16.2	3.0
Filling level	[-]	0.98	0.98	0.98	0.98
Steel factor	[-]	0.99	0.99	0.99	0.99
Gross volume 3D model	[m^3]	85.2	5.9	16.7	3.0

Table 3-3: Energy consumption methanol direct operation

Table 3-4 shows the total required capacity during methanol mode.

Kind of capacity	Unit	Methanol	MGO
Net	[m^3]	98.8	8.9
Gross	[m^3]	101.9	8.7
Net	[ton]	78.1	7.4

Table 3-4 Total required capacity methanol direct operation

The minimum required fuel space is significantly increased in comparison with the conventional base case (52.5 m^3). This is a logical outcome regarding the difference of LHV between methanol and MGO.

3.4 LSW & DWT

The LSW is based on the conventional LSW. Only the weight of the power generation is changed. The weights of the power generation is shown in Table 3-5. The steel weight of the methanol direct case is estimated the same as the conventional case.

Component	Amount	Weight per component [ton]	Total weight [ton]
Main Engine	4	10.7	42.9
Gearbox	4	4.5	17.8
Auxiliary generator set	2	2.6	5.1
Harbour generator set	1	1.1	1.1
Electric systems	1	2.2	2.2
Shafts	4	2.5	10.0
DPF	4	2.2	8.8
SCR system	4	0.9	3.6
Total			91.5

Table 3-5 Power generation methanol-direct

In Table 3-6 is the total lightship weight estimated based on the lightship weight of the conventional vessel shown.

Component	Unit	
Steel weight	[ton]	454
Power generation	[ton]	92
Other	[ton]	228
Total LSW	[ton]	774

Table 3-6 LSW methanol-direct

The DWT is based on the range during methanol mode, the minimum required stocks, and a margin. The DWT overview is shown in Table 3-7.

Component	Unit	
Lube oil	[ton]	9
Fresh water	[ton]	15
Circulation tank	[ton]	15
Required methanol	[ton]	78
Required MGO	[ton]	7
Urea*	[ton]	5
Margin	[ton]	32
Total deadweight	[ton]	161

Table 3-7 Deadweight methanol direct

*Approximately 6% of the fuel capacity

The displacement is based on the 3D Rhino model at a draft of 1.6 m, an overview of the displacement is shown in Table 3-8.

Component	Unit	
LSW	[ton]	774
Deadweight	[ton]	161
Total Displacement	[ton]	935

Table 3-8 Displacement methanol direct

3.5 Emissions

Emission properties

In Table 3-9, the properties of the different kind of emissions are shown for both MGO and methanol.

Emission types			Fuel-based factors [g/g-fuel] [2]	
			Methanol	MGO
GHG	WTT**	CO2-eq	-0.975	0.74400
	TTP	CO2	1.375	3.20600
		CH4	0.000	0.00005
		N2O	0.000	0.00018
		BC	0.000	0.00004
	WTP	CO2-eq	0.000	-
Air pollution		SOx	0.000	0.00137
		NOx*		
		PM10	0.000	0.00090
		PM2.5	0.000	0.00083
		CO	0.000	0.00259
		NMVOC	0.000	0.00240

Table 3-9 Emissions properties methanol and MGO

*SCR is applied to reduce Nox emissions. Compliant with ECA and IMO Tier III regulations. Values based on g/kWh.

**Green electricity: 30g/kWh, assuming 50% solar (48g/kWh) and 50% wind (12g/kWh).

Relative emissions

In Table 3-10, the relative emissions for the methanol-direct vessel during upstream and downstream operation are shown.

Emission types	**Emissions [g/kWh] Upstream**			**Emissions CO2-eq [g/kWh] Upstream**	**Emissions [g/kWh] Downstream**			**Emissions CO2-eq [g/kWh] Downstream**
Fuel type	Methanol	MGO	Total	Total	Methanol	MGO	Total	Total
CO2-eq	-358.703	20.460	-338.243	-338.2	-333.548	50.294	-283.253	-283.3
CO2	505.863	88.165	594.028	594.0	470.388	216.726	687.113	687.1
CH4	0.001	0.001	0.002	0.1	0.001	0.003	0.004	0.1
N2O	0.003	0.005	0.008	2.0	0.002	0.012	0.014	3.8
BC	0.000	0.001	0.001	1.0	0.000	0.003	0.003	2.4
CO2-eq total				258.8				410.2
SOx	0.000	0.038	0.038		0.000	0.093	0.093	
NOx	2.236	0.364	2.600		1.820	0.780	2.600	
PM10	0.000	0.025	0.025		0.000	0.061	0.061	
PM2.5	0.000	0.023	0.023		0.000	0.056	0.056	
CO	0.046	0.071	0.118		0.038	0.175	0.213	
NMVOC	0.000	0.066	0.066		0.000	0.162	0.162	

Table 3-10 Relative emissions methanol-direct case

Absolute emissions

In Table 3-11, the absolute emissions of the methanol-direct case are shown.

Emission types	**Absolute emissions [ton/year] Upstream**	**Absolute emissions [ton/year] Downstream**	**Absolute emissions [ton/year] Total**
CO2-eq WTP	3986.608	1334.234	5320.842
SOx	0.580	0.301	0.882
NOx	40.046	8.457	48.503
PM10	0.381	0.198	0.579
PM2.5	0.352	0.183	0.534
CO	1.812	0.692	2.505
NMVOC	1.017	0.528	1.544

Table 3-11 Absolute emissions methanol-direct case

4 METHANOL-HYBRID PROPULSION

This case is a methanol-hybrid design. The efficiency, energy storage, and emissions will be analysed. The main particulars are the same as the conventional design and are shown in Table 2 2. Also, the operational profile as described in section 2.3 stays the same.

4.1 Power Generation

The ship has 4 ABC 6DZD main engines with a total power of 3816 kW. The ship also has 2 Scania DS-12-70 M auxiliary engines with Stamford generators and one Sisu diesel 49 DTAG with a Stamford generator. General information about the power generation is shown in Table 4-1.

Components	Quantity	Type	Ne [rpm]	Pb [kW]	Pb total [kW]	Weight [ton]	Total weight [ton]
Main engines	4	ABC 6DZD-720-166 [CI-ICE]	720	954	3816	10.7	42.9
Auxiliary engines	2	Scania DS-12-70 M [CI-ICE]	1500	211	422	2.6	5.1
Harbour engine	1	Sisu Diesel 49 DTAG [CI-ICE]	1500	95	95	1.1	1.1
PTI/PTO	4	n EMG-328d-635l	3600	431	1724	1.0	4.0

Table 4-1: Power generation methanol-hybrid case

For the methanol-hybrid propulsion mode a configuration is made regarding the possibility of a methanol-hybrid propulsion system. The philosophy behind the case is that an hybrid system may be more efficient due to turning off two engines while sailing downstream, and power the other two propellers using a combination of a PTO and a PTI. Using only two engines while sailing downstream allows the engines to operate at a more efficient operational point.

4.2 System Efficiency

While sailing upstream, on average the vessel uses 73% MCR and downstream 34% MCR. Upstream the vessel will generate a respective 2800 kW brake power, downstream the vessel will generate a respective 1300 kW brake power.

The systems efficiency is dependent on the operational usage of the vessel. Because the efficiency of the engine is not stated by the engine manufacturer, the efficiency has been approached with an analytic model delivered by MARIN. With this model a BSFC can be obtained to further investigate the influences of different loads. Figure 4-1 shows the engine-diagrams regarding the operating points during up- and downstream. During the upstream operation, there will be 4 engines running which each will drive one propeller. Downstream there are only two engines running which drive 4 propellers with a PTO/PTI combination. This decreases the operating hours of the engines what increases the lifespan of the engines. Table 4-2 shows the total system efficiency. Figure 4-2 gives an overview of the configuration.

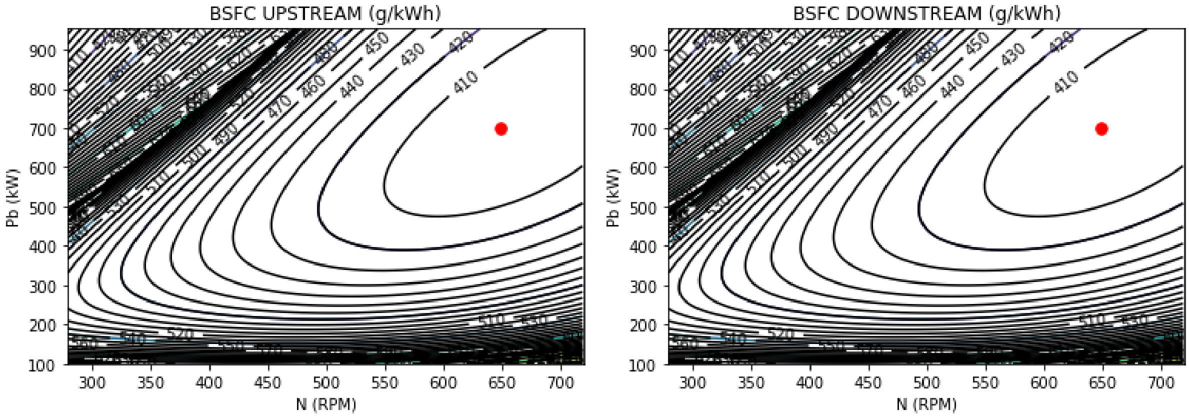

Figure 4-1 Methanol SFC for up & downstream methanol-hybrid case

The BSFC in Figure 4-1 is for methanol only. Pilot fuel is not taken into account in this figure.

Condition	**BSFC [g/kWh]**		**Engine**	**GB 1**	**PTO**	**Electrical**	**PTI**	**GB 2**	**System**	**Combined**
	Methanol	**MGO**	**[-]**	**[-]**	**[-]**	**[-]**	**[-]**	**[-]**	**[-]**	**[-]**
Upstream theoretical	351.3	26.3	0.44	0.97	[-]	[-]	[-]	[-]	0.43	
Upstream practice	367.9	27.5	0.42	0.97	[-]	[-]	[-]	[-]	0.41	
Downstream theoretical	351.3	26.3	0.44	0.97	[-]	[-]	[-]	[-]	0.43	0.40
Downstream PTO/PTI theoretical					0.96	0.97	0.96	0.97	0.37	
Downstream practice	368.5	27.2	0.42	0.97	[-]	[-]	[-]	[-]	0.41	0.38
Downstream PTO/PTI practice					0.96	0.95	0.96	0.97	0.35	

Table 4-2 System efficiency methanol-hybrid

According to Veerhaven, the efficiency is lower in practice. Therefore, the efficiency of the engine while sailing upstream will be lowered with 2%, and the efficiency of the engine while sailing downstream is also lowered with 2%. That makes the engine efficiency during upstream and downstream 42%. According to Veerhaven the electrical efficiency will also be lowered with 2 percent from 97% to 95%.

In this case during upstream, all 4 engines are running on 700 kW to generate the required 2800 kW. In this case while sailing downstream, 2 of the 4 engines are running and the ship is driven by 4 propellers. Two engines direct and two engines via a PTI. The brake power per engine including PTO, PTI, gearbox and electrical efficiency is 708 kW. That makes the total brake power 1416 kW instead of the required 1300 kW due to the efficiencies of the extra components. A calculation of the brake power for downstream is shown in Table 4-3. Figure 4-2 gives an overview of the configuration including the names of the components. Only one side of the complete configuration is shown. The other side is the same.

Steps Pb calculation	unit	value
Pbtot	[kW]	707.69
Ps1	[kw]	315.25
Ps2	[kW]	315.25
Pb 1 direct part	[kW]	325.00
Pb 1 hybrid part	[kW]	382.69
GB 1 efficiency	[-]	0.97
Pbem1	[kW]	371.21
PTO efficiency	[-]	0.96
Pelec 1	[kW]	356.36
elec efficiency	[-]	0.95
Pelec 2	[kW]	338.54
PTI efficiency	[-]	0.96
Pbem 2	[kW]	325.00
GB 2 efficiency	[-]	0.97

Table 4-3 Calculation brake power

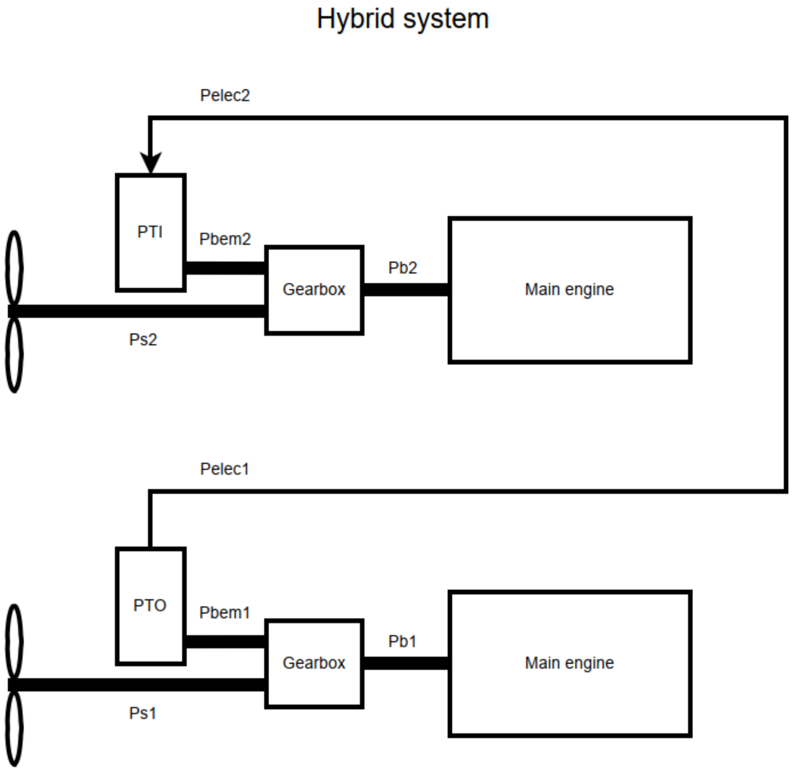

Figure 4-2 Overview configuration

4.3 Energy Storage

Capacity:

The required methanol storage is calculated based on the demanded range of 2 journeys back and forth from Rotterdam to Duisburg. The required methanol capacity is 101.6 m3 or 80.3 ton. The MGO capacity is 7.0 m3 or 6.0 ton.

Autonomy:

Section 2.6.2 shows an explanation regarding the autonomy of the new design. During methanol operation a pilot fuel is used to promote the combustion of methanol. The pilot fuel is MGO, and provides 10% of the energy used during combustion with 100% MCR.

For the upstream operation a MCR of 73% is set. This results in a SFC of 367.9 g/kWh for methanol and 27.5 g/kWh for MGO. These SFC's result in a fuel consumption of 29.7 ton for methanol and 2.2 ton of MGO. A margin of 10% is required for the fuel capacities. The results are shown in Table 4-4. For the downstream operation a MCR of 74% is set for two engines. This results in SFC of 368.5 g/kWh for methanol and 27.2 g/kWh for MGO. These SFC's result in a fuel consumption of 6.8 ton for methanol and 0.5 ton of MGO. A margin of 10% is required for the fuel capacities. The results are shown in Table 4-4.

Calculation steps	Unit	Upstream		Downstream	
		Methanol	MGO	Methanol	MGO
Average voyage time	[h]	28.8		13.1	
Average brake power	[kW]	2800		1400	
Mechanical energy out	[kWh]	80640		18541	
Efficiency	[%]	42.4		42.4	
Chemical energy in	[kWh]	190309		43757	
Fuel consumption 1 trip	[ton]	29.7	2.2	6.8	0.5
Fuel consumption 1 trip	[m^3]	37.6	2.6	8.6	0.6
Round trips	[-]	2	2	2	2
Margin	[%]	10	10	10	10
Total required capacity	[ton]	65.3	4.9	15.0	1.1
Total required capacity	[m^3]	82.6	5.7	19.0	1.3
Filling level	[-]	0.98	0.98	0.98	0.98
Steel factor	[-]	0.99	0.99	0.99	0.99
Gross volume 3D model	[m^3]	85.2	5.9	19.6	1.3

Table 4-4: Calculation energy consumption methanol-hybrid case

Table 4-5 is an overview of the net and gross required capacities.

Kind of capacity	Unit	Methanol	MGO
Net	[m^3]	101.6	7.0
Gross	[m^3]	104.8	7.2
Net	[ton]	80.3	6.0

Table 4-5 Required fuel capacity methanol-hybrid operation

4.4 LSW & DWT

The LSW is based on the conventional LSW. Only the weight of the power generation is changed. The weights of the power generation is shown in Table 4-6. The steel weight of the methanol direct case is estimated to be the same as the conventional case.

Component	Amount	Weight per component [ton]	Total weight [ton]
Main Engine	4	10.7	42.9
Gearbox	4	4.5	17.8
Auxiliary generator set	2	2.6	5.1
Harbour generator set	1	1.1	1.1
Electric systems	1	2.2	2.2
Shafts	4	2.5	10.0
DPF	4	2.2	8.8
SCR system	4	0.9	3.6
PTI/PTO incl extra switchboards	4	1	4.0
Total			95.5

Table 4-6 Overview power generation methanol-hybrid case

In Table 4-7 is the total lightship weight estimated based on the lightship weight of the conventional vessel shown.

Component	unit	
Steel weight	[ton]	454
Power generation	[ton]	96
Other	[ton]	228
Total LSW	[ton]	778

Table 4-7 LSW estimation methanol-hybrid case

The DWT is based on the range during methanol mode, the minimum required stocks and a margin. An overview of the DWT is shown in Table 4-8.

Component	unit	
Lube oil	[ton]	9
Fresh water	[ton]	15
Circulation tank	[ton]	15
Required methanol	[ton]	80
Required MGO	[ton]	6
Urea*	[ton]	5
Margin	[ton]	27
Total deadweight	[ton]	157

Table 4-8 Overview DWT methanol-hybrid case

*6% of fuel capacity

The displacement of the methanol hybrid design with a draft of 1.6 meter is shown in Table 4-9.

Component	Unit	
LSW	[ton]	778
Deadweight	[ton]	157
Total Displacement	[ton]	935

Table 4-9 Displacement methanol-hybrid

4.5 Emissions

The properties of the different kind of emissions are shown inTable 3-9 in section 3.5.

Relative emissions

The relative emissions of the methanol-hybrid case are shown in Table 4-10.

Emission types	**Emissions [g/kWh] Upstream**			**Emissions CO2-eq [g/kWh] Upstream**	**Emissions [g/kWh] Downstream**			**Emissions CO2-eq [g/kWh] Downstream**
Fuel type	Methanol	MGO	Total:	Total:	Methanol	MGO	Total:	Total:
CO2-eq	-358.703	20.460	-338.243	-338.2	-359.288	20.237	-339.051	-339.1
CO2	505.863	88.165	594.028	594.0	506.688	87.203	593.891	593.9
CH4	0.001	0.001	0.002	0.1	0.001	0.001	0.002	0.1
N2O	0.003	0.005	0.008	2.0	0.003	0.005	0.007	2.0
BC	0.000	0.001	0.001	1.0	0.000	0.001	0.001	1.0
CO2-eq total				258.8				257.9
SOx	0.000	0.038	0.038		0.000	0.037	0.037	
NOx*	2.236	0.364	2.600		2.236	0.364	2.600	
PM10	0.000	0.025	0.025		0.000	0.024	0.024	
PM2.5	0.000	0.023	0.023		0.000	0.023	0.023	
CO	0.046	0.071	0.118		0.046	0.070	0.117	
NMVOC	0.000	0.066	0.066		0.000	0.065	0.065	

Table 4-10 Relative emissions methanol-hybrid

Absolute emissions

The absolute emissions of the methanol hybrid case are shown in Table 4-11.

Emission types	Absolute emissions [ton/year] Upstream	Absolute emissions [ton/year] Downstream	Absolute emissions [ton/year] Total
CO2-eq WTP	3986.608	913.600	4900.208
SOx	0.580	0.132	0.712
NOx*	40.046	9.212	49.258
PM10	0.381	0.087	0.468
PM2.5	0.352	0.080	0.432
CO	1.812	0.414	2.226
NMVOC	1.017	0.231	1.248

Table 4-11 Absolute emissions methanol-hybrid

5 CASE COMPARISON

In this chapter, the three cases from the previous chapters are compared.

5.1 Energy Storage

In the minimum required fuel calculations the following assumptions are made:

- All 3 designs contain the same range of 2 roundtrips.
- conventional design will sail 100% of the operations on MGO-mode, while the new methanol designs will sail 100% of the operations in methanol-mode.
- The maximum possible MGO tank capacity for the conventional vessel is significantly larger than the minimum required MGO.
- The methanol designs are also capable of taking in a sufficient amount of fuel.
- The amount of methanol intake influences the possible MGO intake.

The minimum required fuel capacities are shown in table Table 5-1.

Fuel type		Unit	CONVENTIONAL VESSEL	METHANOL DIRECT	METHANOL-HYBRID
Methanol		[ton]	-	78.1	80.3
		[m^3]	-	98.8	101.6
MGO		[ton]	43.8	7.4	6.0
		[m^3]	50.9	8.7	7.0

Table 5-1 Minimum required fuel capacities

For the minimum required fuel intake, the autonomies of the designs remain the same. However, the conventional vessel is capable of exceeding this minimum required fuel intake, where it could be problematic for the methanol designs. When the conventional vessel takes in the most possible fuel intake of 110.4 the range will exceed to 4.2 round trips.

5.2 Efficiencies

Table 5-2 gives an overview of the SFC's and the engine efficiencies of the different cases.

Fuel type		Unit	CONVENTIONAL VESSEL	METHANOL DIRECT		METHANOL-HYBRID	
Fuel type			MGO	MEOH	MGO	MEOH	MGO
Upstream		[g/kWh]	199	367.9	27.5	367.9	27.5
		[-]	0.42	0.42		0.42	
Downstream		[g/kWh]	227	342.1	67.6	368.5	27.2
		[-]	0.37	0.37		0.42*	

Table 5-2 Overview SFC's and efficiencies

*only engine efficiency, the efficiency of other components is not taken into account in this table.

Table 5-3 gives the overall efficiencies of the different cases

Case	Total energy consump-tion	Hours upstream	Hours down-stream	Pb upstream	Ps upstream	Pb down-stream	Ps down-stream	Efficiency
Conventional	236179	28.8	13.1	2800	2716	1300	1261	0.40114
Methanol-direct	236179	28.8	13.1	2800	2716	1300	1261	0.40114
Methanol-hybrid	234066	28.8	13.1	2800	2716	1415	1261	0.40476

Table 5-3 Overall efficiencies

The efficiency of the methanol hybrid case is 0.036 higher than the other cases and is due to the accuracy of the boundary conditions neglectable.

The most efficient case is the one that uses the least amount of energy. Therefore, the energy consumption of the three cases is compared in Table 5-4.

Condition	Unit	CONVENTIONAL VESSEL	METHANOL-DIRECT	METHANOL-HYBRID
Upstream	[kWh]	190309	190309	190309
Downstream	[kWh]	45870	45870	43757
Total	[kWh]	236179	236179	234066
Total in terms of MGO	[ton]	19.914	19.914	19.736

Table 5-4 Comparison energy consumption

Considering sailing both upstream and downstream, the methanol-hybrid configuration uses 0.9 % less energy that the methanol direct configuration. The hybrid case is more efficient because the two engines that are running downstream can run on a more efficient load. Even with the PTO, electrical system, PTI and gearbox that have losses of energy. But due to the accuracy of the boundary conditions, the absolute difference in efficiency is neglectable.

5.3 LSW & DWT

In this section the LSW and DWT will be compared. the comparison is shown in Table 5-5.

Component	Unit	CONVENTIONAL VESSEL	METHANOL DIRECT	METHANOL-HYBRID
LSW	[ton]	773	774	778
DWT	[ton]	162	161	157
Displacement	[ton]	935	935	935

Table 5-5 Comparison LSW and DWT

5.4 Harmful Emissions

In this section a comparison between the absolute emissions per case per year is made. The emissions are shown in Table 5-6.

Emission types	Absolute emissions [ton/year] CONVENTIONAL	Absolute emissions [ton/year] METHANOL-DIRECT	Absolute emissions [ton/year] METHANOL-HYBRID
CO2-eq WTP	15347.84	5320.84	4900.21
SOx	5.21	0.88	0.71
NOx*	48.50	48.50	49.26
PM10	3.42	0.58	0.47
PM2.5	3.16	0.53	0.43
CO	9.85	2.50	2.23
NMVOC	9.13	1.54	1.25

Table 5-6 Comparison emissions

5.5 Engine running hours

In this section the engine running hours are compared. The comparison is shown in Table 5-7.

Condition			CONVENTIONAL		METHANOL-DIRECT		METHANOL-HYBRID	
	hours per trip	trips per year	engines running	total hours	engines running	total hours	engines running	total hours
Upstream	28.8	191	4	22003.2	4	22003.2	4	22003.2
Downstream	13.1	191	4	10008.4	4	10008.4	2	5004.2
Total				32011.6		32011.6		27007.4
Average per engine				8002.9		8002.9		6751.85

Table 5-7 Engine running hours comparison

The methanol hybrid case has less running hours in comparison with the other cases. Less running hours increases the lifespan of the engines. The methanol hybrid case has about 16% less running hours.

5.6 Conclusion

This section gives the conclusion of the methanol cases in percentage towards the conventional case. The results of the comparison are summarised in Table 5-8.

Component	Unit	METHANOL-DIRECT	METHANOL-HYBRID
LSW	[%]	+0.13	+0.64
DWT margin	[%]	-58.01	-64.57
Fuel Volume	[%]	+111.20	+113.36
Fuel Weight	[%]	+95.21	+97.03
Running hours engine	[%]	+0.00	-15.63
Energy consumption	[%]	+0.00	-0.90
Emissions CO2eq	[%]	-65.33	-68.07
Emissions SOx, PM10, PM2.5, NMVOC	[%]	-83.10	-86.30
Emissions NOx*	[%]	+0.00	+0.00
CO	[%]	-74.62	-77.36

Table 5-8 Conclusion comparison towards conventional case

*Methanol offers potential for reduced NOx emissions, exact reduction to be determined in a later design stage

The table above shows that the volume and weight of the fuel is doubled with respect to the conventional case. The DWT margin is decreased in both methanol cases, however sufficient margin is left. The values of the table are including MGO as pilot fuel.

In terms of the efficiency of the propulsion system there are no significant differences between the methanol-direct case and the methanol-hybrid case. However, the methanol-hybrid case significantly reduces the running hours of the engine, which could reduce the maintenance cost.

Since the system efficiencies of the methanol-direct and methanol-hybrid system are almost equal there is also no significant difference between the emissions of both cases. However, relative to the conventional case the methanol cases achieve a significant reduction in both greenhouse gas and pollutant emissions. Unfortunately, the NOx emission are not reduced in both methanol cases.

6 INITIAL METHANOL DESIGN

In this chapter, the design will be presented by a general arrangement, 3D renders, tank capacities and additional systems.

6.1 General arrangement

The philosophy of the design is to create as less as possible cofferdams to save volume for fuel and other equipment. In the new methanol design, the old ballast tanks in the bow on both sides are used for the methanol storage. The general arrangement is added in the attachment.

6.2 Tank capacities

In Table 6-1, a comparison of the gross volumes of the tanks is shown.

MGO	**Volume 3D model [m^3]**	**Min. required volume conventional case [m^3]**	**Min. required volume methanol-direct [m^3]**	**Min. required volume methanol-hybrid [m^3]**
SB1	39.0	-	-	-
SB2	13.4	-	-	-
SB3	9.5	-	-	-
BB1	22.8	-	-	-
BB2	16.3	-	-	-
BB3	9.5	-	-	-
Total	110.4	52.5	8.7	7.2
Methanol				
SB	53.2	-	-	-
BB	53.2	-	-	-
Total	106.4	-	101.9	104.8

Table 6-1 Gross tank volumes

The minimum required volume of the methanol direct case is 101.9 m^3 and the methanol hybrid is 104.8 m^3. That means that there fits enough methanol in the ship to sail the range of the operational profile in both cases. There is also enough capacity to reach the range on MGO only if there is no methanol available.

6.3 Additional systems

A methanol system exists of a lot of components. Not all the required components are shown in the renders in section 6.4. The components that are shown are:

- Engines
- generators
- Methanol tanks
- Methanol overflow tanks
- Fuel preparation rooms
- Airlocks

The required components that are not shown and need to be implemented in a later stadium are:

- Vent system & vent mast/outlets
- Ventilation system
- Nitrogen system
- Double walled piping
- Switchboards
- SCR system & urea tank

6.4 Renders

This section shows the renders of the inside of the vessel. the renders are visible in Figure 6-1 and Figure 6-2. The engines are light green and the MGO tanks are red. Further are the methanol tanks and methanol overflow tanks purple. The blue tanks are for fresh water.

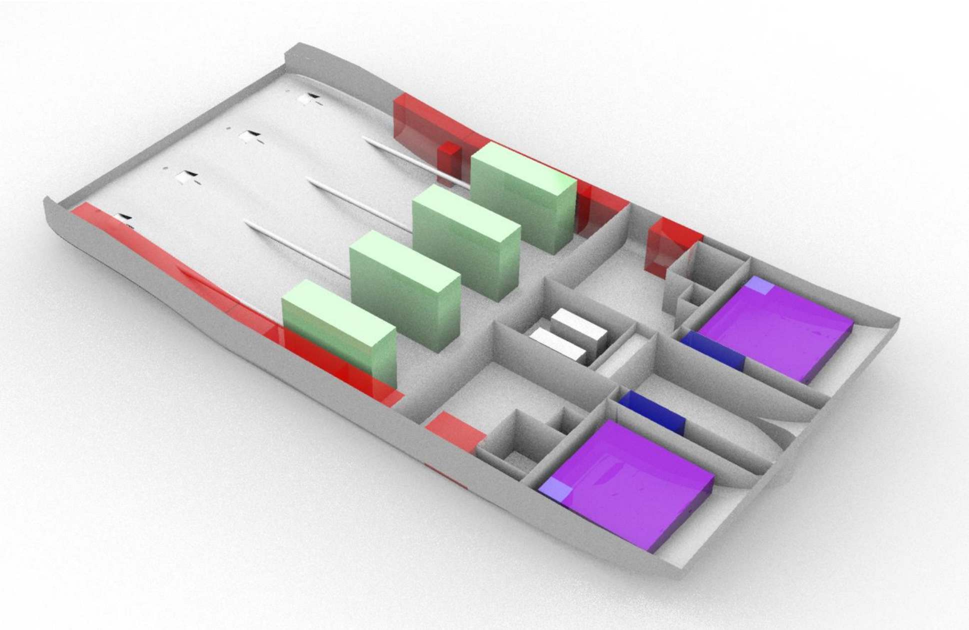

Figure 6-1 Render inside starboard

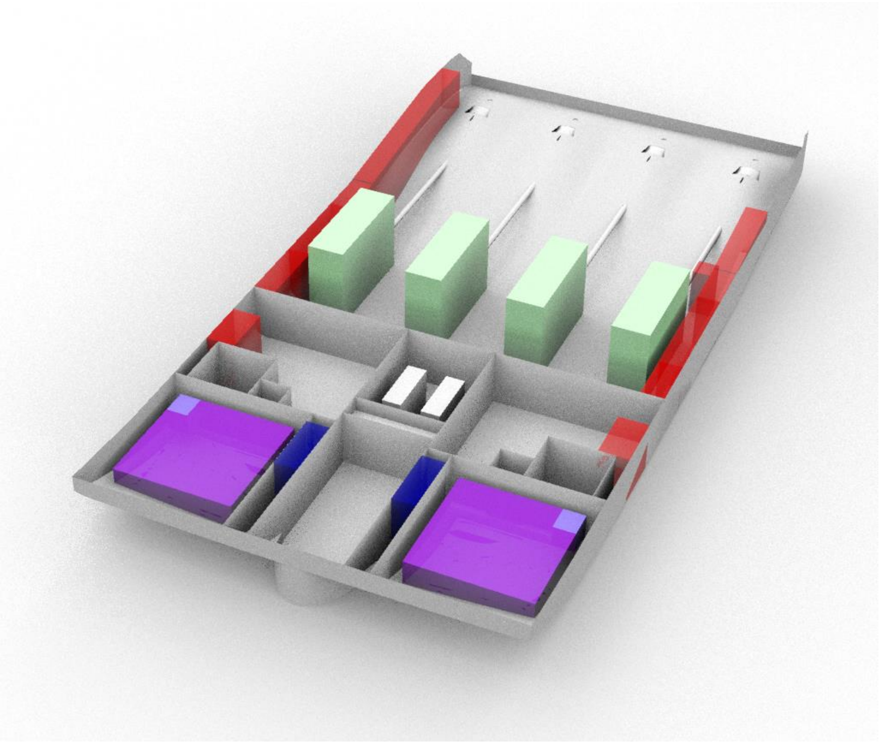

Figure 6-2 Render inside front

The 3D renders of the outside of the ship are shown in section 2.2.

7 CONCLUSION & RECOMMENDATIONS

7.1 Conclusion

To store sufficient fuel for the required autonomy both methanol designs require more than two times as much volume as the conventional design. However, due to the increased breadth of 20 meters, the methanol fuel storage system fits in the vessel.

The methanol vessels require additional components such as an extra engine, a fuel preparation space, and multiple smaller components such as the nitrogen system. All these components fit in the new vessel because of the increased width.

The propulsion system of the methanol-hybrid case requires more space than the methanol-direct case because of the PTO, PTI, and a larger electrical system. However, it is expected that this is also feasible in terms of volume.

In terms of weight both methanol cases are feasible, the methanol designs have a DWT margin of 32 ton for methanol-direct and 27 ton for methanol-hybrid with a maximum draught of 1.6 meter.

The efficiency of the conventional and methanol-direct system are expected to be the same. The overall efficiency of the methanol-direct system is 40.1%, and the efficiency of the methanol-hybrid system is 40.5%. The difference in efficiencies between the methanol-direct and the methanol-hybrid system are considered negligible because of the uncertainty in the estimated efficiencies. However, the engines of the methanol-hybrid system have 15.6% less running hours per trip because the system only uses two combustion engines while sailing downstream. This could significantly reduce the maintenance cost.

The methanol cases emit 65% less CO_2eq emissions compared to the conventional system. Other emissions are reduced with more than 74%. Relative to the conventional case the NOx emission of the methanol cases are not reduced. However, relative to the reference vessel the conventional design has already a reduction of NO_x because of the SCR system.

7.2 Recommendations

For follow-up studies it is recommended to consider the impact of hazardous zones on the design. Hazardous zones are applicable for ventilation and pressure relief vent outlets that can potentially release methanol (vapour) into the air. Hazardous zones can have a large impact on the arrangement of the vessel because regulations forbid entrances, ventilation inlets, and ignition sources to be placed in hazardous zones.

Secondly, it is recommended to do a more detailed LWS analysis in later design stages. Furthermore, because the methanol fuel tanks are located in the forward part of the ship, it is recommended to check the impact of the new configuration on the longitudinal trim of the vessel.

To choose between the methanol-direct and the methanol-hybrid system it is recommendation is to do a cost analyse of the three cases with emphasis on the difference between the methanol-direct and the methanol-hybrid system. This analysis should clarify if the reduction in running hours of the hybrid system compensated the relatively expensive hybrid system.

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