MAR-E-FUEL project

TOTAL COST OF OWNERSHIP (TCO)

Sustainable Maritime Fuels

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TABLE OF CONTENTS:

1. Introduction
2. Definitions
3. Model structure
4. Results in short
    4.1. Economics
    4.2. Large vs small vessels
    4.3. Emissions
    4.4. Conclusions
5. Model description

Enclosure 1: TCO for all fuels analyzed
Enclosure 2: Fuel emissions
Enclosure 3: Ship emissions - Well to Tank & Tank to Wake

1: Introduction:

Transportation by ship provides ca. 3% of global CO_2, and is a global industry, which is hard to regulate. Stakeholders in shipping are living in a volatile commercial setting, and are unlikely to adopt new technologies, unless they are well proven and reasonably predictable. Change in stakeholder behavior require robust incentives, with a focus on cashflow.

The objective of the Total Cost of Operation (TCO) model is to provide an independent and simple tool providing the total costs including fuel and ship costs, which allows stakeholders in shipping to determine **under which conditions and scenarios, it may be feasible to switch from fossil to green fuels, sometime in the future.**

It is technically possible to build a CO_2 neutral ship from 2024 onwards. If a stakeholder decided to build a CO_2 neutral ship today, he will however face a number of dilemmas:

Demand in terms of fuel volume is enormous

A single large containership (15.000 teu) consumes up to 40.000 tons of fuel per year, of which there are many hundreds. Consequently, extremely high quantities of green fuels are required to achieve substantial GHG emission reductions.

Green fuels are not available in massive quantities yet

As long as cheap, sustainable biomass is available, biofuels can provide green fuels, but production capacities have to be built. Green e-fuels on the other hand require electricity, and if all shipping demand shall be met by green fuels, the sustainable electricity capacity will increase substantially. That effort in itself is historic in volumes, and it may take decades to build the new wind- and solar farms required, let alone acquiring property rights and permissions. Only after 2030, will sufficient green fuels become available for a full transition to happen.

The green fuels production will impact on a global scale and needs clarification

Shipping is competing with other industries for electrical and biomass resources. The exact value chains are important for the impact on the environment, and hence transparent green fuel certifications based on life cycle assessments are needed for ship owners to understand the dynamics and the implications for the environment.

Chicken and egg analogy

Who takes the risk of building new green fuel factories, without a secure demand??

Who takes the risk of building a new green ship, without a secure supply chain??

Both shipping and fuel communities are mobilizing and need tools to help manage risks in the short- and long term. This tool is independent and open source.

2: Definitions

Definitions are listed in the TCO model and below. Reference is made to DTU reports as part of the MAR-E-Fuel project.

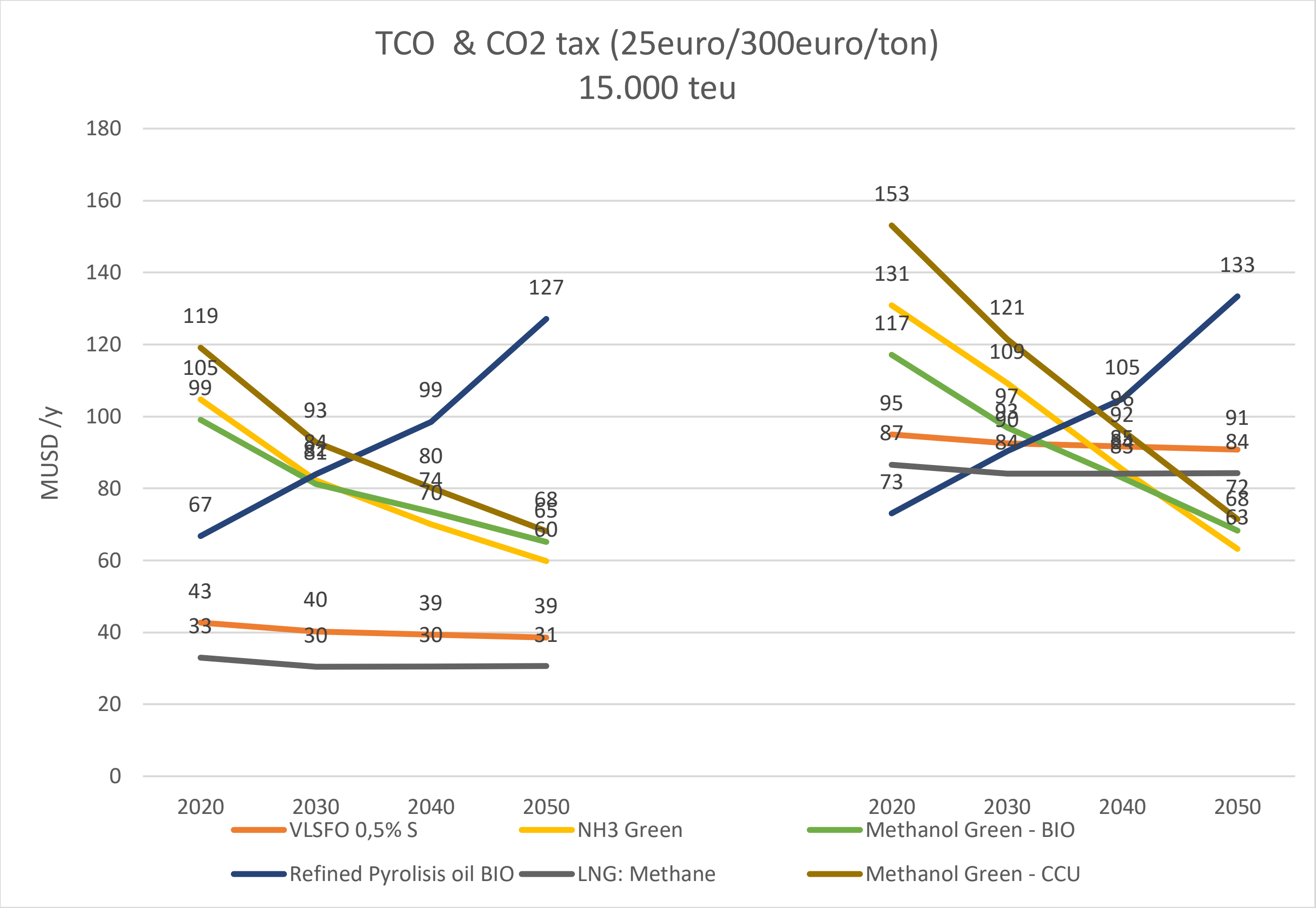
3: TCO Model structure

The model is bottom-up estimation of costs and emissions from operating a containership in the sizes 1200 teu (6mW main engine), 2500 teu (14mW) and 15.000 teu (50mW). The model is striving to include all costs and emissions associated with operating a ship. By nature, the input assumptions are estimates and/or guestimates, subject to input supplied by credible stakeholders and the judgement of the authors, when needed.

Reference is made to an excel file: FINAL 2050_TCO_Shipping feature benefits_29.09.21_tas_pvh_IMO_TTW_logic_fin

4: TCO model results in short

4.1: Economic model:



The 2 clusters of data represent TCO in MUSD/y at **LOW** & **HIGH** CO_2 tax, spanning a period from 2020-2050, for selected fuels:
VLSFO, Ammonia Green, Methanol Green BIO, Refined Pyrolysis Oil-Bio, LNG Methane, Methanol Green CCU.

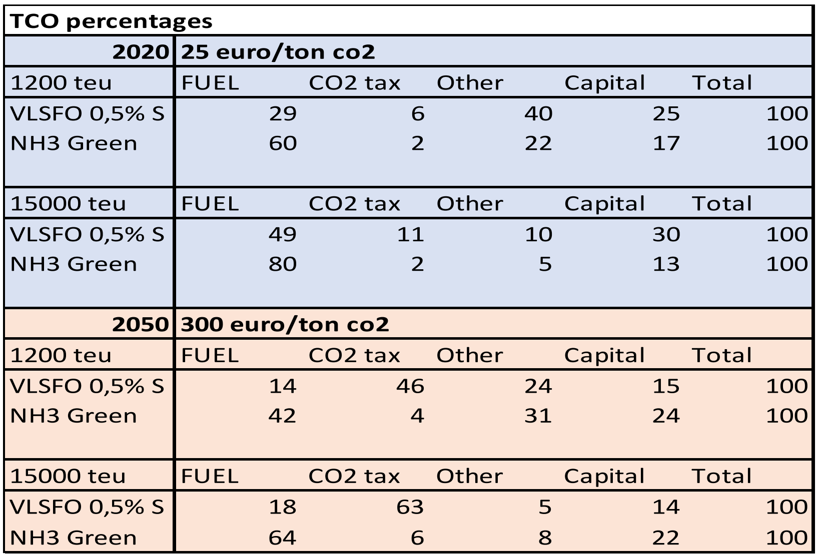
Low CO_2 tax (25€/ton CO_2):
Shipowners have no economic incentive to adopt green fuels, with a low CO_2 tax. The green fuels remain 2-4 times more expensive than fossil fuels from 2020-2050. Unless higher income from operations compensates for extra OPEX and CAPEX, a voluntary shift into green fuels is highly unlikely.

Dynamics: Green NH_3 and green Methanol are forecast to deliver similar cost levels over the period. Refined Pyrolysis oil is initially the cheapest green solution, at only +50% higher than fossil fuels, and can most likely be fitted to existing ships. The price for biomass based green fuels are likely to increase significantly after 2030, due to competing uses of biomass. (Airplanes & industry)

HIGH CO_2 tax (300€/ton CO_2):
Shipowners are likely to have an economic incentive to shift to Refined Pyrolysis oil immediately after a high CO2 tax has been introduced. Refined Pyrolysis oil appear to be an attractive green option, enforced by the benefit of possibly be applied to existing ship, albeit with bigger tanks.
Green Methanol Bio appear to be competitive from 2030 onwards and NH_3 from 2035, as well.
From 2030-2035 the green solutions appear to be lower cost than fossil fuels.

Dynamics: A 300€/ton CO_2 tax level is unlikely to be adopted by EU, US, or China. A gradual step up of tax level is more likely. In that event shipowners will have little incentive to shift into green fuels.

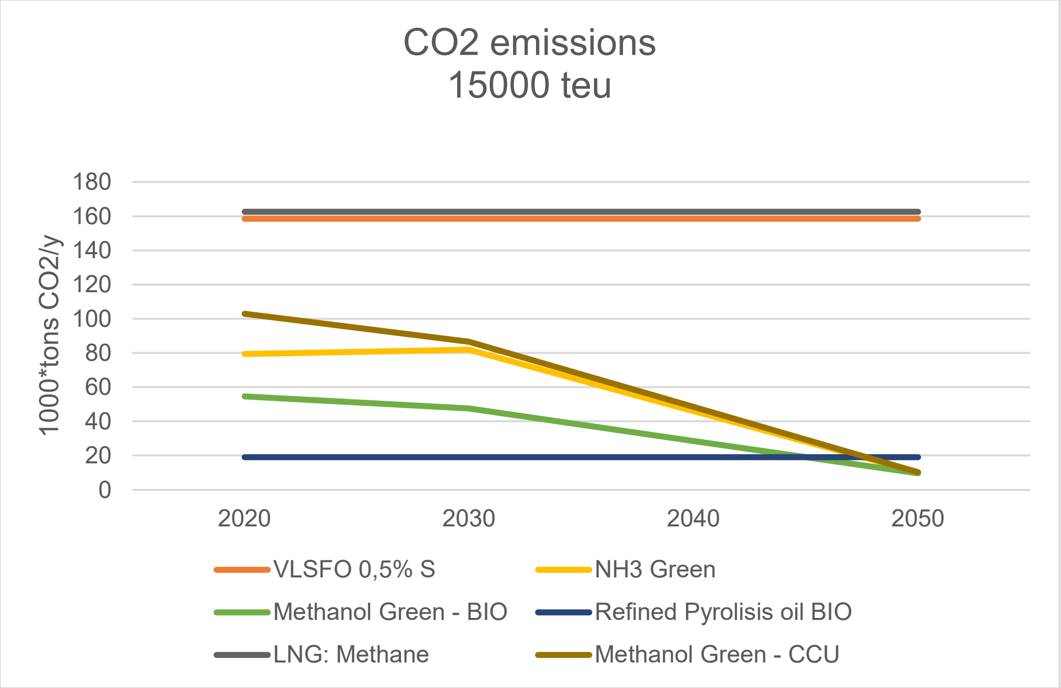
4.2 Large vs small ship:



TCO percentages					
2020	**25 euro/ton co2**				
1200 teu	FUEL	CO2 tax	Other	Capital	Total
VLSFO 0,5% S	29	6	40	25	100
NH3 Green	60	2	22	17	100
15000 teu	FUEL	CO2 tax	Other	Capital	Total
VLSFO 0,5% S	49	11	10	30	100
NH3 Green	80	2	5	13	100
2050	**300 euro/ton co2**				
1200 teu	FUEL	CO2 tax	Other	Capital	Total
VLSFO 0,5% S	14	46	24	15	100
NH3 Green	42	4	31	24	100
15000 teu	FUEL	CO2 tax	Other	Capital	Total
VLSFO 0,5% S	18	63	5	14	100
NH3 Green	64	6	8	22	100

Dynamics: Small ships spend less on fuel than large ships (29% vs 49% based on fossil fuels and low CO_2 tax. The small ship is much less sensitive to an increase in fuel costs, however small ships contribute only a fraction of global shipping CO_2 emissions. It is assumed that 20% of ships deliver approx 80% of emissions. Consequently, policymakers could initially introduce a technical regulation, forcing small ships, (likely to operate near shore) to adopt green solutions, without causing too much economic turmoil in the relevant value chains, ie a ban on CO_2 emissions on ships operating between EU ports, as an example.

4.3 CO_2 emissions model: Well to Wake (production + combustion of fuel)



The TCO model estimates total emissions of CO_2 in *1000 tons/year.
Green fuels are from 2020 onwards a factor 8-16 lower emissions than fossil fuels
In 2020 fossil fuels are at approx. 160.000 tons/year, and refined pyrolysis oil is at 20.000 tons/year, i.e., 8 times less than fossil fuels. Initially high emission, electrical power from fossil sources is mixed into production, for cost reasons.
Eventually in 2050 other green fuels are at emissions of only 10.000 tons/year, i.e., a factor of 16 times less emissions than fossil fuels.
Technically the green fuels can deliver a vast reduction in emissions, however they appear not to be economically viable until 2035, as per section 4.1.

4.4 Conclusion: Technical regulation is likely to be only option to deliver reduced emissions from shipping, and a gradual increase of CO_2 tax will support the transition.

Predicated on the fact that a high CO_2 tax is unlikely for the 10-20 years, then shipowners do not have an economic incentive to reduce emissions.
However, the green fuels can deliver 8-16 times less CO_2 emission, and consequently technical regulation is more likely to deliver a reduction in CO_2 emissions, ie. a total ban on emissions on ships wishing to enter EU and/or US waters and harbors, or many other technical options.

The transition to green fuels will be gradual in the period 2020-2030. Existing ships are not relevant for green fuels except for perhaps refined pyrolysis oil, and therefore green capacity of ships will be predicated on how fast a next generation of ships can be built. In parallel the capacity to deliver electrical power and green fuel factories shall be built from zero, and such expansion is likely to take decades to materialize in practice.
Technical regulation of small ships, operating near shore, is possibly a first step. Small ship spending on fuel is relatively less, and a large increase in fuel costs may have relatively small impact on the relevant value chain total costs, because transportation is in turn a small fraction of total costs, of f.ex clothing.

5:Input description

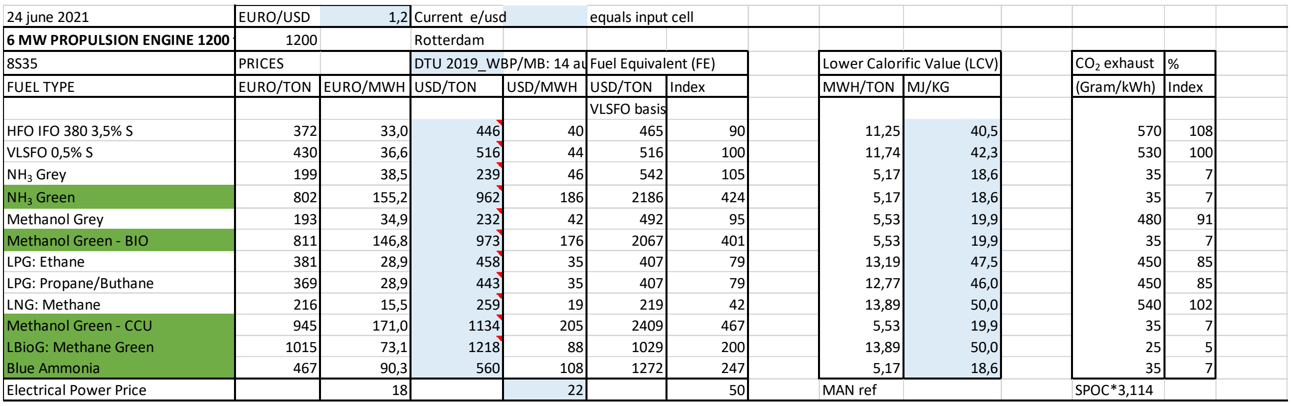
The list of fuels is narrowed down to fuels that are practical and realistic in a ship, in terms of CAPEX and risk.

Type of fuel

Abbreviation	Name	Description
HFO	Heavy Fuel Oil	Conventional fossil fuel.
VLSFO	Low Sulphur Fuel Oil	Conventional fossil fuel. Sulphur content ≤0.5%
AMM-grey	Ammonia (grey)	Conventional ammonia produced from fossil natural gas.
AMM-blue	Ammonia (blue)	Ammonia produced from fossil natural gas with carbon capture.
AMM-green	Ammonia (green)	Ammonia produced from water electrolysis.
MET-Grey	Methanol (grey)	Conventional methanol produced from fossil natural gas.
MET-e-bio	Methanol (e-bio)	Methanol produced from gasification of residual biomass and hydrogen from water electrolysis.
LNG	Liquefied Natural Gas	Conventional fossil fuel.
LPG	Liquefied Petroleum Gas	Conventional fossil fuel.
MET-CCU	Methanol (CCU)	Methanol produced from point source carbon bio energy carbon capture and utilization (BECCU), and hydrogen from water electrolysis.
LBG	Liquefied Biogas	Liquefied biogas generated from manure or organic waste.

Below you can see an illustration from the TCO model spread sheet

TAB: Overview



24 june 2021	EURO/USD	1,2	Current e/usd		equals input cell					
6 MW PROPULSION ENGINE 1200	1200		Rotterdam							
8S35	PRICES		DTU 2019_WBP/MB: 14 au		Fuel Equivalent (FE)		Lower Calorific Value (LCV)		CO_2 exhaust	%
FUEL TYPE	EURO/TON	EURO/MWH	USD/TON	USD/MWH	USD/TON	Index	MWH/TON	MJ/KG	(Gram/kWh)	Index
					VLSFO basis					
HFO IFO 380 3,5% S	372	33,0	446	40	465	90	11,25	40,5	570	108
VLSFO 0,5% S	430	36,6	516	44	516	100	11,74	42,3	530	100
NH_3 Grey	199	38,5	239	46	542	105	5,17	18,6	35	7
NH_3 Green	802	155,2	962	186	2186	424	5,17	18,6	35	7
Methanol Grey	193	34,9	232	42	492	95	5,53	19,9	480	91
Methanol Green - BIO	811	146,8	973	176	2067	401	5,53	19,9	35	7
LPG: Ethane	381	28,9	458	35	407	79	13,19	47,5	450	85
LPG: Propane/Buthane	369	28,9	443	35	407	79	12,77	46,0	450	85
LNG: Methane	216	15,5	259	19	219	42	13,89	50,0	540	102
Methanol Green - CCU	945	171,0	1134	205	2409	467	5,53	19,9	35	7
LBioG: Methane Green	1015	73,1	1218	88	1029	200	13,89	50,0	25	5
Blue Ammonia	467	90,3	560	108	1272	247	5,17	18,6	35	7
Electrical Power Price		18		22		50	MAN ref		SPOC*3,114	

Fuel prices

The input field is USD/ton, and the sources are:

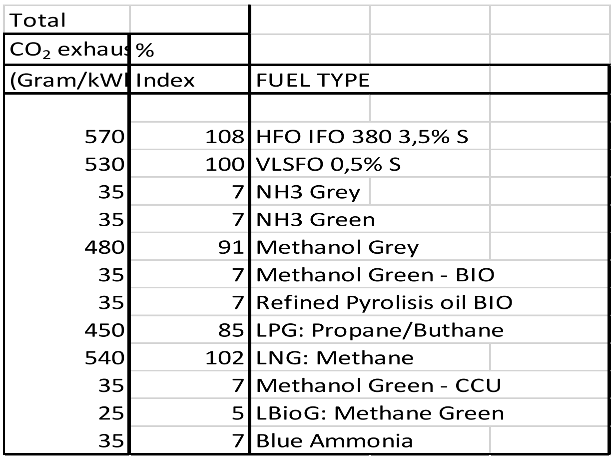
1. Green fuels: DTU MAN cost estimations as per tab DTU Input Costs and Emissions. (See separate reports)
2. Fossil fuels: Estimations from Copenhagen Economics (see separate reports)

USD/ton is converted into Euro/ton and Euro/mWh via the input field Euro/USD and

Lower Calorific Value (LCV). The Euro/USD rate is determined on the date of the model issue from DK public sources, and LCV is referring to MAN official definitions. Fuel Equivalent (FE) is a trade term from shipping, which defines the cost of fuels based on VLSFO, into

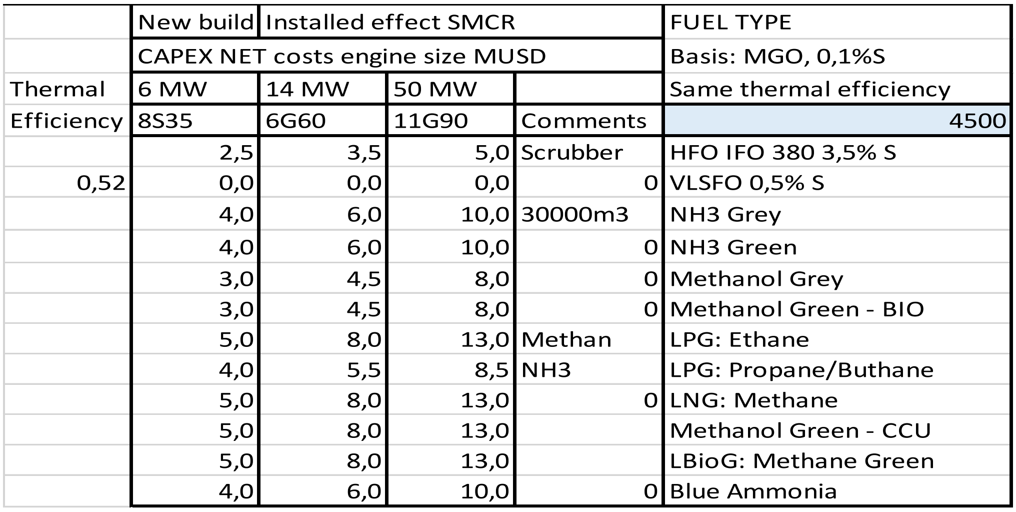
CO2e emissions

See tab „Technical Details". The source is MAN. Exhaust from pilot oil equals VLSFO. The values for fossil fuel is corrected by the thermal efficiency of engine, defined as 52%.



Total		
CO_2 exhau	%	
(Gram/kW	Index	FUEL TYPE
570	108	HFO IFO 380 3,5% S
530	100	VLSFO 0,5% S
35	7	NH3 Grey
35	7	NH3 Green
480	91	Methanol Grey
35	7	Methanol Green - BIO
35	7	Refined Pyrolisis oil BIO
450	85	LPG: Propane/Buthane
540	102	LNG: Methane
35	7	Methanol Green - CCU
25	5	LBioG: Methane Green
35	7	Blue Ammonia

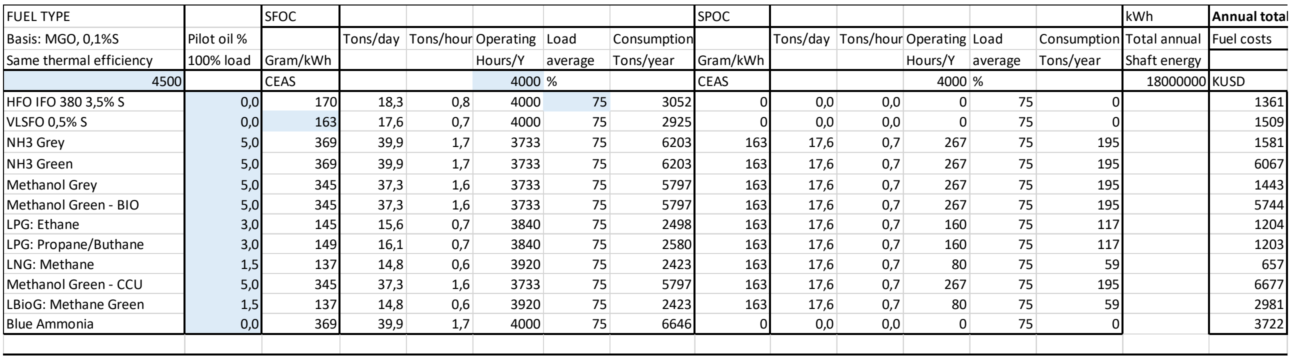
CAPEX from extra tanks, fuel systems, etc.



	New build	Installed effect SMCR			FUEL TYPE
	CAPEX NET costs engine size MUSD				Basis: MGO, 0,1%S
Thermal	6 MW	14 MW	50 MW		Same thermal efficiency
Efficiency	8S35	6G60	11G90	Comments	4500
	2,5	3,5	5,0	Scrubber	HFO IFO 380 3,5% S
0,52	0,0	0,0	0,0	0	VLSFO 0,5% S
	4,0	6,0	10,0	30000m3	NH3 Grey
	4,0	6,0	10,0	0	NH3 Green
	3,0	4,5	8,0	0	Methanol Grey
	3,0	4,5	8,0	0	Methanol Green - BIO
	5,0	8,0	13,0	Methan	LPG: Ethane
	4,0	5,5	8,5	NH3	LPG: Propane/Buthane
	5,0	8,0	13,0	0	LNG: Methane
	5,0	8,0	13,0		Methanol Green - CCU
	5,0	8,0	13,0		LBioG: Methane Green
	4,0	6,0	10,0	0	Blue Ammonia

In addition to CAPEX for a standard VLSFO ship an estimate of extra CAPEX is made, for each size of engine, and type of fuel. The source is a guestimate from the authors, based on experience, and is subject to more detailed engineering.

Fuel consumption and costs



FUEL TYPE		SFOC						SPOC						kWh	**Annual total**
Basis: MGO, 0,1%S	Pilot oil %		Tons/day	Tons/hour	Operating	Load	Consumption		Tons/day	Tons/hour	Operating	Load	Consumption	Total annual	Fuel costs
Same thermal efficiency	100% load	Gram/kWh			Hours/Y	average	Tons/year	Gram/kWh			Hours/Y	average	Tons/year	Shaft energy	
4500		CEAS			4000	%		CEAS			4000	%		18000000	KUSD
HFO IFO 380 3,5% S	0,0	170	18,3	0,8	4000	75	3052	0	0,0	0,0	0	75	0		1361
VLSFO 0,5% S	0,0	163	17,6	0,7	4000	75	2925	0	0,0	0,0	0	75	0		1509
NH3 Grey	5,0	369	39,9	1,7	3733	75	6203	163	17,6	0,7	267	75	195		1581
NH3 Green	5,0	369	39,9	1,7	3733	75	6203	163	17,6	0,7	267	75	195		6067
Methanol Grey	5,0	345	37,3	1,6	3733	75	5797	163	17,6	0,7	267	75	195		1443
Methanol Green - BIO	5,0	345	37,3	1,6	3733	75	5797	163	17,6	0,7	267	75	195		5744
LPG: Ethane	3,0	145	15,6	0,7	3840	75	2498	163	17,6	0,7	160	75	117		1204
LPG: Propane/Buthane	3,0	149	16,1	0,7	3840	75	2580	163	17,6	0,7	160	75	117		1203
LNG: Methane	1,5	137	14,8	0,6	3920	75	2423	163	17,6	0,7	80	75	59		657
Methanol Green - CCU	5,0	345	37,3	1,6	3733	75	5797	163	17,6	0,7	267	75	195		6677
LBioG: Methane Green	1,5	137	14,8	0,6	3920	75	2423	163	17,6	0,7	80	75	59		2981
Blue Ammonia	0,0	369	39,9	1,7	4000	75	6646	0	0,0	0,0	0	75	0		3722

SFOC=Specific Fuel Oil Consumption, based on MAN-ES calculation system CEAS (Computerized Engine Application System). Values are expressed in gram/kWh shaft power. A derating of 75% (load average) is assumed, i.e., a 6000kW engine delivers 4500kW shaft power, based on optimal SFOC. Same derating for all sizes of engines. Annual consumption in tons is calculated for each fuel.

SPOC=Specific Pilot Oil Consumption, based on MAN_ES calculation system CEAS (Computerized Engine Application System). Values are expressed in gram/kWh shaft power. SPOC is defined as VLSFO, and consumption in kWh is considered constant as if rating is 100%, regardless of sustainable fuel type. (See technical details). If SPOC equals 5% (NH3) of kWh of SFOC, and derating is 75%, then SFOC equals approx 7% of kWh shaft power, and likewise in terms of GHG emissions. Annual consumptions in tons is calculated for each fuel.

Operating hours=Estimated full load operating hours of the main engine, predicated on a typical sail pattern for size of ship.

1200	TEU:	4000hours	6mW installed effect
2500	TEU:	6000hours	14mW installed effect
15000	TEU:	6500hours	50mW installed effect

Fuel costs annually is calculated as a multiplication of price per ton by annual consumption per ton.

Ship size: Each size, 1.200, 2.500 & 15.000 TEU is calculated individually, for all fuel types. The model is adaptable to other types of ship, predicated on size of engine and other dimensions.

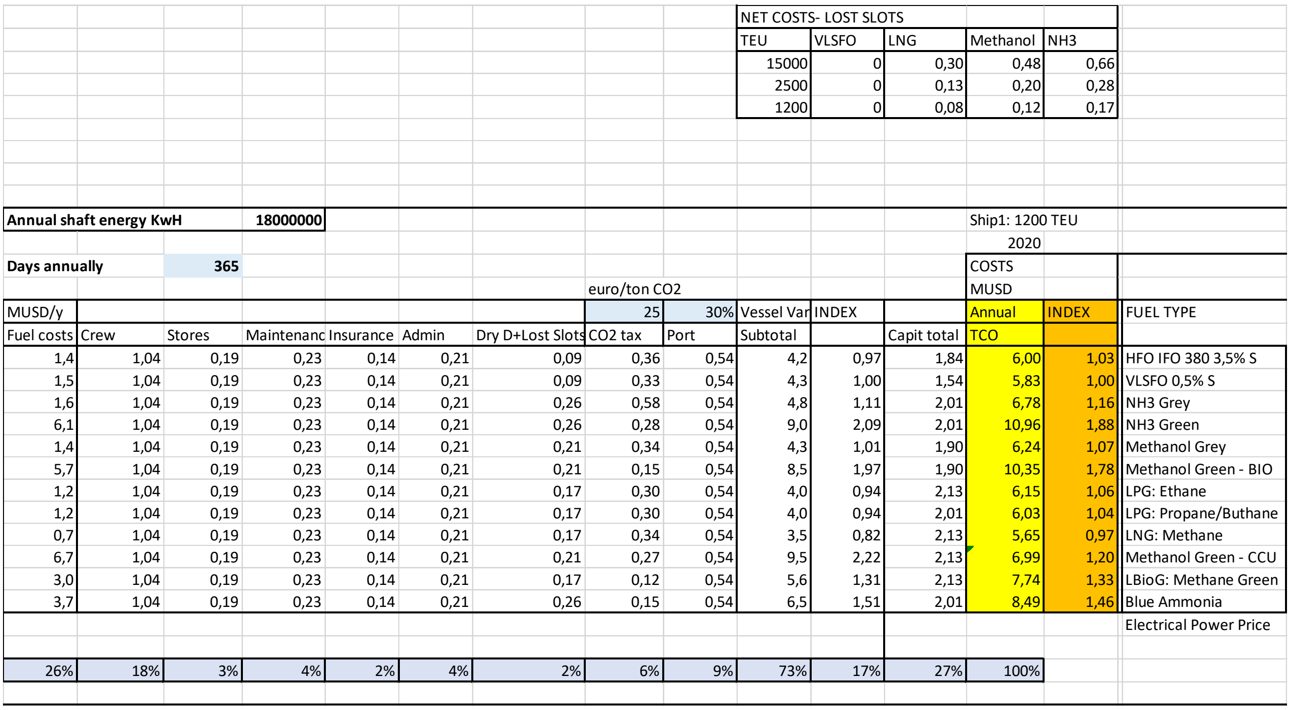
TAB: Economic details

Engine: 6 MW, 8S35	**Ship1: 1200 TEU**			**Hours/y**	**4000**	**Load%**
				Vessel value MUSD:		**18**
	25-feb-20					
	USD/TON	CO2-SHIP		MUSD	Annual	Vessel
Type of fuel	Fuel Price	g/kWh		FUELCAPEX	Fuel Capit	Vessel capit
HFO IFO 380 3,5% S	446	570		2,5	0,29	1,54
VLSFO 0,5% S	516	530		0,0	0,00	1,54
NH3 Grey	239	35		4,0	0,47	1,54
NH3 Green	962	35		4,0	0,47	1,54
Methanol Grey	232	480		3,0	0,35	1,54
Methanol Green - BIO	973	35		3,0	0,35	1,54
LPG: Ethane	458	450		5,0	0,59	1,54
LPG: Propane/Buthane	443	450		4,0	0,47	1,54
LNG: Methane	259	540		5,0	0,59	1,54
Methanol Green - CCU	1134	35		5,0	0,59	1,54
LBioG: Methane Green	1218	25		5,0	0,59	1,54
Blue Ammonia	560	35		4,0	0,47	1,54
Electrical Power Price	22	0				
	USD/mWh			Years	20	25
				Interest	10%	7%
				Annuity	0,12	0,09

Capital costs

CAPEX is defined as the sum of CAPEX of a standard VLSFO ship plus the CAPEX related to type of fuel.
The extra CAPEX is named FUELCAPEX. The FUELCAPEX is higher risk, and amortized over 20 years, with interest of 10%, equal to 12% annuity.

VESSELCAPEX is amortized over 25 years and interest of 7%, equal to 9% annuity.
The risk profile is authors subjective estimation, subject to individual preferences.
Capital costs are calculated as a sum of annuities. Source: Tab MB Newbuild.



NET COSTS- LOST SLOTS				
TEU	VLSFO	LNG	Methanol	NH3
15000	0	0,30	0,48	0,66
2500	0	0,13	0,20	0,28
1200	0	0,08	0,12	0,17

Annual shaft energy KwH **18000000**

Ship1: 1200 TEU
2020

Days annually **365**

												COSTS		
							euro/ton CO2					MUSD		
MUSD/y							25	30%	Vessel Var	INDEX		Annual	INDEX	FUEL TYPE
Fuel costs	Crew	Stores	Maintenanc	Insurance	Admin	Dry D+Lost Slots	CO2 tax	Port	Subtotal		Capit total	TCO		
1,4	1,04	0,19	0,23	0,14	0,21	0,09	0,36	0,54	4,2	0,97	1,84	6,00	1,03	HFO IFO 380 3,5% S
1,5	1,04	0,19	0,23	0,14	0,21	0,09	0,33	0,54	4,3	1,00	1,54	5,83	1,00	VLSFO 0,5% S
1,6	1,04	0,19	0,23	0,14	0,21	0,26	0,58	0,54	4,8	1,11	2,01	6,78	1,16	NH3 Grey
6,1	1,04	0,19	0,23	0,14	0,21	0,26	0,28	0,54	9,0	2,09	2,01	10,96	1,88	NH3 Green
1,4	1,04	0,19	0,23	0,14	0,21	0,21	0,34	0,54	4,3	1,01	1,90	6,24	1,07	Methanol Grey
5,7	1,04	0,19	0,23	0,14	0,21	0,21	0,15	0,54	8,5	1,97	1,90	10,35	1,78	Methanol Green - BIO
1,2	1,04	0,19	0,23	0,14	0,21	0,17	0,30	0,54	4,0	0,94	2,13	6,15	1,06	LPG: Ethane
1,2	1,04	0,19	0,23	0,14	0,21	0,17	0,30	0,54	4,0	0,94	2,01	6,03	1,04	LPG: Propane/Buthane
0,7	1,04	0,19	0,23	0,14	0,21	0,17	0,34	0,54	3,5	0,82	2,13	5,65	0,97	LNG: Methane
6,7	1,04	0,19	0,23	0,14	0,21	0,21	0,27	0,54	9,5	2,22	2,13	6,99	1,20	Methanol Green - CCU
3,0	1,04	0,19	0,23	0,14	0,21	0,17	0,12	0,54	5,6	1,31	2,13	7,74	1,33	LBioG: Methane Green
3,7	1,04	0,19	0,23	0,14	0,21	0,26	0,15	0,54	6,5	1,51	2,01	8,49	1,46	Blue Ammonia
														Electrical Power Price
26%	18%	3%	4%	2%	4%	2%	6%	9%	73%	17%	27%	100%		

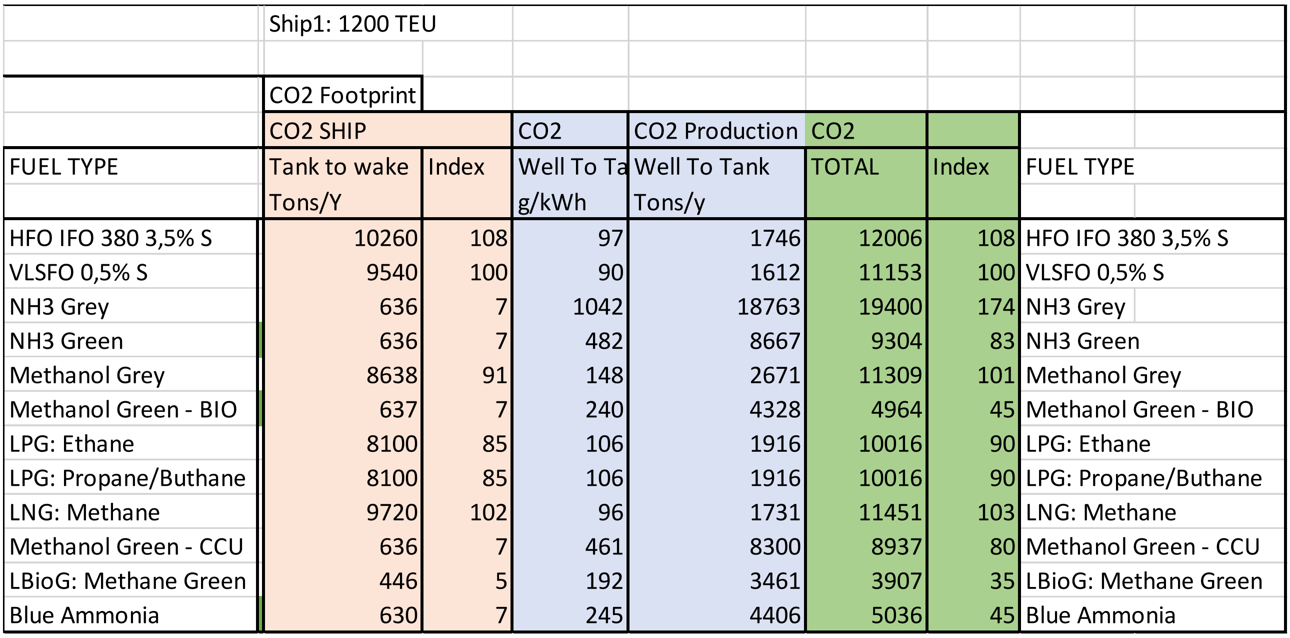
OPEX

Tab MB OPEX defines costs in USD per day, and are subdivided as follows:

- Fuel
- Crew
- Store
- Maintenance
- Insurance
- Admin
- Dry dock costs over 5 years + guestimated “Loss of container” value, due to larger tanks, as per Tab: Lost containers. Source: MAERSK plus authors
- CO_2 Tax: Input field calculates GHG tax as tax rate per ton multiplied by annual emissions in tons. Can easily be varied and is defined as 25 USD/ton in example.
- Port fees

TCO = OPEX + Capital costs as per above

CO$_2$ FOOTPRINT:



	Ship1: 1200 TEU						
	CO2 Footprint						
	CO2 SHIP		CO2	CO2 Production	CO2		
FUEL TYPE	Tank to wake Tons/Y	Index	Well To Ta g/kWh	Well To Tank Tons/y	TOTAL	Index	FUEL TYPE
HFO IFO 380 3,5% S	10260	108	97	1746	12006	108	HFO IFO 380 3,5% S
VLSFO 0,5% S	9540	100	90	1612	11153	100	VLSFO 0,5% S
NH3 Grey	636	7	1042	18763	19400	174	NH3 Grey
NH3 Green	636	7	482	8667	9304	83	NH3 Green
Methanol Grey	8638	91	148	2671	11309	101	Methanol Grey
Methanol Green - BIO	637	7	240	4328	4964	45	Methanol Green - BIO
LPG: Ethane	8100	85	106	1916	10016	90	LPG: Ethane
LPG: Propane/Buthane	8100	85	106	1916	10016	90	LPG: Propane/Buthane
LNG: Methane	9720	102	96	1731	11451	103	LNG: Methane
Methanol Green - CCU	636	7	461	8300	8937	80	Methanol Green - CCU
LBioG: Methane Green	446	5	192	3461	3907	35	LBioG: Methane Green
Blue Ammonia	630	7	245	4406	5036	45	Blue Ammonia

TTW: Ship emissions

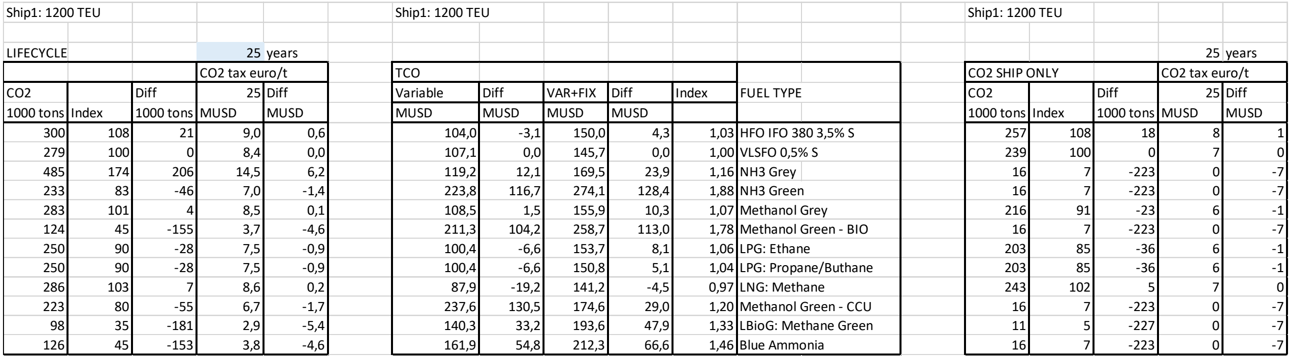
Emissions calculated on TCO model assumptions of fuel consumption in tons per year multiplied by the emission per ton, as per tab: overview.

WTT: Fuel production and transportation emissions

Emissions calculated on TCO model assumptions of fuel consumption in tons per year multiplied by the emission per ton, as per DTU model assumptions, detailed in tab: DTU input costs and emissions. Reference is made to separate DTU model and results reports: *MarE-fuel: Energy efficiencies in synthesising green fuels and their expected cost,* 9/9-2021, DTU Energy. *MarE-Fuel: Roadmaps for sustainable maritime fuels*, 19/10-2021, DTU Management.

TOTAL EMISSIONS equals TTW + WTT, for each fuel type.

25-year TOTAL COST & EMISSIONS



Ship1: 1200 TEU

LIFECYCLE 25 years

			CO2 tax euro/t	
CO2		Diff	25	Diff
1000 tons	Index	1000 tons	MUSD	MUSD
300	108	21	9,0	0,6
279	100	0	8,4	0,0
485	174	206	14,5	6,2
233	83	-46	7,0	-1,4
283	101	4	8,5	0,1
124	45	-155	3,7	-4,6
250	90	-28	7,5	-0,9
250	90	-28	7,5	-0,9
286	103	7	8,6	0,2
223	80	-55	6,7	-1,7
98	35	-181	2,9	-5,4
126	45	-153	3,8	-4,6

Ship1: 1200 TEU

TCO					
Variable	Diff	VAR+FIX	Diff	Index	FUEL TYPE
MUSD	MUSD	MUSD	MUSD		
104,0	-3,1	150,0	4,3	1,03	HFO IFO 380 3,5% S
107,1	0,0	145,7	0,0	1,00	VLSFO 0,5% S
119,2	12,1	169,5	23,9	1,16	NH3 Grey
223,8	116,7	274,1	128,4	1,88	NH3 Green
108,5	1,5	155,9	10,3	1,07	Methanol Grey
211,3	104,2	258,7	113,0	1,78	Methanol Green - BIO
100,4	-6,6	153,7	8,1	1,06	LPG: Ethane
100,4	-6,6	150,8	5,1	1,04	LPG: Propane/Buthane
87,9	-19,2	141,2	-4,5	0,97	LNG: Methane
237,6	130,5	174,6	29,0	1,20	Methanol Green - CCU
140,3	33,2	193,6	47,9	1,33	LBioG: Methane Green
161,9	54,8	212,3	66,6	1,46	Blue Ammonia

Ship1: 1200 TEU

25 years

CO2 SHIP ONLY			CO2 tax euro/t	
CO2		Diff	25	Diff
1000 tons	Index	1000 tons	MUSD	MUSD
257	108	18	8	1
239	100	0	7	0
16	7	-223	0	-7
16	7	-223	0	-7
216	91	-23	6	-1
16	7	-223	0	-7
203	85	-36	6	-1
203	85	-36	6	-1
243	102	5	7	0
16	7	-223	0	-7
11	5	-227	0	-7
16	7	-223	0	-7

A representation of annual costs and emissions scaled up to a total life perspective (25 years). The total VLSFO fuel costs for a small containership(1200 teu) equals approx. 38 MUSD compared to approx TCO of 145 MUSD. In terms of emissions approx 279.000 tons CO_2 are emitted, at no costs to ship operator, because no GHG tax is levied in shipping. If the tax equals 25 euro/ton, its full life value is approx. 8,4 MUSD.

TAB: 2020-2050

Serves as a repository of various scenario versions of the TCO model, predicated on differing input variables from Tab: DTU Emissions and costs.

Result tables are extracted and presented in slides.

TAB: LOST SLOTS (Net=diff from VLSFO ship)

NET COSTS- LOST SLOTS			USD/y	
TEU	VLSFO	LNG	Methanol	NH3
15000	0	300000	480000	660000
2500	0	125000	200000	275000
1200	0	75000	120000	165000

Estimated net loss of slots, as a consequence of larger tanks etc associated with sustainable fuels. Source: MAERSK & Authors.

TAB: DTU input costs and emissions: (bunkering in Rotterdam only)

Repository for input data from costs and emissions associated with production and transportation of types of fuels listed. Reference is made to separate DTU reports in MAR-E-Fuel project.

TAB: Transport rates UG (Ultra Gas)

Calculation and estimate of average transportation costs of fuels from possible production sites of sustainable fuels in Australia, Chile, Marokko and Danmark to Rotterdam, for central bunkering. The costs are input data to the DTU models calculating production and transportation costs and emissions of fuel. This TAB is used in DTU fuel price calculation models, and NOT in TCO model. Source: (Ultra Gas – Carsten Manniche) & authors.

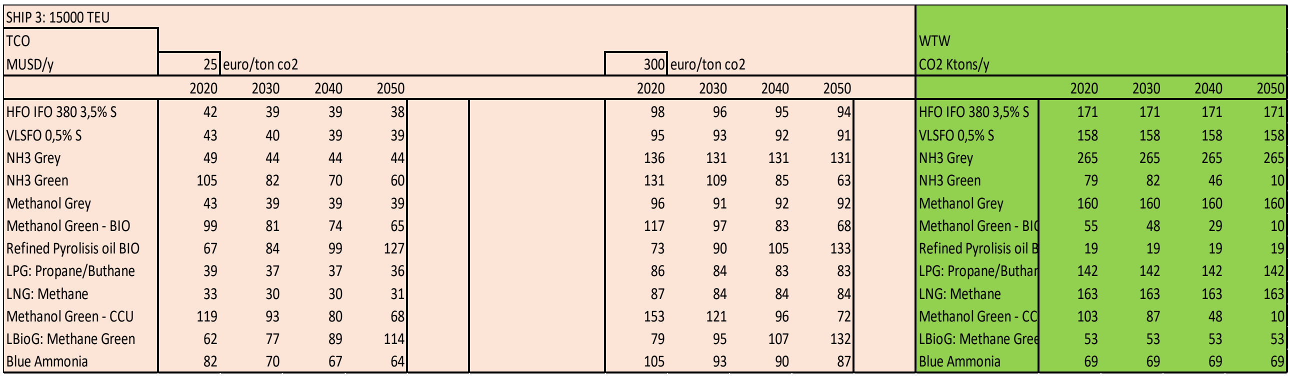
TAB: Technical details

Detailed specs of SPOC and CO_2 emissions from fuels. Source: MAN-ES

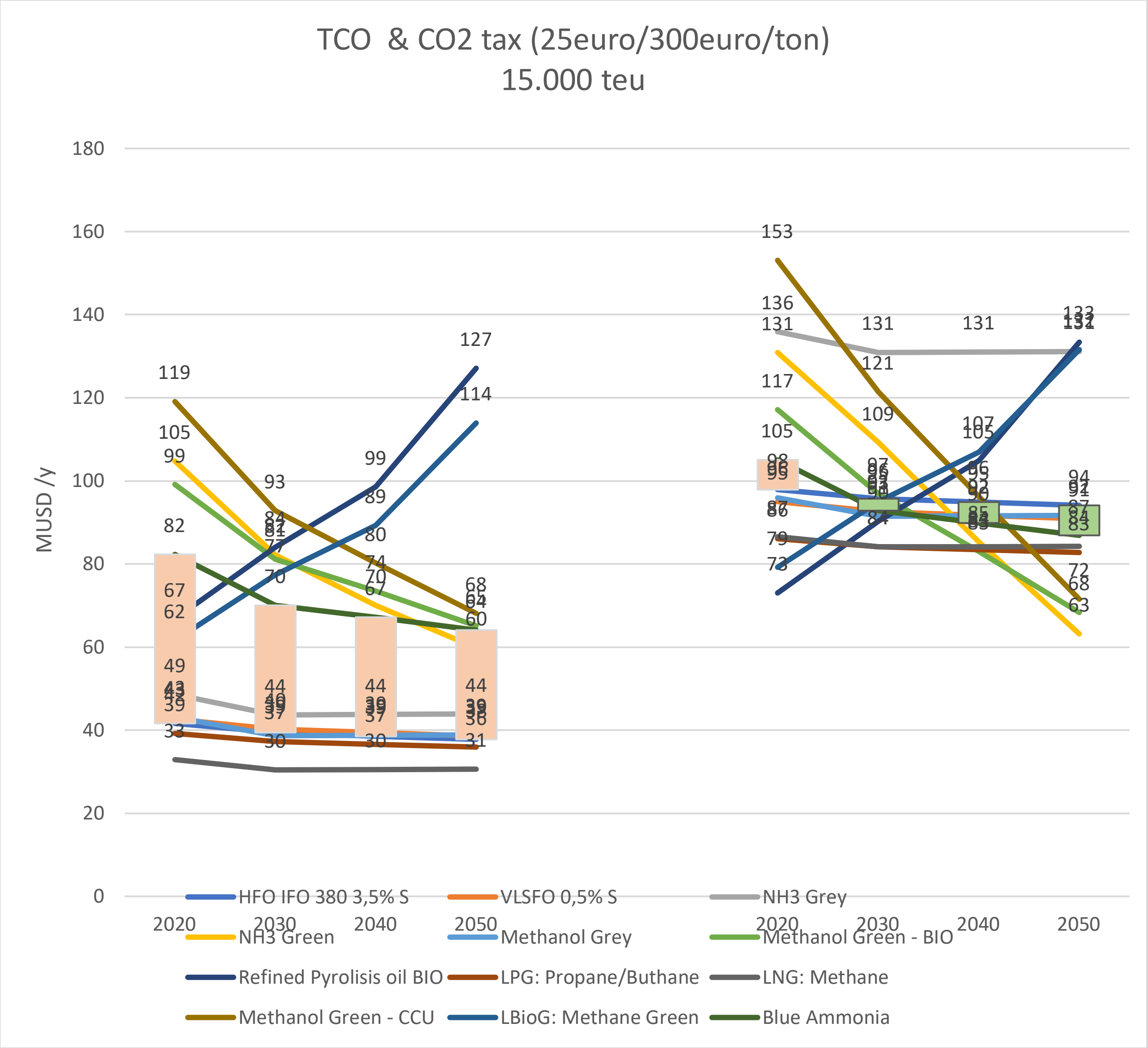
TABS: MB Newbuild prices, MB OPEX and MB bunker costs indicated by MAERSK Broker

Enclosure 1:

More details for all fuels:



SHIP 3: 15000 TEU													
TCO									WTW				
MUSD/y	25	euro/ton co2			300	euro/ton co2			CO2 Ktons/y				
	2020	2030	2040	2050	2020	2030	2040	2050		2020	2030	2040	2050
HFO IFO 380 3,5% S	42	39	39	38	98	96	95	94	HFO IFO 380 3,5% S	171	171	171	171
VLSFO 0,5% S	43	40	39	39	95	93	92	91	VLSFO 0,5% S	158	158	158	158
NH3 Grey	49	44	44	44	136	131	131	131	NH3 Grey	265	265	265	265
NH3 Green	105	82	70	60	131	109	85	63	NH3 Green	79	82	46	10
Methanol Grey	43	39	39	39	96	91	92	92	Methanol Grey	160	160	160	160
Methanol Green - BIO	99	81	74	65	117	97	83	68	Methanol Green - BI	55	48	29	10
Refined Pyrolisis oil BIO	67	84	99	127	73	90	105	133	Refined Pyrolisis oil B	19	19	19	19
LPG: Propane/Buthane	39	37	37	36	86	84	83	83	LPG: Propane/Butha	142	142	142	142
LNG: Methane	33	30	30	31	87	84	84	84	LNG: Methane	163	163	163	163
Methanol Green - CCU	119	93	80	68	153	121	96	72	Methanol Green - CC	103	87	48	10
LBioG: Methane Green	62	77	89	114	79	95	107	132	LBioG: Methane Gree	53	53	53	53
Blue Ammonia	82	70	67	64	105	93	90	87	Blue Ammonia	69	69	69	69


TCO & CO2 tax (25euro/300euro/ton)
15.000 teu
MUSD /y
180
160
140
120
100
80
60
40
20
0
2020
2030
2040
2050
2020
2030
2040
2050
HFO IFO 380 3,5% S
VLSFO 0,5% S
NH3 Grey
NH3 Green
Methanol Grey
Methanol Green - BIO
Refined Pyrolisis oil BIO
LPG: Propane/Buthane
LNG: Methane
Methanol Green - CCU
LBioG: Methane Green
Blue Ammonia
119
105
99
82
67
62
49
39
33
93
70
30
99
89
80
74
70
67
44
37
30
127
114
68
60
44
36
31
153
136
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132
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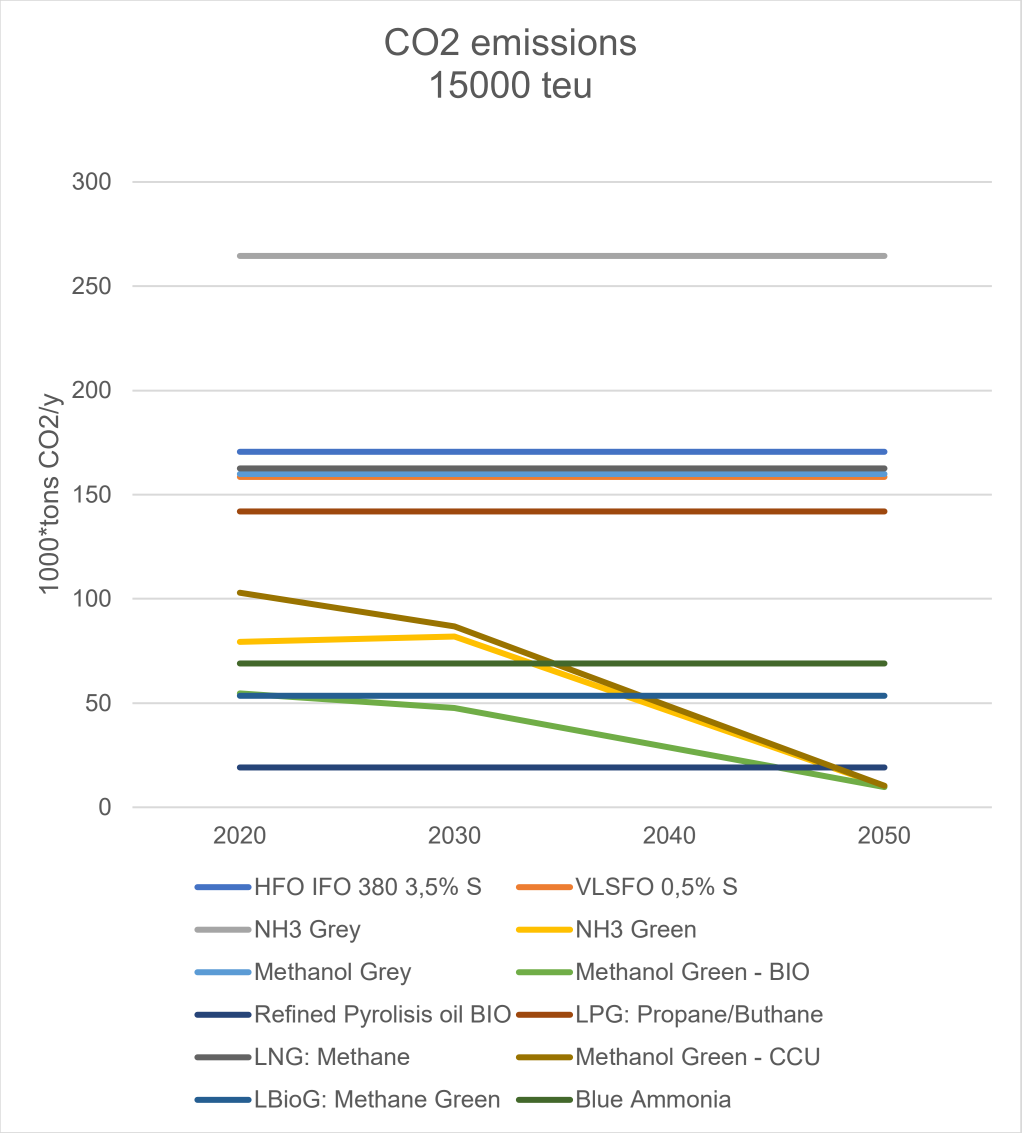
94
72
68
63


CO2 emissions
15000 teu
1000*tons CO2/y
300
250
200
150
100
50
0
2020
2030
2040
2050
HFO IFO 380 3,5% S
VLSFO 0,5% S
NH3 Grey
NH3 Green
Methanol Grey
Methanol Green - BIO
Refined Pyrolisis oil BIO
LPG: Propane/Buthane
LNG: Methane
Methanol Green - CCU
LBioG: Methane Green
Blue Ammonia

Enclosure 2. Fuel Emissions

Below is an excerpt from the report: MarE-Fuel: ROADMAP for sustainable maritime fuels, 2021.

Fuel emissions

An overview of fuels assessed in this report is listed in Table 1. Other pathways for methanol production include methanol from coal, which is disregarded due to the high related greenhouse gas (GHG) emissions. Methanol can also be produced from biomass through gasification without hydrogen input, but this pathway is disregarded due to its low carbon efficiency. Biodiesel from algae was considered but not included due to sustainability concerns[1]. The fuels using electrolysis to produce H_2 as input to the fuel synthesis are characterized as e-fuels. In this note, these are; MET-e-bio, MET-DAC, MET-PS, and AMM-green.

Abbreviation	Name	Description
HFO	Heavy Fuel Oil	Conventional fossil fuel.
VLSFO	Low Sulphur Fuel Oil	Conventional fossil fuel. Sulphur content ≤0.5%
MDO	Marine Diesel Oil	Conventional fossil fuel.
MGO	Marine Gasoline Oil	Conventional fossil fuel.
LNG	Liquefied Natural Gas	Conventional fossil fuel.
LPG	Liquefied Petroleum Gas	Conventional fossil fuel.
MET-Grey	Methanol (grey)	Conventional methanol produced from fossil natural gas.
MET-e-bio	Methanol (e-bio)	Methanol produced from gasification of residual biomass and hydrogen from water electrolysis.
MET-PS	Methanol (PS)	Methanol produced from point source (PS) carbon bio energy carbon capture and utilization (BECCU), and hydrogen from water electrolysis.
MET-DAC	Methanol (DAC)	Methanol produced from carbon from direct air capture (DAC) and hydrogen from water electrolysis.
AMM-grey	Ammonia (grey)	Conventional ammonia produced from fossil natural gas.
AMM-blue	Ammonia (blue)	Ammonia produced from fossil natural gas with carbon capture.
AMM-green	Ammonia (green)	Ammonia produced from water electrolysis.
Refined-PO	Refined pyrolysis oil	Oil from pyrolysis of residual biomass refined to a quality enabling drop-in use in HFO/VLSFO engines.
LBG	Liquefied Biogas	Liquefied biogas generated from manure or organic waste.

Table 1: Overview of assessed fuels.

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[1] If algae cultivation is placed in seawater close to known industrial CO_2 sources with food competition and biodiversity taken into account, the potential is 6 EJ (Correa et al., 2019). If this were to be limited to biogenic CO_2 sources, the potential would be reduced further. The environmentally sustainable potential of biodiesel from Algae is limited to ~1.4 EJ when atmospheric CO_2 is used. This is deemed not to be economically feasible (Somers and Quinn, 2019).

Enclosure 3. Ship emissions - Well to Tank & Tank to Wake

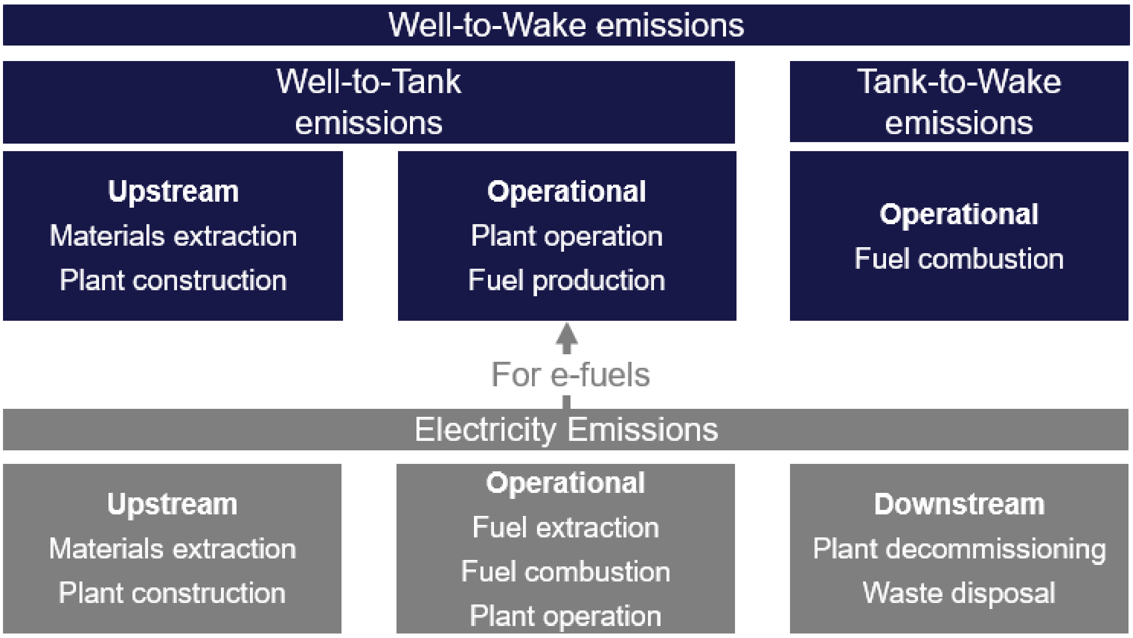
Below is an excerpt from the report: MarE-Fuel: ROADMAP for sustainable maritime fuels, 2021.

Well-to-Tank and Tank-to-Wake

Greenhouse gas emissions (GHG) from production and use of fuels are divided into Well-to-Tank (WTT), covering the fuel production, and Tank-to-Wake (TTW), covering the combustion of the fuel. The sum of WTT and TTW emissions are the Well-to-Wake (WTW) emissions, see Figure 1. The WTW emissions covered here are limited to GHG emissions from fuel production and use. The production of the engines, ships or needed infrastructure to produce these are disregarded as they are assumed to be similar for different types of fuels. For a complete lifecycle analysis, upstream and downstream emissions for ships using other fuels should be included. The upstream emissions from fuel production are made up of emissions from extracting raw materials for building infrastructure and the fuel itself. For e-fuels, there is a significant input of electricity in fuel production, which is why this is shown separately. For fossil-based electricity, most emissions stem from the operational stage of electricity generation, which is associated with extracting and combusting fossil fuels. Still, for renewables, the majority of emissions are in the upstream stage. For example, emissions from wind electricity are minimal, but they are not zero as they include upstream emissions primarily from steel production for building wind turbines, see Figure 5 in the report MarE-Fuel: ROADMAP for sustainable maritime fuels, 2021. Some studies are limited to operational WTT emissions, where non-fossil electricity emissions are zero (Moro and Lonza, 2018; Prussi et al., 2020). This means that the contribution to the WTT emissions of e-fuels can vary significantly in different studies, which makes them difficult to compare. Comparable assumptions of emissions related to electricity use for e-fuels are therefore given focus in section 1.3.4 of the report MarE-Fuel: ROADMAP for sustainable maritime fuels, 2021. This does not make a big difference, when comparing fossil fuels, as a major part of WTT emissions is in the operational stage. However, when looking at e-fuels, the electricity input is substantial and should therefore be taken into account.

Continued excerpt from the report: MarE-Fuel: ROADMAP for sustainable maritime fuels, 2021.

$$WTW = WTT_{upstream} + WTT_{operational} + TTW_{operational}$$



Different targets can be applied for WTT and TTW emissions. Current International Maritime Organisation (IMO) targets for emission reductions are restricted to TTW emissions. There are no IMO guidelines for defining WTT emissions, something the EU, among others, is pushing for (European Parliament, 2020).