Norwegian University
of Life Sciences

Master's Thesis 2024 30 ECTS
Faculty of Environmental Sciences and Natural Resource Management
(MINA)

Evaluating Well-to-Wake Energy & Emission Intensity of Methanol-Fuelled Container Ships for Short-Sea Shipping from a Norwegian Perspective

A Second-Degree Energy Chain Analysis

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Renewable Energy

FOREWORD

This Master's thesis was written to conclude my degree in Renewable Energy at the Norwegian University of Life Sciences. First and foremost, I want to direct my sincerest appreciation towards my main supervisor Erling Holden's dedication, patience and academic expertise throughout this process. His insight was detrimental to shaping the direction and quality of my research. Further, I want to thank my fellow students for five treasured years at NMBU, particularly Ida Lund and Truls Pedersen, for the many hours spent studying at Deichman this final semester.

I also want to extend my gratitude towards external supervisors Rahul Ravi and Oleksii Ivashenko at DNV, who provided invaluable insights into the methodology and information delivery throughout my thesis. Their expertise was greatly valued and contributed to an even larger understanding of the research at hand.

Lastly, I want to give my warmest appreciation towards my family, who has always cheered me on and kept me motivated during challenging times.

Ås, May 15 2024

Susanne Schjelderup Myrene

ABSTRACT

Marine shipping is responsible for in excess of 80 % of international trade, and around 3 % of anthropogenic global greenhouse gas emissions. Offshore shipping serves as the economic backbone for the global economy, as it effectively transports large amounts of goods, connecting continents through trade. Most of these containerships run either on heavy fuel oil (HFO) or marine gas oil (MGO), which greatly contributes to the global warming potential MGO is the most commonly used fuel in the EU Emission Control Areas (ECAs) after the IMO implemented a cap on sulphur emissions. The CO_2 emissions are, however, hardly reduced when switching from HFO to MGO. Reducing emissions from marine shipping by replacing heavy fuel oil with alternative fuels is regarded as a necessity to reach climate goals set through the Paris Agreement. Hydrogen carriers such as liquefied hydrogen, ammonia and methanol are of particular interest, of which methanol has seen the largest increase in uptake according to vessel order books. Methanol is favoured ahead of both hydrogen and ammonia due to its compliance with existing infrastructure, and is seen as an economically and logistically achievable alternative to current fossil fuels.

In this thesis, methanol from four different production pathways were considered as alternative fuels to replace MGO. The research questions reads as follows:

1. *How many MJ_{energy}/tkm is required of electric and primary energy for a typical 2 000 TEU container ship?*
2. *How many CO2eq/tkm are emitted from utilizing different methanol products as fuel in a typical 2 000 TEU container ship?*
3. *How will emissions from methanol production and combustion compare to those from MGO?*

The research questions will be answered by performing energy chain analyses based on secondary data collected from the research literature. These calculations will be done for energy consumption and subsequent emissions from within the system boundary, aiming to present the bigger picture of both energy and emission intensity. An energy chain analysis entails calculating the energy consumption for all partial processes within a set system boundary. Here, the system boundary was set to include all processes from Well-to-Wake, meaning from the point of feedstock extraction to a finished fuel product used for propulsion in a ship.

Two of the energy chains are produced from natural gas, one of which will include carbon capture and storage (CCS). The natural gas goes through steam methane reforming (SMR) before subsequent methanol synthesis and distillation before we have a ready fuel on our

hands. One energy chain is bio-based, specifically produced though the gasification of wood chips. After gasification, the process is deemed equivalent as for the natural gas pathways. The final methanol chain is powered exclusively by electricity. This process combines hydrogen from electrolysis with CO_2 directly captured from ambient air. All of these are measured against the benchmark fossil fuel, MGO.

The results show that bio-methanol has the lowest overall emissions, measured in gCO_2eq/tkm. Notice that the diagonally shaded bars for bio-methanol and e-methanol in the figure below indicate that Tank-to-Wake emissions are considered climate-neutral and do not contribute to the fuels' lifecycle emissions. This is because all methanol products will emit the same amount during propulsion, but as renewable feedstocks have been used for the manufacturing of bio-methanol and e-methanol, the carbon emissions are thought to be a part of the carbon loop in nature. That said, e-methanol shows somewhat higher emissions than bio-methanol, but still far below MGO. Methanol produced directly from natural gas shows the highest overall emissions of the pathways assessed, whereas the pathway that incorporates carbon capture lowers the entire Well-to-Wake emissions to be just below MGO.

The sensitivity analysis shows, however, that by using the EU electricity mix for the processes using electricity, the results shift. Here, e-methanol ranks worst in terms of emissions. This is due to the fact that this is a more energy intensive process as electricity is used to both produce hydrogen and capture carbon dioxide. This, combined with a relatively high fossil share in the EU electricity mix, puts e-methanol as the most polluting contender. Additionally, the pathway that applies natural gas and CCS also performs worse than the benchmark fuel, as a considerable amount of electricity is necessary to power the process. With a EU electricity mix, it is only bio-methanol that has a lower accumulated emission than MGO.

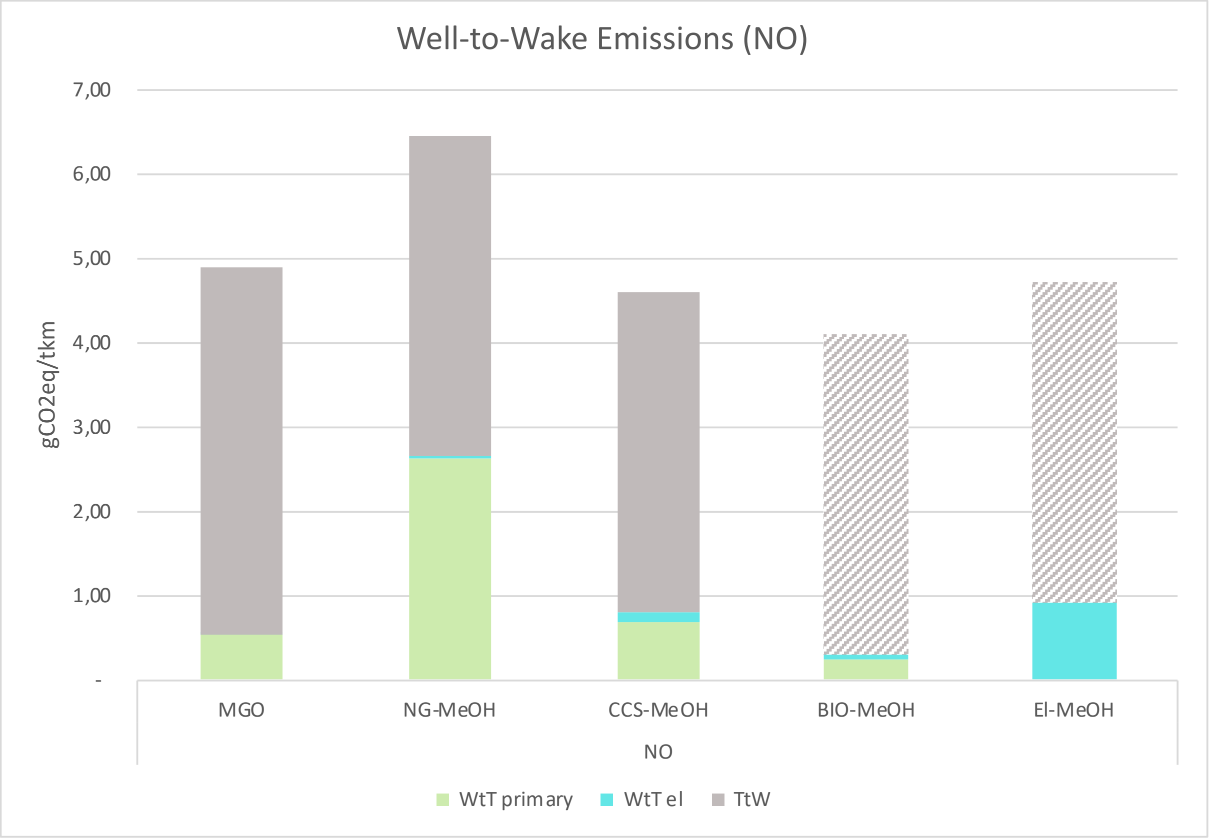


Figure A1: Total Well-to-Wake emissions for all fuel pathways measured in gCO_2eq/tkm.

SAMANDRAG

Internasjonal sjøfart star for meir enn 80 % av internasjonal handel og rundt 3 % av menneskeskapte globale klimagassutslepp. Sjøfart er ein grunnpilar I den globale økonomien gjennom å effektivt transportere store mengder varer og knyte saman kontinent gjennom handel. Dei fleste containerfartøy i dag går på anten tungolje (HFO) eller marin gassolje (MGO), noko som bidreg sterkt til det globale oppvarmingspotensialet. MGO er eit av dei mest brukte drivstoffa i EU sine «Emission Controll Areas» (ECAs), etter at IMO innførte ei grense for svovelutslepp. CO_2-utsleppa blir likevel knapt reduserte ved å bytte frå HFO til MGO.

Å redusere utslepp frå skipsfart ved å erstatte tungolje med alternative drivstoff vert sett på som naudsynt for å nå klimamåla fastsette gjennom Parisavtalen. Hydrogenberarar som flytande hydrogen, ammoniakk og metanol er av særleg interesse, der metanol har hatt den største relative auken i bruk ifølge bestillingslistene for offshore-fartøy. Metanol vert foretrukke framfor både hydrogen og ammoniakk på grunn av samsvar med eksisterande infrastruktur og relativt høge energiinnhald, og vert sett på som eit økonomisk og logistisk oppnåeleg alternativ til dagens fossile drivstoff.

I denne oppgåva vart metanol frå fire ulike produksjonsvegar vurdert som alternative drivstoff for å erstatte MGO. Problemstillingane lyder som følger:

1. Kor mange MJ_{energi}/tkm er naudsynt frå primære og elektriske energikjelder for eit typisk containerfartøy på rundt 2000 TEU?
2. Kor mange CO_2eq/tkm vert sleppt ut ved bruk av ulike metanolprodukt som drivstoff i eit typisk containerfartøy på rundt 2000 TEU?
3. Korleis vil utslepp frå metanolproduksjon og forbrenning i skipsmotor samanliknast med utslepp frå MGO?

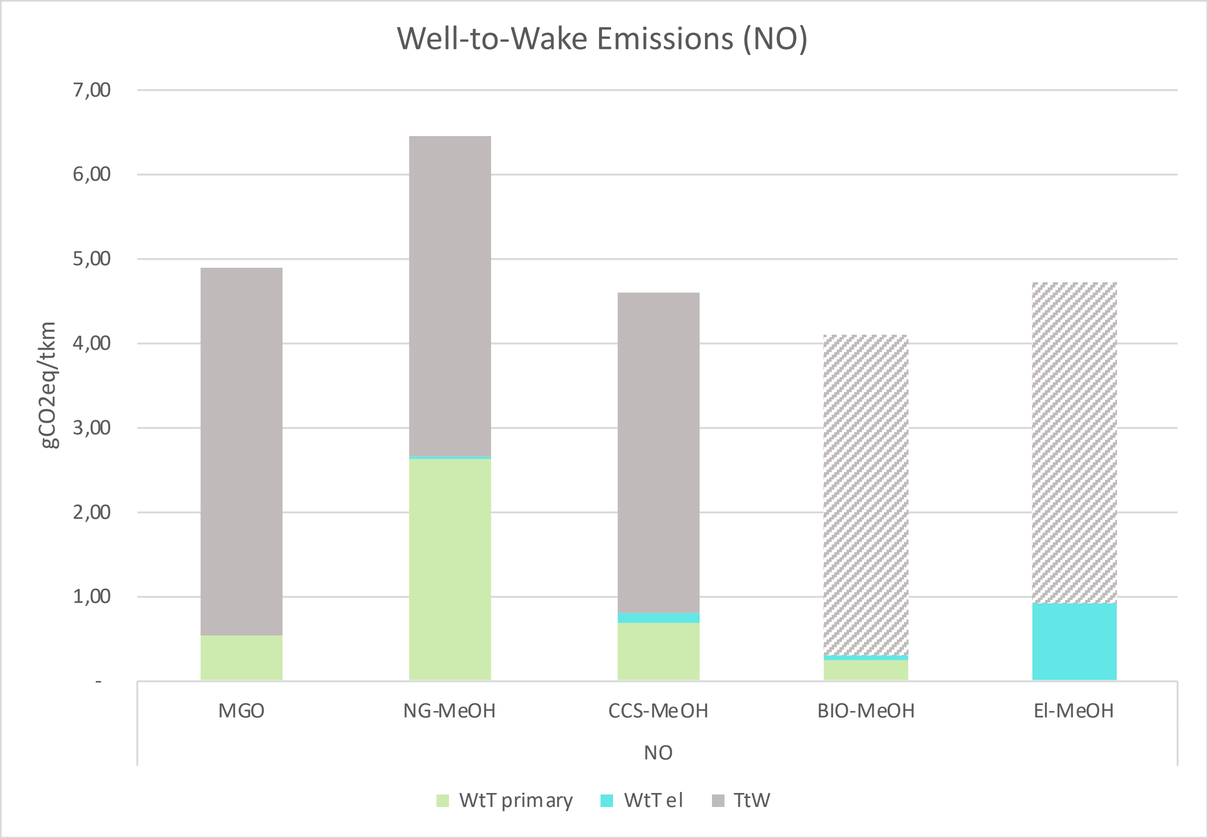
Problemstillingane vil bli besvart ved å utføre energikjedeanalysar basert på sekundære data henta frå forskingslitteratur. Desse berekningane vil bli gjort for energiforbruk og påfølgjande utslepp innanfor den sette systemgrensa, med mål om å illustrere både energi- og utsleppsintensitet for dei ulike kjedene. Ein energikjedeanalyse inneber å rekne ut energiforbruket for alle delprosessar innanfor ei fastsett systemgrense. Her vart systemgrensa sett til å omfatta alle prosessar frå Well-to-Wake, som betyr frå utvinning av råstoff til eit ferdig drivstoffprodukt brukt til framdrift i eit containerskip.

To av energikjedene er produserte frå naturgass, der den eine vil inkludere karbonfangst og lagring (CCS). Naturgassen går gjennom dampreformering (SMR) før påfølgande

metanolsyntese og destillasjon før ein sit igjen med eit ferdig drivstoff. Ei av energikjedene er biobasert, spesifikt produsert gjennom «gassification» av flis frå treforedlingsindustrien. Etter dette steget vert prosessen rekna som tilsvarande for naturgass-kjedene. Den siste metanolkjeda vert driven utelukkande av elektrisitet. Denne prosessen kombinerer fornybart hydrogen frå elektrolyse med CO_2 fanga direkte frå lufta. Alle desse vert målt mot det fossile referansedrivstoffet MGO.

Resultata viser at biometanol har dei lågaste totale utsleppa, målt i gCO_2eq/tkm. Legg merke til dei diagonalt skravertee søylene for biometanol og e-metanol i figuren under, som indikerer at Well-to-Wake-utslepp vert rekna som klimanøytrale og ikkje bidreg til drivstoffa sitt endelege klimarekneskap. Dette er fordi alle metanolprodukt vil sleppe ut den same mengda under framdrift, men sidan fornybare råstoff har vorte brukt for produksjonen av biometanol og e-metanol, vert karbonutsleppa rekna som ein del av karbonkretsløpet som allereie finnst i naturen. Vidare viser e-metanol noko høgare utslepp enn biometanol, men framleis langt under MGO. Metanol produsert direkte frå naturgass viser dei høgste totale utsleppa av dei vurderte kjedene, medan kjeda som inkluderer karbonfangst senkar redusere WtW-utsleppa til å vere like under MGO.

Sensitivitetsanalysen viser likevel at ved å bruke EU sin elektrisitetsmiks for prosessane som brukar elektrisitet, så endrar resultata seg drastisk. Her hamnar e-metanol dårlegast ut når det gjeld utslepp. Dette skuldast at dette er ein meir energiintensiv prosess enn for dei andre energikjedene, sidan elektrisitet vert brukt både til å produsere hydrogen og fange CO_2. Dette, kombinert med ein relativt høg fossil del i EU sin elektrisitetsmiks, gjer at e-metanol vert den mest forureinande kandidaten. I tillegg presterer også løysinga som nyttar naturgass og CCS dårlegare enn referansebrennstoffet, sidan ei betydeleg mengd elektrisitet er naudsynt for å drive prosessen. Med EU sin elektrisitetsmiks er det berre biometanol som har lågare samla utslepp enn MGO.



Figur A2: Totale Well-to-Wake-utslepp for alle energikjedene uttrykt i gCO_2eq/tkm*.*

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ABBREVIATIONS

Mtpa – megatons per annum

MWh – megawatt hours

H_2 – hydrogen

CO_2 – carbon dioxide

CO_2eq – emissions measured in carbon dioxide equivalents

NO_X – nitrogen oxides

SO_X – sulphur oxides

CCS – carbon capture and storage

NH_3 – ammonia

CH_3OH – methanol

PEMFC – proton exchange membrane fuel cell

SOFC – solid oxide fuel cell

MCFC – molten carbonate fuel cell

DMFC – direct methanol fuel cell

ICE – internal combustion engine

FC – fuel cell

GHG – greenhouse gas

IMO – International Maritime Organization

RFNBO – renewable fuel of non-biological origin

RCF – recycled carbon fuels

MGO – marine gas oil

MDO – marine diesel oil

HFO – heavy fuel oil

LNG – liquefied natural gas

LPG – liquefied petroleum gas

CH_3OH – methanol (MeOH)

NG – natural gas

SMR – steam methane reforming

DAC – direct air capture

$PM_{2.5}$ – particulate matter with a diameter of < 2.5

WGS – water-gas shift reaction

1 INTRODUCTION

This thesis aims to identify the potential climate change impacts of substituting conventional marine fuels with methanol. Methanol can originate from different feedstocks such as fossil coal or gas, biomass, or captured carbon dioxide (CO_2). Initially, the motivation and necessary background for choosing this subject will be presented. Then a literature review that presents the status quo within this particular research field will be presented to provide the reader with adequate knowledge to understand the subsequent analyses, in which the results will provide the reader with knowledge of the greenhouse gas abatement potentials of deploying alternative fuels in large marine vessels. As an addition to the main aim of the thesis, a short economic assessment will be carried out, intending to visualise a more complete picture of what alternative fuel implementation can look like, and the trade-offs that shipowners will have to face as regulations tighten.

1.2 BACKGROUND

The global maritime industry is currently navigating a paradigm shift in response to the climate emergency. In 2023, The International Maritime Organisation (IMO) committed to reducing GHG emissions from the marine sector to align with the Paris Agreement and to its proportionate share of GHG, currently at 3%. The goal is to reach net-zero “by or around 2050”. With growing global economies, so comes the demand for consumer goods, from clothing, produce and furniture, to electronics and vehicles. Maritime shipping is one of the most economically sustainable means of shipping, allowing vast volumes to be traded between continents, and playing a large part in the global economy.

Marine shipping is responsible for in excess of 80 % of international trade, reaching 11 billion tonnes in 2021 (UNCTAD, 2023). As a result, GHG emissions increased by 4.7 % between 2020 and 2021, mostly stemming from container ships, bulk ships and cargo ships. The IMO reports that emissions from merchant vessels have increased by 30 % between 2008 and 2023 (Sinay, 2023). An overview of EU and global freight transport are illustrated in Figure 1. But as the global fleet is getting older, new-build rates remain low and shipowners are unsure which technologies will prevail, the rate of alternative technology uptake remains uncertain. Maritime shipping is one of the most cost-effective ways of transporting vast amounts of goods to all corners of the world and thereby serves as the economic backbone of many regions in the world. It does, however, come with some challenges.

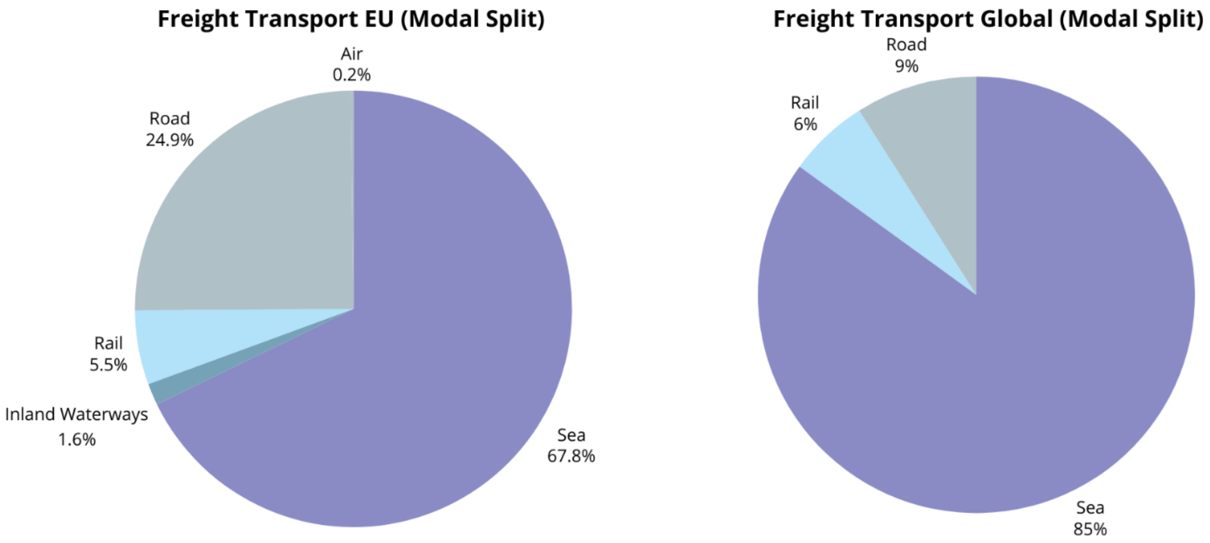


Figure 1 Modal overview of EU and global freight transport. Source: (DHL, 2023; Eurostat, 2022)

The offshore shipping industry accounts for nearly 3 % of total global anthropogenic CO2 emissions, of which the majority comes from container ships, tankers and cargo ships running on Heavy Fuel Oil (HFO) before IMO's sulphur was cap implemented in 2020 (UNCTAD, 2023). Marine vessels have traditionally been using low-quality residuals from crude oil refining. The viscous low-grade heavy fuel oil (HFO) is a leftover product from crude oil refining after purer distillates such as gasoline and diesel have been removed and put to use in cleaner burning engines (ClearSeas, n.d.). HFO is contaminated with aromatics, sulphur, and nitrogen, resulting in more harmful emissions (SNL, 2024). This fuel is both energy-rich and inexpensive to produce, and with engines designed to burn such lower-grade oil residuals, this has been a very cost-effective fuel in the marine sector. As HFO is laden with the very potent SOx compound, and contribute to 13 % of global sulphur oxide emissions, restrictions on these emissions pushed the uptake of scrubbers and sulphur-reduced light fuel oils such as Marine Gas Oil (MGO) and Very Low Sulphur Fuel Oil (VLSFO) in Emission Control Areas (ECAs) (ClearSeas, n.d.). MGO and VLSFO do, however, not significantly reduce the emissions of carbon dioxide to the atmosphere and can hardly be termed sustainable fuel substitutes.

Furthermore, from 2025 onwards, ships trading within EU territory will face strict requirements in GHG-emission reductions, ranging from a 2 % reduction in 2025 to 80 % by 2080 (DNVa, 2023). By 2080, the highest allowed emission intensity from marine fuels levels out at 18.2 gCO_2eq/MJ down from 89.3 in 2025. Per 2015, the global total fuel consumption for the marine sector was 298 million tonnes, 72 % of which can be attributed to HFO, 26 % were various qualities of distillate fuels such as MGO and VLSFO, and a mere 2 % was LNG

(Svanberg et al., 2018). The operational profile of the ship determines which policies that will be determining of alternative fuel uptake. Short-sea shipping is subject to stricter emission policies, which puts forward an incentive for these shipowners to adjust to these criteria through deployment of alternative fuels.

Methanol, often abbreviated to CH_3OH or MeOH, is one the most traded and utilized industrial chemicals in the world and is used to manufacture polymers, formaldehyde, acetic acid, and drop-in fuels. Methanol production and consumption, at around 100 million tonnes per annum, makes up 10 % of globally traded chemicals(Tabibian & Sharifzadeh, 2023), explaining why the global demand for methanol more than doubled from 2006 to 2020 (DNV, 2023; Tabibian & Sharifzadeh, 2023). Methanol is a simple alcohol with a high hydrogen-to-carbon ratio and is liquid at ambient temperatures contrary to most alternative fuels. At present, methanol is typically made through the synthesis of a fossil-derived feedstock like coal or natural gas and is mostly used for further chemical processing in plastics, fabrics, or lubricants. Methanol can also be manufactured through gasification of biowaste (bio-methanol), or through combining renewable hydrogen and captured CO2 (e-Methanol). Energy density is about half of that of HFO, but both grey and green methanol provide 95 % to 98 % reduction of sulphur oxides (SOx), 25 % to 80 % reduction of nitrogen oxides with exhaust gas circulation systems or selective catalytic reduction systems, and 5 % to 10 % CO2-reduction for grey methanol compared to 80 % reduction for green methanol (DNV, 2023). Europe is responsible for about 3 % of global MeOH production capacity, most of which can be traced back to Norway and Germany (Pérez-Fortes et al., 2016).

Though being a commonly traded commodity and having systems in place regarding safe distribution, some hurdles need to be overcome before one can say that this fuel is ready for large-scale implementation. With a low energy density and lower heating value (LHV) of 15.8 MJ/l, methanol fuel tanks will have to be sized up 2.3-2.6 times compared to conventional fuel oil tanks, ultimately displacing some of the cargo (DNV, 2023). Though the additional capital expenditure (CapEx) for retrofitting a ship with a methanol engine and subsequent infrastructure is one-third of that of LNG, there are few ships above the age of 10 years for which this is deemed economically viable (DNV, 2023). With an ageing global fleet, many shipowners will not consider this to be an option. Additionally, the IMO and other regulative bodies are yet to define a regulatory framework for methanol as a maritime fuel, which leaves shipowners in a state of hesitation.

In 2023, the IMO revised its GHG strategies, indirectly stimulating an alternative fuel uptake by restricting emissions from maritime transport and aims to achieve net zero within 2050 (DNVb, 2023). The International Maritime Organisation (IMO) is a UN Specialized Agency tasked to coordinate sustainable development for international shipping (IMO, n.d.). The

Third IMO GHG study stated that a whole 77 % of global fuel consumption consists of HFO, explaining the 2020 sulphur cap (IMOb, 2014). To abide by these regulations, a short-term solution would be to invest in new technologies to purify the exhaust, such as selective catalytic conversion, but ultimately shipowners will have to consider exploring new propulsion technologies.

A significant aspect to consider when assessing methanol is which method of production prevails. Until 2025, the EU ETS scheme merely focused on tank-to-wake, i.e., combustion, but as methanol emits the same amount of GHGs at the point of combustion regardless of how it is produced, all methanol products appear as having similar environmental performance. From 2025 onward, both the EU ETS and the FuelEU Maritime programme apply a Well-to-Wake approach, which entails that non-fossil methanol pathways are favoured (Boulland, 2023). To add to the merits of methanol as a fuel, NOx emissions from methanol engines are Tier II compliant without adjustments and can reach Tier III with tailored adjustments to the engine (Boulland, 2023). DNV's Maritime Forecast to 2050 shows that without the IMO's coming well-to-wake regulations for shipping fuels, emissions will just be transferred to other sectors (DNVb, 2023).

A fundamental hindrance to alternative fuel uptake is the trepidation of the unknown. In an attempt to familiarize the sector with alternative propulsion technologies, The Green Shipping Programme emerged as a partnership that combines private companies and government ministries, aiming to facilitate the Norwegian government's maritime strategies (GSP, n.d.). They state that the Norwegian fleet is characterized by a high average age and thereby not utilizing the most efficient technologies, thus showing higher emission levels than newer fuel- or engine technologies would allow. Shipowners therefore require a safety net that cushions the risk of financial distress, technological knowledge gaps, and policy compliance when considering upgrading their fleet in the form of regulations.

A growing order book for methanol-fuelled ships shows that the shipping industry sees methanol as a promising alternative fuel. The ICCT emphasises the market's interest in investing in methanol as a potential substitute for MGO and highlights that the container ship giant Maersk is investing heavily in large-sized dual-fuel methanol containerships to add to their fleet (Carvalho et al., 2023). An overview of fuel categories of ships currently in operation and new contracts over the last 12 months based on *Dead Weight Tonnage* (DWT) as of May 2024 are presented in the graphics in Figures 2 & 3.

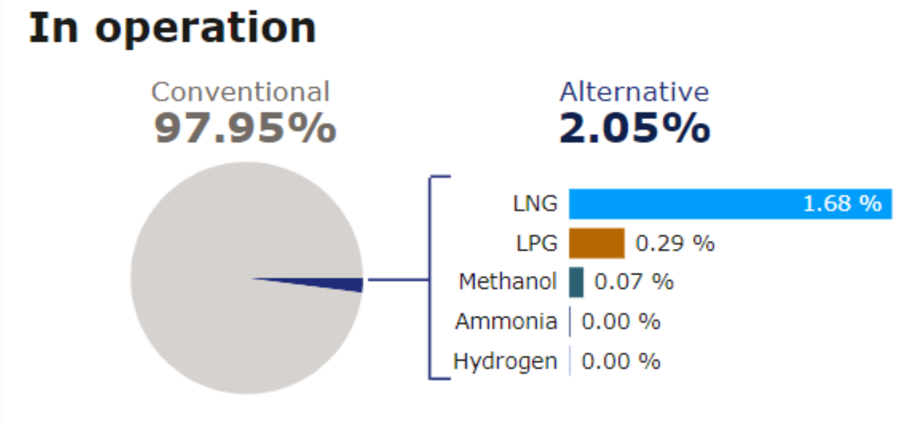


FIGURE 2 GLOBAL SHIPPING FLEET FUEL DISTRIBUTION BASED ON DWT AS PER MAY 2024. SOURCE: (AFI, 2024)

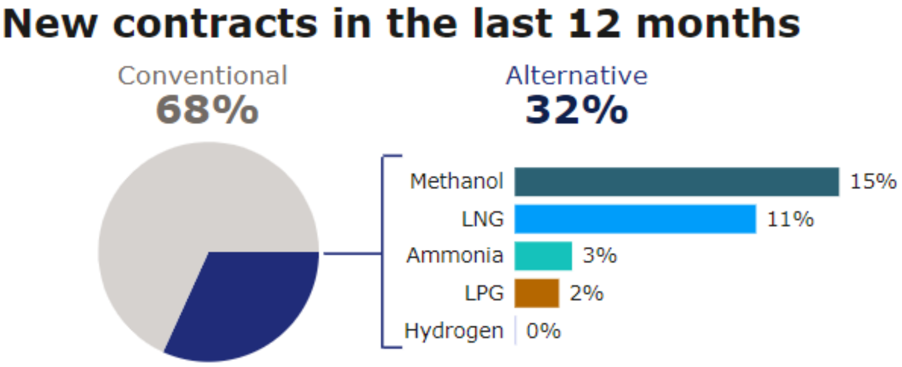


FIGURE 3 NEW CONTRACTS ACROSS GLOBAL SHIPPING FLEET AS PER MAY 2024.SOURCE: (AFI, 2024)

1.3 METHANOL

Methanol (MeOH) is an alcohol with a simple chemical composition with the chemical formula CH_3OH, and has a wide array of applications in the chemical industry (Bernatek, 2022). The ICCT emphasises the market's interest in investing in methanol as a potential substitute for MGO and highlights that the container ship giant Maersk is investing heavily in large-sized dual-fuel methanol containerships to add to their fleet (Carvalho et al., 2023).

The bulk of commercially available methanol is currently produced from natural gas without CCS, but companies are now starting to produce renewable methanol by combining either no- or low-carbon hydrogen with CO_2 captured from industrial flue gas, direct air capture (DAC), or biogenic CO_2 from burning biomass (Marquez, 2023). Methanol as a fuel has an advantage in that it is already a widely produced chemical with several industrial applications and is already used as a drop-in fuel in conventional gasoline today. Though methanol primarily is used in fossil fuel blends, it can also be used in its pure form. When produced from renewable feedstocks, it can approach the net-zero emission threshold seen from a Well-to-Wake perspective.

Methanol has a high H/C-ratio (hydrogen-carbon). Though displaying a lot of the same chemical properties of conventional fossil fuels, methanol is not a long-chain hydrocarbon and thus does not emit particulate matter (PM) to the atmosphere (Zincir & Deniz, 2021). Methanol emits 20 % less CO_2 than diesel oil, however, the lower heating value (LHV) of methanol puts it at the potentially severe disadvantage that over twice the volume is required to propel the ship the same distance as diesel oil. The LHV for methanol, at 19.9 MJ/kg, is 50 % lower than that of HFO at 40.2 MJ/kg. Zincir and Deniz (2021) also state that methanol combustion in an ICE has about 10 % fewer emissions than HFO. Methanol has very low NOx-emissions from combustion and avoids PM and SOx emissions almost entirely.

With relatively minor modifications, methanol can be transported and bunkered via existing infrastructure. With its low kinematic viscosity, lubricants have to be added to avoid corrosion of materials such as aluminium, zinc, copper, lead, magnesium, rubber, and plastics. Additionally, the lack of sulphur facilitates a need for added lubricants.

1.4 THE SHIP

A containership engineered for short-sea shipping was chosen due to the assumption that a containership bunkering at a Norwegian port is likely to operate within the EU Emission Control Areas (ECAs). ECAs are subject to more stringent regulations than international waters, as most shipping activities are located relatively close to land and have more noticeable impacts on local conditions.

1.4.1 SHORT-SEA SHIPPING

Short-sea shipping is the transport of cargo on mid-sized container ships with a capacity of <4000 TEU between countries situated on the same continent, which differs from intercontinental deep-sea shipping (Martin et al., 2023). TEU translates to "*twenty-foot equivalent unit*", which is an industrial standard for measuring the cargo capacity of a ship. One container unit, or TEU, measures 20 feet long, eight foot wide, and eight foot tall (Spurkeland, 2020). Classic examples are the Panamax Standard (3000 to 2400 TEU) and Panamax Max (3400 to 4500 TEU) container ships, which were engineered to take maximum advantage of the size of the Panama Canal port (Rodrigue, n.d.). Short-sea shipping was chosen because we want to investigate for Norwegian conditions, thus ships that can make berth at a Norwegian harbour.

1.5 LITERATURE REVIEW

The following section is meant to portray the status quo within the alternative fuel and methanol research fields, collected from different literature to provide the reader with the necessary insight.

Hydrogen and hydrogen carriers have long been discussed as maritime fuel substitutes but cannot be combusted in the marine engine as is. In a study published by Hoecke et al. (2021), they research the challenges associated with hydrogen (H_2) used as a marine fuel, based on issues related to the efficiency of storage. Though H_2 has the potential to have net-zero life-cycle emissions, depending on the feedstock, it runs into serious challenges regarding onboard storage. The authors highlight that today no sole fuel substitute can compete with known advantages of the traditional fossil fuels, such as commercial availability, non-toxicity, high energy density, and efficient storage and handling. Hydrogen carriers such as liquid H_2, compressed H_2 gas, ammonia (NH_3), methanol (MeOH), metal hydrides, formic acid, Fischer Tropsch-diesels, and so on, are all associated with one or more of the challenges stated above. Though concluding that production of H_2 via electrolysis required the least amount of energy for production at 58 kWh/kg, while FTS-diesel required higher amounts than most of the fuels mentioned at 152 kWh/kg, FTS-diesel still outperformed the other fuels based on energy density. For chemical H_2 storage, the efficiency would greatly improve if heat from an external source could be applied. For e-fuels in general, electrolysis is the most energy-intensive stage in the conversion, which yields less energy per input. Infrastructure challenges for most fuels in the study, apart from methanol, liquid natural gas (LNG), and FTS fuels, were also highlighted as barriers to commercial endorsement. It is noteworthy to mention that alkaline electrolysis, which was the technology considered here, is reportedly less efficient than PEM-electrolysis, which is likely to have a more prominent position in years to come. The research on alternative fuels is not only concerned about energy density and efficiency of production, but also emission intensity.

In 2019, Winebrake et al. (2019) reviewed the pollution trade-offs associated with conventional fossil fuels and natural gas-based fuels. They summarize the three options shipowners have to take to meet the IMO sulphur cap allowance of 5000 ppm for vessels operating in international waters, and 1000 ppm in ECAs such as within European waters. These options are to either retrofit the vessel with exhaust scrubbers, switch to low-sulphur distillates such as *marine gas oil* (MGO) or *very-low sulphur oil* (VLSFO), or switch to alternative fuels, such as LNG or methanol, which are known to reduce certain local pollution from marine shipping. They do stress, however, the importance of assessing the entire life-cycle *greenhouse gas* (GHG) emissions from these natural gas-based fuels before making the switch. Winebrake et al. (2019) apply a total fuel-cycle analysis (TFCA), analysing feedstock-, fuel-, and propulsion-related stages. The results show that MeOH has 10-20 % higher GHG emissions than marine diesel oil (MDO), but that MeOH from biogenic sources such as biomass can reduce overall GHG emissions by 20-25 %. All forms of MeOH have SOx emissions close to those of MDO but perform substantially better in terms of NOx and PM2.5. The authors state that methanol and LNG show reductions of up to 90 % in downstream local pollutants but about 20 % higher in overall GHG emissions, calling for more efficient technologies that limit fugitive emissions and more energy-efficient onboard technologies that limit overall consumption.

Adding to the knowledge about alternative fuels, McKinlay et al. (2021) published a comparative analysis of hydrogen, ammonia, and methanol as marine fuels. They applied a bottom-up approach to facilitate an overall comparison rather than a general energy density comparison, making it unique among the papers found in preparations for this thesis. They avoided exact estimates and put particular emphasis on technical aspects such as relative volume- and energy efficiency. Methanol is commonly produced through the synthesis of natural gas or coal, but technologies for producing net-zero emission methanol fuels are emerging. It is important to note that thermodynamic penalties restrict these processes, resulting in a less efficient yield than methanol produced from fossil feedstocks.

Tank space requirement is a significant aspect to consider when discussing implementation in ships, particularly when retrofitting existing ships. Whereas a conventional fuel oil tank would only require 2 % of the vessel's capacity, ammonia and compressed hydrogen would require 3.5 and 4 to 7 times the tank space respectively, including both space for fuel and cylinder insulation. Compressed, or gaseous, hydrogen could require 8 to 14 times the size, depending on pressure. Though hydrogen is often deemed unsuitable for offshore applications due to its relatively low energy density, the results by McKinlay et al. (2021) show that volume requirements should not deprive hydrogen as a contender in the clean fuel race. They believe hydrogen to be the leading candidate for decarbonizing large-scale shipping.

Malmgren et al. (2021) agree that hydrogen is one of the favoured alternative propulsion options due to negligible tailpipe emissions but also emphasise the physical challenges of storing a fuel that would require vastly more storage space than MGO. This makes hydrogen *carriers* such as methanol a more attractive option. Though there is a tradeoff in that methanol requires roughly 2-3 times more storage space on board than MGO, it has some advantages that conventional fossil fuels cannot reach, such as net-zero tailpipe emissions for methanol from renewable sources. Their HyMethShip concept is looking into manufacturing electro-methanol with direct air capture in an onshore facility and bunkering this fuel onboard the ship. While under voyage, the electro-methanol is split into H2 used for powering an internal combustion engine and CO2 is stored on board, waiting to be unloaded next time the ship makes berth. With this CO2 feedstock directly supplied to shore, more electro-methanol will be manufactured on shore before yet again being bunkered on board the ship, creating a closed carbon loop.

On the contrary, Tabibian and Sharifzadeh (2023) believe that methanol will act as a more direct replacement for oil than hydrogen, and though e-methanol is considered a carbon-neutral fuel, of the 98 Mt methanol produced annually, a mere 0.2 Mt, or 0.2 %, could be considered renewable. Methanol production is expected to reach 500 Mt annually by 2050, but if produced from fossil sources, this can generate 1.5 Gt CO2 annually. The uptake of renewable methanol is primarily hindered by high production costs and value chain uncertainties, which is why policies that penalize the use of fossil fuels will be detrimental to making methanol a cost-effective and widespread fuel.

Few studies regarding methanol in vessels of similar size to container ships have been carried out, but Strazza et al. (2010) did carry out a comparative LCA for methanol-fuelled SOFCs' as auxiliary propulsion systems on board ships. The scope of this paper included fuel cell production, fuel production, and on-board operations. This paper merely considers methanol produced through natural gas synthesis, which means that there will be comparable CO2 emissions as fuel oil at the point of combustion. With so-called gray methanol, the SOFC has a significantly lower environmental impact than the fuel production itself, apart from the global warming potential for the reasons stated. Further, they go on to state that bio-methanol with hydrogen from cracking and electrolysis has the lowest life cycle emissions. Direct methanol fuel cells are weighty and will require a lot of space, making them unlikely to serve as the ship's main engine for a long time. For now, the dual-fuel methanol internal combustion engine is the technically viable option.

In their comparative LCA of alternative marine fuels, Zincir and Deniz (2021) found methanol to be a more promising mitigation fuel than LNG. While LNG has been gaining traction as a marine fuel for several years, their research shows that investigation into fuels like hydrogen, methanol, biofuels, and ammonia increased greatly after the 2020-IMO SOx restrictions came to fruition. Findings show that LNG and methanol will be key transition fuels in the short term, whereas hydrogen-carriers are expected to replace most fuels in the long term. Methanol exhibits several physical properties that align with conventional marine fuels and can be bunkered in the same tanks with minor modifications but proves a slightly higher engine efficiency than the conventional diesel ICE. Though providing a cleaner combustion than diesel, methanol has a lower heating value (LHV) less than half of that of diesel, requiring over two times the size of fuel tanks onboard the ship to propel the ship the same distance. This being said, many vessels can make a trip around the world on one tank of fuel, which effectively means that even halving the fuel tank size will propel the ship over quite long distances.

Zincir and Deniz (2021) considered eight impact categories for 14 different fuels in their well-to-wake LCA. The emission data were obtained from GREET Model 2022, and inventory stages were divided into feedstock, conversion and combustion. Zincir and Deniz (2021)'s results show that in regard to the feedstock phase, E-Fischer-Tropcsh Diesel (E-FT-Diesel) and e-Methanol are the cleanest fuels, as they utilize captured CO2 as a feedstock rather than emitting in upstream processes. During combustion, hydrogen is considered the cleanest fuel, though emitting nearly twice as much NOx as *ultra-low sulphur oil* (ULSFO), the second highest NOx-emitter. In their conclusions, they highlight that it is difficult to recommend a single fuel, but that marine bio-oil seems to have a lower overall environmental impact for five of the eight impact categories in a holistic assessment. However, the technical feasibility, indirect land use changes, value chain robustness, and safety measures are not taken into account. The LCA results for acidification shows that marine bio-oil, LNG and ammonia performed the best, with hydrogen, renewable diesel and ULSFO at the bottom. For the climate change category, e-Methanol clearly outperforms the other fuels assessed with negative CO2eq-emissions, with hydrogen and E-FT-Diesel following close behind with low net-emissions. The worst fuel in this category are ammonia, ULSFO and LNG. Ammonia performs significantly worse in categories such as climate change, freshwater ecotoxicity, and non-cancerous human toxicity. Methanol is on the mid- to lower end on the impact scale for all eight impact categories and has a marginally lower impact than conventional fossil fuels in most categories.

Ammar (2019) reviewed the environmental and economic benefits of powering a 15 000 TEU cellular container ship with a MAN dual-fuel engine with a blend of 89 % MeOH and 11 % MDO, as well as the cost-effectiveness for emission reductions from using a dual-fuel engine relative to a pure diesel engine. Methanol engines reportedly have an equal, or even higher, fuel efficiency compared to conventional engines. It is thereby assumed that this also applies to retrofitted dual-fuel engines. At higher methanol concentrations, emissions of NOx, SOx, CO, CO_2 and particulate matter (PM) are reduced. The ship uses MDO with a sulphur concentration of 0.1 %, well within IMO regulations. With increased specific fuel consumption and lower engine efficiency at low engine loads, the SOx emission rate is higher during manoeuvring than in cruise mode. The diesel engine does not, however, comply with IMO regulations regarding NOx (2.039 kg/min vs. 9.06 kg/min). The dual-fuel engine emits 2.021 kg/min of NOx, putting it within limits, meaning that a dual-fuel engine with 89 % MeOH and 11 % MDO fulfils the IMO constraints.

When switching from a diesel engine to a methanol dual-fuel engine for a container ship, Ammar (2019) reports a reduction in emissions from NOx, SOx, PM, CO2 and CO of 77 %, 89 %, 83 %, 18 % and 55 % respectively. With a reported annual fuel consumption cost 28.16 %

higher than for diesel, a dual-fuel ship will be more costly to bunker. In addition, the cost of engine conversion is evaluated at 10.72 MUSD, meaning that older vessels immediately are unlikely to take on the extra cost. As dual-fuel engines can experience knocking due to high octane number when the methanol ratio is high, it is beneficial to decrease engine output power. At a reduced engine load, both fuel consumption and subsequent emissions are lower. At speeds of 25 knots (MCR), operational ship speed could be reduced to 18 knots.

Production of e-MeOH can be achieved through a variety of techniques. The paper by Pratama et al. (2023) considers the case where bioenergy with carbon capture and storage (BECCS) was used to produce green electricity and e-methanol. The flue gas from burning oil palm residuals was captured for use in methanol production, where any surplus CO_2 would be stored. The green hydrogen required for the methanol synthesis was produced from renewable sources, namely solar PV or geothermal, using PEM electrolysis. This system with integrated BECCS and PV proved to be very efficient. The case where solar PV was used, the negative emissions turned out to -0.83 to -0.70 $kgCO_2eq$/kg MeOH, and for the geothermal scenario, the negative emissions were even lower at -1.65 to 1-52 $kgCO_2eq$ /kg (Pratama et al., 2023). Their results show that the majority of CO_2eq-emissions stem from the fuel production, and secondly feedstock extraction. The LCOE is categorically lower for a BIGCC system with higher production capacities, and though the PV-PEM scenario has a higher LCOE than GEO-PEM, the extraordinarily high learning rate for PEM-systems will lead to a sharp decline in cost projections and is expected to be comparable in price to fossil methanol by 2060. This of course will depend on prices of feedstock, electricity, and carbon taxes.

Taking an alternative approach to the LCA, González-Garay et al. (2019) a Plant-to-Planet analysis of renewable methanol. Their results show that green methanol is 1.3 to 2.6 times more expensive than conventional fossils and would require a carbon tax in magnitude of 430.5 USD_{2019} per tonne CO2eq. The price is mainly driven by the electricity costs from hydrogen electrolysis, making up about 73 % of total costs. Prices are expected to drop as technological advancements allow for more efficient operations, mainly improving catalyst efficiency for H_2O-splitting and improving cost-effectiveness for CO2 capture. Direct Air Capture (DAC) will worsen the economic and environmental footprint if not powered by affordable renewable electricity.

In an environmental assessment of marine fuels, Brynolf et al. (2014) investigated liquefied natural gas (LNG), liquefied biogas (LBG), methanol, and bio-methanol for the functional unit of 1 tonne cargo transported 1 kilometre with a ro-ro vessel in the Northern European ECAs. The vessels fuelled by methane or methanol were modelled to have 4 % lower cargo capacity than HFO due to fuel tank space requirements. Results show that CO2 is the main GHG for all fuels that contribute to GWP_{100}, and that LNG and methanol produced from natural gas has a

GWP level comparable to that of HFO, while LBG and bio-methanol are lower. The results still claim that a transition to LNG or methanol produced from natural gas greatly improves the ship's overall environmental performance compared to HFO when also taking into account marine and terrestrial eutrophication, acidification, particulate matter, and photochemical ozone.

Tomos et al. (2024) performed an LCA to compare hydrogen, ammonia, methanol, and waste-derived biofuels as marine shipping fuels. The study examines 13 different alternative shipping fuels and has estimated that these make up a total of 28.8 % of 4505 vessels in the order book as of March 2024. Of these, 19 % are LNG dual fuel, 2.91 % ammonia ready, 1.93 LPG, and 1.38 % methanol dual fuel, whereas the rest only make up small fractions. In their complete life cycle scores, green hydrogen, bio-MeOH, and FAME biodiesel are the most promising abatement fuels. However, they found that e-methanol and e-ammonia do not effectively reduce life cycle emissions, regardless of how they are produced, if they are used in fuel cells or combustion engines, or how the emissions are allocated. They found that, depending on how you allocate emissions, e-methanol can even perform worse in terms of GHG emissions than HFO. Whereas (Tomos et al., 2024) recorded a 26-50 % emission decrease, other sources have found reduction potential as high as 80 % (Kanchiralla et al., 2022). The paper goes on to state that the largest hurdle to cross before methanol uptake can be deemed viable is the lack of initiative regarding alternative ship designs and securing the value chains for said fuels. As a final note, they suggest that an extensive LCA on e-methanol with regard to several CO_2 feedstock acquisition methods is necessary.

1.6 LITERATURE REVIEW SUMMARY

In reviewing relevant literature on methanol as a marine fuel, I have found that most have approached the topic through a well-to-wake LCA, some of which provide a high-level overview, while a few dove into more detailed processes. I found a lack of research papers comparing several production pathways for methanol for short sea shipping, as well as a lack of papers focussing on Norwegian conditions, which will have an impact on both price and emission intensity. Moreover, the papers read that perform an LCA methodology are hardly comparable and vary greatly in their results, as they differ in the application of functional units, system boundaries, impact categories, and technical parameters such as engine type and production pathway. They also vary in complexity and depth of analysis.

This thesis aims to contribute to the debate on the abatement potentials of alternative marine fuels, evaluating the four principal methanol production pathways and comparing these to a benchmark fuel, specifically MGO, for use in container ships. Most papers specify that the policies imposed by the IMO and the EU ETS entering the offshore sector from 2024, are core reasons as to why such fuels will, or must, become the yardstick. Which of the alternative fuels will be deemed eligible is not clear-cut, but aspects such as availability, infrastructure, and costs will be detrimental constraints for shipowners. Focus on renewable methanol products, namely bio-MeOH and e-MeOH are mostly found in newer research, as up until 2023 less than 0.2 % of globally produced methanol could be considered renewable or net-zero. This thesis aims to add to the discussion regarding abatement potentials from different production methods for methanol used in the marine sector, specifically applying them to Norwegian conditions.

1.7 RESEARCH QUESTION

This thesis aims to explore which methanol production pathway will yield the highest benefits from an environmental point of view. To reach the goal the following three research questions need to be answered are:

4. *How many MJ_{energy}/tkm is required of electric and primary energy for a typical 2 000 TEU container ship?*
5. *How many CO2eq/tkm are emitted from utilizing different methanol products as fuel in a typical 2 000 TEU container ship?*
6. *How will emissions from methanol production and combustion compare to those from MGO?*

The research questions will be answered by performing energy chain analyses based on triangulated secondary data collected from the research literature. These calculations will be done for energy consumption and subsequent emissions from within the system boundary, aiming to present the bigger picture of energy drivers. The methodology will be further presented in Chapter 2.

2 METHODOLOGY

This thesis builds on a method called second-degree energy chain analysis as defined in Blok and Nieuwlaar (2017), and this chapter will explain how this method is used to answer the previously stated research questions. The chapter contains explanations of system boundaries, the methodology behind Well-to-Wake and Well-to-Tank analyses, the method of calculation, and necessary assumptions. Lastly, the scenarios for the sensitivity analysis and scenario analysis will be presented.

2.1 ENERGY CHAIN ANALYSIS

An energy chain analysis is in essence a life cycle analysis, with emphasis on mapping all incoming and outgoing energy flows and associated emissions within the system boundaries. This is used to quantify and compare the environmental impacts of fuel production in terms of primary energy requirements as well as upstream and downstream emissions. The results can thus provide shipowners and investors with relevant information which can be used to make economically and environmentally sound decisions in terms of which propulsion system to prepare their fleet for. The target is to calculate the total amount of primary energy required to deliver a specific amount of energy at the end-phase of the energy chain, in this case propulsion.

This methodological approach differs from a life cycle assessment in that a full LCA is standardised, evaluates several impact categories simultaneously, and can provide a higher level of granularity, thus allowing for more complex systems to be modelled. It is common to use LCA Software like SimaPro, OpenLCA, GaBi, or Brightway, or to construct own models in programming software such as Python. A consequence to using that methodology is that many LCA software have a lot of background information around processes and materials, and less common processes might have limited data. At the same time, the results provided by such software are generally accurate and can be used to evaluate complex systems effectively. There are thereby trade-offs associated with applying either methodology, but the method applied here is an appropriate way to draw the big lines in a way that ensures transparency, and being aware of where in the calculations weaknesses occur.

Further, this thesis follows the principle of the Best Available Technology (BAT), meaning that for instances where there is a range of efficiencies reported for the same process, it is assumed that the most efficient will prevail. This is because the commercial implementation of methanol as a marine fuel is not technologically ready at the time of writing, and more efficient processes will likely have been developed by the point of commercialisation, especially when observing the level of activity in this field globally.

Here, five energy chains are analysed and reviewed to answer the aforementioned research questions, four of which will focus on different types of methanol production, and the last one for MGO, which is one of the most commonly used fuels within the EU ECAs.

2.2 SYSTEM BOUNDARIES

This thesis aims to compare Well-to-Wake emissions, also known as Well-to-Propeller, and energy consumption for five fuel production pathways. Conducting a Well-to-Wake analysis is twofold, namely by separating the assessment into Well-to-Tank and Tank-to-Wake analyses. For the Well-to-Tank analysis, the system boundary is set to include all upstream emissions from extracting, processing and distributing the feedstock and subsequent fuel, whereas the system boundary for the Tank-to-Wake process is concentrated around the downstream emissions stemming from fuel bunkering and usage at the ship's wake in the form of combustion in an internal combustion engine (ICE). The general system boundary is illustrated in Figure 4.

The system boundaries are set to ensure the inclusion of the most significant processes in fuel production and propulsion, and to avoid excessive complexity by including processes that are besides of what this thesis aims to answer. Reported emissions from common infrastructure and maintenance are both inconsistent and inaccurate and are thereby excluded from the system boundaries (Tokede & Rouwette, 2024). Moreover, end-of-life management of the vessel is not included in the system boundary, as this is not what this thesis aims to quantify. Additionally, there are large gaps in the knowledge for recycling etc. of hydrogen and methanol vessels and is considered equal for all options regardless.

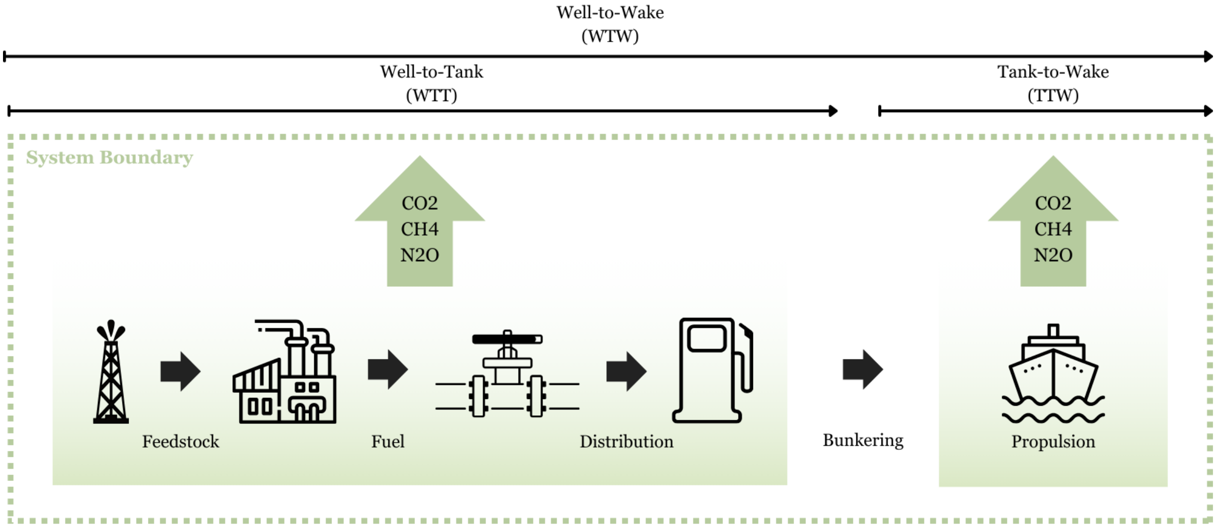


FIGURE 4 GENERAL OVERVIEW OF THE SYSTEM BOUNDARY, WELL-TO-TANK, WELL-TO-WAKE, AND TANK-TO-WAKE.

2.2.1 WELL-TO-WAKE ANALYSIS

The objective of the study is to perform a Well-to-Wake (WtW) analysis for the fuel life cycle. As Figure 4 suggests, the WtW perspective accounts for all fuel cycle stages, from feedstock acquisition to energy conversion in the ship's engine. The process is broken down into two phases, namely production (WtT) of fuel and the consumption of fuel (TtW).

2.2.1.1 Well-to-Tank Analysis

Well-to-Tank depicts the fuel conversion stage, from extraction of feedstock to finished methanol fuel for bunkering. Such analyses require a mapping of all processes in the production pathway for the fuel, from extraction to propulsion. Firstly, the primary energy requirements for each sub-process per unit of fuel are calculated, which will then be the foundation of which the emissions are to be assessed. This methodology is presented by Blok and Nieuwlaar (2017) and is termed *Energy Requirement for Energy* (ERE), the required amount of primary energy input to deliver one unit of energy. A detailed calculation methodology will be presented in Chapter 2.6.

2.2.1.2 Tank-to-Wake Analysis

The stage after fuel bunkering is termed Tank-to-Wake, and relevant downstream emission factors are collected from recent literature. As provided by (Corbett & Winebrake, 2018), a methanol engine primarily emits CO2 and NOx, and small amounts of PM2.5 and SOx, whereas a low-sulphur diesel engine also emits VOC, CO, and small amounts of CH4 and N2O.

2.3 CALCULATIONS (METHOD)

The calculations are focused on two stages: energy intensity for each value chain, and the associated upstream and downstream emissions measured in CO_2, CH_4 and N_2O, translated to CO_2-equivalents, measuring climate change potential. The results will be delivered through the functional units $MJ_{primary}/MJ_{MeOH}$ (ERE), and gCO_2eq/tkm used for propulsion power to reflect exactly how much energy goes into making the fuel carry one tonne of cargo one kilometre.

2.3.1 ENERGY CONSUMPTION AND EMISSIONS

To properly outline the energy intensity for each pathway, the ERE parameter is divided into two, namely $ERE_{primary}$ and ERE_{el}, where the accumulated energy consumption for the process is termed ERE_{total}. This translates to energy requirements from primary sources and electricity to produce the fuels through any of the aforementioned pathways. The values for $ERE_{primary}$ and ERE_{el} will then be used to determine the energy requirement in MJ/tkm, at which point we multiply this by the appropriate emission factors to determine the WtW emissions. The methodology for the calculations is displayed in Table 1 below.

Table 1: Overview of calculation methods used in the subsequent analysis, based on methodology in (Blok & Nieuwlaar, 2017).

	Primary Energy	**Electric Energy**
Energy Consumption per Sub-Process	$ERE_{primary} = \frac{1}{\Pi_{i=1}^{8}\eta_{i,j}}$	$ERE_{el} = \frac{c_{el} * LCV}{\Pi\eta}$
Description	$\Pi\eta$ – the product of the efficiencies for each sub-process	c_{el} – electricity consumption of sub-process LVC – lower calorific value for the fuel $\Pi\eta$ – the product of the efficiencies for each sub-process
Total Energy Consumption		
Total Upstream Energy Consumption	$ERE_{total} = ERE_{primary} + ERE_{el}$	
Well-to-Wake Emissions		
Total Well-to-Wake Emissions	$WtW_{el} = (ERE_{el} * TtW) * e_i$ $WtW_{primary} = (ERE_{primary} * TtW) * f_i$ $WtW_{total} = WtW_{el} + WtW_{primary}$	
Description	ERE_{total} – total upstream energy consumption in MJ/MJ MeOH produced TtW – fuel consumption for propulsion in MJ/tkm e_i – emission factor for electricity mix i f_i – emission factor for feedstock i	

2.4 ASSUMPTIONS

Due to time limitations, there were certain assumptions that had to be made in order to construct an achievable scope. This thesis aims to calculate emissions from the different parts of the energy chains in CO_2eq/tkm, and instances where the emissions only are given in CO_2 instead of CO_2eq, will be clarified. The goal is to assess the *fuel's* life cycle, meaning that this is an energy chain analysis and not a full value chain analysis incorporating e.g., demolition of the ship. It is important to set clear system boundaries, be it geographically, time horizons or the processes to be included. The locations of production sites and where the product is consumed and disposed of are essential to the results.

As the goal is to explore the emission intensities from main engines during cruise speed, auxiliary systems, boilers, thrusters, etc., are not specifically considered. The literature collected all used an averaged fuel consumption per year, per roundtrip or per unit of cargo transported. Medium-speed engines are considered, but it is worth noting that there are some sources that believe that low-speed engines will have a larger abatement potential than high-speed engines (Tomos et al., 2024).

The best-available-technology (BAT) principle for capacity factors and sub-process energy consumptions is applied, as this is thought to be more representable of a future scenario than collecting several capacity factors, and averaging these.

All fuels are assumed too be produced at the same geographical location, specifically at Tjeldbergodden near Equinor's Methanol Production facility as most infrastructure is thought to be established (Equinor, 2019). For simplicity's sake, it is assumed that MGO is produced in close vicinity to this. The ready fuel is then shipped the ~500 km to Sydhavna in Oslo by tank trucks. This is Norway's largest containership harbour, as well as housing the oil terminal for all of Eastern Norway, from which fuel is distributed to i.e., Gardermoen (OsloHavn, n.d.).

All the oil and gas used for production are assumed to be extracted from fields on the Norwegian Continental Shelf (NCS), as Norway is the largest oil and gas producer in Europe following the Russia-Ukraine conflict. As most European methanol plants can be found in Norway and Germany, we proceed with the assumption that the fuel is produced in Norway in the base case and supplement with a scenario analysis where the production is supplied with an EU electricity mix, to reflect how the emission intensities would change if production were to occur elsewhere on the continent. No specific country is considered for the

As fuel consumption for methanol-fuelled engines was difficult to obtain from the literature, it was deemed reasonable to assume the same fuel consumption for MGO and methanol engines in the form of energy. This assumption was verified by DNV (Bøhmer, 2024).

Scope 3 emissions from infrastructure such as factories, roads, pipelines, engines, hulls, and such, are not included in the analysis, as the focus is on the fuel itself. These aspects are not considered to vary significantly among the different production pathways, but it is important to be aware of the fact that these aspects also have an impact on the bottom line. These considerations are particularly important for LCAs conducted for installations for renewable energy (Raadal, 2024). If the material for the catalyst is sourced from a mine in central Africa, the emissions from both extraction and transportation to the manufacturer will have an impact.

2.5 SENSITIVITY ANALYSIS

The sensitivity analysis is a method for assessing the robustness of the initial results by modifying input parameters to reflect a range of possible fluctuations. All scenarios are subject to flows and processes with a certain degree of uncertainty, such as the electricity mix composition and the efficiencies of reforming processes. Any variations in these parameters can have major, moderate, or negligible implications on the final results, which is important for a nuanced assessment.

The energy chains will be tested independently of each other, within a certain percentage range (e.g., +/- 30 %). It is important to note that all parameters are adjusted without considering the effects of improvement of other processes. If there are technological advancements made for one technology, it is not unlikely that proximate processes will be correspondingly improved. Such ripple effects are not accounted for here, and each parameter is adjusted as a standalone process that is unaffected by changes in other parts along the energy chain.

The sensitivity analysis is conducted for the pathways that have a large splay in collected data, particularly for EL-MeOH and BIO-MeOH. The pathways for MGO and NG-MeOH are established processes with very little variance in the data, and the CCS-MeOH is similar to NG-MeOH with added carbon capture.

2.5 SCENARIO ANALYSIS

There are uncertainties as to which technologies will be applied in a future scenario, which is why it is helpful to test certain technologies that are hypothetically likely to be more efficient in the future. This is evident for the “younger” reforming processes, such as BIO-MeOH and EL-MeOH, which can have a variety of pathways. EL-MeOH is dependent on CO_2 input from an external source. The base scenario considers DAC, but it is also possible to apply CCS technology to a nearby industrial plant that otherwise would emit GHGs directly to the atmosphere.

2.5.1 ELECTRICITY MIX

The EL-MeOH pathway is regarded as being exclusively powered by electricity. The DAC unit will require additional heat input, which is assumed to be mainly recycled from the methanol synthesis. There are mainly two ways the production can source its electricity: either from the grid or a standalone power plant, typically wind. While the entire fuel production is set in Norway, and in the base scenario expected to be fed by a Norwegian electricity mix, there is a possibility that commercial methanol plants would be of a size that requires too much energy to source directly from the Norwegian grid, as certain parts of Norway is heading toward an electricity deficit. This could thereby require the production plant to be hooked up to a standalone power plant or be relocated to another production site on the continent. It is important to be aware of how emission levels would react to different electricity mixes and will therefore be tested against scenarios where it relies completely on a standalone offshore power plant, as well as a more carbon-intensive electricity mix in central Europe.

2.5.2 FUEL CONSUMPTION

In order to find out how much primary- and electric energy input would be required to fulfil one tkm of propulsion, we need to know how much fuel a 2000 TEU consumes per unit of work (tkm). This proved particularly challenging, as such numbers are not generally disclosed in the literature. Though getting in touch with several people with knowledge of shipping logistics, a definite answer could not be achieved. Wissner et al. (2023) also state that the energy efficiency of methanol engines is comparable to conventional fuel oil engines, and this was independently verified by DNV (Bøhmer, 2024). These numbers for fuel consumption will serve as the benchmark in the rest of this thesis.

After the initial analysis was conducted, fuel consumptions by Klein et al. (2021) report much higher numbers for fuel consumption, and their research provided the specific fuel consumption for a 2500 TEU containership. Note that these consumption numbers are based on a diesel engine and that diesel fuel oil and MGO/MDO are used interchangeably in the literature. Though the emission factors are recorded for MDO, *NOx-Fondet* relies on the same NOx factor for MDO and MGO, and Statistics Norway does not differentiate between MGO and MDO (NOx-Fondet, 2021; SSB, n.d.). The reason it is believed that the containership will consume less that what is stated in Klein et al. (2021) is simply due to the fact that a containership utilizes its fuel more efficiently per tonne cargo transported one kilometer (tkm) during cruising speed. The specific fuel consumption will differ depending on the engine load, but here we are looking at a voyage average. Due to this, an the findings by Akerbæk (2018) will be used as the benchmark, whereas the numbers from Klein et al. (2021) are used in the scenario analysis. An overview is shown in Table 2.

TABLE 2: FUEL CONSUMPTION FACTORS FOR TWO DIFFERENT CONTAINER SHIPS ~ 2000 TEU.

Fuel Consumption	MGO/diesel	Methanol (DF)	Source:
Container Ship	0.059 MJ/tkm	0.05782 MJ/tkm	(Akerbæk, 2018)
Container Ship, medium load	0.25 MJ/tkm	0.23 MJ/tkm	(Klein et al., 2021)

3 THE ENERGY CHAINS

A total of five energy chains aim to answer the research question. Four of the chains will depict different production routes of methanol and will be compared to a benchmark fuel, MGO. There are several ways of producing methanol, all of which will have a certain tradeoff in terms of emissions and efficiency of production. An overview of the pathways can be seen in Table 3.

TABLE 3: THE FIVE ENERGY CHAINS WITH ASSIGNED PRODUCTION PATHWAY INDEXES AND DESCRIPTIONS.

Production Pathway Index	**Description**
MGO	Conventional distillate applied in an internal combustion engine
NG-MeOH	Methanol derived from natural gas and electrolysis applied in a dual-fuel combustion engine
CCS-MeOH	Methanol derived from natural gas and electrolysis with integrated CCS, applied in a dual-fuel combustion engine
BIO-MeOH	Methanol derived from biomass gassification applied in a dual-fuel combustion engine
EL-MeOH	Methanol derived from captured carbon dioxide and electrolysis, applied in a dual-fuel combustion engine

3.1 MGO

Marine Gas Oil (MGO) is a traditional fossil fuel which allows vessels to be compliant to all regulations in 2024 and is therefore the benchmark to which methanol is compared. MGO is produced through the refining and distillation of crude oil and is a midpoint distillate between diesel and HFO, but is ultimately coined as a light fuel oil product like diesel (Compass-Fuels, 2023). MGO bears a high resemblance to Marine Diesel Oil (MDO), albeit with a somewhat higher energy density. The primary energy source is crude oil extracted on the Norwegian Continental Shelf (NCS), which will be transported by subsea pipelines to an onshore facility for further processing. It is reasonable to assume that the extraction and refining are conducted on the NCS, which historically has proved a high degree of efficiency. As outlined in Figure 5, it is assumed that the crude will be stored in tanks after it makes landfall, which will lead to minute losses, after which it is transported directly by pipelines to a bunkering site.

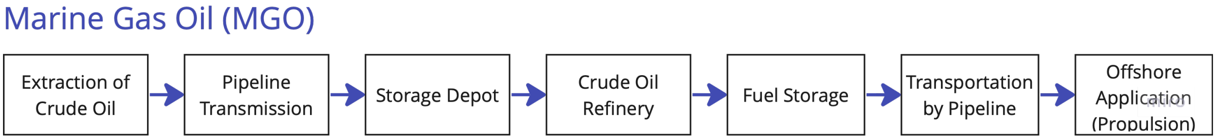


FIGURE 5: A SCHEMATIC OF THE MGO ENERGY CHAIN.

3.2 NG-MeOH

For the chain depicting fossil methanol, natural gas is assumed to be extracted on the NCS and transported via subsea pipelines to shore to a methanol processing facility. Before it goes through the reforming stages, the gas must go through a desulphurisation process to meet the purity requirements of the catalysts that help facilitate the following processes, namely pre-reforming, steam methane reforming and autothermal reforming. Even trace amounts of sulphuric compounds in the gas will degrade the catalysts over time, ultimately resulting in a lower methanol yield. At this point, we have obtained a hydrogen-rich synthesis gas consisting of H2, CO, CO2 and CH4, which will go through a methanol reactor in a process called methanol synthesis. In the hydrogen reactor, CO, CO2 and H2 react and form crude methanol, which then goes through a distillation tower to boil off unwanted compounds and leave behind methanol with purity of > 99.9 % (Equinor, 2019). The finished product will then be shipped off to a port for bunkering.

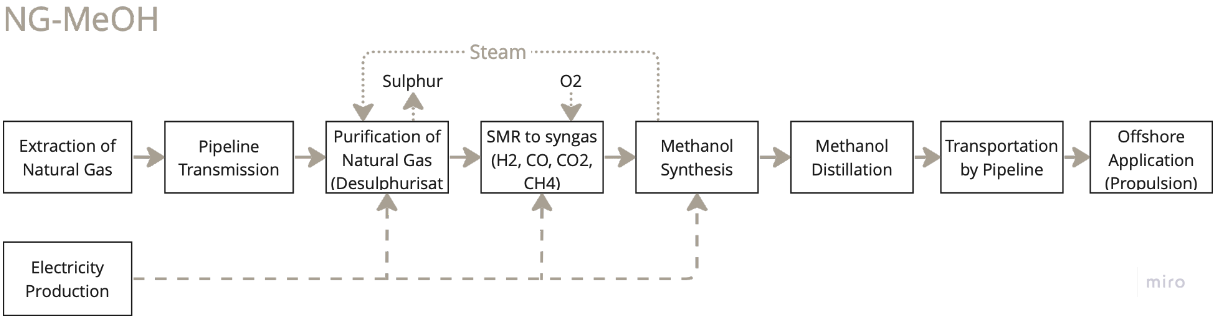


FIGURE 6: A SCHEMATIC OF THE NG-MEOH ENERGY CHAIN.

3.3 EL-MeOH

For the electrofuel EL-MeOH, the end product is manufactured by combining renewable hydrogen with captured CO_2. CO_2 can be allocated from ambient air through Direct Air Capture

(DAC) or carbon capture from an industrial plant. For the base scenario, DAC was the chosen technology based on its prevalence in the literature read in preparation for this analysis. As opposed to capturing flue gas directly from an industrial plant, which has an adequate CO_2 concentration as is, DAC requires an additional compression step to ensure optimal CO_2 density. The electrolyser is powered by a feed of electricity and desalinised seawater. The subsequent MeOH production follows the same path as NG-MeOH, where after hydrogen has been produced through water electrolysis, the hydrogen and captured CO_2 go through a catalytic reaction to synthesise methanol of high purity, before entering the distillation tower to be left with an even purer result (Narayanan, 2023).

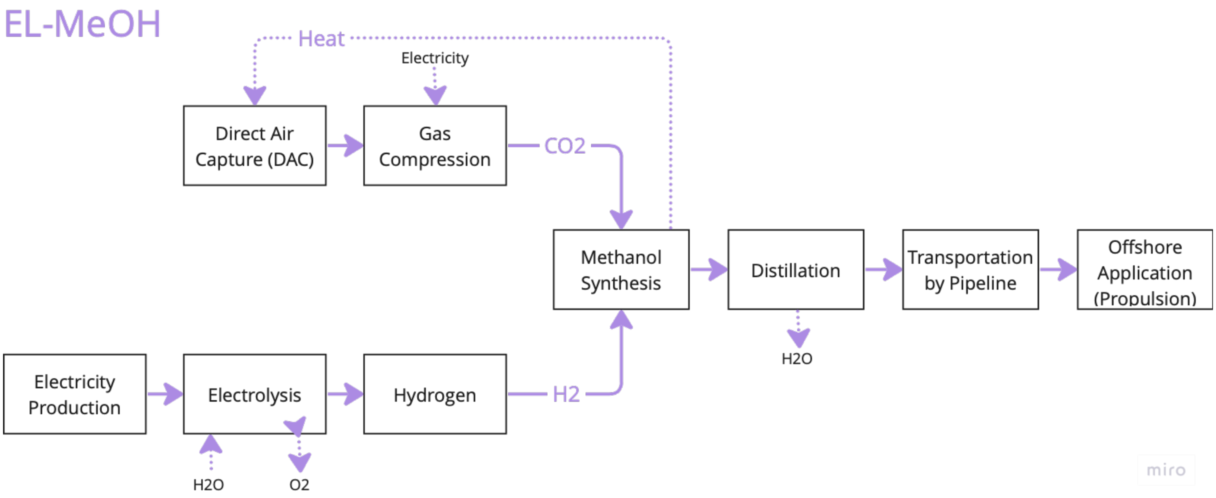


FIGURE 7: A SCHEMATIC OF THE EL-MEOH ENERGY CHAIN.

3.4 BIO-MEOH

For bio-methanol, the syngas required for further production is typically sourced from renewable biogenic sources, such as residual waste from forestry, municipal waste, or biomass from dedicated crops. BIO-MeOH can be produced through several feedstocks. After the syngas have been produced, it is assumed that the following process utilizes the same technology, mass- and energy balances as NG-MeOH (Methanol-Institute, n.d.). The feedstock source is thought to be forestry residues, both because of its prevalence in upcoming bio-methanol projects, but also because Norway has a large waste stream of forestry by-products going to Sweden for further processing. According to NORSKOG, the Norwegian organisation for forest owners, Norway currently mismanages the utilisation of forestry by-products, impeding the entire forestry value chain (NORSKOG, 2022). This will additionally result in avoided emissions from long-haul trucking and shipping to other countries.

The TtW-emissions from solid biomass feedstocks are regarded as climate neutral, and thus the emissions from combustion do not directly contribute to the WtW footprint of bio-methanol.

3.5 CCS-MEOH

CCS-MeOH, or "blue" methanol, is manufactured similarly to NG-MeOH, apart from using blue hydrogen instead of green hydrogen in the methanol synthesis, which will have an impact on the WtW emissions. Just like NG-MeOH, the natural gas feedstock will be purified and processed into syngas through SMR, at which point a CCS-unit will capture the fugitive emissions and sequester them underground. Carbon captured along the Norwegian coast is likely to be stored in subsea saline aquifers.

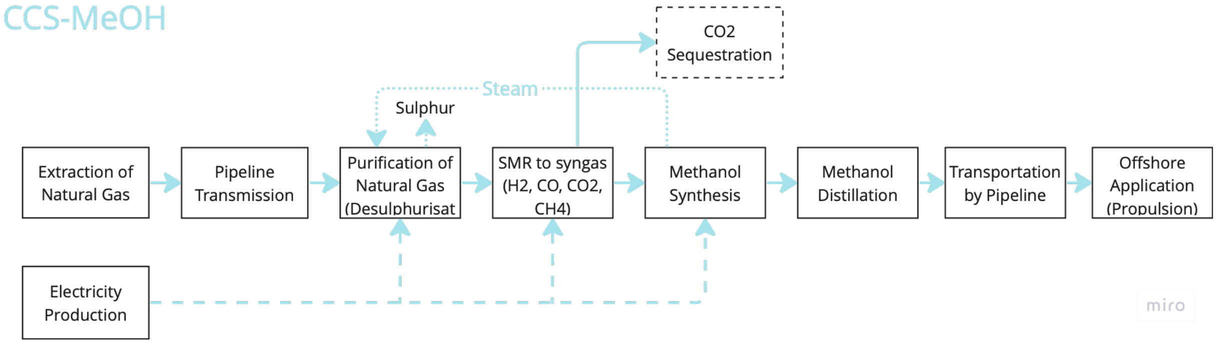


FIGURE 8: A SCHEMATIC OF THE CCS-MEOH ENERGY CHAIN.

4 DATA

This chapter will present the collected data used in the subsequent analysis and the process used to decide which values will go into the analysis. The chapter is sectioned into Well-to-Tank and Tank-to-Wake, with subchapters explaining the numbers collected and used in the analysis.

4.1 DATA COLLECTION

The data applied in the following analyses is largely based on triangulated secondary data, meaning that data is obtained from research papers, books and databases. Secondary data requires collection from several sources to find a representative midpoint, known as triangulation. This is to minimize the weaknesses that may occur when only a few sources are considered, as important nuances are likely to be overlooked. As there are a plethora of research papers concerning one or more of the processes depicted in the energy chains, there is always a possibility that certain details go unnoticed, which is why I have worked towards collecting at least three sources for each sub-process that require energy input.

4.2 WELL-TO-TANK

4.2.1 ELECTRICITY

The energy chains that do not rely on fossil feedstocks rely heavily on electricity input to fuel the production. Depending on the country of origin, the composition of technologies, and thereby the emission factors, can vary substantially. Here, the average EU electricity mix, the Norwegian electricity mix as well as a fully renewable electricity mix were considered to test for the overall impact of varying emission factors from electricity production. The literature differs in whether renewable electricity includes emissions from construction. This aspect is disregarded here, as capital goods are excluded in the REN II Carbon Footprint approach (EUC, 2023; Methanol-Institute, n.d.). As emissions from the operational stage are negligible, we set the emission intensity for a fully renewable energy source to zero. The fractions of fossil and renewable energy consumption in Norway and the EU are divided as shown in Figure 9. This approach is useful in expressing how an electricity mix with a lower fraction of renewable energy impacts the final WtW results.

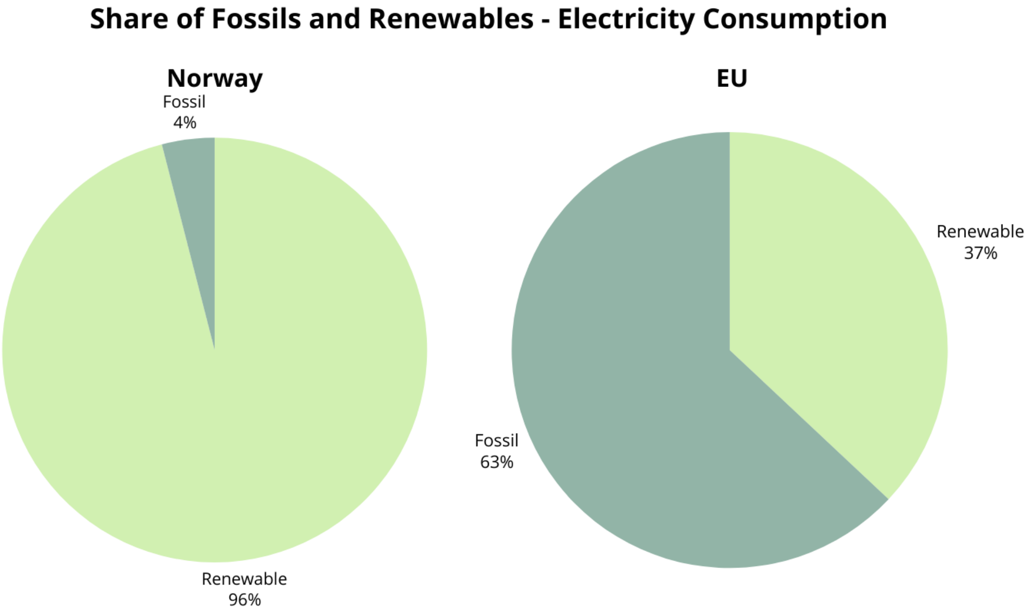


FIGURE 9: SHARE OF FOSSIL AND RENEWABLES FOR NORWEGIAN AND EU ELECTRICITY CONSUMPTION. SOURCES: (EUB, 2024; NVE, 2021)

In this context, it is necessary to highlight the fact that fossil energy and renewable electricity are often measured on different grounds. Fossil energy sources are often hindered by thermal penalties during conversion, which means a lot of the latent energy in the fuel is released as waste heat, which entails that more primary energy input is required than what the final yield represents (Ritchie & Rosado, 2021). This is significant because the total primary energy production does not translate to useful energy, which is much lower. Before renewables were available on the wholesale market, this was a sufficient method of comparison. This is known as the *direct primary energy method* (DPEM). Here, fossil sources are measured in direct primary energy, and renewable electricity is measured with an efficiency of 100 %, where losses remain unaccounted for (Ritchie & Rosado, 2021).

One alternative method to ensure that these energy sources are measured on comparable grounds is through using the *substitution method* (SM). Here, renewable energy sources, such as solar and wind, are assigned efficiencies that reflect the thermal penalties that characterise fossil fuels, known as the thermal efficiency factor. This factor has increased on a global scale from 36 % in 1965 to 41 % in 2022, as thermal conversion has gotten more efficient (Ritchie & Rosado, 2021).

The third and final method is the *physical energy content method* (PECM), applied by Eurostat, the OECD and the IEA (Eurostat, n.d.; IEA, 2023; OECD, 2019). As the name suggests, the actual physical yield from each energy source is used when assigning efficiencies to each energy source.

TABLE 4: A COMPARISON OF THE DIRECT PRIMARY ENERGY, SUBSTITUTION AND PHYSICAL ENERGY CONTENT METHODS APPLIED FOR WIND POWER, HYDRO POWER AND NATURAL GAS

	Direct Primary Energy	Substitution	Physical Energy Content
MJ_{in}/MJ_{out} (wind)	1	2.43	2.08
MJ_{in}/MJ_{out} (hydro)	1	2.43	1.06
MJ_{in}/MJ_{out} (NG)	2.2	2.2	2.2

Table 4 compares how the three different methods impact how different energy sources are measured at the point of conversion. The direct primary energy method implies that to get one MJ of electricity from wind power, you would need 1 MJ of wind to enter the swept area of the turbine, as there are no thermal losses to account for. In practice, wind power has a theoretical maximum efficiency of 59 %, but will, in reality, be somewhat lower due to spatial conditions and technological limitations. For the physical energy content in Table 4, the efficiency was set to 48 %, requiring 2.08 MJ wind energy per MJ_{el}. The substitution method assigns all renewables with 41 %, which penalizes technologies with high conversion efficiencies, such as hydro power, which is about 90 % efficient from "*water to wire*" (Killingtveit, 2020). For all renewable sources, this means an input of 2.43 MJ_{energy} per MJ_{el}.

In summary, the *direct primary energy method* uses an averaged efficiency factor based on the specific technology but is only truly representative of fossil fuel conversion. For countries with a high supply of renewable electricity, this overlooks some detrimental nuances, as the share of renewables and fossils in the supply mix will vary greatly depending on which method is applied. The substitution method compares renewable energy sources with a hypothetical equivalent of conventional energy sources (Segers, 2008). The physical energy content method ensures that the trade-offs between fossil and renewable energy are clearly presented and will be the benchmark method used in the analysis.

Table 5: Share of different energy sources for Norway and EU, and cumulative efficiencies for Norway and EU when applying the PEC-method.

	Share of Final Electricity Consumption		Efficiency Factor (η)	Cumulative η	
	Norway	EU		Norway	EU
Residual oil	2,0 %	1,6 %	34 %	0,68 %	0,54 %
Natural gas	1,0 %	19,6 %	44 %	0,44 %	8,62 %
Coal	1,0 %	15,8 %	40 %	0,40 %	6,32 %
Nuclear power	2,0 %	21,9 %	35 %	0,70 %	7,67 %
Biomass	0,5 %	4,4 %	100 %	0,50 %	4,40 %
Hydroelectric	87,0 %	11,3 %	100 %	87,00 %	11,30 %
Geothermal	0,0 %	0,2 %	100 %	0,00 %	0,20 %
Wind	6,0 %	15,9 %	100 %	6,00 %	15,90 %
Solar PV	0,5 %	7,6 %	100 %	0,50 %	7,60 %
Others	0,0 %	1,7 %	100 %	0,00 %	1,70 %
Sum	100,0 %	100,0 %	-	96,22 %	64,25 %

4.2.1.1 Norwegian Electricity Mix

As shown in Table 5, the Norwegian electricity mix mainly consists of hydropower. These numbers reflect consumed energy as of 2019, meaning that imported electricity from neighbouring countries is included (NVE, 2021). Assigning the PEC parameters to these technologies, we end up with an overall efficiency for the Norwegian electricity mix of 87.2 %. The reason that the overall efficiency is so high, is that the conversion efficiency of hydropower is around 94 % and constitutes the majority of Norwegian electricity consumption (Retgen, n.d.).

4.2.2 Extraction of Natural Gas

The energy chains NG-MeOH and CCS-MeOH use natural gas as their primary feedstock. Up until the carbon capture stage for the CCS-MeOH-chain, the process is deemed equivalent. Since the US and Norway hold the positions of the largest natural gas exporters globally, and the geographical scope of this thesis is set to Europe, Norwegian gas is assumed as the feedstock (EU, 2024). This is significant because the quality and composition of natural gas is dependent on geographical location, and the method of extraction has a large impact on overall efficiency. While the carbon intensity for Norwegian gas will be used in the analysis, I was unable to retrieve an efficiency factor for Norwegian gas production, as seen in Table 6. Following the BAT principle, a general efficiency factor of 99.3 % is applied.

Table 6: Efficiency factor for natural gas extraction.

Efficiency NG Extraction:	Comment:	Source:
99.3 %	General	(Blok & Nieuwlaar, 2017)
96.0 %	China	(Wang et al., 2015)
97.5 %	US	(Winebrake et al., 2019)
96.0 %	China	(Dong et al., 2016)

4.2.3 TRANSPORTATION OF NATURAL GAS

When natural gas is transported in subsea pipelines, it is bound to experience a decrease in pressure the longer it travels due to frictional drag (Molnar, 2022). It is important to note that actual losses and efficiency depend on the material of which the pipe is constructed, the wall thickness, the diameter of the tunnel, the pressure within the pipe, and the length and depth at which the pipeline is laid. This necessitates the installation of intermediate compressor stations, typically every 100 to 200 km along the pipeline, typically powered by natural gas or electricity (Molnar, 2022). Natural gas accounts for about 95 % of energy consumption, at 0.5 % of the volume transported every 100 km. Pipelines of larger diameters tend to have a lower requirement for input energy due to lower friction loss per unit transported. Emmenegger et al. (2015) set an overall transmission loss for Western European countries to 98 %. No exact transportation length has been defined for either of the sources listed in Table 7 and is therefore assumed to be an averaged number.

TABLE 7: EFFICIENCY FACTORS FOR NATURAL GAS SUBSEA PIPELINE TRANSPORTATION.

Transportation efficiency NG:	Source:
98 %	(Emmenegger et al., 2015)
97.5 %	(Sevenster & Croezen, 2006)

4.2.4 EXTRACTION OF CRUDE OIL

Production of MGO requires crude oil, and the general crude oil efficiency factors found are listed in Table 8. Similar to natural gas, oil extraction is a generally efficient process. While exact numbers for Norwegian conditions were not able to be retrieved, it is reasonable to assume that production in the US would be a close approximation, which is set to 98 % by Winebrake et al. (2019).

TABLE 8: EFFICIENCY FACTORS FOR CRUDE OIL EXTRACTION.

Extraction efficiency crude oil:	Source:
98 %	(Winebrake et al., 2019)
93 %	(Wang et al., 2015)
96 %	(Dong et al., 2016)
97 %	(Stepan et al., 2023)

4.2.5 TRANSPORTATION OF CRUDE OIL

The crude oil extracted on the Norwegian NCS is transported to shore through subsea pipelines, which are known to be highly efficient and with low subsequent losses. The crude oil transportation efficiencies are listed in Table 9, and the BAT principle allows to set the efficiency to 99.5 %.

TABLE 9: EFFICIENCY FACTORS FOR CRUDE OIL SUBSEA PIPELINE TRANSPORTATION.

Crude Oil Pipeline Transportation Efficiency:	Source:
78 %	(Wang et al., 2015)
99.5 %	(Holden, 2010)
96 %	(Stepan et al., 2023)

4.2.6 CRUDE OIL REFINING

After the crude has made landfall at the refinery, it is heated up in a distillation tower where the different hydrocarbons are separated as they condense at different temperatures (NorskPetroleum, n.d.). The efficiency factors for crude oil refining are listen in Table 10 below. Marine fuels are divided into three categories; marine gas oil, heavier distillates (marine special distillate), and residual-/heavy fuel oil, whereas ISO standards separate between marine residual fuels and marine distillate fuels. Norwegian-produced marine diesel oil has historically been very similar in composition to marine gas oil, but MDO is being phased out in favour of MGO (Moldestad & Daling, 2006). The energy requirement for distillation depends on the output product, where lighter distillates require more energy for production than heavy distillates such as HFO. While Wang et al. (2015) report an efficiency of 89.1 % and 89.7 % for gasoline and diesel refining respectively, they find that residual oil is 94 % efficient. As MGO is closer to diesel than HFO in composition, the efficiency is set to 91 %.

TABLE 10: EFFICIENCY FACTORS FOR CRUDE OIL REFINING.

Crude Oil Refining:	Source:
89.7 %	(Wang et al., 2015)
91 %	(Winebrake et al., 2019)
90 %	(Stepan et al., 2023)

4.2.6.1 Electricity Consumption Crude Oil Refining

There are small amounts of electricity going into refining. Wang et al. (2004) report that a total of 18.6 kJ of electricity is required to reform 1 kg of crude oil to gas oil, or 0.41 MJ electricity per kg produced gas oil.

4.2.7 MGO STORAGE AND DISTRIBUTION

As MGO is a lighter distillate like diesel, it does not require to be heated during storage in order to keep viscosity low like for HFO. Light oil distillates have a shelf life ranging from weeks to months, so the losses from storage between production and bunkering are termed negligible in this context (Oilfast, n.d.). Rather, the energy losses from transportation and distribution are accounted for, as shown in Table 11. Stepan et al. (2023) report that the transportation of diesel across 5,000 km is 99 % efficient. However, in this context, we assume that the ships make berth at Sydhavna right outside Oslo, and only account for distribution via tank trucks. In this instance, 500 km with an efficiency of 99 % is deemed applicable, as the bunkering site at Sydhavna is located about 553 km from Tjeldbergodden (*Google Maps*, 2024).

TABLE 11: EFFICIENCY FACTORS FOR TRANSPORTATION AND DISTRIBUTION OF FUEL OIL DISTILLATES.

Efficiency Transportation and Distribution:	Comment:	Source:
99%	Transportation (Shipping), 5,000 km	(Stepan et al., 2023)
99%	Distribution, 500 km	(Stepan et al., 2023)

4.2.8 NATURAL GAS PRE-REFORMING

Before going through steam reforming, the gas needs to go through gas sweetening, a process in which impurities are removed to ensure a higher gas quality. Sour gas contains corrosive compounds like CO2 and H2S (hydrogen sulphides). As Norway is not thought to have a large share of sour gas, it is assumed that this process has little overall impact. In (Emmenegger et al., 2015), a methane emission rate of 0.003 % is recorded. This step is integrated with the SMR process presented in Chapter 4.2.8.

4.2.9 STEAM METHANE REFORMING (SMR)

For the SMR process, it is assumed that natural gas fulfils all thermal requirements, as electric SMR is less common. In natural gas processing, a mere 1 % of electricity is applied but is disregarded here (Wang et al., 2015). Steam Methane Reforming (SMR) is both cost-effective and widely applied in industrial applications, such as for thermal heat and as a feedstock for methanol production. SMR utilizes either coal, oil, or natural gas as its feedstock, with the end product being hydrogen. This is an endothermic reaction which relies on an external heat source to heat the natural gas to facilitate the formation of syngas through a water-gas shift reaction (WGS), where carbon monoxide is ultimately converted to CO2 (Bukkholm, 2021; SE, n.d.). The yield from this process is dependent on catalytic reactions, which facilitates a more efficient formation of the product. This entails a lower activation energy than if the molecules are allowed to just react on themselves, which has a huge impact on the rate of production (Topsoe, 2024). The reaction goes as follows:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

An SMR unit consists of feedstock pre-treatment, the SMR unit, the shift reactor for removal of CO, and a PSA unit (Collodi, 2017). The syngas from the SMR stage is fed through a water-gas shift (WGS) reactor containing catalysts to convert CO and H_2O into H_2 and CO_2, in order to achieve the highest H-to-CO ratio (NETL, n.d.). The elimination of CO is particularly important if the hydrogen is to be used in a PEM fuel cell, which has high purity requirements, as CO will degrade the electrodes over time. The efficiency factors listed in Table 12 are assumed to include these steps, as otherwise was not stated. The literature read in preparations did not look at these processes as isolated. Continuing to follow the BAT principle, an efficiency factor of 85 % was applied.

TABLE 12: EFFICIENCY FACTORS FOR STEAM METHANE REFORMING (SMR).

Efficiency SMR:	Source:
74 %	(Abad & Dodds, 2017)
75 %	(HNL, 2022)
80 %	(Rosvold, 2023)
85 %	(Jakobsen & Åtland, 2016)

4.2.9.1 Electricity Consumption SMR

The SMR process utilises some electricity in addition to thermal heat provided by recycling heat from other parts of the methanol production process. 3.46 MJ electricity per hydrogen output was applied for NG-MeOH and 4.42 MJ electricity per hydrogen output was applied for CCS-MeOH. This includes electricity consumption for a CCS unit for the CCS-MeOH pathway. This hydrogen can thus be used for methanol synthesis.

4.2.10 PEM ELECTROLYSIS

Alkaline electrolysis has for a long time been thought of as the most robust hydrogen production path but has faced competition from the Proton Exchange Membrane (PEM) electrolysers that can better handle the fluctuating load profiles associated with electricity generation from solar and wind. The PEM electrolysers does, however, bear a much higher capital cost. This is due to being made up from a unique and costly polymer, as well as the precious metals platinum and iridium (Thomassen et al., 2018). While the alkaline process (gets its characteristic from the highly alkaline potassium or sodium hydroxide electrolyte) is reliable and cost effective, the PEM can offer more compact stacks, and a solid electrolyte that is easier to disassemble and recycle. Electrolysis efficiency is expected to increase from 60 % to 80 % towards 2030 (Cho et al., 2022). Water electrolysis through using US grid will give emissions of 27.3 kg CO2/kg H2 (Cho et al., 2022). Most sources mentioning high efficiencies around 80 %, also mention that the efficiency will likely lie somewhere within the range of 60 % to 80 %, as seen in Table 13. An efficiency factor of 80 % has been used in the following calculations.

TABLE 13: EFFICIENCY FACTORS FOR PEM ELECTROLYSIS.

PEM Electrolysis Efficiency:	Source:
70 %	(Emmenegger et al., 2015)
72 %	(Dolan, 2019)
62 %	(Pratama et al., 2023)
60 %	(Rufer, 2022)
80 %	(Stepan et al., 2023)
80 %	(Kumar & Himabindu, 2019)

4.2.11 CARBON CAPTURE

Most sources provide a range in which the actual efficiency is thought to lie. The uncertainty can be attributed to the fact that there are relatively few large-scale CCS facilities in operation today, and the capture efficiencies are varying as seen in Table 14. While the theoretical potential can be as high as 98-99 %, the reality reflects that capturing efficiencies above 90 % is hampered by economic conditions (Moseman & Herzog, 2021). As carbon taxes increase, we are more likely to see efficiencies closer to 100 %. Applying the condition of the BAT principle, we set the efficiency to 91 %.

TABLE 14: EFFICIENCY FACTORS FOR CARBON CAPTURE AND STORAGE (CCS).

CCS Efficiency:	Comment:	Source:
90 %		(Gazzani et al., 2014)
91 %	Reported range: 90-91 %	(Zheng et al., 2023)
84.26 %		(Okonkwo et al., 2023)

4.2.12 DIRECT AIR CAPTURE (DAC)

The energy input needed for the CO2 extraction is highly dependent on the carbon concentration in the gas (Emmenegger et al., 2015). CO2 capture from ambient air has a concentration of 0.04 %, while exhaust gases from combustion processes are at around 12 %

and biogenic CO2 from the methane upgrade of a biogas facility contains in excess of 99 % and requires no further processing (Emmenegger et al., 2015).

Okonkwo et al. (2023) investigated DAC with integrated bioenergy as an alternative energy source and reported capture efficiencies as high as 91.2 % and 93.9 %. However, in a report by Stepan et al. (2023), they found that direct air capture for e-MeOH specifically is at 76 %, or 24 kWh/kWh MeOH. These are shown in Table 15 below. Though a higher efficiency factor was located in the literature, this seems to be a more appropriate approximation for this specific task.

TABLE 15: EFFICIENCY FACTORS FOR DIRECT AIR CAPTURE (DAC).

DAC Efficiency:	Source:
93.9 %	(Okonkwo et al., 2023)
76 %	(Stepan et al., 2023)

4.2.13 CO_2 COMPRESSION

The energy requirement for DAC depends on the CO2 concentration of the compound extracted. If extracted directly from the air, with a CO2 concentration of 0.04 %, there will be a need to compress the air unto

4.2.14 SOLID BIOMASS GASIFICATION

The methanol synthesis is use wood chips as feedstock. During gasification, biomass is oxidised into syngas, and the yield is dependent on the dehydration of the feedstock, pyrolysis and gasification. After this point, it goes through a catalytic reforming step to produce syngas rich in CO and hydrogen, which can go through methanol synthesis exactly like syngas produced from natural gas. (Gao et al., 2023) record an overall efficiency of 70-90 % of biomass gasification, where the BAT principle allows us to utilise the highest efficiency, as seen in Table 16. It is important to note that the conversion efficiency depends on several conditions, such as the type of reactor. Biogas mainly contains CH4 and CO2, with certain levels of unwanted compounds such as H2S and NH3, which can be removed by e.g., pressure swing adsorption (PSA) (Yang & Ge, 2016).

TABLE 16: EFFICIENCY FACTOR FOR SOLID BIOMASS GASSIFICATION (WOODCHIPS).

Biomass Gasification Efficiency:	Source:
90 %	(Gao et al., 2023)

4.2.15 METHANOL SYNTHESIS

Methanol can be produced in a few different ways but here we rely on a catalytic methanol synthesis, where either syngas from natural gas or captured CO2 is fused with H2 to form methanol according to the following reaction:

$$CO + 2H_2 \rightarrow CH_3OH$$

As displayed in Table 17 below, the literature varies a lot in reported efficiencies, and which processes are included in each reported value. Due to this, it was assumed that both pathway NG-MeOH and CCS MeOH apply 88 % according to the BAT principle.

TABLE 17: EFFICIENCY FACTORS FOR METHANOL SYNTHESIS.

Efficiency Methanol Synthesis:	Comment:	Source:
70 %	Fossil MeOH (US)	(Winebrake et al., 2019)
88 %		(Antwerpen et al., 2023)
83 %	e-MeOH (/w BECCS and dedicated PV system)	(Pratama et al., 2023)
67 %	Fossil MeOH	(Ren et al., 2023)
85 %	Fossil MeOH (85-95 %)	(Narayanan, 2023)
79 %	e-MeOH	(Stepan et al., 2023)
75 %	Bio-MeOH	(Ryste, 2024)
67 %	Fossil MeOH	(Corbett & Winebrake, 2018)

4.2.15.1 Electricity Consumption for Methanol Synthesis

The electricity consumption was set at 0.29 MWh/tonne methanol produced for NG-MeOH and CCS-MeOH. For BIO-MeOH, the electricity input of 0.53 MWh/tonne methanol combines all stages from biomass gasification and methanol synthesis, and for EL-MeOH a much higher electricity input of 9.5 MWh/tonne methanol is seen, and is an aggregated number for electrolysis as well as methanol synthesis.

4.2.16 METHANOL TRANSPORTATION AND DISTRIBUTION

Just as for the MGO pathway, it is assumed that the methanol would be bunkered in Sydhavna, approximately 553 km from the production site. When distributed by tank trucks, the energy losses are rather small at just 2 % for a distance of 500 km. Only one source could be retrieved for distribution losses for methanol but numbers for liquid hydrogen, ammonia and LNG are in the range of 96-98 %, and it is reasonable to assume that methanol ranks similarly (Stepan et al., 2023). These values are presented in Table 18 below.

TABLE 18: EFFICIENCY FACTORS FOR METHANOL TRANSPORTATION AND EFFICIENCY.

Methanol Transportation and Distribution Efficiency:	Comment:	Source:
98 %	Transportation (shipping), 5,000 km	(Stepan et al., 2023)
98 %	Distribution, 500 km	(Stepan et al., 2023)

4.3 TANK-TO-WAKE EMISSIONS

In this chapter, the emission factors applied in the analysis are presented.

4.3.1 CRUDE OIL EMISSION FACTOR

For energy chain MGO, the fuel is produced from crude oil as its primary energy source. The emission factor retrieved from Miljødirektoratet are for Norwegian conditions specifically, but are not given in gCO_2eq. Accounting for CH4 and N2O will give a surcharge of 0.5 to 1.5 %, which results in 73.4 to 74.10 g CO_2eq/MJ. The European Commission's emission accounting methodology shows that diesel oil has an emission intensity of 80.4 g CO_2eq/MJ, while Volker-Quashning reports 74 g CO_2eq/MJ. As this seemingly aligns with the Norwegian estimate, this value is chosen. All values are displayed in Table 19 below.

TABLE 19: CRUDE OIL EMISSION FACTORS.

Crude Oil Emission Factor:	Source:
80.4 g CO_2eq/MJ	(EUC, 2023)
73 g CO2/MJ	(Miljødirektoratet, 2023)
74 g CO_2eq/MJ	(Volker-Quashning, n.d.)

4.3.2 NATURAL GAS EMISSION FACTOR

For NG-MeOH and CCS-MeOH, the primary feedstock comes from natural gas. Emissions from natural gas is highly dependent on gas composition, method of extraction and geographical location. As the thesis is zeroing in on Norwegian conditions, the Ecoinvent database's emission factor for Norwegian gas production is 59.33 g CO_2eq/MJ seen in Table 20 is applied.

TABLE 20: NATURAL GAS EMISSION FACTORS.

Natural Gas Emission Factor:	Source:
59.33 g CO_2eq/MJ	(Ecoinvent, 2024)
55.80 g CO_2eq/MJ	(Volker-Quashning, n.d.)
56 g CO_2eq/MJ	(Blok & Nieuwlaar, 2017)

4.3.3 NORWEGIAN ELECTRICITY MIX EMISSION FACTOR

Domestic consumption was utilised for calculating the emission intensity for the Norwegian electricity mix, as this more accurately reflects the actual carbon intensity of fuel production in Norway. Whereas Norway had a carbon intensity of 6.94 g CO_2eq/MJ in price area NO3 in 2023, the number was 8.06 g CO_2eq/MJ for consumption. Though Norway is generally regarded as a net exporter, the grid is still reliant on imported EU electricity at times of deficit. In 2019, NVE (2021) reported that Norwegian electricity consumption had a carbon intensity of 4.72 g CO_2eq/MJ seen in Table 21, which is quite a bit lower than for 2023 due to less import through the interconnectors to the continent. As new renewable energy projects seem unable to keep up with the deployment of new industrial projects, it is assumed that Norway will be strained to import electricity from the EU or UK going forward, and an emission intensity of 8.06 g CO_2eq/MJ. Additionally, this is more accurate if we assume that the fuel is produced at Tjeldbergodden. To account for varying global warming potential, these values will be tested for in the sensitivity analysis.

TABLE 21: EMISSION FACTORS FOR NORWEGIAN ELECTRICITY CONSUMPTION.

Norwegian Electricity Consumption Emission Factor:	Source
4.72 g CO_2eq/MJ	(NVE, 2021)

4.3.4 EU ELECTRICITY MIX EMISSION FACTOR

The carbon intensity for electricity on the continent varies substantially from country to country. Whereas Sweden, Finland, Lithuania and France reported very low associated emissions from electricity consumption, countries such as Poland and Cyprus heavily contributed to pulling the average up (Bastos et al., 2024). NVE (2021) reported an average emission intensity for EU electricity of 83 g CO_2eq/MJ in 2019, and own calculations based on the dataset provided by Bastos et al. (2024) proved an emission intensity of 83.2 g CO_2eq/MJ in 2021, summarised in Table 22 below. The numbers for 2021 are used in the analysis.

TABLE 22: EMISSION FACTORS FOR EU ELECTRICITY CONSUMPTION.

EU Electricity Consumption Emission Factor:	Source
83 g CO_2eq/MJ	(NVE, 2021)
83.2 g CO_2eq/MJ	(Bastos et al., 2024)

4.3.5 SOLID BIOMASS EMISSION FACTOR

The BIO-MeOH pathway utilises woody solid biomass for its methanol production, see Table 23. The Ecoinvent database shows an emission intensity of 2.7 g CO_2eq/MJ for wood chip combustion in a boiler at temperatures ranging from 800 to 1300 degrees C, ultimately turning into CO_2 and water. The carbon content is calculated for the wood used as a fuel input (Good et al., 2023). This value is a narrow assumption, as the biomass can be originated from many sources. In a report by the Methanol-Institute (n.d.), methanol produced from organic waste, forestry residues and manure has the lowest overall climate impact, whereas methanol produced from manure showed a negative climate impact. Regardless of feedstock, methanol produced from biomass ranged quite similarly, and this value is a good proxy of what emissions would be in a Norwegian produced methanol fuel.

TABLE 23: EMISSION FACTORS FOR SOLID BIOMASS GASIFICATION (WOODCHIPS).

Solid Biomass Emission Factor:	Source
4.72 g CO_2eq/MJ	(Good et al., 2023)

5 RESULTS AND DISCUSSION

The results will be presented for the primary energy and electricity consumption for each pathway, as well as the Well-to-Wake emissions. As previously stated, the base assumption for the electricity mix is measured through the physical energy content method. Two scenarios using the direct primary and substitution methods will also be presented to underscore how renewable accounting can shift the results dramatically. Finally, a sensitivity analysis will be performed for the process steps that come with a large degree of uncertainty. As an addition to the main analysis presented in this chapter, a short economic assessment will be provided in Chapter 6. Table 24 reintroduces the pathways.

TABLE 24: THE FIVE ENERGY CHAINS WITH ASSIGNED PRODUCTION PATHWAY INDEXES AND DESCRIPTIONS.

Production Pathway Index	**Description**
MGO	Conventional distillate applied in an internal combustion engine
NG-MeOH	Methanol derived from natural gas and electrolysis applied in a dual-fuel combustion engine
CCS-MeOH	Methanol derived from natural gas and electrolysis with integrated CCS, applied in a dual-fuel combustion engine
BIO-MeOH	Methanol derived from biomass gassification applied in a dual-fuel combustion engine
EL-MeOH	Methanol derived from captured carbon dioxide and electrolysis, applied in a dual-fuel combustion engine

5.1 WELL-TO-TANK ENERGY CONSUMPTION

The different pathways consume various levels of energy during fuel production as well as propulsion, along the entire Well-to-Wake spectre. To illustrate the energy consumption intensity for the Well-to-Tank stage, the energy input is broken down into $ERE_{primary}$ and ERE_{el}. Additionally, the energy required for propulsion will be presented alongside. ERE_{total} for all fuel pathways is illustrated in Figure 10 below. These values are used to determine how many MJ of energy and emissions are associated with transporting 1 tonne of cargo one kilometre.

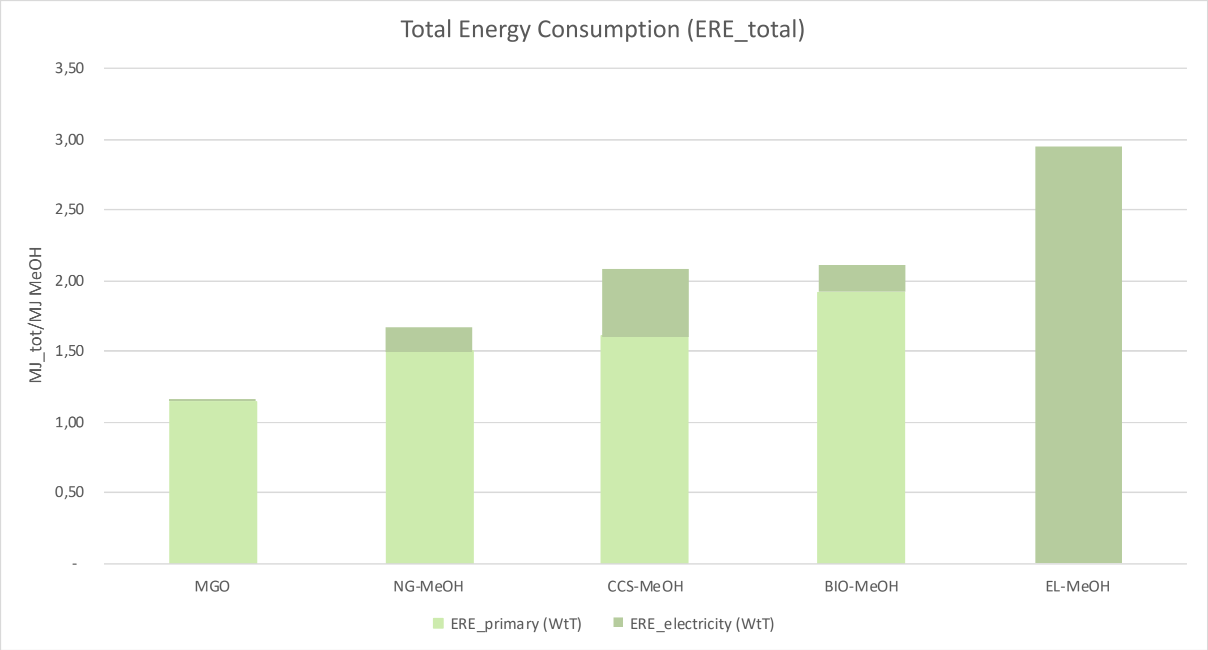


FIGURE 10: ERE$_{TOTAL}$ FOR ALL FUEL PATHWAYS.

5.1.1 *WELL-TO-WAKE ENERGY CONSUMPTION*

To accurately illustrate how much primary- and electric energy is required per unit of work performed by the container ship, the values have been converted to MJ/tkm.

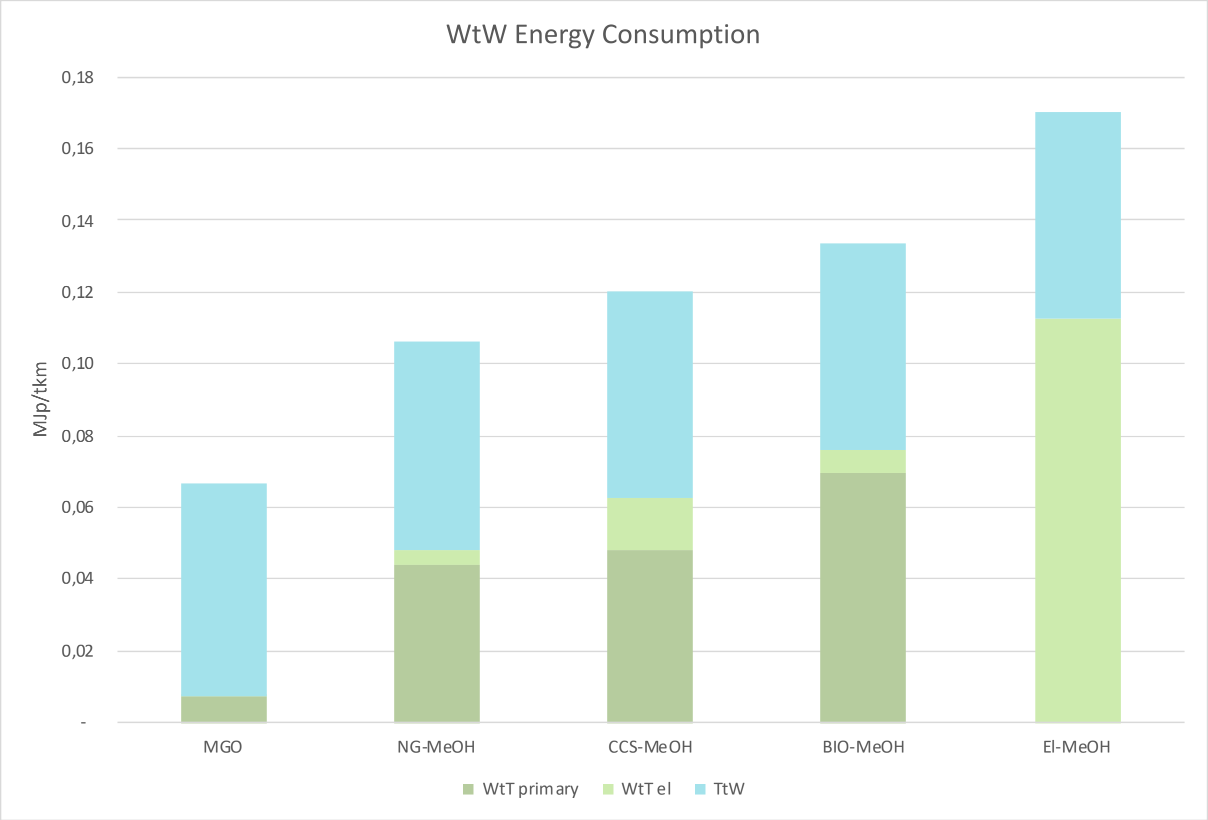


FIGURE 11: WELL-TO-TANK ENERGY CONSUMPTION PER TKM FOR ALL FUEL PATHWAYS.

The MGO pathway is the least energy-intensive process, though crude oil processing is a heavy process that requires a high thermal input and loses about 10 % of its energy through thermal losses. There are negligible amounts of electricity that go into processing gas oil distillates. A total of 0.41 MJ per kg gas oil translates to 0.0011 MJ/tkm, which is too small to show up in Figure 11. Crude oil refining to light oil distillates like MGO is calculated to be 91 % efficient when accounting for losses from extraction, transportation and refining of crude, with a primary energy requirement of 1.15 MJ_{crude}/MJ_{MGO}. Containerships consume comparatively large amounts of fuel per tkm and make up a large fraction of the final energy consumption, shown in Figure 11 under the notation “TtW”.

NG-MeOH also relies predominantly on fossil primary energy, namely natural gas. Though natural gas processing is more efficient than crude oil refining, there are more steps associated with methanol production that impede production efficiency and call for a higher energy input per unit of fuel output. NG-MeOH has an accumulated WtT energy consumption of 0.11 MJ/tkm, of which 0.10 MJ is primary, and 0.01 MJ is electricity, mainly contributed through electricity requirements for the SMR and methanol synthesis. The TtW fuel consumption is equal for all MeOH pathways, and though consuming 2 % less fuel than a conventional otto-engine this makes up a minute fraction of the entire WtW energy consumption. The overall conversion efficiency of 60 % is similar to the efficiency of 67 % reported by Winebrake et al. (2019), where the difference is likely due to the efficiency factors applied in the calculations. The granularity of the calculations may also have an impact on the final result, as more steps often lead to higher reported production losses. Such nuances are accounted for in the sensitivity analysis.

For CCS-MeOH, there is a slight increase in electricity consumption due to carbon capture and CO2 compression but is otherwise comparable to NG-MeOH with an overall conversion efficiency of 54.2 %. As seen in Figure 11, there is a noteworthy increase in electricity consumption. It is reasonable to assume a somewhat higher input of natural gas for thermal processes in the CCS unit, but this is deemed to make up too small a fraction to include here. Unable to retrieve numbers for natural gas consumption SMR, as no values could be retrieved for this addition. CCS-MeOH displays a WtW energy consumption of 0.12 MJ/tkm, of which 0.09 MJ/tkm and 0.03 MJ/tkm can be attributed to primary- and electric energy, respectively.

BIO-MeOH has a marginally higher WtW energy consumption at 0.14 MJ/tkm, of which 0.13 MJ and 0.1 MJ are attributed to biomass and electricity respectively. Figure 11 shows a slight increase in electricity input compared to CCS-MeOH, and a significant increase in biomass input due to a relatively low conversion efficiency requiring a higher feedstock input. This pulls the overall efficiency down to 46 %.

The efficiency for EL-MeOH is substantially lower than the benchmark MGO, at a conversion efficiency of 39 %.

5.2 WELL-TO-TANK EMISSIONS

The Well-to-Wake emissions per tkm travelled for each of the fuels can be viewed in Figure 12, where each fuel is tested for different electricity mixes; fully renewable (REN), the Norwegian electricity mix (NO), and the EU electricity mix (EU). This approach aims to highlight the effects seen in the figure, namely that the CO_2eq concentrations in the electricity mix has a great impact on the production paths that rely heavily on electricity. Unsurprisingly, MGO has almost identical results, as negligible amounts of electricity go into the production of light oil distillates.

NG-MeOH utilises some electricity during production, particularly for the methanol synthesis step. With both the fully renewable and Norwegian electricity mixes, this does not have a detrimental impact on the WtT emissions. The EU mix, however, with its 300 g CO_2eq/kWh has a noticeable impact NVE (2021). As NG-MeOH has a larger primary energy input than MGO, its emissions are increased by 19-21 % depending on the electricity mix.

CCS-MeOH utilises carbon capture during its SMR process, which reduces quite a bit of the emissions seen for NG-MeOH. CCS has not reached a technical maturity to where 100 % of carbon emissions can be captured, meaning that there will be fugitive emissions from the capture process itself, as well as from the natural gas used to power the CCS unit. Thanks to the CCS unit, the emissions from primary energy are reduced to 0.37 gCO_2eq/tkm, but the additional electricity input is responsible for 0.37 and 1.32 gCO_2eq/tkm for NO and EU respectively.

BIO-MeOH requires some additional electricity to fuel its flue gas capture from gasification and subsequent methanol synthesis. The electricity mix impact is overall lower than for the other pathways, at 0.31 and 0.75 gCO_2eq/tkm for NO and EU respectively. This impact is far more evident for the EL-MeOH pathway, which utilises a lot of electric energy to produce “green” hydrogen. If using the average EU electricity mix, emissions can increase by as much as 90 % from the Norwegian electricity mix.

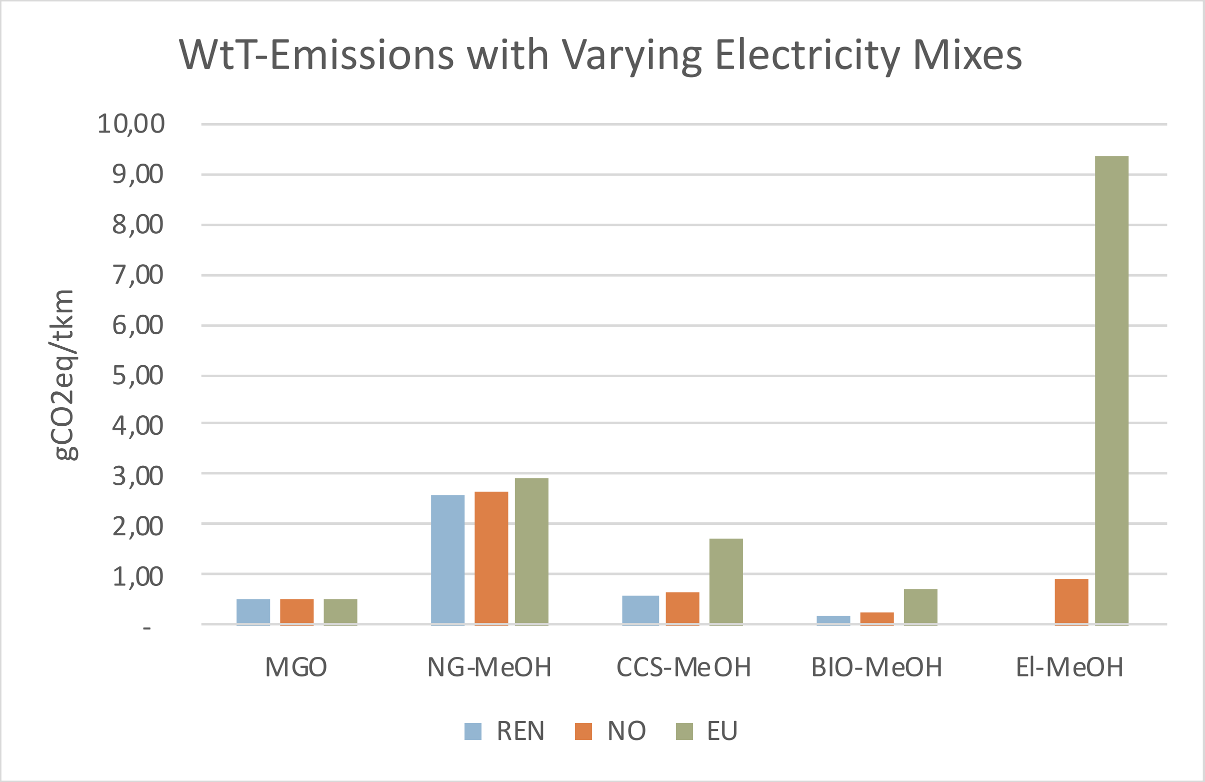


FIGURE 12: IMPACTS ON UPSTREAM WTT EMISSIONS WITH VARYING ELECTRICITY MIX INPUT.

5.3 WELL-TO-WAKE EMISSIONS

The Well-to-Wake emissions are calculated in CO_2eq/tkm, and include the emissions from combustion unlike the results in the above chapter. Figure 13 compares the different pathways, and the base assumption that production consumes Norwegian electricity is applied. The bars for BIO-MeOH and EL-MeOH that indicate combustion are shaded to highlight climate neutrality, as is customary for pathways based on renewable feedstocks (Methanol-Institute, n.d.). They are still shown here to emphasise the fact that the combustion of methanol is not emission-free regardless of the feedstock, as the chemical composition of methanol is the same regardless.

As can be expected, MGO is characterised by relatively low upstream emissions, whereas combustion makes up the bulk of the entire WtW-emissions of 4.91 g CO_2eq/tkm. Methanol requires several steps that require a higher energy input than the fossil benchmark. NG-MeOH, with its additional primary energy input, ranks higher than the rest at 6.66 g CO_2eq/tkm. EL-MeOH has total WtW emissions of 4.52 g CO_2eq/tkm, whereas CCS-MeOH is somewhat lower at 4.26 g CO_2eq/tkm. The calculations for BIO-MeOH show final WtW emissions of 4.3 g CO_2eq/tkm, and is the pathway with the lowest associated emissions.

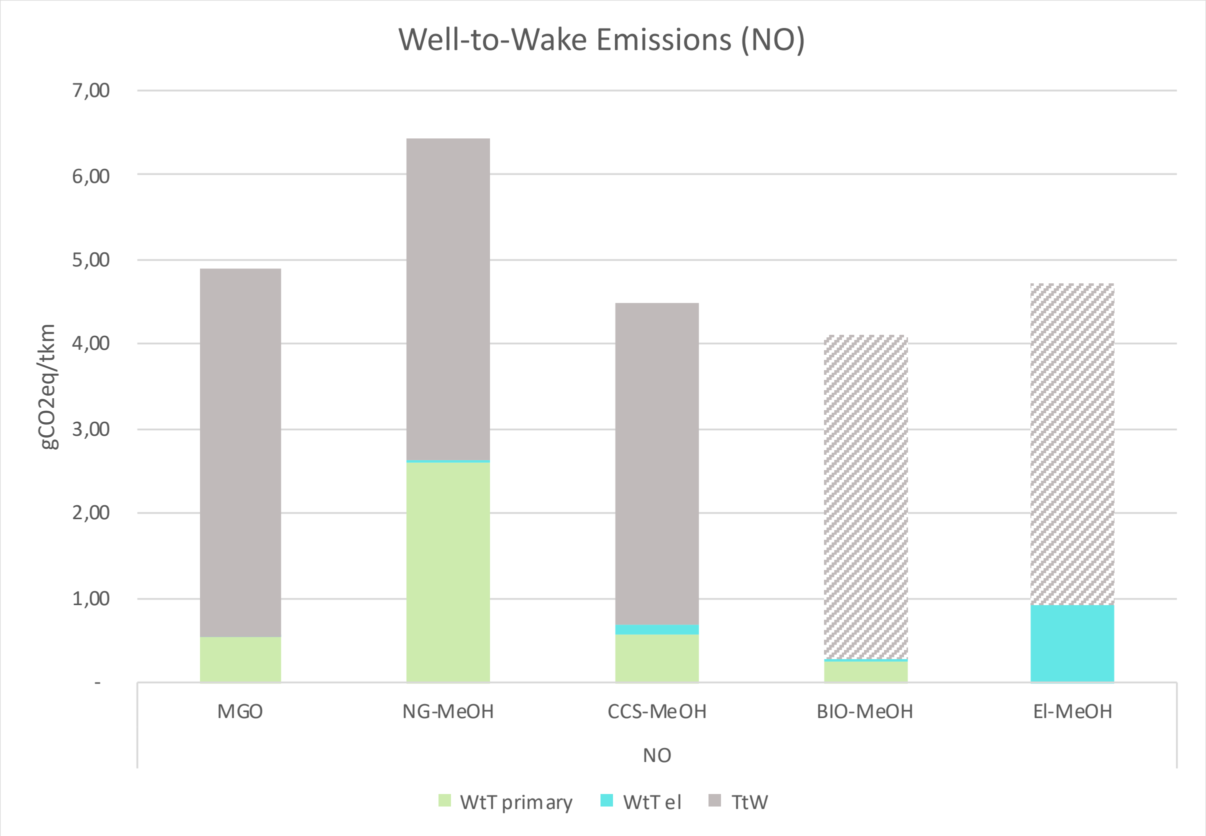


FIGURE 13: WELL-TO-WAKE EMISSIONS FOR THE FIVE PATHWAYS. DIAGONALLY SHADED BARS FOR BIO-MEOH AND EL-MEOH INDICATE THAT EMISSIONS FROM COMBUSTION DOES NOT CONTRIBUTE TO ITS LIFE CYCLE EMISSIONS.

5.4 SCENARIO ANALYSIS

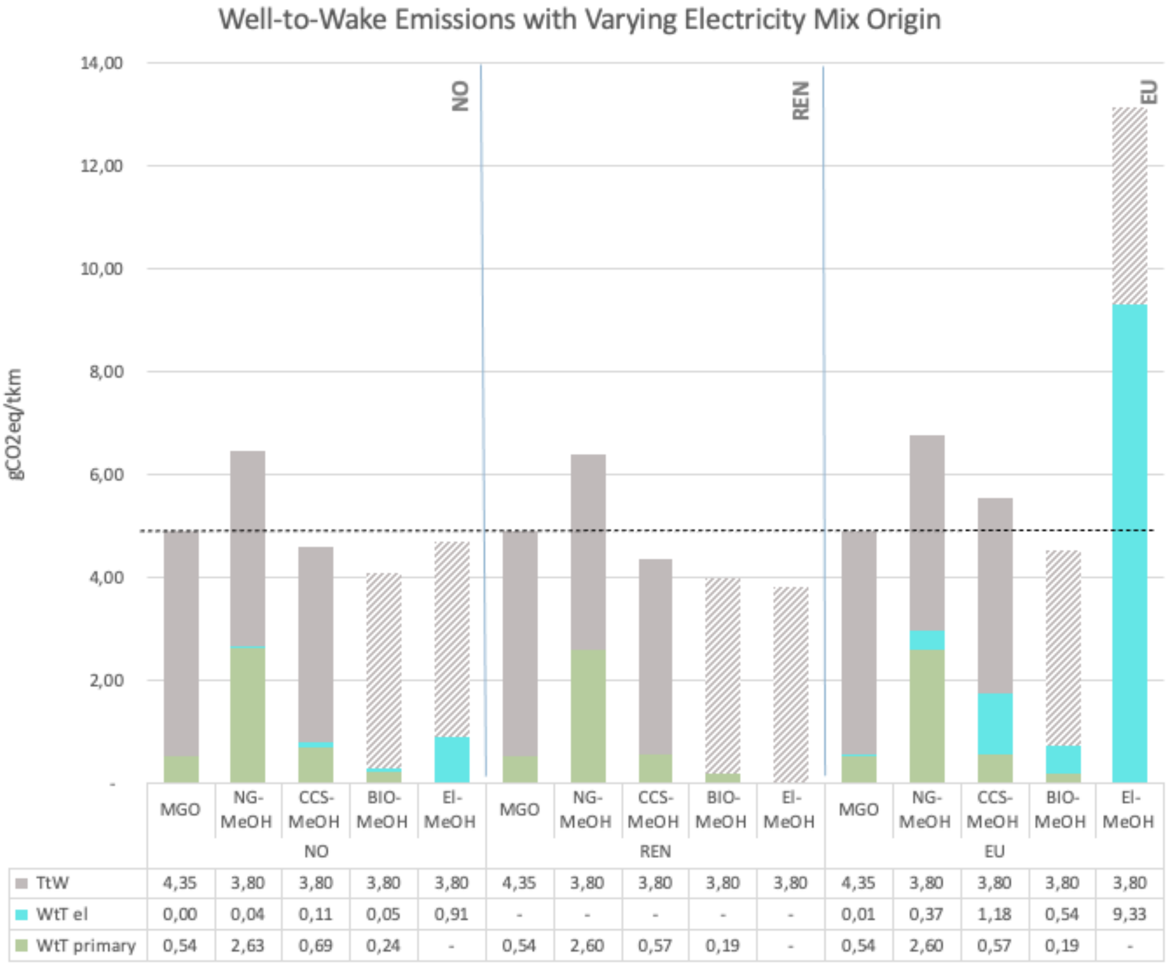
5.4.1 SCENARIO ANALYSIS: ELECTRICITY MIX

The pathways that rely mainly on electricity are assumed to be sensitive to the carbon intensity of the electricity mix used during production. Table X below compares the impact of sourcing electricity from the Norwegian and EU power grids and a fully renewable mix for all five pathways. It is worth noting that the EU electricity mix is expected to approach 80 % renewables by 2030, which is likely to lower its impact noticeably, but not below that of Norway. Currently, the EU mix consists of around 63 % renewables, this was used as the basis in the analysis below (Locci et al., 2023). As a reference, Norway has a 96 % renewable share in its domestic consumption (NVE, 2021).

As illustrated below, the source of electricity has a profound impact on the EL-MeOH pathway. This is because steps like DAC and electrolysis in producing e-methanol are very energy intensive and are hampered by relatively inefficient processes, causing large energy losses throughout the processing chain. Recall that the conversion efficiencies found in the NG-

MeOH chain have developed for centuries and are characterised by very high efficiencies, low thermal losses and developed practices for heat recycling. Methanol is still an energy-intensive process and will thus have more steps through which emissions occur.

CCS-MeOH will reduce its emissions from primary energy, and the added emissions from the increased electricity usage will depend on the carbon intensity of said electricity. Similarly, BIO-MeOH uses a decent amount of electricity for carbon capture and methanol synthesis and is generally characterised by low associated emissions. The performance of each fuel is compared to the emissions from MGO, illustrated by the black dotted line in Figure 14. The keys in the bottom of the figure show the calculated emissions from fuel production ($WtT_{primary}$ and WtT_{el}) as well as combustion (TtW) calculated in gCO_2eq/tkm.

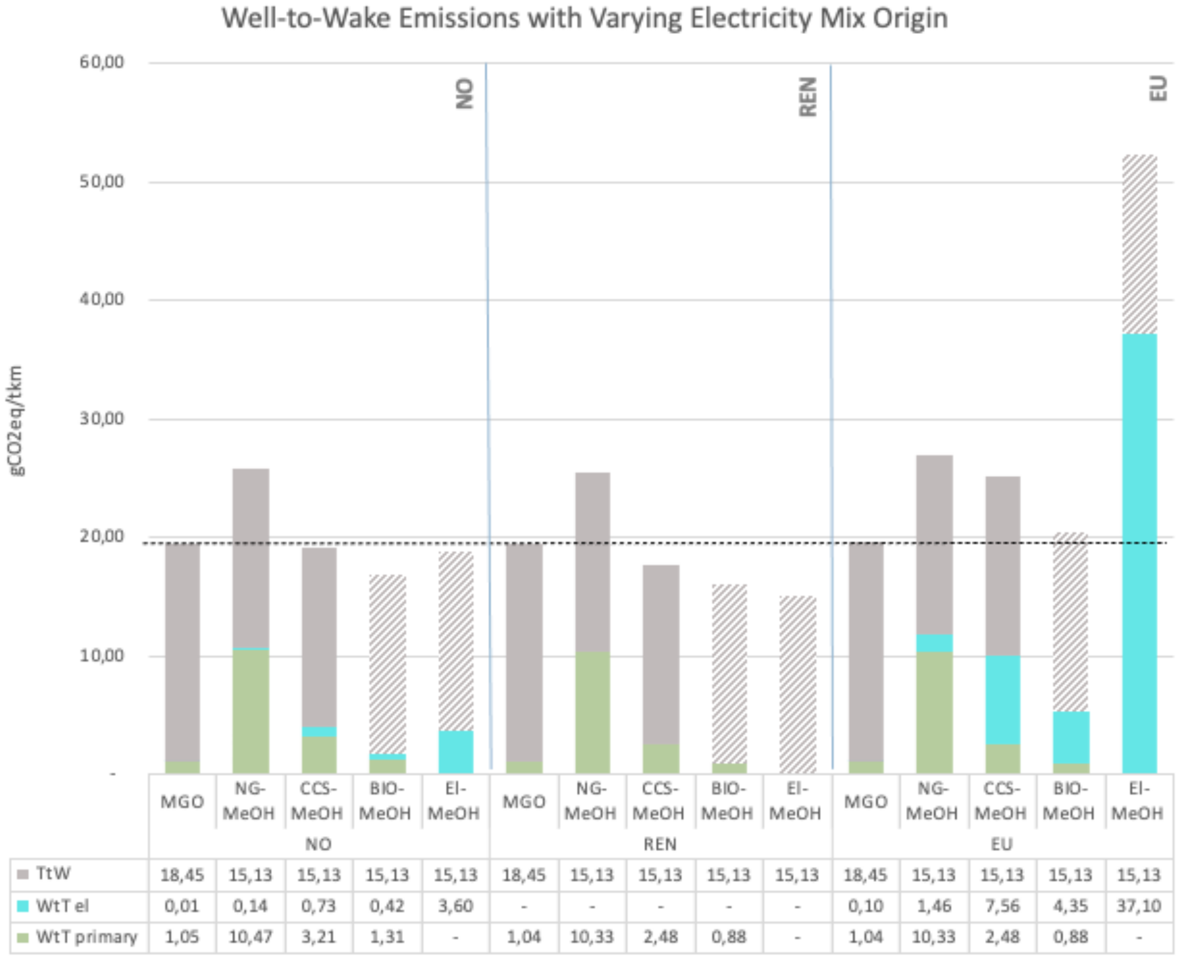


	NO					REN					EU				
	MGO	NG-MeOH	CCS-MeOH	BIO-MeOH	El-MeOH	MGO	NG-MeOH	CCS-MeOH	BIO-MeOH	El-MeOH	MGO	NG-MeOH	CCS-MeOH	BIO-MeOH	El-MeOH
▨ TtW	4,35	3,80	3,80	3,80	3,80	4,35	3,80	3,80	3,80	3,80	4,35	3,80	3,80	3,80	3,80
▨ WtT el	0,00	0,04	0,11	0,05	0,91	-	-	-	-	-	0,01	0,37	1,18	0,54	9,33
▨ WtT primary	0,54	2,63	0,69	0,24	-	0,54	2,60	0,57	0,19	-	0,54	2,60	0,57	0,19	-

FIGURE 14: WELL-TO-WAKE EMISSIONS FOR ALL FUEL PATHWAYS WITH VARYING ELECTRICITY MIX INPUT. THE FIVE FIRST BARS FROM THE LEFT ARE FOR NORWEGIAN ELECTRICITY MIX, THE FIVE MIDDLE BARS ARE FOR PURE RENEWABLES, AND THE FIVE BARS TO THE FAR RIGHT ARE FOR EU ELECTRICITY MIX.

5.4.2 SCENARIO ANALYSIS: FUEL CONSUMPTION

As stated, two very different fuel consumption factors were located in the reviewed literature. As a result, it was decided that a scenario with a high fuel consumption should be done to illustrate the impact such a difference has on the bottom line. Though this does not have a profound impact on the ranking among the production pathways, the emissions are much higher as more fuel throughput is required per tkm, as can be seen on the y-axis of Figure X, as well as the keys at the bottom of the figure. Recall that the diagonally shaded bars indicate that combustion is not accounted for BIO-MeOH and EL-MeOH. The difference between the baseline results and this scenario analysis is a helpful tool in understanding how emissions vary with fuel throughput, and why emissions typically are higher for vehicles that carry less cargo per unit distance travelled.



	MGO	NG-MeOH	CCS-MeOH	BIO-MeOH	El-MeOH	MGO	NG-MeOH	CCS-MeOH	BIO-MeOH	El-MeOH	MGO	NG-MeOH	CCS-MeOH	BIO-MeOH	El-MeOH
	NO					REN					EU				
▨ TtW	18,45	15,13	15,13	15,13	15,13	18,45	15,13	15,13	15,13	15,13	18,45	15,13	15,13	15,13	15,13
■ WtT el	0,01	0,14	0,73	0,42	3,60	-	-	-	-	-	0,10	1,46	7,56	4,35	37,10
🟩 WtT primary	1,05	10,47	3,21	1,31	-	1,04	10,33	2,48	0,88	-	1,04	10,33	2,48	0,88	-

FIGURE 15: WELL-TO-WAKE EMISSIONS FOR ALL FUEL PATHWAYS WITH VARYING ELECTRICITY MIX INPUT AND INCREASED FUEL INPUT. THE FIVE FIRST BARS FROM THE LEFT ARE FOR NORWEGIAN ELECTRICITY MIX, THE FIVE MIDDLE BARS ARE FOR PURE RENEWABLES, AND THE FIVE BARS TO THE FAR RIGHT ARE FOR EU ELECTRICITY MIX.

5.5 SENSITIVITY ANALYSIS

The sensitivity analysis was conducted for BIO-MeOH and EL-MeOH, as the data collected for these processes displayed a large variation. Here, the parameters with a lower efficiency factor were subject to the most inconsistencies in the literature, and will thus be tested for. These include electrolysis, methanol synthesis, SMR and DAC. As there are uncertainties related to fuel consumption and emission factors for the mentioned pathways as well, these parameters were also included. These were then adjusted by a certain percentage to display how volatile the results are to fluctuations in the parameters.

The takeaway from the sensitivity analysis is that the processes are sensitive to fluctuations in the parameters and that a decrease in efficiencies has a substantial effect on the final WtW emissions.

5.5.1 SENSITIVITY ANALYSIS EL-MEOH

For the EL-MeOH pathway, the efficiencies for methanol synthesis and DAC were adjusted, as well as the fuel consumption. The analysis shows that the efficiency for DAC as well as the fuel consumption are to most sensitive to changes, as viewed in Figure 16. A 20 % decrease in DAC efficiency shows an increase of 3.23 % for gCO_2eq/tkm, whereas as a 20 increase in fuel consumption result in nearly 4 % higher emissions. The reason that the subsequent increase or decrease in gCO_2eq/tkm is due to a relatively low fuel consumption per travelled distance for such large vessels.

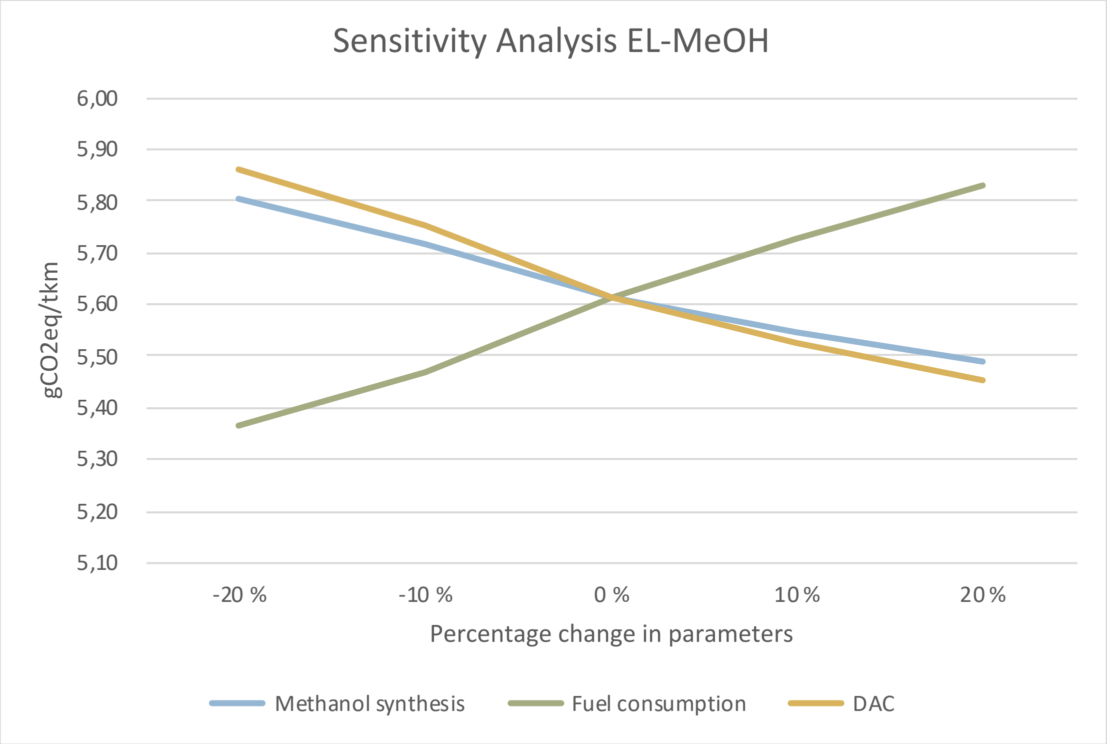


FIGURE 16: SENSITIVITY ANALYSIS EL-MEOH.

5.2.2 *SENSITIVITY ANALYSIS BIO-MEOH*

The second methanol pathway with large uncertainties were BIO-MeOH, and the results from the sensitivity analysis can be viewed in Figure 17. The lower efficiency processes for BIO-MeOH are gasification + synthesis as well as electrolysis. A decrease of 20 % in efficiency for gasification/synthesis increases WtW emissions by about 3 % whereas a 20 % decrease for electrolysis increase emissions with about 2 %.

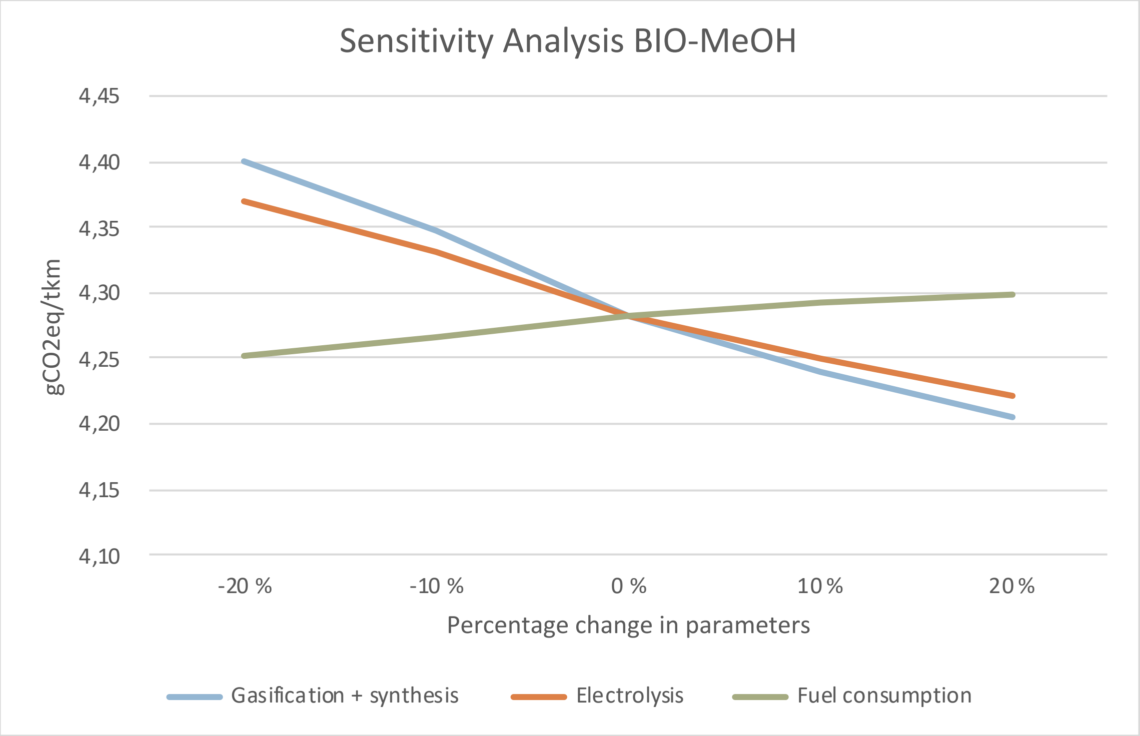


FIGURE 17: SENSITIVITY ANALYSIS BIO-MEOH.

5.6 ASSESSING DATA QUALITY AND LIMITATIONS

Whereas $ERE_{primary}$ was straight forward to calculate, ERE_{el} was a challenging task to navigate, as it was not always clear in the literature which processes were included in the values for electricity consumption. During this process, some data was difficult to obtain, particularly sub-processes for BIO-MeOH and EL-MeOH. Some numbers included several steps, while others were not clear which processes were included or not. The EL-MeOH chain is the most uncertain, as many attempts were made to produce a reasonable answer that made sense holistically. This led to findings that EL-MeOH use 9.5 MWH/tonne methanol upstream, which was the only electricity input considered for EL-MeOH, at which it was divided by efficiency factors downstream such as the other pathways. This means that for the physical electricity input only one source was used, which is important to be aware of. This produced results that looked reasonable compared to the other pathways.

One of the deciding parameters in a WtW analysis is fuel consumption. For the initial analysis conducted, only one source could be traced down for MGO consumption in a containership, in which DNV reports an average of 1.37 grams of fuel per tkm, or 0.0059 MJ/tkm for a 2000 TEU container ship (Akerbæk, 2018). Most methanol-ready ships are fitted with four-stroke dual-fuel methanol engines. A *two*-stroke methanol engine's fuel consumption is reported to be 2 % more efficient than conventional fuels among Waterfront Shipping Canada’s 19 methanol-ready vessels. Due to this, it is assumed that the methanol engine consumes 2 % less fuel per tkm travelled (Marquez, 2023). This is, of course, a large oversimplification, but was deemed necessary as no specific information could be retrieved from literature or professionals. Further, an emphasis was put on average propulsion power, thus not considering auxiliary components like heating and electricity generation on board ships.

Methanol from biomass can be produced in a number of different ways, whereas the most common are biomass gasification and biomass methanation (anaerobic digestion). In this thesis, only biomass gasification was assessed, as well as only one feedstock, namely wood chips. Findings by other sources that use different feedstocks mainly find that bio-methanol ranks better than any other pathways, apart from pathways that rely in entirely pure renewables (Methanol-Institute, n.d.). When producing from manure, the overall lifecycle emissions for bio-methanol can be carbon negative. Additionally, Tthe Ecoinvent database considers their numbers for biogas to be rather weak due to limited tests on methanol from biomass gasification. This leads to even larger uncertainties for the emission factor chosen for the BIO-MeOH pathway.

6 FUEL COST TRAJECTORY

Apart from capital costs and wages, fuel is the largest single expenditure for shipowners (Goulielmos, 2021). The fuel cost is the main hindrance to methanol uptake as a marine fuel. The cost of producing green hydrogen and capturing CO2 at a commercial scale requires vast amounts of electricity input, which are the largest cost contributors to the production of any type of e-fuel. As a supplement to the main analysis in this thesis, a small economic assessment has been conducted to display the bigger picture of which trade-offs shipowners are subject to.

6.1 FUEL PRICES

The Maersk Mc-Kinney Møller Center for Zero Carbon Shipping recently published a bottom-up fuel cost model comparing prices for various alternative fuels (Zerocarbonshipping, 2024). As well as using the interactive tool on their website, one can use the background spreadsheet to calculate these results and replace variables with one's own bottom-up assumptions. As the model has a spatial granularity at a continental scale, a separate price forecast was conducted for the Norwegian power market, as electricity cost is the largest expense for most e-fuels. Notice that the power price forecast uses real prices. This projection is based on numbers from NVE's long-term power market analysis and Statnett's short-term market analysis. There are no recorded numbers for the years 2027-2030 and 2030-2040, so the data has been interpolated to calculate a linear fit. The Statnett report has only included NO2, NO3, and NO4 in their analysis, whereas NVE has used an average for the whole country. Here, we have to assume that these three price regions are appropriate to the average. All prices are adjusted to USD_{2023} and a carbon tax of 200 USD was applied. All other components apart from electricity price were left unchanged as this is only meant as a supplement to the main analysis.

The results in Figure 18 shows that prices for e-methanol will have a steady decline from 2023 onward and will reach around 1500 USD/tonne in 2050. However, Tabibian and Sharifzadeh (2023) found that the price could be as low as 250-630 USD/t by 2050. It is important to note that the costs in Figure 18 are calculated in USD/tonne LSFO (Low Sulphur Fuel Oil) equivalents, and might be an explanation as to why the results are challenging to compare. In the same report, they find that the price for fossil methanol lies within the range of 100-250 USD/t, and bio-methanol between 320-770 USD/t, which are quite a bit lower than showed here. Figure 19 shows how these fuels stack up compared to each other.

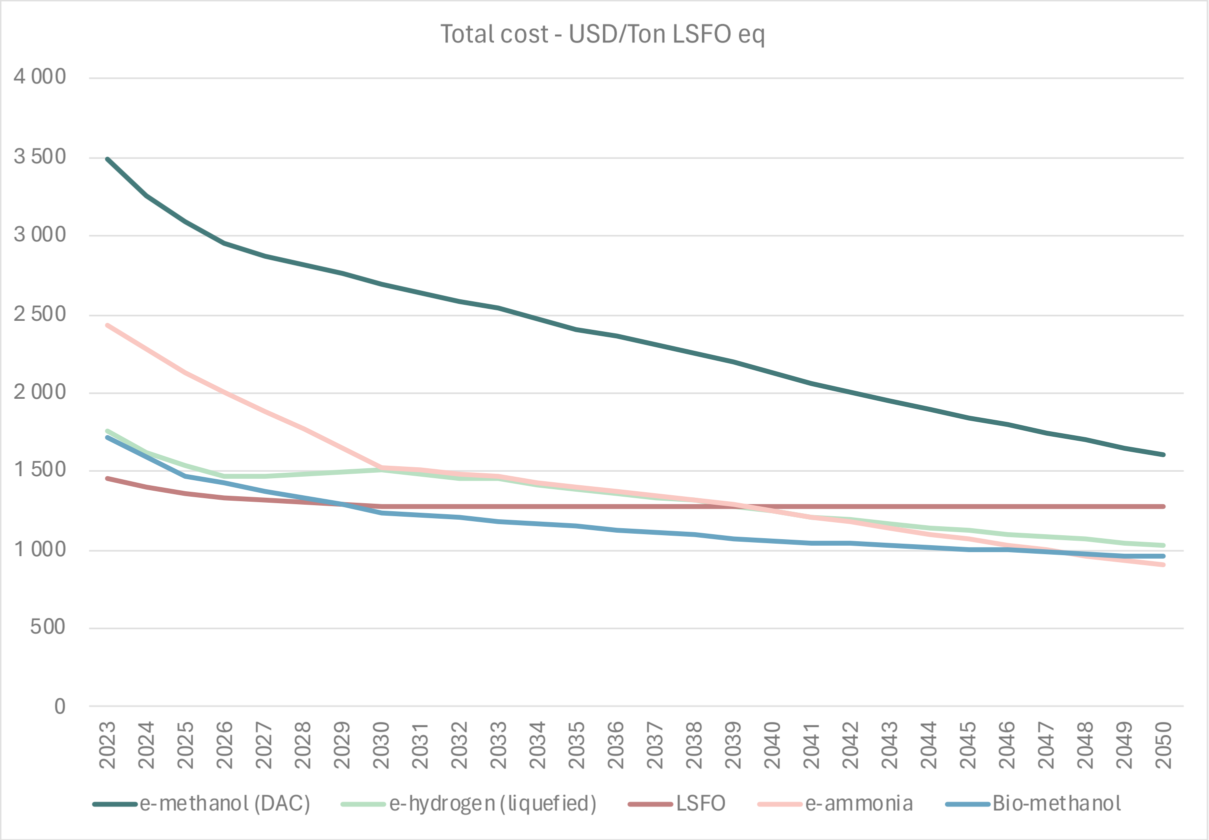


FIGURE 18: TOTAL FUEL COSTS EXPRESSED IN USD/TON LSFO EQ.

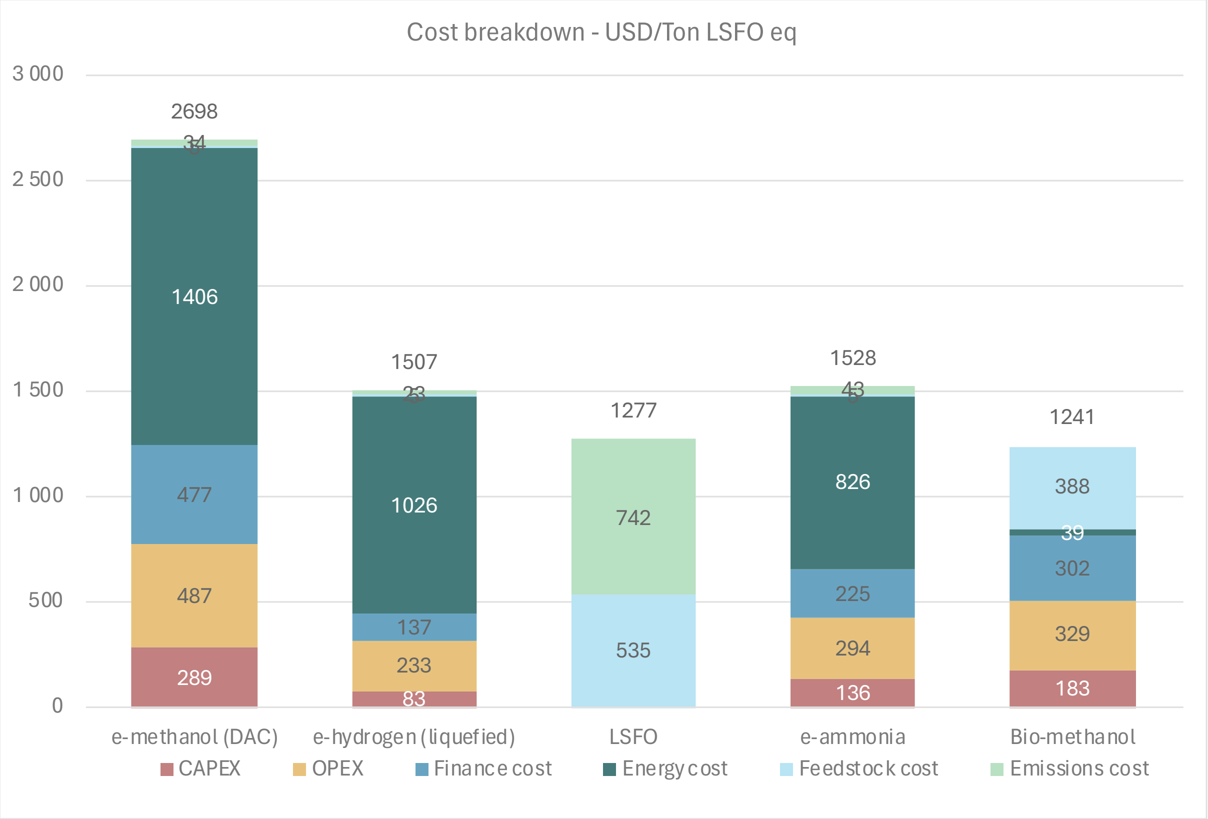


FIGURE 19: COST BREAKDOWN FOR DIFFERENT E-FUELS AS WELL AS LSFO (LOW SULPHUR FUEL OIL) FOR THE YEAR 2030 MEASURED IN UDS/TONNES LSFO EQUIVALENTS.

Methanol produced from SMR with CCS was not considered in the analysis but is comparable to that of NG-MeOH. Findings by Santos et al. (2017) find that for the levelized cost of MeOH (LCOM), the added cost of CO2 handling is rather diminutive. They estimate an added 6 % in annual operation costs compared to a facility without CCS, mostly due to added electricity input.

If changing the parameters to show the results in costs per tonne fuel, the costs for liquefied hydrogen increases substantially due to its low volumetric energy density, as can be seen in Figure 20 below.

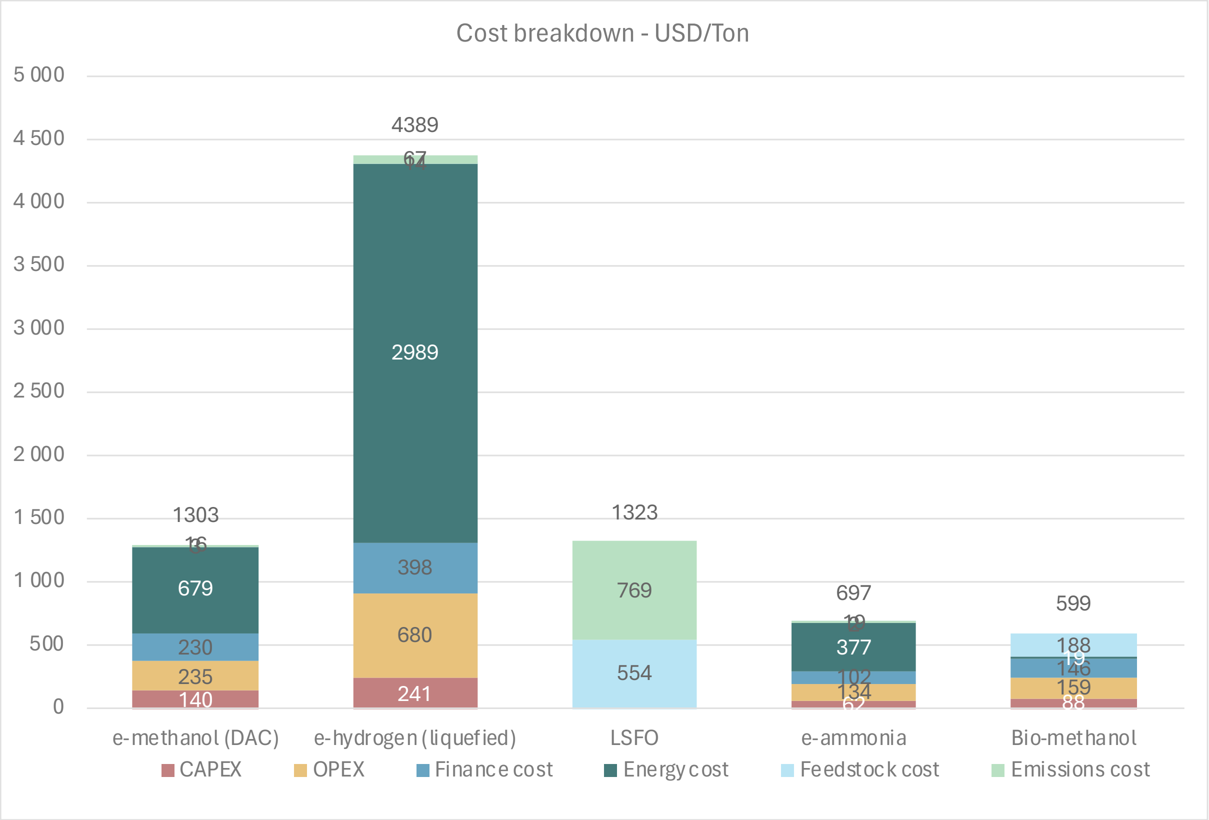


FIGURE 20: COST BREAKDOWN FOR DIFFERENT E-FUELS AS WELL AS LSFO (LOW SULPHUR FUEL OIL) FOR THE YEAR 2030 MEASURED IN UDS/TONNE FUEL.

7 DISCUSSION

As the functional units and system boundaries are inconsistent throughout the literature, a direct comparison to other studies is not possible, but it can still be helpful to investigate what other sources have found. Remember that variations in feedstock composition, varying technologies, as well as supply chain differences may have large impacts on the final results (Methanol-Institute, n.d.). As a consequence, when planning such projects in the real world an individual assessment on a plant scale is necessary, and general estimates should be used with caution.

The WtW emissions in this thesis are calculated in CO_2-equivalents. Whereas CO_2- and CH_4 emissions from burning methanol in an engine are only somewhat lower than for MDO, emissions of NOx and SOx are considerably reduced. The vessel combustion emissions factors used for the calculations show a 12.6 % reduction in NOx-emissions between MDO and methanol engines. While combustion of methanol in its pure form emits 25 % lower NOx emissions, with the application of selective catalytic reduction (SCR) or exhaust gas recirculation (EGR), it can be reduced by as much as 80 % (Wissner et al., 2023).

The results in this analysis show that production of NG-MeOH is the most energy-efficient method of the methanol pathways, but it also emits substantial GHGs both upstream and downstream. Fossil methanol is reported by the Methanol-Institute (n.d.) to have WtT emissions of 115 gCO_2eq/MJ, whereas the analysis in this thesis shows a total 173 gCO_2eq/MJ (alternatively 6.47 gCO_2eq/tkm), putting it at the high end of results found in the literature. As illustrated in the sensitivity analysis, both the efficiency of SMR as well as the emission factor for natural gas will have a large impact. Combustion of both blue and gray methanol is associated with very large emissions, expressed in ~70 gCO_2eq/MJ, but this will ultimately depend on the type of engine (Carvalho et al., 2023; Winebrake et al., 2019). The vessel combustion emission factors for the Methanol-Institute (n.d.) are not stated, which may also have an impact on their bottom line.

Howarth and Jacobson (2021) assessed the emissions associated with different production options for hydrogen through steam methane reforming (SMR). They assessed both CO_2 as well as emissions from fugitive methane from process leaks. They apply a default value of 3.5 % methane leaks and assume that CO_2 can be stored underground indefinitely and without leaks. They found that CO2eq for blue H2 was merely 9 % to 12 % lower than for gray - they also found that overall methane leaks were higher for blue than for gray, mainly due to the added natural gas needed to power CCS. They utilize a capture efficiency of 85 %.

The CCS-MeOH pathway is the second most energy-intensive process, as it requires an additional step in capturing carbon dioxide. The upstream emissions are, however, reduced by 70 %. Though much of the carbon has been removed upstream, the downstream emissions are unchanged as this is still categorized as a fossil fuel. The 30 % of carbon that was not captured in the process, would not have been emitted to the atmosphere if the gas reservoirs were left untouched. This puts the WtW emissions for CCS-MeOH marginally below MGO when using Norwegian sourced electricity but is quite a bit higher than MGO when applying the EU mix.

EL-MeOH requires the highest level of energy input, where its upstream emissions will rely heavily on the carbon intensity of the electricity mix applied. Different types of e-methanol can therefore not be pooled together to provide a universally applicable ranking, but rather assessed on a regional level depending on which electricity sources prevail, and the method used for carbon capture. As far as the pathway for EL-MeOH is concerned, it was challenging to separate integrated processes, therefore making it possible to fall into double counting. Findings by the Methanol-Institute (n.d.) have excluded combustion from their e-methanol assertions, and report WtW emissions ranging from 2 to 150 gCO_2eq/MJ depending on the electricity mix. The pathway relying on hydropower has WtW emissions of a little under 10 gCO_2eq/MJ, whereas the results for my analysis show 17.22 gCO_2eq/MJ for the Norwegian electricity mix, where hydropower stands for 87 % of net domestic consumption. As previously stated in the scenario analysis and discussed in the literature, the emissions from the e-methanol process is almost entirely dependent on the carbon intensity of the electricity mix.

When viewing WtW energy input and emission intensity holistically, the results show that methanol produced from biomass has the lowest impact overall. However, while I in this case investigated woodchips as that is an abundant resource from Norwegian forestry, other feedstocks for bio-based methanol can swing the pendulum in either direction, as shown in the sensitivity analysis. While manure from livestock can result in a carbon-negative output, biomass from crops can result in upstream emissions of up to 35 gCO_2eq/MJ (Methanol-Institute, n.d.). In comparing LNG, methanol, bio-methanol, bio-LNG, bio-liquids and electricity, Balcombe et al. (2019) find that bio-methanol is the fuel that shows the highest likelihood of reaching an 80 % reduction in GHGs compared to HFO.

This leads to the question of whether either of the methanol production pathways' WtW emissions are lower than for the benchmark fuel, MGO. The results show that for Norwegian conditions, the NG-MeOH is the only fuel that underperforms in this regard, due to high upstream emissions. Though emissions from combustion are similar to MGO, the associated production emissions are about 5.5 times higher due to the SMR process. Applying carbon capture almost eliminated production-related emissions, but when including combustion, its WtW emissions are approaching the same level as for MGO. The analysis favours BIO-MeOH from a WtW perspective, but this necessitates that a value chain for Norwegian bio-methanol production be established, which as of today is anything but robust. As most of the waste stream from forestry is shipped out of the country due to economic reasons, it could prove challenging to facilitate a new bio-industry within Norwegian borders.

Results by Winebrake et al. (2019) find that emissions for fossil methanol can be 10-20 % higher than for MDO, whereas the results in this thesis find that they can be as much as 26 % higher. This can be due to several factors, such as the emission factor applied for the upstream calculations, the emission factors for combustion, the overall efficiency of the process, and so forth. The same report shows that MeOH from biogenic sources such as biomass can reduce overall GHG emissions by 20-25 %, whereas the results in this thesis show a WtW emission reduction of about 12 %. All forms of MeOH have SOx emissions close to those of MDO but perform substantially better in terms of NOx and PM2.5. LNG show similar Tank-to-Wake results to MeOH, but depending on the engine, often performs even better in terms of NOx. The authors state that MeOH and LNG show reductions of up to 90 % in downstream local pollutants but about 20 % higher in overall GHG emissions, calling for more efficient technologies that limit fugitive emissions and more energy-efficient onboard technologies that limit overall consumption.

7.1 FURTHER WORK

Throughout this thesis a number of challenges and uncertainties were encountered.
Suggestions for further work are listed as follows:

- Uncertainties from fuel consumption are very impactful for the results. Additionally, emissions from different load profiles should be looked into, and whether emissions are larger during port activities.

- Looking directly into how transportation over several distances will affect the bottom line, as well as for other types of vessels, from ferries to +20 000 TEU containerships.

- The utilisation of direct-methanol fuel cells should be investigated, as fuel cells traditionally are more efficient than combustion engines. The question is whether the added weight and costs will make this economically feasible in the future.

- With an increase in interest and production of e-fuels, it should be investigated how large-scale production of e-fuels will impact the load on the grid, and whether this will indirectly necessitate more production of fossil electricity to cover demand.

- There are very many different feedstocks that can be used to produce bio-methanol, and the actual life cycle impact would be easier to grasp if different feedstocks were investigated in the same study. As far as I have found, there is no such research for Norwegian conditions. Supply chain robustness is a very important factor for production of bio-methanol.
- Including other emissions to investigate effects on other impact categories, such as eutrophication, acidification, human toxicity, particulate matter formation, etc.

8 CONCLUSION

As previously stated, the implementation of new fuels will not be straightforward. Criteria such as technical, economic, and environmental are the first to come to mind, but should not be regarded separately from aspects like safety, logistics, socio-political, indirect costs, and customer expectations. Methanol has several favourable traits that simplify the transition from fossil to alternative fuels, such as its compatibility with existing infrastructure and widespread industrial application. However, the production costs prove that subsidies and strict regulatory policies will be detrimental to facilitating uptake. If the price forecast presented above for renewable methanol is correct in approaching levels of light oil distillates toward 2060, methanol could place itself in a position of economic feasibility over time. However, governmental risk compensation and subsidies could levy commercial uptake at an earlier stage than if the market is left to evolve without intervention.

The thesis aimed to answer the following research questions:

1. *How many MJ_{energy}/tkm is required of electric and primary energy for a typical 2 000 TEU container ship?*
2. *How many CO2eq/tkm are emitted from utilizing different methanol products as fuel in a typical 2 000 TEU container ship?*
3. *How will emissions from methanol production and combustion compare to those from MGO?*

This thesis dissects and examines the environmental aspects of methanol production, evaluating energy consumption and emission intensity from different pathways compared to MGO. The results show that the production method is detrimental to the bottom line. e-methanol is particularly sensitive to electricity origin, and though the combustion of e-methanol can be regarded as net zero, the cumulative WtW emissions are very dependent on the electricity mix origin. NG-MeOH is quite an efficient production method, but unsurprisingly, it has large associated emissions, particularly during SMR. The emissions from combustion for NG-MeOH and CCS-MeOH should also be remembered. The results in this thesis, as well as other works, show that depending on the carbon intensity of the electricity mix, NG-MeOH might fare even better than EL-MeOH.

The economic viability of substituting a conventional marine engine with a dual-fuel engine is not certain. Estimates from Ammar (2019) show that engine conversion can come at a cost of 10.72 MUSD for container ships, whereas installing scrubbers to purify exhaust from MGO can reduce NOx emissions to acceptable levels. The paper further states that the dual-fuel engine is economically equivalent to a conventional diesel engine with scrubbers/selective catalytic reduction (SCR) system for purifying exhaust fumes from NOx to comply with IMO limits. However, as the rate of tightening emission regulations is expected to increase in coming years, this might not prove to be long-lived.

Methanol is a favourable fuel because it has the highest hydrogen-carbon ratio of any fuel at ambient conditions, which makes it very applicable in marine shipping (MAN, n.d.). NG-MeOH and CCS-MeOH get carbon from fossil sources that, if they had been left undisturbed, would not have contributed to further carbon emissions. BIO-MeOH and El-MeOH are termed carbon neutral, as the carbon from captured flue gases or previously bound in organic structures is a part of the carbon loop.

Due to historically favourable power prices, the establishment of fuel production facilities, battery factories, and data centres has long been a topic in Norway. However, the Norwegian electricity grid is not scaled to support many industrial projects and is already under strain in many parts of the country. An e-methanol plant with an installed capacity of 70 MW can produce 55,000 tonnes of MeOH annually, enough to power one large containership. A plant of 70 MW that runs at an annual capacity of 90 %, will consume 551 GWh annually, translating to 0.25 % of Norway's net domestic consumption, or 1.2 % of Norway's net industrial consumption (EFN, 2024; Ørsted, 2024). Say we have 50 ships that we want to fuel, we would need an installed capacity of 3.5 GW, claiming 12.6 % of net domestic consumption. This is capacity that we do not have, facilitating the need for lone-standing power plants or relocating to areas with high surplus. Meanwhile, Norway range as the fourth largest shipping nation in the world measured in market value, only superseded by China, Japan and Greece, making the country a central actor in the fuel transition (Stautland, 2021).

As the results from this thesis and supporting literature show, BIO-MeOH shows the overall largest abatement potential of the fuel chains assessed, and seeing as Norway has abundant resources from forestry waste streams, this could prove to be a promising fuel for Norwegian production, by closing the loop on the domestic forestry value chain, as well as delivering sustainable fuels to the marine sector.

9 SOURCES

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