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Antti Salo

Carbon capture and utilisation in the maritime sector

- Decarbonization of the maritime sector with
e-methanol and carbon capture



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Carbon capture and utilization in the maritime sector

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In order to turn the tide on climate change, decreasing carbon emissions in all sectors is vital. As the marine traffic makes up the majority of global trade and transportation, it is evident that emissions produced by the maritime sector need to be decreased as well.

This thesis dives into the possibilities of carbon capture, storage and utilization in the maritime sector. To further decrease the emissions produced by the maritime sector, the potential of e-methanol used as a fuel was also studied. Aim of the study was to review the possibilities for carbon capture in the maritime sector and to uncover how applying carbon capture systems may affect the operating of vessels. The thesis was conducted as a literature review and supplemented with expert interviews.

Using e-methanol as a fuel can be seen as an efficient way to decrease carbon emissions produced in the maritime sector. Even as combustion of e-methanol produces direct carbon emissions, the well-to-wake emissions of e-methanol can be regarded as net-zero as carbon capture during the production process offsets these emissions. Combined with onboard carbon capture, it is possible to re-use the carbon dioxide in various industrial processes, such as e-methanol or cement production, to create a closed carbon cycle. The results of this thesis indicate that onboard carbon capture is a promising solution for decreasing direct emissions in the maritime sector. However, it is most optimal in relatively short and fixed routes where the accumulation of carbon dioxide is relatively minor, and ships are able to off-load carbon dioxide regularly.

Keywords: Renewable energy, e-fuel, e-methanol, carbon capture, maritime sector

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Antti Salo

Hiilidioksidin talteenotto ja hyödyntäminen meriliikenteessä

- Meriliikenteen päästöjen vähentäminen e-metanolin ja hiilidioksidin talteenoton avulla

Kasvihuonepäästöjen kiihdyttämän ilmastonmuutoksen vastainen työ vaatii kaikilta sektoreilta päästöjen merkittävää vähentämistä. Meriliikenteen kautta kulkee valtaosa globaalista rahdista, ja meriliikenteen päästövähennykset ovat globaalisti merkittävässä roolissa päästöjen vähentämisen kannalta.

Tässä työssä tarkastellaan hiilidioksidin talteenoton käyttöä e-metanolia polttoaineena käyttävän aluksen päästöjen vähentämisessä. Lisäksi työssä tarkastellaan miten talteenotettua hiilidioksidia on mahdollista hyödyntää eri teollisuuden prosesseissa. Työ toteutettiin kirjallisuuskatsauksena, jota täydennettiin asiantuntijahaastatteluilla.

E-metanolin käyttöä polttoaineena voidaan pitää tehokkaana keinona vähentää meriliikenteen päästöjä. Vaikka e-metanolin käyttö tuottaa hiilidioksidipäästöjä suoraan pakokaasusta mitattuna, e-metanolin tuotantovaiheessa talteenotettu hiilidioksidi ja uusiutuvilla energianlähteillä tuotettu sähkö kuitenkin mahdollistavat polttoaineen hiilineutraaliuden. Yhdistettynä aluksella tapahtuvaan hiilidioksidin talteenottoon, on mahdollista palauttaa e-metanolin käytöstä vapautuva hiilidioksidi takaisin kiertoon ja käyttää se uudelleen lukuisissa eri teollisuuden prosesseissa, kuten e-metanolin tai betonin tuotannossa. Tästä opinnäytetyöstä saatujen tulosten perusteella hiilidioksidin talteenotto soveltuu parhaiten kiinteille ja lyhyille reiteille, joissa hiilidioksidin kertymä on suhteellisen pieni ja alukset pääsevät purkamaan hiilidioksidikuorman säännöllisesti.

Asiasanat: Uusiutuva energia, hiilidioksidi, kasvihuonepäästö, e-polttoaine, e-metanoli

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Abbreviations

Abbreviation	Explanation
BECCS	Bio-Energy Carbon Capture and Storage
DAC	Direct-Air-Capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CO	Carbon monoxide
CO ₂	Carbon dioxide
GHG	Greenhouse gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LFSO	Low-sulfur fuel oil
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
NO _x	Nitrous oxide
NTP	Normal Temperature and Pressure
P2X	Power-to-X
PM	Particulate Matter
SO _x	Sulfur oxide

1 Introduction

Greenhouse gases (GHG) are a major driver of climate change and global warming. Majority of GHG are from industries and processes where fossil fuels are used on a daily basis. Moving away from fossil fuels, building production capacity of renewable energy and finding alternative, low-emission solutions are vital elements in the fight against climate change and global warming. Carbon dioxide (CO₂) is the most commonly mentioned GHG, and a lot of work has been done by almost all industrial and transportation sectors to reduce CO₂ emissions.

Despite being effective GHG, CO₂ is a major feed-stock in various industries, but carbon capture, storage and utilization (CCU) technologies are still in the early stages. In 2022 there were approximately 36.8 Gigatonnes of carbon dioxide produced from energy production alone, but only less than percent, approximately 230 Megatonnes, of these emissions were captured and utilized. With CCU, CO₂ can be utilized in a variety of processes, such as production of urea or synthetic fuels, also known as electrofuels or e-fuels. E-fuels are seen to be one possible solution for hard-to-electrify industries and sectors, such as heavy-duty road transportation and maritime sector (Nyári 2024). Most common e-fuels are e-methanol, e-ammonia and e-SAF, or sustainable aviation fuel. E-fuels are produced with renewable electricity, utilizing electrolysis to produce hydrogen and carbon dioxide captured directly from air, flue gases or other sources.

This thesis studies the possibilities of e-fuels, e-methanol in particular, in the maritime sector combined with onboard carbon capture and storage (CCS). E-methanol is a form of renewable methanol. According to Methanol Institute (2025), using renewable methanol decreases carbon dioxide emissions up to 95%, nitrous oxides by 80% and almost completely eliminates sulfur oxides (SO_x) compared to the use of conventional, fossil-based fuels. According to Visonà et al. (2024), naval shipping contributes to over 80% of world trade by

shipping volume. In 2022 emissions produced by naval shipping alone were 706 Mt/CO₂, which was about 2% of global emissions.

In 2023 International Maritime Organization (IMO) adapted a new strategy to reduce GHG produced by the maritime sector by at least 40% by 2040 and to reach carbon neutrality by 2050. Ways to reach these rather ambitious goals include stricter design requirements for energy efficiency, adaptation of new technologies such as carbon capture and moving away from fossil fuels and replacing them with renewable fuels such as e-methanol and ammonia. Shift from fossil fuels also requires additional capabilities from engines and fuel-handling systems onboard (Interview 1, 2025). However, there are already engines which are designed to function as dual-fuel engines, being able to run on conventional fuels and, for example, ammonia or methanol.

CCS is a potential way to utilise technology to reduce carbon emissions. According to Cuéllar-Franca and Azapagic (2014) CCS has potential to lower global warming potential (GWP) from power plants by 63-82%, and it has significantly lower environmental impact in form of GWP compared to CCU, but CCU allows the use of the carbon atom more than once which promotes circular economy in the energy sector.

1.1 Research background

Scope of study for this thesis was first introduced in fall of 2024. It was discussed with principal lecturer Ossi Koskinen from Turku University of Applied Sciences that research was needed, where aim was to review the possibility to create closed carbon system, or green corridor, in maritime environment where ships would use low-carbon fuels, such as e-methanol, combined with onboard carbon capture and storage. It was studied, how to efficiently and economically implement e-fuels in the maritime sector and combine it with carbon capture, storage and utilisation. The possible modifications needed to implement these technologies in existing fleet were considered. It was studied, if it is possible to

re-use captured CO₂, and if the amount of captured CO₂ is high enough to economically gain from captured carbon in the maritime sector.

1.2 Research problem and questions

The research problem for this thesis was to find out how to efficiently and cost-effectively implement carbon capture, storage and utilisation on ships using e-methanol as a fuel, and how to re-circulate captured CO₂ back to e-methanol production facility.

Research questions for this theses were:

- What are the possible techniques to capture CO₂ on ships using e-methanol as a fuel, and what is the technical and economical implementation of these techniques
- How captured CO₂ is stored on ships in economically efficient way
- How the logistics from the ship to e-methanol production facility is implemented
- Is there economical potential in the maritime sector to re-circulate captured CO₂ to e-methanol production facility

These questions directed search of useful material during literature review. They also formed the basic structure of questions in interviews.

1.3 Methods

This thesis was conducted as a literature review supplemented by interviews with experts representing different technological and industrial backgrounds.

Literature review

A search for appropriate material was conducted on several scientific databases, such as ResearchGate, ScienceDirect and Google Scholar. Most of the material was collected from ResearchGate and ScienceDirect, where

multiple studies and articles on the topic from recent years were found. As search for material progressed, it became clear that carbon capture has undergone a lot of research for land-based applications, such as power plants and other industrial facilities, but studies and material for applications in maritime sector were fairly limited in comparison with energy and industrial sector. Material for production of e-fuels, e-methanol in particular, was widely available.

Interviews

To gain more information and to support the theoretical information gathered for this thesis, three interviews with four persons were conducted. Interviews were held on Teams, and they were recorded and litterated. Interviewees were selected on the basis of the industrial background they were representing, along with what kind of products or services related to the topic of the thesis their companies provided. Interviewees represented occupations from design-level to higher management. Results drawn from the interviews were combined and analyzed and they were used to support the information gained from the literature.

To allow the interviewees to hold on to their anonymity, they are not referred directly by their name or by the name of the company they represent.

1.4 Structure

Structure of this thesis is following. First Power-to-X is introduced in order to give a quick look on how renewable electricity can be converted into other forms of energy carriers. Then e-methanol as a chemical substance is introduced in addition with its production. After e-methanol, carbon capture is introduced with different methods of carbon capture. These chapters are meant to function as theory chapters in order to give context on the results drawn from literature and interviews, which are introduced after carbon capture. After results, conclusions are made with discussion of possible shift in policies, attitudes, and foremost

the methods that allow the maritime sector to decrease carbon emissions. It should be noted, that e-methanol itself gets a lot of attention in the text, as it was the exemplary fuel chosen for this thesis, and it has significant potential in decarbonization of the maritime sector.

2 Power-to-X

Power-to-X or P2X is often used term that refers to various processes of converting renewable electricity into other forms of energy carriers, such as hydrogen, heat, liquid fuels etc.. The most commonly used energy carrier of these is hydrogen, which is produced via water electrolysis using renewable electricity. (Hren et. al. 2024, 2-3.) The principle of P2X is to connect different energy sectors via carbon capture to build a closed carbon cycle where no additional CO₂ is produced, and used carbon is cycled back to reproduce renewable fuels or chemicals (Dieterich et al. 2020). Figure 1 illustrates different pathways of transformation of electricity using electrolysis and synthesis.

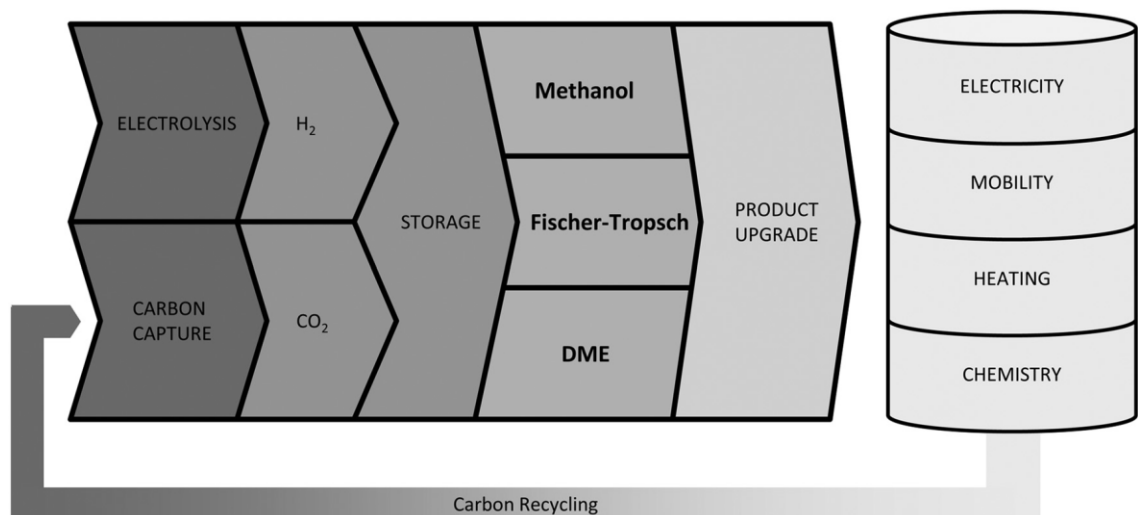


Figure 1. Power-to-X pathways to transformation of electricity to chemicals via electrolysis and synthesis. (Dieterich et al. 2020).

Electrofuels, or e-fuels, are synthetic fuels produced using electricity from renewable energy sources and CO₂ captured from power plants, bio-mass facilities or other emission sources in industrial sector. E-fuels allow conversion of renewable electricity into chemical compounds via electrolysis and synthesis, offering higher energy densities compared to gases. (Dieterich et al. 2020.)

2.1 E-methanol

This chapter gives a short introduction of methanol as a chemical substance and offers an explanation of production process of e-methanol. Methanol (CH_3OH or MeOH) is transparent and colorless substance, which is in liquid form at NTP conditions. It is one of the most commonly used building blocks of chemical and pharmaceutical industry and synthetic hydrocarbons, and it is widely available around the world. (Nyári 2024, 23.) Synthesis of methanol was introduced in the 1920s, and it was based on the Fischer-Tropsch-process, where hydrogen and carbon monoxide were converted into liquid hydrocarbons (Zamboni et al. 2024). Most of the methanol available today is produced from fossil sources such as coal through gasification processes or from natural gas through steam methane reforming. (Sollai et al. 2023,1.)

Methanol is one of the alternative fuels favored by the maritime sector to replace conventional fossil-based fuels, as it has some major advantages over fossil and other alternative fuels for the maritime sector. It can be classified as brown, grey, blue or green depending on the feedstock of the production process. Regardless of the production method, chemical structure of each is similar. (Zamboni et al. 2024.) E-methanol produced with green electricity allows sustainable fuel production with the potential to reduce carbon dioxide emissions in the energy and transportation sectors (Nieminen et al. 2019, 2). Its liquid form in room temperature and atmospheric pressure simplify its storage onboard, allowing the use of existing tank capacity. The formation of PM during combustion significantly decrease due to chemical structure of methanol, and being sulfur-free, SO_x emissions are also decreased. (Latarche 2021.)

2.2 E-methanol production

In order to understand the possibilities of e-methanol as a fuel, one should have an understanding of the production process of e-methanol. While it is true that production of e-methanol is very energy intensive, and it requires large capital investments starting from production of renewable electricity to be used for

electrolysis to obtain hydrogen, to carbon capture and storage, it still holds a huge potential in reducing CO₂ emissions compared to fossil fuels. Figure 2 depicts a simplified pathway of circulation of e-methanol, where renewable electricity is used in electrolysis of green hydrogen. In e-methanol synthesis, green hydrogen and CO₂ captured from feedstock are combined producing e-methanol. If e-methanol is used as a fuel in the maritime sector, direct CO₂ emissions produced by combustion can be captured and re-used in e-methanol production.

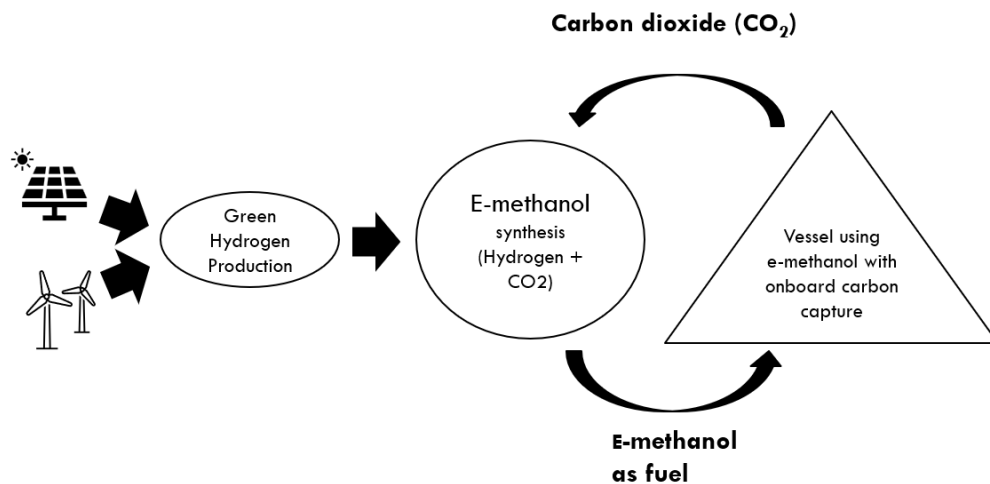


Figure 2. Simplified pathway of e-methanol production and carbon capture resulting in closed carbon circuit. (Ossi Koskinen, 2024).

According to Sollai et al. (2023, 4), following three equations describe the methanol synthesis via (1) CO₂ hydrogenation, (2) CO hydrogenation and (3) reverse water-gas shift:



E-methanol production is based on catalytic hydrogenation of CO₂ using an adiabatic fixed-bed catalytic reactor. Catalysts used in this reaction are mainly

Cu and Zn, but additives such as Al, Zr, Cr, Si, B, Ga etc. are also used. Hydrogenation process usually operates within temperatures between 250 and 300 °C, with pressures between 50 and 100 bar. Exit stream of the process is cooled in order to condense the liquid product which is mainly methanol and water. Liquid is sent to distillation unit to purify methanol and the unreacted gas is recirculated to the reactor in order to improve the efficiency of the conversion. (Sollai et al. 2023.)

Figure 3 shows Aspen Plus modelling of methanol production with a plant capable of producing 500 kg/h, 12 t per day with capacity factor of 0.9 giving annual production of approximately 4000 t.

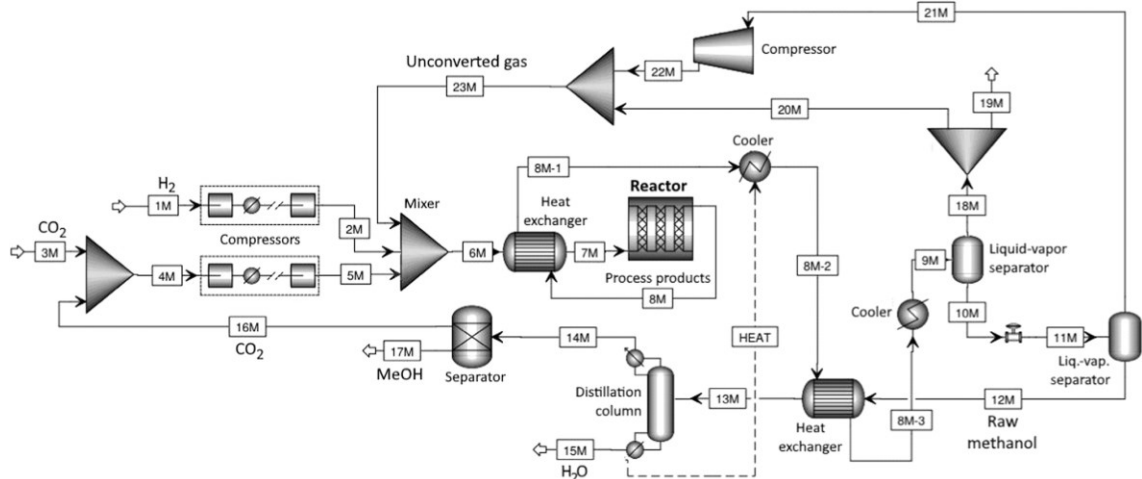


Figure 3. Simplified flowsheet of the methanol synthesis section modelled in Aspen Plus (Sollai et al. 2023).

Sollai et al. (2023) have given the following description of the process in figure 3. Hydrogen stream (1M) from electrolyser and carbon dioxide (3M) are compressed to pressure of 65 bar. They are mixed in the mixer along with recirculated, unconverted gas (23M) from the reactor. The mixture is heated (6M) with the heat recovered from products exiting the reactor (8M). Process products are cooled and unconverted gas is separated from the liquid phase. This unconverted gas (18M and 21M) consists mostly of hydrogen, carbon dioxide with small amount of methanol, water and carbon monoxide, and it is

recirculated back to the reactor. Approximately 1% of unconverted gas is purged and flared to reduce the accumulation of undesired gas in the circulation. Purging slightly increases CO₂ emissions, but it can be neglected as it is approximately 3% of the amount of CO₂ captured from the flue gas. After exiting the separators, the raw methanol (12M) still contains water and unconverted CO₂. Raw methanol is heated to operating temperature of the distillation column, and water is condensed.

As the need for alternative and renewable fuels rise, production capacity must meet the demand. In figure 4, prediction of renewable methanol production capacity from 2023 to 2030 is shown.

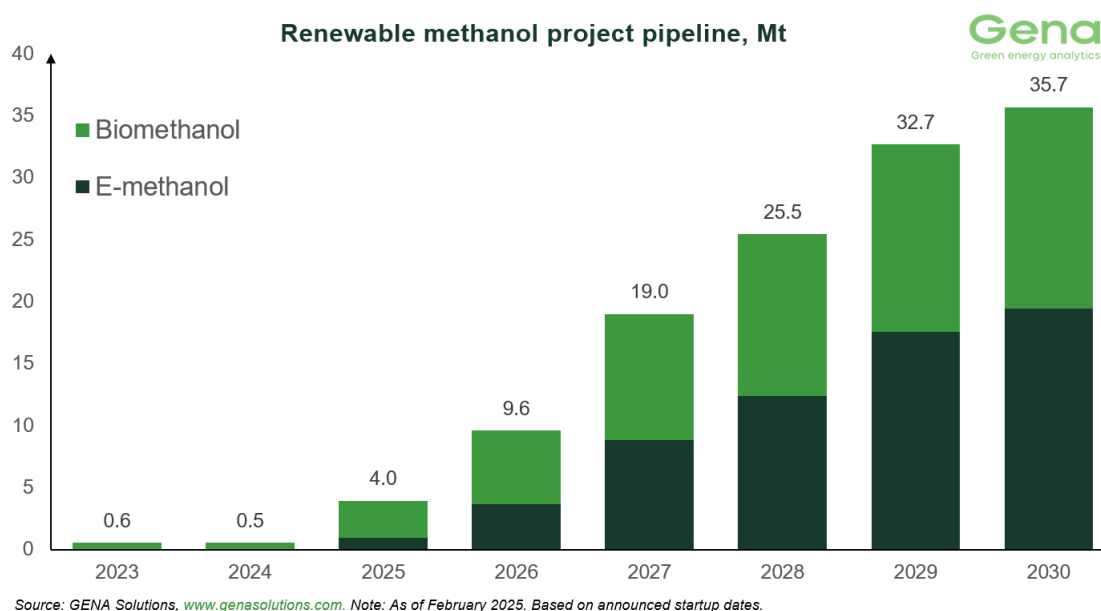


Figure 4. Renewable methanol project pipeline (GENA 2025).

Figure 4 indicates steady growth of renewable methanol production, with e-methanol representing a little over half of the predicted production capacity, around 20 Mt. According to GENA (2025), China and Europe have largest shares of global renewable methanol project pipeline, with China representing 49% and Europe 30% of predicted production capacity. However, it should be noted that figure 4 shows predicted capacity, if all projects announced as of

February 2025 continue to operational phase. For these projects to become operational, some key factors need to be secured for plant to be able to produce e-methanol with reasonable cost. According to Zero Carbon Shipping (2022), cost of e-methanol is mainly affected by 3 factors. First major factor is cost of renewable electricity, which holds the largest portion of the production cost. Regional differences in renewable electricity prices determine the locations of e-methanol production facilities. Second factor affecting the cost of e-methanol is the availability of CO₂ feedstock. Depending whether CO₂ is captured from emitting facility or with DAC, the price of carbon capture has major effect on e-methanol production costs. Third factor is the economics of scale, meaning that larger production facilities are more economical. Amount of available CO₂ certified as renewable may be small, resulting in smaller production facilities, which in turn will not achieve the same economics as conventional methanol plants today. For CO₂ to be regarded as renewable, it should come from sources that are regenerated via photosynthesis or through generation of carbon-based waste, such as municipal waste, biosolids or sludges (U.S. Department of Energy, 2025).

2.3 E-methanol as a fuel

Propulsion systems in the maritime sector are mostly powered by internal combustion engines (ICE), of which most widely used ICEs are diesel engines (Zamboni et al.2024). ICEs can be classified as two-stroke or four-stroke engines according to the number of strokes the piston completes in one working cycle, or as spark-ignition (SI) and compression ignition (CI) engines depending what kind of ignition system is used to initiate the combustion process (Wärtsilä 2025a, 2025b). Due to high autoignition resistance and high latent heat, e-methanol is primarily considered as an SI-engine fuel and it can be used as a pure fuel, or it can be blended with other fuels. To be able to use e-methanol as a fuel in SI-engines, no significant modifications are needed, but changes to operational parameters may need to be done due to condensation in low temperatures. For CI-engines, more significant modifications are needed due to

high autoignition resistance. This has led to dual-fuel technologies, where e-methanol is injected separately from diesel, which in turn is used as a igniter in the combustion process. (Verhelst et al. 2018, 52.) Most used injection types are port injection and in-cylinder direct injection. In port injection, liquid e-methanol is injected at the intake port while intake valve is open and exhaust valve is closed, but in some cases it can be injected downstream of the turbocharger compressor. With in-cylinder direct injection, e-methanol is injected usually close to the top-dead centre of the cylinder. Either way, high-reactivity fuel, which is usually diesel, is injected directly in-cylinder, where it is combusted via compression. (Karvounis et al. 2023, 5.)

Methanol has been proven on several instances to be suitable fuel for the maritime sector. According to Dierickx et al. (2022) MAN has several ships powered with low speed engines, Wärtsilä has successfully applied medium speed engines already for several years and Volvo Penta, representing high speed engines, was demonstrated in LeanShips project. According to Nyári (2024) low molecular but high liquid density of e-methanol favors its use as a marine fuel and with high heat of evaporation, or latent heat, and lower combustion temperature needed, engine volumetric efficiency is increased. Other attributes that favor e-methanol as a marine fuel are low stoichiometric air-fuel ratio, high flame speed, high molecular expansion ratio and high hydrogen-to-carbon ratio. Comparing properties of e-methanol with those of diesel, it has fairly similar density, 790 kg/m^3 compared to 845 kg/m^3 , but significantly lower LHV and volumetric energy density ($20,09 \text{ MJ/kg}$ and $15,87 \text{ MJ/l}$) compared to those of diesel ($43,2 \text{ MJ/kg}$ and $36,5 \text{ MJ/l}$) (Pu et al. 2024). The difference in energy values has a direct effect on the range of the ship, meaning that in order to have same range as with diesel, ship needs to roughly double its fuel-tank capacity or bunker more frequently (Karvounis et al. 2023,2). Verhelst et al. (2019, 75-76) argue, that to combat the need for additional storage onboard, double hulls of vessels could be converted into fuel tanks to store e-methanol, since it is infinitely miscible in water. This means that in case of accident where hull is breached, e.g. grounding or collision, the risk of fuel spill is minimal since e-methanol dissolves in water. If e-methanol is spilled

into ground, it is mostly swallowed and cleaned by bacteria, and it will not result in pollution of the ground as gasoline or diesel will. However, it should be noted that methanol is toxic in high concentrations, so local effects could occur before it is dissolved (Brynnolf et al. 2014, 88).

Despite adaptation of e-methanol having benefits over conventional fuels, implementation of both renewable methanols, bio- and e-methanol, may face risks. These risks consist mainly of production and supply capabilities, and also of production costs. According to Zero Carbon Shipping (2022), scaling of methanol supply chain, and also competition for feedstocks and methanol itself may limit the implementation of renewable methanol in the maritime sector. Also having higher production cost than conventional marine fuels or fossil-based methanol, price of renewable methanol, e-methanol in particular may affect its implementation in the maritime sector. Measures to make cost of renewable methanol competitive with conventional fuels may need to be taken, and these also include regulatory measures.

In case of e-methanol, Zero Carbon Shipping (2022) presents not only risks, but also milestones to implement e-methanol in the maritime sector. In their study, they present production costs of e-methanol from well-to-port to be 3-8 times higher compared to conventional fuels, in their case low-sulfur fuel oil (LSFO). Zero Carbon Shipping predicts production cost of e-methanol to decrease by 13% per annum, reaching 28 USD/GJ by 2050. There is however some variation of cost depending on the capture method of CO₂ feedstock, point capture from the facility producing CO₂ having higher efficiency and lower costs compared DAC. To lower the cost of e-methanol production, commercial e-methanol plants should be operating on low-cost renewable electricity sources. To reduce the risk of reliable and sufficient supply of e-methanol, commercial e-methanol plants should be located near relevant ports, and centralized CO₂ supply and green corridors with sufficient supply of e-methanol should be established.

2.3.1 Fuel-handling and storage

Chemical properties of e-methanol require specific attention in handling and storing it on ships. E-methanol is hygroscopic, meaning it absorbs moisture if exposed to air or other sources of moisture. Excess moisture in e-methanol can lead to fuel quality issues, meaning that storage tanks, piping and fuel-handling systems need to be tightly sealed and protected from moisture. Also the corrosiveness of methanol requires durable materials, such as stainless steel or specially coated steel, to be used in systems that store or carry e-methanol. (Sollai et. al 2023, Interview 1 2025.)

2.3.2 Safety

Proper safety measures in handling of e-methanol are needed in order to avoid accidents and even deaths. E-methanol is a toxic substance and oral, inhalation or skin exposure can lead to acute poisoning. Probable inhalation or skin exposure to e-methanol may happen mostly in occupations where e-methanol is handled. Having oral exposure can be regarded to happen mainly by mistake. Symptoms of e-methanol exposure include headache, dizziness, fainting, blindness and death. To reduce these risks, proper sealing of tanks and pipes is necessary. Also proper safety gear of personnel in contact with e-methanol is necessary, including respiratory protection, clothes made of chemical-resistant materials and eye-protection. (Methanol Institute, n.d.)

E-methanol has a relatively high flammability range compared to gasoline and diesel. It has a flashpoint of 11 °C, which makes it classified as highly flammable. In right conditions, it can also explode in the air. This puts emphasis on firesafety onboard. Given the characteristics of methanol fire, which include less heat production, less heat transfer to surroundings and no soot production which result in flames nearly invisible to the naked eye in daylight, these fires can be hard to detect. For measures regarding fire prevention, vapor control is necessary. Ultimate measure to prevent fuel vaporization would be to decrease the fuel temperature below the flashpoint temperature. If vaporization can not

be controlled, proper measures to detect possible leakages should be taken by using gas detectors. In case of e-methanol fire, dry powder or carbon dioxide fire-extinguishers will most likely offer the best result. Using water to suppress e-methanol fire is also possible, but given the e-methanols solubility with water, which may lead in spreading of fire, a sufficient amount of water should be used to increase the volume of methanol-water solution by at least a factor of 4. (Methanol Institute, n.d..)

2.3.3 Environmental aspect

Using e-methanol as a fuel has also other advantages in addition to lower carbon emission production of the combustion. During combustion event e-methanol produces less pollutant emissions due to its oxygenated structure. Having no carbon-carbon bonds and its only carbon atom being bonded with oxygen atom, combustion of e-methanol is more complete and it produces lower hydrocarbon and CO emissions (Pu et al. 2023). This is supported by Nyári (2024), who argues that e-methanol has significantly decreased PM formation due to its chemical structure, and also due to low sulphur tolerance of the synthesis catalyst used in the production, SO_x emissions are reduced to almost zero. Tank-to-wake CO₂ emissions of methanol, regardless of the origin, are 1,37 kgCO₂/kg_{fuel}, which is significantly lower than tank-to-wake CO₂ emissions of HFO, which are 3,11 kgCO₂/kg_{fuel} (The Engineering ToolBox, 2009). According to Zamboni et al. (2024), while it is true that methanol does produce CO₂ emissions when used as a fuel for internal combustion engines, the production process of methanol has great impact on the lifecycle emissions of methanol, meaning that direct comparison with CO₂ emissions measured from exhaust systems does not tell the whole truth. They continue, that to properly compare the conventional and alternative fuels, the evaluation of well-to-wake GHG emissions, where all the phases from production of fuel to the combustion of the fuel are considered, is fundamental. With obtaining green methanol from biomass or with renewable energy, the carbon emissions can be considered as net-zero, since the CO₂ emissions produced during combustion

event are offset by carbon capture systems or growing crops. (Altosole et al. 2024.)

In addition with having impact on emissions of ships using e-methanol as a fuel, other environmental aspects need also to be considered. Although e-methanol is toxic for humans if ingested, its solubility with water, as stated earlier, greatly improves the overall safety of the maritime sector regarding accidents and fuel spills.

3 Carbon capture, storage and utilisation

This chapter focuses on explaining the principles of carbon capture, storage and utilisation. In addition, main methods of carbon capture are introduced. CCUS is a common name for a group of methods and techniques to reduce the CO₂ emissions from fossil-fueled power plants and other CO₂ sources by capturing CO₂ from emission source and either permanently storing it or utilising it in processes or products where captured CO₂ can be used again.

3.1 Carbon capture methods

According to Hren et. al. (2024, 1-2) carbon capture technologies can be classified into three main categories: pre-combustion, post-combustion and oxyfuel-combustion. Cuéllar-Franca and Azapagic (2014) refer to first two also as pre-conversion and post-conversion regarding other industries than energy production. In figure 5, different carbon capture methods for power plants are visualised.

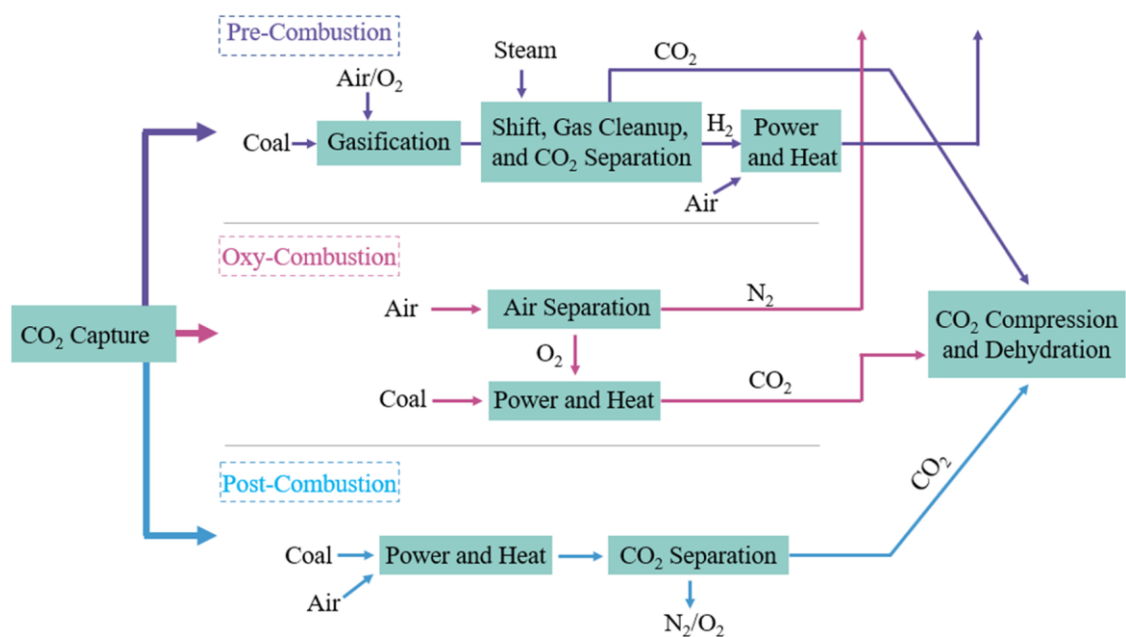


Figure 5. Roadmap of different carbon capture technologies for power plants (Fu et al. 2022, 3).

According to Fu et al. (2022, 2) pre-combustion and oxyfuel combustion technologies have seen relatively low research and development, mainly due to their requirements of materials and conditions for proper function, compared to post-combustion capture, which is proved, widely adopted and efficient method of carbon capture.

3.1.1 Pre-combustion capture

In pre-combustion capture, reforming or gasification process is used resulting in syngas composed of hydrogen and carbon monoxide (CO). CO produced in this process is then converted into CO₂ that is captured before combustion.

(Madejski et al. 2022, 2-3.) A diagram explaining pre-combustion process is shown in figure 3.

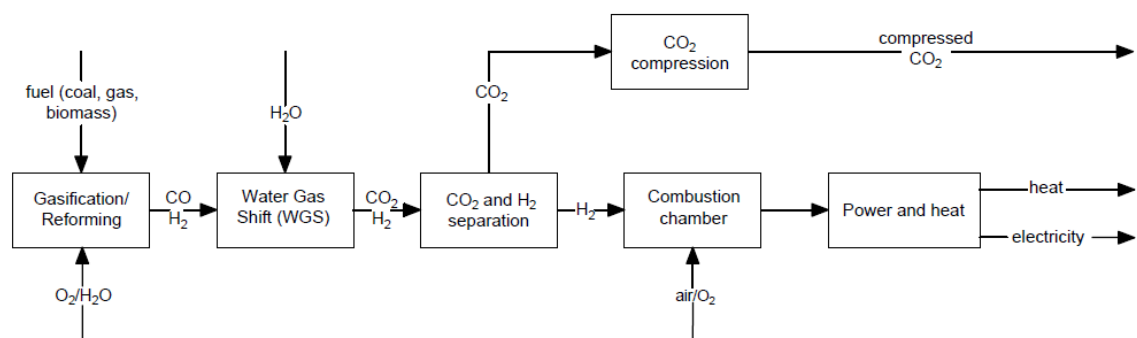


Figure 6. Block diagram of electricity generation and heat production with the use of the pre-combustion CO₂ capture method (Madejski et al. 2022).

Pre-combustion capture involves transforming fossil fuels into a mixture of hydrogen and carbon monoxide, known as syngas, through reforming or gasification processes. The carbon monoxide is further converted into carbon dioxide, which is then captured before the combustion phase. This method is advantageous due to its high capture efficiency, often exceeding 90%, although it can reduce the overall energy production efficiency due to lower fuel volume. (Madejski et al. 2022, 2-3.)

3.1.2 Post-combustion capture

Post-combustion capture removes CO₂ from flue gases after the combustion, and it is seen more suitable solution for existing power plants and other facilities producing CO₂ emissions. However, post-combustion capture is not as effective as pre-combustion, since flue gases typically contain much less CO₂ than the syngas produced in pre-combustion capture. (Hren et al. 2024, 2.)

According to Madejski et al. (2022, 6-11), post-combustion methods can be divided into:

- Absorption solvent based methods, where chemical reaction between CO₂ and chemical solvent is used to capture CO₂. Chemical absorption is the most recognizable method of carbon capture.
- Adsorption-physical separation, which uses a solid surface to remove CO₂ from flue gas. Physical adsorption utilises various materials to absorb carbon, such as activated carbon, aluminium oxide, metallic oxides or zeolites.
- Membrane separation, which can be further divided into gas separation and gas absorption depending of what kind of membrane is used. With gas separation membrane, gas containing CO₂ is driven to the high-pressure side of the membrane, and CO₂ is recovered at the low-pressure side of the membrane. Gas absorption on the other hand utilises a solid microporous membrane, allowing gas flow from flue gas stream through the membrane to the absorption system.
- Chemical looping combustion (CLC) and calcium looping process (CLP). Chemical looping utilises air and fuel reactors. These utilise circulated fluidized beds that are coupled for carrier transport. Air reactor utilises metal particles, usually iron, manganese or copper, which are oxidated with the oxygen from air, resulting in formation of metal oxides. These are carried to the fuel reactor where they react with the fuel. During combustion these oxides are reduced, producing energy and flue gas stream consisting of CO₂ and H₂O, which can be further condensed to

receive pure CO₂. Calcium looping process on the other hand is a form of chemical looping, which is based on a reversible reaction between calcium oxide (CaO) and CO₂. It is based on carbonation of calcium oxide and it results in formation of CaO in the first reactor. CaO is then carried to the second reactor, calciner, where stream of CO₂ with high purity, over 95% is formed via the reversible reaction. Calcium looping is an advantageous technology as it utilises fluidized beds and it is mature, high-temperature technology that generates power as a by-product. It also uses cheap sorbent, lime, and flue gas produced during the process is partially desulfurized.

- Cryogenic method, which uses liquefied natural gas (LNG) to provide cold energy in order to capture CO₂. It is used in oxyfuel combustion and post-combustion capture to separate CO₂, and it produces CO₂ with purity over 99%, but due to high operating costs it is less preferred compared to other capture technologies.

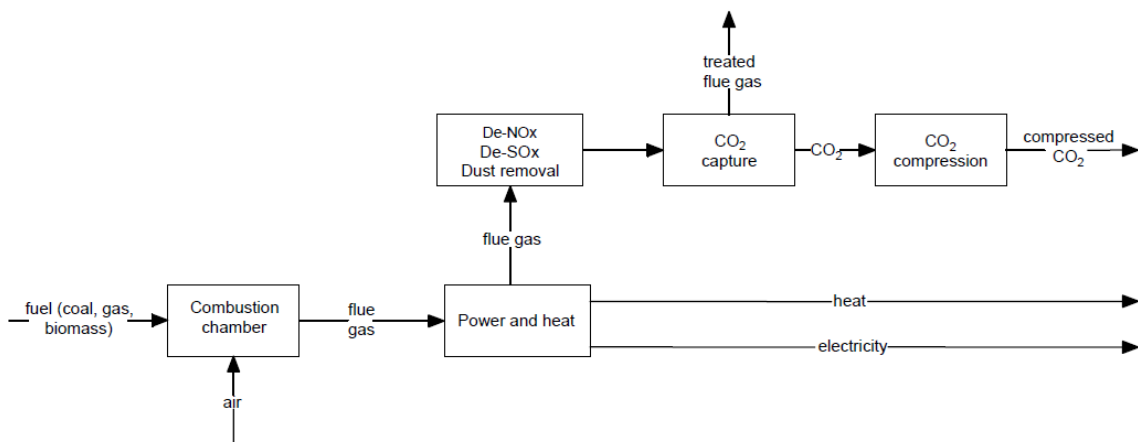


Figure 7. Block diagram of electricity generation and heat production through the use of the post-combustion CO₂ capture method (Madejski et al. 2022)

Among the post-combustion capture technologies, absorption based on amine solution is the most widely recognized method. Commonly used amine solvents are monoethanolamine (MEA), methyldi-ethanolamine (MDEA) and piperazine (PZ). Simulated 300 MW power plant fitted with post-combustion capture based on MEA amine solution was estimated to bring the cost of captured CO₂ to less than 55 \$/tCO₂. (Madejski et al. 2022.) Despite being efficient method of

capture, amine based capture has some disadvantages, such as high corrosivity, toxicity, degradation and high thermal energy requirement for regeneration of solvents (Pancione et al. 2024, 4).

3.1.3 Oxyfuel combustion

In oxyfuel-combustion fuel is burned with pure oxygen in order to produce flue gas that has high CO₂ concentration and does not contain nitrogen or its compounds. A small proportion of CO₂ is used in the process to control the temperature of the flame. Products of oxyfuel combustion are primarily water vapor and CO₂. (Tian et al. 2022, 3.) Figure 6 illustrates oxyfuel combustion process.

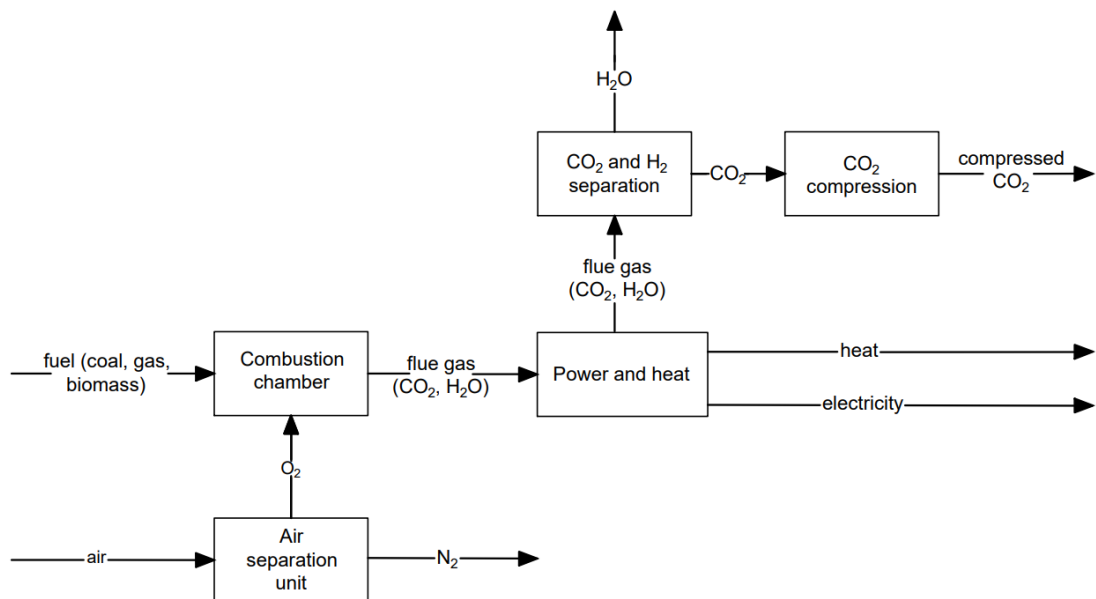


Figure 8. Block diagram of oxyfuel-combustion process (Madejski et al. 2022)

Carbon capture via oxyfuel combustion has high content of CO₂, around 80 to 98%. Having high concentration of CO₂, the cost of capture and CO₂ separation is low, but oxygen-enriched supply has relatively high cost. In addition, controlling the burner in oxyfuel combustion is usually difficult, placing higher requirements on the materials and components used in the system. (Tian et al. 2022, 3.)

3.2 Comparison of different carbon capture methods

Fu et al. (2022, 3) provide a comparison between three main capture methods, with each having their advantages and disadvantages. According to them, advantages of pre-combustion capture are small size of capture equipment and less regenerative energy compared to other methods, but pre-combustion capture has high investment costs and limited operation. Post-combustion capture has low investment costs, flexibility in operation reducing operating costs, and due to maturity of these technologies they are fast to be introduced on existing platforms where carbon capture is applicable. However, as stated earlier and also stated by Fu et al. (2022, 3), lower partial pressure of CO₂ in flue gas lowers the efficiency and increases the energy demand, increasing costs of post-combustion capture. Oxyfuel combustion capture has high concentration of captured CO₂ with lower NO_x formation, but due to high demand of oxygen in the combustion process, investment and operational costs increase in addition with increased energy consumption.

3.3 CO₂ utilisation

What to do with captured CO₂, is a question presented by many. To answer this question, many projects have been started, where the possibility to store CO₂ have been researched and developed. One possible way is to store captured CO₂ in depleted oil or gas formations below seabed under high pressure. (Bashir et al. 2024.) Even though carbon storage has seen a lot of attention, there are some factors that raise concerns regarding the storage of CO₂. Some of these concerns are high cost of storage and possible leakages of CO₂, and potential small earthquakes caused by pressurized CO₂. This has caused a shift of attention into CO₂ utilisation. It must be mentioned, that utilisation alone is not able to permanently remove CO₂ from atmosphere, as will be explained below. For this reason, efficient ways to store CO₂ are constantly researched and developed. (Fu et al. 2022.)

According to Fu et al. (2022), in CCU, the U can be defined as CO₂ utilisation as a resource. They argue, that CO₂ utilisation can be divided further into physical, chemical, biological and mineralization utilisation, which are further explained below.

Physical utilisation is used mainly in food, refrigeration and other industries. It must be underlined, that physical utilisation only delays the release of CO₂ into atmosphere, since it does not sequester CO₂ from environment, hence is not seen as a factual decarbonization technology. Chemical utilisation on the other hand utilises CO₂ as raw material, or feedstock, in chemical reactions where CO₂ can be used as a reactant. Products from chemical conversion of CO₂ can be divided into three groups: bulk chemical, synthetic fuels and polymer materials. Out of these groups, we have in this thesis looked into chemical utilisation of CO₂ as a feedstock in e-methanol production. Chemical utilisation has similar issue as physical utilisation, the release of CO₂ is only delayed. As with synthetic fuels, using CO₂ produced with hydrogenation does not generate additional CO₂ emissions when used, and with carbon capture systems it can be captured and recycled to be used again in said fuel synthetization. In biological utilisation CO₂ is converted into high-value products. This is done by designing new, artificial photosynthesis pathways, to imitate photosynthesis of plants and micro-organisms. Finally mineralization utilisation refers to processes, where carbonates are formed with CO₂. This can be done by imitating weathering of CO₂ in nature, while raw materials react with CO₂. Other way is to create intermediate raw materials with chemical additives, and then introducing CO₂ to cause the reaction. (Fu et al. 2022).

As carbon capture technologies become more efficient and mature, and number of possibilities to utilise captured CO₂ increase, the market for carbon dioxide also grows. To find exact prices for carbon dioxide proved to be difficult, and many of the sources were available only by payment. However, some open-source materials were found, where predictions of market size and value were made. In figure 9, worldwide market size of carbon dioxide gas in 2022 and forecast for the size of the market in 2035 are shown.

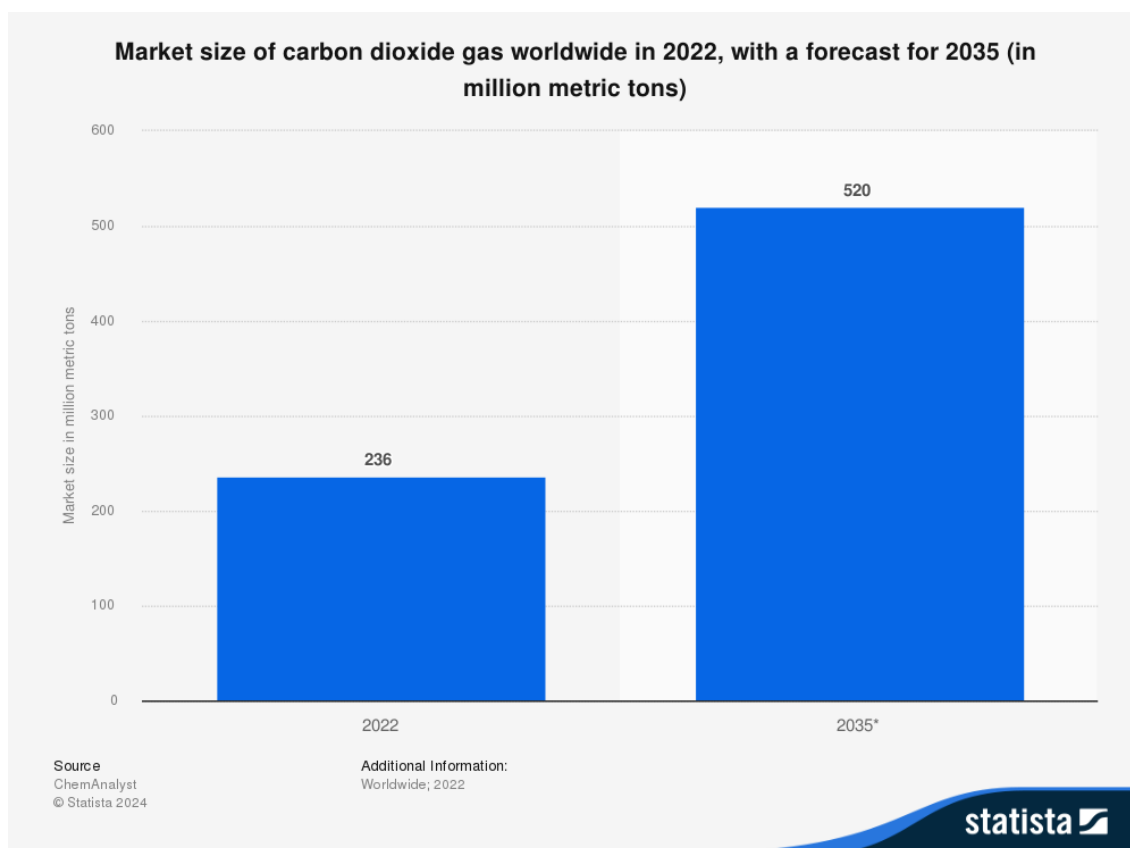


Figure 9. Market size of carbon dioxide gas worldwide in 2022, with a forecast for 2035 (in million metric tons) (ChemAnalyst 2023)

As figure 9 shows, it is predicted that market size of carbon dioxide gas more than doubles its size by 2035. This indicates that interest in utilisation of CO₂ as a feedstock is predicted to increase. This correlates with data shown in figure 10, where global market value of CO₂ is presented in 2022 with prediction of market value in 2030.

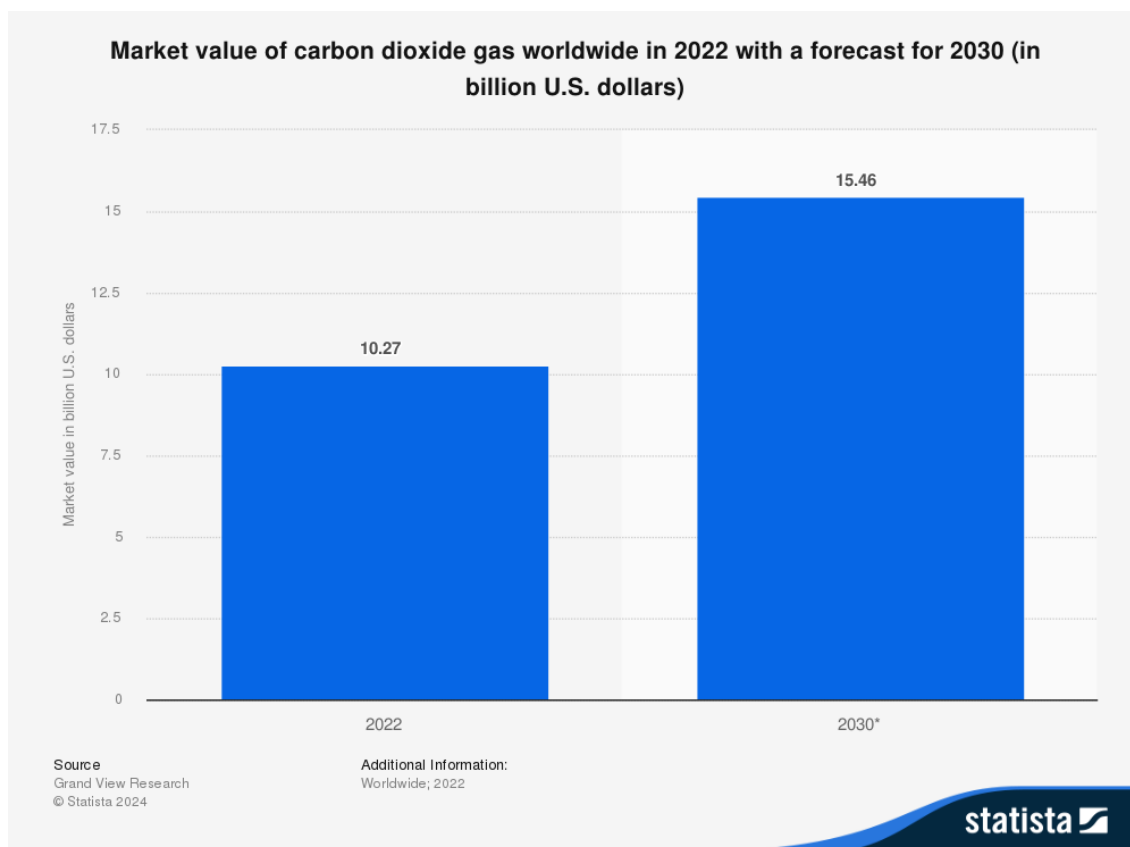


Figure 10. Market value of carbon dioxide gas worldwide in 2022 with a forecast for 2030 (in billion U.S. dollars) (Grand view research 2023)

Compared with figure 9, market value shown in figure 10 does not have such a steep rise as market size does. This may be as a result of increased supply of carbon dioxide leading in decrease in market prices. It must be noted, that specific price for metric ton of CO₂ was not found, as searches for this price only brought up emission fees and carbon taxes imposed by governments and organisations.

If we look back at figure 4, where renewable methanol, which includes bio- and e-methanol, project pipeline for 2030 was introduced, it has certain correlation with predicted growth in market size for CO₂. Although renewable methanol production is not only sector where CO₂ is utilised, the predicted growth of production capacity of renewable methanol will have impact on carbon dioxide market.

All the examples mentioned above show, that utilisation of CO₂ is possible and in some cases even mandatory to reach the wanted end-result of process. As carbon capture technologies become more mature and efficient, adapting these in emission sources such as ships, helps not only to decrease the emissions but also provide a steady supply of CO₂. The prediction of growth in market size and value of carbon dioxide show, that to be able to meet the possible market demand of CO₂, the number of sources of supply must also increase.

4 Results

In this chapter we are going to look at the results from the interviews. Total of 3 interviews with 4 interviewees were conducted. Interviewees represented companies that operate in the maritime sector with different products, such as fuel-handling systems, carbon capture systems and shipbuilding. Results are divided into smaller chapters to get a wide picture of views presented by experts on the matter. After results, conclusions are drawn and the possibilities and challenges regarding the application of e-methanol and carbon capture in the maritime sector are discussed.

4.1 Decarbonizing maritime sector

Decarbonizing maritime sector can be seen as a sum of many different factors, each playing a vital part in the process. During interviews it became evident, that adapting e-fuels and carbon capture are not the only solutions to lower the emissions of maritime sector. In interview 3 (2025), a wide array of methods to lower the emissions were introduced. Solar panels were seen as a possibility to produce energy onboard for auxiliary systems. Solutions such as fuel cells or battery systems were not seen adaptable, atleast not in near future, mostly due to high cost of the development and application. The role of hydrogen and its derivatives, such as e-methanol and ammonia were indeed seen as some of the most promising solutions to decarbonize the maritime sector. Hydrogen used as a fuel was seen tempting and the growth in use of hydrogen was seen to be on the rise. It was argued that some marine engines are already capable of using hydrogen, or hydrogen-fuel blends. Problems with hydrogen were noted, and biggest issue with hydrogen was how to efficiently store it onboard without losing passenger or cargo capacity. Also the price and availability of hydrogen was brought up, since cost of operating vessel on hydrogen was still seen to be too high to be economically feasible. It was noted that in order to gain the full potential of hydrogen and e-fuels, engine technology needs to be improved.

Other measures were also brought up in Interview 2 (2025), such as proper planning of schedules and voyages and limiting the time spent in ports. Ships often use their main or auxiliary engines during port visits to produce the needed energy and electricity for different systems onboard. Limiting the time at port to minimum may have a significant impact on emissions on the global scale. Additionally, other methods, such as lowering the friction of the hull by using proper coating materials, decreasing the overall weight of the vessel, having frequent maintenance and cleaning of the hull, utilising heat recovery and maximizing the efficiency of the propulsion systems were brought up in the interviews. These were seen as cost-effective, short-term solutions in situations where alternative fuels and onboard carbon capture are not adaptable or economically feasible.

In Interview 3 (2025) it was argued that shipowners and shipyards are continuously investing in research and development of new technologies in order to stay competitive and to find new solutions to lower emissions of the maritime sector. However, applying these new technologies on ships require investments, and like with all new technologies, there is some uncertainty of payback, which in turn may affect the willingness to invest in the application of these new technologies. It was noted that as regulations on emissions of maritime sector become more strict and cost of emission fees may rise, it will be one driver to push adaptation of e-fuels and low-emission technologies further. It was also stated that possible savings in emission fees may help with payback of these technologies.

4.2 E-methanol as a fuel

In interviews, e-methanol was seen promising option among other alternative fuels for maritime applications. It was also brought up, that in order to be widely adapted, e-methanol needs to be widely available. This raised concerns about the need of adequate infrastructure in ports in order to support the transition towards alternative fuels. As a short- and mid-term solution, dual-fuel applications combined with carbon capture were seen as realistic and smooth

transition towards alternative fuels. This was also seen as a realistic way to reduce emissions, since powered by engines capable of running with different fuels, ships can operate using e-methanol where it is available, and switch to other fuels when e-methanol is not available. Using different fuels according to the availability was also seen to help reduce the stress imposed on capture system, and CO₂ storage capacity in particular, when it is applied.

Applying e-methanol as a fuel in the maritime sector was seen in interviews to be in its early stages, even as multiple ships currently run on pure methanol fuel or methanol blends, and multiple projects are currently under construction where systems are built methanol-ready. In Interview 1 (2025) it was stated, that there are currently multiple projects globally under construction, where ships are built as methanol-ready, meaning that adaptation of methanol as a fuel is smoother since systems onboard are already able to utilise it. It was also stated that there are geographical differences regarding the speed of adaptation of alternative fuels, for example northern Europe being more advanced in green technologies than southern Europe. Since e-fuels are known as alternative fuels, it means that systems capable of utilising e-methanol are built alongside of main fuel supply systems, potentially resulting in more occupied space onboard.

According to Interview 1 (2025), using e-methanol as a fuel introduces challenges regarding the materials used in systems that are in contact with the fuel. Due to the corrosiveness of e-methanol, pumps, piping and tanks which are used to handle e-methanol need to be manufactured from durable materials such as stainless steel or specially coated steel. Other components used in fuel-handling systems designed for e-methanol have also higher standards compared to those designed for conventional fuels. The lubricability of e-methanol is lower than that of conventional fuels, which means that additive should be used to allow the engine to function properly. In addition with material issues, also the regulatory aspects in transitioning to e-methanol need to be taken into account. Uncertainties in regulations or standardisation, which were brought up in interviews, may lead to situations where component or system manufacturers are not sure about guidelines or regulations that govern their production.

Issues stated above have direct connection with the price of these systems onboard. It was argued that components used for e-methanol systems may have even 5 to 10 times higher price than those used for conventional fuels. This was a rough estimate, which depends on factors such as global market situations causing uncertainties in pricing of materials for components, and classification and standardisation fees for components and systems. These additional fees will ultimately affect the end-price of products, which may have effect on the investment decisions made by ship builders and owners.

In Interview 3 (2025) it was brought up that in order for ship to shift from conventional fuels to e-methanol, some things need to be considered before making the transition. One of the major factors is where the ship is destined to operate, which is obviously linked to the availability of e-methanol in ports. Even if e-methanol was available in area of operations, it was noted that ports should have technical and logistical readiness to bunker ships with e-methanol.

4.3 Carbon capture and storage onboard

Adapting onboard carbon capture is possible and promising solution to decarbonize the maritime sector. The choice of carbon capture system depends on variety of factors such as ship type, available space, safety requirements of installation and logistics onboard. It is also crucial that ship performance has no major negative effects caused by selection and integration of carbon capture systems. According to Pancione et al. (2024, 1-3), post-combustion capture based on absorption, adsorption, calcium looping, membrane separation and cryogenic capture are seen as the most promising technologies to implement onboard carbon capture. Main disadvantage of post-combustion capture is the low CO₂ concentration of the flue gas, which in turn increases the energy demand of these systems. Pancione et al. (2024, 7) continue, that absorption and adsorption are the most promising applications among post-combustion capture technologies for onboard carbon capture, outperforming membrane separation, calcium looping and cryogenic separation. Absorption with amine solution is widely used to capture CO₂ from stationary sources, but it has high

corrosivity and high requirement for energy in regeneration phase, compared to for example, membrane separation. Applying these systems onboard ships face some challenges such as losses in power generation, space requirements for installation and operation of these systems, and the need for adequate space dedicated to store captured CO₂. Risso et al. (2023) argue, that if energy needed for capture system is too high, more energy is produced and more fuel is burned resulting in more emissions, which may affect the efficiency of the capture system. They continue that existing energy production on board may not be enough to support the CCS system, introducing the need for new energy generation systems, but adding new systems on ships is not always possible or economically feasible due to lack of adequate space or required resources.

Another factor affecting the choice of carbon capture system is the need for adequate space to store captured CO₂. The choice of form in which CO₂ is stored has a significant impact on the need of space and the efficiency of the system. CO₂ can be stored in gaseous, liquid or solid states. Storing CO₂ in gaseous form occupies larger volume than liquid state, hence it is not preferred. Pancione et al. (2024) argue, that storing gaseous CO₂ in NTP conditions (1bar, 20 °C) occupies 550-600 times the volume compared to liquid CO₂ in conditions of 50 bar and -23°C. (Pancione et al. 2024, 15.) The challenge of storage capacity is faced first and foremost in ocean-crossing shipping, where distances are long, consumption of fuel is high and thus accumulation of CO₂ is high.

According to Interview 2 (2025), there are applications that are ready to be fitted onboard to capture CO₂ from flue gas. However, these applications are not yet widely applied, mostly due to challenges regarding the adequate space needed for captured CO₂. Integration of carbon capture system itself was seen easy from technical point of view. When asked to name the most suitable method of carbon capture in the maritime sector, no simple answer was found. One of the main reasons for this was, that all the different methods have their advantages and disadvantages, and ultimately the owner and operator of the ship must decide what they want to achieve with these systems and what kind of investments they are willing to make. It was however argued in all interviews, that one of the driving forces across all sectors to lower overall emissions are

emission fees, and the possible economical value gained by selling of captured CO₂.

One example which gave a good insight on possibilities of carbon capture of the maritime sector was given in Interview 2 (2025). They brought up the directives which were put in place to reduce the amount of sulfur emissions. This boosted the adaptation of scrubbers which, as an investment, was predicted to be low-cost option compared to transferring to the use of LSFO in the long run. The adaptation of scrubbers also lowered the risks considering the availability of fuel, and it was seen as more secure option. The example of scrubbers may be similar to what may happen with adaptation of carbon capture in maritime sector. Even as low-carbon fuels are on the rise, and are seen as a promising option to lower the emissions of the maritime sector, the availability of these fuels may become prerequisite and thus push the adaptation and development of carbon capture, since it is not dependent on the availability of fuel.

Interview 3 (2025) brought up similar issues as stated earlier, both in Interview 2 and literature. Available space onboard was seen as the most challenging aspect of applying carbon capture in the maritime sector on existing fleet as a retrofit, mostly regarding the required storage capacity for captured CO₂. It was also noted that applying new technologies onboard, such as carbon capture, require training of crew. Training includes proper safety, operating procedures, fault finding and maintenance of these systems. Required training and qualifications for personnel may increase the overall investment cost of capture systems.

When it comes to amount of carbon captured from ships, it was argued that the current technology is still in its infancy, which means that amount of carbon captured is still very marginal compared to the amount of carbon emissions ships produce with current fuels. Also the amount of carbon emissions is heavily dependent on the fuel ship uses and how and where it is operating.

4.4 Carbon utilisation

As stated earlier, CO₂ can be utilised in various processes and products. Most comprehensive answers to question, what are economical prospects for carbon captured from maritime sector, were given in Interview 2 (2025). They pointed out that the possibility of utilisation is linked to the form the carbon is captured and stored onboard, which in turn may determine where and how it can be utilised. If carbon is stored in sodium carbonate, carbon can be released and used for example in glass production or in the production of washing agents. As for carbon stored in calcium carbonate, it can be utilised in concrete production, which in turn is one of the most polluting industries globally. These simple examples show how carbon capture and utilisation can be used not only to decarbonize the maritime sector, but also used to reduce emissions on other industries as well. However, as tempting as CO₂ utilisation sounds, a regulative aspect needs to be taken into account. Concerns of the utilisation of captured CO₂ were raised in Interview 2 (2025), which regarded the regulations. It is yet to be determined how the source of CO₂ affects the possibilities of the utilisation and how captured CO₂ can be utilised. It was also speculated, that if regulations allow the shipowner to cut their monetary expenses with carbon capture, and they are allowed to sell the CO₂, meaning economical profit, a large and rapid growth in market for capture systems may become evident. It was argued that the future of carbon capture in maritime sector is strongly linked to regulations and legislation posed by IMO, EU and other governmental bodies.

5 Conclusions

Research questions for this thesis were:

- What are the possible techniques to capture CO₂ on ship that uses e-methanol as a fuel, and what is the technical and economical implementation of these techniques?
- How captured CO₂ is stored on ships in economically efficient way?
- How the logistics from the ship to e-methanol production facility are implemented?
- Is there economical potential in maritime sector to re-circulate captured CO₂ to e-methanol production facility?

During the writing of this thesis, a lot of emphasis was put on the properties and applications of e-methanol as a fuel in the maritime sector, which caused writing process and final content to be focused a lot on e-methanol. However, it was necessary to understand the well-to-wake fundamentals of e-methanol in order to find the link between different emissions produced by ships fuelled by e-methanol and technically and economically efficient ways to implement onboard carbon capture and storage.

To answer the question, what are possible techniques to capture CO₂ on ships using e-methanol as a fuel, short and simple answer would be, that it depends on the need of the owner or operator of the ship. Each of the carbon capture methods can be technologically applied in the maritime sector, but at the same time, each have their own advantages and disadvantages. The choice of capture method depends significantly on the available space onboard, required storage capacity for captured CO₂ and energy requirements for the capture and storage system. With information gained from literature and interviews, post-combustion capture seems to be the most applicable of the capture methods at the moment, due its maturity and successful applications in land-based facilities. It should be noted, that advancements in research and development may result in increased efficiency of all the capture methods. The amount of

carbon emissions is linked to fuel consumption of different vessels, and this obviously depends on the fuel that is used and the operating profile of the ships.

In global shipping, distances travelled by ships are long, and consumption of fuel is high resulting in high carbon emissions on ships using conventional fuels. This brings us to the second question, how captured CO₂ is stored on ships in economically efficient way. Again, a simple answer is almost impossible to find. The form in which captured CO₂ is stored has significant impact on the space required for storage capacity. As CO₂ can be stored in either gaseous, liquid or solid form, the size of the ship and available space dictate the possibility to implement the most suitable method of storage. Applying carbon capture in existing vessels is indeed an efficient way to reduce the carbon emissions of the maritime sector before alternative fuels, such as e-methanol and e-ammonia, are sufficiently available globally, but with high accumulation of CO₂ during long voyages the needed space to store captured CO₂ becomes another challenge to be solved. This may lead to the loss of cargo space resulting in losses in revenue, which in turn may not be seen as a feasible solution in the eyes of the owners and operators of ships. Due to this, it may be more sensible to first implement carbon capture on ships that operate regular and relatively short routes, where different technologies can be piloted to find out the best practices to be implemented in the maritime sector. One way to combat the accumulation of captured CO₂ is adaptation of low-carbon fuels such as e-methanol. Adapting e-methanol as a fuel brings another set of challenges, such as shorter range due to the lower energy content of e-methanol resulting in need of increased fuel storage capacity compared to conventional fuels such as diesel oils.

Logistical aspects of captured CO₂ are linked with the form it is stored in the first place. Depending on the form, captured CO₂ can be transported via trucks, pipelines or even train carriages to desired destination. For small quantities over short distances truck or trains may be economic, but for larger quantities, such as megatonnes per year, pipelines and ships are predicted to be most cost effective and efficient. If CO₂ is expected to be utilised in e-methanol production, and production facility is near the port where CO₂ is off-loaded, transportation

with direct pipeline to production facility might prove to be most economic and efficient form of transport.

To mitigate the loss of revenue caused by lost cargo space to accommodate carbon storage onboard, possibility to utilise captured carbon dioxide may prove to be one way to increase the willingness to invest in these technologies. If sufficient fees on carbon emissions are imposed, and some sort of support mechanisms are put in place for those who invest in carbon capture, we may see increase in investments and faster development of these technologies. Combined with possibility to sell captured CO₂ to be utilised either in production of e-methanol, or other industrial processes where CO₂ is used as a feedstock, interest via economical gain may speed up the adaptation of these technologies. However, to be fully able to utilise the possibilities of carbon capture and e-methanol, green corridors in maritime sector should be established. Within these corridors, ships are able to have sufficient source of carbon-neutral fuels and ships are able to off-load captured CO₂ to be transported for utilisation. To be able to establish these green corridors, there must be demand for carbon-neutral fuels in the maritime sector. More and more ships that are able to utilise carbon-neutral fuels such as e-methanol are ordered and built, suggesting that steps towards carbon-neutral shipping are taken. Combined with growing number of projects aimed to establish e-methanol production facilities, a clear correlation with demand and supply can be seen.

In the mid- and long-term, solutions to lower the emissions of maritime sector can be seen to be some sort of combination of alternative fuels, dual-fuel technology and carbon capture. Adapting only one method to lower the emissions of the vessel may not be reasonable due to the long distances that dominate global shipping. As it has been stated before, using e-methanol as a fuel instead of conventional fuels brings up the problem with the amount of fuel needed to replace these conventional fuels, affecting the range ships can travel between bunkering. In existing fleet, the use of space is often optimized to the maximum, and fitting new fuel tanks to accommodate the need for extra fuel may not be an option, since it would mean that cargo space is lost, resulting in

losses in revenue. Some ideas of utilising double-hulls as a fuel storage for ships using e-methanol were presented, but such ideas require further research on the effects on the stability and overall performance of the ships.

To decarbonize maritime sector is not easy or simple task. While technologies may be ready for e-methanol and carbon capture to be applied on ships, high investment costs and uncertainties regarding regulations and future prices of e-methanol hold back the wide implementation of these technologies. Considering the willingness of most European countries, such as Nordic countries, to invest in projects that promote the shift towards decarbonization, environmentally friendly fuels and energy production, Baltic Sea could possibly prove to be a great pilot area regarding the creation of maritime green corridors due to relatively short distances compared to ocean-crossing shipping.

To consider further research, few things that should be investigated more rise up. One possible topic would be to conduct more in-depth study how the problems with fuel capacity and range, when switching from conventional fuels to e-fuels, should be tackled without compromising cargo or passenger capacity. Also deeper techno-economical assessment of what kind of effects the shift from conventional fuels to methanol or e-methanol and the implementation of onboard carbon capture have regarding the emission trading system and how emission fees are regulated if captured carbon is recycled. Another topic, which would complement this study and bring depth to it, would be to research how the source of captured CO₂ affects and limits the possibilities for CO₂ utilisation, and what are the regulations regarding the source of CO₂.

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