University of
South-Eastern Norway

A Sustainable Methanol Ship Fuel Supply Chain for the Maritime Industry: Developing a Framework through a Systematic Litterature Review

Exploring the Technological, Economic, and Regulatory Challenges for a Sustainable Methanol Ship Fuel Supply Chain (SMSFSC)

Candidate name: Camilla Olufsen

University of South-East Norway
Faculty of Technology, Natural Sciences and Maritime Sciences

MASTER THESIS

May 2023

Abstract

The maritime industry faces increasing pressure to reduce greenhouse gas emissions and adopt sustainable fuel alternatives. Methanol has emerged as a promising candidate due to its low emissions profile, compatibility with existing infrastructure, and potential for carbon-neutral production. This thesis aims to develop a conceptual framework for a sustainable methanol ship fuel supply chain (SMSFSC) by conducting a systematic litterature review. The focus is on the well-to-tank supply chain, encompassing sustainable methanol production, transport, storage, and bunkering.

This review reveals that there are various methods for producing methanol from sustainable sources, and that the choice of production method depends on factors such as cost of feedstock and resource availability. Methanol transport and storage are found to be possible to integrate into existing infrastructure, with modifications where needed to accommodate methanol. This includes the development of bunkering facilities and the retrofitting of existing systems.

By synthesizing the existing research, a coherent overview of a sustainable methanol ship fuel supply chain (SMSFSC) is provided, highlighting the importance of considering factors such as feedstock availability and energy efficiency when constructing or adapting supply chains to facilitate the use of methanol as a ship fuel. A conceptual framework for developing a sustainable methanol ship fuel supply chain is presented, developed from the findings of the review.

Acknowledgements

I would like to express my gratitude to the many people who have supported me throughout this process of researching and writing the thesis.

First and foremost, I would like to acknowledge the unwavering support of my family and friends. Especially my mother, Elisabeth Olufsen, for always being there to read through my work. I am also grateful to my boyfriend, Daniel Melvoll, for supporting me through the entire process, and giving insightful comments to the work.

I also want to thank my supervisor, Halvor Schøyen, for excellent ideas and suggestions, as well as availability and guidance. The library at the University of South-East Norway have also been a great help, so I am thankful for that. And at last, I am thankful to the university of South-East Norway for giving me the opportunity to write this thesis.

Table of Contents

List of Abbreviations

DME	Dimethyl ether
E-RWGS	Electrified reverse water gas shift
ESD	Electrostatic discharge
GHG	Greenhouse gas
IMO	International Maritime Organization
NG	Natural gas
PEME	Polymer electrolyte membrane electrolyser
SMSFSC	Sustainable methanol ship fuel supply chain
WGS	Water gas shift

List of Tables

List of Figures

1 Introduction

This chapter will provide an overview of the thesis topic, the aim of the thesis, as well as the research questions. An introduction to key terms such as methanol and supply chain will be given as well. The idea behind the conceptual framework is also presented, with an illustration of a simplified supply chain that is to be expanded later in the thesis.

1.1. Developing a Sustainable Methanol Ship Fuel Supply Chain (SMSFSC) for the Maritime Industry

The International Marine Organization (n.d.) (IMO) has established a policy framework that sets ambitious targets for the reduction of greenhouse gas (GHG) emissions from shipping. One of the primary objectives is to decrease annual GHG emissions by at least 50% compared to 2008 levels by 2050, with the aim of phasing out GHG emissions from shipping altogether. Achieving these goals necessitates the transition to low and zero-carbon fuels. Issues such as safety, regulation, pricing, infrastructural availability, lifecycle emissions, supply chain constraints, barriers to adoption are mentioned when considering different fuel options. With these in mind, methanol, among others, is proposed as a potential alternative for greener fuel (International Marine Organization, n.d.).

Traditional maritime supply chains have been heavily reliant on fossil fuels, with established infrastructure and processes catering to this demand. The transition to greener fuels, such as methanol, requires the development of new supply chains, or the retrofitting of existing ones (International Transport Forum, 2018). This thesis will explore the potential of a sustainable methanol ship fuel supply chain (SMSFSC) and propose solutions for constructing or adapting supply chains to accommodate it, from feedstock to bunkering. To this end, the thesis will examine existing literature and propose ideas and adjustments that can facilitate the incorporation of methanol in the maritime industry, in a greater scale than it is at present time.

1.2. Objectives and Scope of the Thesis

The primary objective of this thesis is to develop a conceptual framework for a sustainable methanol ship fuel supply chain (SMSFSC) by conducting a systematic review of the existing literature on the subject. The article by Seuring and Müller (2008) is the inspiration behind the conceptual framework, where they develop a framework for supply chain management based on the litterature review. The thesis will examine the entire process, from feedstock, sustainable methanol production, storage, and transport to the bunkering of fuel tanks on ships. By synthesizing the existing research, the thesis aims to provide a coherent and integrated overview of the methanol supply chain, from well-to-tank, and to use the information collected to develop a conceptual framework.

The scope of the thesis is intentionally focused on the supply chain from the point of feedstock to methanol production, and to its delivery as fuel, encompassing the transport to fuel pumps at ports and the transfer to ships. This focused approach serves to narrow down the topic and concentrate on the most pertinent aspects relevant to the commercial maritime management master´s program. By analyzing the various components of the supply chain, this thesis seeks to provide valuable insights and recommendations for the successful integration of methanol as a sustainable fuel source in the maritime industry, as well as identify potential gaps in the research to provide recommendations for further studies.

1.3. Research Questions

What are the key components in a conceptual framework for a sustainable methanol ship fuel supply chain (SMSFSC)?

Sub questions:

What are the critical factors and challenges in developing a sustainable methanol ship fuel supply chain (SMSFSC) for the maritime industry?

What are the current and emerging technologies for sustainable production of methanol as ship fuel?

1.4. Structure of the Thesis

The introductory chapter provides an overview of the thesis topic and defines key terms such as methanol and supply chain. A base for a conceptual framework is presented, which will be expanded later in the discussion chapter. The research methodology chapter presents the methodology used in the thesis, detailing the approach taken for the litterature review, as well as why a litterature review was chosen for this specific topic. In addition, the search strings for the litterature search and the selection process of publications for the review will be presented. Following this, the findings chapter outlines the results of the litterature review, along with a quality assessment and a thorough review of the findings related to the different parts of the supply chain. The discussion chapter offers a critical analysis of these findings, discussing the different parts of the supply chain. At the end of the discussion, the conceptual framework for a sustainable methanol ship fuel supply chain (SMSFSC) is presented, where findings from the previous chapter have been used to develop a coherent framework. The thesis concludes with answers to the research questions, and its implications for theory and practice.

1.5. Methanol and its Structure, Production Pathways, and Environmental Aspects

Methanol is the simplest alcohol, comprised of four parts hydrogen, one part oxygen, and one part carbon. The chemical representation is CH3OH. The clear, water-soluble liquid is biodegradable. Methanol is extensively employed across various industries. Its application ranges from being an essential component in the production of plastics, paints, and cosmetics to serving as a clean-burning, biodegradable fuel (Methanol Institute, u.a. -a).

Predominantly produced from natural gas, methanol is versatile in its production pathways. Alternative production methods include the utilization of renewable feedstocks such as waste, sewage, renewable electricity and captured carbon dioxide (Methanol Institute, u.a. -a). Feedstock is defined by Merriam-Webster (2023) as the raw material supplied. When methanol is produced with renewable feedstocks, the greenhouse gas (GHG) emissions is significantly reduced (Methanol Institute, u.a. -a). Renewable methanol cuts carbon dioxide emissions by up to 95%, reduces nitrogen oxide emissions by up to 80%, and sulfur oxide and particulate matter emissions are eliminated (Methanol Institute, u.a. -c).

There are different types of methanol. The different types are based on how the methanol is produced, and with what resources. Below is a table that shows the different names, what the source is to make the methanol and the environmental aspect to the specific type of methanol, with information found at Bureau Veritas (2022).

Name	**Source**	**Environmental aspect**
Brown methanol	Coal	High well-to-tank CO_2 emissions
Grey methanol	Natural gas	High well-to-tank CO_2 emissions
Blue methanol	Blue hydrogen in combination with captured carbon dioxide	Significantly lower CO_2 emissions
Green methanol		Considered to reach carbon neutrality
	Bio-methanol	Biomass
	E-methanol	Green hydrogen, captured CO_2 and renewable electricity

Table 1: Types of methanol, their source, and the environmental aspect (Bureau Veritas, 2022).

1.6. A Simplified Methanol Supply Chain – From Production to Bunkering

A supply chain, as defined by Bozarth and Handfield (2019, p. 3), is a network of manufacturers and service providers. The network collaborates to create the products and services demanded by end users. These providers are linked through the physical flow of products or services, information flows, and monetary flows. Supply chain activities mostly revolves around the conversion, storage, and movement of materials and products when the primary focus is on physical goods (Bozarth & Handfield, 2019, p. 3).

For the purpose of this thesis, a simplified supply chain for methanol would include the key stages of feedstock, production, transport, storage, and bunkering, as well as loading and unloading before and after transport. The term “well-to-tank” is used to describe the steps required to produce and distribute a fuel. The starting point is the primary energy resource, with the last point refueling (HASS et al., 2014). This simplified version of the supply chain represents the well-to-tank part of the supply chain.

The initial step in this supply chain is the feedstock, followed by production. After production, methanol is stored before being transported to a port or terminal. Upon arrival at the port or terminal, the methanol is once again stored, before ships are bunkered. This simplified version of a potential methanol supply chain draws inspiration from the article by Al-Breiki and Bicer (2020) where an illustration of the methanol supply chain is presented. In the illustration, natural gas (NG) production, methanol production, loading, shipping, unloading and storage is presented with regards to the different energy requirements and boil-off gas (BOG) losses during the supply chain. However, to illustrate a more appropriate picture of the well-to-tank sustainable methanol ship fuel supply chain (SMSFSC) in this thesis, certain changes has been made.

Although this simplified supply chain highlights the most critical stages, it does not account for additional factors, such as different suppliers and distributors (Bozarth & Handfield, 2019, p. 3). Nonetheless, this simplified version is sufficient for the purpose of this thesis. The illustration of the simplified supply chain for sustainable methanol ship fuel is presented below. Horizontal arrows represent the flow of the supply chain and its direction. This illustration will later be expanded using the findings of the litterature review to present a conceptual framework, with the final illustration being presented in section 4.7.

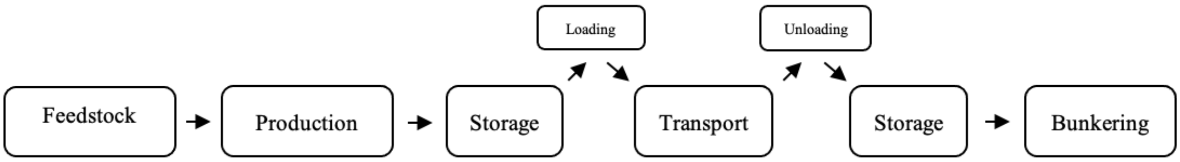

Figure 1: Simplified illustration of a supply chain for methanol, inspired by Al-Breiki and Bicer (2020).

2 Research Methodology

This chapter outlines the systematic litterature review process employed to explore the topic of the thesis. An introduction to litterature reviews will be done, emphasizing the importance of a systematic approach in this specific research. The chapter then details the strategy employed in information searches and databases used for the search are presented. The chapter further presents the search strings for the different databases and corresponding results, as well as initial criteria for eligibility. Additionally, it gives a detailed explanation of the selection process, and the secondary criteria for eligibility is presented. The chapter ends with a presentation of the quality assessment tool that will be used for the selected results, and ethical considerations associated with the thesis. As for the overall aim of the chapter, it is to provide a comprehensive, transparent, and replicable process for the litterature review, supporting the thesis´s research objectives.

2.1. General Introduction to Litterature Reviews

A litterature review is a systematic examination of research findings, theories and practices by scholars and researchers related to the topic in focus. It aims to present a critical, accurate and comprehensive understanding of the current state of knowledge on the subject matter, highlighting areas that require further investigation to advance the knowledge of the topic (Efron & Ravid, 2018). Litterature reviews are particularly valuable when the objective is to provide an overview of a specific issue, and are useful, as they are typically conducted as an evaluation of the state of knowledge on a specific topic (Snyder, 2019).

There are four different archetypes of litterature reviews according to Dekkers (2022). There are narrative overviews, narrative reviews, systematic literature reviews, and systematic reviews. Narrative overviews have a narrow scope of sources, with a subjective selection of information which can lead to a biased review and the potential for incomplete sources. Narrative reviews, while also subjective in the selection of information, they contain all key works on the topic. In contrast, systematic litterature reviews adheres to a pre-specified method where the litterature is collected, reviewed, and assessed. The rationale or review questions and the methods for data collection are prepared in advance to minimize bias. Systematic reviews are similar to systematic litterature reviews; however, their focus is on comparing studies for treatment, practices, etc. (Dekkers, 2022).

2.2. Systematic Litterature Reviews and the Employment of a Systematic Litterature Review to Explore Methanol as Fuel and its Potential Supply Chain

For the topic that will be researched in this thesis, a systematic litterature review appears to be the most appropriate method, as it is useful when assimilating information for a range of studies investigating the same topic. There is also a reduced likelihood of bias, compared to narrative reviews (Dekkers, 2022). As stated by Kitchenham and Charters (2007), the primary motivations for undertaking systematic litterature reviews include summarizing existing evidence, identifying gaps in current body of research, and providing a framework for new research activities. In the context of this thesis, the primary objective is to synthesize the available evidence pertaining to a sustainable methanol ship fuel supply chain.

When doing a systematic litterature review, the methods for source retrieval and data collection are predefined and will later guide the actual review process (Dekkers, 2022). The adoption of a systematic litterature review for this thesis is advantageous as it enables the identification of key factors, challenges, and potential solutions in the development of a sustainable methanol ship fuel supply chain, thereby contributing to a robust and nuanced understanding of the topic.

Consequently, the remainder of this chapter will provide the various preparations for the systematic litterature review, including aspects such as the search strategy, inclusion and exclusion criteria, data collection, and finally, the extraction of the data found. The aim is that by adhering to these methodological guidelines, the systematic litterature review will provide a solid foundation for the development of a comprehensive framework for a sustainable methanol ship fuel supply chain (SMSFSC) for the maritime industry.

2.3. Information Sources and Search Strategy

To identify suitable databases for the literature search, the list of available databases through the university of South-East Norway was examined. Furthermore, resources from the library at the university was consulted for additional guidance, leading to the selection of the following databases:

1. Scopus
2. EBSCO host, Academic and Business
3. Web of Science
4. IEEE Explore

These databases are all well-established, consistently updated, and provide a wide range of publications, many of whom are peer-reviewed. Additionally, they are available through the library of the University of South-East Norway. To ensure the discovery of as many relevant articles and publications as possible, all four databases were utilized. There is an expectation of overlap between these databases, however, duplicates will be removed throughout the process.

The search terms used in the searches were found by listing keywords used in different articles relevant to the topic of a sustainable methanol ship fuel supply chain (SMSFSC), as well as relevant terms. The term "methanol" was a matter of course, as well as terms relating methanol to the maritime and supply chain. The term supply chain gave a very limited number of results, and it was decided to add the various parts of the supply chain such as production, transport, and storage. To increase the chances of finding the largest number of relevant results, synonyms were added to the search string and tested by doing searches in the different databases. After this process, the final search strings were developed with the assistance of the library at USN Vestfold.

With guidance from the library at USN Vestfold, it was determined that the first part of the search string was methanol. The second part was related to the maritime aspect, and the terms added were maritim*, marin*, ship*, boat* or naval. The "*" behind is to include all terms that start with the word before the "*". The idea was that this would give the relevant results related to a maritime industry supply chain for methanol fuel. The third, and last, part was relevant to the supply chain part of the search. Transport*, production, distribution, storage “supply chain” and “value chain” were the terms used in this part of the search string. This was an aim to cover all the supply chain aspects of the search. The final search strings are presented in the table below.

Database	**Search string**	**Results**
Scopus	(KEY (methanol) AND TITLE-ABS-KEY (maritim* OR marin* OR ship* OR boat* OR naval) AND TITLE-ABS-KEY (transport* OR production OR distribution OR storage OR "supply chain" OR "value chain"))	473
EBSCO host, Academic and Business	(SU methanol AND maritim* OR marin* OR ship* OR boat* OR naval AND transport* OR production OR distribution OR storage OR "supply chain" OR "value chain")	280
Web of Science	(methanol (Topic) AND transport* OR production OR distribution OR storage OR "supply chain" OR "value chain" (All Fields) AND maritim* OR marin* OR ship* OR boat* OR naval (All Fields))	1597
IEEE Explore	(methanol) AND (((maritim* OR marin* OR ship* OR boat* OR naval)) AND (transport* OR production OR distribution OR storage OR “supply chain” OR “value chain”))	18
Total		2367

Table 2: Search strings and results in four databases.

The search was conducted on February 13th across all databases, except for IEEE Explore, where the search was performed on March 14th. The different dates for the searches were due to a reconsideration of the importance of the few results from the IEEE Explore database, as there were only 18 results when the search was done. The initial searches yielded a total of 2,368 results across all four of the databases. Subsequently, the search results were refined according to the inclusion and exclusion criteria specified in the following section to reduce the number of results, with the aim of keeping the relevant results.

2.4. Criteria for Eligibility and the Searches in the Various Databases

This section will provide insight into the initial inclusion and exclusion criteria, as well as the performed searches in the databases presented in the previous section.

2.4.1. Initial Inclusion and Exclusion Criteria for Eligibility

The initial inclusion and exclusion criteria were applied during the search in the different databases. Further inclusion and exclusion criteria will be presented in section 2.6.1.

Initial criteria for inclusion:

- Published in the English language
- Published after 2011
- Relevant to the topic of a methanol supply chain
- Methanol is used in the context of the thesis

Initial exclusion criteria:

- Published in other languages than English
- Published before 2012
- Not relevant to the topic of a methanol supply chain

- Methanol is used for purposes not relevant to the thesis

The initial inclusion and exclusion criteria refer to the database searches. Limitations regarding the publication language and publication years were applied during the search. The reason behind limiting to publications from 2012 onwards is that it appeared most publications relevant to the topic of a sustainable methanol ship fuel supply chain (SMSFSC) were published during this time frame. This observation was corroborated by examining publications published before 2012. After these limitations, the search results were further refined using various exclusion methods across the four databases. The following section provide a detailed account of the limitations and exclusions applied to each database.

2.5. The Limitations end Exclusions Done in the Searches in each of the Four Databases

Scopus database: After limiting the results to English language publications, the number of results were 459. To exclude results that were not relevant to methanol within the scope of the thesis, the following subject areas were excluded: immunology and microbiology, pharmacology, toxicology and pharmaceutics, and medicine. Prior to their exclusion, the results within the excluded subject areas were briefly reviewed, sorted by relevance, to ensure no relevant subject areas were excluded. Following this exclusion, 325 results remained.

The same exclusion process was applied to keywords, leading to the exclusion of the keywords unclassified drug, algae, animals, and animal. The results were reviewed similarly to the review for subject areas, resulting in 229 remining articles. To further refine the search and obtain the most current results, the time window was set to after 2011, providing results from 2012 until present time. The remaining results after applying the time limit were 159. These results were examined by assessing both titles and abstracts, with relevant results imported to EndNote. The number of imported results to EndNote were 78.

EBSCO host, Academic and Business databases: In this database, fewer results were obtained, 278 results remained after limiting the search to English language publications. As the process of adding limitations and exclusions was not as straightforward in this database than in the other databases, the next limitation applied was the publication year limit. After excluding results published before 2012, 208 results remained. Given the diverse subjects represented in these results, excluding specific subjects was deemed more time-consuming than reviewing titles and abstracts. Consequently, 85 results relevant to the thesis were exported to EndNote after eliminating unrelated articles.

Web of Science database: After limiting to English language only, the search yielded 1584 results, the highest number in any of the databases. The exclusion process in this search was therefore the most extensive. The exclusion sequence is described in the table below.

Exclusion area	Terms	Results
Categories	food science technology, microbiology, pharmacology pharmacy, meteorology atmospheric sciences, nanoscience, nanotechnology, toxicology, nutrition dietetics, veterinary sciences, physiology, reproductive biology, biotechnology applied microbiology, chemistry medicinal, agricultural engineering, nanoscience nanotechnology, biology, cell biology, genetics heredity	964
Research areas	biochemistry molecular biology, physics, geology, integrative complementary medicine, parasitology, agriculture, nuclear science technology, tropical medicine, legal medicine, polymer science, geology, fisheries, oceanography	800
Citation topics	marine biology, herbicides, pesticides and ground poisoning, mycotoxins, applied physics, phytochemicals, plasma physics, microbial biotechnology, bacteriology, molecular & cell biology, drug delivery chemistry, bioengineering, inorganic and nuclear chemistry, paper & wood materials science	577

Table 3: Categories, research areas, and citation topics removed excluded from the search.

Upon limiting the results to after 2011, a total of 491 results were obtained. Given the substantial number of results, the method of exclusion was deemed insufficient in the Web of

Science database. A review of the remaining categories revealed numerous irrelevant categories, prompting the decision to refine the search based on specific categories rather than exclusion. The search was refined using the following categories: energy fuels, green sustainable science technology, environmental sciences, thermodynamics, transportation, environmental studies, transportation science technology. With this refinement, the results remaining were 277. This gave fewer results, which was more manageable. After carefully reviewing titles and abstracts, 87 results were deemed relevant and exported to EndNote.

IEEE Explore: In this database, only 18 results were obtained, rendering the exclusion steps done in the other databases unnecessary. Instead, a thorough examination of the titles and abstracts was conducted. The language and publishing years of the results were also evaluated. Four publications were found to be conforming to the initial inclusion criteria and subsequently exported to EndNote.

2.6. Selection Process of the Publications Exported to EndNote

The total number of exported publications to EndNote was 254. EndNote is a reference management tool. Some of the benefits of using EndNote is that it can be connected to Microsoft Word, and one can insert citations directly into Microsoft Word, and it is helpful to organize the references. By using this tool, references can be imported directly from the database used for the search, and limited time is used on writing the references manually (EndNote, n.d.). The reason behind exporting the references to EndNote at this time is that the program can remove duplicates, instead of doing this one by one as well as sorting the references. The links to the different publications as well as the entire abstract is also imported to the program, which makes it easier to go through all the publications in one program instead of four different databases in this case (EndNote, n.d.).

2.6.1. Secondary Criteria for Inclusion and Exclusion

The articles exported to EndNote adhered to the initial inclusion criteria, however, the relevance had to be assessed in a narrower term than the initial scan through of the titles and abstracts. Full texts were obtained directly from the links provided in EndNote and reviewed.

The secondary inclusion and exclusion criteria were established to evaluate the results more rigorously.

Firstly, duplicate results needed to be addressed. If two or more identical results were exported from different databases, the additional results had to be removed. Additionally, full texts had to be accessible through the university library, as no funding was available for this thesis, purchasing access was not an option. For a more focused evaluation of relevance, each article needed to discuss at least one aspect of the supply chain. This could be either feedstock, production, transport, storage, or bunkering. The secondary inclusion and exclusion criteria, as outlined below, facilitated a more comprehensive appraisal of the results´ relevance to the topic of the sustainable methanol ship fuel supply chain (SMSFSC).

Secondary criteria for inclusion:

- Non-duplicate publications
- Full text available through the university of South-East Norway´s library
- One or more parts of the SMSFSC is presented in the publication

Secondary exclusion criteria:

- Duplicate publications
- Full text not available through the university of South-East Norway´s library
- No direct relevance to the SMSFSC in the publication

The initial step following the exportation to EndNote involved removing duplicates, resulting in the elimination of 81 publications with 173 publications remaining. Out of the 173 publications: 28 of these publications were not available through the University of South-East Norway. Most of these were found through the database EBSCO Host. One publication was retracted and therefore removed. As for relevance, 21 publications were directly related to the tank-to-wake part of the supply chain and therefore not relevant to this thesis. The 124 other publications that were excluded because of relevance did not include any relevant information or findings regarding the supply chain of methanol as fuel for the maritime industry and were therefore removed. The exclusion process and exclusion reasons are presented in the figures 2 and 3 below.

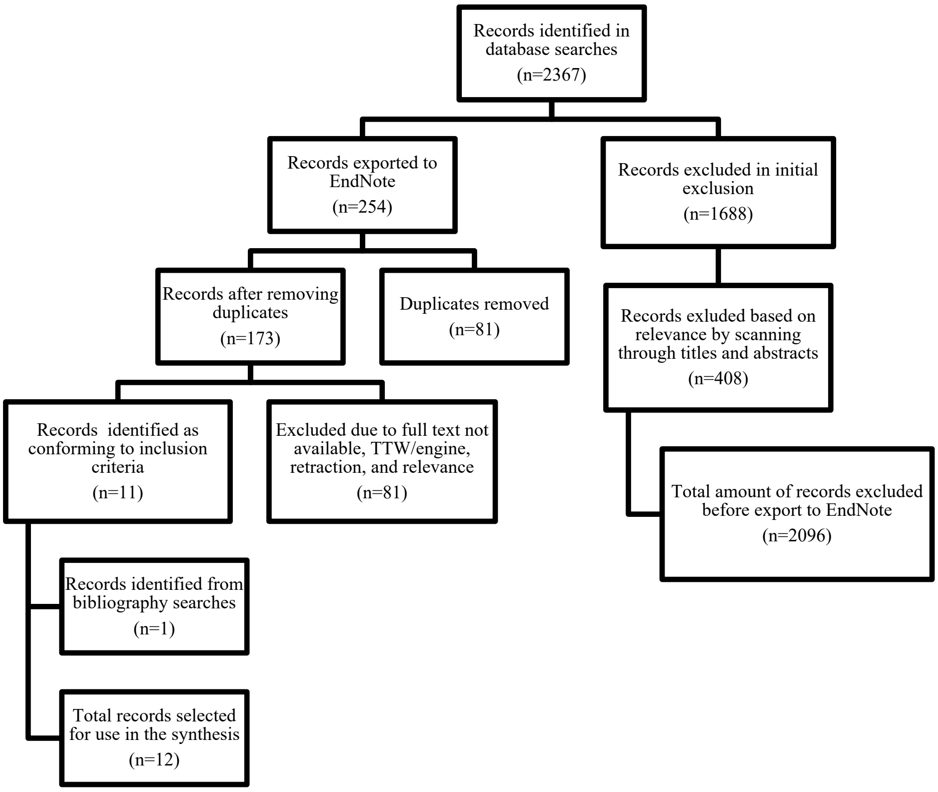

Figure 2: Flow chart of the selection process of records.

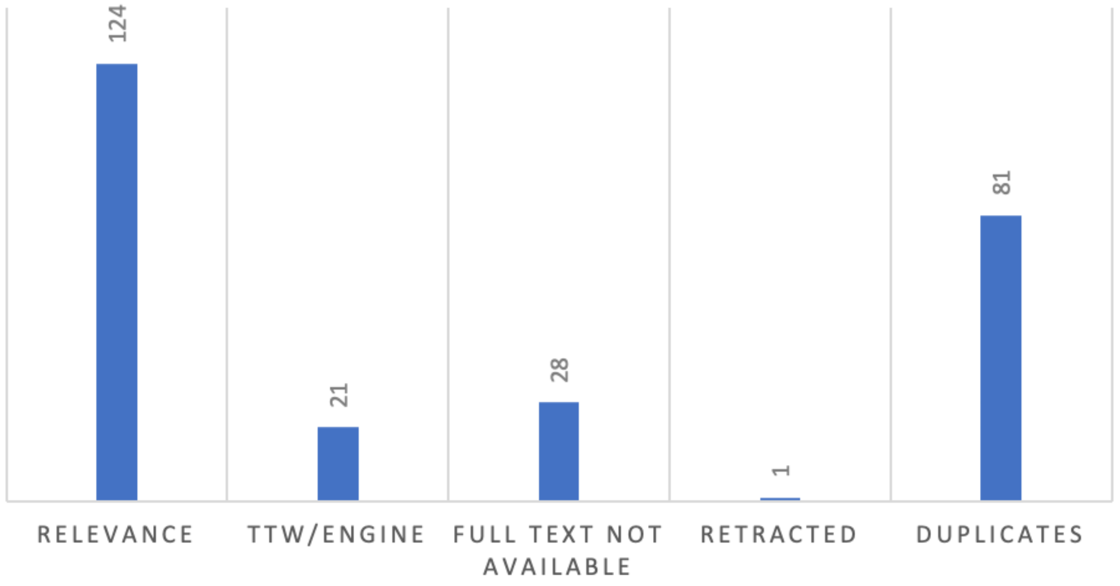

Figure 3: Reasons for exclusion.

2.7. Quality Assessments

To evaluate the methodological quality of the results selected for use in the synthesis, a set of questions utilized by Gillman & Pillay (2018), as cited in Dreyer (2018). These questions were adapted from the Critical Appraisal Skills Programme (n.d.). The original article by Gillman & Pillay was attempted to be found, however, after consultation with the library of the University of South-East Norway it was deemed not available. The screening questions will be presented in the table on the next page.

Screening questions		
1.	Aim/s:	Was the aim of the research clear?
2.	Method:	Was the research methodology used appropriate?
3.	Design:	Did the study design address the aims of the research?
4.	Data:	Did the data collected address the research aim?
5.	Data analysis:	Was the data analysis sufficiently rigorous?
6.	Bias:	Was any bias considered adequately?
7.	Findings:	Are the findings clearly stated?
8.	Gap/s:	Have gaps in the literature been clearly identified?
9.	Acceptance:	Can I accept the findings as true?
10.	Value:	Can I apply these findings to my own work?

Table 4: Critical appraisal questions, from Gillman & Pillay (2018), as cited in Dreyer (2018).

These questions will aid in whether the results are valid, based on a total quality percentage. The answers are either “Yes”, “Limited”, or “No/Not applicable”. With a “Yes” answer, the quality percentage will increase by 10%, with “Limited”, a 5% increase, and a “No/Not applicable” will not change the percentage. The summary and percentages will be presented in section 3.3.

2.8. Ethical Considerations

Elsevier (n.d.-b) states that the ethics topics to consider is the following: authorship of the paper, originality and plagiarism, data access and retention, multiple, redundant, or concurrent publication, acknowledgement of sources, disclosure of conflicts of interest, fundamental errors in published works, reporting standards, hazards and human or animal subjects, use of patient images or details.

Authorship of the paper: The authorship should be limited to those with significant contributions to the conception, design, execution, or interpretation of the study. Transparency is encouraged, and a CRediT (Contributor Roles Taxonomy) author statement can be used. This offers the opportunity for authors to share accurate and detailed descriptions of the contributions to the work (Elsevier, n.d.-a, n.d.-b).

Camilla Olufsen: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing original draft and review and editing, visualization, and project administration. **Halvor Schøyen:** Supervision and project administration.

Originality and plagiarism: All work done by others used in this paper is cited and can be viewed in the reference list at the end of the paper.

Data access and retention: The paper is a litterature review, and all publications used have been assessed for quality.

Multiple, redundant, or concurrent publication: This paper is a master thesis, and as of now, there is no plan to publish in one or more journals or publications. It will be published within the university archive, USN Open Archive, solely.

Acknowledgement of sources: All work done by others has been cited, with in-text citations and full reference in the reference list.

Disclosure of conflicts of interest: There is no relationships that can be viewed as potential conflicts of interest.

Fundamental errors in published works: If fundamental errors are found in this paper after publication in the USN Open Archive, the university of South-East Norway will be contacted for retraction or change of the thesis.

Reporting standards: The methodology of this thesis is thoroughly described earlier in this chapter, specifically section 2.2.-2.6.

Hazards and human or animal subjects: There has not been done any research in this thesis that involves hazards or human or animal subjects.

Use of patient images or details: There is no use of patients in this thesis, and therefore no patient images or case details.

3 Findings

This chapter will present the results and findings from the data collection described in the previous chapter. Results from the database searches will be presented with the use of tables, figures and describing text. The quality assessment tool presented in chapter 2, section 2.7., will be applied to the selected publications, and the results of the quality assessment will be presented. The findings will be separated into the different parts of the simplified supply chain, and this process will be explained. The different parts of the supply chain are feedstock, production, storage, transport, and bunkering, and production will be split into production methods and production costs. The different parts will then be presented separately.

3.1. The Process of Data Extraction

The data extracted from the results gathered included author(s), year published, title, journal or publisher, country, research design, and the findings in the results relevant to the supply chain of methanol. The extraction was done manually and independently by the author of this thesis.

3.1.1. Results

The following table will present the authors of the publications selected, along with the publishing year and the title of the publication.

Author(s)	Year	Title
A. De La Garza	2022	Waiting for the Green Ship to Come in
C. Chatterton	2019	Methanol as a vessel fuel & energy carrier
D. Connolly, B. V. Mathiesen, I. Ridjan	2014	A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system
D. Conti, F. Harahap, S. Silveira, A. Santasalo-Aarnio	2019	A techno-economic assessment for optimizing methanol production for maritime transport in Sweden
F. Schorn, J. L. Breuer, R. C. Samsun, T. Schnorbus, B. Heuser, R. Peters, D. Stolten	2021	Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations
G. Dolan	2015	Methanol takes on LNG for future marine fuels
J. A. Martens, A. Bogaerts, N. De Kimpe, P. A. Jacobs, G. B. Marin, K. Rabaey, M. Saeys, S. Verhelst	2017	The Chemical Route to a Carbon dioxide Neutral World
L. E. Basini, F. Furesi, M. Baumgartl, N. Mondelli, G. Pauletto	2022	CO_2 capture and utilization (CCU) by integrating water electrolysis, electrified reverse water gas shift (E-RWGS) and methanol synthesis
M. Bukhtiyarova, T. Lunkenbein, K. Kähler, R. Schlögl	2017	Methanol Synthesis from Industrial carbon dioxide Sources: A Contribution to Chemical Energy Conversion
M. Svanberg, J. Ellis, J. Lundgren, I. Landälv	2018	Renewable methanol as fuel for the shipping industry

M. Al-Breiki, Y. Bicer	2020	Technical assessment of liquefied natural gas, ammonia, and methanol for overseas energy transport based on energy ad exergy analyses
S. Perathoner, K. M. V. Geem, G. B. Marin, G. Centi	2021	Reuse of carbon dioxide in energy intensive process industries

Table 5: Summary of the studies included in the litterature review.

3.1.2. Uptake in Relevant Publications in Later Years

Upon examining the bar chart below, which displays the number of publications per year, it becomes apparent that more recent years exhibit a higher concentration of relevant results. This observation suggests a potential upward trend in the publication of relevant publications pertaining to the use of methanol as fuel in the maritime industry. Although the gathered data is insufficient to draw definitive conclusions, it can be hypothesized that the growing interest in methanol as a bunkering fuel for the maritime industry has led to an expansion of research within this field of research and related topics.

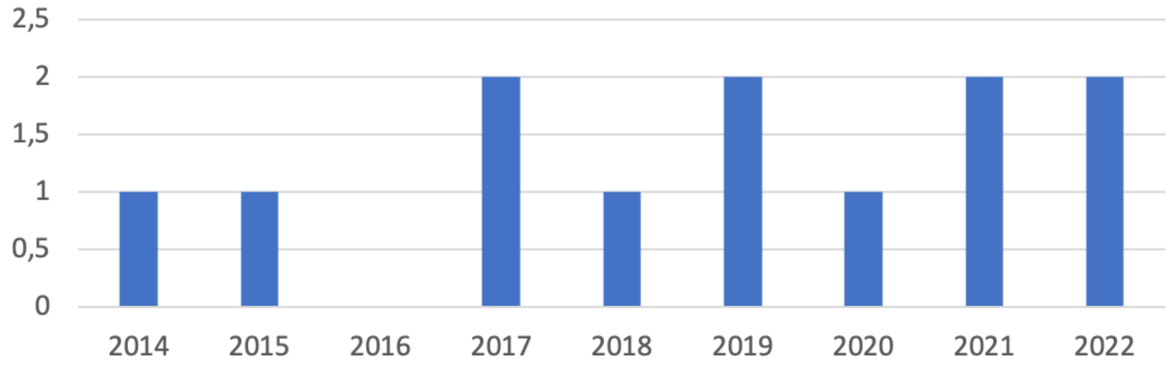

Figure 4: Number of papers selected published each year.

3.2. Study Characteristics

The following table provides an overview of the characteristics of the results from the data collection. The data included is author, year, country, and the findings of the papers. The findings that are extracted are the findings that are directly related to the topic of a sustainable methanol ship fuel supply chain (SMSFSC) for the maritime industry. Other findings deemed irrelevant to the topic of the thesis in the publications selected are not included.

Study	Country	Design	Journal	Relevant Findings
A. De La Garza, (2022)	USA	News article	Time International (South Pacific Edition)	Methanol, a carbon-based fuel, can be produced sustainably by using biogenic carbon sources like biomass or carbon dioxide. Direct air capture is expensive and energy intensive, making biogenic carbon the current best option. Although there may be a future shortage of biogenic carbon dioxide, Maersk believes there is enough biomass to support methanol-powered ships for now.
C. Chatterton, (2019)	Unknown	Forum proceedings	International tanker technical forum	Chatterton discusses the safety and operational requirements for bunkering methanol-fueled ships. He covers the design and setup of refueling stations and outlines the necessary features of refueling systems.
D. Connolly, B. V. Mathiesen, I. Ridjan, (2014)	Denmark	Exploratory	Energy	Methanol production can be done by bioenergy hydrogenation and fermentation and CO_2Hydro and co-electrolysis. In the maritime industry, methanol/DME is an attractive liquid fuel due to its energy density and low infrastructure adjustment costs. While bioenergy hydrogenation and fermentation are initially more efficient CO_2Hydro and co-electrolysis may become the preferred method as electricity production costs decrease and bioenergy resources become limited.

Study	Country	Design	Journal	Relevant Findings
D. Conti, F. Harahap, S. Silveira, A. Santasalo-Aarnio, (2019)	Sweden	Case study	ECOS	The paper states that biomass costs significantly impact methanol production costs, accounting for roughly 50% of final cost. Increasing plant conversion efficiency could reduce methanol production costs, and transporting methanol instead of biomass is more cost-effective.
F. Schorn, J. L. Breuer, R. C. Samsun, T. Schnorbus, B. Heuser, R. Peters, D. Stolten, (2021)	Germany	Simulation study	Advances in Applied Energy	The paper examines hydrogen-based methanol as a renewable energy carrier, emphasizing its potential advantages. They find that methanol production costs rely on hydrogen and carbon dioxide expensed, but with decreasing costs and supportive policies, green methanol could become competitive.
G. Dolan, (2015)	Unknown	News article	Hydrocarbon Processing	Methanol is gaining interest as an alternative marine fuel due to its potential to reduce emissions. To meet the demand of methanol, there is an overhang of 20 to 40 MMton to meet marine fuel demand.

Study	Country	Design	Journal	Relevant Findings
J. A. Martens, A. Bogaerts, N. De Kimpe, P. A. Jacobs, G. B. Marin, K. Rabaey, M. Saeys, S. Verhelst, (2017)	Germany	Review	Chemsuschem	Capturing carbon dioxide from point sources and converting it into useful chemicals is a high priority as it accounts for around 50% of global CO_2 emissions. Existing large-scale catalytic technology for methanol production can be applied with some re-engineering, while other techniques, such as electrocatalysis and biocatalysis, are still being explored and not yet commercially available.
L. E. Basini, F. Furesi, M. Baumgartl, N. Mondelli, G. Pauletto, (2022)	Germany	Simulation study	Journal of Cleaner Production	The paper presents an innovative process for producing methanol using residual carbon dioxide from a biogas plant combined with hydrogen from a PEM electrolyser. The process involves an E-RWGS step and a downstream methanol synthesis, which results in over 90% energy efficiency. By converting carbon dioxide from biogas plants, the process achieves negative carbon dioxide emissions due to the renewable nature of the feedstock.
M. Bukhtiyarova, T. Lunkenbein, K. Kähler, R. Schlögl, (2017)	Germany	Experimental	Catal Lett	The paper studied the carbon dioxide hydrogenation route for methanol production to find optimal conditions. They investigated the influence of temperature, space velocity, and the presence of benzene in the gas feed mixture on catalytic performance. Findings suggest that exhaust gases from steel mills is an alternative carbon source for methanol production.

Study	Country	Design	Journal	Relevant Findings
M. Svanberg, J. Ellis, J. Lundgren, I. Landälv, (2018)	Sweden	Review	Renewable and Sustainable Energy Reviews	The review found renewable methanol from biomass as a technically viable option for the shipping industry, with no major challenges in the supply chain, except for economic barriers. The transition to renewable methanol can be facilitated by using fossil feedstock as a complement.
M. Al-Breiki, Y. Bicer, (2020)	Qatar	Comparative case study	International Journal of Hydrogen Energy	The paper found that low BOG losses make methanol suitable for long overseas transport, as it loses only a small amount of its mass during the supply chain. Most BOG losses occur during loading, unloading, some during shipping, and land storage significantly less.
S. Perathoner, K. M. V. Geem, G. B. Marin, G. Centi, (2021)	Unknown	Review	Chemical Communications	The paper highlights low technology readiness as a major hurdle for decarbonizing energy-intensive industries such as iron and steel, cement, refineries, petrochemistry, and fertilizers. Transforming carbon dioxide to carbon monoxide via WGS reaction is crucial, as it opens various bio-chemical and catalytic conversion routes in the steel and chemical sectors.

Table 6: Overview of selected papers.

3.3. Quality Assessments

Based on the questions presented in section 2.8., the following table presents the answers to the questions for each of the selected articles.

Publication	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**
Waiting for the Green Ship to Come in, (A. De La Garza, 2022)	**Y**	**N**	**N**	**Y**	**N**	**N**	**Y**	**N**	**L**	**Y**
Methanol as a vessel fuel & energy carrier, (C. Chatterton, 2019)	**Y**	**N**	**N**	**Y**	**N**	**N**	**Y**	**N**	**L**	**Y**
A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system, (D. Connolly, B. V. Mathiesen, I. Ridjan, 2014)	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**L**	**Y**	**Y**
A techno-economic assessment for optimizing methanol production for maritime transport in Sweden, (D. Conti, F. Harahap, S. Silveira, A. Santasalo-Aarnio, 2019)	**Y**	**Y**	**Y**	**Y**	**Y**	**L**	**Y**	**Y**	**Y**	**Y**
Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations, (F. Schorn, J. L. Breuer, R. C. Samsun, T. Schnorbus, B. Heuser, R. Peters, D. Stolten, 2021)	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**L**	**Y**	**Y**
Methanol takes on LNG for future marine fuels, (G. Dolan, 2015)	**Y**	**N**	**N**	**Y**	**N**	**N**	**Y**	**N**	**L**	**Y**
The Chemical Route to a Carbon dioxide Neutral World, (J. A. Martens, A. Bogaerts, N. De Kimpe, P. A. Jacobs, G. B. Marin, K. Rabaey, M. Saeys, S. Verhelst, 2017)	**Y**	**N**	**N**	**Y**	**Y**	**N**	**Y**	**L**	**Y**	**Y**

CO_2 capture and utilization (CCU) by integrating water electrolysis, electrified reverse water gas shift (E-RWGS) and methanol synthesis, (L. E. Basini, F. Furesi, M. Baumgartl, N. Mondelli, G. Pauletto, 2022)	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**L**	**Y**	**Y**
Methanol Synthesis from Industrial carbon dioxide Sources: A Contribution to Chemical Energy Conversion, (M. Bukhtiyarova, T. Lunkenbein, K. Kähler, R. Schlögl, 2017)	**Y**	**Y**	**Y**	**Y**	**Y**	**L**	**Y**	**L**	**Y**	**Y**
Renewable methanol as fuel for the shipping industry, (M. Svanberg, J. Ellis, J. Lundgren, I. Landälv, 2018)	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**Y**	**L**	**Y**	**Y**
Technical assessment of liquefied natural gas, ammonia, and methanol for overseas energy transport based on energy ad exergy analyses, (M. Al-Breiki, Y. Bicer, 2020)	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**Y**	**L**	**Y**	**Y**
Reuse of carbon dioxide in energy intensive process industries, (S. Perathoner, K. M. V. Geem, G. B. Marin, G. Centi, 2021)	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**Y**	**L**	**Y**	**Y**
Y=Yes, L=Limited, N=No/Not applicable										

Table 7: Quality assessment of selected publications.

3.3.1. Overall Quality of Publications

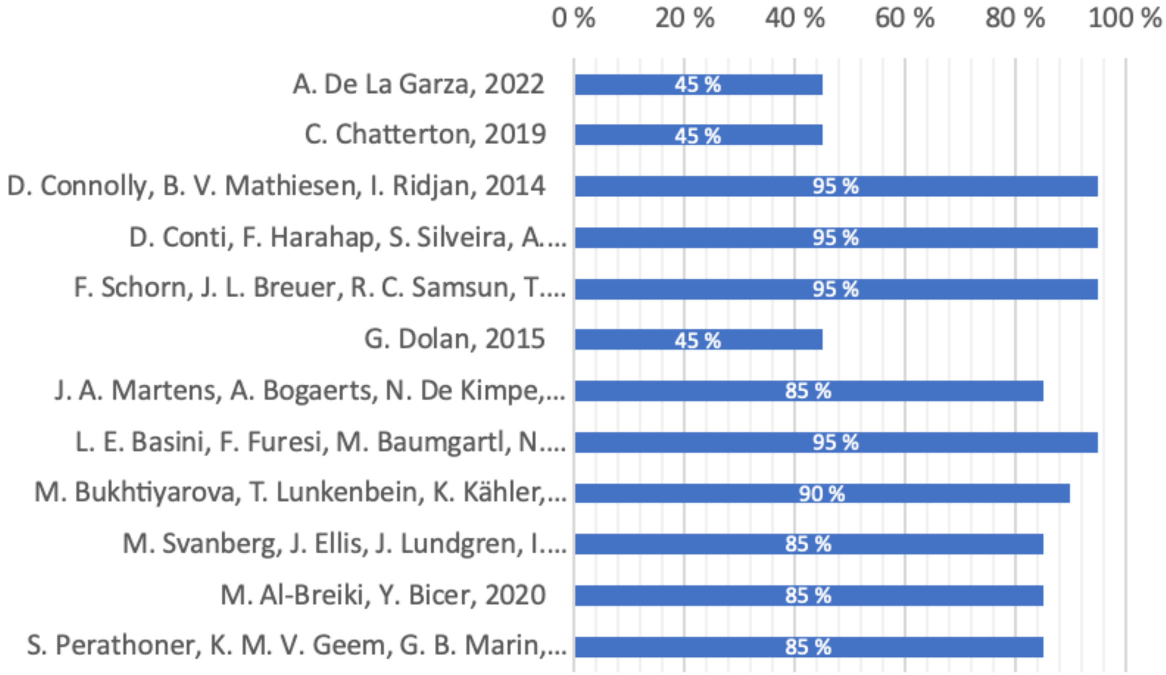

Figure 5: Percentages from quality assessment.

Figure 5 shows that most of the studies are of high quality, with a score of 85% and above. However, the publications by Garza (2022), Chatterton (2019), and Dolan (2015) gets lower scores of 45%. The main reason behind the low scores is due to the nature of the publications, as they are not scientific research articles like the others. The quality assessment method was therefore not applicable on all questions, and "No/Not applicable", which gives 0% score was given on multiple questions. However, the publications are assessed to be useful in the thesis, with a sufficient quality based on where they were published.

Garza (2022) was published in TIME Magazine, which is an established magazine. According to the magazine´s webpages, it is an authoritative and informative guide to current affairs (TIME, n.d.). Dolan (2015) is published in Hydrocarbon Processing, which is a trade publication for the oil and petroleum products industry (EBSCOhost, n.d.). These two publications are informative and gives some insights that are useful for the topic of the thesis, however, the reader is advised to take this into consideration when reading the findings of the thesis. The publication by Chatterton (2019) is not a research article either, but rather an informative presentation from the International Tanker Technical Forum in Singapore in 2019. It cannot be assessed as a research article and therefore it receives a low score. However, it is informative and from the industry, and is therefore considered of high enough quality to contribute to the thesis. It is, however, from the Methanol Institute, so the reader is advised to keep in mind that there are chances of some bias, considering the topic of the publication, and that the publisher is a trade organization for the methanol industry (Methanol Institute, u.a. -b).

3.4. Categorizing the Different Publications

The different papers selected contains findings and relevant information related to different parts of the supply chain. By categorizing the different papers by production, storage, transport, and bunkering the overview was easier. 10 out of the 12 papers selected included information about the production of methanol, either production methods, costs, or energy requirements. Five papers had elements of transport, three including elements of storage, and only two papers had any information about bunkering. Some of the papers contain relevant information about more than one category, and the percentage system below shows the percentage of papers containing findings and information on the different categories. It shows that there is a significant majority of the papers containing information about production with 50%. Bunkering is as little as 11%.

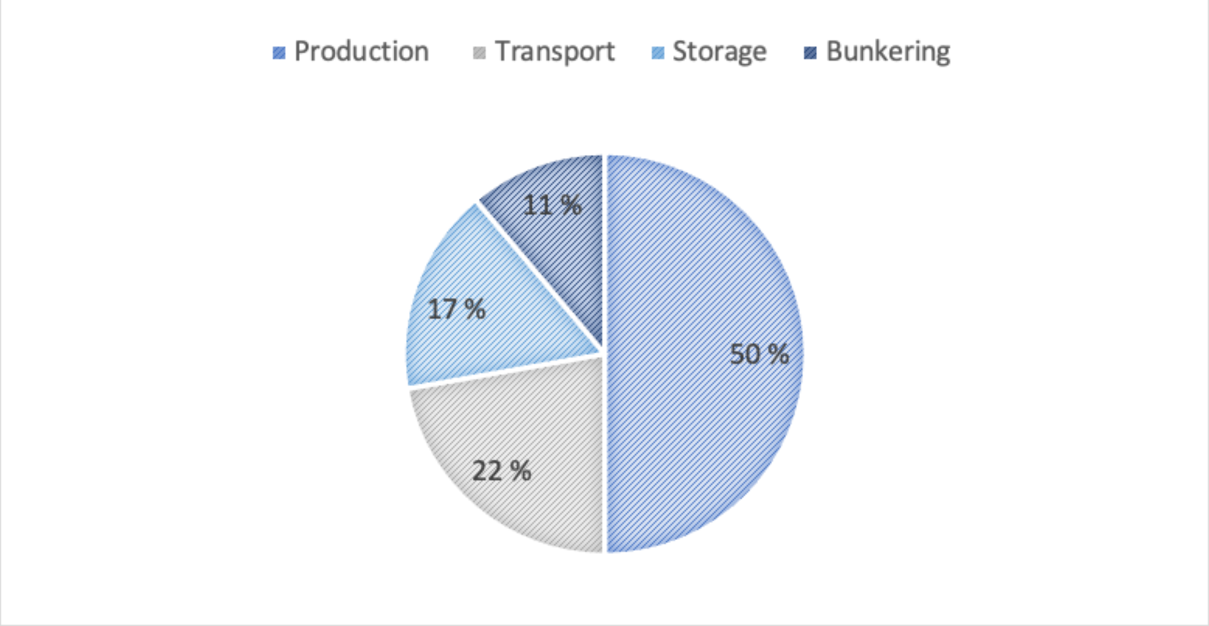

Figure 6: Percentages of the different categories in the selected papers.

3.5. General about Methanol Demand, Why Methanol etc.

Methanol is one of the most widely shipped commodity chemicals worldwide, and much of this supply of methanol is shipped between continents. The world´s major shipping hubs handles hundreds of thousands of tons of methanol every year, while smaller ports handle thousands of tons (Dolan, 2015).

In the maritime industry there is a lot of long-distance and heavy-duty transport which requires energy dense fuel. Connolly et al. (2014) finds that the most attractive form of this type of fuel in the future is methanol/dimethyl ether (DME) as a liquid fuel. The paper by Schorn et al. (2021) investigates hydrogen-based methanol and its potential as a renewable energy carrier. Methanol as an energy carrier has high volumetric density, broad applicability, and mature technology for producing it.

When looking at percentages of the breakeven contribution of boil-off gases (BOGs), loading and unloading stands for 33% respectively of the total BOG losses during the supply chain. Shipping accounts for 30%, while land storage is respectively 2% for each period of storage. The percentages are illustrated in figure 7 below (Al-Breiki & Bicer, 2020).

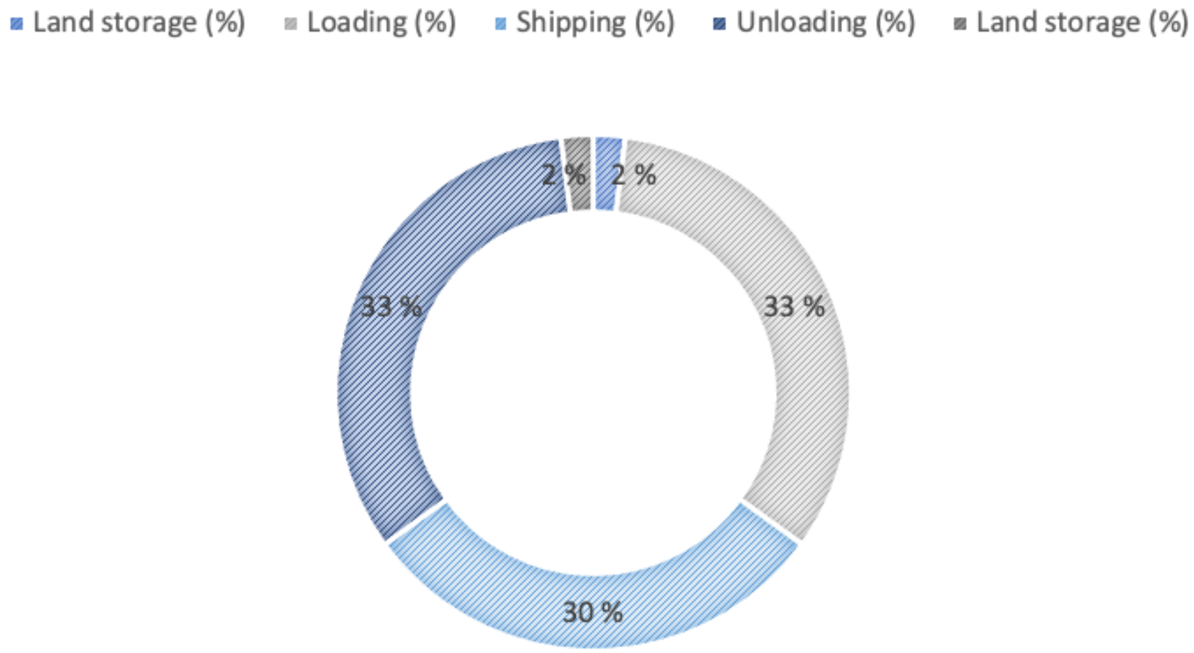

Figure 7: Breakeven BOG contribution during the different phases of the supply chain.

3.6. Production

The largest number of papers in this review has production as the focus. This section will state what has been identified in the papers. The section is divided into production methods and production costs to provide a more comprehensive overview of the topic.

3.6.1. Production Method

There are two methods of producing methanol which have been presented in the article by Connolly et al. (2014). First, there is bioenergy hydrogenation and fermentation, which is a method of methanol production that enhances existing bioenergy resources (Connolly et al., 2014). This type of method would produce bio-methanol. Both Connolly et al. (2014) and Garza (2022) agrees that bio-methanol is the most efficient option in the early stages. In the review by Svanberg et al. (2018) they argue that renewable methanol produced from biomass for use in the shipping industry is a technically viable. Garza (2022) writes that the current best option is to find sources of biogenic carbon, however, there is not enough resources of biogenic carbon dioxide to sustain this method over time. The available amount only counts for a fraction of what is needed to decarbonize shipping.

Despite the potential future struggle with finding biogenic carbon dioxide, Maersk believes there is enough biomass for now to use methanol-powered ships and to bet on methanol for their green fuel (Garza, 2022). A suggestion was made in the paper by Svanberg et al. (2018) to facilitate the transition from fossil fuel to renewable methanol is to use methanol from fossil feedstock as a complement. Connolly et al. (2014) also states that bioenergy resources are projected to become limited in the future.

The second method, CO_2Hydro and co-electrolysis synthesizes a synthetic methanol or dimethyl ether (DME) by combining carbon dioxide with hydrogen and would be classified as e-methanol. Garza (2022) mentions that the challenge is to find carbon that is already in circulation in the climate system. Since methanol is a carbon-based fuel, a lot of carbon is required to make methanol. However, by using carbon that is already in circulation, the carbon balance would not be tipped any further. Direct air capture technology makes it possibly to pull carbon dioxide directly from the atmosphere, however the process is expensive and energy-intensive which leads some experts to believe it will never reach cost effectiveness (Garza, 2022). Because of the limited biomass available, Connolly et al. (2014) believes this method could be the future of methanol production since it does not require biomass input.

Approximately 50% of the global carbon dioxide emissions happen at point sources. Martens et al. (2017) states that it is energetically advantageous to work with concentrated carbon dioxide streams, and that the logical first step is to capture the carbon dioxide from these point sources and then to convert it. Carbon capture technology development and conversion into useful chemicals is of high priority. The readily available large-scale catalytic technology for methanol production from carbon monoxide/carbon dioxide and hydrogen gas in the petrochemical industry can be applied with eventual re-engineering of certain process steps. Numerous techniques are still being explored, such as chemical catalysis, electrocatalysis, photocatalysis, plasma technology and biocatalysis. Most of these are not yet commercially available (Martens et al., 2017).

With regard to the identified logical first step by Martens et al. (2017) to work with concentrated carbon dioxide streams, Perathoner et al. (2021) finds that there is low technology readiness for the development of carbon dioxide reutilization technologies. This is identified in the paper as one of the major hurdles for decarbonization of energy intense industries. The energy intense industries looked at in this paper is iron and steel, cement, refineries, petrochemistry and fertilizers. The transformation of carbon dioxide to carbon monoxide out of water gas shift (WGS) reaction plays a key role. Once the carbon monoxide is produced from the carbon dioxide, there are many conversion routes that opens, both bio-chemical and catalytic in the steel and chemical sector (Perathoner et al., 2021).

During the study done by Bukhtiyarova et al. (2017), the authors found that the steel sector is an interesting option for methanol production, as mentioned by Perathoner et al. (2021) above. Bukhtiyarova et al. (2017) aimed to find optimal conditions to obtain this high efficiency of methanol production with low concentrations of side products. The reasoning behind this is that a high selectivity of methanol is preferrable as it is the desired product of methanol synthesis, and because of its toxicity, less concentrations of carbon monoxide.

The carbon dioxide hydrogenation route for the chemical energy storage over a commercial Cu/ZnO/Al_2O_3 catalyst has been studied. To find the optimal conditions, the influence of temperature and space velocity on the catalytic performance has been demonstrated. To investigate the possibilities of the usage of alternative carbon sources, time-on-stream measurements in the absence and presence of benzene in the gas feed mixture were performed. The findings that the presence of benzene in the feed does not lead to catalyst deactivation leads to methanol production from exhaust gases from steel mills as an interesting alternative for methanol production in a sustainable way (Bukhtiyarova et al., 2017).

Another alternative is using carbon dioxide from the production of biogas. The potentials for this innovative process scheme for producing methanol has been shown by Basini et al. (2022). The methanol is produced using the residual carbon dioxide obtained from biogas production in a biogas plant combined with hydrogen from a polymer electrolyte membrane electrolyser (PEME). An electrified reverse water gas shift (E-RWGS) step and a downstream methanol synthesis is involved in the process. With the E-RWGS reactor operating at high temperatures would be possible, and the energy efficiency would then be higher than 90% increasing the CO yield. The energy consumption is at 11kWh/kg_{MeOH} with a carbon efficiency of 90%. While traditional CCU plants rely on the sequestration and conversion of the carbon dioxide produced in the combustion of fossil fuels, the conversion of carbon dioxide available from biogas plants would allow for the achievement of negative carbon dioxide emission. This is possible given the renewable nature of the feedstock (Basini et al., 2022).

3.6.2. Production Costs

The economics of methanol production methods is a crucial factor in determining their feasibility and attractiveness for the shipping industry. According to Connolly et al. (2014), the method of methanol production, and whether it is feasible and attractive for the industry, depends on the relative costs of bioenergy resources and electricity production. As electricity production becomes more affordable than bioenergy, as anticipated by the authors, CO_2Hydro and co-electrolysis could become the most used method for supplying methanol, as it does not have any requirements for bioenergy input.

Conti et al. (2019) also emphasize the significant impact of biomass costs on methanol production costs, with biomass costs accounting for approximately 50% of the final cost. The authors suggest that improving plant conversion efficiency and reducing transportation distances for biomass could help minimize production costs. As the quantities for biomass are greater than those of methanol, transportation costs for methanol are lower, further emphasizing the need to optimize biomass transport distances (Conti et al., 2019).

Al-Breiki and Bicer (2020) have determined the energy requirement for methanol production to be 22.356MJ/kg, further highlighting the importance of energy efficiency in the process. Schorn et al. (2021) have found that renewable methanol production costs have a high level of dependency on the expenses of hydrogen and carbon dioxide. With current production costs, renewable methanol is two to three times more expensive than fossil fuel market prices. However, if hydrogen costs decrease to less than 2.5€/kg and carbon dioxide prices are below 80€/t in the country that produces hydrogen, the energy specific costs of importing methanol could become lower than those for hydrogen. The additional costs of transforming hydrogen to methanol can be outbalanced by the lower shipping costs of methanol when compared to hydrogen.

The paper by Schorn et al. (2021) also states that the competitiveness of green methanol against fossil fuels would be facilitated by policy measures. If there is no carbon dioxide available in the hydrogen producing country, the carbon dioxide prices in the country of destination must be 181-228 €/t less expensive than direct air capture in the country of origin. This is to balance out the more expensive shipping of hydrogen. Moreover, Schorn et al. (2021) suggests that if direct air capture target costs of 100€/t are achieved, producing methanol in the origin country would be more cost-effective, regardless of the carbon dioxide prices in the destination country (Schorn et al., 2021).

In the review by Svanberg et al. (2018) finds that the primary obstacle for a methanol supply chain is the economic barrier. However, the paper states that the economic challenge does not seem to be insurmountable.

In conclusion, a comprehensive understanding of the economic aspects of various methanol production methods is essential for determining their feasibility in the maritime industry Factors such as the costs of bioenergy resources, electricity production, hydrogen, carbon dioxide and transportation distances, as well as improvements in energy efficiency and carbon capture technologies, all play critical roles in shaping the future of methanol production.

3.7. Transport

According to Al-Breiki and Bicer (2020) the energetic boil off gas (BOG) is 0.015% and exergetic BOG is 0.087% during 30 days shipping. Due to the low BOG losses of methanol, it can be transported for long overseas transport. The low exergetic BOG is due to the low temperature difference between the liquid methanol and the environment around. However, the loading and unloading of methanol stands for 66% of the total BOG during the supply chain investigated. The exergetic BOG for loading and unloading is 0.0141% and the energetic BOG is 0.016%.

As for infrastructure, Schorn et al. (2021) argues that it is possible to partially re-use the existing energy transport and distribution infrastructure, further minimizing costs associated with methanol adoption. This notion is supported by Svanberg et al. (2018) stating that the infrastructure for transport is to some extent already in place or can be adapted easily. Connolly et al. (2014) states that the anticipated costs of infrastructure adjustments to methanol are relatively low, which further supports the statement of reusing and adapting existing infrastructure for the transportation of methanol. Dolan (2015) states that the infrastructure adjustments to offer methanol as a bunker fuel would be simple, further supporting the statements of the papers mentioned above. Methanol is an easily transportable liquid, and twice as high volumetric energy density as hydrogen. However, methanol is approximately half the volumetric energy density of gasoline and diesel (Martens et al., 2017).

3.8. Storage

Methanol can be stored in mild steel tanks and is already present at almost every chemical port or terminal (Dolan, 2015). During three days of storage, there is a percentage of 0.00096% energetic BOG, while the exergetic BOG is 0.0009%. Compared to LNG and ammonia, methanol only loses 2% of the total BOG losses during storage, while LNG and ammonia loses 5% (Al-Breiki & Bicer, 2020).

Compared to natural gas, hydrogen and gasoline, methanol is much safer because of its limited danger of explosion (Martens et al., 2017).

3.9. Bunkering

While methanol presents several advantages as a sustainable ship fuel, such as its limited risk of explosion compared to natural gas, hydrogen and gasoline, there are safety hazards that must be considered when handling methanol. Methanol vapors pose significant health risks due to its high toxicity. Exposure to these vapors can lead to blindness (Martens et al., 2017).

3.9.1. The Refueling Station

To obtain ventilation the refueling station should be located on open deck (Chatterton, 2019). There should also be a device for safe disposal of leaked fuel and a collection tray below the joint for safe collection. The refueling should be monitored and controlled from a safe location. An overfill alarm and automatic cutoff to monitor the bunker level and overfill should be equipped at the monitoring location. As for personnel protection, there must be an available shower and eyewash station for emergencies (Chatterton, 2019).

3.9.2. The Refueling System

Refueling lines near the shore connector should be fitted with a manual shutoff valve as well as a emote shutoff valve connected in series. Chatterton (2019)also states that the refueling system should be able to degas the refueling line and perform gas inerting. Equipment to purge the fuel from the refueling line after refueling should also be equipped, and a refueling electrostatic discharge (ESD) cut-off system should be equipped on the ship. This can be operated from the ship to be refueled or from the refueling station (Chatterton, 2019).

4 Discussion

This chapter provides an in-depth exploration and discussion of the various aspects of a sustainable methanol ship fuel supply chain (SMSFSC). Production methods and production costs are examined, as well as transport, storage, and bunkering. Significant challenges in terms of sustainability, scalability, and energy intensity are revealed. Topics for further research is also recommended. At the end of the chapter, the conceptual framework for a sustainable methanol ship fuel supply chain (SMSFSC) is presented, offering a visual guide to the key factors in developing such a supply chain. The chapter concludes by identifying limitations of the study and recommendations for further research, thereby setting the stage for future research in this field.

4.1. Production

The production section is split up into production methods and production costs, as it was in the previous chapter where the findings were presented.

4.1.1. Production Methods

The production of methanol as a sustainable ship fuel presents various challenges and opportunities for the maritime industry. Bioenergy hydrogenation and fermentation offer a promising start for methanol production, with Connolly et al. (2014) and Garza (2022) agreeing on its efficiency in the early stages. However, the reliance on biogenic carbon sources raises concerns about sustainability and scalability of this method. The availability of biogenic carbon dioxide is insufficient to meet the decarbonation needs of the maritime industry in the long term. Furthermore, Connolly et al. (2014) predict a future limitation of bioenergy resources, which could hinder the widespread adoption of bio-methanol.

On the other hand, CO_2Hydro and co-electrolysis present an alternative that does not rely on biomass input. However, this method faces challenges in sourcing carbon that is already in circulation within the climate system, to avoid putting even more carbon into circulation, and losing its sustainability. Direct air-capture would be a promising alternative, expect for the skepticism about its cost-effectiveness because of the expensive and energy intensive nature of the method of sourcing carbon (Connolly et al., 2014; Garza, 2022)

Martens et al. (2017) suggest that concentrated carbon dioxide streams from point sources could be energetically advantageous, and carbon capture technology development remains a high priority. Nevertheless, the low technology readiness of carbon dioxide reutilization technologies poses a significant barrier to progress in this area (Perathoner et al., 2021).

The steel sector, as investigated by Bukhtiyarova et al. (2017), offers an interesting alternative for methanol production using exhaust gases. This approach, along with Basini et al. (2022) exploration of carbon dioxide from biogas production, demonstrates the potential for innovative process schemes in methanol production. However, the scalability and commercial viability of these methods remain to be seen.

In conclusion, while both bioenergy hydrogenation and fermentation and CO_2Hydro and co-electrolysis present potential pathways for sustainable methanol production, each method faces significant challenges. The limitations for biogenic carbon sources, the energy intensity of direct air capture technology, and the low technology readiness of carbon dioxide reutilization technologies indicate that further research and development are necessary. Innovative methanol production process schemes, such as those proposed by Bukhtiyarova et al. (2017) and Basini et al. (2022), offer promising directions for future investigation and research.

4.1.2. Production Costs

The economic viability of various methanol production methods remains a central challenge in the pursuit of sustainable ship fuels. Building on the findings outlines in section 3.6.2., this discussion aims to explore the interplay between technological advancements, policy measures, and economic factors that could influence the feasibility of different production methods.

First, it is important to acknowledge the impact of biomass costs on methanol production. As Conti et al. (2019) highlight, these costs account for a significant portion of the final production costs. Therefore, optimizing the supply chain, including transportation distances and plant conversion efficiency, could lead to substantial cost reductions. Another critical factor in the cost dynamics of methanol production is the relative pricing og electricity and bioenergy resources. As Connolly et al. (2014) hypothesize, cheaper electricity production could shift the preference towards CO_2Hydro and co-electrolysis methods.

The role of policy measures in supporting the adoption of renewable methanol cannot be overstated. Schorn et al. (2021) suggest that the competitiveness of green methanol against fossil fuels could be facilitated by targeted policy interventions. Policymakers should consider implementing incentives and regulations that encourage the use of renewable methanol in the maritime industry, such as carbon pricing mechanisms, subsidies, or research grants.

Technological advancements in carbon capture and carbon utilization, as well as hydrogen production, also play a crucial role in determining the economic feasibility of methanol production. As Schorn et al. (2021) mention, achieving direct air capture costs of 100€/t could make methanol production more cost-effective. Focusing on advancing carbon capture technologies, as well as investigating the potential of alternative carbon sources, such as those proposed by Bukhtiyarova et al. (2017) and Basini et al. (2022) are important for making methanol production more feasible in the future. Further research could help overcome the economic barriers that currently hinder widespread adoption, concluded by Svanberg et al. (2018). It is important to note that the economic feasibility is a challenge, however, not an insurmountable one.

By focusing on the economic factors, technological advancements, and policy measures that are crucial for promoting renewable methanol as a sustainable ship fuel, these economic barriers can be overcome. Researchers, policymakers, and industry stakeholders can pave the way for a more sustainable future in the maritime industry by overcoming these obstacles.

4.2. Transport

The discussion around the transportation part of the supply chain for sustainable methanol ship fuel encompasses several aspects, including BOG losses, infrastructure adaptability, and energy density. Based on the findings provided in section 3.5., this discussion will explore potential improvements and strategies to address these aspects.

Firstly, the low energetic and exergetic BOG losses of methanol during shipping, as reported by Al-Breiki and Bicer (2020), offer an advantage for long overseas transport. However, given that loading and unloading processes account for a significant portion of total BOG losses, ways to optimize these processes should be investigated.

Secondly, the potential for reusing and adapting existing energy transport and distribution infrastructure for methanol, as suggested by Schorn et al. (2021), Svanberg et al. (2018), and Connolly et al. (2014), is an important factor associated with methanol adoption. Investigation into the most effective strategies for adapting existing infrastructure to accommodate methanol is important going forward. Factors such as regional differences, scalability, and long-term viability must be considered. Guidelines, regulations, and incentives must be developed to promote the efficient conversion of existing infrastructure.

Lastly, the energy density of methanol compared to other fuels, as pointed out by Martens et al. (2017), has implications for the fuel´s storage and transportation requirements. Although methanol has a higher volumetric density than hydrogen, it is still lower than that of gasoline and diesel. This poses a challenge since space and weight constraints are crucial considerations in the maritime industry. The development of storage solutions that optimize space utilization on ships are necessary.

Addressing the challenges of BOG losses, infrastructure adaptability, and energy density is important when considering the transportation of methanol as ship fuel. Future research into preventing BOG losses during loading and unloading safely and efficiently is essential to optimize these processes. Additionally, it would be beneficial to investigate the impact of different shipping durations and conditions on BOG losses for better understanding of how methanol performs under various scenarios.

4.3. Storage

Given the somewhat limited findings regarding storage, this discussion will mostly provide insight into possible further research, potential improvements, and strategies to address these aspects. However, the factors such as storage materials, BOG losses, and explosion risks will be considered in the discussion.

The compatibility of methanol with mild steel tanks, as reported by Dolan (2015), offers a practical advantage for storage infrastructure. However, it is essential to investigate the long-term performance of mild steel tanks, as well as alternative materials, under various storage conditions and durations. This would provide insights into material degradation, corrosion, and other factors that might impact the integrity of storage systems. Future research could explore the design and development of innovative storage systems that optimize space utilization and maintain safety. Space utilization is important due to the volumetric density of methanol being higher than the fossil fuels currently in use in the maritime industry Martens et al. (2017).

The low energetic and exergetic BOG losses of methanol during storage, as indicated by Al-Breiki and Bicer (2020), are advantageous and provides possibilities for long term storage. Even though the BOG losses are smaller than LNG and ammonia, further research to minimize the BOG losses even would help ensure methanol's benefits as a sustainable fuel.

The safety aspect of methanol, as highlighted by Martens et al. (2017) is an essential consideration during methanol adoption in the maritime industry. Methanol has limited explosion risks compared to natural gas, hydrogen, and gasoline which presents a significant advantage. However, it is crucial to continue investigating safety implications of methanol storage to develop good practices, guidelines and regulations that ensure safe storage. This research could include examining the effects of varying environmental conditions, such as temperature and humidity, and assessing the risks associated with potential spills, leaks or other incidents.

4.4. Bunkering

Considering the safety hazards associated with methanol as a sustainable ship fuel, it is important to have a comprehensive discussion on best practices for bunkering, specifically addressing the design and operation of refueling stations and systems. A key aspect to consider is the adequate management of methanol vapors, given their high toxicity (Martens et al., 2017).

The findings regarding bunkering in section 3.9. provide some insight into how a refueling station and system should be set up, however, there is need for more research as it provides a limited view. As for ventilation, ventilations systems should be optimized to better manage methanol vapors and reduce the associated risks. The best technologies for leak detection, remote monitoring, control systems, and ESD cut-off systems for this use of methanol should be identified, and developed further, to ensure the safety of personnel operating the system and more efficient operations. Safety equipment and protocols should be assessed, and improved, contributing to enhances protection for personnel involved in the bunkering process. Regulatory frameworks and industry standards related to methanol bunkering would further ensure the safety of personnel.

4.5. Presentation of a Conceptual Framework for a Sustainable Methanol Ship Fuel Supply Chain (SMSFSC)

The conceptual framework for a sustainable methanol ship fuel supply chain (SMSFSC) is presented below. By expanding figure 1 presented in section 1.6. the illustration shows the key factors for developing a sustainable methanol ship fuel supply chain (SMSFSC). The boxes with solid lines represent the main parts of the supply chain with arrows showing the direction of the supply chain. The boxes with dotted lines represent the different options found for feedstock and production methods, connected with dashed lines to the part of the supply chain the options concern. The boxes with dashed lines represent the findings found in the litterature review that is relevant to the different parts of the supply chain, also connected with dashed lines. These dashed lined boxes represent the findings where there were no alternate options, but rather specific findings.

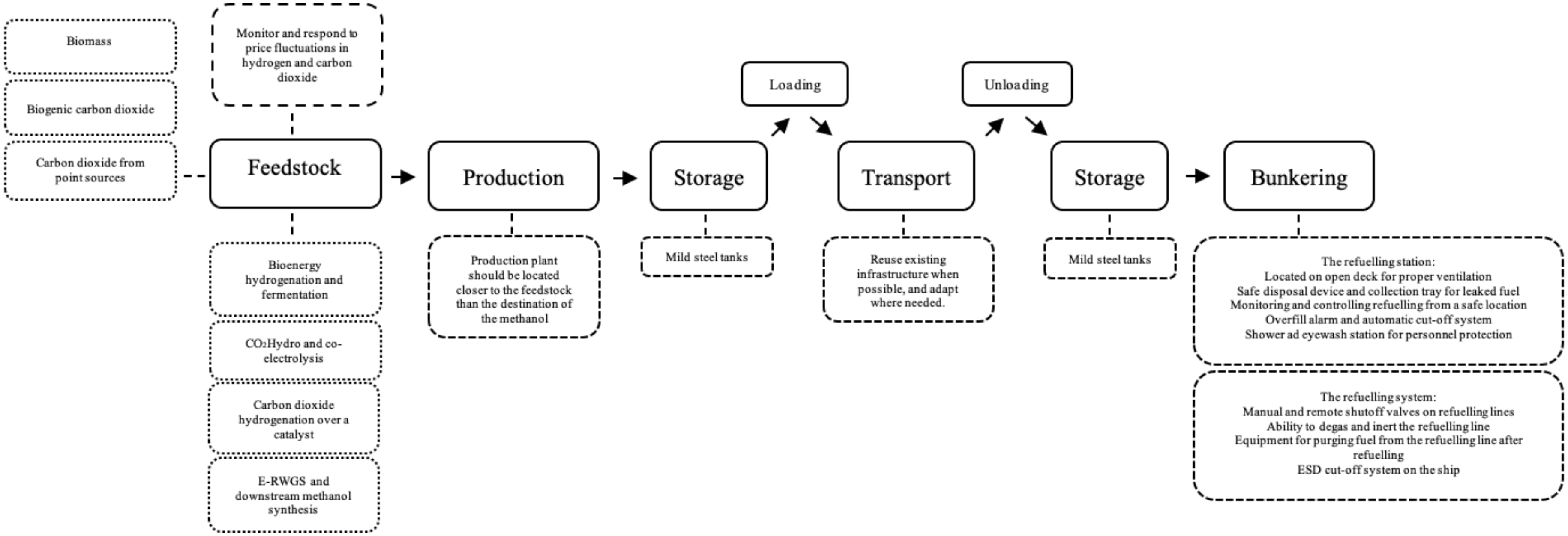

Figure 8: Framework for a sustainable methanol ship fuel supply chain (SMSFSC).

4.6. Limitations

There are some limitations to the study that must be addressed. This section will provide the current limitations as well as potential limitations.

There is a limited number of publications used in the study. This systematic litterature review has a relatively small sample of 12 publications, which provides a limited comprehensiveness of the aspects of the topic. As for the scope of the study, there are some limitations connected to this aspect, as the somewhat narrow scope does not cover all aspects of a sustainable methanol ship fuel supply chain (SMSFSC). An example of this is regional or sector-specific challenges and opportunities. Since it is a systematic litterature review, the thesis relies on findings of existing studies, and does not provide any primary research. This does limit the study´s ability to provide new insights and explore specific aspects of the topic in greater depth. The time constraint on the study is about 5 months, which is a limitation to the depth and width of the analysis, and with more time a more exhaustive study could have been conducted.

It is also worth mentioning that this thesis has not considered the amounts of methanol needed to sustain the maritime industries supply chain´s, and if there are enough resources to produce the amount needed. This requires further research.

Due to the limitations stated above, further research is recommended for all parts of a potential sustainable methanol ship fuel supply chain (SMSFSC). Specific recommendations for further studies have been stated in the discussion of each of the different parts of the supply chain, where some parts require more research than others. Furthermore, continued research, development, and policy support are crucial in overcoming economic barriers and promoting widespread adoption of sustainable methanol as a shipping fuel.

5 Conclusion

Firstly, the key components in a conceptual framework for a sustainable methanol ship fuel supply chain (SMSFSC) is feedstock, production, storage, transport, and bunkering. The choice of feedstock primarily depends on the availability, cost, and the environmental impact of the source. Methanol can be produced from a variety of feedstocks, such as biomass, biogenic carbon dioxide, and carbon dioxide from point sources. Current and emerging technologies to produce methanol include bioenergy hydrogenation and fermentation, CO_2Hydro and electrolysis, carbon dioxide hydrogenation over a catalyst, E-RWGS and downstream methanol synthesis. The choice of production method would be influenced by factors such as the availability and cost of the feedstock, as well as plant conversion efficiency. Methanol could be stored in mild steel tanks, with safety measures put in place to prevent leaks and fires. Transportation of methanol from production sites to ports or terminals could be done with utilizing existing infrastructure and adapting the existing infrastructure where needed. Bunkering involves refueling ships with methanol at ports or terminals. Specific facilities and safety measures are required.

Secondly, the critical factors and challenges in developing a sustainable methanol ship fuel supply chain (SMSFSC) for the maritime industry is sustainable production technologies, economic challenges, and regulatory challenges. The choice of the most attractive production method depends on factors such as the price of bioenergy resources, the cost of hydrogen, and the availability of carbon dioxide. The main economic challenges when transitioning to a sustainable methanol ship fuel supply chain (SMSFSC) include high production costs and the need for increased efficiency in plant conversion. As for regulatory challenges, sustainable methanol´s competitiveness against fossil fuels would be facilitated by policy measures, which can help bridge the gap between sustainable methanol production costs and current market prices for fossil fuels.

Lastly, the current and emerging technologies for sustainable production of methanol as ship fuel include bioenergy hydrogenation and fermentation, CO2Hydro and co-electrolysis, carbon dioxide hydrogenation over a commercial catalyst, E-RWGS and downstream methanol synthesis. Factors such as the cost of bioenergy resources, electricity, and the availability of carbon dioxide and hydrogen play a crucial role in determining the method most suited.

5.2. Implications for Theory and Practice

5.2.1. Implications for Theory:

Theoretical studies and models can be developed to better understand the complex dynamics of a sustainable methanol ship fuel supply chain (SMSFSC), including the cost implications and potential synergies with existing energy systems. A comparison of methanol with other alternative fuels can provide valuable insights into the benefits and drawbacks of each fuel type, contributing to the development of comprehensive theoretical frameworks for sustainable shipping. Examining the potential impact for various policy measures, such as carbon pricing, subsidies, and regulations, can help identify effective strategies for promoting the adoption of methanol and other sustainable fuels in the shipping industry.

5.2.2. Implications for Practice:

The practical implementation of methanol as a ship fuel requires the development and adaptation of infrastructure for production, transport, storage, and bunkering. Existing infrastructure can be partially reused, but investments in new infrastructure may be necessary to support the widespread adoption of methanol. Implementing appropriate safety measures and protocols for handling and bunkering methanol is crucial to protect personnel and minimize risks. Innovations in methanol production, transport, storage, and bunkering technologies can lead to cost reductions, improved efficiency, enhanced safety, and thus making methanol a more attractive option for the maritime industry. Collaboration within the industry is important as well to create a supportive environment for the adoption of methanol as a sustainable ship fuel. This includes establishing clear regulations, standards, and incentives for its use.

Reference List

Al-Breiki, M., & Bicer, Y. (2020). Technical assessment of liquefied natural gas, ammonia and methanol for overseas energy transport based on energy and exergy analyses [Article]. *International Journal of Hydrogen Energy*, *45*(60), 34927-34937. https://doi.org/10.1016/j.ijhydene.2020.04.181

Basini, L. E., Furesi, F., Baumgartl, M., Mondelli, N., & Pauletto, G. (2022). CO2 capture and utilization (CCU) by integrating water electrolysis, electrified reverse water gas shift (E-RWGS) and methanol synthesis. *Journal of Cleaner Production*, *377*, Article 134280. https://doi.org/10.1016/j.jclepro.2022.134280

Bozarth, C. C., & Handfield, R. (2019). *Introduction to operations and supply chain management* (Fifth edition / Cecil C. Bozarth, Robert B. Handfield.; Global edition. ed.). Pearson.

Bukhtiyarova, M., Lunkenbein, T., Kähler, K., & Schlögl, R. (2017). Methanol Synthesis from Industrial CO Sources: A Contribution to Chemical Energy Conversion [Article]. *Catalysis Letters*, *147*(2), 416-427. https://doi.org/10.1007/s10562-016-1960-x

Bureau Veritas. (2022, February 23.). *Different Types of Methanol*. Bureau Veritas. https://marine-offshore.bureauveritas.com/insight/infographics/different-types-methanol

Chatterton, C. (2019). *Methanol as a vessel fuel & energy carrier* International Tanker Technical Forum, Singapore. https://www.methanol.org/wp-content/uploads/2019/09/Methanol-as-a-vessel-fuel-and-energy-carrier.pdf

Connolly, D., Mathiesen, B. V., & Ridjan, I. (2014). A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system [Article]. *Energy*, *73*, 110-125. https://doi.org/10.1016/j.energy.2014.05.104

Conti, D., Harahap, F., Silveira, S., & Santasalo-Aarnio, A. (2019). A techno-economic assessment for optimizing methanol production for maritime transport in Sweden. 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2019,

Critical Appraisal Skills Programme. (n.d.). *CASP Systematic Review Checklist*. CASP. Retrieved May 9. from https://casp-uk.net/images/checklist/documents/CASP-Systematic-Review-Checklist/CASP-Systematic-Review-Checklist-2018_fillable-form.pdf

Dekkers, R. (2022). *Making Literature Reviews Work : a Multidisciplinary Guide to Systematic Approaches* (L. Carey & P. Langhorne, Eds.). Springer Nature Switzerland AG.

Dolan, G. (2015). Methanol takes on LNG for future marine fuels [Opinion]. *Hydrocarbon Processing*, *94*(5), 37-38. https://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=102537999&site=ehost-live

EBSCOhost. (n.d.). *Publication Details For "Hydrocarbon Processing"*. EBSCOhost. Retrieved May 9. from https://web.s.ebscohost.com/ehost/command/detail?vid=11&sid=3cc91ee1-7a66-4114-8d24-d2991a2e984e%40redis&bdata=JnNpdGU9ZWhvc3QtbGl2ZQ%3d%3d#jid=HYD&db=aph

Efron, S. E., & Ravid, R. (2018). *Writing the Literature Review: A Practical Guide*. New York: Guilford Publications.

Elsevier. (n.d.-a). *CRediT author statement*. Elsevier. Retrieved May 9. from https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement

Elsevier. (n.d.-b). *Policies & guidelines*. Elsevier. Retrieved May 9. from https://www.elsevier.com/authors/policies-and-guidelines

EndNote. (n.d.). *Focus on what matters most: your research.* EndNote. Retrieved April 26. from https://endnote.com/

Garza, A. D. L. (2022). Waiting for the Green Ship to Come In. In (Vol. 200, pp. 64-64): TIME USA, LLC.

HASS, H., HUSS, A., & MAAS, H. (2014). *TANK-TO-WHEELS Report - Version 4.a* (Report EUR 26241 EN). https://op.europa.eu/en/publication-detail/-/publication/1cffb832-f2bc-42df-9dc2-59db08e24eee/language-en

International Marine Organization. (n.d.). *IMO's work to cut GHG emissions from ships*. IMO. Retrieved February 1. from https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

International Transport Forum. (2018). *Decarbonising Maritime Transport*. ITF/OECD. https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport.pdf

Kitchenham, B., & Charters, S. (2007). Guidelines for performing Systematic Literature Reviews in Software Engineering. *2*.

Martens, J. A., Bogaerts, A., De Kimpe, N., Jacobs, P. A., Marin, G. B., Rabaey, K., Saeys, M., & Verhelst, S. (2017). The Chemical Route to a Carbon Dioxide Neutral World. *CHEMSUSCHEM*, *10*(6), 1039-1055. https://doi.org/10.1002/cssc.201601051

Merriam-Webster. (2023, April 29.). *Feedstock*. Merriam-Webster,. https://www.merriam-webster.com/dictionary/feedstock

Methanol Institute. (u.a. -a). *About Methanol*. Methanol Insitute, . Retrieved February 1. from https://www.methanol.org/about-methanol/

Methanol Institute. (u.a. -b). *THE METHANOL INSTITUTE*. Methanol Insitute, . Retrieved May 9. from https://www.methanol.org/

Methanol Institute. (u.a. -c). *Renewable Methanol*. Methanol Insitute, . Retrieved February 1. from https://www.methanol.org/renewable/

Perathoner, S., Van Geem, K. M., Marin, G. B., & Centi, G. (2021). Reuse of CO2 in energy intensive process industries [Article]. *Chemical Communications*, *57*(84), 10967-10982. https://doi.org/10.1039/d1cc03154f

Schorn, F., Breuer, J. L., Samsun, R. C., Schnorbus, T., Heuser, B., Peters, R., & Stolten, D. (2021). Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations [Article]. *Advances in Applied Energy*, *3*, Article 100050. https://doi.org/10.1016/j.adapen.2021.100050

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, *16*(15), 1699-1710. https://doi.org/https://doi.org/10.1016/j.jclepro.2008.04.020

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333-339. https://doi.org/https://doi.org/10.1016/j.jbusres.2019.07.039

Svanberg, M., Ellis, J., Lundgren, J., & Landälv, I. (2018). Renewable methanol as a fuel for the shipping industry [Article]. *RENEWABLE & SUSTAINABLE ENERGY REVIEWS*, *94*, 1217-1228. https://doi.org/10.1016/j.rser.2018.06.058

TIME. (n.d.). *About TIME Magazine*. TIME Magazine. Retrieved May 9. from https://subs.time.com/about-time