Erasmus University Rotterdam

MSc in Maritime Economics and Logistics

2023/2024

Navigating Toward Sustainability: A Comprehensive Analysis of Marine Alternative Fuels and Price Forecasting with Machine Learning

By

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Abstract

The maritime industry is under growing pressure to lower its substantial greenhouse gas emissions. This thesis investigates prospective marine alternative fuels in response to the 2050 International Maritime Organization's decarbonization targets. Alternative fuels play a crucial role in the industry's efforts to reduce its carbon footprint. This study's primary goal is to assess alternative fuels and project their future price in 2030. This year is considered a critical point when the widespread adoption of such fuels is expected to be more feasible. A comparative analysis of their economic viability and a comprehensive evaluation of their strengths and weaknesses is essential for identifying the best option.

The study combines a qualitative and quantitative approach. It includes a detailed literature review where the existing literature is examined. Initially, there is an overview of the potential alternative fuels, where Methanol, Ammonia, Hydrogen and Biodiesels are analysed, and their suitability as marine fuels is examined. Subsequently, data about the prices of alternative fuels are collected and analysed, offering insights on the historical trends of the data and factors that affected them. That facilitates the implementation of prediction algorithms to forecast the future prices of selected alternative fuels, Methanol, Hydrogen, and FAME (biodiesel). The most important models that are utilized are XGBoost, Random Forest and Prophet. Finally, through price prediction, this study evaluates the economic viability of the alternative fuels.

Because of its advantages over other fuels in terms of cost and environmental impact, methanol is determined to be the most practical and cost-effective alternative fuel in the studied timeline. Its existing infrastructure makes easier its utilization. FAME, on the other hand, provides a balance between economic feasibility and environmental impact. Nevertheless, its limited availability is an important drawback. Finally, hydrogen is the most promising long-term solution for achieving net-zero emissions. Currently its price is high but based on estimations it is going to decrease significantly in the future. It is carbon neutral and has high energy density. However, hydrogen requires significant advancements in technology and infrastructure to further decrease its production cost and facilitate its utilization.

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List of Abbreviations

ADF	Augmented Dickey-Fuller
ATR	Autothermal Reforming
CNN	Convolutional Neural Networks
DME	Dimethyl Ether
DA	Directional Predictive Accuracy
FAME	Fatty Acid Methyl Ester
FT Diesel	Fischer-Tropsch Diesel
GGE	Gasoline Gallon Equivalent
GRU	Gated Recurrent Unit
GHG	Greenhouse Gas
GHS	Greenhouse Gas Study
HFO	Heavy Fuel Oil
HTL	Hydrothermal Liquefaction
HVO	Hydrotreated Vegetable Oil
IA	Index of Agreement
IFO	Intermediate Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
IMO	International Maritime Organization
KPSS	Kwiatkowski, Phillips, Schmidt, and Shin
LBM	Liquefied Biomethane
LNG	Liquefied Natural Gas
LSTM	Long Short-Term Memory
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MAPE	Mean Absolute Percentage Error
NSE	Nash-Sutcliffe Efficiency
PEM	Proton Exchange Membrane
PP	Phillips-Perron
RF	Random Forest

RNN	Recurrent Neural Network
SMR	Steam Methane Reforming
SVO	Straight Vegetable Oil
TI	Theil Index
ULSFO	Ultra-Low Sulphur Fuel Oil

1. Introduction

1.1. Background and Problem Identification

The maritime industry is a crucial backbone of global trade. It is responsible for transporting approximately 90% of the world's goods (Feingold and Willige, 2024). Its significance is apparent, due to the ways it facilitates international trade. Nevertheless, the industry faces numerous challenges and pressure to evolve. In order to function properly, it has to adjust to the growing environmental and economic pressures. One of the foremost concerns is the industry's substantial contribution to global greenhouse gas emissions.

According to the International Maritime Organization (IMO), the total shipping greenhouse gas emissions rose from 977 million tonnes in 2012 up to 1,076 million tonnes in 2018, which indicates a 9.6% rise. These emissions include carbon dioxide, methane, and nitrous oxide. Specifically, carbon dioxide emissions increased from 962 million tonnes in 2012 up to 1,056 million tonnes in 2018, a 9.3% increase. Additionally, there are projections suggesting that emissions levels could rise to 90-130% of 2008 levels of emission by 2050 (International Maritime Organization, 2020). These data underscore the urgent need to reduce maritime emissions on a global scale.

To resolve this urgent issue, IMO developed its Greenhouse Gas Study (GHS), the latest version of which is the revision of 2023. It is divided into three key objectives. Firstly, reducing the carbon emissions of international shipping by at least 40% by 2030, in comparison to the 2008 levels. Moreover, ships have to produce at least 5% (the aim is 10%) of their energy with zero or near-zero greenhouse gas (GHG) emission technologies by 2030. Finally, the ultimate goal is to reach net zero GHG emissions around 2050, with indicative checkpoints a reduction of 20 to 30% by 2030 and 70 to 80% by 2040. To achieve these targets, the IMO developed several regulations under the International Convention for the Prevention of Pollution from Ships (MARPOL). Most of these measures are already implemented and the most important ones are the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan

(SEEMP), the Energy Efficiency Existing Ship Index (EEXI), the Fuel Oil Consumption Data Collection System (DCS) and the Carbon Intensity Indicator (CII) (DNV, n.d.).

As a result, it is apparent that the global maritime community has identified the significance of this problem, and its main objective is to resolve it rapidly and efficiently. In their research, Bouman et al. (2017) studied and compared the existing literature regarding the ways to reduce the GHG emissions in shipping. With their comparison, they identified the most important factors that are capable of resolving this issue, and they managed to categorize them and compare the categories and their effect.

In particular, there are five main ways to reduce GHG emissions in shipping. The first is to modify the hull design of the vessels. By changing the vessel size, altering the hull shape, using LW materials, air lubrication, resistance reduction devices, hull coating or ballast water reduction, it may be possible to reduce CO_2 emissions up to 30%. The second category is power and propulsion system, which includes hybrid propulsion, propulsion efficiency devices, waste heat recovery and other smaller changes, which can lead to a reduction up to 20%. Moreover, another category consists of operation changes. By optimizing the speed of the vessels, better utilize their capacity, voyage optimization and other operational measures it is possible to significantly affect the emissions. Each of these changes can lead to CO_2 emissions reduction up to 40% (range from 5 to 40%, for each measure individually). Finally, the last two categories include alternative energy sources and alternative fuels. Alternative energy sources such as wind power, fuel cells, cold ironing and solar power can lead to emission reductions up to 25%. However, it is evident that alternative fuels are expected to have the most impact on reducing emissions. In their research they include Biofuels and LNG. Both have an important effect, however, biofuels can lead to a reduction up to 80% (Bouman et al., 2017).

Based on the abovementioned, it is immediately apparent that alternative fuels are expected to be one of the most important factors that will influence the next few years the maritime industry. This thesis aims to explore their potential in significantly reducing GHG emissions. Given the sector’s substantial contribution to global emissions, it is paramount to identify and implement effective solutions. By forecasting the prices and analyzing the economic and environmental impacts of various alternative fuels, this research provides critical insights into their viability and effectiveness. A comparison of the economic costs and the environmental implications of adopting fuels such as biofuel, methanol, ammonia, and hydrogen is crucial for the future of the shipping industry and it will assist to achieve the current global objective, net-zero emissions by 2050.

1.2. Research Question and Objectives

Motivated by the problem stated in the previous section, the decarbonization of the shipping industry and the adoption of alternative fuels, this thesis focuses on the following research question:

"Which alternative fuel type is considered the best to be used in the future to reduce the carbon emissions and achieve the IMO 2050 goals at the lowest possible cost?"

It is evident that to address this main research question, this study aims to provide a thorough analysis of various alternative fuels. By forecasting the future prices and identifying the strengths and weaknesses of alternative fuels, it is possible to determine which one is the most suitable to be adopted by the maritime industry. This analysis will consider a range of factors, including the economic feasibility, the environmental impact, and the operational implications of each fuel type. In addition to that, it will consider the supply chain dynamics of these fuels, as well as their commercial availability and widespread use. By providing a comprehensive assessment of these aspects, this study will provide valuable insights into the future of maritime fuel use, and it will support the efforts to meet the IMO 2050 emission reduction target in the most cost effective and sustainable way.

To adequately respond to the main research question, the following sub-research questions must be answered:

1. What are the potential future alternative fuels?
    - It is essential to identify and categorize all the potential alternative fuels, such as biofuel, methanol, ammonia, and hydrogen.

2. What are the strengths and weaknesses of each alternative fuel?
    - After the initial identification of the type of fuel, it is necessary to have a detailed analysis of each type, evaluating their advantages and disadvantages. This evaluation must concern their efficiency, their environmental impact, their availability, and the infrastructure requirements.
3. What are the ways of production of each type of fuel?
    - This question indicates the necessity to explore the different production methods for each alternative fuel. Principal factors that should be considered are raw materials, energy consumption and emissions in production.
4. What is the timeline for the utilization of new types of fuel?
    - It is important to establish what timeline is considered ideal to implement the utilization of alternative fuel. Factors such as the development of new technologies, the modification of the current fleet or the renewal of the current fleet must be considered.
5. What is the best model to predict the future prices of alternative fuels?
    - Based on the existing literature and new machine learning algorithms, it is necessary to identify which model and which programming language should be used for the forecasting of the future prices of alternative fuels.
6. What is the predicted cost of each alternative fuel?
    - After the implementation of the model, what is the outcome for each fuel individually.
7. What factors are affecting the alternative fuel prices?
    - Individually for each alternative fuel, it is essential to identify and analyse which factors influence the prices.

By addressing these sub-research questions, this study aims to provide a comprehensive analysis of alternative fuels for the maritime industry. The answers to the above-mentioned questions could be beneficial for policymakers and industry stakeholders in their efforts to a more sustainable and decarbonized future in the shipping industry.

1.3. Research Design and Methodology

This thesis aims to identify the most suitable alternative marine fuel, to contribute to the global efforts in reducing the carbon emissions and achieve the IMO 2050 objectives at the lowest possible cost. The research is divided into three main phases, literature review and theoretical background, model development and implementation and results analysis. This structure indicates that this research combines a qualitative and quantitative approach. The first part, including literature review and the theoretical background is the qualitative part, while the model implementation and its results are the quantitative part.

- Literature Review and Theoretical Background

1. Overview of current Literature: It is essential to analyze similar scientific studies to identify different methodologies and gaps in the current literature regarding price prediction methodologies.
2. Selection of Alternative Fuels: The first objective is to identify and categorize potential alternative fuels. Their selection is essential, and only feasible solutions should be taken into consideration. This analysis is based on existing research and expert opinions. The first sub-research question is answered in this part.
3. Evaluation of Strengths and Weaknesses: Detailed analysis of the advantages and disadvantages of utilizing the selected alternative fuels. By assessing factors such as efficiency, environmental impact, availability, and infrastructure requirements, it is possible to filter the alternative fuels and eliminate not viable options. The second sub-research question is answered in this part.
4. Analysis of Production Methods: It is important to explore the different production methods for each alternative fuel and examine their environmental impact. If an alternative fuel's production is non-sustainable, it should be eliminated from this study. The third sub-research question is answered in this part.

- Model Development and Implementation

1. Timeline for Fuel Utilization: Establishing an ideal timeline for the implementation of alternative fuels in the maritime industry is essential. Based on the current global fleet age, and the regulatory changes. The fourth sub-research question is answered in this part.

2. Development of Forecasting Model: Identification and development of a prediction model based on similar studies. The prediction model's purpose is to predict future alternative fuel prices. This answers the fifth sub-research question.
3. Data selection and preparation: Due to the limited availability of data for alternative fuels, data should be collected individually for each option of fuel. Proper modification is essential for the utilization of the selected model.
4. Factor Analysis: Identify the factors that affect the prices for each alternative fuel and answer the seventh research question.
5. Model Implementation: Based on the data and the factor analysis, the model must be tuned properly.

   - Results and Analysis

1. Cost Prediction and Analysis: Based on the determined timeline, a cost is predicted for all the alternative fuels (sixth sub-research question).
2. Comparative Analysis: Compare the predicted costs and benefits of each alternative fuel and answer the main research question of this study. This part combines the findings of the qualitative and quantitative research.
3. Conclusion and Recommendations: Presentation of insights and recommendations for the maritime industry based on this study.

This structured approach ensures a thorough examination of the studied topic, providing a clear pathway toward achieving a more sustainable future in shipping.

1.4. Thesis Structure

This thesis is organized into the following main sections, ensuring a logical flow and thorough exploration of the topic.

Introduction (Chapter 1): It is a summary of the thesis, where initially the problem is identified, and subsequently they are presented the research question and the sub-research questions. All the steps of writing this thesis are presented, to present the flow of the research.

Literature Review (Chapter 2): Focuses on a comprehensive review of the literature, concerning fuel price prediction methodologies. The studied scientific papers are analyzed, and an overview of the models, data, and evaluation metrics that are utilized is presented.

Alternative Fuels and Fuel Selection (Chapter 3): This chapter analyze alternative fuels for the maritime industry. This includes identifying future alternatives fuels, analyzing their strengths and weaknesses, and exploring their production methods. Moreover, there is a comparison analysis between the fuels and the selection of fuels for the model implementation.

Methodology (Chapter 4): It details the framework for forecasting the future prices of alternative fuels. Firstly, there is an analysis of the current maritime industry, regarding the age of the vessels. In this way, the timeline of the implementation of alternative fuels is projected. Subsequently, it presents the data and the collection and preparation process. Finally, the utilized prediction models are introduced and analyzed, to explain the rationale behind their selection. In addition to that, information regarding their implementation is presented.

Results and Analysis (Chapter 5): Presents the results of the study. That includes the predictions of future fuel prices and a complete comparison analysis of all the selected alternative fuels. This chapter will also discuss the implications of the findings for the maritime industry, and how the global objectives can be helped from these findings.

Conclusions (Chapter 6): Summarizes the key finding of the research and their significance for the maritime industry and identifies the limitations of this study. Additionally, there are suggestions for future research to further enhance the understanding of alternative fuels in the maritime industry and cover the limitations of this study.

2. Literature Review and Analysis

This section is an extended analysis of the current literature regarding studies similar to this study. Each of the analyzed research papers is studied individually to identify any possible gaps in the literature. The main focus is to understand the objective of each scientific paper, identify the datasets they utilize, the models they implement and the way they measure the performance of their models. All the analyzed papers are published scientific papers, the selection of which is based on their topic of research. All of the papers are focused on fuel price prediction, with the majority of them utilizing timeseries data for their forecasts. The order of the analyzed papers is based on their relevance to this study, and not in chronological order.

2.1. Literature Review of Fuel Price Prediction Methodologies

To begin with, in their research paper Luo et al. (2022) discuss their method to predict future methanol price. The study aims to develop a novel methanol price prediction model for smart coking plants to improve economic returns through intelligent production scheduling. Their key goals are to predict future fluctuations in methanol prices accurately and improve their prediction accuracy by addressing the limitations of existing models, particularly in processing complex, high-dimensional and nonlinear time-series data. They utilize historical methanol prices data, considering both time-dependent and periodic characteristics that influence price fluctuations. They utilize two different datasets with distinct characteristics. Their main data include historic methanol prices, information about imports and exports of methanol, information about the current inventory for each time series, and the production cost at each moment. Data cleaning and standardization are some important parts of their methodology, as well as handling the missing data and sorting the data accordingly. Their prediction method is called multicycle CNN-GRU and Attention Mechanism, where they utilize convolutional neural networks (CNN) and gated recurrent unit (GRU). CNN is usually used in in image, speech, and text recognition tasks but it can also be used in prediction projects and GRU neural networks are ideal for time series data. They combine these two models with attention mechanism, which can ameliorate the accuracy of the models and make them focus on the essential information in the data. Their model is called MCGAT, and it combines the abovementioned models. In their paper they analyze extensively how they implement their model, and they provide information regarding the performance of their model and the ways they evaluate it. In particular, they use mean absolute error, the root-mean square error, and the mean absolute percentage error as their performance indicators. By implementing different models, they compare the performance of their model with them, and they prove that their model has the optimal performance. Finally, a significance analysis is utilized to prove the validity of the prediction algorithm. By performing T-test they verified the statistical significant difference between the results from the different models.

Furthermore, a similar study was conducted by Stefanakos and Schinas (2014). In their study, their main goal was to forecast marine fuel prices, which affect the whole operation of the maritime industry. In their research, they examined two different multivariate cases. In the first one, the tetra-variate case, they utilized time series of bunker prices from four ports, Rotterdam, Fujairah, Singapore, and Houston. The examined fuel was HFO. Their goal was to predict the bunker prices four months ahead and then compare their results with the real data. It is important to mention that this time period is not random, but it was selected because the bunkering agreements are usually discussed and negotiated 4-6 weeks before the bunkering of the vessels. In their research, it was important to prove the non-stationarity of their data, which they achieved by performing three unit-root tests, the Augmented Dickey-Fuller (ADF) test, the Phillips-Perron (PP) test, and the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) test. In their second case, they used the abovementioned four time series plus four different versions in different times of bunkers prices from Rotterdam. All their data were collected from Clarkson’s database. They implemented a multivariate non-stationary stochastic model, originally presented by Athanassoulis and Stefanakos in 1995. It treats a long time series of bunker prices as a nonstationary stochastic process with periodic mean and standard deviation, allowing for seasonal pattern modelling. The model is extended to the multivariate case, where it accounts for interactions between different time series by using a covariance matrix to capture these dependencies. Seasonal characteristics are estimated through re-indexing and averaging procedures, and the model allows for the application of VARMA models if the residual components are stationary. This integrated approach is useful for forecasting future values of the time series by combining multivariate Gaussian processes with the estimated seasonal and residual components. Finally, they evaluated the performance of their model based on the Mean Absolute Percentage Error (MAPE) of their results. They forecasted up to 52 weeks ahead of the data, and their MAPE stabilized around 9.5% and 14.5%.

Moreover, a different approach was conducted by Kim et al. (2022) in their study. Their goal was to forecast LNG bunker prices. They believed that it is essential to forecast in short term the bunker prices in order to establish their cost management strategy. Their data consisted of time series, which offered information about the weekly prices of LNG bunkers from Singapore. The range of their data started from September 2019 until July 2021 and included 144 weekly time series. These data were divided into train and test data with a ratio of 8 to 2. Similarly to Stefanakos and Schinas (2014), they conducted a non-stationarity test, the ADF test. In their study, they used a simple Recurrent Neural Network (RNN) model to analyse their time series data. Unlike the traditional neural networks, the RNN gave them the opportunity to have feedback loops, allowing them to process sequences of data over time. Nevertheless, the simple RNN model has difficulties of capturing long term dependencies, which led them to employ Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) models. These models allowed them to manage memory and preserve long-term information. In this way they set up a supervised learning environment, which was using time series in order to predict future values. The model's performance was evaluated using standard metrics like Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE), with the Diebold–Mariano test employed to compare the statistical prediction performances of different models.

Additionally, another interesting research is published from Escribano and Wang (2021). Their ultimate objective was to forecast gasoline prices. They wanted to achieve that by advancing the literature on nonlinear econometric models and introduce their approach, a more general dynamic methodology that leverages the strengths of machine learning. Their data consisted of weekly time series of gasoline prices. They started on January 2010 until November 2019. They split these data in training and test datasets, 405 observations for the training and then 102 for the test. The authors aim to model deviations from linearity more effectively led them to utilize a flexible Random Forest (RF) method. This mixed RF approach is designed to improve the identification key variables driving structural changes in the economy and to generate more robust estimates in comparison to traditional nonlinear least squares methods. Except from their mixed random forest approach, they also implemented a simple random forest model and a LOGISTIC-ECM model for comparison reasons. Nevertheless, the mixed RF model displayed the most accurate results. As performance indicators, they used RMSE and MAE, both of which showed the best performance in the mixed RF model. The forecasting power of this model is considered strong both in the short-term and the medium-term predictions. It manages to capture the non-linearities in gasoline prices, especially the asymmetric price adjustments related to changes in international oil prices. However, even though the ECM model is less accurate, all three models provide reasonable forecasting capabilities based on the results.

A different approach in the forecasting or fuel prices was conducted by Miyagawa and Goto (2022). In their study, they analyzed and made a comprehensive review of existing literature on hydrogen production cost forecasts. Their aim was to analyze historical trends and assess the potential for broader adoption of hydrogen technologies. They examined 174 cost forecast data points from publications between 1979 and 2020, and they used statistical tests to compare trends. The tests that they utilized are the Kruskal-Wallis's test and the Wilcoxon Rank-Sum test. They implemented them in three different types of hydrogen, gray hydrogen, renewable electrolysis hydrogen and biomass hydrogen. Their results indicate that certain trends exist in the historical hydrogen cost forecasts.

Finally, it is important to include the study of Ghosh and De (2024), in which they predicted price of VLSFO in different ports by using Least Square Boosting and Facebook Prophet. Their data consisted of the spot prices of VLSFO, LSMGO and IFO380 in five different ports, in Amsterdam, Antwerp, Hamburg, Gothenburg, and Rotterdam. Their dataset started in January 2020 and lasted until January 2023. Their data showed nonlinear patterns in VLSFO price movements in all the researched ports. Their dataset is split in 80% training and 20% test data. The first step in their research was to employ the Minimum Redundancy Maximum Relevance (MRMR) technique. This technique identifies the most relevant explanatory variables for the predicted class, which in this case was the VLSFO prices. The MRMR algorithm selects features that exhibit high relevance while minimizing redundancy. In this way, it enhances the predictive power of the model. Following this, they utilized LSBoost, a gradient boosting method that optimizes the prediction accuracy through a sequence of regressions trees. LSBoost leverages the least squares loss function to improve model interpretability and computational efficiency. In addition to these two algorithms, they also implement Facebook's Prophet, which captures complex time series dynamics such as trends and seasonality by using Bayesian inference. By combing these three models, they created their own mixed model, capable of understanding the predictability of VLDFO prices and the factors that affect it. Finally, in order to evaluate their model, they deploy four performance metrics, the Nash-Sutcliffe Efficiency (NSE), the Theil Index (TI), the Index of Agreement (IA) and Directional Predictive Accuracy (DA).

2.2. Literature Analysis and Conclusions

To sum up, based on all the above-mentioned scientific papers there are many studies on price predictions concerning fuels. This extended analysis of these papers offers important insights on their methodology, their datasets, and the ways in which they measured the performance of their prediction models. Moreover, it facilitates identifying what is the research gap in the current literature. The majority of the models utilized are backbox models that only looks at historical prices and identifies the trends. The factors that affect the prices are not explained and the external influences are ignored. The following table (Table 1) includes all the key information extracted from the literature review. It is immediately apparent that most models rely heavily on time series data, such as historic prices and inventories. Additionally, the predominant metrics for evaluating the model performance are RMSE, MAE and MAPE. Regarding the model selection, there are different methodologies, the majority of which are based on machine learning or statistical prediction algorithms.

The key insight from this literature review is the identification of the types of data utilized in price prediction methodologies, the variety of models that are employed and the performance metrics that are utilized to evaluate these models. This information provides a better understanding of the current landscape in fuel forecasting research. This literature review does not directly provide answers to the research questions studied in this thesis. However, it helps to address the questions regarding the best model to predict the future prices and the factors that affect the alternative fuel prices.

Table 1 Literature on Fuel Price Prediction Comparison

Paper	Data Used	Model Used	Performance Metric
Luo et al. (2022)	Historic methanol prices, imports/exports data, inventory, production cost	Multicycle CNN-GRU with Attention Mechanism (MCGAT)	MAE, RMSE, MAPE
Stefanakos and Schinas (2014)	Bunker prices from 4 ports, HFO prices	Multivariate non-stationary stochastic model	Mean Absolute Percentage Error (MAPE)
Kim et al. (2022)	Weekly LNG bunker prices from Singapore	RNN, LSTM, GRU	MAE, RMSE
Escribano and Wang (2021)	Weekly gasoline prices (2010-2019)	Mixed Random Forest (RF)	RMSE, MAE
Miyagawa and Goto (2022)	Hydrogen production cost data points (1979-2020)	Statistical tests (Kruskal-Wallis, Wilcoxon Rank-Sum)	-
Ghosh and De (2024)	Spot prices of VLSFO, LSMGO, IFO380 in 5 ports	Least Square Boosting (LSBoost), Facebook Prophet, MRMR	Nash-Sutcliffe Efficiency (NSE), Theil Index (TI), Index of Agreement (IA), Directional Predictive Accuracy (DA)

Unlike the aforementioned studies, this research emphasizes on alternative fuels. By forecasting multiple fuels' prices and making a comparative analysis, the aim of this study is to identify which is the optimal alternative fuel for the maritime industry. Both the financial and the sustainability impact of the studied fuels are considered. This broader perspective sets this research apart, as it seeks to offer practical predictions which might be applicable in the future of the maritime industry. Furthermore, this study identifies external factors that affect the prices and models them for the forecasting.

3. Alternative Fuels and Fuel Selection

The transition to alternative fuels is crucial for the efforts of the maritime industry to decarbonize and meet its environmental targets. This chapter delves into the various alternative fuels that have been proposed as viable options to reduce greenhouse gas emissions from shipping. It provides a comprehensive overview of these fuels, including methanol, ammonia, hydrogen, and biofuels. By identifying and highlighting the strengths and weaknesses of each alternative fuel, this analysis aims to offer a clear understanding of their potential. The most crucial factors that are analyzed are environmental impact, availability and required infrastructure.

3.1 Alternative Fuels in Maritime Industry

As mentioned above, this study focuses on four alternative fuels, which are considered the most prominent options in the decarbonization of the maritime industry. These alternative fuels are methanol, ammonia, hydrogen, and biofuels. In the following sub-sections, each of these fuels is analyzed individually to offer a better understanding of them and their strengths and weaknesses.

3.1.1. Methanol

Methanol, which is also known as methyl alcohol, is mostly used in the chemistry industry, but it is also utilized as fuel. It was firstly found by Sir Robert Boyle in 1661. At ambient conditions, it is liquid, colorless and with high polarity and moderate vapor pressure. It is the simplest aliphatic alcohol, and its chemical formula is CH_3OH (Ott et al., 2012). In comparison to all the liquid fuels, it has the highest hydrogen-to-carbon ratio at regular ambient conditions. As a result, it is considered ideal to be used as an alternative fuel. Methanol can be used in both diesel and Otto internal combustion engines. Its boiling point is 65 °C and its freezing point -97.6 °C. Its octane number is 110 and its calorific value 19.9 MJ/kg. Finally, its ignition temperature is 470 °C and its density 791 kg/m^3 (MAN, n.d.).

3.1.1.1. Methanol Types and Production

There are four main types of methanol, categorized based on the way of its production. These types are brown, grey, blue, and green methanol. Brown methanol, derived from coal, is not expected to decrease well-to-wake carbon dioxide emissions due to how it is produced. Similarly, grey methanol, which is produced from natural gas, also falls short in the efforts to reduce greenhouse gas emissions. As a result, it is apparent that brown and grey methanol are not sustainable enough. Their production includes only the use of non-renewable resources, and it has extremely high carbon intensity, especially the brown methanol. Most of the methanol production is through the utilization of gas and coal (Marine & Offshore Bureau Veritas, 2022).

On the other hand, blue and green methanol can have a significant impact on the decarbonization efforts. Blue methanol is produced using blue hydrogen along with carbon capture technology. In particular, the process is similar to grey methanol where natural gas is used. After the reforming, there are special carbon capture and storage equipment that massively reduces the emissions during the production. Subsequently, blue hydrogen is utilized for the further process and the final production of blue methanol. This process shows that the production of blue methanol uses some non-renewable resources, but it has significantly lower carbon intensity than gray and brown methanol. Green methanol is either bio-methanol, made from biomass, or e-methanol, produced from green hydrogen, captured CO_2 and renewable electricity (Marine & Offshore Bureau Veritas, 2022). Both types of green methanol use mostly renewable resources and have low carbon intensity. Hence, it is evident the types of methanol that concern the maritime industry are blue and green methanol. These types can have a significant impact in the fight towards decarbonization.

3.1.1.2. Methanol Benefits and Disadvantages

It is essential to further discuss methanol's advantages and disadvantages in order to determine its suitability as a marine fuel. To start with the benefits, it is important that methanol remains in a liquid state under ambient conditions. In this way, it can be used as drop-in fuel with existing internal combustion engines. Moreover, the production of methanol is already on a large scale (industrial scale), which makes it easier to cover the increased demand of green fuel in the maritime industry. In addition to that, the bunkering infrastructure is already advanced and increases significantly every year. Also, methanol is accepted by the IGF Code, which is part of the IMO interim guidelines as of November 2020. That proves its suitability for the maritime industry and that it can be utilized immediately. Regarding its properties as fuel, it has some interesting characteristics. It is soluble to water, which means that it can be easily decomposed. That can prevent future environmental disasters from ship accidents that lead to fuel leaks. Additionally, its octane number (110), is considered high, and it shows that it is an efficient fuel type. Finally, as it is mentioned above, especially when green or blue methanol is used, the well to wake GHG emissions are significantly lower in comparison to when traditional fuels are utilized. This is the ultimate goal, to reduce the emissions and maintain a positive environmental impact (MAN, n.d.).

On the other hand, there are some challenges regarding the utilization of methanol. As mentioned above, the majority of methanol is produced from gas and coal. The production of green and blue methanol is limited, which leads to higher prices than the traditional fuels. Moreover, the toxicity of methanol is a prominent issue. If it is ingested it can be deadly, which leads for the need to prepare the crews, and train them properly to safeguard them from this danger. In addition to its toxicity, it is highly flammable. Both these two properties lead to more complex safety systems than the ones used with traditional fuel types. Furthermore, methanol has a significantly lower energy density compared to conventional fuels. It requires almost 2.25 times more fuel by mass to achieve the same energy output. That will lead to increased fuel tank capacity in the ships and higher fuel costs. Additionally, methanol is corrosive. That may cause damage to fuel systems over time, and it is probable to have leakages in the pipes of the ships or the tanks. The fuel tanks must be properly sealed, coated and protected. Finally, it can absorb moisture from the atmosphere. Most of the abovementioned indicate that methanol needs to be handled cautiously. By following the rules and the precautions indicated by IMO’s guidelines the ships can utilize it safely and take advantage of its benefits (MAN, n.d.)

3.1.1.3. Methanol Project, Supply, Demand and Storage

Methanol is already in use since 2006 in the maritime industry. The first project was METHAPU (Validation of Renewable Methanol Based Auxiliary Power System for Commercial Vessels). This project tested the utilization of methanol in Solid Oxide Fuel

Cell. It was test in a Car Carrier, where they tried to provide it with electrical power to cover its services. After that, more projects followed the lead and continued the research of methanol in ships. In particular, chronologically ordered, the next projects where Effship, SPIRETH, “Methanol: The marine fuel of the future”, MethaShip, Waterfront Shipping, LeanShips, proFLASH and SUMMETH. Most of these projects were successful and provided insights in the utilization of methanol in ships. They uncovered the dangers that exist and the benefits of using methanol. At the same time, the most prominent engine manufacturers in the shipping industry researched the use of methanol. Wartsila and MAN were among the first engine manufacturers that created dual fuel methanol and MGO marine engines (Ellis and Tannerberger, 2015).

Regarding the production of methanol, it is a significant and growing industry. In recent years, methanol demand has surged, especially in China, where it is used increasingly as a gasoline alternative or additive (Ellis and Tannerberger, 2015). By taking a look in the global market, methanol demand shows an upward trend. This trend is expected to continue, with annual demand already climbing from 61 million metric tons in 2012 to 90 million tons in 2022. There are projections that this demand will reach 136 million tons in 2032 (CHEMANALYST, 2023). Meanwhile, this escalating demand has spurred increased production efforts. Notably, in the United States, it has shown a significant increase. It is apparent in the following Figure (Figure 1) that methanol productions show a steady increase on a yearly basis. In 2011, less than one million metric tons of methanol were produced in the United States. However, that increased to almost 6 million metric tons in 2019. Nevertheless, United states, is not the only country that contributes to the global production of methanol. The total global annual production was 100 million tons in 2013 (only 1 million tons in the US). Europe also contributes to methanol production, with significant facilities located in Norway and Iceland. This widespread and diversified production base highlights methanol’s potential as a key player in the future energy landscape (Ellis and Tannerberger, 2015).

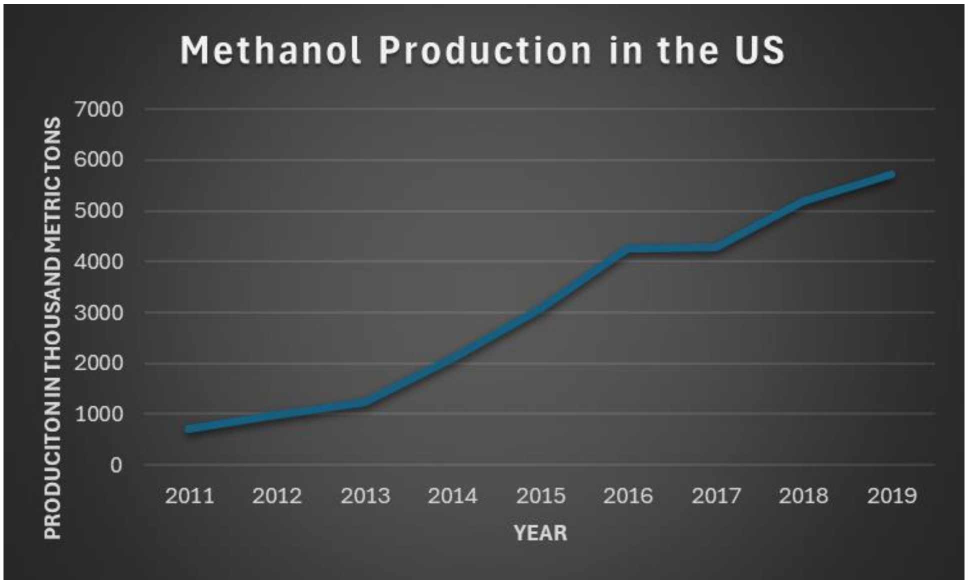

Figure 1 Methanol Production in the US (Statista, 2023b)

Finally, from a storage perspective, methanol is relatively easy to manage compared to other emerging fuels. Unlike fuels that require cryogenic tank systems or high-pressure conditions, methanol can be stored in standard tanks, without these additional requirements. That offers flexibility in tank design and shape. Nevertheless, the low volumetric energy density of methanol leads to the need of increased storage capacity (at least 2.5 times larger). Safety considerations are also paramount. The tanks and pipelines that store and transport methanol must be double walled to prevent leaks (MAN, n.d.).

3.1.1.4. Methanol Key Takeaways

In summary, methanol presents itself as a versatile and promising alternative fuel for the maritime industry. Its various forms, brown, grey, blue, and green, offer different levels of environmental impact. While the current production relies on fossil fuels, leading to higher carbon emissions in brown and grey methanol, the development of blue and green methanol provides a pathway toward a more sustainable shipping industry. The ongoing advancements in methanol production, coupled with its favorable properties as a marine fuel, suggest that with the right investments and regulatory support, methanol could play a significant role in the decarbonization of the industry. However, the challenges associated with its lower energy density, corrosiveness, and toxicity must be carefully managed to ensure its safe and effective use. The regulatory authorities are responsible to set effective precautions and regulations that will mitigate the dangers and help the industry to take advantage of the sustainable benefits of methanol. As the industry continues to evolve, methanol's potential to contribute to a cleaner future becomes increasingly clear, making it a key focus in the transition to sustainable maritime energy.

3.1.2. Ammonia

Ammonia is a colorless gas, composed of nitrogen and hydrogen. Its chemical formula is NH_3 and it is mostly used as a fertilizer. It was firstly created in 1774, by an English physical scientist named Joseph Priestley. It is one of the most produced chemicals in the world (top five in the United States). The most common way to produce it is by the Haber-Bosch process, where elemental nitrogen is reacting directly with elemental hydrogen. It has a sharp and penetrating odor. Except from the fertilizer industry, it has other uses too. In particular, it is used to create explosives such as TNT, nitroglycerin, and nitrocellulose. Moreover, it is utilized as a catalyst in the production of various resins or in some metallurgical processes Its freezing point is -77.7 °C and its boiling point is -33.35 °C (Zumdahl, 2019). The energy density of ammonia is 12.9 MJ/L, which is significantly lower than the one of MGO (35.95 MJ/L), however, its octane number is around 130 (Laursen et al., 2023a).

3.1.2.1. Ammonia Types and Production

In the same way as with methanol, there are four types of ammonia. According to ALFA LAVAL et al. (2020), these four types are conventional ammonia, blue ammonia, green ammonia, and hybrid green ammonia. Traditionally, ammonia is produced from fossil feedstocks, natural gas, but also coal can be used. The carbon footprint of ammonia production varies based on the efficiency of the plant and the type of feedstock used. The modern plants, which are more efficient, can have a carbon footprint as low as 1.6 tons of CO_2 per ton of ammonia. Meanwhile, older plants used to emit almost 2 tons of CO_2 per ton of ammonia, or even 3 tons of coal is used. Blue ammonia is produced using the same methods as conventional ammonia, but with the added step of capturing, liquefying, and storing the CO_2 produced during manufacturing (carbon capture storage technology). This reduces the overall carbon footprint of the ammonia produced. On the other hand, green ammonia, also known as renewable ammonia or sustainable ammonia, is produced entirely from renewable electricity, air, and water, with no fossil feedstocks involved. As a result, green ammonia is considered to have zero CO_2 footprint. Nevertheless, this does not include the full life-cycle emissions, such as those from plant construction and transportation to bunkering sites. According to projections, green ammonia could reduce life-cycle emissions by more than 90% when produced using wind power, and by more than 75% when produced using solar energy. These reductions are expected to improve even more over time as the production of renewable energy technologies becomes more efficient and less carbon intensive. Finally, hybrid green ammonia is produced in facilities that utilize both fossil fuels and renewable electricity. These hybrid plants can be created by modifying the existing ones, where conventional ammonia was manufactured in the past. By having this dual processing capability, hybrid plants are an attractive option for gradually shifting to more sustainable ammonia production.

3.1.2.2. Ammonia Benefits and Disadvantages

It is essential to analyze the benefits and the challenges of utilizing ammonia as a marine fuel. To begin with the advantages of using ammonia, one of its most important advantages is its potential to be carbon-free. As mentioned above, when produced using renewable energy sources, ammonia does not release carbon dioxide when burned (green ammonia). It emits only nitrogen and vaporized water. This makes it an environmentally friendly option for energy storage and combustion. Moreover, ammonia has a high energy density. That makes it an efficient way for storing and transporting energy over long distances. Its storage requirements are also more manageable compared to other energy carriers like hydrogen. It only needs modest pressure and a relatively mild temperature of -33 °C, which simplifies handling and reduces costs. Furthermore, ammonia promotes the adoption of renewable energy by serving as a reliable storage solution for intermittent renewable sources, such as wind and solar power. Its production using renewable energy also drives demand for renewables, contributing to the broader energy transition. Lastly, ammonia’s infrastructure already exists. It is developed for its use in the fertilizer industry and that can be leveraged to facilitate its integration into the energy sector. That makes it a practical and cost-effective option for future energy systems. Its price is already relatively low for a carbon neutral fuel (Koons, 2023).

On the other hand, ammonia utilization as a fuel comes with several notable disadvantages that present challenges for its widespread adoption. One of the primary concerns is its toxicity. Ammonia is a highly toxic substance, and exposure to high concentrations can cause severe health issues. It is toxic both to human and aquatic life. Some of the most common hazards include severe skin burn, damage to the eyes or the respiratory system, skin illnesses such as dermatitis and lung injuries. Considering the extremely low temperature that it has when it is liquid form, it can also lead to frostbites (Laursen et al., 2023a). This makes essential to stringent safety measures to protect workers and prevent accidental releases. Additionally, while ammonia combustion does not produce carbon dioxide, it can generate nitrogen oxides, which are some of the most dangerous greenhouse gases that contribute to air pollution and the global warming. This issue is particularly problematic when ammonia is burned in internal combustion engines. To reduce these emissions, it is necessary to utilize advanced combustion technologies and catalytic converters. That increases the complexity of utilizing ammonia and increases the costs of using it as a marine fuel. In addition to that, there are important infrastructure and technological challenges associated with ammonia as a fuel. The electrolyzer technology required to produce green hydrogen, a key feedstock for green ammonia, is not yet commercially scaled, limiting the availability of carbon-free ammonia. As a result, it is essential to further improve the infrastructure for ammonia manufacturing, transport, and storage to support its large-scale adoption as an energy carrier (Koons, 2023). Furthermore, some of the physical and chemical properties of ammonia introduce several risks. The low temperatures, which is needed for ammonia's storage, can cause material embrittlement, leading to a loss of elasticity in structural materials. Ammonia is also flammable, with a lower flammability limit of 15%, and an upper limit of 28% by volume in air. That and other factors lead to high explosion and fire hazard from ammonia. Finally, ammonia's alkaline and corrosive nature can lead to material degradation and equipment damage over time, raising maintenance costs and operational challenges (Laursen et al., 2023a). All these factors highlight the significant dangers associated with ammonia as a fuel, underscoring the need for careful handling and advanced safety measures.

3.1.2.3. Ammonia Projects, Supply, Demand and Storage

The utilization of ammonia as a marine fuel is a concept that maritime industry studies increasingly the last few years. According to Cames et al. (2021), there are already several projects considering the use of ammonia in the maritime sector. In particular, both 2-stroke and 4-stroke internal combustion engines are being researched by the most prominent engine manufacturers. They examine the sole utilization of ammonia as fuel, but also the dual fuel propulsion system. Except from the engine development, the ammonia supply chain is studied, in order to be ready to handle the increased demand in the future years. In addition, the authorities examine how the infrastructure around the ports can be utilized to accommodate the needs of adopting the use of ammonia as marine fuel. In all these projects, various parties are collaborating. This indicates the global belief that ammonia is among the best candidates as the marine fuel of the future.

It is essential to analyze the supply and the demand of ammonia. From the figure below (Figure 2), it is immediately apparent that the production of ammonia is increasing through the years. Currently, it is around 180 million metric tons per year. According to ALFA LAVAL et al. (2020), only 75 percent of the current production capacity is used. As a result, the worldwide production capacity of ammonia is estimated around 243 million metric tons. To cover an essential part of the current marine fuel consumption, that capacity should be increased by at least 30%, which means that the current ammonia production should be increased by around 150 million metric tons. These data indicate that to utilize ammonia as a marine fuel, its production should increase drastically. Currently, the demand for ammonia as fuel is limited, however, that is going to change in the coming years. Based on linear projections, by 2040 the global demand for ammonia will reach 600 to 1000 million tons per year. Nevertheless, considering that only the green ammonia is carbon neutral, the current green ammonia production is only 5 million metric tons per year. As a result, it is apparent that ammonia's production needs to increase at least 3-4 times per year to reach the required production (Laursen et al., 2023a).

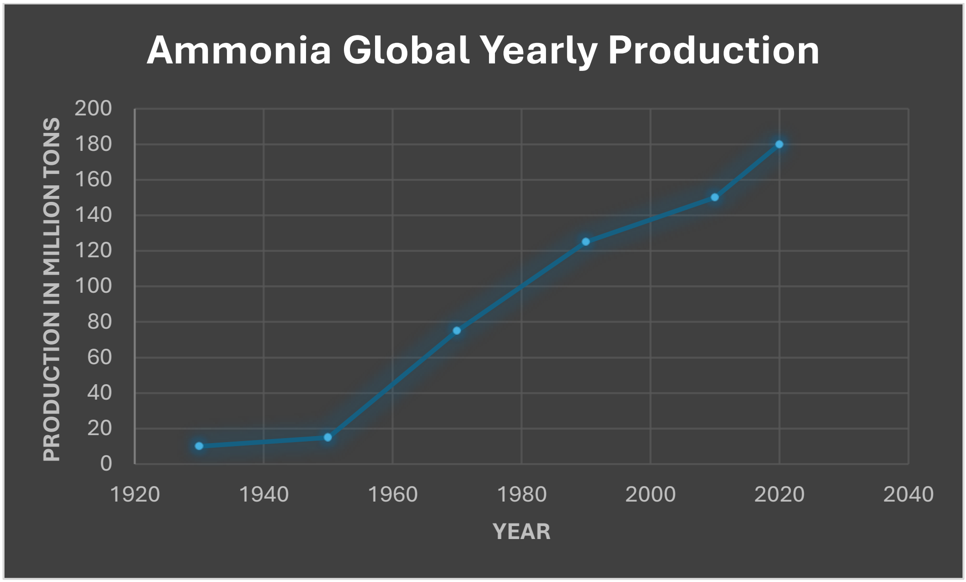

Figure 2 Ammonia Global Yearly Production (ALFA LAVAL et al., 2020)

Storage is one of the main concerns regarding the utilization of ammonia. Already, around 25-30 million tonnes of ammonia are transported globally each year, including 18-20 million tons by ship. That indicates that the storage and distribution infrastructure for ammonia is advanced. One of the most significant challenges in ammonia storage is the risk of stress corrosion cracking in carbon steel pressure vessels. This problem became apparent in the 1950s when ammonia was widely used in the United States agricultural sector. To address these issues, they were developed guidelines, which were later became part of IMO's IGC Code (a code that governs the construction and equipment of ships carrying liquified gases). Ammonia's ability to be stored in a liquefied state at moderate pressures and temperatures offers significant advantages over other gaseous fuels. In this way, its storage is possible with more cost-effective materials such as carbon manganese or low-nickel steels. Finally, the fact that the existing LPG carrier fleet can carry ammonia, provides a readily available infrastructure that could facilitate the adoption of ammonia as a marine fuel. This will make the transition smoother and more cost-effective (Laursen et al., 2023a).

Given the fact that ammonia and hydrogen are produced through the same similar processes, it is important to establish what is the advantage of ammonia against hydrogen. The utilization of hydrogen as fuel presents significant challenges. It requires storage either in a highly compressed state, 250-700 bar, or as a liquid at extremely low temperatures, -253 °C, to minimize the onboard storage space. Even at its liquid form, hydrogen occupies about four times more volume than fuel oil. Moreover, storing liquid hydrogen requires insulated spherical tanks to reduce heat ingress. That leads to an increased storage volume. As a result, ammonia is generally favored over hydrogen due to its higher energy density by volume, higher boiling point, and the fact that marine engines are being developed to use ammonia with similar efficiency to hydrogen. Finally, converting hydrogen into ammonia using the Haber-Bosch process incurs relatively low energy losses, further positioning ammonia as a more practical choice for widespread use as a marine fuel (Laursen et al., 2023a).

3.1.2.4. Ammonia Key Takeaways

To sum up, ammonia presents a compelling option as a marine fuel, offering both significant advantages and notable challenges. The potential to produce a carbon free fuel, green ammonia, could be the key towards the decarbonization of the maritime industry. The existing infrastructure for its storage and transportation further enhances its viability. Nevertheless, the adoption of ammonia as a marine fuel is not without risks. Some of the most prominent issues includes its toxicity, the potential for stress corrosion cracking and the complexities of safe storage and handling. By addressing these challenges, through continued research and technological advancements, ammonia will succeed to become the future marine fuel and it will successfully integrate into the maritime industry.

3.1.3. Hydrogen

Hydrogen, often mentioned as the fuel of the future, is emerging as the solution in the global shift towards cleaner energy. The first researcher who thought about the concept of hydrogen as a fuel was an engineer, called Lawaceck, in 1968. Subsequently, the first paper regarding the hydrogen economy was published in 1972 by Appleby. After that, more researchers started to look into hydrogen (Bockris, 2013). So far, hydrogen is widely used as a building block for many products, mainly chemical and pharmaceutical. One of these products is the above mentioned, ammonia. Hydrogen is colorless, without an odor and in gas form at atmospheric temperature and pressure. Its energy density is 8.51 MJ/L (MGO has 35.95 MJ/L) and its lower heating value is 120 MJ/kg. Its auto-ignition temperature is 585 °C and its boiling point is -253 °C. Finally, its octane number is more than 130 (Laursen et al., 2023b).

3.1.3.1. Hydrogen Types and Production

As with methanol and ammonia, there are several ways to produce hydrogen, based on which there is a distinction between different types of hydrogen. According to Laursen et al. (2023b) and Sürer and Arat (2022), there are four main types, grey, blue, turquoise, and green. Gray hydrogen is produced from methane or coal (fossil sources), either by steam methane reforming (SMR) or autothermal reforming (ATR). SMR is the cheapest way right now to produce industrial hydrogen. Gray hydrogen production leads to CO_2 emissions, which makes it a non-attractive option for the future. Blue hydrogen is produced in the same way as the gray hydrogen, however, carbon capture and storage systems are utilized to capture the carbon emissions and store them for future use. Its production is more expensive, due to the additional equipment that it is needed, and there is still space for improvements, as, the emissions are not completely zeroed (lower than 95% emission reduction). Another drawback of blue hydrogen is that its production is dependent on fossil fuels. Turquoise hydrogen is produced only from methane after pyrolysis. The carbon is transformed into solid carbon, which facilitates its transportation. It is still under research and its production is in pilot phase. Finally, green hydrogen is the most sustainable type of hydrogen. It is produced from renewable energy sources, and it is considered to be one of the solutions towards decarbonization. There are four ways to produce green hydrogen. Firstly, it can be produced through renewable energy and water. After the electrolysis of the water, the outcome is the production of green hydrogen and emission of oxygen in the atmosphere. Subsequently, another way to produce green hydrogen is the direct solar hydrogen production, where the sunlight is used as an energy source to retrieve the hydrogen from the water and emit oxygen. Moreover, the third way to produce green hydrogen is biomass fermentation, which is a biochemical process. It is an advanced process (technologically), and it requires less energy than the other processes. Finally, the last way to produce it is thermochemical biomass conversion, which is a combination of pyrolysis and gasification. This method needs biomass, which is firstly decomposed and then turned into the green hydrogen.

3.1.3.2. Hydrogen Benefits and Disadvantages

It is important to analyze the benefits and drawbacks of hydrogen as a fuel, to have a better understanding of it, and decide if it is the future marine fuel. One of its most significant advantages is its high flame propagation rates. That enables rapid and efficient combustion across a wide range of temperatures and pressures. This characteristic makes it possible for hydrogen fueled engines to achieve high power output and efficiency. Moreover, unlike the conventional fuels, hydrogen combustion does not emit carbon monoxide or dioxide. The primary emissions are water vapor and nitrogen oxides. Another notable benefit is its high effective octane number (more than 130 as mentioned above). This allows more efficient combustion and higher compression ratios, contributing to better engine performance and higher thermal efficiency. Furthermore, hydrogen disperse quickly, which minimizes the risks of fire and explosion in the event of a leak. That enhances the safety (Karim, 2007). Nevertheless, as it is immediately apparent, the most important benefit of hydrogen is that it can be produced without emissions, and it can be combusted without emissions, especially the green hydrogen. That makes it an attractive option as an alternative fuel. Moreover, in the hydrogen-based engines (fuel cells), there are no moving parts, which leads to significantly lower noise and lower maintenance costs (Sürer and Arat, 2022).

On the other hand, while hydrogen holds significant promise as a future fuel for shipping, it also presents several notable challenges that need to be addressed before it can be widely adopted. One of the primary limitations is the difficulty of storing hydrogen efficiently on-board ships. Compressed gas storage leads to low storage density, even at high pressures. This not only limits the amount of hydrogen that can be stored, but also increases costs and safety risks due to the need for more robust materials and complex handling systems. Liquid form also presents some difficulties. The process of liquefying hydrogen is highly energy intensive because it requires extreme cooling to maintain hydrogen at -253°C. The cryogenic technology that is needed is expensive, which makes the operational costs associated with maintaining liquid hydrogen storage extremely high and hydrogen a less viable option for many shipping applications. Furthermore, the transportation of hydrogen shows some additional complexities. Although liquid organic hydrogen carriers and ammonia are viewed as more cost-efficient alternatives for long-distance hydrogen transport, integrating them into merchant shipping would necessitate significant modifications to onboard storage tank designs. These limitations illustrate that hydrogen shows promise primarily for short sea vessels. Technological advancements and future research are required so that it can be more widely adopted (Laursen et al., 2023b).

3.1.3.3. Fuel Cells

Considering hydrogen as a marine fuel, it is essential to have a better understanding of fuels cells. Fuel cells are devices that generate electricity by converting chemical energy from a fuel, such as hydrogen, into electrical energy. The electrical energy is produced through an electrochemical reaction with oxygen or another oxidizing agent. Fuel cells require a continuous supply of fuel and oxygen to maintain the reaction, allowing them to produce electricity as long as these inputs are available. They offer several advantages such as higher energy efficiency, low to zero emissions and quieter operation compared to traditional combustion engines. The utilization of fuel cells leads to the need of additional equipment to convert the generated electrical power into rotational energy for propulsion. This setup typically includes fuel cell stacks, an electric motor, and a battery system. In this way it is possible to handle on-board energy needs efficiently. The average lifespan of fuel cells is estimated at 10 years. Moreover, their efficiency in converting energy to propulsions is around 55%, significantly higher than the efficiency of internal combustion engines, which is around 40% (Laursen et al., 2023b). Nevertheless, fuel cell technology is still under development, as it is modern technology. The major barrier of its utilization is its cost, which in the future is expected to be reduced and more attractive to the shipping industry.

3.1.3.4. Hydrogen Projects, Supply, Demand and Storage

During the last decades, there are numerous projects that show the development of hydrogen and its utilization in marine vehicles. In their paper, Sürer and Arat (2022) present some examples of vessels that utilize hydrogen as a fuel. Most of the vessels have hybrid systems that combine diesel engines and fuel cells (hydrogen). It is apparent that the first marine project that they present started in 2003, and during the last years there is an increasing number of projects. Similarly, based on EMSA's report (Laursen et al., 2023b) there is an increasing number of green hydrogen production projects. In 2021, the majority of the produced hydrogen was gray and the global electrolyser capacity was only 0.3 GW. However, based on the global announced plans, this capacity the next years will increase to 260 GW, making it possible to massively increase the production of green hydrogen.

The supply of green hydrogen is immediately connected to the capacity of electrolysers, based on the way of its production that is mentioned above. Figure 3 illustrates the current production of green hydrogen and the projections for the future. Currently, the 0.5 to 1 million metric tons of green hydrogen that are produced yearly are not enough to cover the global needs. This production has to increase massively to assist in the efforts towards sustainability, not only in the maritime industry, but in all carbon emitting industries. Based on the estimations, in 2040 the global green hydrogen capacity will be in between 17 and 30 million metric tons, however, the required capacity for shipping will be in between 93 and 156 million metric tons (Laursen et al., 2023b). These data show that despite the efforts and the increasing number of projects regarding the production of green hydrogen, there is still a necessity to further increase the global production of this carbon free fuel.

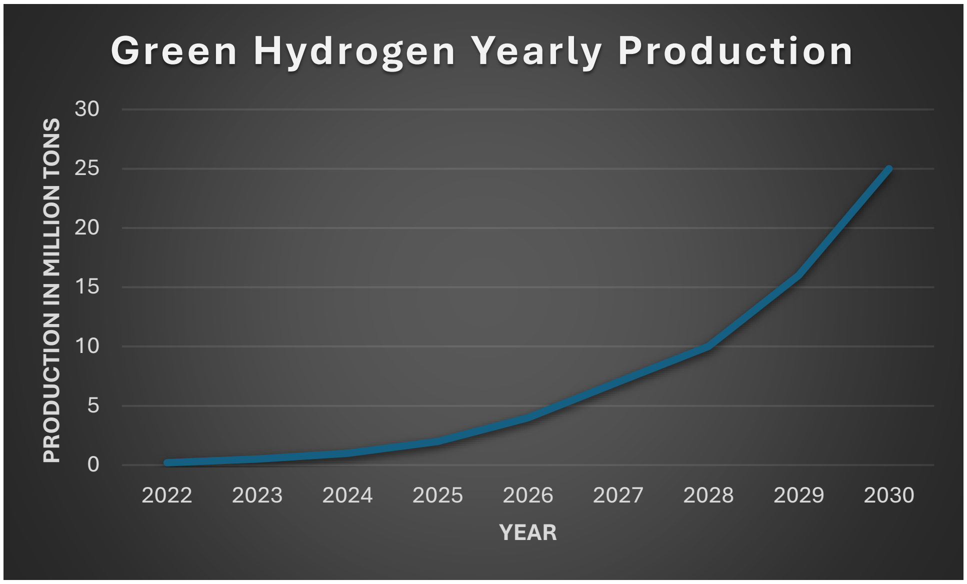

Figure 3 Green Hydrogen Yearly Production (BloombergNEF, 2022)

Hydrogen storage, as mentioned above, is a critical aspect for the practical use of hydrogen. Current technologies mainly involve storing hydrogen as compressed gas or in liquefied form. However, both methods have significant limitations that are mentioned in the drawbacks section above. Both these methods are suitable for temporary use in the emerging hydrogen economy, however, they are not ideal for long term solutions. There are predictions, based on which, in the future, hydrogen storage will utilize solid-state materials that can either chemically bind or physically adsorb hydrogen at densities greater than that of liquid hydrogen. The promising advancements in nanotechnology and material science are paving the way for more efficient hydrogen storage. Nevertheless, ongoing research is still required to identify materials that can meet all these criteria while also being cost-effective, safe, and durable (Crabtree and Dresselhaus, 2008).

3.1.3.5. Hydrogen Key Takeaways

To conclude, hydrogen holds significant promise in the transition towards a cleaner energy landscape. However, while its potential is vast, the challenges associated with hydrogen storage and production are equally formidable. Current storage methods, such as compressed gas and liquefied hydrogen, are practical in the short term but fall short on efficiency on long-term use. Further advancements in technology are needed to ameliorate the hydrogen storage and increase even more its production, especially the one of green hydrogen. As the global push for sustainability intensifies, expanding even more the production of green hydrogen and refining its storage will be critical steps in realizing hydrogen's role as a cornerstone of a sustainable energy future, especially within the maritime industry.

3.1.4. Biofuels

Biofuels are another alternative for the maritime industry to replace the carbon-based conventional fuels. They are a source of renewable energy, as, they are made from biomass. Despite their environmentally friendly side, many critics are concerned about their utilization due to the economic and environmental costs of the refining process, as well as the potential loss of large areas of arable land that could otherwise be used for food production (Lehman and Selin, 2018).

3.1.4.1. Biofuels Types and Production

According to Laursen et al. (2022) there are several types of biofuels that can be utilized in the maritime industry. These types of biofuels are categorized into four main groups, biodiesels, bio-alcohols, biocrudes and gaseous biofuels. Biodiesels and bio-alcohols can be used as drop-in fuels for distillate marine fuels, while biocrudes are appropriate replacements for conventional fuel oils like HFO, VLSFO, and ULSFO. Gaseous biofuels, such as liquefied biomethane (LBM), can serve as drop-in substitutes for fossil-derived liquefied natural gas (LNG). To have a better understanding of these four fuel groups, they should be analysed individually.

Biodiesels are produced from various feedstocks, such as crops, waste residues or non-food biomass. There are several production pathways, which have an influence on their GHG reduction potential. Typically, they are used as drop-in replacements for commonly used distillates like marine gasoil. The most common biodiesels are FAME, HVO, FT Diesel and DME. FAME, which stands for Fatty acid methyl ester, is the most ordinary form of biodiesel. It is primarily utilized in the road transport sector. It is produced through a transesterification process, where bio-oil reacts with methanol or ethanol, yielding FAME as the main product, along with glycerol and water as by-products. As feedstock, usually rapeseed oil, palm oil, used cooking oil and soybean oil are being used. It is a suitable alternative to plant oils for diesel engines and can replace marine diesel oil and MGO. Nevertheless, engine modifications might be necessary for the proper utilization of the engines. It is considered a drop-in biofuel, often used in blends of up to 30% with fossil fuels. Another biodiesel is the Hydrotreated vegetable oil (HVO), which is also known as renewable diesel. It is produced through the hydrotreatment of various feedstocks, including vegetable oils, animal fats and used cooking oils. This process has two main stages. Firstly, hydrogen is used to remove oxygen and saturate double bonds in the molecule, forming alkanes and then these alkanes are isomerized and cracked to produce a fuel that is close to diesel. It is a high-quality fuel, and it is used as a drop-in fuel without significant modifications to the diesel engines. Moreover, Fischer-Tropsch (FT) diesel is another type of biodiesel, which is produced using a combination of gasification and Fischer-Tropsch synthesis. In this process, biomass is gasified at high temperatures and pressures to produce syngas, a mixture of hydrogen and carbon monoxide After a catalytic reaction, this syngas is cleaned and converted to a biodiesel fuel. It can be used alone or blended with a carbon-based fuel. Finally, the last biodiesel fuel is Dimethyl ether (DME), which is produced through the gasification of biomass, followed by catalytic fuel synthesis. For its production, a wide variety of biomass feedstocks can be used. DME can be blended with marine gasoil (MGO) or marine diesel oil (MDO) in small percentages with limited engine modifications, although higher blends are limited by storage and fuel supply constraints. To use DME as a pure fuel, dedicated engines are required (Laursen et al., 2022).

Similarly, bio-alcohols are also liquid biofuels derived from multiple feedstocks and production pathways. The most common within the maritime industry are bioethanol and bio-methanol. Bioethanol is a renewable fuel, which is primarily produced through the fermentation of sugar and starch crops. Its production includes three main steps, pre-treatment, hydrolysis, and fermentation. Although it has potential as a drop-in fuel, it requires engines and fuel systems specifically designed for ethanol use. Furthermore, bio-methanol is produced by gasifying biomass and synthesizing the resulting gas into methanol. The feedstocks for bio-methanol include lignocellulosic biomass or wet biomass. It can be blended in small amounts with marine diesel for use in marine engines or used in higher percentages in adapted multi-fuel engines, or even as a 100% methanol fuel in direct-methanol fuel cells (Laursen et al., 2022).

The difference from the previous types of biofuels with biocrudes, is that they are not refined liquids that come from biological origin. There are 4 types of biocrudes, Straight Vegetable Oil, Pyrolysis Oil, HTL Bio-crude, and Solvolysis Oil. All four of them can replace fuel oils. Straight Vegetable Oil (SVO) is a type of biocrude obtained directly by extracting oil from biomass without any intermediate production steps. SVO can be used as a direct fuel in marine diesel engines or as a feedstock for biodiesel production. Ships that typically run on intermediate fuel oil (IFO), heavy fuel oil (HFO), very low sulphur fuel oil (VLSFO), or ultra-low sulphur fuel oil (ULSFO) can switch to SVO or a blend of SVO and traditional fuel oil. By blending it, there is a reduced risk of damaging the engine. Additionally, pyrolysis oil is produced by heating biomass at high temperatures, from 300 to 650 °C, in the absence of oxygen. This process is called pyrolysis. There are two types of pyrolysis, slow pyrolysis, and fast pyrolysis. Pyrolysis oil has high viscosity, corrosiveness, and other challenging characteristics. As a result, it is not compatible with the existing marine engines without modifications. Furthermore, Hydrothermal Liquefaction (HTL) is a bio-oil similar to crude oil. It is produced from biomass using HTL technology. This process needs high temperatures and pressures and water to act as solvent, reactant, and catalyst. It is not compatible with existing marine engines, and it is not considered a drop-in fuel. However, it can be blended with marine gas oil (MGO), or marine diesel oil (MDO). The last biocrude is solvolysis oil, which is produced through a thermal process similar to hydrothermal liquefaction but uses a supercritical organic solvent under high temperature and pressure. It is an efficient way of converting biomass into bio-oil and it can be combined with bioethanol. It can be blended with marine diesel oil or even processed into a drop-in fuel with low oxygen content (Laursen et al., 2022).

Finally, the last group of biofuels is gaseous biofuels, which is mainly biomethane. There are three main feedstock groups that are used for its production, lignocellulosic residues, algae, and lignocellulosic crops. After digestion or gasification, Liquefied

Biomethane (LBM) is produced, a fuel that can replace Liquefied Natural Gas (LNG) (Laursen et al., 2022).

3.1.4.2. Biofuels Benefits and Disadvantages

In general, the utilization of biofuels has many benefits and drawbacks. One of their main advantages is that they can be blended and utilized with carbon-based fuels without any engine or fuel system modifications. That is feasible mostly for short-term utilization. This characteristic, that they can immediately take the place of traditional fuels is their most attractive, as it facilitates their utilization. Another essential benefit that biofuels offer is their environmental impact. Depending on the way they are produced, biofuels can offer a renewable energy source with limited contribution to the greenhouse gas emissions (ABS, 2021). Their well to wake emissions are significantly lower than those of traditional fuels, making their utilization a valuable tool towards a sustainable future.

On the other hand, biofuels show some important challenges. One of the major issues is the compatibility of biofuels. The variety of feedstocks and blends that are utilized make it essential to have proper management. Moreover, there are corrosion risks. Certain materials in fuel systems may corrode due to biofuel's acidity, particularly with high-concentration biodiesels. This affects components like gaskets, hoses, and fuel filters, requiring careful material selection. Moreover, fuel degeneration and microbial growth are a problem. Biofuels can degrade over time, especially in the presence of water. That leads to microbial growth. This can be managed through water removal, regular testing, and the use of additives like biocides. Furthermore, biofuel with high oxygen content may deteriorate over time. Proper storage in dark environments and timely use can prevent this, along with the use of antioxidant additives. Another issue is the effect of cold weather in biofuels. At low temperatures, biofuels can cloud and gel. Cold flow and anti-gel additives are required to maintain their operability in such conditions. Additionally, biofuels might have an impact on the lubricating oil. Some biofuels may affect the properties of lubricating oil. That leads to more frequent oil changes and increased costs (ABS, 2021). Finally, according to Kesieme et al. (2019), some other important limitations of biofuels are their availability, which is limited, technological development and their technological integration.

3.1.4.3. Biofuels Projects, Supply, Demand and Storage

According to Laursen et al. (2022), there are several projects and research and development activities regarding biofuels. The focus of these projects is to research for ways to ameliorate the production pathways of biofuels. Their aim is to improve the current capacity drastically, while at the same time increase the sustainability of their production. Most of these projects are focused on biocrudes and alcohols, and concern both the marine sector and the aviation industry. In addition, some of the biggest global stakeholders are collaborating with these projects, to test and utilize the researched blends on a pilot basis. That indicates the importance of biofuels for the maritime industry. All these research and development activities have shown positive results in the past, as the data show a decrease in the production cost of biofuels. That is promising for the future and shows that as technology advances the prices of biofuels will decrease even more.

The supply of biofuels is one of their major issues. Currently, their production is not enough to cover the global needs and replace the traditional fuels. As it is depicted in the following figure (Figure 4), over the last years the biofuel yearly production shows an upward trend. In 2000, the production of biofuels was only 0.59 million tons per year. Currently, based on the latest data, it has reached 47 million tons per year. These data show that technological advancements and the constant increase in the focus on producing biofuels have resulted in significant rises in the global biofuel production capacity. These data are promising for the maritime industry, as they indicate that their production will increase even more in the future. Nevertheless, the needs of the maritime industry are much greater than the current production capacity, which shows that the efforts should increase even more to cover the global needs.

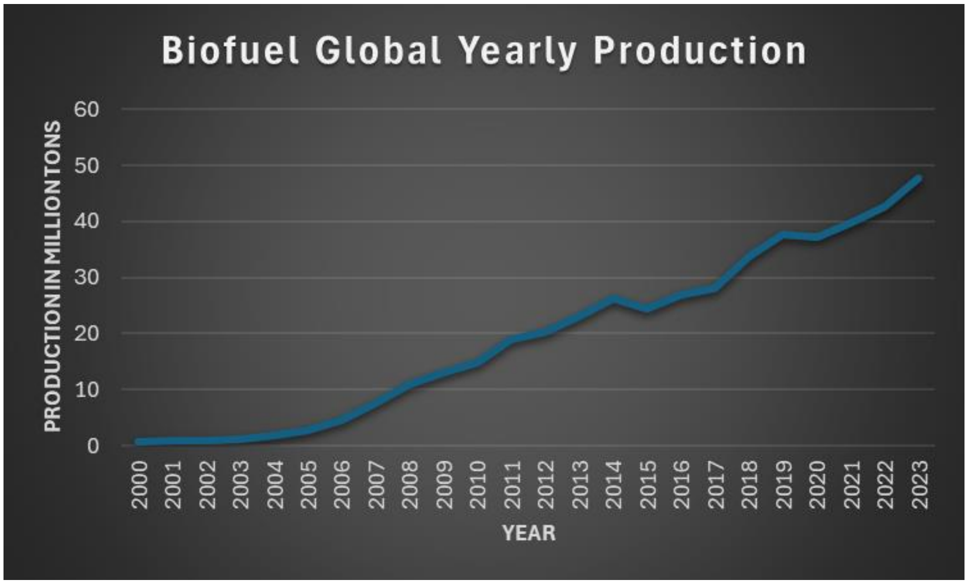

Figure 4 Biofuel Global Yearly Production (Statista, 2024)

Finally, proper storage of biofuels is essential to maintaining their quality and ensuring efficient engine performance. Temperature control is crucial to maintain appropriate viscosity levels. That enhances their flow characteristics, reduces clogging and optimized fuel injection, atomization, and combustion. Biofuels should be stored at temperatures around 10-15 °C. This temperature may vary depending on the biofuel type, blend, and feedstock. Additionally, some blends may necessitate more frequent bunkering or larger storage tanks, due to their lower energy content in comparison to diesel. Biofuels also tend to degrade over time due to their poor oxidation stability. This can be addressed with antioxidant additives. Their long-term storage is possible with careful handling, although the specific storage interval depends on the biofuel's characteristics. Furthermore, tanks may need appropriate coatings and fittings to avoid corrosion, as certain material are incompatible with biofuels. Some of the recommended materials with biofuels are steel aluminum, fiberglass, Teflon, fluorinated polyethylene, and polypropylene. On the other hand, there are materials such as bronze, brass, copper, lead, tin, and zinc that are incompatible with biofuels (ABS, 2021). The difference between all the different types of biofuels indicates the need for proper guidelines, so that the owners know the proper storage requirements for their fuel.

3.1.4.4. Biofuels Key Takeaways

Taking everything into account, biofuels present a promising alternative for the maritime industry. They are a renewable energy source capable of reducing greenhouse gas emissions. Despite their potential, their adoption is accompanied by significant challenges. Issues such as the economic and environmental costs of production, material compatibility, fuel degradation and microbial growth must be carefully managed. Also, the current limited production capacity and the need for proper storage highlight the complexities of integrating biofuels into existing maritime operations. Ongoing research and development aim to address these challenges. As technological advancements continue and global production scales up, biofuels could play a crucial role in the maritime sector's transition toward more sustainable solutions.

3.2. Alternative Fuels Comparative Analysis

This section is a comparative analysis of the four abovementioned alternative fuels. The main focus is their physical properties, and identification and comparison of their benefits and disadvantages. The two tables below (Table 2 and Table 3) summarize the key properties and the benefits and weaknesses of the of these fuels.

The analysis of all the information provided below offers some important insights. Methanol and biofuels are both liquid at ambient conditions. That makes them easier to store and handle in comparison to ammonia and hydrogen, which require more complex storage infrastructure. However, methanol's relatively low energy density and high toxicity present challenges that biofuels, depending on the type, may avoid.

On the other hand, ammonia and hydrogen offer higher energy densities and are projected as strong candidates for carbon free fuel solutions, especially in the global efforts of reducing GHG emissions. Nevertheless, both fuels require significant advancements in infrastructure and safety measures, due to ammonia's toxicity and hydrogen's storage challenges.

Biofuels stand out for their easy implementation and their compatibility with the existing engines and infrastructure. That makes them feasible short-term solution. Nevertheless, their limited availability constrains their potential as a long-term alternative.

Table 2 Properties Comparison of Alternative Fuels

Property	Methanol	Ammonia	Hydrogen	Biofuels
Chemical Formula	CH_3OH	NH_3	H_2	Varies (CH3(CH2)nCOOCH3 for FAME)
State at Ambient Conditions	Liquid	Gas (colourless)	Gas (colourless, odourless)	Liquid
Energy Density (MJ/L)	19.9	12.9	8.51	Varies (26.8 for FAME)
Lower Heating Value (MJ/kg)	20	18.6	120	Varies (37.1 for FAME)
Octane Number	110	~130	>130	Varies
Boiling Point (°C)	65	-33.35	-253	Varies
Freezing Point (°C)	-97.6	-77.7	-259	Varies
Ignition Temperature (°C)	470	651	585	Varies
Density (kg/m3)	796 (at 15°C)	620 (at 16°C)	70.8 (at -253°C)	Varies (860 for FAME at 15°C)
Storage Requirements	Stored in standard tanks	Requires modest pressure and mild cooling	Requires high pressure or extreme cooling	Varies, often stored at ambient conditions
Infrastructure	Well-developed for bunkering	Existing infrastructure from fertilizer industry	Limited, requires significant development	Limited, dependent on biofuel type
Toxicity	Highly toxic if ingested	Highly toxic, causes severe health issues	Non-toxic	Varies (low to moderate depending on type)
Corrosiveness	Corrosive, requires special handling	Corrosive, risks of material degradation	Non-corrosive	Varies (some biofuels are corrosive)

Table 3 Benefits and Disadvantages of Alternative Fuels

Fuel Type	Benefits	Disadvantages
Methanol	- Liquid at ambient conditions, drop-in use. - Large-scale production, existing infrastructure. - Accepted by IGF Code. - Water-soluble, high octane (110). - Lower GHG emissions with green/blue types.	- Mainly produced from gas/coal, high cost for green/blue. - Toxic, flammable, requires safety measures. - Low energy density, needs more storage. - Corrosive, moisture absorption risk.
Ammonia	- Carbon-free potential. - High energy density. - Existing infrastructure. - Easier storage than hydrogen. - Relatively low cost.	- Toxic, health risks. - Produces nitrogen oxides. - Underdeveloped infrastructure. - Material embrittlement risk. - Flammable, corrosive.
Hydrogen	- Efficient combustion, no CO2. - High octane (>130). - Quick dispersion, safer. - Zero-emission with green hydrogen. - Low noise and maintenance in fuel cells.	- Storage challenges: low density, high costs. - Energy-intensive liquefaction. - Complex transportation. - Needs advanced storage solutions.
Biofuels	- Drop-in use with fossil fuels. - Renewable, low GHG emissions. - Immediate adoption possible.	- Compatibility issues. - Corrosion, fuel degradation. - Cold weather sensitivity. - Limited availability, higher costs.

Each of the four alternative fuels presents a unique set of advantages and challenges. The choice of an alternative fuel by the maritime industry will ultimately depend on balancing these factors but also another important factor, the price of each fuel. As the energy industry continues to evolve, the prices will also change. As a result, a projection of the future prices is essential to complete this comparative analysis and identify the prominent alternative fuel.

3.3. Alternative Fuel Selection

In the previous sections, there are analyzed the most prominent alternative fuels that can be utilized in the maritime industry. These fuels, each with their own unique advantages and challenges, represent the forefront efforts of the maritime industry towards a more sustainable future, with the utilization of sustainable energy sources. However, to provide a comprehensive evaluation these alternative fuels, it is crucial to focus on forecasting their future prices and determine their economic viability.

To achieve this, it is necessary to select a subset of these alternative fuels, due to time and data constraints of this study. The selection of these fuels is based on a combination of factors, with most important the comparative analysis presented above and the current availability of data. To complete this study, it is necessary to historical data (timeseries) of the fuels.

Methanol, FAME, and Hydrogen are the alternative fuels that are studied in this research, due to their distinct characteristics and the availability of historical price data. In particular, data for methanol and fame are available for the purposes of this study. Regarding hydrogen, there are no historical data available, however, there are data regarding the price of electrolyzers, which are utilized to produce hydrogen and are one of the most key factors that affect its price. By predicting the price of electrolyzers, it makes it possible to make estimations about the price of hydrogen.

4. Methodology

This chapter offers a comprehensive examination of the methodology employed in this study. Initially, the current state of the maritime industry is analysed. It is essential to have information regarding the current age of the global fleet to estimate when fleet renewal is likely to occur. Furthermore, the chapter delves into the data collection process. There is an in-depth discussion of the data utilized in the research, including how the data was gathered, prepared and analysed. The data for each of the studied alternative fuel are studied separately. Finally, there is an overview of the studied models for the specific research. It includes a detailed review and analysis of the theoretical foundations of the selected model and information regarding its implementation.

4.1. Global Fleet and Timeline for the Utilization of Alternative Fuels

In this subchapter, we delve into the composition and characteristics of the global maritime fleet. There is a detailed overview of the number of ships across various categories and their distribution by age. Understanding the current state of the global fleet is essential for estimating the timeline for the adoption of alternative fuels within the industry. By analysing he age profile of the fleet and its renewal cycles, it is possible to identify key opportunities and challenges for the integration of alternative fuels into the maritime sector. This analysis serves as a foundation for projecting how and when these new energy sources might be utilized on a broader scale, ultimately shaping the future of maritime transportation.

The global maritime fleet is diverse, encompassing a wide range of vessel types that cater to different segments of international trade and transportation. The following figure (Figure 5) illustrates the distribution of ships globally by type, offering the composition of the global fleet. It is immediately apparent that general cargo vessels dominate in number, with a significant total of 20,553 vessels. These ships are crucial for transporting a diverse range of goods, from raw materials to finished products across the world. The second largest category are bulk carriers, with 13,182 vessels. This underscores the importance of bulk carries, which have an important role in transporting raw materials such as coal, ore and grains, foundational materials in the global industries. Trailing behind bulk carriers, oil tankers form the third largest group with 12,309 vessels. This substantial number reflects the ongoing reliance oi oil as a key. Additionally, another integral to the global logistics vessel type is containerships, which are 5855 globally. These ships are the backbone of international trade, facilitating the efficient movement of consumer goods worldwide. Lastly, there is a large and diverse category of 54,816 vessels. This category includes all the other existing vessels, including specialized ships, passenger ships and other. This global distribution of vessels highlights the structure of the global fleet. All these types of vessels will be affected by the transition to alternative fuels. Nevertheless, each type has its own distinct energy requirements and operational characteristics, so the effects will be different in some vessel types.

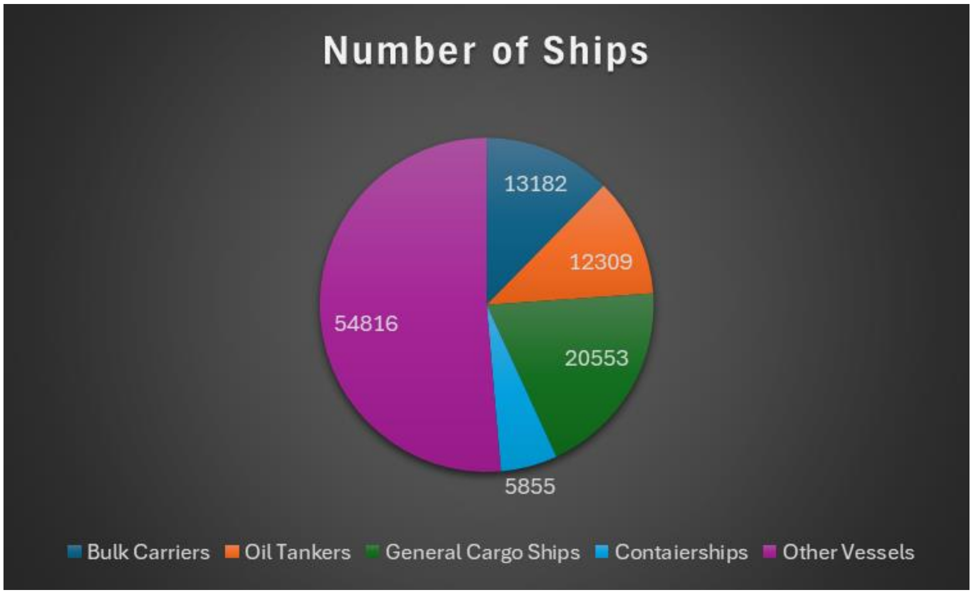

Figure 5 Number of Ships per Type (Atlas Magazine, 2023)

The age distribution of the global fleet plays a critical role in shaping the industry's future, particularly in the context of adopting new technologies and alternative fuels. Understanding the current state of the fleet allows stakeholders to estimate when significant investments in new vessels will be required. The following figure (Figure 6) illustrates the age distributions of the global fleet per ship type. Starting with bulk carriers, the majority of the vessels are within the 5 to 9 and 10-to-14-year age brackets, 31% for each bracket. That indicates a relatively young fleet. Only 11% of bulk carriers are over 20 years old, which suggests that most of the bulk carriers will not require replacement in the immediate future. Moreover, containerships have a slightly older profile, with 19% of the fleet being over 20 years old. From the rest, the 28% fall within the 10 to 14 years range and 20% within 15 to 19 years range. This age distribution indicates that in the next few years, there will be a steady demand for new container ships, however a significant amount of the current fleet will remain relatively modern (32% are younger than 9 years old). Oil tankers present a different scenario. Currently, 34% of the fleet is more than 20 years old, and 35% are older than 10 years old. This suggest a pressing need for fleet renewal in the near future, especially considering the environmental standards that are constantly evolving. In even worse condition are the general cargo vessels, with 58% of the global fleet being over 20 years old. This indicates that a large-scale renewal of this segment is likely in the near future. The younger age categories (0 to 9 years old) make up only 15% of the fleet, highlighting the need for modernization. Lastly, the rest of the vessels, such as passenger ships, ro-ro vessels and smaller specialized ships, with 47% of these older than 20 years old show that they also need replacement, especially with the emerging environmental restrictions.

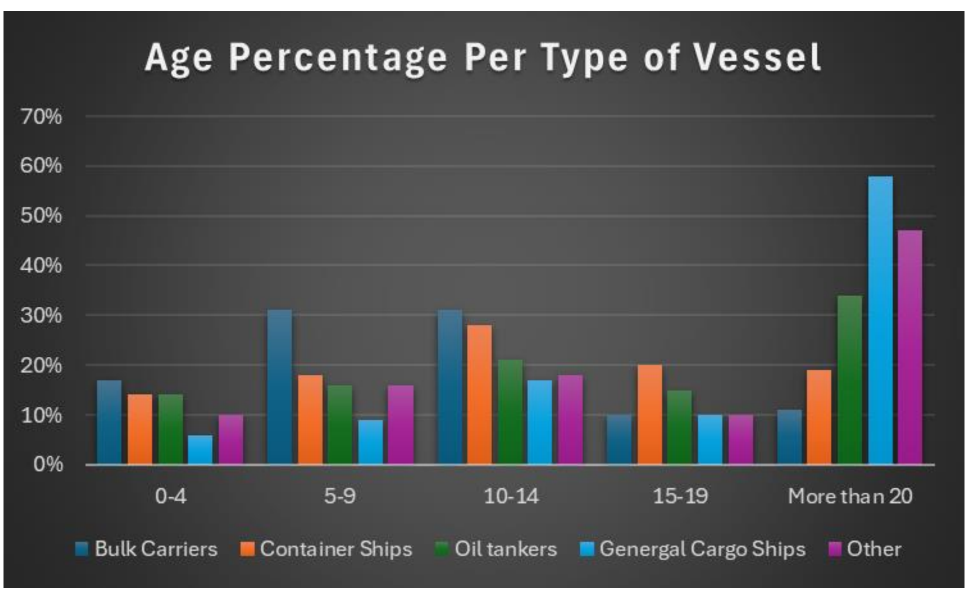

Figure 6 Age Percentage Per Type of Vessel (Statista, 2023a)

As mentioned above, the age of the fleet is a key factor in the transition to alternative fuels within the maritime industry. Older vessels may face challenges in retrofitting or adapting to new fuel technologies. It is essential to consider what are the actions of some of the biggest companies identify when the majority of the companies will move the new sustainable fuels. For example, Maersk, a leading company in the maritime industry, is committed to adopt zero-emission fuels. By the end of 2026, Maersk's fleet is projected to have a capacity-weighted age of 14.4 years, with 88% of its ships still relying on traditional fuels. In contrast, another major carrier, CMA CGM is expected to have a younger fleet with an average age of 9.7 years, and only 60% of its vessels will still be using conventional fuels. Considering these data, and the estimations of Clarkson's Research that ships older than 14 years old will not be CII compliant, it is evident that most of the companies will renew their fleets in the coming years (Moody's Investors Service, 2024).

According to the review of maritime transport of UNCTAD (2023), the average age of the global merchant fleet is 22.2 years. Considering the abovementioned, this statistic underscores the urgency for the maritime industry to transition to alternative fuels, particularly as many vessels in operation today are nearing the end of their operational lives. In this study, the pivotal point for the maritime industry is 2030, when a significant portion of vessels are expected to utilize alternative fuels. This timeline is informed by several key factors. Firstly, regulatory pressures are increasing, with IMO targeting at least a 40% reduction in greenhouse gas emissions by 2030 compared to 2008 levels. Subsequently, the age of the vessels, and the abovementioned CII restriction, indicates that a lot of companies need renewal of their fleet. Finally, advancements in alternative fuel technologies are expected to accelerate in the coming years, making 2030 a realistic target for widespread adoption. Despite the fact that no single alternative fuel will meet global demand on its own, there is hope that a combination of all the alternative fuels mentioned in the previous chapter will collectively satisfy this demand.

4.2. Data collection and preparation

In this sub-chapter, there is an analysis of data regarding potential alternative fuels in the maritime industry. It is essential to gather, prepare and analyse the data individually for each studied alternative fuel to have a better understanding of them. For each alternative fuel there are different types of data due to the limitations of the current literature. Most of these fuels are not currently widely adopted, which hinders the collection of data.

4.2.1. Methanol Data

As mentioned in previous chapters, the maritime industry seeks to transition towards more sustainable and environmentally friendly fuels. Methanol has emerged as a promising alternative fuel, able to reduce the greenhouse gas emissions and comply with stricter environmental regulations. The advantages and disadvantages of methanol are analysed in Chapter 2. Based on those, there are estimations that methanol will play a crucial role in the future of the maritime industry.

Understanding the historical price trends of methanol is essential for assessing its economic viability and the feasibility of its widespread adoption. By analysing the fluctuations of the methanol price, it is possible to gain valuable insights into the market dynamics that could affect the future cost and the availability of methanol. Moreover, the methanol historical prices are utilized in this study to make predictions and estimations of its future price, after the implementation of different models.

The historical methanol price data utilized in this study are sourced from Methanex, one of the world's leading producers and suppliers of methanol. Methanex plays a pivotal role in the global methanol market, with operations spanning across major international markets in North America, Asia Pacific, Europe, and South America. Its headquarters are in Vancouver, Canada, while it has maintained productions sites in several strategic locations such as Canada, Chile, Egypt, New Zealand, Trinidad and Tobago and the United States. Methanex, through their website, offers comprehensive data regarding the historical methanol pricing. By leveraging this data, this study can analyse them and extract useful information from them (Methanex, 2024).

The figure below (Figure 7) illustrates the methanol prices from May 2001 to May 2023 in US dollars. All the analysed prices in this study concern the US market for comparative reasons. It is immediately apparent that the methanol prices have experienced significant fluctuations through time, reflecting the dynamic and the volatility of the methanol market. In the early 2000s, prices remained relatively stable, ranging around $100 to $200 per metric ton. However, from 2006 to 2008 there was a sharp increase, with prices peaking at nearly $800 per metric ton. This dramatic rise can be attributed to various factors, including increased demand, potential supply constraints, but most importantly the global financial crisis of 2008. Following the financial crisis, methanol prices dropped substantially. They returned to levels around $200 and $300 per metric ton by 2009. Prices then increased again, with moderate fluctuations around $300 and $500 per metric ton, until another peak occurred in 2014, when prices exceeded $600 per metric ton. After 2015, the market fluctuated a lot, between $300 and $600 per metric ton. It is evident that some of the peaks of the price are happening when important geopolitical events occur. To be more precise, one of the peaks is in 2019, when COVID-19 pandemic caused a lot of disruptions in the global economy. More recently, in 2022, the market increased even more due to the geopolitical tensions resulting from the war between Russia and Ukraine. The influence of Russia in the global fuel market is high, due to their increased supply of natural gas in the global markets. That is evident in the prices, where they skyrocketed after the war started and the majority of the world's most powerful nations-imposed embargoes on Russia's natural gas, severely restricting its access to global markets.

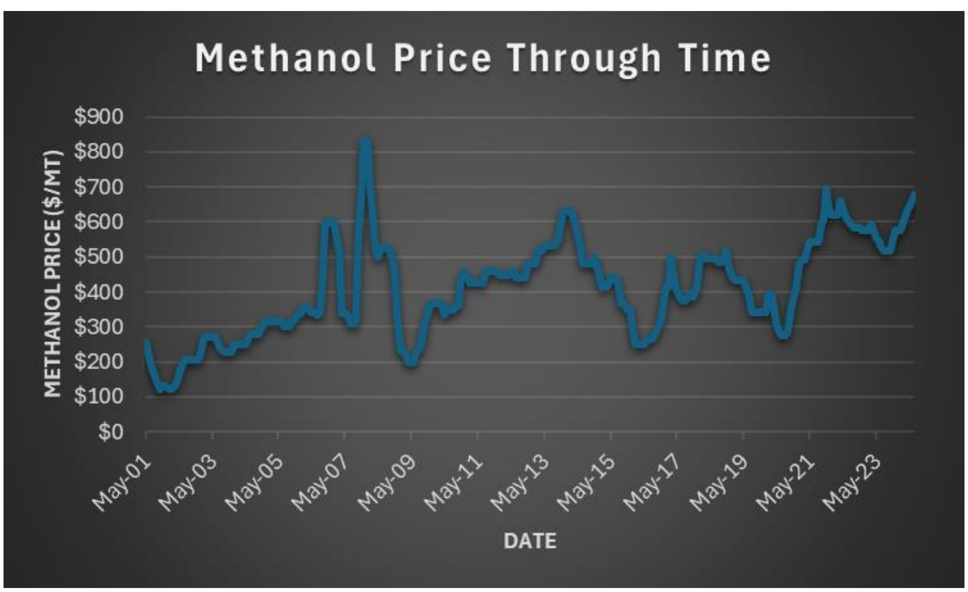

Figure 7 Methanol Price Through Time (Methanex, 2024)

The statistical analysis of methanol prices over the observed period (2001-2024) provides valuable insights into the behaviour of and volatility of the market. As presented in Table 4, the mean price of methanol is $411 per metric ton. This price indicates the value around which the prices are fluctuating. The median is slightly higher, at $416 per metric ton, suggesting a slight skewness in the distribution towards higher prices than the mean value. Both these two values are close, suggesting that the distribution of methanol prices is relatively symmetric. Standard deviation and variance make it evident that the data fluctuate a lot, with values of 139 and 19,523 respectively. Regarding the range of the data, the minimum value is $119.7 per metric ton back in 2001 and the maximum value reaching as high as $831.5 per metric ton in 2008. This wide range shows the impact of various market forces in the methanol price. The first quartile and third quartile are $309.3 and $516 per metric ton. This interquartile range highlights the typical variation in the methanol prices through the years, indicating that 50% of the observed prices fall between that range. Overall, these statistics offer a better understanding of the data and provide useful insights regarding the methanol market. The fluctuations are highly influenced by global geopolitical changes, and the global changes in supply and demand.

Table 4 Methanol Statistics

Statistics	Value
Mean	411
Median	416
Standard Deviation	139.728
Variance	19523.92
Minimum Value	119.7
Maximum Value	831.5
First Quartile	309.3
Third Quartile	516

4.2.2. Fame biodiesel Data

In this sub-section, the focus shifts to the analysis of FAME, a prominent biodiesel. It is also considered as an alternative fuel for the maritime industry to potentially replace the conventional fossil fuels. Given its renewable nature and its lower greenhouse gas emissions compared to the traditional fuels, understanding the historical price trends of FAME is crucial for evaluating its economic viability in the long term. This section delves into the historical data of FAME prices and explores the various factors that have influenced its market behaviour over time.

The data that are utilized in this study are retrieved from the United States Department of Energy, through their Alternative Fuels Data Center. This data provider is a comprehensive, dynamic and reliable resource that has been providing information on alternative and renewable fuels since its inception, in 1991. It was established after the Alternative Motor Fuels Act of 1988 and the Clean Air Act Amendments of 1990. Originally, it was designed as a repository for alternative fuel vehicle performance data. Over the years, it has evolved into a hub for a wide range of stakeholders, offering data and resources. It is annually updated by experts and industry leaders to ensure that it remains at the forefront of the rapidly changing transportation industry. All these makes it a valuable source for obtaining reliable and up to date information regarding the FAME prices, the biodiesel that is studied in this thesis (U.S. Department of Energy, 2024).

The historical prices of FAME that were collected through the Alternative Fuels Data Center are presented in the following Figure (Figure 8). The line illustrates the historical price fluctuations of FAME measured in gasoline gallon equivalents (gge). The data range from September 2005 to January 2024. The FAME price trend reveals several notable peaks and troughs, like the ones of methanol. Initially, in 2005 its price started at $3.3 per gge, and it gradually increased until it peaked at mid-2008, when the financial crisis occurred. Afterwards, FAME price dropped to $3 and then stabilized to $4 per gge. However, starting in 2014, prices followed a downward trend, reaching their lowest point in 2016, at $2.76 per gge. That possible reflects the global oversupply of biodiesel at the given moment and lower crude oil prices during this period. After that point, the FAME price started to slowly increase, with small fluctuations, until 2022, when the Russia-Ukraine war started. Then the market demands led the price to skyrocketing and reaching its peak at $5.48 per gge. Currently, in 2024, the price is around $4.5 per gge.

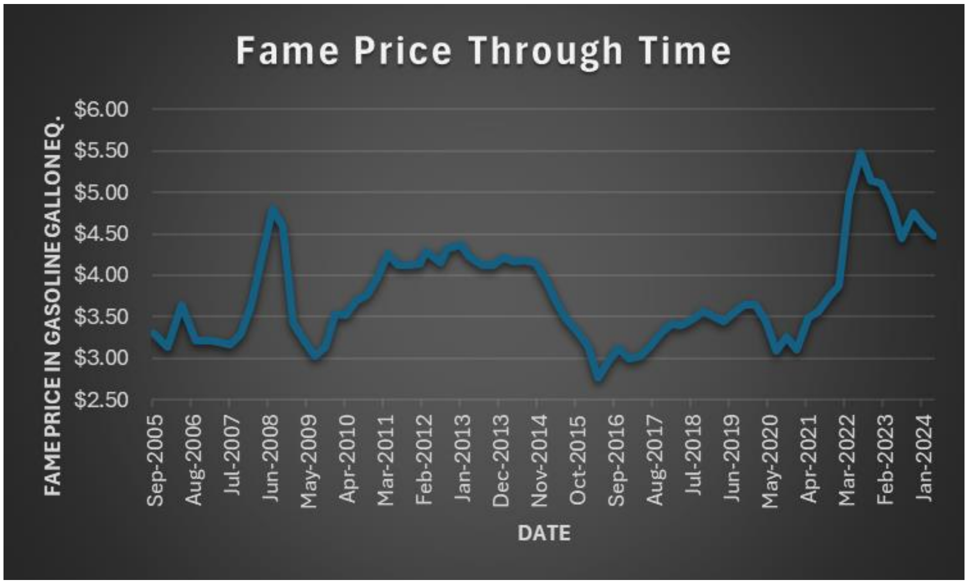

Figure 8 Fame Price Through Time (U.S. Department of Energy, 2024)

Moreover, except from the FAME prices, the price of gasoline and diesel are extracted from the Alternative Fuels Data Center to examine their connection with fame. As illustrated in Figure 9, it is immediately apparent that there is a strong correlation between the prices of FAME, gasoline, and diesel over this period. This highlights the close relationship between these fuel markets. Their trends are being influenced by common global events and market dynamics.

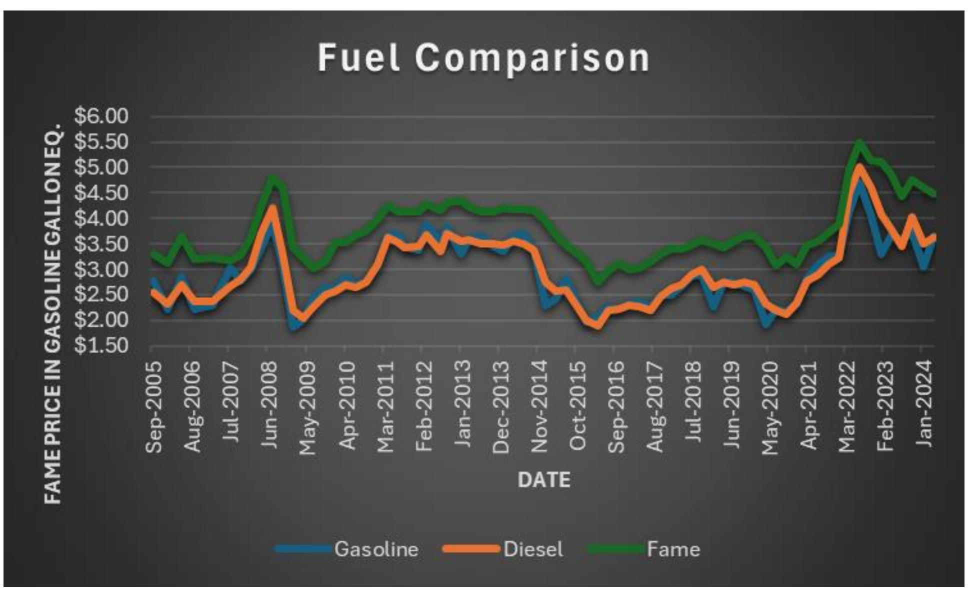

Figure 9 Gasoline, Diesel, Fame Price Comparison (U.S. Department of Energy, 2024)

It is essential to have a statistical analysis of FAME historical prices to better understand them. All the statistics are presented in Table 5. The mean price of FAME is $3.79 per gge, which indicates the average cost over the data time. The median value is slightly lower, at $3.65 per gge, which shows a positively skewed distribution of the data, however the values are close, proving that the distribution is symmetrical. The standard deviation of 0.608 highlights that while prices fluctuate, these fluctuations are small. This is further supported by the variance, which is 0.37 and quantifies how spread are the data. The minimum and maximum prices per gge are $2.76 and $5.48, respectively. That shows a significant range in the price fluctuations over the period. This wide range could be attributed to the various factors such as the geopolitical or economic crisis, that as mentioned before, highly influence the fuel markets. Nevertheless, this range is not close to the reality, which is better illustrated by the first and third quartiles. Their values $3.298 and $4.18 per gge, respectively. The 50% of the FAME prices are within that range, which is smaller than the minimum-maximum range. The interquartile range offers a better understanding of the central tendency of the FAME fuel price. Overall, these statistical values reveal the fluctuations of the FAME prices and offers a better understanding of the trends that its price follows over time.

Table 5 Fame Statistics

Statistics	Value
Mean	3.788
Median	3.65
Standard Deviation	0.608
Variance	0.37
Minimum Value	2.76
Maximum Value	5.48
First Quartile	3.298
Third Quartile	4.18

4.2.3. Hydrogen Data

The third alternative fuel that is studied is hydrogen. Hydrogen is an emerging fuel, which does not facilitate finding extensive historical price data. As an alternative type of data, in this study the electrolyzers cost is utilized. As mentioned in previous chapters, electrolyzers are used in the production of green hydrogen and are one of the main factors that influence the price of green hydrogen. In this way, by forecasting the future cost change of producing electrolyzers, it is possible to estimate the future change in cost of hydrogen. In addition to electrolyzers it is essential to have estimations on the electricity cost, as it is also affecting the production cost of hydrogen.

Regarding the capital costs of electrolyzers, there are historical data of the cost reduction of PEM Electrolyzers, which are also provided by the department of energy of the United States. These data are presented in the following figure (Figure 10). Since 2001, the uninstalled capital cost for proton exchange membrane (PEM) electrolyzer has decreased by more than 90%, with an 80% reduction occurring since 2005. These significant cost reductions have been achieved through the research, development and demonstration efforts funded by the Hydrogen and Fuel Cell Technologies Office, under the United States Department of Energy's Office of Energy Efficiency and Renewable Energy. That decrease in the price proves the importance of technological advancements in the price of electrolyzers, which significantly drove down the costs of PEM electrolyzers, as the figure illustrates. Nevertheless, it is evident that the last few years, there is decreased pace in the reduction rate of the production cost. That indicates that in the following years, this price will continue its downward trend, however, its pace will be steady and slow (Randolph et al., 2022).

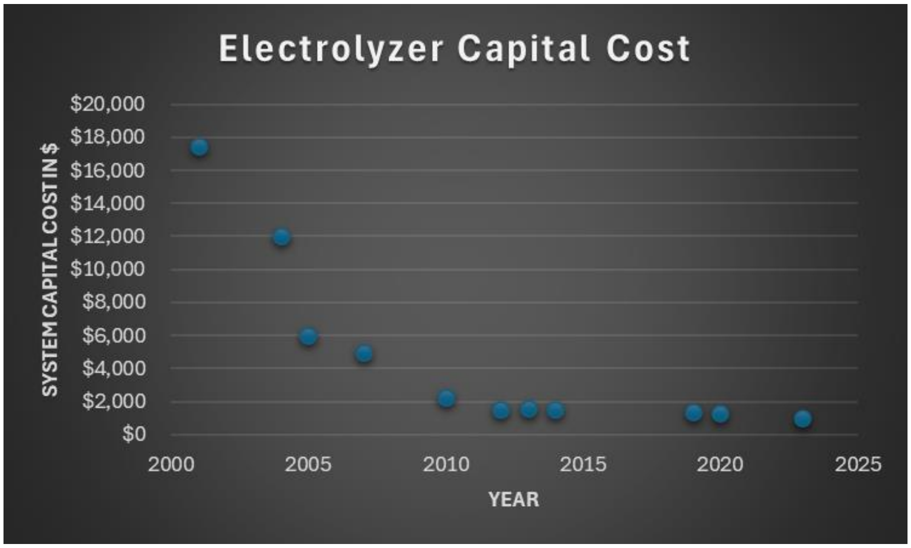

Figure 10 Electrolyzer Capital Cost in U.S. (Randolph et al., 2022)

The second important component in the production cost of green hydrogen is electricity. Data regarding electricity are retrieved from the United States Bureau of Labor Statistics, which showcases the trend in average yearly electricity prices from 1978 to 2024. These data are presented in Figure 11 below. The electricity price shows a gradual increase over the years. Notably, the chart depicts a lot of fluctuations, however, overall, there is an upward trend. Some sharp increases are noted in 2008 and 2022. That proves that the global financial crisis and the war in Ukraine affected the prices and increased the rate of their increase (U.S. Bureau of Labor Statistics, 2024). This

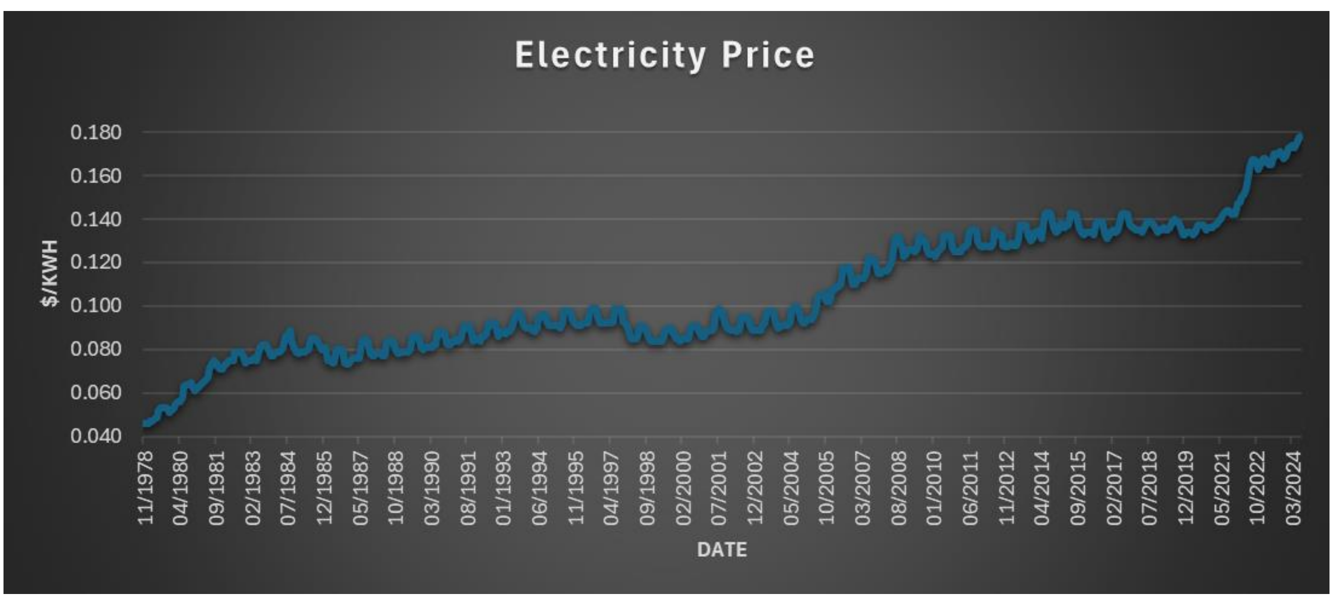

Figure 11 U.S. Yearly Electricity Price in $/kWh (U.S. Bureau of Labor Statistics, 2024)

constant increase can be explained from the increased demand of electricity. Technological advancements lead to increased need for electricity, and that trend leads to a continuous upward trend.

According to the United States National Clean Hydrogen Strategy and Roadmap (n.d.), electrical energy is responsible for the 52% of the production cost of hydrogen and capital costs (electrolyzers costs) for the 27%, which combined represent almost 80% of the production cost of hydrogen. The rest of the cost will not be projected in this study and will be considered stable the following years.

Finally, it is essential to have a base price of hydrogen, so that based on the projected values of electrolyzers capital costs and the electricity price it can be calculated a projection of the hydrogen cost in 2030. The current cost of producing hydrogen from electrolysis is around $5 per kg (United States National Clean Hydrogen Strategy and Roadmap, n.d.).

4.3. Model Development and Implementation

In exploring the feasibility of methanol, fame, and hydrogen as alternative fuels in the maritime industry, it is crucial to have predictions or estimations of their future prices. By developing machine learning and statistical models this study aims to utilize the abovementioned data and forecast future trends in their prices. Each model chosen for this analysis brings a unique set of tools ideal for deciphering the specific patterns and challenges in the data.

4.3.1. Model Analysis

The examined models that were utilized in this study are Prophet, XGBoost, Random Forest, Arima and Non-linear Least Squares Statistical Model. Each of these models has its own strengths and weaknesses. Based on the current literature and the type of data studied in this research, they are considered the most suitable options. For better understanding of the models, below, there is a short analysis of each one individually.

The first model that it is tested is Prophet, a forecasting tool developed by Facebook's Core Data Science team. It is open-source and accessible for use both in R and Python. It is based on Stan, a statistical model platform. It is designed to handle time series data through a robust and flexible framework that accommodates various irregularities that are commonly found in real-world data. It is particularly effective for datasets displaying strong seasonal effects. That makes it ideal for economic and financial forecasting where these patterns exist. It operates on an additive model where non-linear trends are paired with seasonalities, daily, weekly, or yearly. It also includes the effects of holidays, which are crucial for capturing unusual spikes or dips in the data. One of the most prominent features of Prophet is its robustness to missing data and its capacity to automatically detect changes in trends. This makes it suitable for utilization with real-world data. Also, it can effectively manage outliers, ensuring that they do not skew the overall forecasts. Another important characteristic that it offers, is that it allows the user to tweak many parameters and tune the model accordingly to the data. All these makes it exceptionally suitable for forecasting future fuel prices based on historical data. Especially the capability to incorporate holiday effects and adapt to sudden changes in trends makes it a good choice for the given data, where occurrences like the 2008 global financial crisis and the war in Ukraine have an immediate effect in the data (Prophet, n.d.).

Another model that is utilized is XGBoost. XGBoost stands for Extreme Gradient Boosting and it is a cutting edge and highly efficient implementation of gradient boosted decision trees designed for speed and performance. It is famous for its efficiency and flexibility in handling regression, classification, and ranking problems, which makes it a valuable tool for predictive modelling in various fields. Some of the benefits of XGBoost are its ability to handle complex data structures, its robustness to overfitting, its efficiency and scalability and its flexibility in modelling. The inclusion of XGBoost in this research allows to handle the time series data properly and examine for non-linear relationships. The external shocks like the 2008 global financial crisis and the recent geopolitical tensions (war in Ukraine) can also be modelled. In general, XGBoost provides a powerful tool, offering both speed and accuracy in forecasting. Its wide adoption in the machine learning community further attests its capability, making it a suitable model for this research (Nvidia, n.d.).

Furthermore, random forest is another widely used model for forecasting. It is an ensemble learning method, renowned for its robustness and versatility across various applications. Leo Bierman and Adele Cutler developed it. Regarding the way it works, it combines the predictions from multiple decision trees, (to produce a more accurate estimate than any individual decision tree could achieve alone. That surpasses the incapability of decision trees to work with data that need overfitting. Except from the robustness to overfitting, some other important benefits of random forests are its ability to handle complex interactions, its feature importance analysis, that provides insights into which feature is more important, and its flexibility as it can both numerical and categorical data and it can be used both for classification and regression. Random forest is well-suited for forecasting fuel prices due to its ability to handle both small and large datasets, with complex, non-linear relationships influenced by numerous factors (IBM, n.d.).

The third model that was tested on the given data is ARIMA, which stands for Autoregressive Integrated Moving Average model. It is widely used as a statistical tool for time series forecasting, particularly valued for its ability to predict future values based on past data. It is especially useful in economic and financial analysis, where historical trends are strong indicators of future outcomes. ARIMA operates by combining three key components, Autoregression, which helps the model to understand how past values in the time series influence current values, Integration, which makes the data stationary, and Moving Average, which focuses on the dependency between an observation and a residual error from a moving average model to lagged observations. ARIMA is particularly effective when there is a long history of data, making it well-suited for time series. It can also handle non-stationary data, and its forecasting capabilities includes short-term forecasting. ARIMA is suitable for fuel price prediction due to its adaptability. It can be tailored to account for shocks and irregularities in the data. Also, it is reliable in volatile markets, which given the fluctuations in the fuel prices is beneficial (Hayes, 2024).

Finally, the last model that is utilized in this study, is a statistical model, the Non-Linear Least Squares statistical model. It is an advanced statistical technique that extends linear regression to accommodate more complex relationships in data. It allows the modelling curves to take multiple intricate patterns, and not straight lines. In Non-Linear Least Squares model, the relationship between the dependent variables and the independent variables is expressed through a nonlinear equation. The parameters are estimated using the method of least squares, where the goal is to minimize the sum of the squared differences between the observed and predicted values. The model deploys iterative techniques to identify the best fitting parameters. Regarding its advantages, it is flexible in modelling complex relationships and utilizes the data efficiently. This statistical model is not suitable for all the alternative fuels that are analyzed in this study, however, its utilization is ideal for the prediction of the future price of electrolyzers, due to the distinct characteristics of electrolyzers' data (NIST, n.d.).

Overall, the abovementioned models are utilized in R-studio environment. The libraries that are utilized for the forecasting and the data modification are the following: "prophet", “readxl”, “dplyr”, “writexl”, “xgboost”, “data.table”, “lubridate”, “ggplot2”, “radnomForest”, “lubridate”, “minpack.lm”. Moreover, the detailed data and the code utilized (only for methanol, similar for hydrogen and FAME) are presented in Appendix A and B.

4.3.2. Methanol Model Implementation

This chapter discusses the implementation of three of the abovementioned models used to forecast methanol prices. In particular, for methanol, the three optimal models in this study are Prophet, XGBoost and Random Forest. Each model is tuned to optimize performance, leveraging the historical methanol price data and the significant global events that affected its price. The other models analyzed in the previous section, after testing are considered not suitable for the forecasting of methanol price. All the available data are utilized for the training of the models to maximize their performance and their predictive power.

4.3.2.1. Methanol Prophet Implementation

The first model is Prophet, which is strong with seasonal patterns and potential irregularities due to different occurrences. For the implementation, price data are transformed accordingly, creating a data column and a target variable. A capacity column is added, limiting the growth of predictions to 1.5 times the maximum historical price. This prevents the model from forecasting unrealistic price spikes, spikes that are not expected from the market's behavior. Moreover, noteworthy events such as the global financial crisis, COVID-19 and Russia-Ukraine war are included as holidays. These events introduce potential changepoints, which the model must handle to prevent overfitting non-recurring anomalies.

Regarding the hyperparameters of the model, they are tuned accordingly, in order to provide the best results. Changepoint Prio Scale is set to 0.1. This parameter controls the flexibility of the model in fitting changepoints. A low value is selected, to reduce the likelihood of the model overfitting to short-term variations. In this way, the model focuses on capturing significant changes in the trend. Also, Seasonality Prior Scale is set to 0.1. This parameter dictates the model's ability to capture seasonal effects. By selecting this value, the model has balanced flexibility, and it can capture yearly cycles. Finally, the model uses adjusted growth, which is set to logistic growth. The logistic growth is chosen to reflect real world constraints in the escalation of the price of the fuel.

4.3.2.2. Methanol XGBoost Implementation

The second model utilizes XGBoost, a powerful machine learning algorithm, especially good with structured data. The data are enhanced with binary indicators for major global events and time-based features, which show month, quarter, and year. These features are crucial for allowing the model to learn from-term patters and trends. Also, lag features are created, which capture long-term dependencies and patterns in the time series.

Regarding the tuning of the model, as objective function, it is selected the squared error function. This minimized the squared error between the predicted and actual prices and is suitable for regressions tasks where the goal is to minimize the error. Also, the learning rate is set to 0.01. A low rate ensures that the model learns slowly and steadily., preventing it from overshooting the optimal solution. This is essential in time series forecasting, where too aggressive learning rates might lead the model to chase noise and not underlying trends. The Maximum Tree Depth is set to 8. This parameter controls the complexity each tree in the model, and after tuning 8 is considered the best choice.

Subsample is set to 0.8. By setting the subsample to 80%, the model trains on a random subset of the data for each iteration, which reduces the likelihood of overfitting and enhances the model ability to generalize. Moreover, the column subsampling is also set to 0.8, which limits the number of features used by each tree and promotes diversity in the trees. Furthermore, there is regularization of the model. By setting lambda and alpha values to 1 and 0.1, respectively, large weights are penalized and sparsity is encouraged. These settings help prevent the model from becoming too complex, which is especially important when dealing with multi-dimensional data. Finally, there is a rolling forecast, where predictions are made iteratively for each future time step, using the previous predictions as inputs for the next step. All the hyperparameters are also presented in the following table (Table 6).

Table 6 Methanol XGBoost Hyperparameters

Hyperparameter	Value
Objective Function	Squared Error
Learning Rate	0.01
Maximum Tree Depth	8
Subsampling	0.8
Column Subsampling	0.8
Regularization parameter lambda	1
Regularization parameter alpha	0.1

4.3.2.3. Methanol Random Forest Implementation

The third model applies a Random Forest algorithm, which is effective in capturing non-linear relationships and complex interactions between features in the data. Similar to the XGBoost data, the methanol price data is prepared with time-based features and event indicators. Extensive lag features are developed to enable the model to capture long-term dependencies in the price data.

The model is built using 500 trees, a number chosen to balance model accuracy and computational efficiency. After this number of trees, the marginal gains decrease significantly. In order to prevent overfitting, feature subsampling is set to the square root of the total number of features. Additionally, bootstrap aggregating, also known as bagging, is used to train the multiple trees on different random subsets of the data. After that, the results are averaged to produce the final prediction. This reduces variance and improves model's robustness. Finally, out-of-bag error estimation technique is utilized to evaluate the performance of the model on data not seen during training, helping to provide reliable estimate of the model's predictive power.

4.3.3. FAME Model Implementation

This chapter discusses the implementation of three models used to forecast the prices of FAME. The selected models are Prophet, XGBoost and Random Forest. Each one of them is trained and optimized based on the historical prices of FAME, to achieve the best forecasting performance. In the following sections most of the parameters are presented briefly, as they are analysed above, in the methanol case.

4.3.3.1. FAME Prophet Implementation

The first model employed is Prophet. Similarly to methanol implementation, the data are transformed to include a date column, a target variable and a capacity column. Holiday events are also included to represent potential changepoint that the model must avoid. A floor values is also set to ensure that the model does not predict unrealistically low prices. Regarding the model tuning, changepoint prior scale is set to 0.2, slightly higher than the one in methanol to allow capturing of more subtle trend changes. Seasonality prior scale is set to 0.05, low value to smooth out seasonal effects and growth model is set to logistic growth model to reflect the real-world constraints.

4.3.3.2. FAME XGBoost Implementation

The second model utilized is XGBoost. The FAME price data is enhanced with time-based features, such as month, quarter and year. Binary indicators are added to present the occurrence of significant events that affected the prices in the past. Regarding the implemented techniques and the tuning of the model, the same process as with methanol is followed. The hyperparameters are presented in the following table (Table 7).

Table 7 FAME XGBoost Hyperparameters

Hyperparameter	Value
Objective Function	Squared Error
Learning Rate	0.01
Maximum Tree Depth	8
Subsampling	0.8
Column Subsampling	0.8
Regularization parameter lambda	1
Regularization parameter alpha	0.1

4.3.3.3. FAME Random Forest Implementation

The final model that is utilized for the forecast of future prices of FAME is random forest. The FAME price data is similarly with methanol prepared with time-based features and event indicators. Lag features are also developed to capture long-term dependencies. Regarding the tuning of the model, the selected number of trees are 500 and the same techniques as with methanol are employed (feature subsampling, bagging and out of bag error estimation.

4.3.4. Hydrogen Model Implementation

As mentioned above, for the price prediction of hydrogen, there are projections of the electrolyzers price and the electricity price, the main factors that affect the hydrogen production costs. This chapter discusses the implementation of models, that are used to forecast the costs of electrolyzers and electricity. The selected models for these tasks are the Non-Linear Least Squares Model for electrolyzers and Prophet model for electricity prices. These models are implemented and tuned accordingly to optimize their performance.

4.3.4.1. Electrolyzers Non-Linear Least Squares Model Implementation

The cost of electrolyzers has historically followed a downward trend as presented above. Based on the data, the most suitable model for their trends is considered an exponential decay function. This approach is suitable for capturing the rapid decline in costs as technology advances and economies of scale are achieved. The initial high costs show that in the future will decrease at a diminishing rate, making exponential decay an appropriate representation. The historical price data require no modifications.

The exponential decay function has three main parameters, a, b, and c, which should be initialized before the implementation of the model. As initial parameters, a is set to 20,000, be is set to 0.2 and c is set to 500. There is a utilization of a non-linear least squares methods which minimizes the residual sum of squares between the observed and predicted cots. That minimizes the prediction error, and it can be utilized due to the non-linearity of the model. In this way the model is utilized to predict electrolyzer costs up to 2030, indicating a continuing decline in costs as technology advances.

4.3.4.2. Electricity Prophet Implementation

The second part of this section focuses on forecasting electricity prices using the Prophet model. Data preparation and model tuning are like methanol and FAME model implementation. Electricity price data are pre-processed to include a date column, a target variable, and a capacity column. Also, holiday events are included in the training of the model to avoid the effect of these changepoints. Finally, changepoint prior scale and seasonality prior scale are both set to 0.1 and the growth model is a logistic growth model, to avoid excessive price escalations.

4.3.5. Limitations on Models Implementation

In this study, in the pursuit of developing accurate and reliable predictive models for alternative fuel prices, significant efforts are made to include various critical factors. These factors include technological advancements, demand of the fuels, and their supply. These factors are known to have substantial influences on market dynamics and on fuel prices, especially the alternative type of fuels. However, despite these efforts the implementation of models that effectively integrate these parameters proved challenging.

One of the primary challenges encountered was the difficulty in accurately modeling technological advancement. Although regressors are created to represent technological progress, these models are not performing as expected. The complexity of modelling technological advancements, which do not follow a linear or easily predictable patterns, made this study unable to model them. Different scenarios, with slow, moderate, and high technological growth rates are used to model the effect of technology in the predictions. Nevertheless, the results of the models show no effect from the implementation of this external regressor.

Similarly demand and supply dynamics presented significant modelling challenges. While these are fundamental economic factors that influence alternative fuel prices, the limitations of the data do not make it possible to model them properly and examine their effect in the alternative fuel prices. In the same way, different demand and supply growth rates are examined, however, the models fail to identify their effect in the prices.

These challenges underscore the need for more advanced modelling techniques, richer datasets and perhaps another approach on how these factors are conceptualized and integrated in the forecasting models. Especially the limited amount of data regarding the alternative fuels does not facilitate the completion of this approach.

5. Results and Analysis

This chapter presents the results and analysis of the forecasting models applied to each of the studied alternative fuels, methanol, FAME and hydrogen. The forecasts generated by the models are evaluated and interpreted to understand the expected future trends in fuel prices and costs. For each fuel, the results are discussed individually. Afterwards, there is a comparative analysis between the fuels, their costs, and their total characteristics in order to answer the main research question of this paper, which one of them is the best option for the future of the maritime industry.

5.1. Methanol Results and Analysis

As described in Chapter 4, there are utilized three different models for the prediction of methanol prices in 2030. In this sub-section there are presented the results of the implemented models and there is an analysis of the results and the trends that led to them.

The first implemented model is Prophet, the results of which are depicted in Figure 12. The graph illustrates the model's forecast for methanol prices from 2000 to 2030. The red dots represent the historical prices and the blue line the forecasted price through the years. Overall, it is evident that there is an upward trend in the price of methanol with periodic seasonal fluctuations. The forecasted price of methanol for 2030 is $600.68 per metric ton. The shaded blue area represents the model's confidence interval. This area indicates a range of potential prices around the central forecast. The model captures the historical price movements reasonably well and projects that the prices will continue to rise steadily. Nevertheless, there are potential drawbacks in the prediction of the model that are worth noting. The confidence intervals are considered wide, which offers uncertainty for the results and limits the reliability of the forecast. Also, the resulted blue line shows a periodicity that it is not apparent in the given data.

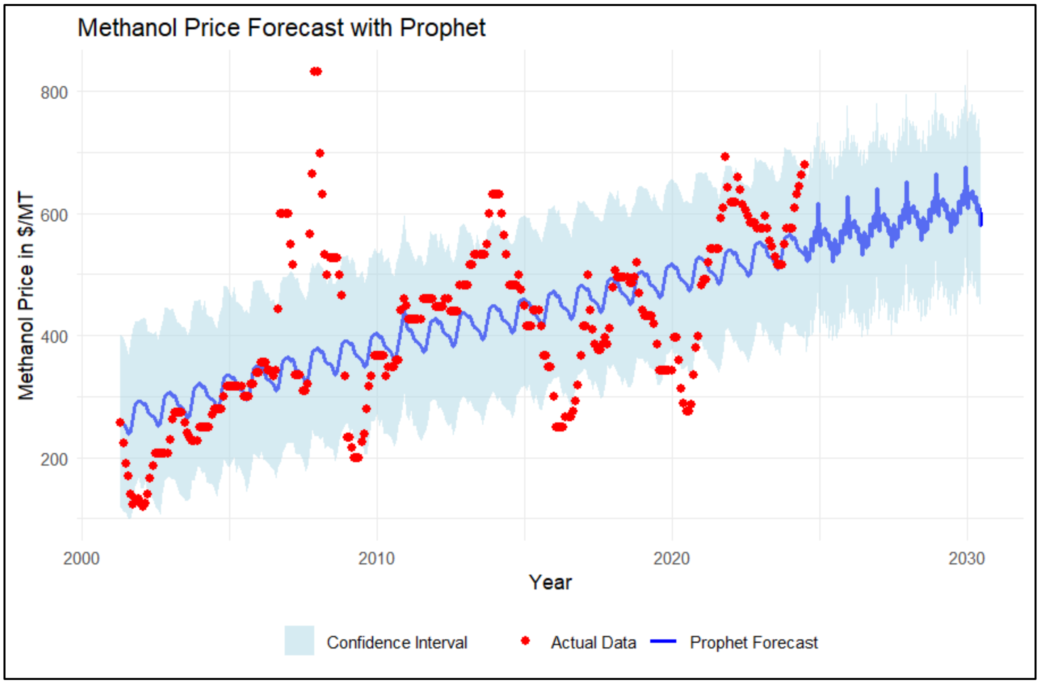

Figure 12 Methanol Price Forecast with Prophet

Subsequently, the results from the implementation of the XGBoost model are presented in Figure 13. The graph shows a continuation of the fluctuating trends observed in the historical data. The blue line represents the historical prices and the red line the projected future prices up to 2030. During the forecast period, the model predicts a relatively stable trend in methanol fluctuations, with minor fluctuations around $500 and $600 per metric ton range. Regarding the required date, 2030, the model predicts that the price of methanol will be $487.73 per metric ton, a price significantly lower than the one projected by Prophet model.

Compared to the historical data, which exhibits significant volatility, including sharp spikes and deep troughs, the forecasted prices suggest a more stable market in the coming years up to 2030. The model does not predict any dramatic price increases or decreases, implying an expectation of steady market conditions without major disruptions. This indicates that the model effectively recognized the impact of the specified holidays, the ones mentioned in the previous chapters, and that helped to smooth the forecast and prevent many of the sharp price spikes seen in the historical data. Moreover, it helps to extract a useful conclusion, that without major disruptions, the market is considered steady with moderate fluctuations.

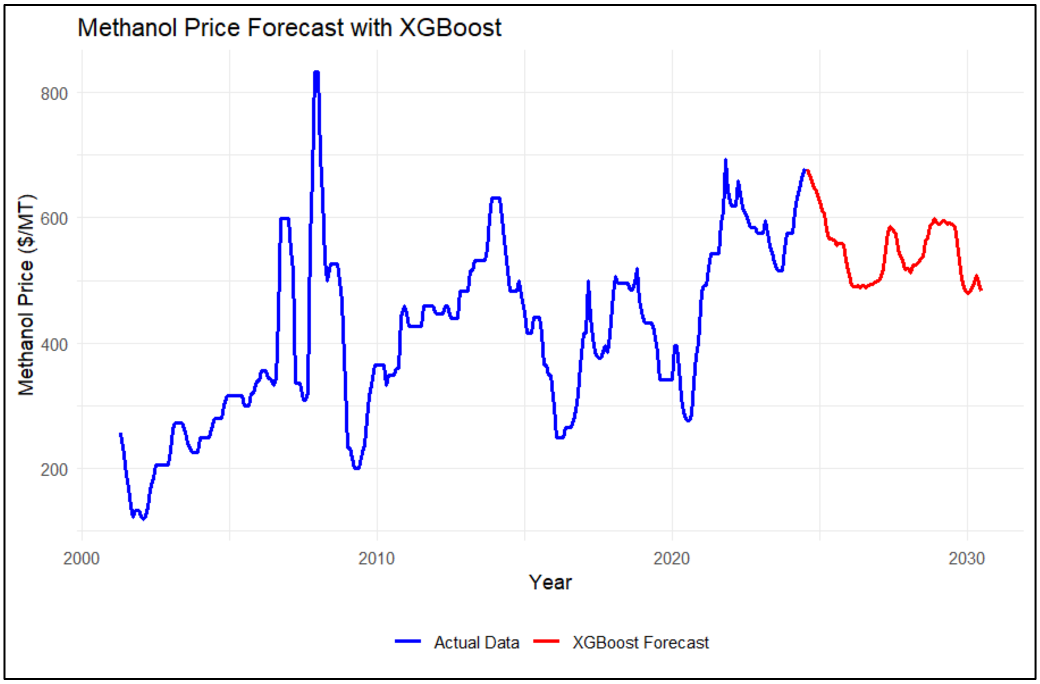

Figure 13 Methanol Price Forecast with XGBoost

Finally, the random forest model's forecast for methanol prices is depicted in Figure 14. The figure illustrates the projected prices from 2023 to 2030 with a red line, with the historical data shown in blue. The forecast indicates a general stabilization in methanol prices over the coming years, with minor fluctuations around $500 to $600 per metric ton. Based on the forecast of the model the predicted price for methanol in 2030 is $492.02.

The relatively smooth forecast suggest that the random forest model has effectively captured the key patterns in the historical data, without including the anomalies or the outliers. This might indicate that the model managed to smooth out extreme variations and focus on the underlying trends. Overall, the forecast of random forest is similar to the forecast of XGBoost. That is mostly explained due to the fact that both models are based on decision trees.

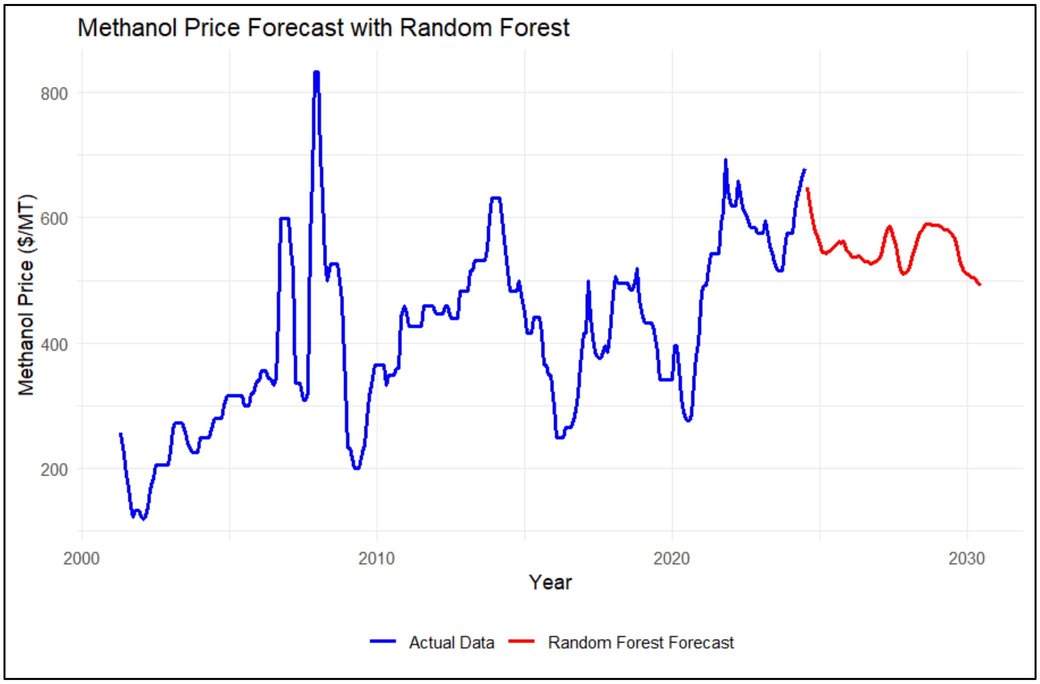

Figure 14 Methanol Price Forecast with Random Forest

The forecasts generated by the three models offer different perspectives on the future trajectory of methanol prices. Both the XGBoost and the Random Forest models provide more stable forecasts compared to the Prophet model, which shows a gradual increase but with higher uncertainty. The Prophet model explicitly incorporates global events as holidays, which may contribute to its broader confidence intervals and gradual upward trend. In contrast, the machine learning models (XGBoost and Random Forest) focus more on historical data patterns, leading to more stable but potentially less sensitive forecasts. All the results are concentrated in the table below (Table 8).

Table 8 Methanol Price Forecasting

Model	Forecasted Price in 2030 ($/MT)
Prophet	600.68
XGBoost	487.73
Random Forest	492.02

Regarding the further evaluation of the models, the RMSE of the models is calculated. RMSE shows the average error between predicted and actual values, so it is ideal to have a low RMSE. Despite the fact that XGBoost and Random Forest's results appeared more accurate at first, their RMSE proves the opposite. For XGBoost the RMSE is 213.33 and for Random Forest is 202.38. On the other hand, RMSE for Prophet is almost the half in comparison to the other two decision tree-based models, 109.59. This indicates that the in the forecasting of methanol, Prophet is the most accurate model.

As it is described in previous sections, the forecasted price of methanol is utilized for a comparative analysis between the studied alternative fuels. To facilitate this analysis, the selected price of methanol is calculated as the mean value of the three projections resulting in:

Methanol 2030 Forecasted Price = 526.81 $/MT

5.2. Biodiesel (FAME) Results and Analysis

In the same way as with methanol, the same three models are utilized for the prediction of FAME price in 2030. This section presents and analyses the results of the models.

The first employed model is Prophet, the results of which are presented in Figure 15. The historical data are represented by the red dots and the blue line represents the predicted values of the model. The model's forecast indicates a general upwards trend in FAME prices over time. The projected price in 2030 is $4.38 in GGE. The forecasted prices suggest a steady increase over time. The confidence intervals indicate increased uncertainty, higher than the uncertainty in methanol predictions, which reflects the challenges in predicting trends in volatile markets like FAME market. The smoothness of the forecast curve indicates that the model has successfully identified and incorporated the impact of significant holidays in the prices. Overall, while the model provides a useful projection, the high levels of uncertainty decrease the value of the model.

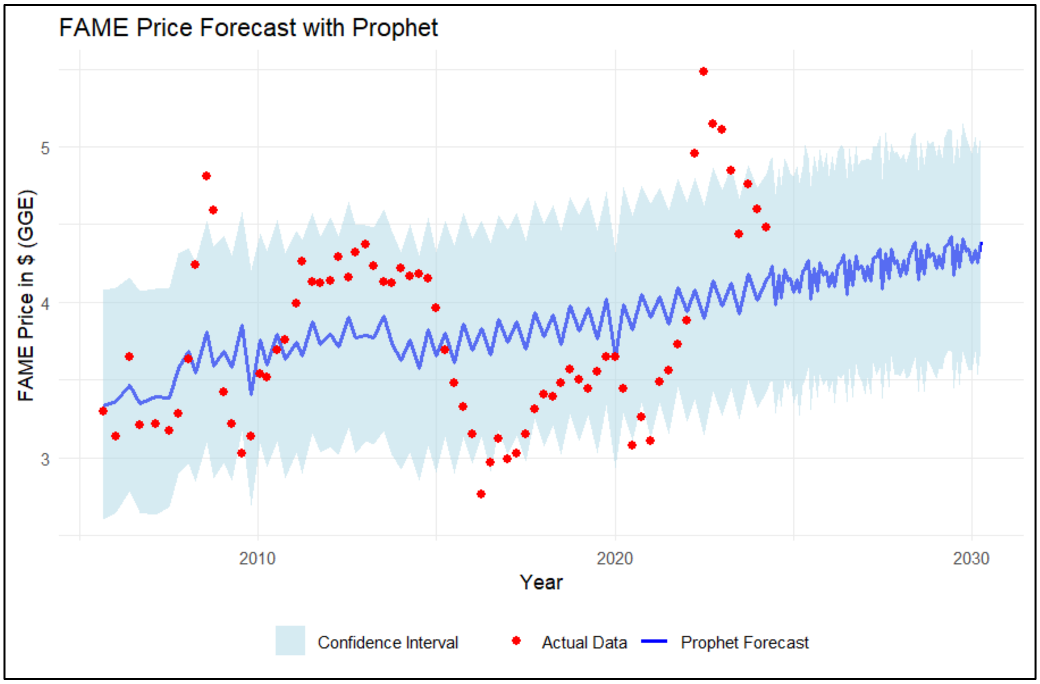

Figure 15 FAME Price Forecast with Prophet

The second implemented model is XGBoost, the forecast of which is presented in Figure 16. The forecast from the XGBoost model suggests that FAME prices will continue to fluctuate in the coming years. There are noticeable cyclical patters emerging between 2025 and 2030, unlike what the Prophet model predicted. This is likely due to the model's capability to capture complex interactions and dependencies within the historical data. The projected price for 2030 is $4.55 in GGE, while over the years the price fluctuates between $4 and $5 in GGE. That indicates that model expects the price of FAME to reduce, after its sharp spike that occurred from the Ukraine-Russia war.

The cyclical patterns in the forecast suggest that FAME prices are influenced by many sensitive factors, such as changes in demand, supply chain dynamics, fluctuations in the global economy and market interventions. Overall, XGBoost offers a more dynamic forecast compared to Prophet, which is useful for short to medium term price fluctuations forecast.

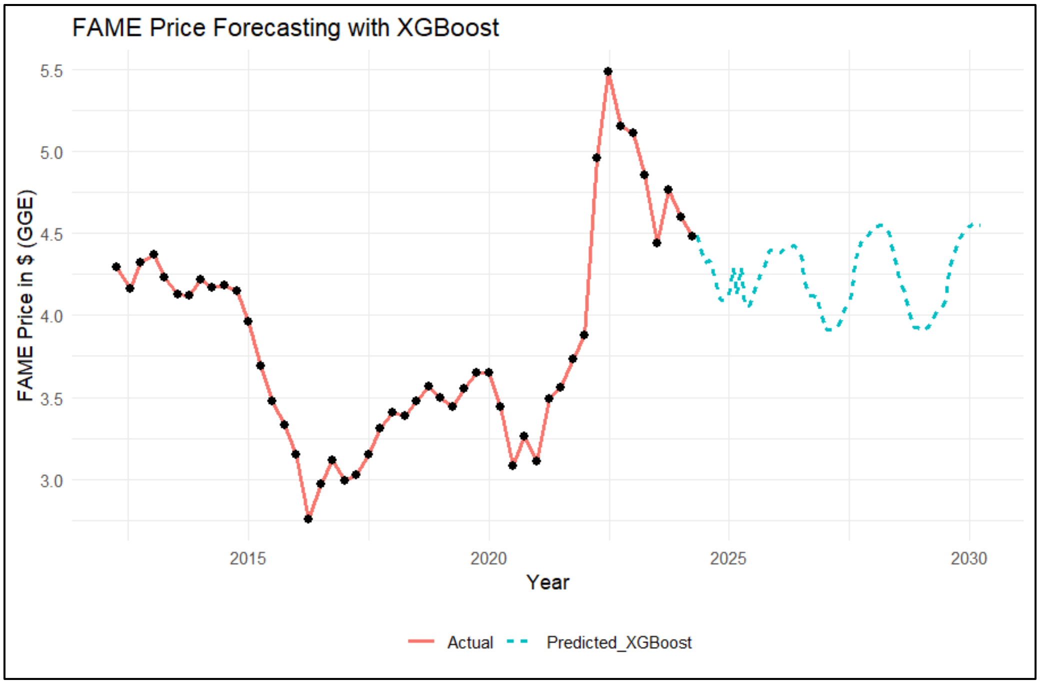

Figure 16 FAME Price Forecast with XGBoost

Finally, the last implemented model is Random Forest, the forecasting of which is presented in the following figure (Figure 17). The model offers results similar to XGBoost, that show periodic cycle behaviour. The prices range from \$4 to \$4.5 in GGE and the forecasted price for 2030 is \$3.79 in GGE. The forecasted trend, show a gradual decline in prices, with minor peaks and troughs. Overall, the Random Forest provides a balanced forecast with moderate price fluctuations and offers a conservative perspective on future volatility.

Each of the utilized models offer a distinct perspective on the future trajectory of FAME prices. The random forest model provides the most stable and conservative forecast, with limited volatility compared to the other models. XGBoost on the other hand predicts more pronounced cycles and fluctuations and Prophet suggest a steady increase in the price. XGBoost appears to be the most sensitive to historical data, because it captures and projects cyclical volatility into the future. It is important that all the models show no significant price spikes, which indicates the proper modelling of holidays.

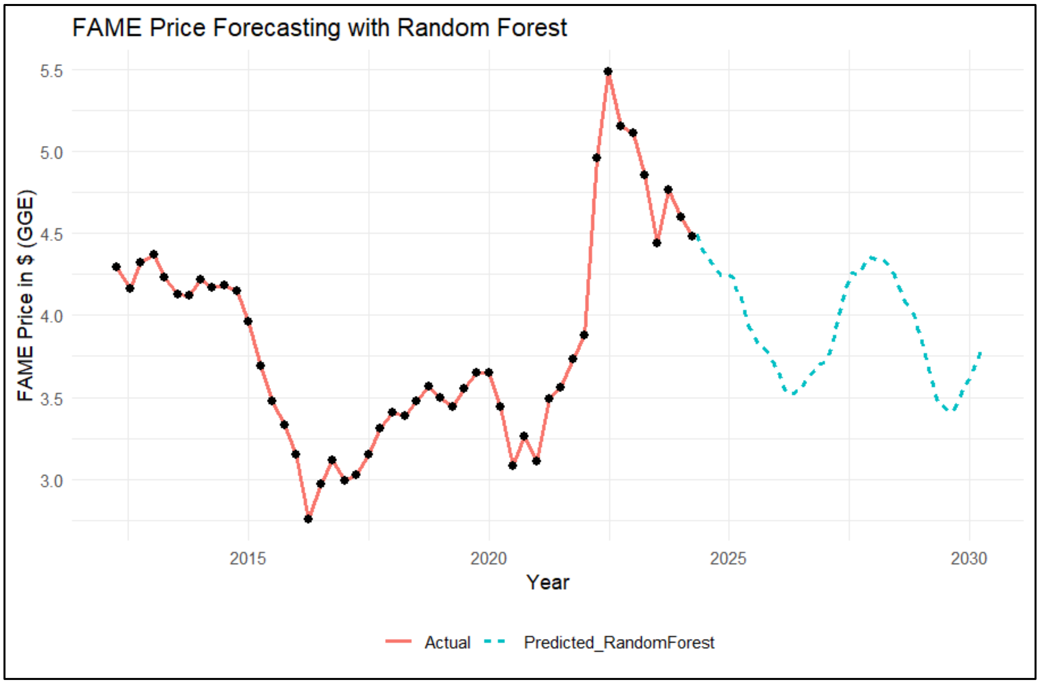

Figure 17 FAME Price Forecast with Random Forest

Table 9 FAME Price Forecasting

Model	Forecasted Price in 2030 ($ in GGE)
Prophet	4.38
XGBoost	4.55
Random Forest	3.79

The table above (Table 9) presents all the projections for 2030. Similarly with methanol, the RMSE of the utilized models is calculated to evaluate their performance. In this case, the values are significantly better and prove that all the prediction models function with more accuracy. The best model in this case is Random Forest, with 0.48 RMSE. That proves that it has strong prediction power, and its results are close to the real results. On the other hand, Prophet comes second with 0.56 and XGBoost third with RMSE 0.74.

Again, as explained in the methanol section, it is essential to calculate the forecasted price of FAME for 2030. By taking the average of the three projected prices, the final forecasted price is calculated:

FAME 2030 Forecasted Price = $4.24 in GGE

5.3. Hydrogen Results and Analysis

This sub-section offers the results of the implementation of models that forecasted the future prices of Electrolyzer and electricity in 2030. Based on these results, it is possible to make an estimation of the price of green hydrogen in 2030. The detailed calculation of hydrogen price is included in this section.

Firstly, it is important to present the results regarding the forecasting of electrolyzer capital cost. The following figure (Figure 18) illustrates the forecasting curve of Non-Linear Least Squares Model. The blue dots indicate the actual historical data points. It is immediately apparent that the model captures the significant downward trend in costs over the years. The model effectively fits the historical data, indicating that the exponential decay function used is well-suited to capture the cost reductions. The flattening of the curve suggests that the most significant cost reductions have already occurred, and future declines will likely be more gradual. This trend is consistent with the idea that as technology evolves, after a point further cost reductions become more difficult. The predicted electrolyzer cost for 2030 is $687.1.

The last prediction performed in this study concerns the electricity price. By implementing Prophet model, the forecasted prices are presented in Figure 19. The blue line shows the model’s forecast while the red dots represent the historical price data of electricity. The shaded blue area represents the confidence intervals, which indicate the level of uncertainty around the predictions. The forecast from the model suggests that electricity prices will continue their upwards trend. The model anticipates many fluctuations in prices, however, the trend remains upward. Based on the model predictions, in 2030, electricity price will reach $0.178 per kWh. Overall, the implementation of Prophet model is considered a good fit to electricity prices data, as the confidence intervals have a small range, which indicates low levels of uncertainty and a robust forecast of electricity prices. That is also proved from the RMSE of the model, which is 0.006, an extremely low value considering the price range of electricity.

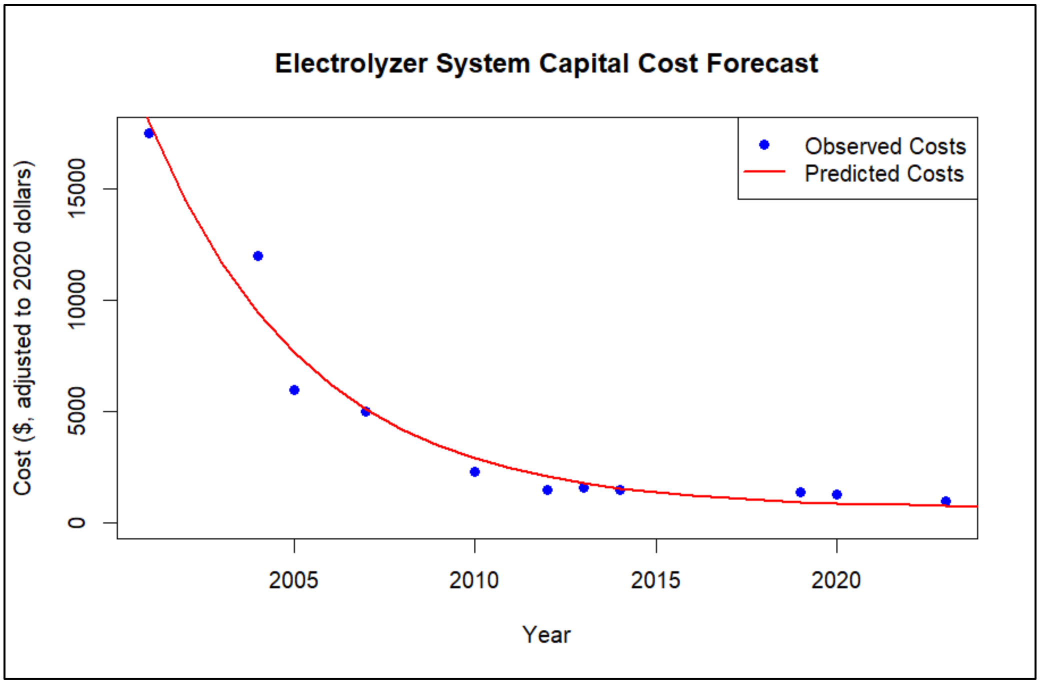

Figure 18 Electrolyzer Price Forecast

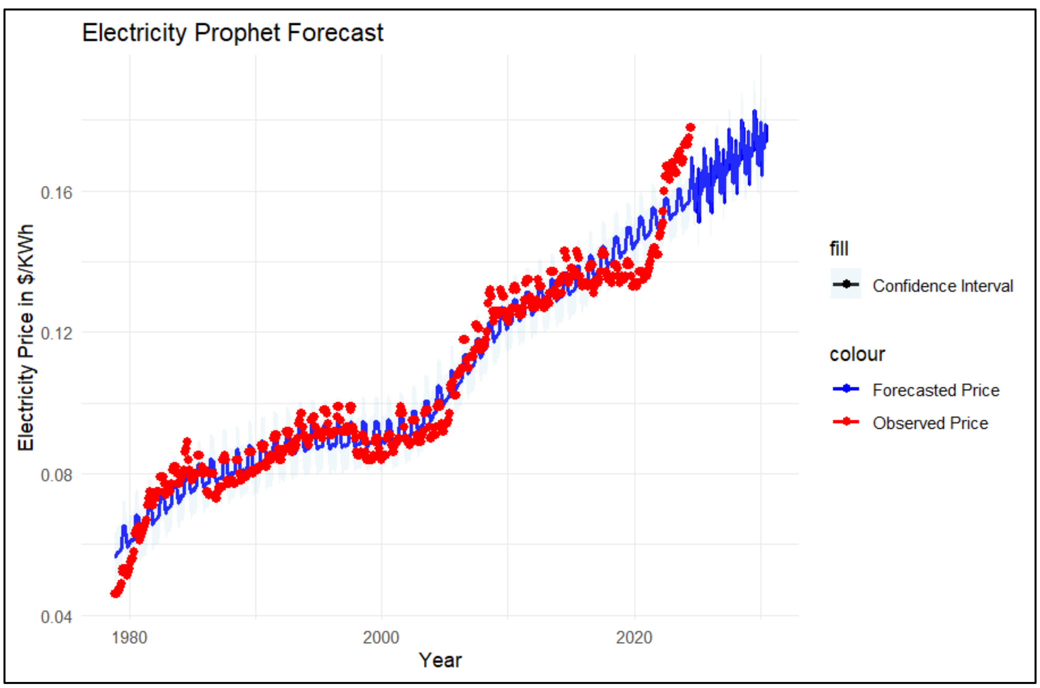

Figure 19 Electricity Price Forecast

Based on the results on the future price of electrolyzers and electricity it is possible to make an estimation of the future price of hydrogen. As mentioned in the data chapter, electricity is responsible for 52% of hydrogen production cost and electrolyzers for 27%.

According to Schelling (2023) the price of green hydrogen in 2023 was around $5 per kg. In addition, the price of electricity in 2023 was $0.168 per kWh and the price of electrolyzer around $1000. This means that electricity cost increased by 6% and electrolyzer cost reduced by 31%. Based on that, considering that the rest of the costs in the production of hydrogen remain the same, the reduction of the price of hydrogen due to the reduction of the price of electrolyzers is $0.42 per kg. In the same way, the increase due to the increase in electricity cost is $0.15 per kg. That lead to a decrease in the price of hydrogen by $0.27 per kg and the forecasted price of hydrogen is:

Hydrogen 2030 Forecasted Price = $4.73 per kg

5.4. Comparative Analysis

In the previous chapters, an analysis of how this study forecasted the prices of alternative fuels in 2030 is presented. The predicted prices are presented in the table below (Table 10). It is immediately apparent that the units of the predicted prices do not facilitate comparison. It is necessary to transform them into a uniform unit which will allow comparison. Moreover, as described in previous chapters, the studied alternative fuels have different energy densities, which leads to the need of different quantities of fuels. In this study, the most suitable unit for comparison of the prices of the fuels is the amount of dollars per kWh.

Table 10 Alternative Fuels Price Predictions

Alternative Fuel	Forecasted Price in 2030
Methanol	526.81 $/MT
FAME	$4.24 in GGE
Hydrogen	$4.73 per kg

For the transformation of FAME, it is also needed the fuel conversion factor from GGE to normal gallons of FAME, based on the U.S Department of Energy (n.d.), that factor is 1.05. That makes the price of FAME $4.04 per gallon, and by transforming the gallons in tons, $1,154 per metric ton. On the other hand, the cost of hydrogen in $ per tons is $4,730 per metric ton.

The calculation in the needed unit requires the lower heating value of each fuel, the values for each fuel are presented in the following table (Table 11). Moreover, it is important to transform the MJ to kWh, which is done by dividing with 0. 2777778 (1 megajoule equals to 0. 2777778 kilowatt-hours). The calculations are also apparent in the following table.

Table 11 Price of Alternative Fuels in $/kWh

Alternative Fuel	Lower Heating Value (MJ/kg)	Forecasted Price in 2030 ($/MT)	Produced kWh per MT	Forecasted Price in 2030 ($/kWh)
Methanol	20	526.81	5,556	0.09
FAME	37.1	1,154	10,306	0.11
Hydrogen	120	4,730	33,333	0.14

In order to compare the three fuels, it is crucial to consider not only their price, but also their benefits and disadvantages that are also mentioned in Chapter 3.

Methanol is the most cost-effective alternative fuel among the studied, with a price of only $0.09 per kWh. This makes methanol a highly attractive option from an economic standpoint, especially in comparison to FAME and hydrogen. This lower cost per kWh suggests that methanol could be a highly competitive option in the future of the industry. Methanol's large-scale production and its acceptance by the IGF Code further enhance its practicality as a fuel. Nevertheless, methanol also comes with significant drawbacks. Currently, it is primarily produced from natural gas or coal, which limits its environmental impact. Also, according to Laursen et al. (2023b), methanol produces 0.2486 kg of CO_2 per kWh, while hydrogen and FAME produce zero. Additionally, its low energy density means that more storage is required, and its toxicity and flammability lead to the need of increased safety measures.

FAME, with a price of $0.11 per kWh, is slightly more expensive than methanol. It offers a balance between cost and environmental benefits. Although FAME has a higher energy content per metric ton, its higher production costs elevate its price. Despite being more costly than methanol, FAME remains a viable alternative fuel, especially due to its renewable nature and its potential zero carbon footprint. However, FAME also has some drawbacks. Currently, there is limited availability of FAME, which might pose barriers to its widespread adoption. Moreover, corrosion risk and sensitivity of cold weather might become important problems in its utilization.

Hydrogen, the price of which is predicted at $0.14 per kWh, is the most expensive of the three fuels. While hydrogen offers the highest energy content per metric ton, its production costs significantly increase its price. Its higher cost reflects the challenges associated with its current production, however, if these challenges are tackled, hydrogen may be the most prominent solution towards decarbonization. In general, hydrogen's infrastructure is still under development, which in the future might lead to even lower prices. Also, the challenges regarding its storage and transportation make it a more complex solution. Despite these challenges, hydrogen's potential makes it one of the best zero-emission energy sources, especially in the long term.

Overall, methanol stands out as the most economically viable option with established infrastructure, making it the best option for near-term adoption. FAME, on the other hand, offers renewable energy with moderate cost increases, with the most important challenge its potential volume increase. Hydrogen, while currently the most expensive, holds the greatest potential for long-term sustainability, but it requires substantial research and development in infrastructure to overcome its current challenges. Based on these factors, this study estimates that further in the future, the prominent alternative fuel will be hydrogen, however, in the studied timeline, the study estimates that in 2030 the most suitable option for the maritime industry will be **METHANOL** with a predicted price of $526.81 per metric ton.

Finally, it is important to compare the predictions of this study with other predictions to evaluate the results. According to Laursen et al.(2023b), the cost of hydrogen and biodiesel (FAME) are projected to be around 60€/GJ and 20 to 30€/GJ, respectively. By transforming these units to $ per metric ton, the estimation for hydrogen is $7992 per metric ton and for FAME $1029 per metric ton. It is apparent that FAME prediction is close to their forecast, while hydrogen's price has a significant difference. That is mostly justified because the prediction in this study is based on the production in the United States, while Laursen et al. (2023b), make an estimation for the cost in Europe. The production costs of Hydrogen in the United States are different from the production costs in Europe. Regarding methanol, the literature on the prediction is limited and comparative data cannot be collected to compare the prediction of this study with other studies.

6. Conclusion

To conclude, this thesis explores the potential alternative fuels for the maritime industry based on the increased sustainability awareness and the decarbonization goals of the International Maritime Organization for 2050.Through a combination of literature review, qualitative research, data analysis, and predictive modelling this research completes its goals to answer its research question and its sub-research questions, introduced in the introduction chapter (Chapter 1).

6.1. Answers to Research Questions

The research conducted in this thesis has successfully answered its key research question and the sub research question. Below follow the answers, firstly to the sub-research questions and subsequently to the main question.

1. What are the potential future alternative fuels? (Chapter 3)

- After extensive qualitative research, including a detailed review of existing literature, the most prominent alternative fuels identified are Methanol, Ammonia, Hydrogen, and Biofuels. These fuels are distinguished based on their potential to significantly reduce the greenhouse gas emissions and their feasibility for adoption in the maritime industry.

2. What are the strengths and weaknesses of each alternative fuel? (Chapter 3)

- Methanol: Methanol stands out for its existing infrastructure and cost-effectiveness. It can be easily integrated into current maritime operations. However, its lower energy density compared to conventional fuels and its toxicity present some challenges that need to be managed carefully.
- Ammonia: Ammonia offers high energy density and has the potential to be carbon-free, particularly when produced using renewable energy sources. Its infrastructure is already advanced due to its utilization in the fertilizer industry. Nevertheless, ammonia’s toxicity and the complexity of safely storing it and transporting it, pose significant challenges to its adoption as a fuel.

- Hydrogen: Hydrogen presents high potential to completely eliminate carbon emissions. Its high energy content is one of its most appealing characteristics. Nevertheless, hydrogen is currently one of the most expensive solutions and its storage and transportation require further development. The current hydrogen infrastructure is limited.
- Biofuels: Biofuels are renewable and can be used as drop in fuels in existing engines, offering a practical short-term solution. However, their limited availability leads to increased prices and poses and obstacle for their widespread use. Moreover, storage of biofuels can also be a problem, requiring specific conditions.

3. What are the ways of production of each type of fuel? (Chapter 3)

- Methanol: Methanol is produced through several methods, including natural gas reforming, coal gasification and more sustainable methods such as natural gas reforming with carbon capture (blue methanol) and through renewable electricity and CO_2 (green methanol). Each production method has different environmental impact.
- Ammonia: Ammonia is produced from fossil fuels, with or without the utilization of carbon capture, or entirely from renewable sources. There is also a hybrid type of ammonia which combines the fossil fuels and the renewable electricity.
- Hydrogen: Hydrogen is produced through several processes, including steam methane reforming (grey hydrogen), electrolysis using renewable energy (green hydrogen), and pyrolysis (turquoise hydrogen). Blue hydrogen is also produced using steam methane reforming with carbon capture technology.
- Biofuels: Biofuels are produced from biomass with various processes. Some of these processes are transesterification for biodiesel, gasification for bio-methanol, and fermentation for bioethanol. Based on the feedstock and the production way of each fuel there are different greenhouse gas emissions.

4. What is the timeline for the utilization of new types of fuel? (Chapter 4)

- After an evaluation of the shipping industry, the ages of the vessels and the current level of alternative fuel utilization, the estimated timeline for the utilization of new types of fuel that is estimated in this study is until 2030. After that year, it is projected that the industry will turn to the adoption of these fuels.

5. What is the best model to predict the future prices of alternative fuels? (Chapter 4)

- Based on the findings from the implementation of the models, Prophet and Random Forest models are identified as the most effective for predicting future fuel prices. These models excel in handling large datasets with non-linear patterns. Nevertheless, XGBoost model also offered important insights, however, less accurate and reliable than the other two models.

6. What is the predicted cost of each alternative fuel? (Chapter 5)

- The predicted price for the studied alternative fuels is presented in the table below (Table 12):

Table 12 Alternative Fuels Predicted Prices

Alternative Fuel	Forecasted Price in 2030 ($/MT)	Forecasted Price in 2030 ($/kWh)
Methanol	526.81	0.09
FAME	1,154	0.11
Hydrogen	4,730	0.14

7. What factors are affecting the alternative fuel prices? (Chapter 4 and 5)

- After the qualitative and quantitative research several factors are identified. Production costs, technological advancements and supply and demand fluctuations are considered to have significant influence on the prices. However, from the analysis of the data, it is immediately apparent that geopolitical events have a huge impact on the prices. Events like the Russia-Ukraine war, COVID-19 and the global financial crisis of 2008 led to apparent spikes in the prices.

Research Question: ***Which alternative fuel type is considered the best to be used in the future to reduce the carbon emissions and achieve the IMO 2050 goals at the lowest possible cost? (Chapter 5)***

- After a comprehensive analysis, it is clear that methanol emerges as the most viable option in the near to medium term for reducing carbon emissions at the lowest cost. Methanol is particularly attractive due to its existing infrastructure, its lowest costs in comparison to the other studied fuels, and its compatibility with the current marine engines. While its environmental impact varies, methanol‘s overall benefits make it the best candidate for meeting the IMO 2050 goals in the short term. Nevertheless, hydrogen is identified as the most promising long-term solution due to its zero-emission potential and its high energy content. Although it currently has the highest costs and significant infrastructural challenges, ongoing advancements in technology can make hydrogen the best long-term solution. Thus, while methanol is recommended for immediate adoption, hydrogen represents the optimal long-term solution for the maritime industry and its decarbonization targets.

6.2. Limitations and Future Work

While this study provides valuable insights into the potential use of alternative fuels in the maritime industry, several limitations must be acknowledged. Firstly, data limitations may affect the results of the study. The predictive models utilized in this study rely on historical data for the forecasting of the future prices. However, data for the emerging alternative fuels, particularly hydrogen and ammonia are limited. That limitation lead to the exclusion of ammonia in the prediction process and to an alternative approach for the prediction of hydrogen’s price.

Moreover, as described in Chapter 4, this study tries to implement the effect of technology, demand and supply in the prediction process. These parameters have an important role in the prices of alternative fuels. Nevertheless, the programming efforts and the approach of this study is not successful in integrating these effects in the modelling process. More detailed data and additional research time is needed for the incorporation of these factors in the prediction process.

Finally, this study is not considering the impact of future regulations and policies. These factors could play a crucial role in shaping the economic viability and widespread adoption of alternative fuels. These changes could possibly affect the timeline for adoption and the future demand and supply of alternative fuels.

While this thesis provides valuable insights into the potential use of alternative fuels, there is still space for future research. Given the above limitations, this study suggests that future studies should have enhanced data collection. Data are the cornerstone of similar studies and are essential for the better implementation of the models. Moreover, modelling of technological advancements, demand and supply and examination of different scenarios for the future can provide more robust analysis of future fuel prices. In this way the models, will uncover more factors that influence the price trends, and the predictions will become more accurate. Additionally, exploration of hybrid fuels solutions that combine benefits of different alternative fuel types can be beneficial. This topic has limited research and might be one of the prominent solutions in the future. Finally, examination of different policy scenarios might lead to more accurate results, closer to real-world situations. By addressing these areas in future research, the maritime industry can be better prepared for the adoption of alternative fuels, in a way more economically viable and environmentally sustainable.

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Appendix A: Alternative Fuel Data

Methanol Data

Date	$/MT	Date	$/MT	Date	$/MT	Date	$/MT
May-01	$256	Oct-03	$226	Mar-06	$356	Aug-08	$526
Jun-01	$223	Nov-03	$226	Apr-06	$356	Sep-08	$526
Jul-01	$190	Dec-03	$226	May-06	$343	Oct-08	$499
Aug-01	$170	Jan-04	$249	Jun-06	$343	Nov-08	$466
Sep-01	$140	Feb-04	$249	Jul-06	$333	Dec-08	$333
Oct-01	$123	Mar-04	$249	Aug-06	$343	Jan-09	$233
Nov-01	$133	Apr-04	$249	Sep-06	$442	Feb-09	$233
Dec-01	$133	May-04	$249	Oct-06	$599	Mar-09	$216
Jan-02	$125	Jun-04	$269	Nov-06	$599	Apr-09	$200
Feb-02	$120	Jul-04	$279	Dec-06	$599	May-09	$200
Mar-02	$125	Aug-04	$279	Jan-07	$599	Jun-09	$200
Apr-02	$140	Sep-04	$279	Feb-07	$549	Jul-09	$226
May-02	$166	Oct-04	$279	Mar-07	$516	Aug-09	$239
Jun-02	$186	Nov-04	$299	Apr-07	$336	Sep-09	$279
Jul-02	$206	Dec-04	$316	May-07	$336	Oct-09	$316
Aug-02	$206	Jan-05	$316	Jun-07	$336	Nov-09	$333
Sep-02	$206	Feb-05	$316	Jul-07	$309	Dec-09	$366
Oct-02	$206	Mar-05	$316	Aug-07	$309	Jan-10	$366
Nov-02	$206	Apr-05	$316	Sep-07	$319	Feb-10	$366
Dec-02	$206	May-05	$316	Oct-07	$565	Mar-10	$366
Jan-03	$229	Jun-05	$316	Nov-07	$665	Apr-10	$366
Feb-03	$263	Jul-05	$299	Dec-07	$832	May-10	$333
Mar-03	$273	Aug-05	$299	Jan-08	$832	Jun-10	$349
Apr-03	$273	Sep-05	$299	Feb-08	$698	Jul-10	$349
May-03	$273	Oct-05	$319	Mar-08	$632	Aug-10	$349
Jun-03	$273	Nov-05	$319	Apr-08	$532	Sep-10	$359
Jul-03	$258	Dec-05	$339	May-08	$499	Oct-10	$359
Aug-03	$239	Jan-06	$339	Jun-08	$526	Nov-10	$442
Sep-03	$233	Feb-06	$356	Jul-08	$526	Dec-10	$459

Jan-11	$449	Oct-13	$549	Jul-16	$266	Apr-19	$432
Feb-11	$426	Nov-13	$599	Aug-16	$266	May-19	$432
Mar-11	$426	Dec-13	$632	Sep-16	$276	Jun-19	$419
Apr-11	$426	Jan-14	$632	Oct-16	$293	Jul-19	$386
May-11	$426	Feb-14	$632	Nov-16	$319	Aug-19	$342
Jun-11	$426	Mar-14	$632	Dec-16	$366	Sep-19	$342
Jul-11	$426	Apr-14	$599	Jan-17	$416	Oct-19	$342
Aug-11	$459	May-14	$565	Feb-17	$416	Nov-19	$342
Sep-11	$459	Jun-14	$532	Mar-17	$499	Dec-19	$342
Oct-11	$459	Jul-14	$482	Apr-17	$442	Jan-20	$342
Nov-11	$459	Aug-14	$482	May-17	$409	Feb-20	$396
Dec-11	$459	Sep-14	$482	Jun-17	$386	Mar-20	$396
Jan-12	$446	Oct-14	$482	Jul-17	$376	Apr-20	$359
Feb-12	$446	Nov-14	$499	Aug-17	$376	May-20	$313
Mar-12	$446	Dec-14	$475	Sep-17	$386	Jun-20	$289
Apr-12	$446	Jan-15	$449	Oct-17	$396	Jul-20	$276
May-12	$459	Feb-15	$416	Nov-17	$386	Aug-20	$276
Jun-12	$459	Mar-15	$416	Dec-17	$412	Sep-20	$286
Jul-12	$439	Apr-15	$416	Jan-18	$479	Oct-20	$336
Aug-12	$439	May-15	$442	Feb-18	$506	Nov-20	$379
Sep-12	$439	Jun-15	$442	Mar-18	$496	Dec-20	$399
Oct-12	$439	Jul-15	$442	Apr-18	$496	Jan-21	$482
Nov-12	$482	Aug-15	$416	May-18	$496	Feb-21	$492
Dec-12	$482	Sep-15	$366	Jun-18	$496	Mar-21	$492
Jan-13	$482	Oct-15	$366	Jul-18	$496	Apr-21	$519
Feb-13	$482	Nov-15	$349	Aug-18	$485	May-21	$542
Mar-13	$516	Dec-15	$349	Sep-18	$485	Jun-21	$542
Apr-13	$516	Jan-16	$299	Oct-18	$496	Jul-21	$542
May-13	$532	Feb-16	$249	Nov-18	$519	Aug-21	$542
Jun-13	$532	Mar-16	$249	Dec-18	$469	Sep-21	$592
Jul-13	$532	Apr-16	$249	Jan-19	$442	Oct-21	$609
Aug-13	$532	May-16	$249	Feb-19	$432	Nov-21	$692
Sep-13	$532	Jun-16	$266	Mar-19	$432	Dec-21	$642

Jan-22	$619
Feb-22	$619
Mar-22	$619
Apr-22	$659
May-22	$639
Jun-22	$615
Jul-22	$605
Aug-22	$595
Sep-22	$585
Oct-22	$585
Nov-22	$585
Dec-22	$575
Jan-23	$575
Feb-23	$575
Mar-23	$595
Apr-23	$575
May-23	$555
Jun-23	$545
Jul-23	$529
Aug-23	$516
Sep-23	$516
Oct-23	$516
Nov-23	$549
Dec-23	$575
Jan-24	$575
Feb-24	$575
Mar-24	$609
Apr-24	$632
May-24	$645
Jun-24	$662
Jul-24	$679

FAME Data

Report Date	Gasoline	Diesel	Fame	Report Date	Gasoline	Diesel	Fame
9/1/2005	$2.77	$2.54	$3.30	**4/1/2017**	$2.38	$2.27	$3.03
1/1/2006	$2.23	$2.32	$3.14	**7/1/2017**	$2.26	$2.20	$3.15
5/24/2006	$2.84	$2.69	$3.65	**10/1/2017**	$2.49	$2.46	$3.31
9/4/2006	$2.22	$2.37	$3.21	**1/1/2018**	$2.50	$2.63	$3.41
2/21/2007	$2.30	$2.37	$3.22	**4/1/2018**	$2.67	$2.70	$3.39
7/3/2007	$3.03	$2.67	$3.17	**7/1/2018**	$2.88	$2.89	$3.48
10/2/2007	$2.76	$2.81	$3.28	**10/1/2018**	$2.91	$2.99	$3.57
1/21/2008	$2.99	$3.05	$3.63	**1/1/2019**	$2.27	$2.65	$3.50
4/1/2008	$3.43	$3.71	$4.24	**4/1/2019**	$2.76	$2.75	$3.44
7/21/2008	$3.91	$4.22	$4.81	**7/1/2019**	$2.76	$2.71	$3.55
10/2/2008	$3.04	$3.27	$4.59	**10/1/2019**	$2.68	$2.74	$3.65
1/12/2009	$1.86	$2.19	$3.42	**1/1/2020**	$2.59	$2.71	$3.65
4/1/2009	$2.02	$2.04	$3.22	**4/1/2020**	$1.91	$2.33	$3.44
7/20/2009	$2.44	$2.27	$3.03	**7/1/2020**	$2.22	$2.20	$3.08
10/16/2009	$2.64	$2.50	$3.14	**10/1/2020**	$2.18	$2.13	$3.26
1/19/2010	$2.65	$2.57	$3.54	**1/1/2021**	$2.32	$2.35	$3.11
4/2/2010	$2.84	$2.71	$3.52	**4/1/2021**	$2.82	$2.77	$3.49
7/12/2010	$2.71	$2.65	$3.69	**7/1/2021**	$3.09	$2.90	$3.56
10/4/2010	$2.78	$2.75	$3.76	**10/1/2021**	$3.25	$3.10	$3.73
1/24/2011	$3.08	$3.09	$3.99	**1/1/2022**	$3.28	$3.22	$3.88
4/1/2011	$3.69	$3.62	$4.26	**4/1/2022**	$4.13	$4.50	$4.96
7/14/2011	$3.68	$3.54	$4.13	**7/1/2022**	$4.70	$5.02	$5.48
9/30/2011	$3.46	$3.42	$4.12	**10/1/2022**	$4.05	$4.60	$5.15
1/13/2012	$3.37	$3.46	$4.14	**1/1/2023**	$3.31	$4.08	$5.11
3/30/2012	$3.89	$3.69	$4.29	**4/1/2023**	$3.69	$3.78	$4.85
7/13/2012	$3.52	$3.36	$4.16	**7/1/2023**	$3.59	$3.45	$4.44
9/28/2012	$3.82	$3.70	$4.32	**10/1/2023**	$3.72	$4.02	$4.76
1/10/2013	$3.29	$3.55	$4.37	**1/1/2024**	$3.06	$3.51	$4.60
3/29/2013	$3.59	$3.58	$4.23	**4/1/2024**	$3.65	$3.62	$4.48
7/12/2013	$3.65	$3.50	$4.13				
10/4/2013	$3.45	$3.51	$4.12				
1/1/2014	$3.34	$3.49	$4.22				
4/1/2014	$3.65	$3.56	$4.17				
7/1/2014	$3.70	$3.51	$4.18				
10/1/2014	$3.34	$3.38	$4.15				
1/1/2015	$2.30	$2.75	$3.96				
4/1/2015	$2.42	$2.56	$3.69				
7/1/2015	$2.82	$2.61	$3.48				
10/1/2015	$2.35	$2.30	$3.33				
1/1/2016	$1.98	$1.99	$3.15				
4/1/2016	$2.06	$1.90	$2.76				
7/1/2016	$2.26	$2.19	$2.97				
10/1/2016	$2.22	$2.21	$3.12				
1/1/2017	$2.32	$2.30	$2.99				

Electrolyzer Data

Year	Estimated System Capital Cost (2020$)
2001	$17,500
2004	$12,000
2005	$6,000
2007	$5,000
2010	$2,300
2012	$1,500
2013	$1,600
2014	$1,500
2019	$1,400
2020	$1,300
2023	$1,000

Electricity Data

Date	Price ($/KWh)	Date	Price ($/KWh)	Date	Price ($/KWh)	Date	Price ($/KWh)
11/1978	0.046	01/1980	0.053	03/1981	0.065	05/1982	0.075
12/1978	0.046	02/1980	0.055	04/1981	0.066	06/1982	0.079
01/1979	0.046	03/1980	0.056	05/1981	0.067	07/1982	0.079
02/1979	0.047	04/1980	0.056	06/1981	0.071	08/1982	0.079
03/1979	0.047	05/1980	0.058	07/1981	0.073	09/1982	0.079
04/1979	0.048	06/1980	0.063	08/1981	0.075	10/1982	0.077
05/1979	0.049	07/1980	0.064	09/1981	0.074	11/1982	0.074
06/1979	0.052	08/1980	0.064	10/1981	0.072	12/1982	0.075
07/1979	0.053	09/1980	0.065	11/1981	0.071	01/1983	0.075
08/1979	0.053	10/1980	0.063	12/1981	0.071	02/1983	0.075
09/1979	0.053	11/1980	0.061	01/1982	0.073	03/1983	0.076
10/1979	0.053	12/1980	0.062	02/1982	0.073	04/1983	0.075
11/1979	0.051	01/1981	0.063	03/1982	0.075	05/1983	0.077
12/1979	0.052	02/1981	0.064	04/1982	0.075	06/1983	0.081

07/1983	0.082	04/1986	0.074	01/1989	0.079	10/1991	0.087
08/1983	0.082	05/1986	0.074	02/1989	0.079	11/1991	0.084
09/1983	0.082	06/1986	0.080	03/1989	0.079	12/1991	0.085
10/1983	0.080	07/1986	0.080	04/1989	0.079	01/1992	0.085
11/1983	0.077	08/1986	0.080	05/1989	0.080	02/1992	0.084
12/1983	0.077	09/1986	0.080	06/1989	0.086	03/1992	0.086
01/1984	0.078	10/1986	0.074	07/1989	0.086	04/1992	0.086
02/1984	0.079	11/1986	0.073	08/1989	0.086	05/1992	0.087
03/1984	0.079	12/1986	0.073	09/1989	0.086	06/1992	0.092
04/1984	0.080	01/1987	0.075	10/1989	0.081	07/1992	0.092
05/1984	0.081	02/1987	0.076	11/1989	0.080	08/1992	0.091
06/1984	0.086	03/1987	0.076	12/1989	0.081	09/1992	0.092
07/1984	0.087	04/1987	0.076	01/1990	0.081	10/1992	0.088
08/1984	0.089	05/1987	0.076	02/1990	0.081	11/1992	0.086
09/1984	0.084	06/1987	0.084	03/1990	0.081	12/1992	0.088
10/1984	0.081	07/1987	0.084	04/1990	0.082	01/1993	0.089
11/1984	0.079	08/1987	0.085	05/1990	0.082	02/1993	0.087
12/1984	0.078	09/1987	0.084	06/1990	0.088	03/1993	0.088
01/1985	0.079	10/1987	0.078	07/1990	0.087	04/1993	0.088
02/1985	0.079	11/1987	0.077	08/1990	0.087	05/1993	0.090
03/1985	0.079	12/1987	0.077	09/1990	0.088	06/1993	0.094
04/1985	0.080	01/1988	0.078	10/1990	0.083	07/1993	0.095
05/1985	0.080	02/1988	0.078	11/1990	0.082	08/1993	0.097
06/1985	0.085	03/1988	0.078	12/1990	0.082	09/1993	0.097
07/1985	0.085	04/1988	0.077	01/1991	0.084	10/1993	0.093
08/1985	0.085	05/1988	0.077	02/1991	0.084	11/1993	0.091
09/1985	#N/A	06/1988	0.084	03/1991	0.085	12/1993	0.090
10/1985	0.082	07/1988	0.084	04/1991	0.084	01/1994	0.090
11/1985	0.080	08/1988	0.084	05/1991	0.085	02/1994	0.090
12/1985	0.080	09/1988	0.084	06/1991	0.090	03/1994	0.089
01/1986	0.081	10/1988	0.080	07/1991	0.091	04/1994	0.088
02/1986	0.075	11/1988	0.078	08/1991	0.090	05/1994	0.090
03/1986	0.075	12/1988	0.078	09/1991	0.091	06/1994	0.095

07/1994	0.095	04/1997	0.092	01/2000	0.084	10/2002	0.091
08/1994	0.096	05/1997	0.093	02/2000	0.085	11/2002	0.089
09/1994	0.096	06/1997	0.099	03/2000	0.085	12/2002	0.089
10/1994	0.093	07/1997	0.099	04/2000	0.085	01/2003	0.089
11/1994	0.091	08/1997	0.098	05/2000	0.085	02/2003	0.089
12/1994	0.091	09/1997	0.099	06/2000	0.090	03/2003	0.089
01/1995	0.091	10/1997	0.093	07/2000	0.091	04/2003	0.091
02/1995	0.091	11/1997	0.092	08/2000	0.091	05/2003	0.092
03/1995	0.091	12/1997	0.090	09/2000	0.091	06/2003	0.097
04/1995	0.090	01/1998	0.086	10/2000	0.088	07/2003	0.098
05/1995	0.092	02/1998	0.085	11/2000	0.086	08/2003	0.098
06/1995	0.098	03/1998	0.085	12/2000	0.086	09/2003	0.098
07/1995	0.098	04/1998	0.085	01/2001	0.088	10/2003	0.093
08/1995	0.098	05/1998	0.086	02/2001	0.088	11/2003	0.090
09/1995	0.097	06/1998	0.091	03/2001	0.089	12/2003	0.090
10/1995	0.094	07/1998	0.091	04/2001	0.089	01/2004	0.091
11/1995	0.092	08/1998	0.090	05/2001	0.090	02/2004	0.091
12/1995	0.091	09/1998	0.089	06/2001	0.097	03/2004	0.091
01/1996	0.091	10/1998	0.086	07/2001	0.099	04/2004	0.091
02/1996	0.091	11/1998	0.084	08/2001	0.098	05/2004	0.093
03/1996	0.092	12/1998	0.084	09/2001	0.097	06/2004	0.099
04/1996	0.092	01/1999	0.084	10/2001	0.093	07/2004	0.099
05/1996	0.092	02/1999	0.084	11/2001	0.090	08/2004	0.100
06/1996	0.096	03/1999	0.084	12/2001	0.090	09/2004	0.099
07/1996	0.099	04/1999	0.084	01/2002	0.089	10/2004	0.094
08/1996	0.099	05/1999	0.085	02/2002	0.089	11/2004	0.092
09/1996	0.099	06/1999	0.089	03/2002	0.089	12/2004	0.092
10/1996	0.095	07/1999	0.090	04/2002	0.088	01/2005	0.094
11/1996	0.092	08/1999	0.089	05/2002	0.089	02/2005	0.094
12/1996	0.092	09/1999	0.090	06/2002	0.095	03/2005	0.094
01/1997	0.092	10/1999	0.087	07/2002	0.095	04/2005	0.095
02/1997	0.092	11/1999	0.085	08/2002	0.095	05/2005	0.097
03/1997	0.093	12/1999	0.085	09/2002	0.095	06/2005	0.104

07/2005	0.105	04/2008	0.118	01/2011	0.125	10/2013	0.132
08/2005	0.105	05/2008	0.120	02/2011	0.125	11/2013	0.130
09/2005	0.106	06/2008	0.128	03/2011	0.127	12/2013	0.131
10/2005	0.102	07/2008	0.131	04/2011	0.127	01/2014	0.134
11/2005	0.102	08/2008	0.132	05/2011	0.129	02/2014	0.134
12/2005	0.102	09/2008	0.130	06/2011	0.134	03/2014	0.135
01/2006	0.108	10/2008	0.126	07/2011	0.135	04/2014	0.131
02/2006	0.108	11/2008	0.123	08/2011	0.135	05/2014	0.136
03/2006	0.109	12/2008	0.124	09/2011	0.135	06/2014	0.143
04/2006	0.109	01/2009	0.126	10/2011	0.130	07/2014	0.143
05/2006	0.110	02/2009	0.126	11/2011	0.128	08/2014	0.143
06/2006	0.118	03/2009	0.126	12/2011	0.127	09/2014	0.141
07/2006	0.118	04/2009	0.125	01/2012	0.128	10/2014	0.136
08/2006	0.118	05/2009	0.126	02/2012	0.128	11/2014	0.134
09/2006	0.118	06/2009	0.132	03/2012	0.127	12/2014	0.135
10/2006	0.112	07/2009	0.131	04/2012	0.127	01/2015	0.138
11/2006	0.110	08/2009	0.130	05/2012	0.129	02/2015	0.138
12/2006	0.110	09/2009	0.130	06/2012	0.135	03/2015	0.136
01/2007	0.113	10/2009	0.126	07/2012	0.133	04/2015	0.137
02/2007	0.113	11/2009	0.124	08/2012	0.133	05/2015	0.137
03/2007	0.113	12/2009	0.124	09/2012	0.133	06/2015	0.143
04/2007	0.113	01/2010	0.124	10/2012	0.128	07/2015	0.142
05/2007	0.115	02/2010	0.123	11/2012	0.127	08/2015	0.142
06/2007	0.122	03/2010	0.125	12/2012	0.127	09/2015	0.141
07/2007	0.122	04/2010	0.126	01/2013	0.129	10/2015	0.136
08/2007	0.121	05/2010	0.127	02/2013	0.129	11/2015	0.134
09/2007	0.121	06/2010	0.132	03/2013	0.128	12/2015	0.133
10/2007	0.117	07/2010	0.133	04/2013	0.128	01/2016	0.134
11/2007	0.115	08/2010	0.133	05/2013	0.131	02/2016	0.134
12/2007	0.115	09/2010	0.132	06/2013	0.137	03/2016	0.134
01/2008	0.116	10/2010	0.127	07/2013	0.137	04/2016	0.134
02/2008	0.116	11/2010	0.125	08/2013	0.137	05/2016	0.133
03/2008	0.116	12/2010	0.125	09/2013	0.137	06/2016	0.138

07/2016	0.139	04/2019	0.135	01/2022	0.147
08/2016	0.139	05/2019	0.136	02/2022	0.148
09/2016	0.139	06/2019	0.139	03/2022	0.150
10/2016	0.134	07/2019	0.140	04/2022	0.151
11/2016	0.131	08/2019	0.139	05/2022	0.154
12/2016	0.133	09/2019	0.139	06/2022	0.160
01/2017	0.134	10/2019	0.136	07/2022	0.164
02/2017	0.135	11/2019	0.133	08/2022	0.167
03/2017	0.134	12/2019	0.133	09/2022	0.167
04/2017	0.135	01/2020	0.134	10/2022	0.166
05/2017	0.137	02/2020	0.134	11/2022	0.163
06/2017	0.142	03/2020	0.134	12/2022	0.165
07/2017	0.143	04/2020	0.133	01/2023	0.168
08/2017	0.142	05/2020	0.134	02/2023	0.168
09/2017	0.142	06/2020	0.137	03/2023	0.166
10/2017	0.137	07/2020	0.137	04/2023	0.165
11/2017	0.136	08/2020	0.137	05/2023	0.165
12/2017	0.136	09/2020	0.137	06/2023	0.170
01/2018	0.135	10/2020	0.135	07/2023	0.169
02/2018	0.135	11/2020	0.136	08/2023	0.170
03/2018	0.135	12/2020	0.136	09/2023	0.171
04/2018	0.134	01/2021	0.136	10/2023	0.169
05/2018	0.136	02/2021	0.137	11/2023	0.168
06/2018	0.139	03/2021	0.138	12/2023	0.169
07/2018	0.139	04/2021	0.139	01/2024	0.173
08/2018	0.139	05/2021	0.140	02/2024	0.173
09/2018	0.138	06/2021	0.142	03/2024	0.174
10/2018	0.136	07/2021	0.143	04/2024	0.173
11/2018	0.134	08/2021	0.144	05/2024	0.175
12/2018	0.135	09/2021	0.144	06/2024	0.178
01/2019	0.135	10/2021	0.142	07/2024	0.178
02/2019	0.136	11/2021	0.142		
03/2019	0.135	12/2021	0.142		

Appendix B: Model Implementation in R

Methanol Model Implementation

```
library("prophet")
library("readxl")
library("dplyr")
library("writexl")
library("xgboost")
library("data.table")
library("lubridate")
library("ggplot2")
library("randomForest")
library("data.table")
#Model 1 (Prophet)
# Load data
data <- read_excel("methanol_data.xls")
data$Date <- as.Date(data$Date, format = "%Y-%m-%d")
data <- mutate(data, ds = Date, y = `$/MT`, cap = 1.5 * max(`$/MT`)) # Add capacity
# Define special events as holidays
holidays <- data.frame(
  holiday = c('Global Financial Crisis', 'COVID-19 Pandemic', 'Russia-Ukraine Conflict'),
  ds = as.Date(c('2008-09-15', '2020-03-11', '2022-02-24'))  # Start dates of each event
)
# Prophet model with logistic growth and holidays
model <- prophet(data, holidays = holidays, changepoint.prior.scale = 0.1, seasonality.prior.scale = 0.1, growth = "logistic")
# Future dataframe with capacity
future <- make_future_dataframe(model, periods = 365 * 6)
future$cap <- 1.5 * max(data$y)  # Maintain the same capacity in the future
future$ds <- as.POSIXct(future$ds, format = "%Y-%m-%d")  # Ensure POSIXct format
forecast <- predict(model, future)
data$ds <- as.POSIXct(data$ds, format = "%Y-%m-%d")
# Plotting with ggplot
forecast_plot <- ggplot() +
  geom_line(data = forecast, aes(x = ds, y = yhat), color = "blue") +
  geom_ribbon(data = forecast, aes(x = ds, ymin = yhat_lower, ymax = yhat_upper), fill = "lightblue", alpha = 0.5) +
  geom_point(data = data, aes(x = ds, y = y), color = "red") +  # Plotting the original data points
  labs(title = "Methanol Prophet Forecast",
```

```
      x = "Year",
      y = "Methanol Price in $/MT") +
  theme_minimal()
print(forecast_plot)
result1 <-tail(forecast$yhat,n=1)
# Output results and save plot
#ggsave("Methanol_Prophet_Forecast.png", forecast_plot, width = 10, height = 6)
#write_xlsx(forecast, "forecast_methanol.xlsx")
prophet_plot_components(model, forecast)
####################################################################################################
#Model 2
# Assume 'data' has already been loaded and includes a `Date` and `$\MT` column
# Prepare the data
data <- read_excel("methanol_data.xls")
data$Date <- as.Date(data$Date, format = "%Y-%m-%d")
dat <- data
dat <- mutate(dat,
              date = as.Date(dat$Date, format = "%Y-%m-%d"),
              y = dat$`$/MT`)
dat <- select(dat, date, y)
# Add special holidays as binary features
dat <- mutate(dat,
              FinancialCrisis = as.numeric(year(date) == 2008 & month(date) >= 9),
              Covid19 = as.numeric(year(date) == 2020),
              UkraineWar = as.numeric(year(date) >= 2022))
# Add time-based features (e.g., month, quarter, year)
dat <- dat %>%
  mutate(month = month(date),
         quarter = quarter(date),
         year = year(date))
# Convert to data.table
lagged_data <- data.table(dat)
# Create lag features (increase the number of lags to capture longer-term dependencies)
num_lags <- 12 * 16  # Assuming monthly data, create up to 16 years of lags
for (i in 1:num_lags) {
  lagged_data[, paste0("lag_", i) := shift(y, i)]
}
# Remove rows with NA values created by lagging
```

```
lagged_data <- na.omit(lagged_data)

# Split the data into features and target variable

target <- lagged_data$y

features <- lagged_data[, c(paste0("lag_", 1:num_lags), "month", "quarter", "year", "FinancialCrisis", "Covid19", "UkraineWar"), with
= FALSE]

# Convert to matrix format for XGBoost

dtrain <- xgb.DMatrix(data = as.matrix(features), label = target)

# Set parameters for XGBoost with regularization

params <- list(

  objective = "reg:squarederror",

  eval_metric = "rmse",

  eta = 0.01,

  max_depth = 8,  # Increase depth for more complex interactions

  subsample = 0.8,

  colsample_bytree = 0.8,

  lambda = 1,  # L2 regularization

  alpha = 0.1  # L1 regularization

)

# Train the model

model_xgb <- xgboost(data = dtrain, params = params, nrounds = 1000)

# Prepare future data for prediction up to 2030

future_steps <- as.integer(year("2030-12-31") - year(lubridate::ceiling_date(max(dat$date), "year")) + 1) * 12

predictions <- numeric(future_steps)

# Initialize the last known values

last_values <- tail(lagged_data, 1)[, c(paste0("lag_", 1:num_lags), "month", "quarter", "year", "FinancialCrisis", "Covid19",
"UkraineWar"), with = FALSE]

# Initialize the starting date for forecasting

forecast_start_date <- max(dat$date)

for (i in 1:future_steps) {

  # Prepare the data for the next prediction

  new_data <- as.matrix(last_values)

  # Make prediction

  predictions[i] <- predict(model_xgb, new_data)

  # Update the last values for the next iteration (shift the lags)

  last_values <- c(predictions[i], as.numeric(last_values)[1:(num_lags - 1)], last_values$month, last_values$quarter,
last_values$year, 0, 0, 0)  # No new holidays assumed

  last_values <- data.table(t(last_values))  # Convert back to data.table

  colnames(last_values) <- c(paste0("lag_", 1:num_lags), "month", "quarter", "year", "FinancialCrisis", "Covid19", "UkraineWar")
```

```
  # Update the date-related features for the next prediction
  forecast_start_date <- forecast_start_date %m+% months(1)
  last_values[, month := month(forecast_start_date)]
  last_values[, quarter := quarter(forecast_start_date)]
  last_values[, year := year(forecast_start_date)]
}
# Combine the historical and predicted data for plotting
forecast_dates <- seq(max(dat$date) %m+% months(1), by = "month", length.out = future_steps)
forecast_data <- data.table(date = forecast_dates, prediction = predictions)
# Plot the historical and forecasted data
ggplot() +
  geom_line(data = dat, aes(x = date, y = y), color = "blue") +
  geom_line(data = forecast_data, aes(x = date, y = prediction), color = "red") +
  labs(title = "Time Series Forecast with XGBoost", x = "Year", y = "Methanol Price ($/MT)") +
  theme_minimal()
result2 <-tail(forecast_data, n=1)
################################################################################
#Model 3
# Load your data
data <- read_excel("methanol_data.xls")
# Convert Date column to Date format
data$Date <- as.Date(data$Date, format = "%Y-%m-%d")
# Prepare the data for modeling
data <- mutate(data, ds = Date, y = data$`$/MT`)
data <- select(data, ds, y)
# Add time-based features (e.g., month, quarter, year)
data <- data %>%
  mutate(month = month(ds),
         quarter = quarter(ds),
         year = year(ds))
# Add event indicators (1 during event, 0 otherwise)
data <- data %>%
  mutate(covid = ifelse(ds >= as.Date("2020-01-01") & ds <= as.Date("2021-12-31"), 1, 0),
         war = ifelse(ds >= as.Date("2022-02-24"), 1, 0),
         financial_crisis = ifelse(ds >= as.Date("2008-09-01") & ds <= as.Date("2009-06-30"), 1, 0))
# Create lag features
num_lags <- 12 * 16  # Lag by up to 16 years (assuming monthly data)
lagged_data <- data.table(data)
```

```r
for (i in 1:num_lags) {
  lagged_data[, paste0("lag_", i) := shift(y, i)]
}
# Remove rows with NA values created by lagging
lagged_data <- na.omit(lagged_data)

# Split the data into features and target variable
target <- lagged_data$y
features <- lagged_data[, c(paste0("lag_", 1:num_lags), "month", "quarter", "year", "covid", "war", "financial_crisis"), with = FALSE]
# Train the Random Forest model
set.seed(123)  # Set seed for reproducibility
model_rf <- randomForest(x = features, y = target, ntree = 500, mtry = floor(sqrt(ncol(features))), importance = TRUE)
# Print the model summary
print(model_rf)
# Plot variable importance
varImpPlot(model_rf)
# Prepare future data for prediction until 2030
last_year <- max(data$year)
future_years <- seq(last_year + 1, 2030, by = 1)
future_steps <- length(future_years) * 12  # Months until end of 2030
predictions <- numeric(future_steps)
# Initialize the last known values
last_values <- tail(lagged_data, 1)[, c(paste0("lag_", 1:num_lags), "month", "quarter", "year", "covid", "war", "financial_crisis"), with =
FALSE]
# Initialize the starting date for forecasting
forecast_start_date <- max(data$ds)
for (i in 1:future_steps) {
  # Prepare the data for the next prediction
  new_data <- as.matrix(last_values)

  # Make prediction
  predictions[i] <- predict(model_rf, newdata = new_data)

  # Update the last values for the next iteration (shift the lags)
  last_values <- c(predictions[i], as.numeric(last_values)[1:(num_lags - 1)], month(forecast_start_date %m+% months(1)),
quarter(forecast_start_date %m+% months(1)), year(forecast_start_date %m+% months(1)), 0, 0, 0)
  last_values <- data.table(t(last_values))
  colnames(last_values) <- c(paste0("lag_", 1:num_lags), "month", "quarter", "year", "covid", "war", "financial_crisis")
  forecast_start_date <- forecast_start_date %m+% months(1)
```

```
}
# Combine the historical and predicted data for plotting
forecast_dates <- seq(max(data$ds) %m+% months(1), by = "month", length.out = future_steps)
forecast_data <- data.table(date = forecast_dates, prediction = predictions)
# Plot the historical and forecasted data
ggplot() +
  geom_line(data = data, aes(x = ds, y = y), color = "blue") +
  geom_line(data = forecast_data, aes(x = date, y = prediction), color = "red") +
  labs(title = "Time Series Forecast with Random Forest", x = "Year", y = "Methanol Price ($/MT)") +
  theme_minimal()
result3 <-tail(forecast_data, n=1)
```