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Fueling the future of storage, how the introduction of e-fuels will impact the storage infrastructure industry

by

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There is a mine for silver
and a place where gold is refined.
Iron is taken from the earth,
and copper is smelted from ore.
Mortals put an end to the darkness;
they search out the farthest recesses
for ore in the blackest darkness.
Far from human dwellings they cut a shaft,
in places untouched by human feet;
far from other people they dangle and sway.
But where can wisdom be found?
Where does understanding dwell?

Job 28:1-4, 12 (New International Version)

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Martijn Krijgsman, September 2024

Abstract

To further decarbonize our economy, e-fuels will be introduced to the energy mix. E-fuels, produced from renewable electricity and CO₂ captured from the air, combusting these fuels results in zero emissions. This research examines what the impact of the introduction of e-fuels for the storage infrastructure industry will be. Explanatory research is done in literature, and open interviews are conducted with stakeholders from knowledge institutions, e-fuel producers, and storage experts. Analysis of literature and interviews show a positive impact of e-fuels on the infrastructure industry. Supply chains will change at the beginning, while demand centers remain unchanged, leading to new product market combinations for storage infrastructure. The lower energy densities of e-fuels will require additional storage volume, while segregation of certified product is required at the start of the transition, next to flexibility in modes of transport. Finally, additional value creation is driven by expertise on how to store hazardous products safely and efficiently, combined with rapid anticipation of changing markets.

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List of abbreviations

ARA	Amsterdam-Rotterdam-Antwerp
CEO	Chief Executive Officer
CO ₂	Carbon dioxide
DAC	Direct air capture
EU	European Union
EUR	Euro
GHG	Greenhouse gas
H ₂	Hydrogen
H ₂ O	Water
IEA	International Energy Agency
IMO	International Maritime Organization
ISO	International Organization for Standardization
kWh	kilowatt hour
LNG	Liquid Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
mb/d	Million barrels per day
MJ	Megajoule
Mtoe	Million tonnes of oil equivalent
N ₂	Nitrogen
PV	Photovoltaic
SAF	Sustainable aviation fuel
UK	United Kingdom
US	United States of America

1. Introduction

This chapter delves into the foundational aspects of this research, starting with an overview of the background that sets the context for this thesis. Followed by the key research questions that drive this study, and a clear outline of the objectives. Subsequently, the research design, detailing the methodological choices made to address the research questions. Finally, the structural framework of this thesis, providing a roadmap for navigating the subsequent chapters.

1.1 Background

Since the industrial revolution in the late 18th century, the world started to use fossil fuels as a source of energy. By inventing the steam machine, the wheels of production in a mechanized way were invented. Powered by the heat of coal, humankind started to burn fossil fuels in larger quantities than ever before. It caused a boom in production output, and with falling prices of goods, welfare took flight. Fast-forward to today's reality, it can be argued that fossil fuels never became old-fashioned. Over the 150 years since the industrial revolution the energy demand increased significantly, to an amount of 140 Terawatt hours in 2023 (Hannah Ritchie & Pablo Rosado, 2024). With the consumption of coal still an important source of energy, next to oil and gas. Fossil fuels are now used in everyone's daily lives, and they are still a significant driver of wealth and welfare.

However, in the meantime, the negative effects of burning fossil fuels are better understood. Next to these fossil resources being limited, the negative effects on the environment are seen. Burning fossil fuels leads to harmful emissions. Coal, oil, and gas account for around 75% of global greenhouse gas emissions and 90% of carbon dioxide, leading to global warming and climate change, with all negative effects of such (*Causes and Effects of Climate Change*, n.d.).

As the world recognizes the fact of global warming and climate change, clear action is needed for decarbonization. In 2015, in Paris, world leaders signed a historic agreement to fight global warming and climate change. Among the binding resolutions to: "Substantially reduce global greenhouse gas emissions to hold global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (*The Paris Agreement*, n.d.). Since the start of the industrial revolution, fossil resources have been the fuel of our economy. Today's world economy must be fueled by alternatives to fossil energy to reduce greenhouse gas emissions and halt global warming. Alternative low- or zero-carbon sources of

energy are applied increasingly in our daily lives, such as electricity from solar panels and wind turbines.

Investments in energy and its associated infrastructure have been enormous, to catch up with a growing global demand. The World Energy Investment report published by the International Energy Agency (2024) researched the global investments in fossil fuels and clean energy over time and found that by now the investment in clean energy is twice as large as in fossil fuels. Which means two trillion US dollar is invested this year in clean energy, compared to one trillion US dollars in fossil fuels. Included in the two billion dollar mentioned for clean energy, renewable power and investments in energy efficiency and use, form the biggest chunk of investments, while on a third-place grids, and storage of power is mentioned.

Electrification plays a key role in decarbonizing our economy, as these investment numbers show, but also comes with its limitations. On a small scale, when you need to charge your electric car every 250 kilometers, compared to a diesel car which lasts for approximately four times that distance. Also, on a larger scale when looking at industrial processes and transport modalities which rely on fossil fuels and feedstocks. These come with much higher energy densities and at a much lower price.

Fossil fuels can be, and are already, being replaced by biofuels. These fuels are considered sustainable from a perspective of CO₂ emissions, since they use biological grown crops for example, which extracted CO₂ from the air initially. However, they do not seem to be a solution on a large scale, as multiple disadvantages are seen as well. Producing biological inputs for biofuels comes at the price of land and water which may be used for food production. And, when only waste is used in more advanced methods of biofuel production, it is still impossible to reach volumes of significance (M. Torkashvand et al., 2022).

Decarbonization by electrification meets the world of fossil fuels in the concept of e-fuels. In short, the technology to transform (renewable) electricity, water and carbon dioxide or nitrogen into liquid fuels with similar characteristics as conventional fossil fuels (Viscardi et al., 2021). This may overcome barriers of hard to abate sectors such as the shipping and aviation sectors (Van Kranenburg et al., 2020).

While the IEA reported the spending will be considerable on clean energy, little is written about the implications for supporting infrastructure throughout the supply chain. Investments needed in ports and storage infrastructure, for example, are as prominent as those seen in power-related infrastructure (World Energy Investment 2024, n.d.).

1.2 Research questions and objectives

This thesis combines the two factors described, of future e-fuels and the need for storage infrastructure, the following main question will be answered:

What will be the impact of the introduction of e-fuels for the storage infrastructure industry?

This thesis aims to shed light on how the introduction of e-fuels will impact the storage infrastructure industry in specific, as limited research is yet done for this industry. By answering the following research sub-questions, a better understanding of the implications for the storage infrastructure industry will appear:

1. What role does storage infrastructure play in the e-fuel value chain?
2. What are e-fuels and how will its demand and supply look like?
3. What will be the impact on the business model of storage infrastructure companies?
4. Which storage locations are likely to play a role in the e-fuel supply chain?
5. What requirements for storage infrastructure follow the introduction of e-fuels?

Many articles are written about e-fuels, their potential and whether these can be successfully introduced or not. Less of an area of attention is how infrastructure in current or new forms play a role in this transition. This research aims to shed light on the impact the introduction of e-fuels has on the storage infrastructure industry. In what ways the storage industry should prepare itself, in terms of potential changing requirements of both at the terminal level, as well as at which locations are impacted.

1.3 Research design

The research starts with an elaborate literature review, to ensure existing knowledge is considered and being applied to this research. Next to literature review interviews are conducted with multiple stakeholders in the supply chain of e-fuels. Stakeholders being involved in the production or consumption of e-fuels, being knowledge institutions or active players in the storage infrastructure industry. Because of the premature overall e-fuel market, a focus is applied on the shipping and aviation markets, which seem to be the first markets adopting e-fuels as (partial) substitutes of the current fuels being used (Terry Ellis et al., 2024).

Interviews being conducted and transcribed, coded and grouped to provide triangulated findings, as well as insights which help answering the research- or sub-research questions. Insights from

the different stakeholders are triangulated to ensure consistency and sufficient scientific value. Both the literature review and interview outcomes form the basis for the research outcomes

1.4 Conceptual framework

To put the research question in perspective in a conceptual framework, the five forces model of Porter was used as starting point (Michael E. Porter, 2011). Porter's Five Forces model is a framework for analyzing the competitive landscape of an industry. It identifies five key factors that influence the level of competition and attractiveness of an industry: the threat of new entrants, bargaining power of buyers, bargaining power of suppliers, threat of substitute products or services, and the intensity of rivalry among existing competitors. In addition to the five forces model, Porter's diamond model was used, which is a framework for understanding the competitive advantage of nations and regions, due to the global dynamics e-fuels will encounter. The element of government is adopted from this model (Michael E. Porter, 1990).

The model is adjusted to form six elements which all interact and are investigated in this research. The forces Porter uses are all applied to an industry and can exist of multiple items impacting that same industry or company within an industry. This model aims to use the forces applied to e-fuels in specific, to focus on the impact of the introduction of e-fuels, how this relates to supply and demand of e-fuels itself and what can be said about the storage industry itself and potential substitutes.

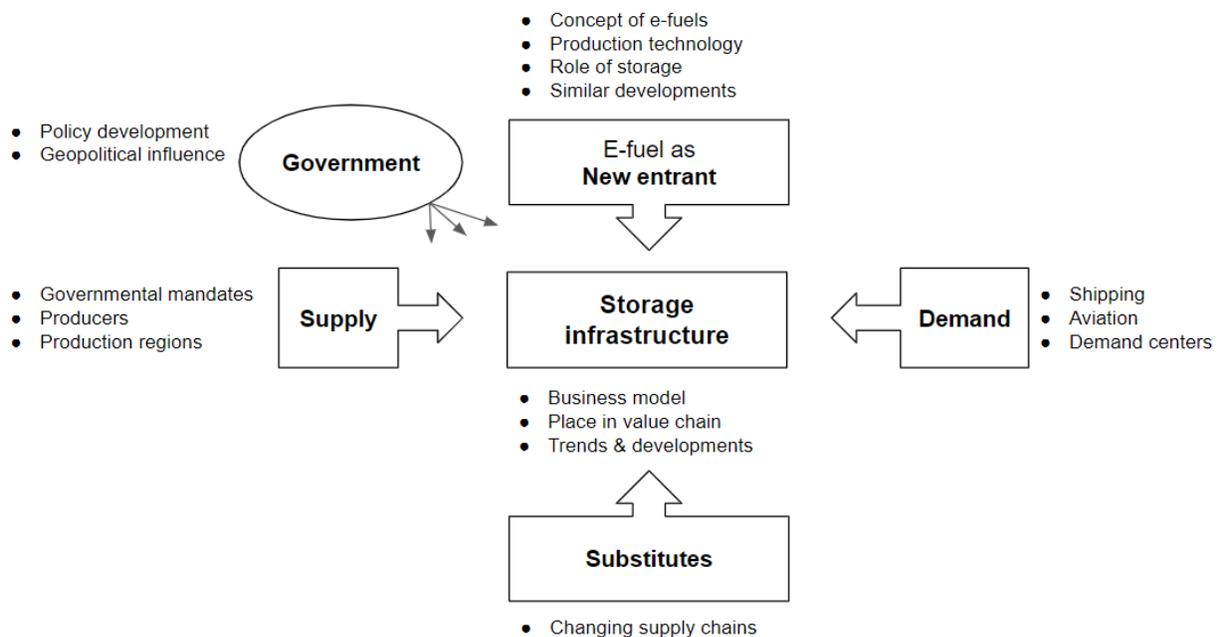


Figure 1. Conceptual framework based on five-forces and diamond models of Porter

The new entrant in this model is the introduction of e-fuels as a replacement for fossil fuels, which are stored by liquid bulk terminals today. The concept of e-fuels is explained, including different technologies to produce them, how storage will play a role in a successful introduction and lessons learned from similar developments are evaluated.

Supply is researched as a driver of the need for storage capacity, while the governmental aspect is covered with policy development and geopolitical influence. Furthermore, the producers and location of production are discussed. On the demand side, focus is on the offtake by the shipping and aviation industries, which are most likely to adopt these fuels as drop-in fuels. Changing supply chains, to more decentral networks, is discussed as a substitute for storage which may be caused by the introduction of e-fuels in the energy mix.

It all impacts the storage industry itself, next to the four previously mentioned forces. To gain better understanding of the business model of the industry, place in the value chain and trends and developments are researched. These five forces together with the governmental aspect, form a conceptual framework to assess the impact of the introduction of e-fuels on the storage infrastructure industry.

1.5 Structure of thesis

The introduction of e-fuels will impact the storage infrastructure industry. This industry relies on most of its revenues on fossil fuel. By a changing, lower-carbon, energy mix, the related infrastructure must also be adapted. Introducing e-fuels will lead to new supply chains and impact required storage.

After this introductory chapter, this thesis's structure is as follows. The second chapter explains what e-fuels are, how they are produced, what supply, and demand is foreseen and how this typical supply chain will look like. Economic data is analyzed defining the supply, demand, and deferred cost. Thereafter a more theoretical review is done on the business model of storage infrastructure and the impact of the introduction of e-fuels is evaluated. Next to this, the research methodology is explained in chapter 3. Interviews are conducted and analyzed with different stakeholders from the industry. These include knowledge institutes, think tanks, customers, and customers of customers. Chapter four provides an overview of the outcome of conducted interviews. The last chapter combines insights from literature review and interviews in the form of key factors for the future storage of e-fuels while chapter six answers the research questions, provides signposts to the industry and recommendations for future research.

2. Literature review

This chapter provides a comprehensive literature review that serves as a foundation for the analysis and findings presented in subsequent chapters. The review is structured around four key thematic areas:

- Fuel storage infrastructure business model and role in global supply and value chain: this section delves into the diverse business models that underpin the storage industry, exploring how different players generate revenue, manage assets, and interact within the market ecosystem. Also looking into global supply chains, serving as a critical component in ensuring the efficient flow of goods, managing fluctuations in demand and supply, and mitigating risks associated with disruptions.
- Strategic trends and developments in the storage infrastructure industry: this section provides an overview of the key strategic trends and developments shaping the future of the storage industry.
- Similar developments in new energies and their Impact on the storage Industry: this section examines the parallels between the evolution of the storage sector and the development of new energy sources, highlighting how advancements in renewable energy technologies and the transition towards a low-carbon economy have shaped the demand for and role of storage solutions.
- An explanation of e-fuels as a concept: and it's foreseen drivers and resulting supply and demand, cost of production and whether new supply chains will make storage infrastructure obsolete or not.

By synthesizing insights from a wide range of academic literature, industry reports, and relevant case studies, this chapter aims to provide a nuanced understanding of the current state of the storage industry, its underlying business models, the influence of broader energy trends, and its vital role in global supply chains. This understanding forms a crucial foundation for the analysis and recommendations that follow in subsequent chapters.

2.1 Fuel storage infrastructure business model

Since trade is happening a need for storage exists. It is mentioned in the holy books of the three major European religions (Boysen & de Koster, 2024). This historical function is also reflected in the history of a major independent storage provider such as Vopak, which found its oldest forerunner in the Blaauwhoedenveem established in 1616 in Amsterdam. "When the ships of the

Dutch East India Company (VOC) unloaded their wares here, the storehouses transported the goods to a weigh house, where they were inspected and weighed, and then on to warehouses.” Products stored in bulk these days were, for example tea or spices, different from liquid products today (Boudewijn Pothoven, 2016).

This research focuses on liquid and gaseous products since e-fuels will come in these forms as well. For the same reason dry bulk, such as coal or iron ore are excluded in this literature review.

2.1.1 Warehousing in general

The most basic need for warehousing or storage can be described as decoupling the time of production from the time of consumption of any given good (Boysen & de Koster, 2024). In more detail, two major roles of warehousing are mentioned in literature. First, buffering of products to guarantee a flow of product thereafter, to function after storage as a steady flow of feedstock for a production process for example. The second key role is consolidation, combining different flows of either the same, or various products which in turn are supplied to a next actor in the value chain (Gu et al., 2007).

Gu et al. (2007) describe some problems of warehousing to be solved in the correct way, categorized under warehouse design and warehouse operation. These broad categories also apply to bulk liquid storage facilities. Related to the design, the overall structure of the facility is mentioned, as well as sizing and layout for optimal operations. Choices made in terms of automation and materials used will lead to enhanced efficiency. Regarding the warehouse operations, decisions must be made on the flow of products throughout the facility. Receiving, storage, handling and finally shipping of the product need to happen according to the product and market which is being served.

Next to size, and to a lesser extent mentioned by Gu et al. Is the location where the warehouse or storage facility is being located. Coming back to the definition given at the start of this paragraph, when production and consumption are decoupled, so are the locations of production and consumption for some markets not the same. To overcome this imbalance, storage terminals play a significant role in the value chain.

2.1.2 Liquid bulk storage as core business

Warehousing in general deals with storage and handling of a wide variety of goods, including packaged products, pallets, and loose items. It enables efficient inventory management, order fulfillment, and storage of various goods in different forms. This research focuses on the impact

of the introduction of e-fuels on storage infrastructure and looks in more detail at liquid bulk storage infrastructure. Liquid bulk storage is specialized for handling enormous quantities of liquids, often hazardous or requiring temperature control, in tanks or silos. It focuses on efficient transfer and safe containment of liquids (Peter Davidson, n.d.).

Liquid bulk storage is a business model and comes as such in different forms, being independent, semi-captive or captive (Patrahau et al., 2022).

- Independent storage companies function as landlords, renting-out their facilities to third parties and not owning any of the products stored within their tanks. This allows them to offer their expertise in safety and storage to diverse customers without being tied to a specific industry or company.
- Semi-captive storage companies utilize a portion of their capacity to store their own products while also renting out the remaining space. These companies may be involved in trading, distribution, refining, or other related activities. This model provides flexibility, allowing them to benefit from both storage services and their core business operations.
- Captive storage companies own and operate storage facilities exclusively for their own products. These companies are typically large producers, such as oil and gas companies or chemical manufacturers. Owning their storage infrastructure gives them complete control over the storage and distribution of their products.

These three forms of storage business, irrespective of any profitability and operational performance, will be of importance when researching the impact of e-fuels on the storage infrastructure industry. For all these terminals, whether independent or (semi) captive, the following elements are the core of a successful business.

- Economies of scale: captive and larger semi-captive companies often benefit from economies of scale due to their larger storage volumes. This means their per-unit storage costs are lower than smaller, independent companies. Larger companies can invest in advanced technologies and infrastructure, further reducing costs and increasing efficiency (Patrahau et al., 2022).
- Safety: all tank storage companies, regardless of their model, prioritize safety due to the hazardous nature of many stored liquids. Larger companies may have more resources to invest in comprehensive safety measures, training, and equipment. However, independent companies specializing in specific types of liquids might possess highly specialized safety knowledge and protocols (Universal Engineering Services, 2020).

- Operational efficiency: larger companies often have more streamlined operations, benefiting from standardized processes and integrated systems. However, smaller, independent companies may offer more personalized services and greater flexibility to adapt to specific customer needs (*How Tailored Storage Tanks Maximize Efficiency, 2024*).

The better storage facilities perform on these metrics, the better their service to their customers will be, leading to a commercial attractive business model.

2.1.3 Liquid bulk storage in the bigger picture

This paragraph describes the place of liquid bulk storage in the value chain, key services these infrastructure providers deliver and which logistical functions they have. The storage infrastructure company Royal Vopak, with presence all over the world, is taken as the main source of input describing this. This leading and independent firm is stock listed and therefore transparent in these topics, and representative of the industry.

2.1.3.1 Value chain

Liquid bulk storage may serve a single supply chain once or multiple times. Figure 2 gives a schematic overview at which point in the supply chain storage plays a role.

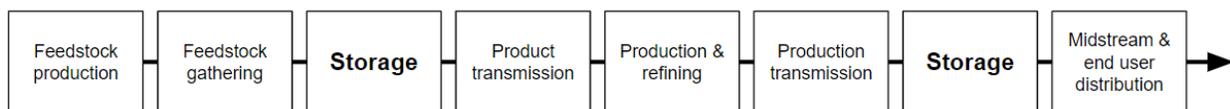


Figure 2. Storage role in the supply chain (Vopak, 2014c)

Wherever production and consumption do not happen at the same place, at the same time or in the same volumes, imbalances exist. These imbalances are bridged by storage solutions, by which value is created.

Value creation follows from establishing balance where discrepancies exist. These imbalances, particularly in product volume, can be attributed to several factors. A primary factor, as discussed in the context of warehousing, is the geographical disconnect between production and consumption. The export and import of goods necessitate storage, illustrated by crude oil production in the Middle East and its consumption in European refineries for example. Additionally, disparities arise in the volumes transported within this export-import dynamic. Efficient shipping often involves enormous quantities that exceed immediate consumer demand. Beyond location and volume, timing also contributes to imbalance. Seasonality impacts certain products, such as

gas, where ample winter supplies require summer storage. As depicted in figure 2, storage serves as a bridge between supply, demand, and transport, primarily driven by these imbalances.

Related to this, storage facilities play a crucial role in ensuring security of supply. This is the case in the example of energy supply in a region, but also to industrial clusters which cannot bet on availability in the long run. Production by these facilities needs to continue in any case, which requires storage of sufficient 'feedstock' at the start of the process.

Thirdly, storage providers deliver value in ensuring product quality. While bridging the imbalances of locational availability, volume and time, the quality of product needs to remain intact. Maintaining product quality throughout the storage period is essential for customers and owners of the product. Effective quality control measures, such as regular inspections, proper handling procedures, and environmental monitoring, ensure that goods remain in optimal condition, minimizing the risk of damage, spoilage, or contamination. This prevents financial losses due to product degradation, and potential supply chain issues.

2.1.3.2 Key services

Following these value-adding activities in the broader supply chain, multiple services are offered to customers. Storage itself forms the main service these terminals are offering. A place to keep certain liquid bulk products to bridge imbalance as described before. For Vopak, market leader in independent storage, this service accounts for around 80% of total revenues (Vopak, 2024). In this storage service, an agreement is made which volumes of handling are included in the charge, this may be a couple of times the rented capacity as throughput.

Next to the storage, services are offered for additional product movement, or throughput of volumes through the terminal. When these volumes of a customer exceed the storage fee, this leads to additional fees. Agreements can also be made for which modes of transport certain products will be handled.

The last group of services can be called 'handling services', which relates to the third value driver of storage, ensuring product quality. Services such as temperature control, blending and certification are examples of this.

2.1.3.3 Logistical functions

The value and services combined lead to storage infrastructure fulfilling different logistical functions. Storage infrastructure, often referred to as terminals, may be characterized as the following:

- Export terminals are designed to facilitate aggregation of multiple smaller product flows, and the ability to export these to demand centers elsewhere. Connectivity for multiple modes of transport is required, such as road and rail to bring products to the terminal, and marine which typically are used for export.
- Import and distribution, on the other hand, play the opposite role. These terminals are designed to receive substantial amounts of product and make them available for distribution into the hinterland via, for example, road and rail.
- Industrial terminals are directly connected to industrial complexes and ensure the 'feedstock' of these facilities. As well as the 'rundown' product, the product which comes out of the refinery for example (Vopak, 2014b).
- To hub terminals is often referred to terminals which fulfill a significant role in the supply chain and where commodity trade happens. Product which is stored at a terminal may be sold or acquired by different customers (traders) at the same location (Vopak, 2014a).

Storage terminals often fulfill multiple logistical functions at the same time, for example an industrial terminal which also functions as an import terminal of raw materials, and distribution terminal for finalized products.

2.1.4 Strategic trends and developments in the storage industry

The Hague Centre for Strategic Studies conducted research in 2022, looking at global value chains in which storage plays a role (Irina Patrahau et al., 2022). Part of this research was the evaluation of strategic trends and developments affecting the tank storage industry, especially in Europe. While the scope of this thesis is not limited to Europe only, this, however, gives good indications of what the industry may expect in the years to come on a global level.

Decarbonization is the first trend mentioned. Transport systems will further decarbonize, resulting in new products being introduced to the energy mix. Storage companies may play a crucial role in making this happen. By ensuring that new fuels and feedstocks can be stored under the right conditions. Segregation of product will be increasingly of importance since product grades will differ increasingly. The same applies to blending, which will be required in more cases, to upgrade

conventional fuels with lower-carbon products. As part of decarbonization and changing economics, it is expected some European refineries will close in the years to come. A gap, caused by local production and continued demand, will increase imports with an increased need for storage capacity.

Security of supply, as also mentioned in the previous paragraphs, will be of increasing importance. Countries, in Europe and beyond, will increase energy independence. To mitigate vulnerabilities of importing large quantities of product and being strategically exposed to foreign countries. Especially with increasing geopolitical tensions around the world, this impacts the need for storage positively. Strategic storage, a country's buffer for times of supply chain issues and geopolitical measures will remain of significant importance.

2.1.5 Similar developments

The global shift from fossil fuels towards e-fuels, driven by the urgent need to decarbonize various sectors, shows similarities with other recent developments in the energy domain. The growth of Liquefied Natural Gas (LNG) for example, as well as Japan's pioneering efforts in introducing e-methane as a key component of its energy transition. Both transitions share familiar challenges and opportunities, including the need for substantial infrastructure investments, regulatory adjustments, and navigating evolving market dynamics.

2.1.5.1 Liquefied Natural Gas

Natural Gas, in liquefied form, has attracted significant attention in recent years due to its multifaceted role in the energy landscape. It is widely considered a cleaner alternative to traditional fossil fuels, a crucial transition fuel to renewables, and a vital component for enhancing energy security. LNG's lower carbon emissions profile compared to coal and oil, positions it as a more environmentally friendly option. Furthermore, its ability to provide reliable and flexible energy supply makes it an indispensable tool in meeting growing energy demands while mitigating the intermittency challenges associated with renewable sources such as wind and solar. In this context, LNG serves as a crucial product in balancing environmental concerns with the need for a stable and secure energy supply (Pierina Fiestas, 2023).

The recent geopolitical tensions, particularly the conflict between Russia-Ukraine and subsequent disruptions in energy supply chains, have underscored the critical importance of energy self-sufficiency. As highlighted by the European Commission (European Commission, n.d.), LNG's role in diversifying energy sources and reducing dependence on potentially volatile pipeline

imports is of importance. LNG's flexibility in transportation and storage enables countries to enhance their energy security and resilience, mitigating the risks associated with geopolitical instability and ensuring a stable energy supply even amidst disruptions.

Looking into the market dynamics, Peña and Canales (Ignacio de la Peña-Zarzuelo et al., 2020), highlight the following key factors, characterizing the LNG market:

- Highly volatile prices with significant regional variations.
- High seasonal demand with stable production requires effective stock management.
- Abundant alternative fuels influence LNG production and delivery, making it subject to various unpredictable factors.
- Capital-intensive nature of LNG leads to long-term contracts with complex risk allocation mechanisms.
- Technical aspects like boil-off gas require streamlined logistics to minimize losses.
- The market is vulnerable to external factors like weather, natural disasters, political unrest, and conflicts.
- Open market with numerous players on both supply and demand sides.

Looking at these market characteristics, some of these can be applied to the development of e-fuels as well. Volatile prices and regional variations can be seen especially in the availability of renewable electricity and the availability of CO₂. The fact alternative fuels, to e-fuels these are fossil fuels, are widely available at way lower cost, make development of e-fuels more difficult. The transition to and production of e-fuels is similarly capital expensive, as well the open-market structure which is similar. Seasonality, is discussed after the findings of Economides and Wood (2009)

Economides and Wood found, when reviewing the prospects of natural gas in 2009, that land-based storage especially could help further development of the products supply chain. In a global market, which is the energy market, efficient transportation between exporting and importing countries is of importance as is the storage of products in between these locations. The study highlights land-based storage capacity development as a key factor to reduce price volatility, especially caused by seasonality.

Seasonality, mentioned as a key market characteristic by Peña-Zarzuelo et al. (2020), can have significant impact on the storage industry with regards to e-fuels as well. First, from a production side, the availability of renewable electricity is per definition more intermittent than fossil fuels. This potentially requires transportation and storage in earlier stages of the production process.

For example, hydrogen being produced in different regions at various times of the year. These flows need to move to processing facilities which are static. From the consumption perspective, focusing in this research on the aviation and shipping industry, this is limited on a global scale, while may have differences on a more local level.

A study by Al-Haidous et al. (2021), evaluated the LNG supply chain resilience using a strengths, weaknesses, opportunities and threats (SWOT) analysis, focused on the supply chain of the State of Qatar. This paper examines the factors relevant to the transition to e-fuels, and how this will impact the storage industry. Strengths of LNG are mentioned the abundant resources, a large LNG-fleet and long-term contracts, where environmental factors are considered weaknesses. Growing energy demand and strategic partnerships are opportunities, while on the other side of external factors, unexpected or unfavorable regulations are mentioned.

However this study's focus was on Qatar, these findings can be applied to the transition to e-fuels. An abundance of resources exists in terms of renewable electricity; growing energy demand will also drive the need for e-fuels and partnership form opportunities to get e-fuels flying. A large fleet to carry these new e-fuels, already exists, as most carriers of fossil fuels will be able to also transport e-fuels. The same applies to a lesser extent to storage terminal capacity.

A problem often referred to as a 'chicken and egg situation,' existed for LNG and will exist for e-fuels as well. What comes first: demand or supply? To order or retrofit ships for LNG, sufficient places for bunkering need to exist as well. Other way around, to build an LNG bunkering facility, several ships need to demand these fuels (John Snyder, 2020). The same applies for an investment decision for a pure storage facility. Flows of product must exist or should be committed to build storage infrastructure.

2.1.5.2 Japan's journey

Japan, the third largest economy in the world, went through a journey when it comes to its energy mix. Of origin, Japan was highly reliant on imported oil. It already changed, by adding LNG and nuclear power to the mix in the early 2000's. However, the Great East Japan Earthquake in 2011, made them stop all nuclear plants, accounting for 11.2% of total energy supply. With the part of nuclear energy out of service, to be checked and gradually restarted over time, the dependency on import and other countries increased (Agency for Natural Resources and Energy, 22023).

Next to Japan's aim to be less dependent on importing energy, Japan committed to become net-zero by 2050. Japan, now, is serious in its ambition to make the move to e-methane to replace current

city gas. The Japan Gas Association, backed by the major gas utilities of the country, presented a plan already in 2020, to have e-methane being introduced between 2030 and 2050. Starting with 1% of e-methane in 2030 and growing the share to 90% in 2050. The complete shift would reduce the country's entire CO₂ emissions by 10% (Shi Weijun, 2023). The volumes of e-methane will be imported, since the country announced multiple partnerships with foreign countries, such as. From that perspective, this will live-up to the decarbonization goals compared to the energy independence ambitions they have.

One of the key reasons for Japan to aim for e-methane replacing conventional gas, is the existing infrastructure (Mike Weber, 2023). Intermittency is an issue with renewable energy, while e-methane, as synthetic fuel made of green hydrogen and captured CO₂, can be stored more easily. Existing infrastructure, like the current LNG shipping fleet, pipeline network and storage facilities may be easily reused for e-methane which is chemically identical to conventional methane.

The strategy of e-methane as a drop-in fuel is recognized by other countries too. Germany included the fuel in their 'hydrogen strategy' as well. Also, for Germany the existing gas-grid and adjacent infrastructure is mentioned as a strategic reason to use e-methane as a drop-in fuel, which is identical to currently used gas. Like Japan, it is expected most product volumes will be imported (TES, 2023).

The journey of Japan, and similarly the ambitions of Germany, provide insights in how the transition to e-fuels may happen in the decades to come. For this research, the main takeaways are two-fold. First, the deciding factor of re-using and leveraging existing infrastructure. Secondly, the need for import of product is highlighted, meaning product will be consumed in a different location than where it is produced, which leads to required storage facilities.

2.1.5.3 Other analogies

Next to the introduction of LNG in the energy system, and a strategy of Japan to switch to e-methane, some more analogies are found. Showing different drivers for a transition and adding valuable insights to the development of e-fuels.

Coal to Liquids in Africa

E-fuels are often referred to as power to liquid, similarly coal-to-liquid technology exists. This is used for distinct reasons, but especially in South Africa this plays a key role in their economy. Forced to develop diverse ways of fuel production, when international sanctions blocked their oil supply, coal was widely available within the country (Höök & Aleklett, 2010). Similar developments

are still ongoing, in for example Botswana. The land-locked country announced to build a multi-billion-dollar coal-to-liquids plant only in 2022, to leverage available coal and become less dependent on imports (Reuters, 2022).

In both cases, whether forced or not, further independence of the local energy supply is the main driver to transition. This may play a key role in the transition to e-fuels as well.

Synthetic Rubber caused by war

Not only energy related, but also for other products, an analogy can be made to the transition towards e-fuels. The natural rubber industry is an example. This industry experienced significant disruptions during World War II, as major rubber-producing regions in Southeast Asia fell under Japanese control. This created rubber shortage for the western countries like the US, who relied heavily on rubber for tires, gaskets, and other components. Necessity drove rapid innovation, and extensive research efforts resulted in the development and large-scale production of synthetic rubber. Several types were produced, including styrene-butadiene rubber (SBR), which became the dominant type due to its versatility and cost-effectiveness.

Two similarities can be seen in today's development towards e-fuels. A strong driver for innovation must be there. Because the United States lost its access to natural rubber supplies in Southeast Asia, this led to a government sponsored program to develop synthetic rubber on a large scale. Similarly, today, with climate change as a strong driver, governments also need to step in to make a change happen. This is clearly the case with regards to e-fuels, today mainly driven by governmental policies and mandates. Next to the driving force behind innovation, independence is an analogy. Where the US depended on Southeast Asia for its rubber, this is the case for fossil fuels for a lot of countries. That dependency shows a risk, which might be reduced when entering the next area of energy, in the form of e-fuels.

2.2 E-fuels

To get a better understanding of its application and potential economics, first a description is given of what e-fuels are, how these are produced, at which costs and what supply and demand will be like.

2.2.1 E-fuel production

This thesis is about e-fuels for which different terms are used for the same type of fuels: e-fuels, synthetic fuels, and often collectively referred to as 'power-to-liquid' or 'power-to-x'. While electricity is one of the main components, it comes not in the form of electrons but as liquids and gases (Viscardi et al., 2021).

Burning these fuels still leads to emissions. To ensure that e-fuels are regarded as carbon-neutral, it needs to be produced with renewable electricity and CO₂ from biogenic sources or which is captured from the air directly. In other words, the feedstock to produce e-fuels needs to be renewable. Figure 3 shows, simplified, the input needed to produce a single liter of e-fuels. Which comes down to 27.5 kWh of renewable electricity, 3.6 kg CO₂ captured from the air and 0.5 kg of hydrogen for which 4.5 liters of water is needed (Kaitlyn Ramirez et al., 2023).

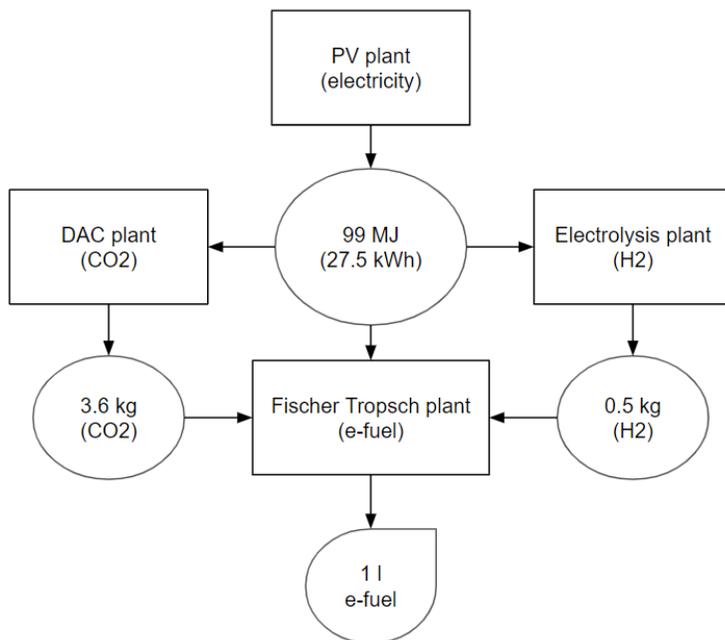


Figure 3. Input for a liter of e-fuel (D'Adamo et al., 2024)

These inputs need to be converted into liquids or gases leading to final, e-fuel, products. Different processes and methods can be applied for the conversion of electricity, water and Carbon dioxide or Nitrogen dioxide. A brief description of the different conversion methods.

1. Fischer-Tropsch-Process, a collection of chemical reactions that convert a mixture of carbon monoxide and hydrogen (synthesis gas) into liquid hydrocarbons. These hydrocarbons can be, for example, gasoline and diesel fuel (NETL, n.d.).
2. Methanation, the process of converting carbon monoxide and/or carbon dioxide into methane (CH_4) using hydrogen. It is often used to remove trace amounts of carbon oxides from hydrogen-rich gases or to produce synthetic natural gas (Wang et al., 2023).
3. Methanol synthesis, a chemical process that produces methanol from synthesis gas, a mixture of carbon monoxide, carbon dioxide, and hydrogen (Mäyrä & Leiviskä, 2018).
4. Ammonia synthesis, also known as the Haber-Bosch process, this is an industrial process that creates ammonia (NH_3) from nitrogen gas and hydrogen gas. It is crucial for producing fertilizers and other nitrogen-containing chemicals (Encyclopaedia Britannica, 2024).

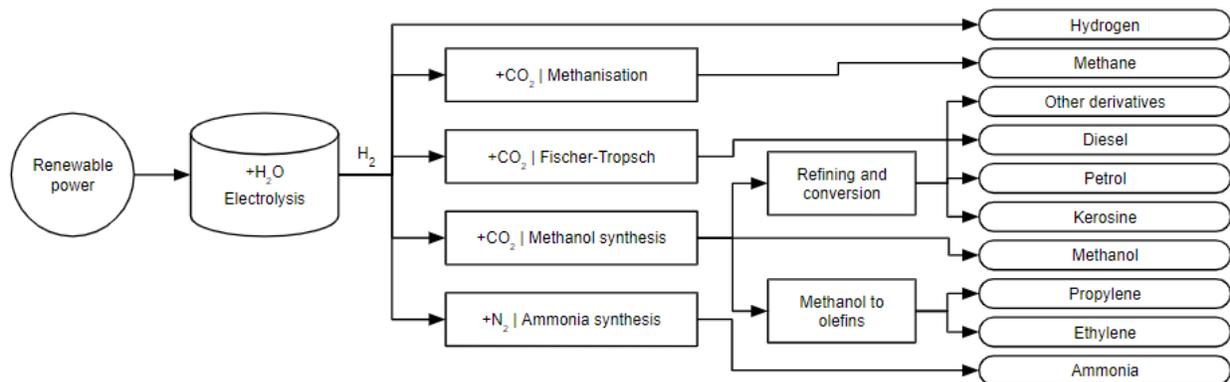


Figure 4. From power to liquid fuels via different processes (Viscardi et al., 2021)

The conversion leads to multiple final products, as can also be seen in figure 4. Applications can be multiple, comparable to the current use of fossil fuels. Viscardi et al. (2021) highlight four areas for application. Industrial applications, for example chemical production, crude oil refineries, or industrial processes requiring high volumes of heat. Transportation is mentioned as a second area of application, replacing conventional fuels in aviation, shipping, and road transport. Also heating and cooling of buildings, and re-electrification are mentioned. In case of the latter one, e-fuels are used as energy carriers since these are produced from electricity in the first place.

This research focuses on the application of e-fuels in aviation and shipping, since these seem to be the most up front in the transition (Van Kranenburg et al., 2020) and are an important end-market for storage infrastructure solutions.

2.2.2 Cost of production

Another element to successfully introduce e-fuels is the cost of production. This cost will determine the margins in other stages of the supply chain.

In April 2024, a study was published by D'Adamo et al. (2024), researching the cost of producing 1 liter of e-fuels. The research modelled 4 plants, required to produce a liter final product. Being 1) a photovoltaic system to produce renewable electricity, 2) a Direct Air Capture (DAC) plant to capture CO₂ from the air, 3) an electrolysis plant to produce green hydrogen and 4) a E-fuel production plant to apply the Fischer-Trops process and produce the final product. Assumptions were made on the scale of the plants and their related investments.

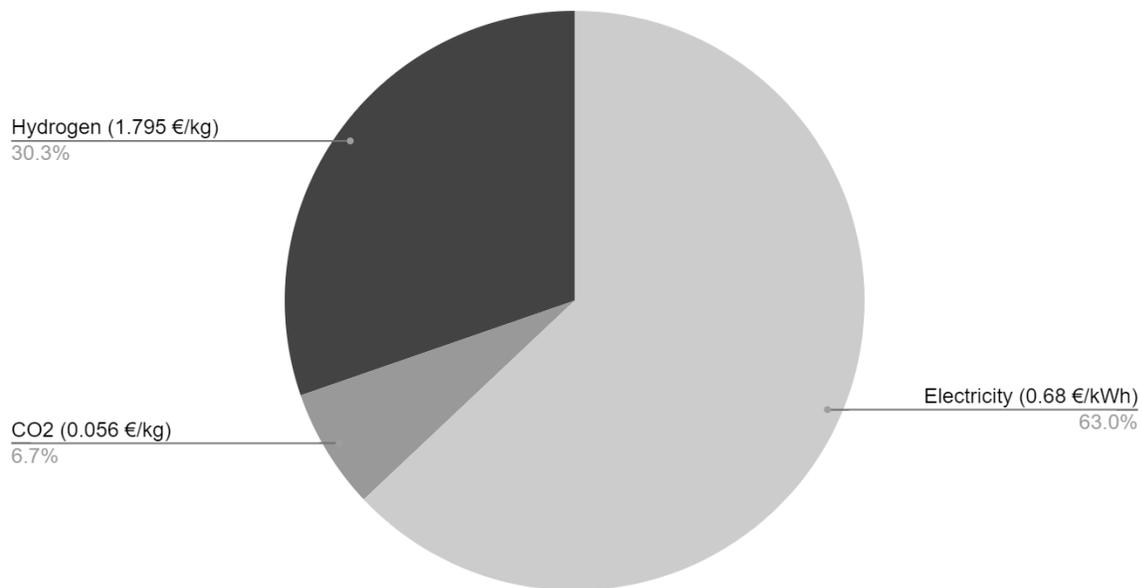


Figure 5. Levelized cost of production of 1 liter e-fuels

As a result, as also can be seen in figure 5, the levelized cost of 1 liter e-fuel is EUR 3.10/liter. Cost of energy, in this case by a photovoltaic system being the biggest part (60%) followed by the cost of hydrogen (29%), with the remaining part for the CO₂ capture and the Fischer-Trops process (7% and 4% respectively). The cost of EUR 3.10 per liter where in line with other case studies, and a sensitivity analysis showed that 84% of the values range between EUR 2.80 and EUR 3.40 per liter.

To put these costs into perspective, the cost of production of a liter of fossil fuel is significantly lower, the cost of regular jet-fuel for example is around EUR 0.60/liter (IATA, n.d.). A more sustainable and wider available alternative, for example biodiesel, costs around EUR 1.00 per liter on average, both are highly dependent on the cost of feedstock, which can vary significantly over time. Since the product characteristics are similar, it is assumed the cost of logistical services to end-markets and consumers is also similar for all these products.

Leading to a conclusion e-fuels are currently not competitive with fossil fuels for end-markets, unless the consumers are willing to pay a premium, governments provide a subsidy or enforces the use of these fuels (D'Adamo et al., 2024).

2.2.3 Demand and supply

This part of the literature review focuses on the demand and demand of e-fuels, to get a better understanding of the size of the potential flows of the product. Its highlights regulation as driver first, followed by supply and demand, using public sources.

2.2.3.1 Driven by regulation

Regulation and political mandates have only been formalized in the European Union up to now. The Fit for 55 package is an European Union initiative aiming to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. As part of this comprehensive plan, the RefuelEU and FuelEU Maritime directives specifically address the decarbonization of the aviation and maritime sectors, respectively, by promoting the use of sustainable fuels.

ReFuelEU Aviation is a regulatory initiative under the European Union's "Fit for 55" package, designed to decarbonize the aviation sector by promoting the use of sustainable aviation fuel (SAF) in general. The initiative mandates progressively increasing SAF blending targets for aviation fuel suppliers, starting from 2% in 2025 and reaching 70% by 2050. ReFuelEU Aviation has specific implications for e-fuels, translated in sub-targets for e-fuels. In 2030 the share of SAF in jet-fuel must be 6%, of which 1.2% of e-fuels. In 2050, this will be 35% e-fuels as part of a total of 70% SAF.

This means that by 2030, at least 1.2% of the jet fuel supplied at EU airports must be e-kerosene, and this share will progressively increase to 35% by 2050. The regulation will incentivize further investments in e-fuel production by creating a guaranteed market with specific blending targets, aiming to scale up production to meet growing demand (EU, 2023).

The FuelEU Maritime regulation, enacted by the European Union, is a significant step towards decarbonizing the maritime sector. It sets ambitious targets for reducing greenhouse gas (GHG) emissions from ships, promoting the use of renewable and low-carbon fuels, including e-fuels.

This regulation will drive a surge in demand for e-fuels as shipping companies seek to comply with stricter GHG intensity limits. Consequently, this will drive investment in e-fuel production and infrastructure, boosting the e-fuels industry. The targets will progressively lower the greenhouse gas emissions from fuels used in the shipping industry, beginning with a 2% reduction by 2025 and culminating in an 80% reduction by 2050. The targets will become stricter over time to encourage technological advancements and the increased use of renewable and low-carbon fuels. In required calculations for energy used by a ship a multiplier of '2' can be used to reward the ship for the use of e-fuels, being a catalyst to (partly) use these (FuelEU, 2023). Additionally, the FuelEU Maritime regulation could create a ripple effect, influencing similar policies in other regions and further solidifying e-fuels as a crucial component of the global energy transition.

Next to regulation and mandates, to a lesser extent, consumers are driving the transition to net-zero emissions. Consumers of goods and services may pay a premium to acquire products with a lower- or net-zero footprint. Extensive research is done, showing different results depending on the type of product and differs across generations. PwC (2024) found in a study that consumers are willing to pay almost 10% premium in acquiring goods and services, on the back of most respondents experiencing climate change. Some luxury brands show commitment to innovation and sustainability especially for marketing and branding purposes. An example can be found in Porche (2022), which invested in an e-fuel production facility of HIF Global in Chili.

From these two categories of drivers, governmental mandates on the one hand and consumer willingness to pay a green premium, especially the first one is driving the change. Ongoing changes in perspectives are applicable to both. Policy instruments on an EU-level as well as human behavior change drastically while these long-term transformations are ongoing.

2.2.3.2 Supply of e-fuels

The foreseen e-fuel supply is expected to experience significant growth over the next few years. The e-Fuel Alliance (eFuel alliance, 2024) published a map with announced or existing production sites, which is used for this research. The data is extracted from their website, and the capacities are normalized from different units of measure to announced metric tons per year. The heatmap in figure 6 shows the results of what capacity is announced over the world, annex 1 shows the data being retrieved and converted. It becomes clear most of the existing or announced

production will take place in Europe, around two-thirds of the projects being in the dataset, versus one-third in the rest of the world. Especially in the Nordic countries, like Sweden, Norway, and Denmark, where next to favorable governmental policies, renewable energy and biogenic CO₂ is available in sufficient quantities.

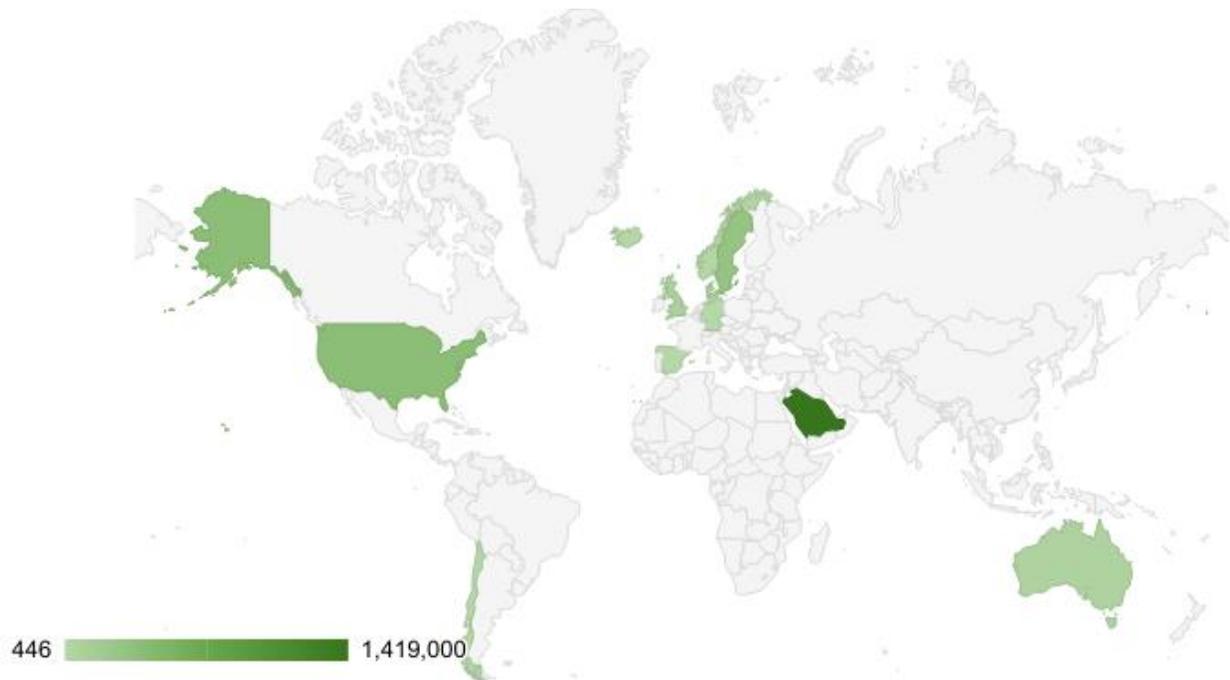


Figure 6. Announced production capacity of e-fuels (in MT/year) around the world (eFuel alliance, 2024)

The announced project of NEOM, to produce green ammonia and green hydrogen in Saudi Arabia, amounts to more than 1.4 million metric tons of production capacity, by 2026. This represents around 60% of all capacity considered in this overview (Wouters, 2024). Driven by an abundance of solar and wind, thus renewable energy, it is expected the project in Saudi Arabia can produce a kilogram of hydrogen below EUR 2, considered as an acceptable price. This may result in the biggest production site of e-fuels, being centrally located between main import regions like Europe, and Asia.

Linking back to figure 6, showing the expected long-term cost of green hydrogen, the heatmap of figure 7, shows similarities in where projects to produce e-fuels are announced. Especially in Chile, the Middle East and Australia, this becomes clear. When looking at timelines of capacity becoming operational, most projects are planned to be commissioned in the second half of this decade. Next to the discussed NEOM project, around half of the announced from the dataset are to become operational after 2025.

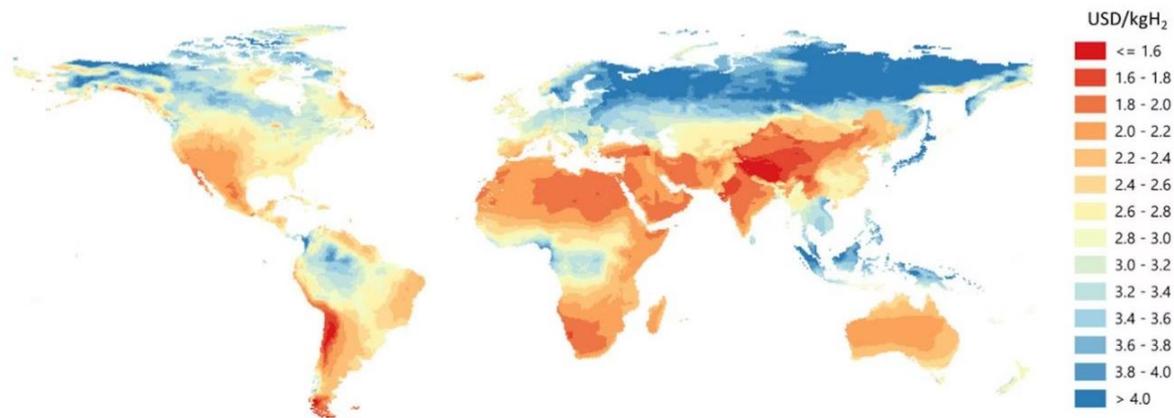


Figure 7. Long-term hydrogen cost based on hybrid solar and onshore wind systems (IEA, 2019)

2.2.3.3 Demand centers

Driven by the discussed regulations, this research focuses on two main demand centers, aviation, and marine fuels. Leaving, industrial, heating and electricity applications, mentioned as other potential demand centers out of scope. The locations where these products will be consumed will be discussed in chapter 4, as a key insight for the storage infrastructure industry, combining this literature review with the interviews held.

For aviation, a specific percentage of e-kerosene as drop-in fuel is given by the ReFuelEU Aviation policy of the European Union. When looking at the demand outlook by IEA until 2030, a demand for e-fuels as drop-in fuel can be derived. Table 1 shows how the demand for the years to come, combined with the SAF outlook, and the synthetic part underneath. The outlook is provided until 2030, however, to calculate 2050 the growth rate of 1.1% per year is used, which is similar to the period until 2030. This results in an aviation e-fuel demand of 887 Mton per year in 2030, growing to more than 32,000 Mton per year in 2050.

	2025	2026	2027	2028	2029	2030	2050
Jet/Kerosene (mb/d)	1.5	1.6	1.6	1.6	1.6	1.6	2.0
SAF mandate	2.00%	2.00%	2.00%	2.00%	2.00%	6.00%	70.00%
Of which synthetic						1.20%	35.00%
E-fuel demand (Mton/year)						887	32,342

Table 1. Derived estimated demand of e-fuels in Europe (IEA, 2024a)

Especially for 2030, this represents a minor share, however storage will be required. While the European Union initiated a minimal percentage as policy requirement, other countries have made or are developing policies too. Within the EU, Germany starts with a minimum of 0.5% already in 2026 for example (T&E, 2024b). In the United States, the use of sustainable aviation fuel, including e-SAF, is encouraged by the Inflation Reduction Act (2022). A sustainable aviation fuel tax credit can be granted for reducing CO₂ emissions. The EU demand is only 1.6 million barrels a day as part of a worldwide total of 9.1 million barrels per day of kerosine, meaning that the potential if a worldwide average mandate of 1.0% would mean a factor 5 of e-kerosine demand.

Looking at marine fuels, the other focus area of this research, a less detailed mandate is provided compared to aviation fuels. FuelEU Maritime imposes annual caps on the average greenhouse gas emissions from the energy consumed by large ships (over 5,000 gross tonnage) visiting European ports, regardless of their flag.

An outlook for the scale of marine fuels being e-fuels in the future is more complicated, in absence of clear mandates. Various sources are reviewed to come to estimated demand for the marine sector as can be found in table 2.

Outlook

Source	Year	Quantity*	Rationale
WoodMackenzie (Alan Gelder et al., 2024)	2050	53.28 Mtoe	A ramp up is expected primarily in Europe, driven by the Emissions Trading Scheme and the introduction of the Fuel EU Maritime regulation. Share of e-fuels will grow after 2040 to around 1 mb/d in 2050
Transport & Environment (T&E, 2024a)	2050	24.35 Mtoe	Green e-fuels offer the greatest potential for reducing emissions in the shipping industry and will remain compliant with regulations for the longest time. They can be produced at large scales, providing clean energy even for the largest ocean-going vessels. Although currently expensive, significant investment in their production is expected to lower costs over time.
DNV (2023)	2050	65.57 Mtoe	During the 2030s, the adoption of e-fuels based on hydrogen will gradually increase, with a significant uptake anticipated in the 2040s. European RED III will create a market ramp-up for e-fuels, make e-fuels to grow to ca. 19% of the shipping fuel mix.

**Find actual conversion calculations in appendix 3*

Table 2. Analysis of e-fuel consumption outlook

Looking at the different quantities of outlook, all for the year 2050, we note some differences. WoodMackenzie and DNV are broadly aligned, and the most respected sources of this overview. According to DNV, with the highest outlook in the quantity of e-fuels in 2050, around 20% of the shipping fuel mix may exist of e-fuels. If this outlook materializes, this means a significant part of product will change in the decades to come in the maritime industry, and as such, impacting the storage industry.

2.2.4 Substitution

In line with what is written in chapter 2.1.1, a natural need for storage follows from a situation of decoupled production and consumption. Following this reasoning, when production and consumption take place at the same place, storage is required. This paragraph elaborates whether storage may be substituted by a different supply chain setup.

By the introduction of new products, in this case e-fuels, the opportunity is offered to design supply chains differently. The introduction of electric vehicles, for example, resulted in a different infrastructure set up, compared to the fueling network which existed for regular car fuels (IEA, 2023) . Next to the development of open-access charging stations, millions of local charging points were installed. At a random parking place, or at EV-owners own places. Without going into detail into this situation, it clearly shows that the introduction of a new form of energy to the mix might have major implications on existing and future infrastructure requirements.

Regarding e-fuels, this is closely related to renewable electricity production, as this is the main production source (see also 2.2.2). The production of renewable electricity can be done anywhere if sunlight and wind are available, or other sources of renewable energy. Renewable produced energy may be put on the local grid or being used directly for different purposes. The latter one is seen as necessary to prevent the grid from intermittency constraints (McKinsey, 2024). Considering this research, when focusing on the production of e-fuels, this will be done on a large scale, as discussed in 2.2.3. On the other hand, innovations are ongoing to produce e-fuels in smaller quantities. For example, Zero Emission Fuels is developing micro-plants to create e-methanol from solar and air (ZEF, 2024). Fueled by a small number of solar panels, technology is connected to electrolyze water, capture CO₂ directly from the air and do methanol synthesis. This may be employed stand-alone and off the grid.

In both scenarios, whenever e-fuels are centrally produced on a large scale, or locally on a smaller scale, a supply chain needs to be designed to get the produced product to demand centers. A situation where supply exactly meets demand is unlikely to be the case. Supply chains will look

different, but in any case, consolidation of smaller products flows into larger volumes is expected. Modes of transport may be different, fit for the volume being produced and consumed. An important reason the assumption of a different consumption from production location is justified, is the fact that renewable electricity is not widely available everywhere. Following the map from IEA (2.2.2), it becomes clear a lot of places with high potential for low-cost renewable energy production are low in population density. While on the other hand, the biggest demand centers do not have the physical space available to cater for production of renewable energy and e-fuels. Meaning export, import and distribution terminal functions likely to be required.

2.3 Conclusion

The introduction of e-fuels as a crucial component in the transition to a decarbonized energy landscape presents a compelling opportunity for the storage infrastructure industry. While e-fuels offer the potential to reshape supply chains and reduce reliance on traditional fossil fuels, their successful integration depends on the ability to address key challenges. The high cost of production, driven primarily by the reliance on renewable electricity and carbon capture technology and availability, poses a significant hurdle to widespread adoption. However, ongoing technological advancements and economies of scale may alleviate these cost pressures in the future.

Moreover, the mismatch between regions with abundant renewable resources and those with high e-fuel demand necessitates the development of import- and export- infrastructure, creating a substantial role for storage facilities. The potential for localized, small-scale e-fuel production through micro-plants offers an alternative, but large-scale production remains crucial to meet the projected demand, particularly in sectors like aviation and shipping. As regulations like ReFuelEU Aviation and FuelEU Maritime drive the adoption of sustainable fuels, the demand for e-fuels is poised to surge, further emphasizing the importance of storage infrastructure.

The transition to e-fuels, like the rise of LNG and Japan's e-methane strategy, highlights the criticality of leveraging existing infrastructure while adapting to evolving market dynamics. The storage industry, with its expertise in handling and storing diverse liquids, is well-positioned to play a pivotal role in facilitating this transition. By embracing innovation, investing in innovative technologies, and collaborating with stakeholders across the value chain, storage infrastructure providers can ensure the safe, efficient, and sustainable flow of e-fuels, contributing to a greener and more resilient energy future by means of storage infrastructure.

3. Research methodology

This chapter outlines the methodological approach employed to investigate the central research question of this thesis: What factors will drive a successful location for e-fuels storage infrastructure? Given the exploratory nature of this study and the need to integrate both existing knowledge and novel insights, a mixed-methods research design was adopted. This design involves the synthesis of a comprehensive literature review, as can be found in chapter 2. Next to literature review data was collected through semi-structured interviews.

The literature review serves as the foundation of this study, providing a theoretical framework and identifying existing gaps in the current understanding of the storage infrastructure industry, its business model and how e-fuels conceptually work. The findings from the literature review formed input for the development of the interview approach, ensuring the relevance and depth of the primary data collection.

3.1 Research method

The selection of semi-structured interviews as the primary data collection method for this research on the impact of e-fuels on the storage industry is well-justified, particularly given the high degree of uncertainty surrounding the topic. This approach aligns with established methodological principles and is supported by relevant academic literature. The two main reasons to go with this methodology are explained below.

- Exploration of a complex and uncertain topic: E-fuels in general represent an emerging and multifaceted field characterized by technological, economic, environmental, and policy uncertainties. Semi-structured interviews provide the flexibility to delve into these complexities, allowing interviewees to elaborate on their unique perspectives and insights. This is crucial when dealing with a topic where there are no clear-cut answers or established consensus.
- Adaptability: The semi-structured format enables the interview to be adapted based on the responses of the individual participants. This allows for probing deeper into specific aspects of the impact of e-fuels on the storage industry that emerge during the interview, ensuring a comprehensive exploration of the topic. The ability to ask follow-up questions and clarify ambiguous responses is particularly valuable in an area characterized by uncertainty and rapid development.

3.1.1 Support from Academic Literature

The use of semi-structured interviews in exploratory research on complex and uncertain topics is widely supported in academic literature. For example, Denzin and Lincoln (Norman K. Denzin & Yvonna S. Lincoln, 2022) highlight the value of qualitative interviews for exploring the meaning and interpretation of phenomena, especially in areas where there is limited existing knowledge. Similarly, Rubin and Rubin (Herbert J. Rubin & Irene S. Rubin, 2012) emphasize the flexibility and adaptability of semi-structured interviews, making them ideal for capturing the diverse perspectives of interviewees in complex contexts such as this topic.

In the specific context of e-fuels, several studies have employed semi-structured interviews to investigate the perspectives of experts and stakeholders. For instance, various research reviewed, used semi-structured interviews to explore the technical, economic, and environmental aspects of e-fuels, providing valuable insights into the potential of this emerging technology.

3.1.2 Considered alternatives

Given the fact e-fuels in general are still in the initial stages of development, let alone adjacent infrastructure, trusted data regarding their production, application and supply chains remains scarce. Much of the available information is based on projections, simulations, and pilot projects, resulting in a landscape dominated by future expectations rather than concrete empirical evidence. Despite data from reputable sources used in chapters 2, data analysis as a prime and only way of research method is considered insufficient.

Next to the fact actual data is not yet available, the industry around e-fuels in the broadest sense is still scattered. Currently, expertise is not centralized for the entire supply chain, including storage. Knowledge and experts exist but are focused on a certain element of the supply chain. The complexity mentioned, next to the diverse range of stakeholders in this area, makes it difficult to design a survey that accurately captures the nuances of the topic. The survey would need to account for various levels of technical understanding, varying interests, and conflicting perspectives. Finally, due to the reasons mentioned, it would be hard to get responses on the survey by sufficient respondents.

3.2 Interviews

Following the chosen research method of conducting interviews, this paragraph explains the defined target groups, number of interviews to be conducted in which timeline and limitations seen with this approach.

3.2.1 Target groups

To gain a holistic understanding of the e-fuels landscape, including storage infrastructure, this study targets three distinct groups of interviewees:

- **Producers of e-fuels:** this group includes companies involved in the research, development, and production of e-fuels. Their insights will shed light on the technological advancements, production processes, costs, and scalability potential of e-fuels. By engaging with them, the study aims to uncover the challenges and opportunities they face in bringing e-fuels to market.
- **Knowledge institutions and industry research:** this group includes research institutes, and industry associations involved in research and development of e-fuels. Their expertise provides a broader context for understanding the scientific, technical, and regulatory aspects of e-fuels. Engaging with them will offer a comprehensive overview of the current state of knowledge, ongoing research initiatives, and potential future developments in the field.
- **Storage providers:** this group encompasses companies specializing in the storage and distribution of e-fuels. Their insights are crucial in understanding the logistical challenges and infrastructure requirements for integrating e-fuels into the existing energy system. Their perspectives on storage technologies, transportation, and safety considerations will provide valuable insights into the practical implementation and scalability of e-fuels.

By interviewing individuals from these three groups, the objective of the interviews is to capture a diverse range of perspectives on e-fuels and more specifically on the impact on the storage infrastructure. The combination of technical expertise, market insights, and scientific knowledge will provide a comprehensive understanding of the e-fuels landscape and its potential impact on the storage infrastructure requirements of the future.

3.2.2 Sample size

To ensure multiple perspectives are considered a sample size of at least three individuals from each target group is deemed sufficient for this study. In-depth interviews with three representatives from each group allow for a comprehensive exploration of all aspects relevant for the different research questions. The targeted interviewees are not random individuals but rather carefully selected experts in their respective fields. Their knowledge and experience make their insights particularly valuable, even with a smaller sample size. The study will employ triangulation, comparing the findings from the different interviewees and data sources to enhance the validity

and reliability of the results. This approach can compensate for the smaller sample size by ensuring that the findings are not solely reliant on the views of a single individual.

3.2.3 Participant selection

After the three different target groups were defined, the selection of participants took place. Outreach was done to the own network of professionals, via e-mail and LinkedIn. In most cases a relationship is already established earlier, for several reasons, which will help in getting the support to participate in this study.

The initial contacts within the network will serve as a starting point for snowball sampling, where interviewees recommend other relevant topics to study. This can lead to the identification of additional experts and stakeholders who may not have been initially identified to the researcher. In annex 2 a list is provided with the details of the interviewees, including to which target group they are considered.

3.2.4 Timeline of interviews

The interviews have been conducted in July and August 2024. The scheduling is flexible, accommodating the availability of the interviewees and aiming to maximize participation within the two-month period allocated for this phase of the research. The interviews typically lasted between 45 and 60 minutes each, providing time for in-depth discussions and exploration of the interviewees' perspectives on the impact of e-fuels on the storage infrastructure industry.

3.2.4 Limitations

Several limitations should be considered when interpreting the findings of this research, because of the method discussed.

Firstly, most interviewees are based in the Netherlands, which may introduce a geographical bias to the results. The perspectives and experiences shared by these Dutch stakeholders may not be fully representative of the global landscape of e-fuels and adjacent storage infrastructure.

Secondly, while efforts were made to include diverse perspectives, the initial reliance on existing networks to identify potential interviewees might have led to a somewhat limited sample. Despite this, a significant portion of respondents were not known beforehand, helping to ensure a wider range of viewpoints and making the sample more representative of the broader population of stakeholders involved in the e-fuels industry.

Third, the use of both Dutch and English as interview languages, while necessary for accommodating the interviewees' preferences, may introduce nuances in communication and interpretation. When respondents' native language is Dutch, the interview are conducted in Dutch, in all other situations the interview will be held in English.

Finally, while the sample size as described is considered sufficient for this exploratory study, a larger sample would have allowed for greater statistical validity and a more comprehensive representation of the diverse perspectives within each group. The limited sample size may restrict the generalizability of the findings to the broader e-fuels landscape.

3.3 Interview design and analysis

To prepare for the interviews, a question framework, based on the conceptual model is constructed. This paragraph explains what interview questions were prepared. Also is explained how analysis after the interviews takes place.

3.3.1 Question framework

Prior to conducting the interviews, questions are prepared to be asked during the interview. Since the semi-structured approach, it is not required to have all questions scripted, however the framework serves for consistency. It also helps with time management during the interview, to have all topics covered. The same conceptual framework was the basis for setting up the question framework.

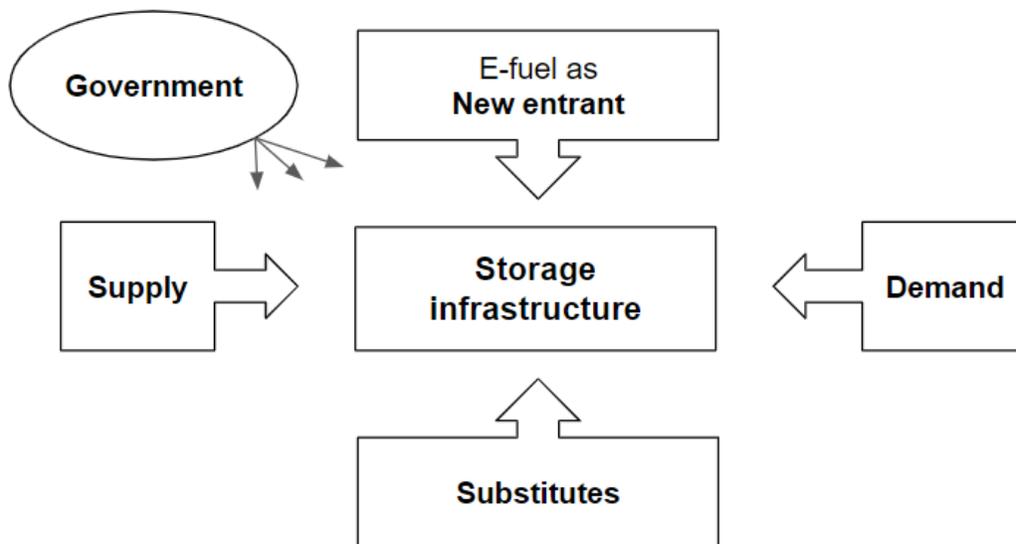


Figure 8. Conceptual framework leading to question framework

The following questions, structured in the key elements of the conceptual framework, were formulated to prepare for the interviews.

- E-fuels as new entrants
 - What kind of technology is used?
 - Where are feedstocks sourced from?
 - What drives the development and introduction of e-fuels?
 - How do governmental mandates and policy play a role?
- Supply
 - Which volumes are produced or planned to be produced?
 - What will be the production locations? And why?
 - Does supply and production require storage?
- Storage industry
 - Does the introduction of e-fuels affect the business model?
 - Is there additional value seen in storage for e-fuels?
 - Which trends & developments impact the industry? Regarding e-fuels?
- Demand
 - Which are the biggest foreseen demand centers?
 - Where do the demand centers exist?
 - Which role is seen for storage infrastructure?
- Substitutes
 - Is there a chance supply chains will change drastically?
 - Under which circumstances is less storage infrastructure required?

These questions, developed based on preliminary literature review and industry observations, provide a framework for guiding the interviews and exploring the key factors that shape the development and adoption of e-fuels. The interview findings will be used to synthesize the impact on storage infrastructure according to interviewees, contributing to a more nuanced understanding of the e-fuels landscape.

3.3.2 Interview analysis

To analyze the information gathered from the interviews, a comprehensive process of transcription and coding was employed. Firstly, each interview was transcribed in its entirety, ensuring an accurate and complete record of the participants' responses. These transcripts served as the foundation for a two-fold coding approach. Transcripts are not published as an

appendix, to ensure interviewee privacy. When there is a need to go through these transcripts, this is possible after contacting the author of this thesis.

The first coding phase focused on identifying and categorizing statements related to the five elements of the question framework. This involved examining the interview transcripts for explicit mentions or implicit references to the e-fuels as new entrant, supply, and demand, what it means for the storage infrastructure industry and what potential substitutes exist. Each relevant statement is copied in a table with the corresponding framework element, allowing for a systematic comparison of different perspectives on these key issues.

The second coding phase broadens the scope of analysis to encompass other elements that emerge from the interviews, particularly those that shed light on the potential impact of e-fuels on the storage infrastructure industry. This includes statements related to the storage requirements of e-fuels, the challenges and opportunities associated with integrating e-fuels into existing storage systems, and the potential for new infrastructure development. By coding these statements, the study aims to uncover the way in which e-fuels may reshape the storage infrastructure landscape and identify potential areas for future research and investment.

A table will be set up to list all quotes from the interviewees, related to the framework. These quotes can be combined into an overarching theme, being input for the research outcome chapter.

This dual coding approach, combining the question framework analysis with a broader exploration of emerging themes, will ensure a comprehensive and insightful interpretation of the interview data.

3.4 Conclusion

In conclusion, this thesis uses a mixed-methods approach to investigate the impact of e-fuels on the storage industry. The literature review of chapter 2 laid the foundation by providing a theoretical framework and identifying existing gaps in knowledge. Semi-structured interviews with diverse stakeholders, including producers, consumers, and industry experts, offers valuable insights into the technological, economic, and environmental aspects of e-fuels, particularly concerning the storage infrastructure.

The findings of this study, based on both literature analysis and primary data collection, contribute to a better understanding of the e-fuels landscape, with a focus on the bulk storage industry. They highlight the key challenges and opportunities associated with the adoption of e-fuels, particularly concerning the repurposing of existing infrastructure and the potential for new infrastructure

development. These insights can inform decision-making by industry stakeholders, policymakers, and investors, guiding the transition towards a more sustainable energy system. Further research may be needed to address the limitations of this study and explore additional dimensions of the e-fuels landscape, as also described in chapter 6.3.

4. Research outcome

Following the interviews with stakeholders in the field, the interview transcripts are analyzed. According to the research methodology as explained in chapter 3. The stakeholders, providing different perspectives and overlapping observations. Statements were given a reference, which is shown in between brackets in the text.

Regarding e-fuels in general and specifically the impact on the storage industry, three main themes arise from the interviews. Firstly, the challenging economics around the transition to e-fuels and the impact on the storage industry. Secondly, observations in the supply chain, which relate to supply and demand, and to substitutes in the conceptual model. Thirdly, observations can be clustered around storage requirements, mentioned specifically by the interviewees. These requirements focus on the center of the conceptual model, being the storage infrastructure industry itself.

4.1 Challenging economics

The transition to e-fuels faces challenges which can be grouped as follows: production economics, product pricing, regulatory challenges, business rationale and customer needs.

4.1.1 Cost of production

Mentioned often as the cause for a significantly higher cost of production of e-fuels, is the fact that new facilities need to be developed and constructed. Three production systems need to be developed:

- Hydrogen production by electrolysis;
- CO₂, by direct air capture;
- A reactor for the chemical conversion of both inputs to e-fuel output (S4136).

These investments are significant, next to investments which need to be made in adjacent infrastructure (S4142). Existing infrastructure like storage capacity can contribute to getting capital investments down (KI13).

Not only the initial capital investment required to start producing e-fuels, also the cost of input resources is also high. Renewable electricity, being a major part of input, especially to produce hydrogen, needs to be available at low cost and at maximum stable production duration (S4173). A look at the world map with low local renewable electricity prices indicates where e-fuels may be produced cheaply (S134). Regarding the other main input, CO₂, availability is an issue next to

cost per ton. As required under current policies, CO₂ should come from biogenic sources or from direct air capture. Direct air capture technology is expensive, while biogenic sources being cheaper than direct air capture, “are not plentiful everywhere” (KI2124), and will be used in full, between 2040 and 2050 (S2174). Therefore, the advantages of e-ammonia are mentioned multiple times. E-ammonia does not require CO₂ to be produced (S4170).

4.1.2 Product pricing

For what is acceptable in terms of cost of e-fuels compared to fossil fuels, interviewees came with multiple insights. First it should be noted that the price of e-fuel products should not be compared to purely fossil fuels, but to lower-carbon biofuels. As soon as the cost of production of e-fuels equals that of biofuels, the acceptance will start (KI117). Biofuels are, as an already existing alternative, more expensive compared to fossil fuels, however, mandates are forcing the use of biofuels and for sustainability reasons customers are willing to pay a premium. This will be the case for e-fuels as well, at least at the levels of biofuels. A disadvantage of biofuels, which does not exist for e-fuel, is that biofuels compete with food for human consumption (S399). When discussing at which price levels e-fuels are acceptable to consumers, it is noted that customers at the moment are willing to pay 2 to 3 times the price of fossil fuels (S4172). This means for example for methanol, cost of EUR 1,000 per ton for e-fuels compete with fossil methanol which cost around EUR 300-500 at the moment (S4171). Companies, such as airlines and shipping companies will, because of increasing fuel cost, invest in more efficient assets as well; to reduce fuel consumption (KI2127) The cost of efficiency needs to weigh off to the additional cost of e-fuels in that case.

Translating this to implications for the storage industry, the fact that products to be stored are becoming more expensive is seen as positive. Storing products of higher value means relative storage costs come down (SI1175). This may lead to less pressure on new to negotiate storage rates or leads to even higher margins (SI1176), as the risk to store more expensive products increases as well. On the negative side, enhanced efficiency of ships and planes will lead to a reduction of fuel usage, leading to less required storage (S4151).

Despite the fact e-fuels will be more expensive than conventional fossil fuels, the ability to use them as drop-in fuel will make them bearable (SI1182). The same molecules, produced in a sustainable form, can be blended with conventional fuels, making conventional fuels more sustainable. For example, 5% of e-methanol can be added to traditional methanol, already contributing to decarbonization, at only part of the price difference compared to a 100% switch

(S4141). The fact e-fuels offer the possibility to replace fossil fuels partly, makes the switch to renewable fuels more gradual, and increased fuels expenses less significant.

4.1.3 Political pressure

Looking at policy development around the world, again the European Union plays a key role with concrete legislation, enforcing minimum volumes of e-fuels to be adapted from 2030 onwards. For aviation and marine, these are most concrete and will represent most e-fuel volumes (S265). Aviation among these is seeing a stronger mandate (S130) while for marine this may become a minimum requirement when the industry does not sufficiently decarbonize by itself (S268). Next to the European Union, also the United States developed policies to stimulate the adoption of e-fuels, while not enforcing to do so with a given percentage (S3110). The United Kingdom (UK) also put policy in place to enforce the use of e-fuels, even stronger than the EU, showing independence from the European Union, and are an example for individual countries around the globe (S286).

From a different angle, political forces also play a role in the transition towards e-fuels. Governments and supra-governmental organizations regulate the economy to a certain extent, by policy development and mandates.

The second element brought up in this respect is the strategic value of fuels in geopolitical perspective (KI16). In Europe, strategic independence and strategic autonomy are popular phrases these days, which may impact policy development for the introduction of e-fuels to the energy system (KI17). Some production is desired within the European region, but not at all costs (KI114). At the same time, with the European capitalistic ideology in mind, imports will happen, when products can be produced at lower costs outside the European Union (KI111). Also, within the European Union, individual countries aim to maximize their added value in this transition. Denmark, for example, can leverage their abundance of renewable wind-power (KI113). The European Nordic countries are favored with renewable electricity. Next, to electricity from wind, hydroelectric power is widely available (S133). With regards to solar power in Europe, Spain and Portugal are mentioned. However, not to proportions as more southern located countries, and with the supply of biogenic CO₂ limited (S138).

Interviewed stakeholders also expressed their concerns and skepticism towards these political policies. Especially with regards to local production, which is expensive, and may lead to an uncompetitive business environment (S269). Which links back to strategic independence as mentioned earlier, may be counterproductive when competing regions put different policies in

place (S3112). Also, the unpredictability and uncertainty of politics is highlighted. Elections in for example the United States, may cause a change in developed policies, and puts more uncertainty in the market with regards to global trade and integration (SI2188).

4.1.4 Business rationale

Skepticism is seen in the political arena and in business itself. Leadership of major players in energy and chemical markets like Shell and BASF are changing their commitments to invest in major new-energy projects. What can be seen in the news is that CEOs of these companies struggle to move on with investments not providing financial returns comparable to business in the fossil field (SI2192). For example, the project to build a biofuels production facility in Rotterdam, which was put on hold by Shell, despite the fact that construction had already started. These decisions will impact future investment decisions and cause additional uncertainty in the markets (SI2196).

The cost of these developments is increasing, caused by more expensive building materials. Pursuing these opportunities will become more difficult, as business cases become unviable (S153). During this research, Ørsted, one of the companies interviewed, made an announcement regarding the termination of their e-methanol project in Sweden. The project, which was poised to become the largest production unit of e-methanol in Europe, was canceled due to slower-than-anticipated development in the e-fuel market (Ajsa Habibic, 2024). Showing timelines of both the market demands as well as infrastructure development are challenging currently. Multiple projects are delayed already (S4167). Also, with mandates effective as of 2030, the expectation is final investment decisions will be taken later this decade, to be only ready as soon as the demand is actual as well (S266). The importance of joint ventures between multiple industry partners is recognized. Higher success rates are foreseen when projects are executed with multiple industry stakeholders at the same time (SI2185)

4.1.5 Voice of the customer

The transition to e-fuels will impact the end-consumer. To a lesser extent, this can be linked to the storage industry, but the transition will impact the need for storage. Interviewees mention, next to political mandates, in some cases a pull from end-customers exists. A personal drive to acquire products which are produced sustainably (S131). Especially for niche products in luxurious segments, where consumers are less price sensitive (S285). Premium car brands are mentioned as examples, or companies which use sustainability for marketing purposes, like Lego or BIC

(S129, S284). In contrast, end-consumer price pressure, enlarged by more expensive fuels, is mentioned as a factor which will influence the transition negatively (S287).

4.2 Supply chain observations

A broader look into the observations regarding global and local supply chains to successfully transition to e-fuels. A transition away from fossil fuels will be in most cases a less efficient and more costly exercise. Cost of production of oil products are low and the supply chain has been made as efficient as possible with improvements over time (KI122), which raises the bar for any transition away from conventional fossil fuels.

4.2.1 Production inputs

To start the supply chain with the production of e-fuels and the required inputs needed. Looking at these inputs, or feedstocks as called by the industry, a difference in availability can be seen. Between biogenic CO₂ in the northern hemisphere versus abundant renewable energy more concentrated in the southern hemisphere (S139). To bridge the imbalance between these two, storage infrastructure plays a role. Input products are to a lesser extent commodity products, like for example, crude oil. Making trading and availability more difficult. Point-to-point contracts need to be negotiated between suppliers and customers for these products. For LNG, as an energy product, it took around 20 years to become the traded commodity it is today (SI1179). It will contribute to supply chains to become more efficient and transparent as soon as, for example, hydrogen and CO₂ are traded with commodity characteristics.

4.2.2 Supply chain optionality

Different scenarios exist to get the different inputs, electricity, hydrogen, and CO₂ at the same place to produce final e-fuels with the transport of final products to the demand centers thereafter. Or alternatively, semi-finished products are transported to a central e-fuel production unit. Some scenarios, despite being possible, are having limitations:

- Transportation of electricity not being put on a local grid will be difficult, it requires a carrier, preferably in liquid form to allow for transportation (S262)
- Transportation of hydrogen can happen; however, it is expensive and inefficient, and therefore less likely as semi-finished product for e-fuels (S136).
- Hydrogen transportation may be done with Liquid Organic Hydrogen Carriers (LOHC) may play a role, which makes transport safe and uncomplicated. This process is inefficient as it needs to couple and decouple hydrogen to and from its carriers (KI14).

More likely to happen is the transportation of finalized e-fuels, in analogy to final fuels today. Announced projects for e-fuel production are limited in size, which results in consolidation in established storage locations, such as Rotterdam (S4150). When talking about transportation, and related costs, it is indicated that the relative cost of transportation will not be of negative significance (S4153). In any of these cases, input materials, semi-finished and finished products will find their way into markets from and to various places, with a role for storage (SI1177). Different options require different storage requirements, which is elaborated on in 4.3.

4.2.3 Existing locations

Interviewees believe current hub locations, such as Rotterdam, Singapore, the Middle East and Houston remain to play a vital role in new, e-fuel, supply chains (S4152). Key reason for this is the demand centers these locations serve (KI121). Demand centers which are well-established and developed into efficiently working supply chains (S3108). Unchanging demand centers such as refineries, chemical factories, and end-consumers, ensure the demand for storage infrastructure in the same or connected and adjacent places.

Closely related is physical connectivity between storage infrastructure and demand centers. An extended pipeline network, for example throughout the Amsterdam-Rotterdam-Antwerp (ARA) region, is not easily adjusted nor replaced (KI13). Especially for the shipping and aviation markets, this is a leading cluster. Physical connections by pipelines between ports and airports are irreplaceable. The same applies to Rotterdam as a leading bunker market for shipping fuels. Next to storage capacity, an ecosystem of companies and knowledge is centered in the Rotterdam cluster (S141).

Another reason current locations and existing infrastructure is valued is the invested capital in a stable environment. Companies will always be cautious about where to invest their money. Preferably at locations with limited governmental or social risk (SI1180). A stable business environment is shaped over a longer period, and for new projects to take place in unstable environments, the cost of capital will destroy project value (SI1197).

The Middle East, a leading fossil fuel producing and exporting region, is considered politically stable, with the funds available to invest in new infrastructure (KI18). Next to stability and funding capacity, electricity from solar may also be successfully developed in the region (S4156), while the region lacks the availability of biogenic CO₂. Being short on CO₂ may lead to the fact the Middle East focuses on ammonia production, which does not require CO₂ (S151). Alternatively, lack of CO₂ can be resolved by direct air capture installations or imports of CO₂ (SI1178).

4.3 Storage requirements

The actual impact of e-fuels on storage infrastructure is also discussed with the different stakeholders. An outlook is given on what expected requirements are for storage terminals.

4.3.1 Changing products

E-fuels come in the same chemical composition as their fossil counterparts. In multiple cases, because of a better controllable production process, e-fuels are of higher quality (S3109). Looking purely at the storage and handling of these e-fuel products, not considering the transition effect and volumes, no immediate changes are required compared to conventional fuels (S155).

A gradual transition in the energy mix will happen, with an increasing share of e-methanol, e-kerosene (also referred to as e-SAF) and e-ammonia as mentioned by multiple interviewees (KI2113). E-methanol will increasingly serve the shipping industry, around 300 ships are already ordered which are compatible for methanol (S126). The aviation industry will be served by e-kerosene, which is a net-zero fuel, not requiring current planes to be adjusted significantly (S394). E-ammonia is mentioned in relation to industrial production and is expected to be used as a semi-finished product. The scale of e-ammonia facilities is expected to be larger than for the previously mentioned products, producing large volumes of product (S150, 151). These products, especially methanol and ammonia are used today mainly in chemical context, but will move into energy products in the future, resulting in specific requirements for storage infrastructure (S157).

The energy densities of some of these products are much lower than most fossil fuels today. Methanol and ammonia have lower energy densities, meaning more volume needs to be consumed for the same amount of energy. This factor leads to the requirement for a larger storage capacity (S4147). Also supply chains will be impacted by this, for example more bunkering points on a journey to cater for sufficient energy required along the route (S273).

Lower energy densities of main e-fuel products translate in the requirement of physical space of storage infrastructure. If larger volumes need to be stored, larger storage facilities will be a logical result (SI1183). The question is whether this space is still available in the bunkering hubs mentioned, and whether expansions can be realized adjacent to existing infrastructure. For e-kerosene energy densities are not materially different from fossil-based kerosene.

Finally, with the introduction of e-fuels, and a changing energy mix, storage infrastructure adaptability and the speed of adaption will be key drivers for success (S4163). The storage industry should monitor developments in the energy mix closely, and timely adjust infrastructure,

as volumes are required (S4164). It might be the case that smaller terminals play a role early in the transition, due to their scale, which is a good fit for the start-up volumes on the market (SI2191).

4.3.2 Terminal characteristics

The impact of the introduction of e-fuels on storage terminals, in the operational philosophy of a facility, was also discussed with contributing stakeholders.

The drop-in characteristics of e-fuels, replacing fossil fuels over time, require strict segregation between both flows of product. Sustainably produced e-fuels, being more expensive and higher in quality, need to be certified as such, to ensure its value and sustainability (S144). This causes segregation between certified e-fuel products and the conventional counterpart. Due to the limited volumes of e-fuels at the start of the transition, smaller tanks will be needed to store these products economically. A business case for smaller tanks is unfavorable, as less economies of scale can be applied (S148).

Another requirement specifically mentioned is the capability for bunkering. E-methanol, which will serve as shipping fuel, will be bunkered too. A different operation than common today, where methanol serves the industry via point to point connected pipelines. Jetties at the waterfront need to be fit for purpose to execute these bunker operations (SI145). This requires a change at either chemical terminals storing methanol today, not serving bunkering markets, or at oil terminals which are used to perform bunker operations but do not commonly store methanol (SI2187). For the aviation sector, the operational philosophy will not significantly change. To serve these markets, connectivity between storage terminal and airport remains the major success factor. Preferably by a direct pipeline, alternatively by barges or truck modalities (S3106).

Connected modes of transport in general are a point of attention for the introduction of e-fuels. Storage facilities normally cater for a subset of transportation modes, via water, road, rail, and pipeline. These configurations might change, to be the right fit for products to be stored (S4139). An example of e-methanol is given, available in ISO-containers, which requires a storage terminal to handle trucks and rail wagons efficiently to receive product, while barges may be used to distribute the fuel further (S4144).

Blending will be a strategic requirement for the storage of e-fuels (S3105). The product will be blended with specifications required by end-users, like aviation (S3107). This leads to a broader role for the storage infrastructure industry. When the markets for e-fuels mature and trading as it does for commodities, blending will potentially not be needed anymore. When Certifications and

quality control are standardized a banking system can be introduced. Sustainable e-fuels are not always required to be transported, it may become a paper reality. This could further decarbonize, as less transport is required, and efficient markets will lead to more adoption of these e-fuels (S4161). For storage providers, this means a network of terminals covering multiple locations will be valued by customers.

Finally, knowledge on how to store and handle e-fuels safely and efficiently will play a role in building these new supply chains (SI2193). For certain products, like e-methanol, this might not be too complicated, whereas for e-ammonia, this requires more safety knowledge (S4148). Knowledge and experience of storage providers can be leveraged.

4.4 Conclusion

The transition to e-fuels faces economic challenges due to the high cost of production and resulting product prices. The cost of production is high due to the need to develop and construct new facilities, as well as the expensive input feedstocks like renewable electricity and CO₂. The price of e-fuels needs to be competitive with biofuels, while excessive cost may lead to a reduction in fuel usage and less required storage. Political pressure is also a factor in the transition to e-fuels, with governments and organizations defining the change and timeline through policies and mandates. Strategic independence and strategic autonomy are important considerations, but there are concerns about the cost of local production and the unpredictability of political policies. The business rationale for investing in e-fuels is also uncertain, resulting in companies like Shell and BASF struggling to justify investments that do not provide comparable financial returns to fossil fuels. The cost of development is increasing, and the business case is becoming less viable. The voice of the customer is important, with some consumers willing to pay a premium for sustainably produced products. However, price pressure from end-consumers may negatively influence the transition.

Overall, the transition to e-fuels faces challenges in economics, politics, and business rationale. The voice of the customer and the need for storage will also be impacted by this transition.

There are various scenarios for producing e-fuels, involving transportation of either final products or semi-finished products. Transportation of electricity and hydrogen, while possible, faces limitations. Existing hub locations like Rotterdam, the Middle East, Singapore, and Houston are expected to remain crucial due to established demand centers, physical connectivity, and stable investment environments.

Storage requirements caused by transition in the energy mix will impact the layout of storage facilities as products are added to the mix. Energy densities, being lower for some e-fuels, compared to currently used fossil-fuels, will require additional storage volume and therefore more physical space. The ability and speed to adapt to current infrastructure will be a key success factor. Sustainable e-fuels will require extensive certification and therefore segregation from fossil counterparts, expected in smaller tanks. Terminal configurations need to cater for different modes of transport, to receive small volumes of product and for bunkering operations. Knowledge to handle difficult products safely and efficiently may be leveraged in the transition to e-fuels.

5. Discussion and synthesis

Literature review combined with interviews leads to multiple findings for the storage infrastructure industry, which are described in this chapter. So-called key factors to be considered with the introduction of e-fuels for the storage industry, summarizing the findings especially for the storage industry. The second part of the chapter provides in summarized form answers to the research questions.

5.1 Key factors

The market for storage is driven by dynamics in the markets of the products being stored. Therefore, these key factors shed light on the supply chains and demand center first, with their implications described for the storage market. Thereafter, in 5.1.3 more operational aspects are highlighted.

5.1.1 Supply chains will change at its beginning

Looking at the supply chains for e-fuels, from production to consumption, multiple scenarios exist. Depending on the choice of what products will be shipped, storage will play a different role in the supply chain.

A storage terminal may play distinct roles in various locations or play distinct roles in an individual location. Figure 9 explains the conceptual different routes which can be followed.

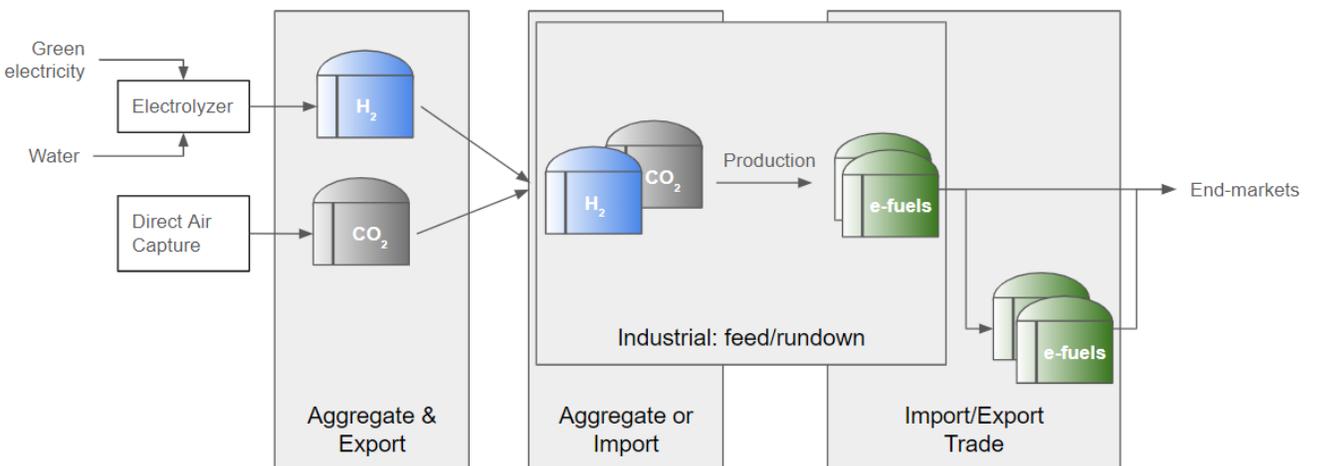


Figure 9. Distinct roles of liquid bulk storage for e-fuels

Production of e-fuels requires three basic elements: electricity, water, and CO₂, as input for production. The storage industry plays no or a limited role in the storage of electricity and/or water, which is left out in this figure, and only shown as input for electrolysis. Some terminal operators made their first steps in the storage of electricity, which potentially means an extra role at the left-hand of the model.

After electrolysis of water by green electricity, a flow of hydrogen (H₂ in figure) exists. Depending on the location where the electrolysis will be operated, this may lead to export at the place of production and import in the place where e-fuels will be produced, resulting in two locations for storage of H₂. The electrolysis and e-fuel production may also be at the same location, which limits the number of storage points to only 1 location for H₂.

The same applies to CO₂, as the second main component for e-fuel production. Resulting from Direct Air Capture or from biogenic sources, a flow of CO₂ is introduced. If decentral production will happen, this requires multiple storage facilities, to aggregate, export and import to the location of e-fuel production. Only one location may be needed when these storage roles are combined.

These two flows lead to feedstocks for e-fuel production. By producing via the named methods in chapter 2.2.1, e-fuels themselves are introduced as single or multi-product flows. Storage of these products will be required before they may be 1) shipped to end-markets, 2) exported and imported to end-markets or 3) trade will happen with these products at the same location before end-markets are served.

When the model is translated into the impact of storage infrastructure in the supply chain, it comes to two conceptual directions.

1. Construction of hydrogen and CO₂ storage infrastructure is needed

In the case of hydrogen and CO₂ being exported and imported, storage capacity at these locations must be developed. Currently, storage capacity to store and handle either hydrogen or CO₂ is limited. Infrastructure is required at the location from where export will take place, as well as where import will happen. The locations of imports are expected to be the same as where storage infrastructure exists today. Different from today's export locations of energy products, will be hydrogen and CO₂ export locations, driven by renewable energy. Storage infrastructure providers will be included in setting up supply chains. In line with developed LNG supply chains, these are developed at once to establish point-to-point connections if commodity trade is limited. However,

investments in new storage infrastructure for hydrogen and CO₂ will be expensive and often made by industry partners to ensure a sound business case.

2. Repurposing current storage infrastructure at pace of transition

In the second conceptual direction, e-fuels will come to storage infrastructure replacing conventional fossil fuels. This will start happening in elevated volumes towards 2030 and at significant volumes in 2050, driven by mandates. Especially in the EU, the Amsterdam-Rotterdam-Antwerp region will see this happening. The market for e-fuels, as it evolves over time, must be followed closely to adapt accordingly. Investments will be minor in tankage, but the flexibility a storage terminal offers regarding handled modes of transport will be crucial. 5.1.3 will further explain what operational requirements can be distilled from literature review and analyzed interviews.

Learning from the journey Japan is on, to fully leverage the existing grid infrastructure, for e-methane, shows infrastructure may be a decisive factor in the transition. The infrastructure industry, by repurposing existing infrastructure for e-fuel products, may have a positive contribution to supply chains and expedite the transition.

Both conceptual directions may exist next to each other. Depending on choices made by producers of e-fuels, it can be determined whether hydrogen and CO₂ terminals need to be developed, and to what scale and actual locations. The second conceptual model of repurposing existing capacity will be required in any case. Key success factor is the adaptability of current assets.

5.1.2 Demand centers remain unchanged

This research focuses on the aviation and shipping markets, which will be significantly impacted by the introduction of e-fuels. From literature it can be concluded that in the EU 35% of aviation fuels will be e-kerosene in 2050, driven by political mandates. At the same time, for marine fuels, the part of e-fuels is expected to be 20% by 2050. It should be noted that the marine industry has more options to decarbonize compared to the aviation industry, meaning it may be significantly different if other innovations come up in the meantime.

In any case, by the introduction of e-fuels to the energy mix, the same end-markets are served by storage infrastructure as is the case today. The ability to serve these markets by infrastructure such as jetties for loading bunker barges or pipelines to airports remains unchanged in importance.

A notable change the introduction of e-fuels will bring is a wider range of products, for these markets. It will transition from one product serving one market, to multiple products serving a single market, especially in the marine market.

Current locations will remain of value, due to demand centers close or connected to these.

5.1.3 New product market combinations requiring storage

The introduction of e-fuels will cause new product market combinations, impacting the business model of terminals and the operational process. Figure 10 aims to highlight the impact on both, especially caused by the introduction of e-fuels. This chapter focuses on the change which will happen at existing terminals, to a lesser extent storage terminals to be developed.

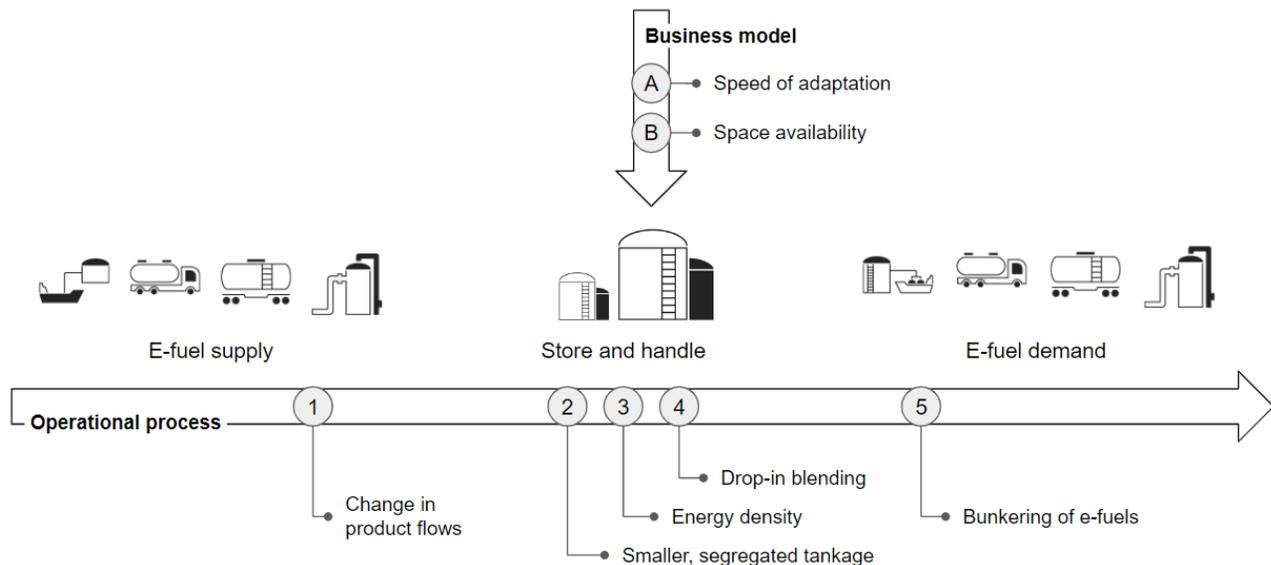


Figure 10. Impact on storage business model and operational process

The operational process can be divided into three phases, receiving product depicted as e-fuel supply in the figure, storage and handling and thirdly delivery of product to demand centers. The seven elements of impact are described below:

1. Change in product flow, caused by the introduction of e-fuels. More differentiated products will be received by a storage terminal. At the start of the transition the volume of these flows will be limited, requiring flexibility in how these flows may be received. Road and rail modalities will play a bigger role. Terminal facilities need to be prepared to handle these unconventional products at smaller volumes
2. Due to limited volumes of e-fuels received by storage terminals, and the requirement to store these segregated from conventional fuels, smaller tankage is required. Segregation

is needed to control quality and certification proving the sustainable character of the product. Storage facilities need to adapt their capacity to the needs of customers' volumes, to stay competitive in pricing. Renting out large capacities for limited volume will not be acceptable to customers.

3. Despite expected lower volumes at the start of the transition, lower energy densities of e-fuel will cause the opposite effect. To provide the same amount of energy, more products are required and must be stored. Especially for marine fuels, this leads to larger facilities in the long-term, when volumes play a significant role in the total energy mix.
4. Blending of products is of increasing importance. The drop-in effect, where e-fuels are blended with their fossil counterparts, requires storage facilities to cater for enhanced blending capabilities. This will lead to increased activity at the terminals and additional added value for customers.
5. Bunkering of unconventional products will be a change when loading product from the terminal. Marine fuels are changing, with volumes of around 20% e-fuels in 2050. Bunkering infrastructure is required for e-methanol for example, with distinctive characteristics from fossil fuels. Limited storage terminals are equipped for this product market combination yet.

From a business model perspective, e-fuels will have an impact on two elements of storage facilities:

- A. The speed of adaptation of terminal infrastructure to the flows of e-fuels coming on the market becomes a key success factor. A changing energy mix, in combination with described operational impacts, leads to increased flexibility. Driven by a set of uncertainties, such as political mandates, price developments and energy demand, leading to a continuous assessment of whether existing storage capacity is fit for the future. Translating the latest insights and requirements into physical terminal changes becomes a capability driving success.
- B. Physical space must be available, especially for the long term. Driven by lower energy densities, more volume is required. In a scenario where e-methanol, for example, replaces heavy fuel oil, three times the volume is required to store similar energy. Room for physical expansion in ports is a key driver for success of a storage terminal. Building additional capacity too far from existing infrastructure, will lead to higher prices and a less competitive service offering

In short, the terminal operational philosophy needs to be fit for purpose. Existing out of a combination of the right size tankage and handling corresponding modes of transport in receiving and delivering product. The variability will increase as a wider range of products will serve a single market. Defining terminal layout and planning to adjust to the right set of requirements will be a key success factor.

6. Conclusion

This chapter provides a summarized answer to the research questions formulated at the introduction of this thesis. Sub research questions are answered first, leading to the answer to the main question finally. Secondly, signposts are provided for the storage infrastructure industry, to keep up with developments related to the transition towards e-fuels. Finally, limitations of this research and future research directions for the academic audience are described.

6.1 Answering research questions

This paragraph answers, in summarized form, the main- and sub-research questions.

1. What role does storage infrastructure play in the value chain?

Storage in general is required when decoupling exists between production and consumption. Which is the case for liquid energy products today and e-fuels in the future. Storage capacity, either independent or (partly) owned by producers or consumers themselves, bridge imbalances of geographical availability, volume disconnects and timing constraints. Economies of scale, safe and efficient storage and handling provide value to consumers. Also, the strategic role storage plays in geopolitical aspect, securing energy supply. Services provided by liquid bulk terminals are next to pure storage, and to a lesser extent handling and movement of products. Logistically, storage infrastructure plays a role when products need to be exported, imported, and distributed, or can be linked to industrial clusters. Hub terminals, on top of multiple logistical functions, enable traders to be active.

2. What are e-fuels and how will its demand and supply look like?

E-fuels, also known as synthetic fuels, are produced using renewable electricity and captured CO₂ to ensure carbon neutrality. Production involves converting electricity, water, and CO₂ or N₂ into liquid or gaseous fuels via processes like the Fischer-Tropsch, methanation, methanol synthesis, and ammonia synthesis. E-fuels have potential applications in various sectors, including industry, transportation, heating, and re-electrification.

However, the cost of e-fuel production is significantly higher than that of fossil fuels. This cost disparity presents a challenge for the widespread adoption of e-fuels unless governments provide subsidies, mandates are implemented to enforce their use, or consumers are willing to pay a premium.

3. What will be the impact on the business model of storage infrastructure companies?

The impact of e-fuels on the business model of liquid bulk storage infrastructure will be positive. Conventional fossil energy products exist in liquid and gaseous form, which continues to be the case with e-fuels. Decarbonization of aviation and marine fuels will be done via e-fuels, both industries which will continue to require bulk storage.

E-fuels, being more valuable than fossil fuel products, on top of additional specific requirements, can drive higher margins and therefore improve the business model.

4. Which locations are likely to play a successful role in the e-fuel supply chain?

Locations of production and consumption of e-fuels determine the impact of storage in the first place. It can be concluded that these locations will be decoupled, and transportation will be required to match supply and demand. At locations of export and import, storage terminals consolidate and distribute to customers.

Driven by the need for renewable electricity, production of e-fuels will happen at locations with an abundance of renewable energy. Locations like Chili, northern America and Europe, the Middle East and Australia are suitable as competitive production locations. The first e-fuel production facilities are operational or announced in these countries as well, from which export of product take place.

Demand locations, and such in need for import and distribution storage capacity, will remain located at the same hubs as for fossil fuels. Driven by the connected demand centers which will not change significantly. Current infrastructure will remain to play a vital role, especially due to connectivity to industrial clusters, airports, and pipeline networks. Locations which will see a flow of e-fuels early will be in the Amsterdam-Rotterdam-Antwerp region and ship bunkering locations like Singapore and the Middle East.

5. What requirements for storage infrastructure follow the introduction of e-fuels?

Storage requirements caused by transition in the energy mix will impact the layout of storage facilities as products are added to the mix. Energy densities, being lower for some e-fuels, compared to currently used fossil-fuels, will lead to additional storage volume and therefore more physical space. The ability and speed to adapt the current infrastructure will be a key success factor. Sustainable e-fuels will require extensive certification and therefore segregation from fossil counterparts, expected in smaller tanks. Terminal configurations need to cater for different modes

of transport, to receive small volumes of product and for bunkering operations. Knowledge to handle difficult products safely and efficiently may be leveraged in the transition to e-fuels.

Main research question: what will be the impact of the introduction of e-fuels for the storage infrastructure industry?

The introduction of e-fuels will positively impact the storage infrastructure industry. The demand for storage will increase due to the need to accommodate new e-fuels like e-methanol, e-kerosene, and e-ammonia, which will partially replace traditional fossil fuels in the aviation and marine sectors. The shift in supply chains, with e-fuel production potentially located in regions abundant in renewable energy, will necessitate storage solutions for efficient transportation and distribution to demand centers. The lower energy density of some new e-fuels replacing conventional fossil fuels will require additional storage volume, creating a need for larger or more numerous storage facilities. Furthermore, the requirement for strict segregation and certification of e-fuels will necessitate dedicated storage tanks and infrastructure.

The storage industry can capitalize on this transition by adapting its infrastructure to handle e-fuels, offering blending and bunkering services, and leveraging its expertise in safe and efficient storage. The industry's ability to anticipate and respond to the evolving e-fuels market, coupled with investments in flexible and adaptable infrastructure, will be crucial for its continued success in this changing energy landscape.

6.2 Signposts for the storage industry

This research reflects a first exploration into the impact of e-fuels on storage infrastructure. E-fuels are already produced in pilot projects, and on the market, nevertheless significant volumes will follow only from 2030 onwards. The industry has time to prepare for further decarbonization and the introduction of e-fuel products. To be well-prepared and ready to take investment decisions for new projects for hydrogen and CO₂, or to repurpose existing infrastructure, the following signposts can be followed. Signposts indicate a direction which is helpful for the storage infrastructure industry:

- National and supranational policy development: which is a significant driver of the transition. Whether policies are already in force or only announced, the latest developments around policy development will help understand the phase and speed of the transition.

- Intergovernmental organizations: such as the International Energy Agency which publishes periodically energy outlook and views on how energy markets will develop. Next to the International Maritime Organization by the United Nations, which provides guidelines for the shipping industry and regulatory frameworks to be adhered to internationally.
 - Example signpost: the IAE organizes webinars regarding e-fuels and datasets are available for detailed market analysis.
- New build ship orderbook: announcements by shipping firms of newly ordered ships are made regularly, providing insight into the fuel demand of the future. Since it takes multiple years to build ships, which will be operational multiple decades after, it gives clear indication of what fuels will be required in the future.
 - Example signpost: “COSCO Shipping Lines orders a dozen methanol-fuelled boxships” (Katherine Si, 2024).
- Announced e-fuel production facilities: as for example collectively done by the E-fuel Alliance. Keeping an up-to-date database of where production will take place provides insight in newly developed supply chains. Also, from a perspective on what locations will be leading in the transition this provides detailed insights.
- Membership of knowledge institutions: multiple international institutions exist to enhance knowledge on certain products. Joining these networks will provide additional intelligence which can be used for future investment decisions.
 - Examples of these organizations include the Methanol Institute, Hydrogen Council and Ammonia Energy Association.

This list is not intended to be exhaustive but provides sources and examples which are widely available in public sources. Additionally, research or consultancy can be acquired to gain insights for specific questions.

6.3 Future research

While this research provides valuable insights into the role of storage infrastructure in the e-fuels landscape, it is crucial to acknowledge its limitations. The future of e-fuels remains highly uncertain, and this study, being explanatory in nature, primarily focuses on understanding the current state rather than predicting future trends and volumes.

Data analysis revealed various aspects of storage infrastructure but did not delve into adjacent infrastructure like gas pipelines or the electricity grid, which could significantly impact the e-fuel ecosystem. Moreover, the research primarily concentrated on aviation and marine applications, leaving questions about its relevance to power generation, industrial use, and other demand centers unanswered.

Future research could address these gaps by focusing on:

- Predictive modeling: developing models to forecast the future of e-fuels and their storage needs under various scenarios.
- Adjacent infrastructure: exploring the interplay between storage infrastructure and other critical components of the energy system.
- Diverse demand centers: investigating the storage requirements for e-fuels across various sectors, beyond aviation and marine.
- Technological advancements: evaluating the impact of emerging technologies on e-fuel storage and distribution.

By addressing these limitations, future studies can provide a more comprehensive understanding of the e-fuel landscape and inform decision-making for policymakers, investors, and industry stakeholders.

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Appendices

Annex 1 – data related to worldwide announced production units of e-fuels

Source	Project	Country	Region	Capacity/yr ment	Adj. Capacity (Ton/year)*	Product	COD**
e-fuel alliance	Atmosfair Fairfuel	Germany	Europe	350 tonnes	350	eCrude	2022
e-fuel alliance	Bilbao Decarbonization Hub	Spain	Europe	2750 m3	2,200	e-fuels	2024
e-fuel alliance	Demonstration Plant Haru Oni	Chile	Rest of World	446 tonnes	446	e-fuels	2023
e-fuel alliance	FlagshipONE	Sweden	Europe	50000 tonness	50,000	e-methanol	2023
e-fuel alliance	HIF Global - HIF Matagorda	United States	Rest of World	300000 tonnes	300,000	green hydrogen	2027
e-fuel alliance	INERATEC Pioneer Plant	Germany	Europe	3.5 mln liter	2,800	e-fuels	2023
e-fuel alliance	Liquid Wind - FlagshipTHREE	Sweden	Europe	130000 tonnes	130,000	e-methanol	2027
e-fuel alliance	Liquid Wind - FlagshipTWO	Sweden	Europe	112000 tonnes	112,000	e-methanol	2026
e-fuel alliance	Next GATE	Germany	Europe	350 tonnes	350	e-fuels	2022
e-fuel alliance	Nordic Electrofuel - Plant 1	Norway	Europe	4.4 mln liter	3,520	eKerosine	2025
e-fuel alliance	Norsk e-Fuel - Alpha	Norway	Europe	12.5 mln liter	10,000	e-fuels	2024
e-fuel alliance	ReuZe Project	France	Europe			e-fuels	2026
e-fuel alliance	Sunfire - Synhelion Solar Fuels	Germany	Europe	10000 liter	8	e-fuels	2023
e-fuel alliance	Sunfire - Synhelion Solar Fuels Spain	Spain	Europe	500000 liter	400	e-fuels	2025
e-fuel alliance	Arcadia eFuels - Project Endor	Denmark	Europe	100 mln liter	80,000	e-fuels	2027
e-fuel alliance	Arcadia eFuels - Project Naboo	United Kingdom	Europe	100 mln liter	80,000	e-fuels	2029
e-fuel alliance	Arcadia eFuels - Project Arc	United States	Rest of World	100 mln liter	80,000	e-fuels	2028
e-fuel alliance	CAC Synfuel Plant	Germany	Europe	1000000 liter	800	e-fuels	
e-fuel alliance	George Olah Renewable Methanol Plant	Iceland	Rest of World	4000 Mt	4,000	e-methanol	2012
e-fuel alliance	HIF Global - HIF Tasmania	Australia	Rest of World	20 million gal	60,566	e-fuels	2028
e-fuel alliance	Infinium Electrofuels - Corpus Facility	United States	Rest of World			e-fuels	2023
e-fuel alliance	NEOM Green Hydrogen Project	Saudi Arabia	Rest of World	1.2 mln tonnes	1,419,000	e-ammonia	2026
e-fuel alliance	Bell Bay Powerfuels Project	Australia	Rest of World	70000 tonnes	7,000	e-methanol	2024

* For calculation when multiple products will be produced, referred to as e-fuels the characteristics for e-diesel/e-kerosene are assumed

** Commercial Operation Date

Annex 2 – Table of interviewed industry stakeholders

#	Target group	Name	Organization	Business title	Date
1	Knowledge institute	Pehr Teulings	VOTOB, association of Dutch tankterminals	Manager public affairs	12-Jul-24
2	Knowledge institute	Pier Stapersma	Centre for International Energy Policy (CIEP)	Deputy Director (ad interim)	16-Jul-24
3	Producer	Sander Smit	Ørsted	Commercial Manager P2X	18-Jul-24
4	Producer	Sjors van Deijk	OCI Global	Sales Manager Fuels Europe	31-Jul-24
5	Producer	Kasper Spitzen	SkyNRG	Commercial Manager	5-Aug-24
6	Knowledge institute	Annalicia Poehler	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping	Fuel Manager	6-Aug-24
7	Producer	Hessel Jongbreur	Zero Emission Fuels	Co-Founder	19-Aug-24
8	Storage industry	Robert van der Hoek	LBC	Commercial manager	23-Aug-24
9	Storage industry	Marcel van de Kar	Royal Vopak	Sr. Vice President Hydrogen	26-Aug-24

Annex 3 – Conversion Marine e-fuel demand

Conversion and Rationale

WoodMackenzie 2050:

- Quantity: 1 mb/d (million barrels per day)
- Rationale: Ramp up is expected primarily in Europe, driven by the Emissions Trading Scheme and the introduction of the Fuel EU Maritime regulation. The share of e-fuels will grow after 2040 to around 1 mb/d in 2050.

Conversion:

- Assuming an average crude oil energy content of 5.8 MMBtu per barrel (a commonly used value).
- $1 \text{ mb/d} = (1,000,000 \text{ barrels/day}) * (5.8 \text{ MMBtu/barrel}) * (1.05505585 \text{ GJ/MMBtu}) * (1/39.6566683) \text{ Mtoe/GJ} * (365 \text{ days/year})$
- $1 \text{ mb/d} \approx 53.28 \text{ Mtoe}$

Transport & Environment 2050

- Quantity: 24.35 Mtoe
- Rationale: Green e-fuels offer the greatest potential for reducing emissions in the shipping industry and will remain compliant with regulations for the longest time. They can be produced at large scales, providing clean energy even for the largest ocean-going vessels. Although currently expensive, significant investment in their production is expected to lower costs over time.

Conversion:

- No conversion needed as it is already in Mtoe.
- $24.35 \text{ Mtoe} = 24.35 \text{ Mtoe}$

DNV 2050

- Quantity: 2,600 PJ (Petajoules)
- Rationale: During the 2030s, the adoption of e-fuels based on hydrogen will gradually increase, with significant uptake anticipated in the 2040s. European RED III will create a market ramp-up for e-fuels, make e-fuels to grow to ca. 19% of the shipping fuel mix.

Conversion:

- $2,600 \text{ PJ} * (1/39.6566683) \text{ Mtoe/PJ}$
- $2,600 \text{ PJ} \approx 65.57 \text{ Mtoe}$