Faculty of Business and Economics
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Ports at the crossroads of the energy transition: navigating shifts in energy flows

Scenarios and strategic implications

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Abstract

The global energy transition is one of the most significant challenges of the 21st century, driven by the urgent need to reduce greenhouse gas emissions and mitigate climate change. Despite growing policy support and the increasing adoption of renewable energy sources, the global energy system remains heavily reliant on fossil fuels, and long-term energy demand remains uncertain. This uncertainty supports a scenario-based analyses to explore potential pathways toward a decarbonized future. Ports play a critical role as nodes in global trade and energy flows in this transition, particularly for the import, export, storage, and handling of alternative energy carriers such as hydrogen and ammonia.

This dissertation investigates how European energy transition scenarios impact liquid bulk ports, particularly concerning storage investments and alignment with strategic objectives for a hydrogen-based economy. The central research question is formulated as follows: *How do European energy transition scenarios influence major liquid bulk ports with respect to storage investment and their strategic goals for a hydrogen-powered economy?* This dissertation assess the storage requirements, associated costs, and spatial demands for integrating these alternative energy carriers. Furthermore, it explores the extent to which the anticipated hydrogen imports align with the strategic objectives of port authorities, such as environmental stewardship, innovative leadership and regulatory compliance. By understanding this alignment, the research provides insights into how ports can adapt their development strategies to meet the increasing demand for green energy imports while also fulfilling their broader long-term goals. Through scenario-based analysis, this dissertation offers actionable recommendations for port authorities and policymakers to accelerate the transition toward a hydrogen-powered economy, supporting sustainable growth.

The systematic literature review revealed a growing interest only in the last researched decade in the intersection of low-carbon energy transition, sustainability and the liquid bulk sector, with an increase in publications since 2009. However, there is a gap in research in the combination of maritime liquid bulk transport and energy transition, although liquid bulk is responsible for 32% of global maritime trade, highlighting the need for further exploration of best practices from other sectors.

This study combines both quantitative and qualitative methods to address the main research question. The methodology consists of five key steps: establishing a theoretical framework, collecting and analyzing data from sources such as Eurostat, developing qualitative and quantitative sub-scenarios for future energy transitions and calculating port-specific outputs, including storage capacity, costs and space requirements. The final step evaluates how the adoption of a hydrogen scenario aligns with the strategic objectives of port authorities. Data is gathered through interviews and surveys with energy transition experts within port authorities, where respondents assess the importance of port objectives and the potential success of a hydrogen-powered hub scenario in achieving those goals. These evaluations are quantified using a scoring system, and the consensus across respondents is measured through the homogeneity index (H-index). This approach provides insights into whether the hydrogen transition supports port objectives.

The findings on energy transition scenarios indicate that the need for space and investments in storage facilities within European ports is influenced by energy demand, reductions in carbon energy imports and domestic non-carbon energy production. The three sub-scenarios analyzed (Accelerated non-carbon growth with fossil stability, Moderate non-carbon expansion with fossil stability and Full decarbonization pathway) show varying impacts, with some countries still relying on carbon energy imports, conflicting with EU regulations. The Full decarbonization scenario aligns most closely with EU regulations but introduces risks, especially concerning reliance on domestic production. Storage and cost requirements for hydrogen and ammonia varied across scenarios, with the Full decarbonization pathway demanding significant investment in storage (up to 68 hectares). A sensitivity analysis revealed that ammonia storage is more cost- and space-

efficient than hydrogen. Moreover, pipeline infrastructure played a crucial role in increasing import volumes and reducing costs, and proximity to exporting countries also influenced import volumes. The sensitivity analysis on extended storage times increased the costs of storaging. The last sensitivity analysis on lower maritime transport costs reduce per-unit shipping expenses, they lead to increased traffic, higher import volumes and more infrastructure demand.

Interviews and surveys showed that all port objectives were scored important. Furthermore, the interiews and surveys reveal a strong alignment between hydrogen adoption and key objectives such as environmental stewardship, economic competitiveness and safety & security. The results suggest that enhancing alignment between hydrogen adoption and port strategic goals will foster greater support for infrastructure investment and accelerate the energy transition.

Overall, the research underscores the vital role of ports in Europe's energy transition, highlighting the need for proactive investments in infrastructure, regulatory alignment and international collaboration to meet future energy demands. This dissertation offers recommendations to guide port authorities, policymakers, and stakeholders in aligning infrastructure invest-ments with sustainability goals, ensuring economic competitiveness and enhancing energy security. By focusing on specialized storage, hinterland connectivity and operational strategies, ports can effectively transition to non-carbon energy systems. However, the study also highlights several challenges, such as the need for unified regulatory frameworks and investments in infrastructure, especially in ports specialized in petrochemical trade such as Antwerp-Bruges and Rotterdam.

While this study provides comprehensive insights into port infrastructure and non-carbon energy, certain aspects, such as the geopolitical impacts on energy flows were not fully explored. Future research should focus on these areas, as well as the environmental implications of ammonia transportation, the scalability of renewable energy carriers and the integration of new technologies. Further investigations into pipeline transportation costs and public acceptance of ammonia in urban areas will also be essential for advancing the energy transition in ports.

Nederlandstalig abstract

Havens in de energietransitie: de koers bepalen bij verschuivende energiestromen

Scenario’s en strategische inzichten

Thesis ingediend ter verkrijging van de graad doctor in de toegepaste economische wetenschappen

De wereldwijde energietransitie is een van de grootste uitdagingen van de 21e eeuw, gedreven door de dringende noodzaak om de uitstoot van broeikasgassen te verminderen en de klimaatverandering te beperken. Ondanks toenemende beleidssteun en een groeiend gebruik van hernieuwbare energiebronnen, blijft het wereldwijde energiesysteem sterk afhankelijk van fossiele brandstoffen en is de langetermijnvraag naar energie onzeker, onder meer door variabele economische groei, technologische ontwikkelingen, geopolitieke spanningen en beleidswijzigingen die het tempo en de richting van de energietransitie beïnvloeden. Deze onzekerheid rechtvaardigt een scenariogebaseerde analyse om mogelijke paden richting een koolstofvrije toekomst te verkennen. Havens spelen een cruciale rol als knooppunten in wereldwijde handel en energiestromen in deze transitie, met name voor de invoer, uitvoer, opslag en verwerking van alternatieve energiedragers zoals waterstof en ammoniak.

Dit proefschrift onderzoekt hoe Europese energietransitiescenario’s een invloed hebben op vloeibare massagoedhavens, in het bijzonder met betrekking tot opslaginvesteringen en de afstemming op strategische doelstellingen voor een waterstofgedreven economie. De centrale onderzoeksvraag luidt: *Hoe beïnvloeden Europese energietransitiescenario’s grote vloeibare massagoedhavens op het vlak van opslaginvesteringen en hun strategische doelen voor een waterstofeconomie?* Het onderzoek beoogt de opslagvereisten, bijhorende kosten en ruimtelijke noden in kaart te brengen voor de integratie van deze energiedragers in havenoperaties. Daarnaast wordt onderzocht in hoeverre de verwachte waterstofimporten aansluiten bij strategische doelstellingen van havenautoriteiten, zoals duurzaamheid, concurrentiekracht en toekomstbestendige infrastructuur.

Via scenariogebaseerde analyse biedt dit proefschrift concrete aanbevelingen aan havenautoriteiten en beleidsmakers om de overgang naar een waterstofgedreven economie te faciliteren, duurzame groei te ondersteunen en bij te dragen aan de bredere Europese energietransitie.

De systematische literatuurstudie toont een groeiende interesse op het vlak van de koolstofarme energietransitie, duurzaamheid en de vloeibare massagoedsector, met een opvallende toename in publicaties sinds 2009. Toch blijft onderzoek naar vloeibaar massagoed maar goed voor 32% van het wereldwijde maritieme vrachtvolume, wat de noodzaak onderstreept om best practices uit andere sectoren te bestuderen.

Het onderzoek combineert kwantitatieve en kwalitatieve methoden om de centrale onderzoeksvraag te beantwoorden. De methodologie omvat vijf stappen: het opstellen van een theoretisch kader, het verzamelen en analyseren van data (o.a. via Eurostat), het ontwikkelen van kwalitatieve en kwantitatieve subscenario’s voor de energietransitie, en het berekenen van haven-specifieke outputs, waaronder opslagcapaciteit, kosten en ruimtebehoeften. In de laatste stap wordt geëvalueerd in hoeverre het waterstofscenario aansluit bij de strategische doelstellingen van havenautoriteiten. Data werd verzameld via enquêtes met energietransitie-experten binnen havenautoriteiten, waarbij respondenten het belang van havenobjectieven en de verwachte slaagkansen van een waterstofscenario beoordeelden. Deze beoordelingen werden gekwantificeerd via een scoresysteem en de mate van consensus tussen respondenten werd gemeten met de homogeniteitsindex (H-index). Deze aanpak biedt inzichten in de mate waarin de

waterstoftransitie havenobjectieven ondersteunt, en biedt een gestructureerd kader om de haalbaarheid en afstemming van waterstofimplementatie te evalueren.

De resultaten van de scenarioanalyse tonen aan dat de nood aan ruimte en investeringen in opslagfaciliteiten binnen Europese havens sterk afhankelijk is van de energievraag, de afname van koolstofimporten, en de binnenlandse productie van koolstofvrije energie. De drie geanalyseerde subscenario's (Accelerated non-carbon growth with fossil stability, Moderate non-carbon expansion with fossil stability and Full decarbonization pathway) tonen uiteenlopende effecten. Sommige landen blijven afhankelijk van fossiele energie, wat botst met EU-regelgeving. Het volledig decarbonisatiepad sluit het best aan bij Europese regelgeving, maar houdt risico's in door een sterke afhankelijkheid van binnenlandse productie. Opslag- en kostvereisten voor waterstof en ammoniak variëren tussen scenario's, waarbij het decarbonisatiescenario aanzienlijke investeringen vraagt (tot 68 hectare opslagruimte). Een gevoeligheidsanalyse toont aan dat ammoniak efficiënter is qua kost en ruimte dan waterstof. Bovendien speelt pijpleidinginfrastructuur een belangrijke rol in het verhogen van importvolumes en het verlagen van kosten, en beïnvloedt nabijheid tot exportlanden eveneens de importvolumes. De gevoeligheidsanalyse rond langere opslagduur leidde tot hogere opslagkosten. De laatste gevoeligheidsanalyse, over lagere maritieme transportkosten, toonde aan dat hoewel de kosten per eenheid dalen, dit leidt tot meer scheepvaartverkeer, hogere importvolumes en een grotere vraag naar infrastructuur.

Uit interviews en enquêtes met experts in energietransitie van havenautoriteiten blijkt een sterke afstemming tussen de adoptie van waterstof en kernobjectieven zoals milieubeheer, economische competitiviteit en veiligheid. De resultaten suggereren dat een betere afstemming tussen waterstofadoptie en strategische doelstellingen van havens kan leiden tot meer steun voor infrastructuurinvesteringen en een versnelling van de energietransitie.

Samengevat benadrukt dit onderzoek de essentiële rol van havens in de Europese energietransitie, en wijst het op de noodzaak van proactieve investeringen in infrastructuur, regelgeving en internationale samenwerking om toekomstige energievraag te kunnen opvangen. Dit proefschrift biedt aanbevelingen voor havenautoriteiten, beleidsmakers en andere stakeholders om infrastructuurinvesteringen beter af te stemmen op duurzaamheidsdoelen, economische concurrentiekracht te behouden en de energiezekerheid te versterken. Door in te zetten op gespecialiseerde opslag, transportnetwerken en operationele strategieën kunnen havens effectief de overgang maken naar koolstofvrije energiesystemen. Tegelijkertijd worden uitdagingen belicht, zoals het gebrek aan uniforme regelgeving en de nood aan investeringen, vooral in havens met een focus op petrochemie (vb. raffinaderijen voor aardolie) zoals in de haven van Antwerpen-Brugge en Rotterdam.

Hoewel dit onderzoek diepgaande inzichten biedt in haveninfrastructuur en koolstofvrije energie, werden bepaalde aspecten, zoals geopolitieke invloeden op energiestromen, niet volledig onderzocht. Toekomstig onderzoek zou zich kunnen richten op deze thema's, evenals op de milieueffecten van ammoniaktransport, de opschaalbaarheid van hernieuwbare energiedragers, en de integratie van nieuwe technologieën. Verder onderzoek naar kosten van pijpleidingtransport en maatschappelijke aanvaarding van ammoniak in stedelijke gebieden zal eveneens cruciaal zijn om de energietransitie in havens te bevorderen.

Contents

ACKNOWLEDGEMENTS V

ABSTRACT IX

NEDERLANDSTALIG ABSTRACT XI

CONTENTS XIII

LISTING OF FIGURES XV

LISTING OF TABLES XVI

LISTING OF ACRONYMS XVII

CHAPTER 1 INTRODUCTION 1

1.1. Background ... 1
1.2. Geopolitical Landscape ... 12
1.3. Regulatory Framework ... 14
1.4. Research questions ... 15
1.5. Added value and contribution of the thesis ... 16
1.6. Thesis outline ... 17

CHAPTER 2 ENERGY TRANSITION IMPACT ON LIQUID BULK MARKET AND PORTS: A SYSTEMATIC LITERATURE REVIEW 21

2.1. Systematic literature review ... 22
2.2. Positioning in the academic literature ... 28
2.3. Conclusion ... 29

CHAPTER 3 METHODOLOGY 31

3.1. Towards energy transition scenarios for ports ... 32
3.2. Data information ... 33
3.3. Country level ... 35
3.4. Port level ... 36
3.5. Alignment port objectives ... 44
3.6. Conclusion ... 45

CHAPTER 4 TOWARDS ENERGY TRANSITION SCENARIOS FOR LIQUID PORT FLOWS 47

4.1. Theoretical framework for transition scenarios ... 48
4.2. Global energy market outlook ... 51
4.3. Energy scenario outlook for Europe ... 59
4.4. Energy transition descriptive scenarios for ports ... 70
4.5. The challenges and opportunities of the different scenarios ... 72
4.6. Scenario selection ... 74
4.7. Conclusion ... 74

CHAPTER 5 EXPLORING HUB ALLOCATION FOR ENERGY FLOWS: A STRATEGIC ANALYSIS 77

5.1. Assumptions for energy sub-scenarios ... 77
5.2. Energy sub-scenarios of the Hydrogen-powered hub scenario ... 80
5.3. Evaluating the sub-scenarios in the current policy and technological context ... 87
5.4. Conclusion ... 87

CHAPTER 6 COST AND SURFACE ANALYSIS FOR FUTURE PORTS IN THE CONTEXT OF THE ENERGY TRANSITION: A SCENARIO-BASED APPROACH 89

6.1. Supplier country analysis for hydrogen and ammonia ... 89
6.2. Storage possibilities for hydrogen and ammonia ... 93
6.3. Sub-scenarios quantification ... 94
6.4. Sensitivity analysis ... 104
6.5. Conclusions ... 114

CHAPTER 7 ASSESSING HYDROGEN ENERGY PROJECTS IN RELATION TO THE OBJECTIVES OF PORT AUTHORITIES OF MAJOR EUROPEAN CARBON ENERGY IMPORTING COUNTRIES 117

7.1. Port authority roles and objectives in energy matters 118
7.2. Hydrogen-powered hub scenario 121
7.3. Methodology 122
7.4. Data collection 124
7.5. Results 124
7.6. Conclusion 128

CHAPTER 8 CONCLUSIONS 131

8.1. Findings 131
8.2. Recommendations 139
8.3. Future research directions and limitations 141

REFERENCES 145

APPENDIX A – ENERGY TRANSITION TIMELINE 159

APPENDIX B – DATA COLLECTED 160

APPENDIX C – FILL IN FORM 162

APPENDIX D – H-INDEX 165

APPENDIX E – WILCOXON RANK TEST 166

APPENDIX F – WILCOXON RANK TEST (N&S) 167

Listing of Figures

Figure 1.1: Liquid bulk supply chain ... 3
Figure 1.2: Liquid bulk maritime ecosystem ... 5
Figure 1.3: Evolution of global seaborne trade, mt ... 7
Figure 1.4: World Seaborne trade liquid bulk ... 8
Figure 1.5: Fleet development crude oil, chemical, combo, LNG & LPG tankers ... 9
Figure 1.6: Thesis outline ... 17
Figure 2.1: Systematic literature scheme ... 23
Figure 2.2: Analysis of published papers on researched keywords ... 24
Figure 2.3: Filtered papers, counted per decade ... 25
Figure 2.4: Relevant papers sorted by theme and period ... 26
Figure 2.5: Analysis of relevant topics ... 27
Figure 3.1: Research method ... 31
Figure 3.2: Reporting countries ... 34
Figure 3.3: The total energy calculation ... 35
Figure 3.4: Currently considered H_2 pipeline network - ... 38
Figure 4.1: A conceptual framework of transition systems ... 48
Figure 4.2: Driving forces of global energy scenarios ... 50
Figure 4.3: World primary energy supply by source ... 51
Figure 4.4: World final energy demand by carrier ... 52
Figure 4.5: Electricity generation (TWh) from different sources and share of renewable power in total generation (%) ... 54
Figure 4.6: World seaborne oil trade ... 55
Figure 4.7: Gross electricity generation EU27 + UK, Norway and Switserland ... 60
Figure 4.8: Net generation by plant type in EU28 in the EUCO30 scenario ... 61
Figure 4.9: Countries carbon-based energy overview (2022) ... 63
Figure 4.10: Countries importing carbon-based energy (relative share) ... 64
Figure 4.11: Countries exporting carbon-based energy (relative share) ... 65
Figure 4.12: Calculation of total energy supply ... 66
Figure 5.1: total world energy supply Net Zero Emmission Scenario ... 78
Figure 5.2: The percentage change relative to the reference year 2022 ... 79
Figure 5.3: World energy demand total and per sector ... 80
Figure 5.4: Total energy consumption (EJ) ... 80
Figure 5.5: Net import of non-carbon energy SS1 ... 82
Figure 5.6: Net import of non-carbon energy SS2 ... 83
Figure 5.7: Non-carbon energy import by 2030, 2040 and 2050 SS2 ... 84
Figure 5.8: Net import of non-carbon energy SS3 ... 85
Figure 5.9: Non-carbon energy import by 2030, 2040 and 2050 SS3 ... 86
Figure 6.1: Hydrogen storage technologies ... 93
Figure 6.2: % average share of H2 import in each sub-scenario per port ... 95
Figure 6.3: Complete pipeline infrastructure versus considered pipeline network SS3 ... 106
Figure 6.4: South Africa/Namibia non-carbon import ... 107
Figure 6.5: Morocco non-carbon import ... 108
Figure 6.6: Brazil non-carbon import ... 109
Figure 6.7: Egypt non-carbon import ... 110
Figure 6.8: Comparison H2 output through PoR from different exporting countries (tonnes) ... 111
Figure 7.1: Sub-research questions and goals ... 118
Figure 7.2: Methodology approach H-index ... 122
Figure 7.3: Map of interviewed ports ... 124

Listing of Tables

Table 3.1: Transport cost over sea for LH_2 and NH_3 40
Table 3.2: Hinterland transport cost LH_2 and NH_3.................... 40
Table 3.3: Energy density value of ammonia.................... 43
Table 4.1: Top 10 global energy-supplying countries.................... 56
Table 4.2: Importing amount of liquid bulk in top 20 ports in handling cargo volumes (thousand tonnes) 68
Table 5.1: Parameters Sub-scenario 1.................... 81
Table 5.2: Parameters Sub-scenario 2.................... 83
Table 5.3: Parameters Sub-scenario 3.................... 84
Table 6.1: Overview of potential green hydrogen supplier countries for Europe 90
Table 6.2: Volumes of hydrogen and ammonia (tonnes) port of Rotterdam: 2030, 2040 & 2050.................... 97
Table 6.3: Output parameters sub-scenarios for port of Rotterdam 98
Table 6.4: Volumes (tonnes) of hydrogen and ammonia port of Antwerp-Bruges: 2030, 2040 & 2050.................... 99
Table 6.5: Output parameters sub-scenarios for port of Antwerp-Bruges.................... 100
Table 6.6: Volumes (tonnes) of hydrogen and ammonia port of Amsterdam: 2030, 2040 & 2050 102
Table 6.7: Output parameters sub-scenarios for port of Amsterdam.................... 103
Table 6.8: Port outputs non-carbon imports SS3: ammonia.................... 105
Table 6.9: 6 weeks storage volumes and costs.................... 112
Table 6.10: Transport cost predictions 2050.................... 113
Table 6.11: PoR decreased maritime costs.................... 114
Table 7.1: Basic port management models 119
Table 7.2: Port objectives final 121
Table 7.3: Objectives relevance scoring 125
Table 7.4: Objectives success scoring.................... 125
Table 7.5: Comparison table 127

Listing of Acronyms

ACER	Agency for the Cooperation of Energy Regulators
ACES	Advanced Clean Energy Storage
ASEAN	Association of Southeast Asian Nations
BP	British Petroleum
BNEF	Bloomberg New Energy Finance
CCS	Carbon Capture and Storage
CH_2	Compressed Hydrogen
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
COP26	26th UN Climate Change Conference of the Parties
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
EJ	Exajoule
EU	European Union
EUCO30	European Union Climate Objective 2030
EED	Energy Efficiency Directive
EIA	Environmental Impact Assessment
EC	European Commission
FCW	Fuel Cell Works
GDP	Gross Domestic Product
GIS	Geographic Information System
GHG	Greenhouse Gas
GM	Geometric Mean
GWh	Gigawatt-hour
GW	Gigawatt
HA	Hectares
H_2	Hydrogen
H-index	Homogeneity Index
HAROPA	Port of Le Havre, Rouen, and Paris
IEA	International Energy Agency
IEP	International Energy Program
IAPH	International Association of Ports and Harbors
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency

LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LH_2	Liquid Hydrogen
MTPA	Million Tonnes Per Annum
MW	Megawatt
NH_3	Ammonia
NUTS	Nomenclature of Units for Territorial Statistics
NUTS2	Nomenclature of Units for Territorial Statistics, Level 2
OPEC	Organization of the Petroleum Exporting Countries
OPEC+	Extended Organization of the Petroleum Exporting Countries
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaic
PoA	Port of Amsterdam
PoAB	Port of Antwerp-Bruges
PoR	Port of Rotterdam
RES	Renewable Energy Sources
RED II	Renewable Energy Directive II
S&P	Standard & Poor's
SS1	Sub-scenario 1
SS2	Sub-scenario 2
SS3	Sub-scenario 3
SLR	Systematic Literature Review
STEPS	Stated Policies Scenario
TPA	Tonnes per Annum
TWh	Terawatt Hour
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
US	United States
WTO	World Trade Organization
WWF	World Wildlife Fund

Chapter 1

Introduction

1.1.Background

The global energy transition is one of the most significant challenges of the 21st century, requiring coordinated efforts from governments, industries, companies and society to reduce greenhouse gas emissions and mitigate global warming. The urgency of this transition is underscored by the continuation of record-breaking temperatures in the past decades, highlighting the pace of climate change (Copernicus, 2024; European Commission, 2023e). At the same time, future energy demand remains uncertain, as economic and population growth can increase energy needs, while efficiency improvements and policy measures may lead to reductions (Bhattarai et al., 2022; Ishaq et al., 2022). The International Energy Agency (IEA) (2024d) projected three energy demand scenarios in which the demand remains the same or declines by 7% or 15%. These variations illustrate the difficulty of long-term energy forecasting and highlight the importance of scenario-based analysis to account for uncertainties.

While a decline in energy demand could support emissions reductions, this is not guaranteed. The global energy mix still relies heavily on fossil fuels, and without strong policy interventions, greenhouse gas emissions could remain high or even increase. The largest sources of emissions are the power industry, industrial combustion and processes, transport, fuel exploitation and waste (European Commission, 2023c). The increasing greenhouse gas emissions (GHG) emitted using carbon energy cause environmental problems and cause global temperature to rise. This underscores the importance of climate policies in steering the transition away from fossil fuels and ensuring emissions reductions align with global climate targets. Climate change drives the global transition from conventional to renewable energy resources (Ishaq et al., 2022). In Europe, this shift is urgent, as the continent has warmed at twice the global average since the 1980s, leading to profound socio-economic effects on the region's ecosystems (European Commission, 2023e).

As hubs of international trade, ports have centralized positions in this energy transition. Ports are crucial in importing, storing, distributing and processing renewable energy flows such as hydrogen. Bulk-traded commodities are the dominant goods shipped by sea in terms of volume (Shipping Intelligence Network, 2024). Crude oil, oil products, coal, chemical and gas trade account for 43,3% of seaborne trade volume in 2023 (Clarkson Research, 2024). The share of crude oil in total trade has decreased from 28.5% in 1990 to 16.1% in 2024 (Clarkson Research, 2024). This decline reflects a combination of factors, including the increasing adoption of alternative energy sources, improvements in energy efficiency and evolving industrial demand patterns (Clarkson Research, 2024). The shift to alternative energy sources presents strategic challenges for ports, including infrastructure constraints, space limitations and market uncertainties. These challenges call for careful planning to address future demand for renewable energy imports while aligning with technological, economic and political developments.

The energy transition is a transformative process reshaping global energy systems. This introduction chapter focuses on understanding the urge of the energy transition and the scope of this dissertation. Liquid bulk, including fuels and chemicals, plays a critical role in the current and future energy supply chain. The shift to renewable energy sources demands changes in infrastructure, regulatory frameworks and stakeholder collaboration. This chapter explores the energy transition context, delving into its definitions, the role of liquid bulk and the broader supply chain challenges shaping this transition.

1.1.1. Defining and contextualizing the term “Energy transition”

The energy transition refers to the structural shift from fossil-based energy systems to renewable sources, involving transformations in production, consumption and governance systems. The research of Zolfagharian et al. (2019) defines a transition as follows: “*A transition involves far-reaching structural changes in socio-technical systems that enable particular desirable societal functions”*. In the energy context, this shift offers opportunities for economic growth, enhancing energy security and environmental benefits. However, it also faces barriers such as technological feasibility and regulatory challenges.

Building on the study of Zolfagharian et al., the field of transition studies has experienced rapid growth over the last decade. Earlier research in transition research has focused on studying the characteristics of historical transitions and utilizing the insights gained to develop governance frameworks that support and steer ongoing transition processes in areas such as energy, food and health. (Zolfagharian et al., 2019)

Jaccard (2020) offers a concise definition of energy transition, describing it as “*A major structural change to energy supply and consumption in an energy system.”* By 2024, the global push toward sustainable energy is accelerating to address climate change, with renewable energy at its core. For this reason, the energy transition is often synonymous with the renewable energy transition.

Overarching institutions, such as S&P Global (2020), provide a more comprehensive perspective, defining the energy transition as: "*The global energy sector's shift from fossil-based systems of energy production and consumption – including oil, natural gas and coal – to renewable energy sources like wind and solar, as well as lithium-ion batteries"*. Furthermore, they also define key drivers of the energy transition: the increasing penetration of renewable energy into the energy supply mix, the onset of electrification and improvements in energy storage (S&P Global, 2020).

To conclude, the energy transition is a significant process that involves major changes with the shift to renewable energy as its focus. The energy transition influences global trade systems. As renewable energy gains prominence, its implications for the maritime transport of liquid bulk products become increasingly critical. The next section explores the role of liquid bulk in the energy transition and how this segment must adapt to meet decarbonization goals.

1.1.2. The role of liquid bulk in maritime transport

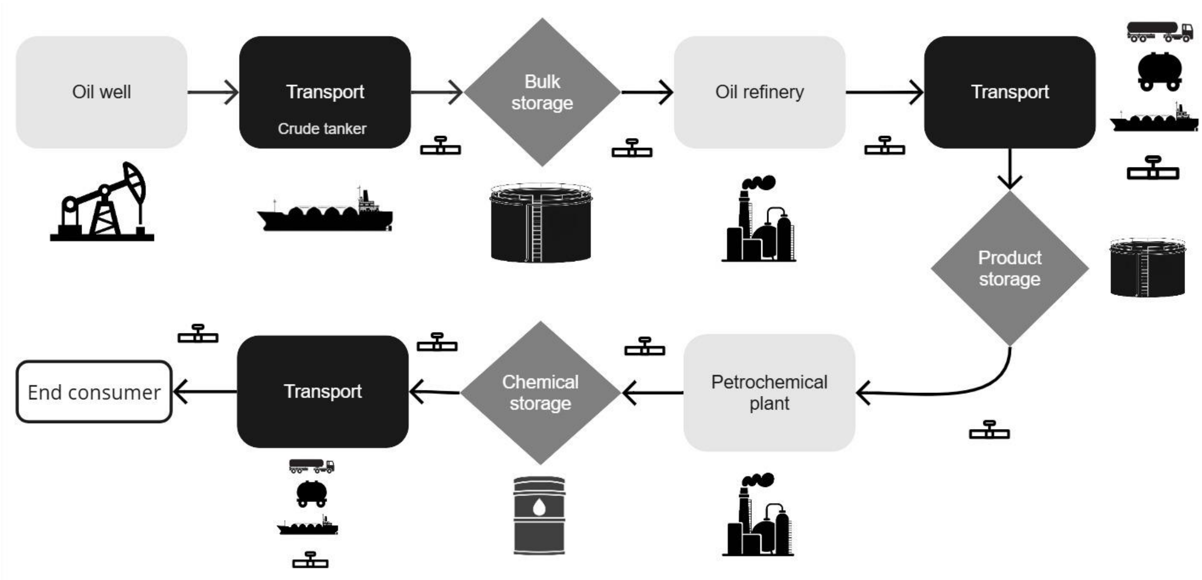
Liquid bulk products, such as fuels, feedstocks for the chemical industry and liquefied gases such as LNG are critical to the global energy supply chain. These commodities account for 30 to 35% of global trade (Clarkson Research, 2024; UNCTAD, 2024). This section examines the supply chain dynamics of liquid bulk and the critical adaptations required to align with a decarbonized future. In particular, ports must adjust their infrastructure and supply chains to facilitate the transition toward alternative fuels such as hydrogen and ammonia. Liquid bulk includes all products transported in tankers and can be divided into two main types: liquid and gas (Stopford, 2009). The definition of liquid bulk of Stopford is: *"The liquid cargoes shipped by sea fall into three main groups: crude oil and products; liquefied gas, principally LNG and LPG; vegetable oil and liquid chemicals such as ammonia, phosphoric acid, etc."* (Stopford, 2009). This dissertation focuses specifically on energy-related liquid bulk flows in ports, and therefore does not consider food-based liquids that are not used for energy purposes. While some vegetable oils can be used as feedstocks for biofuels, food-based liquids as such fall outside the scope of this research, as their use as energy carriers remains limited to small-scale applications. The reasoning behind the exclusion of vegetable oils and similar products is further detailed later in this section. Fossil fuels dominate the liquid bulk segment and contribute to global CO_2 emissions, highlighting the urgency of transitioning to renewable alternatives.

Ports play a crucial role in facilitating this transition, as they must adapt their infrastructure, storage capacity and distribution networks to accommodate new energy carriers. As a result, ports are increasingly investing in alternative energy carriers and exploring the repurposing of existing fossil fuel infrastructure (Manav, 2024).

The definition of liquid bulk of Stopford focuses on crude oil, fuels and liquid chemical products. The definition immediately states the importance of fuels in the liquid bulk segment. The definition of Stopford will probably be extended in the future and focus more on renewable fuels due to their importance in the liquid bulk segment. This shift is reflected in broader industry trends, as highlighted by the DNV Energy outlook report (DNV, 2020, 2022). A comparison of the 2020 and 2022 editions of the DNV reports reveals that they expect a transition from fossil to renewable energy sources, but dates of implementation are already shifted backward if the two versions are compared (Appendix A).

The supply chain of liquid bulk products varies due to the specific characteristics of each product (Dohmen, 2016). The choice of transport mode is more extensive in a liquid bulk supply chain than other segments such as container transport, distinguishing among different supply chains (pipeline, rail, barges, trucks, and deepsea vessels). The mode choice depends on several factors, such as the product type, the distances, costs, time, reliability and the availability of infrastructure. Additionally, the transportation of hazardous goods requires specialized infrastructure and safety protocols, which adds complexity to these supply chains. Figure 1.1 presents an example of a liquid bulk supply chain of crude oil, emphasizing the pivotal role of ports in handling, storage, processing and distribution. Most oil refineries and storage facilities, as shown in the figure below, are located in the port to facilitate efficient distribution of liquid bulk. As the transition to alternative fuels progresses, ports will need to expand their role as energy hubs, integrating new storage technologies and optimizing supply chains for renewable energy carriers.

Figure 1.1: Liquid bulk supply chain



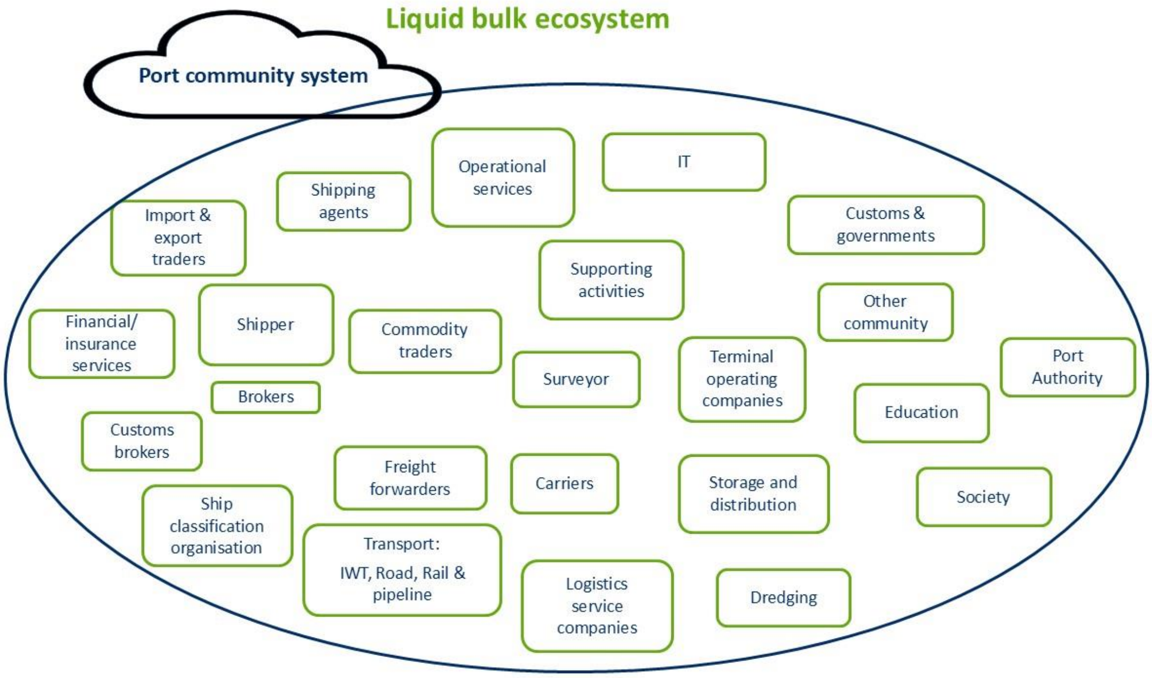
Source: Own composition based on Dohmen (2016)

The flowchart above illustrates an example of a supply chain of crude oil, one of the most commonly transported liquid bulk commodities which can utilize a variety of transport modes, such as pipelines, barges, vessels, trucks and trains (Dohmen, 2016). These modes are well-established and operate relatively easily due to the clear procedures, safety protocols and infrastructure already in place. The product can flow through the supply chain with minimal disruption from extraction at production sites to transportation to refineries, storage facilities, and eventually to consumers. The distances between oil sources, refineries, production plants, and consumers are often vast, but the logistics are well-defined compared to other good segments. It should be noted that the illustrated supply chain is a simplified version focusing on energy-related flows. In reality, there is a much broader value chain, particularly after chemical storage, which includes the production of intermediate products such as plastics and chemicals. After the end consumer stage, recycling processes (e.g., pyrolysis) can return liquid raw materials to the supply chain, contributing to circularity. However, for the purpose of this dissertation, the focus remains on the energy-related flows of liquid bulk products. (Dohmen, 2016)

However, the transition to alternative energy sources introduces significant complexity to the supply chain. Unlike crude oil, alternative fuels such as ammonia or hydrogen are much more challenging to transport, particularly because ammonia is a hazardous substance requiring specialized safety protocols (Galimova et al., 2023; Giddey et al., 2017). The transportation of dangerous goods introduces additional risks and constraints, such as the need for more robust safety measures and specialized infrastructure for storage and handling. Ammonia, for example, cannot simply be transported via the same pipelines or vessels used for crude oil. The shift to these alternative energy sources demands significant investments in infrastructure and greater collaboration among stakeholders to ensure safety and efficiency. A key distinction lies in the logistical flexibility of alternative energy sources compared to crude oil. Crude oil typically requires large, specialized terminals at deep-sea ports, whereas alternative fuels like ammonia and hydrogen can more readily access inland or smaller ports. This enhanced accessibility could facilitate more localized and diversified supply chain models, reducing bottlenecks at major oil hubs. (Galimova et al., 2023; Giddey et al., 2017)

Additionally, the supply chain for renewable energy sources such as hydrogen or ammonia will require increased storage capacities at both production sites and ports. Non carbon energy is often more challenging to store and handle compared to crude oil (Avery, 1988; Clean Hydrogen Partnership & Deloitte., 2023). This increased demand for non-carbon energy storage is linked to both volume and the need for specific handling processes due to the characteristics of each energy type. Given the complexity of integrating these renewable energy sources, it is essential to assess the key stakeholders involved in the liquid bulk supply chain and determine where ports play a pivotal role in facilitating storage, transport and distribution. These actors are essential in facilitating liquid bulk's safe and efficient movement and ensuring that the energy transition proceeds smoothly. Figure 1.2 based on Sys & Vanelslander (2020) shows the main stakeholders in the maritime liquid bulk supply chain. Stakeholders are connected and need to work together towards a sustainable future.

Figure 1.2: Liquid bulk maritime ecosystem



Source: own composition based on Sys & Vanelslander (2020)

The ecosystem covers maritime companies, financial players, operational players, safety players, etc. A liquid bulk product in a supply chain differs from other segments such as containers. Every link between the actors is crucial for a smooth flow of the liquid bulk product. The complexity of this supply chain is largely due to the physical and chemical properties of liquid bulk, requiring specialized handling, storage and transportation infrastructure. Shippers (e.g. TotalEnergies, BASF, Shell) ask shipping companies (Euronav, Exmar, Teekay Tankers etc.) to ship their products through the supply chain. The network of stakeholders involved is extensive and while the most prominent actors are highlighted in this figure, the list is not exhaustive.

An example of an essential role in the ecosystem is the surveyor's role, crucial in the liquid bulk supply chain to do the safety controls (e.g. Intertek, Sparks Surveyors, Cargo Inspection, Freight Limited etc.). Compared to other segments, such as containers, the liquid bulk segment stores many products on the terminal in storage companies such as VOPAK, ICT Rubis, ADPO, etc. Nevertheless, some roles are smaller than those in other segments, such as the role of freight forwarders. This is primarily because many liquid bulk shippers, such as major oil and chemical companies, prefer to manage their own logistics and transportation arrangements. These companies often have dedicated logistics teams or long-term partnerships with shipping companies, reducing the need for intermediaries. IT companies gain importance with automating processes and innovating processes. In addition to surveyors and storage companies, commodity traders also play a significant role in the liquid bulk supply chain. These traders, such as Vitol, Glencore and Trafigura, are players in the buying, selling and transportation of liquid bulk, including oil, chemicals, and increasingly, green energy products such as hydrogen and ammonia. They act as intermediaries between producers and consumers, managing supply and demand fluctuations. They often take on the financial and logistical risks associated with the transport and storage of these commodities.

Pipelines are vital in the hinterland since this is the most sustainable way to transport liquid bulk into the hinterland. Pipelines have the advantage of being efficient and eco-friendly. While pipelines are most often associated with the transport of large quantities of the same type of liquid bulk due to economies of scale, they can also transport different products by using various separation techniques, such as pigging, which allows for the efficient transport of different liquids in the same pipeline. However, the downside of pipelines is that they may not be a viable option for smaller players in the liquid bulk market, unless freight is consolidated (Chand, 2013). The pipeline network must be extended to enable more players to have access to pipelines for renewable energy (Chand, 2013). The future energy landscape will require ports to invest in hydrogen-ready pipeline infrastructure and ammonia-compatible transport networks to maintain their competitive position.

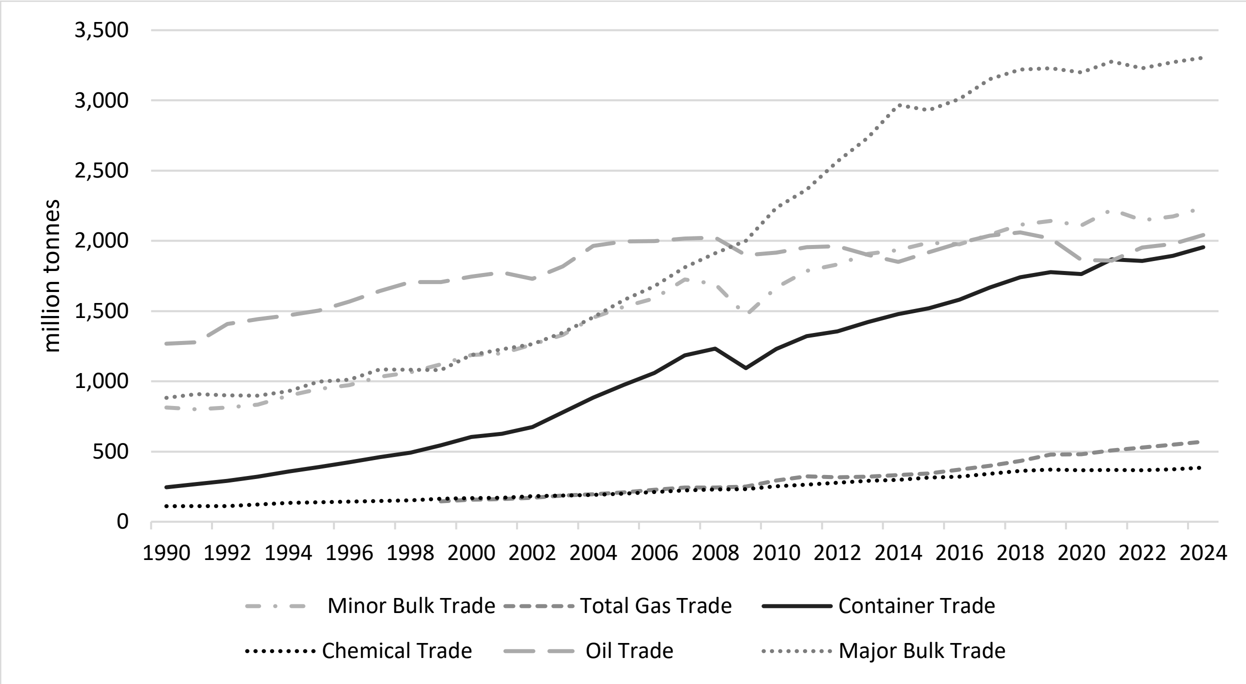
All these actors are somehow connected to each other. Still, companies are not too eager to share information on platforms with other actors. By not sharing information between these actors, efficiency is lost. Research by Port Plus, a company that creates digital platforms and solutions to optimize port calls, shows that 50% of the time spent at a berth is inefficient and could be improved by such data-sharing platform (N. Maes, personal communication, April 20, 2022). A slight change in the energy transition in ports can affect the entire supply chain, making the collaboration of all stakeholders crucial. This explains the importance of all stakeholders and their collaboration within the energy transition in ports. To understand the feasibility and impact of such infrastructure investments, it is crucial to analyze the global trade flows of energy carriers through ports, as these serve as key nodes in the supply chain, connecting production sites, storage facilities, and hinterland distribution networks. Examining the dynamics of global trade (via maritime shipping) illustrates how liquid bulk positions itself relative to other segments, such as containers, chemical oil and gas trade. Understanding these shifts is essential for determining how ports can effectively adjust to these changes and maintain their role in the global economy.

The dynamics of trade flows, particularly in the liquid bulk market, reveal a volatile and unpredictable landscape. This volatility is especially pronounced in the crude oil segment, where tankers often serve as floating storage during periods of low market activity. The dependence of certain nations, particularly those in the Organization of the Petroleum Exporting Countries (OPEC), on the crude oil trade illustrates the complexity of this market. OPEC, which holds 80% of the world's oil reserves, was established in 1960 to influence global oil prices by regulating crude oil supply. Currently, OPEC accounts for around 40% of global crude oil production, while its members contribute approximately 60% of the worldwide petroleum trade (Ellerbeck, 2022).

Further complicating the landscape is oil's sensitivity to geopolitical tensions, such as the ongoing conflict between Russia and Ukraine. As part of the extended OPEC+ group, Russia plays a key role in global production adjustments. For example, OPEC+ decided in April 2020 to cut output by 2 million barrels per day, a move criticized by the United States for potentially bolstering Russian oil revenues (Ellerbeck, 2022). This decision, stemming from OPEC+'s 2016 response to declining crude prices, highlights the sensitivity of the liquid bulk market to political and economic shifts (Ellerbeck, 2022). These factors demonstrate how supply and demand disruptions in the tanker market can impact related areas like time charter rates, fuel costs, voyage rates, export volumes and overall profitability (Kilian et al., 2020).

Examining the seaborne trade flows is important to better understand the liquid bulk market. Figure 1.3 presents the division of the major segments in the seaborne trade from 1990-2024.

Figure 1.3: Evolution of global seaborne trade, mt



Source: Clarkson Research (2024)

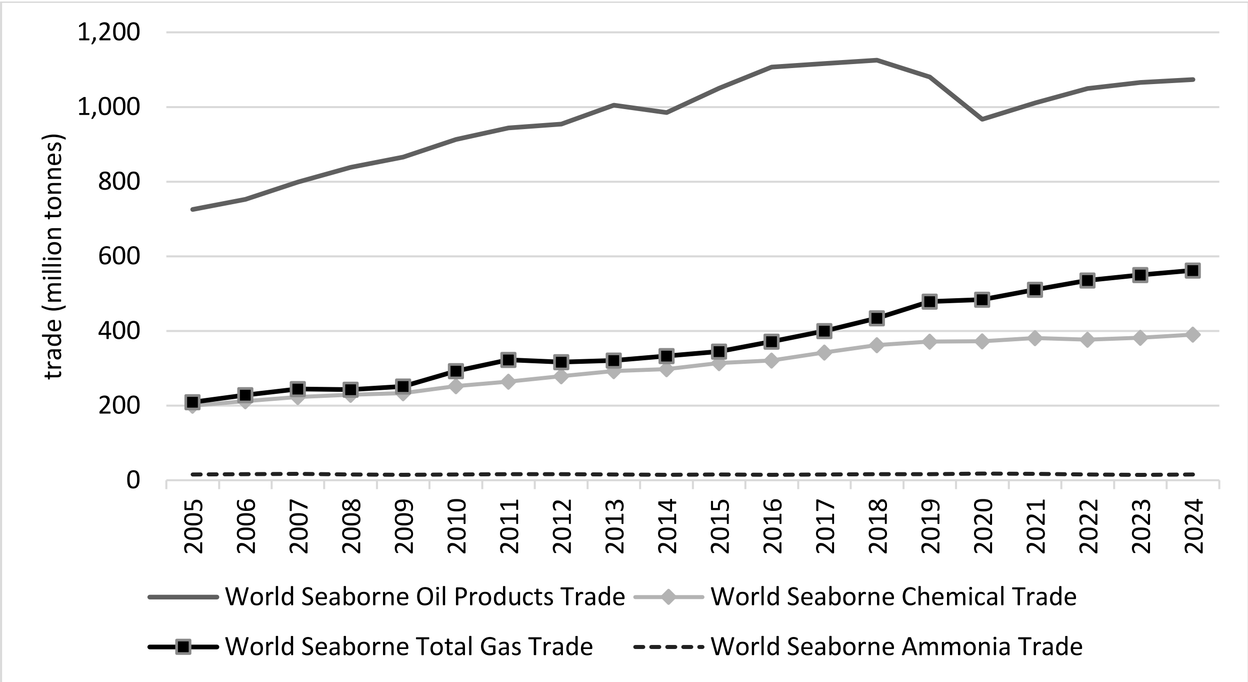
The largest share until 2009 was the oil trade in terms of tonnes transported. In 2009, the major bulk segment (e.g. iron ore, coal and grain) passed the crude oil segment. In 2024, 3.3 billion tonnes of major bulk were transported. After 2017, also minor bulk (i.e. steel products, sugar, cement) passed the crude oil trade. Minor bulk transported 2.2 billion tonnes in 2024. Chemicals represent the smallest share, transporting approximately 385 million tonnes in 2024. Almost two billion tonnes of containers were transported and 570 million tonnes of gas in 2024. (Clarkson Research, 2024)

Striking in this figure is the stagnating trend in the oil trade from 2004 until 2024 after the uptake from 1990-2004 (Clarkson Research, 2022, 2024). In 1990, the world seaborne crude oil trade had a share of 30% in all seaborne trade. The share of crude oil remained stable until 2000. After 2000, there was a decrease in the share of crude oil in total seaborne trade until 2024. This trend can be attributed to multiple factors, including increased energy efficiency, a gradual shift toward renewable energy sources and geopolitical tension affecting oil demand. (Clarkson Research, 2024)

In 2024, the major bulk trade holds the largest volume of all seaborne transport. Meanwhile, container trade volumes, at almost two billion tonnes, highlight the ongoing expansion of globalized trade networks and the rise of e-commerce. Despite these shifts, the chemical trade remains a niche segment, constrained by its specialized handling requirements and relatively smaller market size compared to other commodities. (Clarkson Research, 2024)

After the overview of the general split of the segments in the seaborne trade, it is interesting to look more in detail to the liquid bulk segment. Figure 1.4 shows the division into sub-flows: oil products, chemical trade, total gas trade (LNG and LPG) and ammonia trade.

Figure 1.4: World Seaborne trade liquid bulk

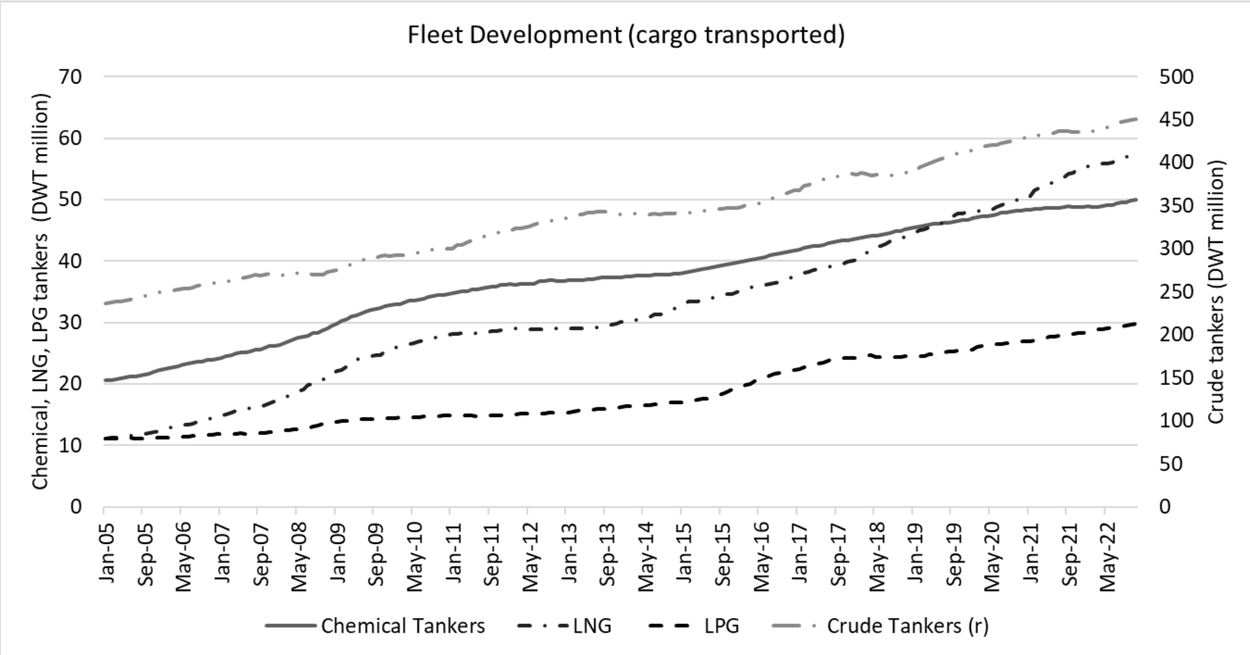


Source: (Clarkson Research, 2024)

Figure 1.4 presents the evolution of liquid bulk for each specific segment: oil products trade, gas trade, chemical trade and ammonia trade. The world oil product trade has the largest share (Clarkson Research, 2024). From 2005 until approximately 2017, the trend went upwards while the period after 2017 until the first half of 2019 the trend went down firmly. The tariffs imposed by the US and China in 2018 have slowed down growth and contributed to inflation (Pankratyeva, 2019). Thereafter, the oil product trade retook the increasing trend. However, the level of 2017 was not yet reached. Also, the total gas trades feature a growing trend over 2000-2023. The same goes for the chemical trade, although the trend was more a steady increase without big fluctuations. The trade of ammonia expressed in million tonnes is still low compared to other segments. In 2007, 17.3 million tonnes of ammonia were transported (Clarkson Research, 2022, 2024). In contrast to all regulations imposed by the European Union, the graph shows still an increase over time up till 2022 of oil product trade and little promising for alternatives to oil products such as ammonia. Ammonia trade grew from 7.1 million tonnes in 1990 to 15.1 million tonnes in 2024. According to NGLS (2022), the ammonia seaborne trade is expected to grow to 160 million tonnes by 2040. Similar to ammonia, the gas trade is increasing (i.e. LNG and LPG) from 209 million tonnes in 2005 to 562 million tonnes in 2024.

After examining the demand side, it is important to analyse the supply side. Figure 1.5 represents the fleet development of crude oil, LNG and LPG tankers from January 1996 until January 2022 (Clarkson Research, 2022, 2024).

Figure 1.5: Fleet development crude oil, chemical, combo, LNG & LPG tankers



Source: Clarkson Research (2022)

The primary axis shows the development of the chemical, LNG and LPG tanker fleet in the development of the million tonnes deadweight tonnage (DWT). The crude oil tanker fleet development is shown on the secondary axis. The figure shows that the chemical fleet, LNG fleet, LPG fleet and crude oil fleet tankers grew from Jan 2005 – Nov 2022. The crude oil tanker segment is still the largest segment. In November 2022, it reached 450 million tonnes. The LNG tanker fleet development shows the fastest acceleration and surpassed the chemical tanker fleet development in June 2019. LNG offers potential cost savings in addition to ensuring compliance with Emission Control Areas (ECA). LNG is versatile in use (transportation, heating, and electricity generation) but still not emission-free. At the end of 2022, its level reached 57 million tonnes of DWT. Additionally, the growth in LPG tankers demand is increasing, driven in part by the fact that LPG tankers can be used to transport ammonia safely and efficiently (Clarkson Research, 2022).

To conclude, the crude oil fleet development is still not decreasing. The crude oil trade seems to have stagnated in the last decade, although the intention is to phase out fossil energy for a sustainable future. In this context, this dissertation will specifically examine the costs, required storage area, and volumes for hydrogen and ammonia in the port environment, focusing on how ports can adapt to handle the complexities of these alternative fuels, while contributing to the decarbonization of global trade. The successful integration of hydrogen and ammonia into port operations will depend on infrastructure investments, regulatory frameworks, and the role of renewable energy in enabling these transitions.

1.1.3. The role of renewable energy

Renewable energy sources play a crucial role in mitigating climate change such as wind and solar. As these sources generate energy in various forms, energy carriers are essential for storing, transporting and converting this energy into usable power. Energy carriers Energy carriers facilitate the transmission and utilization of energy, playing a crucial role in facilitating the transmission and utilization of energy. Examples of green energy carriers include ammonia and hydrogen when produced sustainably. Understanding the distinction between alternative fuels and energy carriers is essential because it highlights distinct aspects of the energy supply chain. Energy carriers are substances or forms of energy that facilitate the transport, storage and conversion of energy from one form to another. Energy carriers are substances or forms of energy that facilitate the transport, storage, and conversion of energy from one form to another. To ensure energy security and flexibility, the storage of energy-dense, sustainable energy carriers such as hydrogen and ammonia is preferable for managing large quantities of energy over extended periods (Morlanés et al., 2021).

This dissertation addresses energy flows through ports, encompassing all sectors and applications in the hinterland of the ports. While a wide array of alternative fuels and hydrogen carriers are under consideration in the global energy transition, including methanol, Liquid Organic Hydrogen Carriers (LOHCs), and biofuels such as Hydrotreated Vegetable Oil (HVO), this dissertation deliberately narrows its focus to scalable, carbon-free energy carriers with high potential for long-distance trade via ports. The emphasis on green hydrogen and green ammonia is based on their carbon-free nature, higher technological readiness, and suitability for bulk storage and transport. Other carriers, such as LOHCs, are excluded primarily due to lower energy efficiency, additional conversion steps, emitting characteristics, or dependency on biomass. HVO, while applicable as an alternative fuel, falls outside the scope of this study due to its biogenic origin, the limited availability of sustainable feedstocks, and the fact that it still emits CO_2 upon combustion, making it a less suitable fully carbon-free solution for large-scale, cross-border energy transport through ports. (Zeman et al., 2019)

Electricity from wind and solar will be crucial in the energy transition, but it is mostly transported through grids rather than through port infrastructure. However, green electricity plays an important indirect role in this dissertation, as it is a necessary input for producing green hydrogen and green ammonia. These energy carriers are often produced in regions with an abundance of renewable energy, where solar and wind power are available at low cost and high capacity. The green electricity is used to electrolyze water into hydrogen, which can then be transported in various forms such as liquid hydrogen or ammonia via port infrastructure to importing regions. In this way, ports act as enablers in the global redistribution of renewable electricity through energy carriers that are more suitable for long-distance transport. (Ishaq et al., 2022; Oliveira et al., 2021)

This thesis's scope is delineated to carbon-free solutions, with a particular focus on green hydrogen and green ammonia because they are both carbon-free and highly promising energy carriers to contribute to reduce CO_2 emissions across various sectors (IEA, 2019). Low-carbon alternatives such as green methanol or biofuels are seen as part of the broader energy transition and may offer complementary solutions in certain applications. However, they fall outside the scope of this dissertation due to their emitting character upon usage and their reliance on biomass, which raises questions regarding long-term scalability, land use and sustainability (Valera-Medina et al., 2021). Moreover, options such as green methanol involve additional conversion steps (such as synthesis from hydrogen and captured CO_2) which result in energy losses and reduce overall system efficiency compared to the direct use of carbon-free carriers such as green hydrogen and green ammonia (Chehade & Dincer, 2021; Morlanés et al., 2021). Although e-methanol can be considered a low-carbon alternative, it is not entirely carbon-free. This is because while it is produced from captured CO_2, the CO_2 emissions from its use are not eliminated, they are part of a circular process where the same CO_2 is re-released. Therefore, the overall CO_2 emissions are neutral, but this process relies heavily on the availability of renewable energy for the production of hydrogen and CO_2 capture (Sánchez et al., 2024). This carbon-neutral aspect of e-methanol depends on its production process and the energy mix used. These factors add complexity and cost to the overall process, making it a more energy-intensive and expensive option compared to direct use of hydrogen or ammonia. Ammonia's hydrogen content per unit volume is higher compared to methanol (Sánchez et al., 2024). This dissertation therefore focuses on scalable, carbon-free solutions for energy transport via ports.

The choice for green hydrogen for enabling transportation and storage, is based on hydrogen as a carbon-free energy carrier with significant potential for the energy transition (Notteboom & Haralambides, 2023; Oliveira et al., 2021). Hydrogen can be stored and transported in large amounts of energy without CO_2 emissions, making it an ideal candidate for decarbonizing sectors such as industry, transportation and energy storage (Schiffler, 2024). The most commonly considered hydrogen supply chains include liquid hydrogen, compressed hydrogen, Liquid Organic Hydrogen Carriers (LOHC) and ammonia (NH_3).

Liquid hydrogen (LH_2) offers advantages in terms of storage and transport, as it is much more compact in liquid form at -253°C than in its gaseous state, enabling large-scale hydrogen transport over long distances. The growing global interest in hydrogen, supported by investments in infrastructure and technology, makes LH_2 a strategic choice for countries aiming for energy independence and carbon reduction, making it an essential source of clean energy (Oliveira et al., 2021).

Although LOHCs are also being explored as hydrogen carriers, this dissertation focuses on ammonia and LH_2 because of their higher energy efficiency and greater technological readiness for large-scale shipping (IEA, 2024b; Morlanés et al., 2021; Notteboom & Haralambides, 2023; Oliveira et al., 2021; Schiffler, 2024). The focus on LH_2 instead of LOHC is due to its higher energy efficiency and simplicity of the LH_2 system (Niermann et al., 2019). LOHC involves chemically binding hydrogen to a carrier and releasing it for use, introducing two additional energy-intensive steps that reduce overall efficiency (Notteboom & Haralambides, 2023). While LOHC can appear attractive due to its ambient storage conditions and compatibility with existing infrastructure, multiple studies show that the hydrogenation and dehydrogenation processes lead to significant energy losses and lower round-trip efficiency compared to ammonia and $LH_{2.}$ Technological developments in LOHC are acknowledged, and future evolutions may change its role in the energy landscape. However, for this study, the current technological maturity and infrastructural readiness guide the selection of energy carriers. Moreover, while first operational ships for green ammonia and liquid hydrogen transport are already being developed or launched, such as the Suiso Frontier for LH_2, LOHC-based maritime transport remains at a conceptual or pilot level without commercial-scale operational vessels (DNV, 2018a; Ratnakar et al., 2021). As technology advances, the roles of other energy carriers like LOHCs could become more viable, but as of now, the industry is more inclined toward LH_2 and ammonia due to their established infrastructure and better performance (IEA, 2024b).

Transporting hydrogen as compressed hydrogen (CH_2) faces challenges compared to liquid hydrogen. CH_2 has a lower volumetric energy density, requiring larger tanks, while LH_2 achieves higher density through cryogenic cooling. CH_2 avoids the energy-intensive process of liquefaction required for LH_2 but still needs significant energy for compression and uses heavy, high-pressure tanks, which raise costs and safety concerns. LH_2, while lighter to store, requires advanced insulation to prevent boil-off. CH_2 is better suited for short distances, whereas LH_2 is more efficient for long-range, large-scale transport which will be more interesting for the import of hydrogen from promising supplying areas. (Notteboom & Haralambides, 2023)

In contrast, LH_2 offers a direct solution for storage and transport without the need for chemical conversions during loading and unloading. Additionally, the regeneration of LOHC materials often requires high temperatures and specialized catalysts, adding further costs and complexity. Although LH_2 has challenges, such as energy losses during liquefaction and boil-off during transport, ongoing advancements in cryogenic technology and storage solutions continue to improve its efficiency and scalability, reinforcing its relevance for large-scale hydrogen trade. (Oliveira et al., 2021)

The commercial viability of ammonia as an energy carrier is supported by its high volumetric, high gravimetric energy density and the lower cost per unit of energy stored (0.54 \$/kg-H_2) compared to hydrogen (14.95 \$/kg-H_2) (Morlanés et al., 2021). Ammonia has been produced and transported globally for over a century, supported by an established high-capacity infrastructure for liquefied ammonia, including pipelines, bunker ships, tank trucks, etc. (Morlanés et al., 2021). Ammonia is seen as an excellent storage provider for blue and green hydrogen. Ammonia is a hydrogen carrier that has a hydrogen equivalent of 17.6%. It has the highest energy efficiency (34-37%) and lowest cost per nominal cubic meter compared to LOHC or LH_2 (Bøe et al., 2021). Apart from energy transportation and storage, ammonia can be directly used for power generation. Green ammonia is a carbon-free fuel with a zero-carbon footprint when used. However, ammonia is hazardous due to its toxicity and potential to cause severe respiratory, eye and skin damage upon exposure. Additionally, it is highly flammable under certain conditions, posing fire and explosion risks (Morlanés et al., 2021). These safety challenges are actively being addressed through technological advancements such as improved containment systems, better detection methods and regulatory frameworks, ensuring its safe handling during storage and transport. (Morlanés et al., 2021)

Ammonia is already in use across various industries and has proven highly effective. It serves as a key ingredient in fertilizers, enabling large-scale agricultural productivity. Beyond agriculture, ammonia is increasingly explored as a carbon-free fuel due to its high energy density and established transport infrastructure. Pilot projects and real-world applications have demonstrated its potential for reducing greenhouse gas emissions, particularly in maritime shipping and power generation (Morlanés et al., 2021). Its versatility and scalability make it a promising energy carrier in transitioning toward sustainable energy systems. Galimova et al. (2023) researched the feasibility of green ammonia trading via pipelines and shipping with cases in Europe, North Africa and South America. The study of Galimova et al. (2023) presents that imports of e-ammonia are cheaper to ship from Morocco and Chile to Europe (i.e., Germany and Finland) than to transport via pipeline from Morocco to Europe, not only because it is more cost-effective but also because pipelines are not available everywhere, making shipping a more feasible option in certain regions (Galimova et al., 2023). Additionally, ammonia's role as a direct energy carrier and hydrogen carrier (via cracking to release hydrogen) makes its use appealing across different sectors.

1.2.Geopolitical Landscape

The geopolitical landscape significantly impacts the energy transition, shaping the future of international trade and energy flows (IEA, 2024e). Countries currently heavily dependent on crude oil exports, such as Russia, Saudi Arabia, Nigeria, United Arab Emirates, Iraq, Venezuela etc. generate significant revenue from the export of oil and gas. Since 2014, the oil market has shown fluctuations for some of these countries. The earnings from oil and gas have decreased by 40% for Iraq and 70% for Venezuela (IEA, 2018). These nations, whose economies are very reliant on crude oil exports, will experience challenges as demand for oil declines. Their rich economic and political influence may be significantly reduced, leading to potential instability in global markets and redefinition of their geopolitical power. Regional conflicts and geopolitical tensions highlight significant fragilities in global energy systems, making clear that the transition to cleaner and more secure technologies is crucial.

In contrast, countries with strong renewable energy sources (RES) infrastructure are likely to experience a growing role in terms of geopolitical power and will benefit from the global transition towards green energy (World Economic Forum, 2022). They are well positioned to leverage their RES capabilities for domestic consumption and export to countries less equipped to produce renewable energy at scale. This shift in the global energy landscape will likely increase competition among nations for access to clean energy resources, readdressing the power balance worldwide. (World Economic Forum, 2022)

Geopolitical tensions and competition over these non-carbon energy flows will influence energy distribution worldwide. The competition for energy resources and trade routes will intensify (IEA, 2018). The energy transition will affect global trade relations, as countries with the capacity to produce or access renewable energy compete against countries still very dependent on fossil fuels. Wealthier countries are starting to invest in renewable energy exporting countries, including those with fewer financial resources, to facilitate trade and ensure access to these energy sources. (Port of Antwerp Bruges, 2024; Port of Rotterdam, 2024b)

The impact of these shifts will determine the strategic location of port hubs or new ports, and hinterland connections will emerge. Ports strategically situated to handle the import, export and distribution of renewable energy carriers such as hydrogen and ammonia will become increasingly important. The development of new infrastructure will be necessary to accommodate these flows of green energy, requiring significant investments in port facilities and connectivity to transport these energy sources efficiently to and from the hinterlands (IEA, 2024e).

An important recent development reflecting the geopolitical relevance of ports in the green energy transition is the Clean Energy Marine Hubs (CEM Hubs) Initiative (2022), launched under the Clean Energy Ministerial (Clean Energy Ministerial, 2025). This initiative, by the governments of the United Arab Emirates, Canada, the Netherlands, and the International Chamber of Shipping, aims to accelerate the global trade of low-carbon fuels, particularly hydrogen and ammonia, through strategic port partnerships. By enabling international collaboration between energy-producing and energy-importing countries, the CEM Hubs initiative highlights the geopolitical repositioning of ports as enablers of clean energy flows (ICS, 2023). It also underscores how future energy security will depend not on national capacities, on cross-border alliances and harmonized standards for safety, certification, and infrastructure. Ports that are part of this initiative receive preferential investments, infrastructure development and political support, positioning them as key geopolitical nodes in the energy transition. (Clean Energy Ministerial, 2025)

The growing importance of supranational organizations and collaboration, such as the International Energy Agency (IEA), International Renewable Energy Agency (IRENA) and the European Union (EU), will shape the geopolitical landscape (IEA, 2024e). These organizations will play a crucial role in setting the regulatory framework for energy transition, developing new rules and establishing strong collaborations between countries to support the transition to renewable energy. These supranational organizations will be central in defining global standards, setting targets for renewable energy production and consumption and coordinating the development of necessary infrastructure.

Access to renewable energy sources will increasingly be seen as a key indicator of global power (Panchenko et al., 2023), with countries that can secure reliable access to green energy gaining a significant competitive edge in international politics, trade and economic development. Access to renewable energy will become a crucial element of geopolitical strategy as nations position themselves as leaders in the global energy transition.

Additionally, the war in Ukraine, have further intensified Europe’s need to diversify energy sources. The EU has rapidly reduced its dependency on Russian gas, leading to an acceleration of renewable energy investments and new hydrogen import strategies. At the same time, shale gas, especially from the United States, has been used as a temporary substitute to ensure energy security. However, this reliance on fossil sources does not align with the EU’s long-term climate goals, reinforcing the urgency of scaling up green energy imports. (Abnett & Abnett, 2025)

Furthermore, recent geopolitical shifts, such as the stance taken by the Trump administration regarding the green energy transition, have important implications for the global energy landscape. During his tenure, President Trump is skeptical of the need for a rapid shift toward renewable energy and climate change mitigation, often promoting the continued use of fossil fuels and rolling back environmental regulations (The Economist, 2024). While this ideological approach impacted international policies on energy transition, potentially delaying the pace of renewable energy adoption, particularly in the United States, the global push for green energy continues.

This shift also had ripple effects on trade policies, including the implementation of import tariffs on energy trade, green technologies, and renewable energy equipment, which could affect the affordability and accessibility of these technologies. However, even with such geopolitical hurdles, the demand for green energy carriers is likely to increase as countries and ports seek to align with long-term sustainability targets. This context highlights the uncertainty in global energy markets and underscores the importance of factoring in political resistance to the green transition when analyzing energy flows and port logistics. While certain nations may resist embracing green technologies, global momentum for cleaner energy solutions is likely to continue. The trade barriers imposed by some nations could influence the availability and cost of green energy carriers such as hydrogen and ammonia, but the need for these technologies in ports remains critical for achieving future energy goals. As such, future developments in US policy and global geopolitics could shape the strategic positioning of ports and their role in the renewable energy supply chain, with long-term implications for green import requirements. Despite these political challenges, the demand for green imports, including hydrogen and ammonia, is expected to rise in the coming years due to increasing pressure from environmental goals and international agreements. At the same time, public protests against Trump's administration's climate policies, with demonstrators demanding stronger action on green energy, reflect the growing discontent. It shows the ongoing push for renewable energy, accelerating the need for cleaner energy carriers.

The geopolitical dynamics surrounding the energy transition will reshape global trade, power relations and the role of ports and logistics networks. As countries adapt to new energy flows, supranational organizations will guide these changes, ensure cooperation and establish new rules for sustainable and secure energy.

1.3.Regulatory Framework

Climate agreements set sustainable goals, such as the Kyoto Protocol in 1997, the Paris Agreement in 2015 and the Glasgow Climate Pact in 2021. The Kyoto Protocol legally bound countries to reduce greenhouse gas emissions by an average of 5.2% below 1990 levels between 2008 and 2021, using for example, the emission trading mechanisms (United Nations, 2024b). The Paris Agreement is an international treaty that commits countries to reduce their CO_2 emission to limit global warming to below 2°C, aiming for 1.5°C (United Nations, 2024a). The Glasgow Climate Pact strengthens commitments to emission reductions and the transition to sustainable energy (Nations, 2024a). The countries commit to accelerating action in mitigating climate change and moving away from fossil fuels (Nations, 2024a).

Furthermore, international trade regulations are important to enable the energy transition (WTO & IRENA, 2024). The World Trade Organization establishes policies on free trade and import tariffs relevant to new streams such as hydrogen and ammonia (WTO & IRENA, 2024). As geopolitical tensions and protectionism rise in 2025, the WTO's role in ensuring fair trade for clean energy markets is becoming less influential. While still important, its ability to reduce trade barriers and promote cooperation is challenged by the increasing shift toward regional and bilateral agreements, which limits its impact on the transition to renewable energy systems.Europe has more specific climate and energy regulations for its area. A pivotal framework is the European Green Deal Industrial Plan, adopted in 2023, which updates the European Green Deal. The European Green Deal was originally adopted in 2019 to ensure that Europe emits no greenhouse gas emissions by 2050, that economic growth is decoupled from resource use, and that no person and no place is left behind (European Commission, 2021b). The Green Deal Industrial Plan is an update to the European Green Deal, specifically aimed at accelerating industrial decarbonization. Unlike the original Green Deal, which focused on broad climate targets, the Industrial Plan focuses on creating a competitive, sustainable industrial base within Europe. It addresses the need for scaling up the deployment of clean technologies, with particular attention to critical raw materials, clean hydrogen, and renewable energy. One of the key updates is the establishment of a European Hydrogen Bank to streamline investments in clean hydrogen technologies, as well as an increase in support for energy-intensive industries (European Commission, 2023g).

The Green Deal Industrial Plan remains a central and enduring policy framework, continuously shaping subsequent climate and energy legislation. It is the overarching strategic vision that frame the EU's legislative, technological and financial responses to climate change. For example, The Clean Energy package was adopted in 2019 by the European Commission and will enable Europe to switch from fossil fuels to cleaner energy sources (European Commission, 2019a). The European Commission offers an energy policy framework to facilitate a clean energy transition to accelerate the switch (European Commission, 2019a). The EU Climate Law is also part of the European Green Deal in 2021 and the Fit for 55 are legally binding targets to reduce net emissions by at least 55% by 2030 (European Commission, 2024a). Furthermore, the European Commission sets out specific regulations such as the EU Hydrogen Strategy in 2020, in which all twenty action points were implemented and delivered in the first quarter of 2022 (European Commission, 2024c). The Renewable Energy Directive III, adopted in 2024, establishes ambitious targets for renewable hydrogen and ammonia, mandating their integration into industrial and transport energy use by 2030, alongside the EU hydrogen import strategy to streamline standards and support decarbonization. It aims to increase the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030, with a further indicative target of 2.5% (European Commission, 2024d). Furthermore, the European Investment Bank has invested 1.3 billion euro in hydrogen technologies. In 2022, the European Hydrogen Bank is launched to support European and global renewable hydrogen production. (European Commission, 2024b)

A comprehensive understanding of the regulatory landscape is crucial to contextualize the energy transition and its impact on shifting trade flows. Regulations such as international climate agreements, trade policies, and European directives create the framework for countries and industries to navigate this transition. They establish legally binding targets, incentivize the adoption of renewable technologies, and set consistent standards to enable innovation and cross-border collaboration to target these goals successfully and stay competitive with other continents and countries. Clear policies on the imports of non-carbon energy reduce uncertainties for investors and stakeholders, ensuring a smoother transition from carbon-intensive energy sources such as coal and crude oil. This regulation is essential to achieving global sustainability goals while adapting infrastructure and supply chains to meet renewable energy demands. This section stresses the connection between policy, innovation and economic transformation.

These market dynamics are related to geopolitical developments, as the liquid bulk trade focusing on energy is heavily influenced by international relations, regional conflicts, and strategic resource dependencies. The interconnectedness of trade routes, energy supply chains, and political alliances highlights the critical role of geopolitics in shaping the liquid bulk market. Examining the geopolitical landscape is essential to understand the factors that drive volatility and long-term trends within this sector (Morlanés et al., 2021).

1.4.Research questions

The previous section highlighted the research context. The main objective of the thesis is to determine the non-carbon energy import volumes, required storage capacity and storage costs at European ports[1], by making use of different energy scenario. A key aspect of this transition is the role of port authorities in shaping and facilitating the shift towards alternative energy carriers, such as hydrogen.

[1] The further research and the formulation of research questions are based on data as specified in this thesis, which is obtained from Eurostat datasets covering the European Union and Norway

Ports are logistics hubs and play a strategic role in enabling the energy transition. To remain competitive and sustainable, ports define a set of strategic port objectives that guide their long-term development and decision-making. In the context of non-carbon energy flows, ports must balance these priorities while adapting to emerging energy markets. This dissertation examines the extent to which the projected import of hydrogen aligns with these strategic port objectives. Alignment in this context refers to the degree of consistency between the anticipated non-carbon energy flows and the strategic priorities of ports. If ports are to facilitate the hydrogen transition effectively, their infrastructure planning and financial commitments must be in step with the expected scale and pace of hydrogen imports. A misalignment between the implementation of hydrogen and port objectives could influence the priority that ports assign to hydrogen development, as they primarily aim to meet their strategic goals. To assess this alignment, the research applies a scoring system that evaluates both the importance of the port objectives and the success of integrating hydrogen in contributing to strategic port objectives.

This leads to the main research question:

Main RQ: How do European energy transition scenarios impact its major liquid bulk ports with respect to storage investment and their strategic goals for a hydrogen-based economy?

The main research question is broken down into five sub-questions:

RQ1: What are the key trends, themes, and research gaps in the academic literature on liquid bulk, energy transition and sustainability in ports?

RQ2: What are the energy transition scenarios for Europe?

RQ3: *How will the energy flows of the major carbon-importing countries in Europe be impacted by the energy transition scenarios?*

RQ4: What are the storage investment costs and storage requirements linked to the imported volumes of hydrogen and ammonia in key European ports?

RQ5: How well are the strategic objectives of port authorities aligned with the ambitions of transitioning towards a hydrogen-powered hub?

Together, these five sub-questions (RQ1-RQ5) help answer the main research question.

1.5. Added value and contribution of the thesis

Building on the research objectives and the questions explored in the previous section, this dissertation offers significant added value for research in energy transition, changing energy flows and its effect on ports. One of the key academic contributions of this research is that it addresses a gap in the literature regarding the impact of the energy transition on infrastructure investments and surface calculations in ports. Despite growing interest in energy transition, very little research has focused on how this shift influences the spatial and infrastructural needs of ports, especially in relation to non-carbon imports like hydrogen and ammonia. This gap becomes evident in the systematic literature review chapter, where the limited focus on energy infrastructure in port contexts is highlighted. Additionally, this dissertation is the first to explore port objectives specifically in the context of the energy transition, which offers a new perspective on how ports can strategically align their objectives to accommodate non-carbon energy flows. By developing a scenario-based analysis, this dissertation provides new insights into how ports can transition into hubs for non-carbon imports, explicitly focusing on the volumes, space and storage costs for integrating hydrogen and ammonia into their operations.

In addition to the academic contributions, this research offers insights on how ports can more effectively align their strategic objectives to accelerate the adoption of non-carbon energy, particularly hydrogen. By developing a scenario-based analysis, this dissertation provides new insights into how ports can transition into hubs for non-carbon imports, explicitly focusing on the volumes, space and storage costs for integrating hydrogen and ammonia into their operations. Furthermore, this research offers significant value for policy-makers and businesses. By calculating the infrastructure requirements, spatial allocation needs, and cost structures associated with hydrogen and ammonia imports, the research provides actionable insights that can support sustainable port development and the integration of renewable energy sources. These findings can help policymakers design effective regulations and strategies for the energy transition, while businesses can use the results to plan infrastructure investments, ensuring that ports are well-prepared for the growing demand for green energy imports.

One of the key contributions of this research is the adaptability of the developed scenarios beyond the case studies examined. The scenarios could be applied to other countries and ports. The research can be extended to various non-carbon energy flows, allowing flexibility in adjusting assumptions to align with changing demand, import, efficiency, supply, etc. This adaptability makes the research relevant for various stakeholders, offering a tool that can be modified as markets and regulatory landscapes evolve.

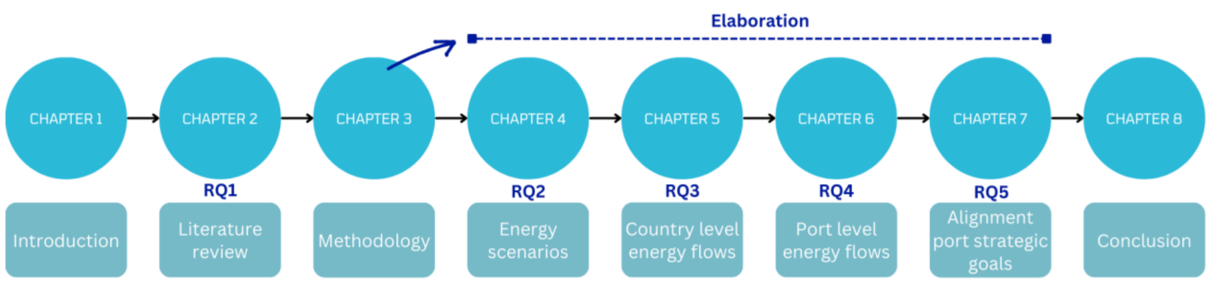
Furthermore, this research provides valuable insights for decision-makers in the energy and logistics sectors. By calculating the infrastructure requirements, spatial allocation needs and cost structures associated with hydrogen and ammonia imports, this dissertation equips policymakers and industry leaders with actionable findings to support sustainable port development and the integration of renewable energy sources. This model aligns with climate objectives and provides recommendations for strategic port development, ensuring that European ports are well-prepared to meet future energy demands while contributing to the broader energy transition.

Ultimately, the added value of this dissertation lies in creating a quantitative model that serves as a strategic tool for port planning. It empowers ports to shape their role actively in the global energy transition, supporting sustainable growth while adapting to rapidly changing energy production, transport and consumption trends. Finally, the last chapter assesses if a hydrogen scenario aligns with and contribute to achieving strategic port objectives. The following section presents the dissertation's outline.

1.6.Thesis outline

The dissertation consists of eight chapters. Chapter 2 to 7 indicate the core or main body of the research that has been conducted. Figure 1.6 illustrates the outline of the thesis.

Figure 1.6: Thesis outline



Source: own composition

After this introductory chapter, Chapter 2 provides a systematic literature review of research concerning liquid bulk and the energy transition. The research conducted in Chapter 2 answers sub-research question 1. The systematic literature review gives an initial literature screening, an in-depth analysis and topic categorization of key research areas in liquid bulk together with the energy transition. This chapter indicates earlier research, the research gaps and main focus themes in liquid bulk and energy transition in ports of this thesis.

Chapter 3 of the thesis presents the methodology, serving as the foundation for Chapters 4, 5, 6 and 7. The chapter begins by the explanation of Chapter's 4 importance, the build-up chapter for scenarios. Thereafter, Section 2 provides an overview of the data used and detailed information on the data sources used. Next, the chapter delves into the analytical framework, which uses quantitative methods. Quantitative analysis includes energy balance calculations at the country and port level. This country-level analysis is crucial for understanding the broader context in which ports operate, as it allows estimating how much renewable energy needs to be imported in each country to meet future demand. The analysis at the country-level enables the calculation of energy balances and non-carbon energy imports at the country level. Thereafter, the calculations are explained to calculate port's needs for non-carbon energy (from country to port level): vessel requirements, space requirements, transport cost estimation. The gravitation model used for these calculations is explained. The last section before the conclusions elaborates on the method used to calculate the alignment of the hydrogen imports with port objectives.

Chapter 4 examines the development of descriptive port scenarios and their associated challenges. It answers sub-research question 2. The chapter starts by exploring the concept of energy transition systems in general and specifically within ports. The theoretical framework also presents drivers and factors shaping the global energy markets. These drivers and factors will help to understand how the scenarios further in the dissertation could be affected. The chapter looks at global energy outlooks and zooms in on Europe, offering an outlook for the region. The chapter's core is creating three descriptive energy scenarios for ports: the dominance of renewable energy, the potential of hydrogen-powered hubs and the diverse energy mix. Each scenario highlights paths for future ports and shows the energy transition's potential impact on infrastructure and strategy. The chapter concludes by evaluating the potential of these scenarios and synthesizing their implication for the future of ports in the energy transition.

Chapter 5 quantifies non-carbon energy sub-scenarios at a country level out of the Hydrogen-powered hub scenario, described in Chapter 4. It further identifies global energy countries, collects data analyses the existing energy flows in Europe and answers sub-research question 3. Assumptions are needed to develop reliable sub-scenarios. Therefore, supply and demand are analysed and used to create assumptions from leading energy institutions. The core of this chapter is to create sub-scenarios for further analysis. Based on projections from international and European authorities, the first sub-scenario suggests a slight decrease in energy demand and a significant increase in non-carbon energy production. The second sub-scenario envisions moderate growth in non-carbon energy production, while the rest of the assumption maintains the same as in Sub-scenario 1. The third sub-scenario assumes a complete elimination of carbon production and imports by 2050, highlighting the urgent need for infrastructure development across various European countries while maintaining the same foundational assumptions as Sub-scenario 1. The three sub-scenarios with different non-carbon import outputs are input for the last analytic sub-scenario.

Chapter 6 quantifies non-carbon energy sub-scenarios at port level and gives an answer to sub-research question 4. It analyses the import of non-carbon energy in ports, especially hydrogen and ammonia. Chapter 6 allows to calculate storage needs and costs of storage. Furthermore, a sensitivity analysis is applied on the third sub-scenario of Chapter 5 for further application and plays with various parameters, such as connected to every NUTS2 region or only connected to the regions with a hydrogen network passing their NUTS2 region, to show the impact of each parameter on cost and surface calculations. This analysis provides a deeper understanding of the economic and spatial implications of scaling up hydrogen and ammonia imports in alignment with the energy transition. The sensitivity analysis allows an holistic approach. Chapter 6 shows the impact of the energy transition and multiple parameters on ports.

After developing the non-carbon import sub-scenarios and port output calculations, Chapter 7 analyses how the non-carbon import flows, more specifically hydrogen, align with port objectives. Chapter 7 answers research question 5. The chapter begins by examining the roles and objectives of port authorities, providing a foundation for the analysis. It presents the hydrogen-powered hub scenario to serve as a reference point for the assessment. The data collection and detailed methodology are outlined, including port selection, port objectives selection, interviews and scoring to calculate the end scores. The methodology uses qualitative (interviews) and quantitative (scoring) analysis. The chapter presents the assessment results, focusing on the importance and success scoring of hydrogen energy projects in relation to port authority objectives. Additionally, the consistency and differences in responses from port authorities are analyzed. Finally, the chapter concludes by summarizing the key findings and implications for the alignment of hydrogen energy projects with the objectives of European ports.

Finally, Chapter 8 emphasizes the overall conclusion of the work conducted in this dissertation. In addition, recommendations for stakeholders and directions for future research will be formulated. This chapter highlights the practical implications of the thesis, emphasizing how the findings can be applied in real-world contexts.

Chapter 2

Energy transition impact on liquid bulk market and ports: a systematic literature review

Ports are essential in connecting various countries via shipping, acting as hubs for the international movement of goods and commodities (Global Maritime forum, 2022). The maritime sector is responsible for approximately 2.5% of global greenhouse gas emissions (Bøe et al., 2021 & Fun-sang Cepeda et al., 2019). The United Nations (UN) imposed the Sustainable Development Goals (SDG) for sustainable growth (without extreme poverty, inequality, injustice and climate change). In 2015, the SDGs were adopted by all member states to ensure a sustainable future. SDG 13 about climate action aims to take urgent action to combat climate change and its impacts. SDG 14 is about life below water to conserve and sustainably use the oceans, seas and marine resources for sustainable development. SDGs 13, 14 and 17 affect the maritime industry (United Nations, 2022).

While this literature chapter focuses on the global context of the energy transition and liquid bulk ports, it is important to consider global research, as developments worldwide influence Europe as well. However, the research will primarily focus on Europe when developing specific scenarios for the future of ports in the context of non-carbon energy flows. At the European level, the Green Deal launched in 2019 aims to achieve climate neutrality by 2050 and works towards a green transition (European Commission, 2019b). In 2021, the European Commission committed to zero CO_2 emissions by 2050. This commitment underscores the EU's determination to address the pressing challenges posed by climate change and to lead the global effort in mitigating its impacts. This adaptation is needed to stay competitive with other continents, countries and ports.

In line with the Green Deal's goals (European Commission, 2019b), the European Commission presented in 2020 its Sustainable and Smart Mobility Strategy aiming to create a sustainable, smart and resilient European transport system. In addition to the Sustainable and Smart Mobility Strategy, its Fit for 55 (2021) packages will turn the European Union's (EU) ambitions into reality. Fit for 55 proposals will revise climate, energy, and transport-related legislation and implement new legislative initiatives (European Commission, 2022b). The Fit for 55 package contains a renewable energy directive which targets to increase the objective of 32% renewable energy sources in the overall mix at EU-level to at least 40% by 2030 (European Commission, 2022b).

Furthermore, six key policies formulated by the European Commission are impacting maritime transport in particular in the European region (Wettengel, 2022). Four of them are regulations and two are directives. The first regulation is the EU emissions trading system extended to maritime transport. The second regulation, Fuel EU Maritime Initiative, aims to limit the greenhouse gas (GHG) intensity of energy used onboard and implement obligations for liners to use on-shore power. Thirdly, the Alternative Fuel Infrastructure Regulation (AFIR) includes obligations for ports to provide on-shore power supply and infrastructure. The final regulation is the Carbon border adjustment mechanism which aims to price carbon imports into the EU. Two out of six policies are directives, including the Renewable Energy Directive, which increased the target of 40% for renewables in the final energy demand by 2030 and the Energy Taxation Directive, which directs to remove the tax exemption on bunker fuels sold and used within European Economic Area (EEA) (European Commission, 2019a). The question arises how ports will be impacted.

Within the maritime industry, the tanker segment faces unique challenges related to the energy transition as this market has a great role in transporting alternative energy and the outfacing of crude oil. During the last decades, a lot of research was already conducted on alternative fuels such as Al-Enazi et al. (2021); Foretich et al. (2021); Prussi et al. (2021); Kouzelis (2022) etc. However, despite this research, there remains a gap in understanding the holistic impacts of the energy transition on the maritime ecosystem. Beyond the technical aspects of fuel substitution, the transition towards cleaner energy sources has affected the entire maritime value chain, encompassing port operations, tank shipping companies, storage facilities and hinterland connections etc. The transformation towards sustainable practices necessitates a comprehensive reassessment of existing infrastructure, logistics and business models within the maritime sector to ensure resilience and adaptability in the face of evolving environmental regulations and market dynamics.

This chapter identifies research gaps in the liquid bulk segment in view of the global energy transition and analyses earlier research conducted concerning liquid bulk and energy transition. While the detailed scenario development will focus on Europe, understanding the global landscape is crucial for framing these regional scenarios. This chapter primarily focuses on the liquid bulk segment, climate change, energy transition and port sustainability. Therefore, the research question is formulated as follows: *What are the key trends, themes and research gaps in the academic literature on liquid bulk, energy transition and sustainability in ports?*

This chapter uses a systematic literature review (SLR). The following section elaborates on the method of the systematic literature review. Starting with an extensive search of published papers and turning into a more detailed search. The second section positions our work into the academic literature. The last section, the conclusion summarizes the findings.

2.1.Systematic literature review

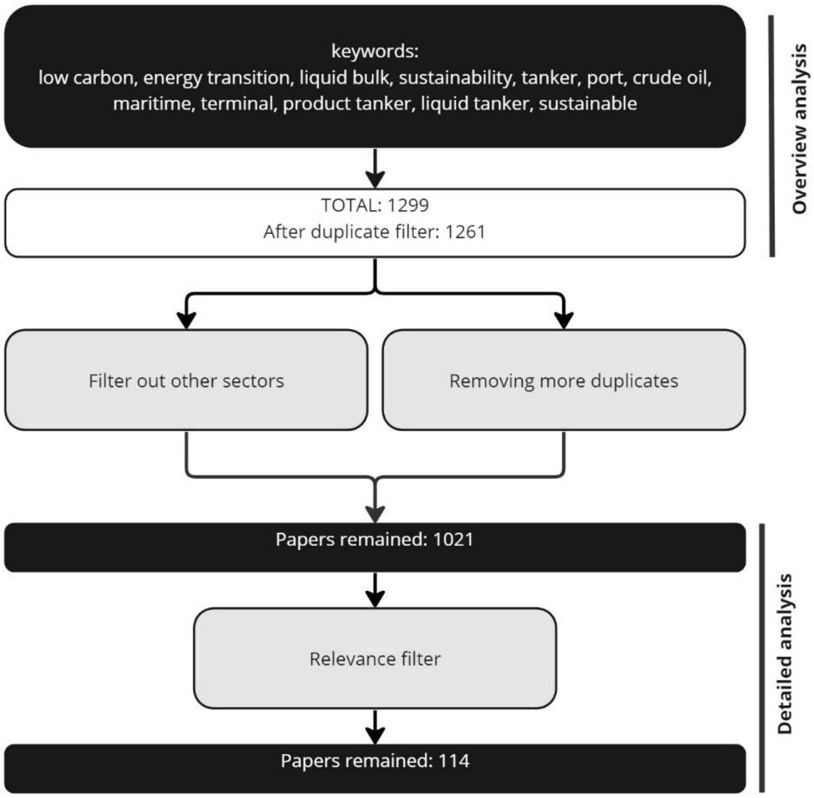
The literature review creates familiarity with previous findings and research and what can be learned from past research. The SLR allows identifying important topics and opportunities concerning the current and future trends that define and limit the research problem. The literature review applies a quantitative and qualitative approach to compare previous published scientific papers by topic. The research of Grübler (1990) states that the transition from sail to steam power and from steam propulsion to internal combustion engines in shipping unfolded over approximately a hundred years. Therefore, the researched period for the SLR is from 1900 until 2022.

Previous research of literature reviews in the maritime transport field focused on the greening of ports such as Davarzani et al. (2016) or more in general analysing on what is researched in maritime transport such as Shi and Li (2017). The paper of Shi and Li (2017) focuses on the contributing organizations to the literature which is not the focus of this paper. This chapter focuses on the gaps in the research concerning liquid bulk in combination with energy transition in ports while the research of Davarzani et al. (2016) focuses on sustainability and so does the research of Shin et al. (2018). However, the way of determining key words is similar to the research of Davarzani et al. (2016). The first step in Davarzani et al. (2016) is to define an initial set of keywords and a search structure. Then, the researchers review the resulting articles and journals to ensure appropriate coverage, identifying and excluding irrelevant articles, research areas and keywords. This process is further refined by eliminating unrelated subject areas to narrow down the search results effectively.

The SLR data collection was done using the software tool "Publish or Perish" (Harzing, 2007). This data collection tool allows searching in multiple databases such as Google Scholar, Scopus and Web of Science. Publish or Perish allows deriving an Excel file, which collects all relevant information such as title, citations, year of publication, journal, DOI etc.

The papers were retrieved by utilizing selected relevant keywords. The method for the selection of this keywords is based on Davarzani et al (2016). The keywords were found by trial-and-error attempts by checking the resulting papers if they ensure the appropriate coverage of papers. On this basis, the keywords were updated accordingly. This resulted in the following keywords used in the title of the papers: low carbon, energy transition, liquid bulk, sustainability, sustainable, tankers, ports, crude oil, maritime, terminal product tanker and liquid tanker. Figure 2.1 presents the approach of the SLR.

Figure 2.1: Systematic literature scheme



Source: own composition

The further analysis is split up into a two-step analysis in which the first step gives an overview of papers published since 1900 with the twelve selected key words (overview analysis). Thereafter, papers that contain the words ‘container’, ‘cruise’ or ‘marine’ were deleted because the aim of this chapter is to have a look into the research that was conducted concerning liquid bulk and the energy transition. The terms 'liquid bulk' and 'tanker' for example were purposefully included due to their direct relevance to shifting energy flows and port infrastructure within the context of the energy transition.

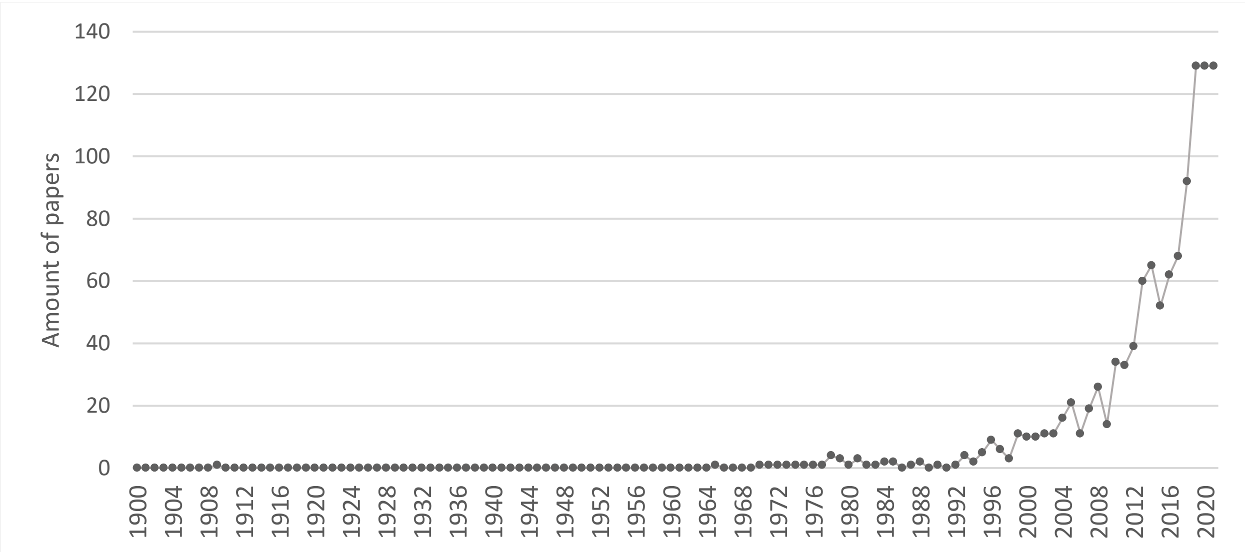
The present chapter research papers after the oil crisis of 1973 and wants to study the effect of the energy transition in ports focused on liquid bulk. Therefore, the papers published before the period of 1980 and duplicates were filtered after the overview analysis. Furthermore, papers related to other sectors or modes of transport such as air transport, cruise shipping, container transport, wastewater-related problems and fishing were removed. Subsequently, 1021 papers remained.

The next step in the research was to overlook these papers by the relevance of their title. Papers with unrelated topics were deleted. These topics were far out of the scope of ports, liquid bulk and energy transition. This resulted in 114 papers. The next step, the detailed analysis, discovers which topics were researched over the last five decades and to find research gaps for future research. In this last step, the reserach excluded very technical or engineering-focused papers, such as those dealing with the design of energy infrastructure, process technologies, or fuel conversion systems. Furthermore, studies in operations research, such as those focused on the optimisation of efficiency at terminals, scheduling algorithms are left out. While these contributions are valuable within their own fields, they do not align with the broader energy transition.

2.1.1. Initial literature screening and overview

The search in which two keywords of the list are combined of which the combination makes sense results in 1,299 papers. After removing the duplicates, 1,261 remained. Figure 2.2 presents the result of the first analysis over the period of 1900-2021. The year 2022 was not yet finished at the moment of search, which means that these papers are left out in this overview but are further analysed in the detailed search. Otherwise, this will give a distorted view. Furthermore, the blanks of which no year could be found are left out of the figure below.

Figure 2.2: Analysis of published papers on researched keywords



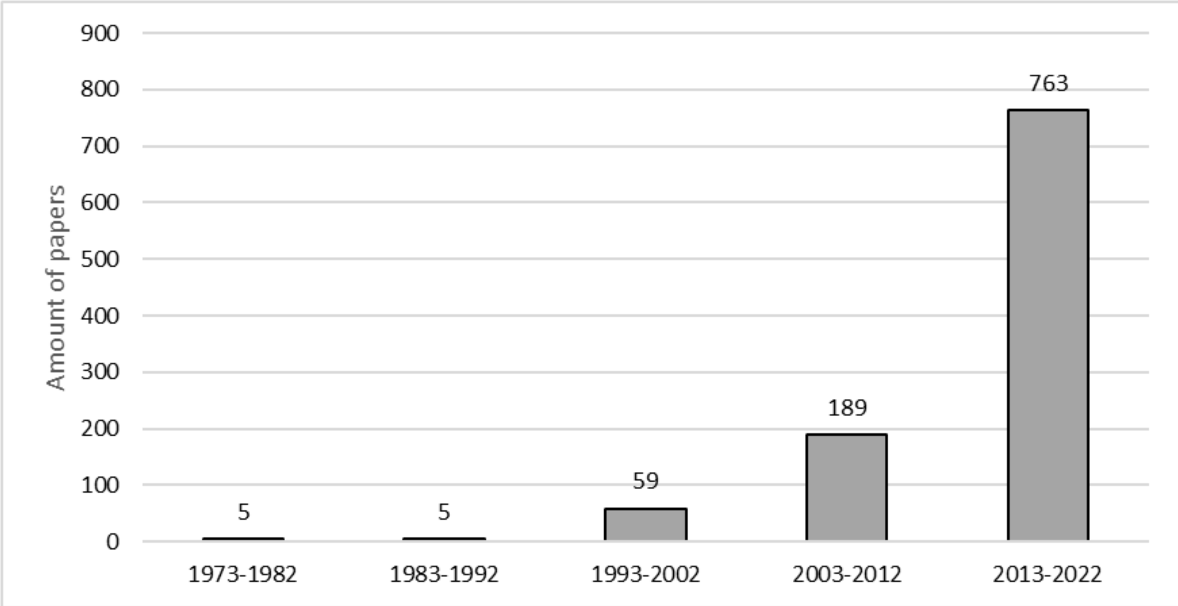
Source: own composition

Figure 2.2 indicates a growing interest in the field of low carbon, energy transition, liquid bulk, sustainability, sustainable, tanker, port, crude oil, maritime, terminal product tanker and liquid tanker since the start of the search. The earliest publication in Publish or Perish dates back to 1909. After the year 2005, when 21 papers were published, there was a more substantial growth in the number of papers published. In 2019, 2020 and 2021, 129 papers were published each year related to these keywords in their titles. If the search only contains two keywords contained too many irrelevant papers for this research to sort the papers by topic. Hence, a more detailed search is needed.

2.1.2. In-depth analysis and topic categorization

Out of the 1021 papers remaining, only fifteen papers contain the words liquid bulk or tanker in their title, using the earlier deliberated choice of keywords. Terms such as 'liquid bulk' and 'tanker' were selected due to their strong relevance to the context of the energy transition and the role of ports in accommodating shifting liquid energy flows. While alternative terms such as 'crude carrier' might have resulted in additional studies, the selected keywords were chosen to align closely with the scope and objectives of this research, specifically focusing on liquid bulk and the evolving energy landscape. Figure 2.3 presents the remaining papers sorted per decade.

Figure 2.3: Filtered papers, counted per decade



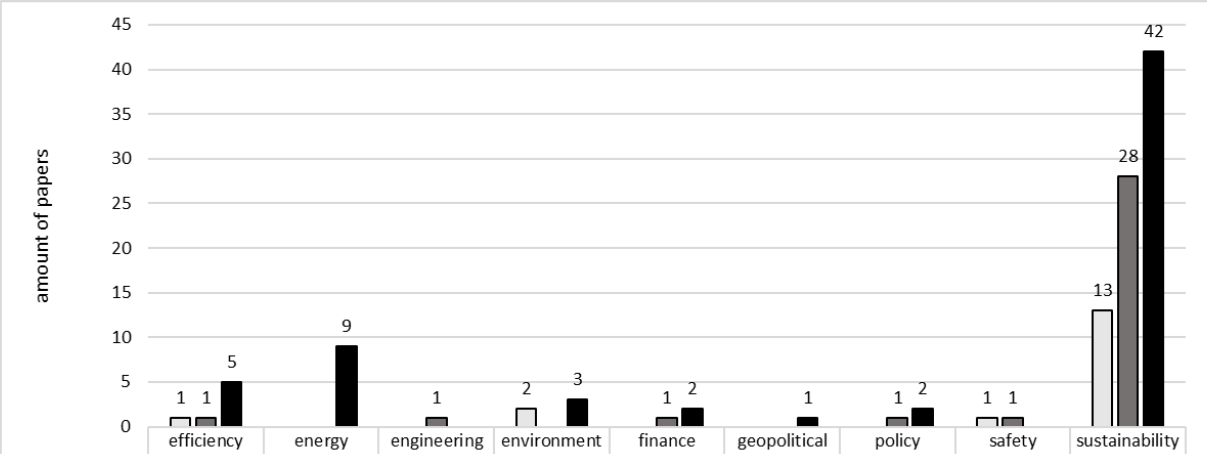
Source: own composition

Research in the early decades in the domain concerning liquid bulk, low carbon, energy transition, sustainability, tankers, ports, crude oil, maritime and terminals was almost non-existent. However, there is a growing interest over the researched period. Only five papers were found in both periods in 1973-1982 and 1983-1992. In the 1970's the oil crisis starts to hit the economic market after this period research related to the topic increased. In the next decade the number of papers published grows from five papers to 59 papers. In the period 2003-2012, 189 papers were found related to the combination of the above-mentioned keywords. Between 2013-2022, 763 papers were found related to these topics, even though the year 2022 did not finish at the time of the search. It shows the largest number of papers throughout the five researched decades.

The European Union introduced the Environmental Impact Assessment (EIA) directive in 1985 (Sheate, 2012). Institutions (e.g. IMO) and the EU are introducing regulations to mitigate climate change and encourage companies to rethink their business. The increase in the last three decades in Figure 2.3 may correspond to the implementation of policies and regulations of the EIA of the European Union, reinforced by the overaging support of leading institutions in energy such as IRENA and IEA. In the last decades, there has been significantly increased attention on the energy transition and climate change. (2019b; 2024d; 2022a)

Out of the 1,021 papers remaining, the aim was to see their main researched topic. Many papers included research concerning air transport topics or were related to inland ports of which the theme deviates too far from liquid bulk and energy transition. The papers were analyzed by their title (and if needed also the abstract was read). The papers were then divided by their core topic, when looking at the title. In case where a title seemed to reflect multiple relevant themes, the abstract was read to ensure correct categorisation. However, this did not occur within the selected keyword combinations. Had it occurred, a separate category would have been created to accommodate such papers. Except when the title was unclear, the abstract was also analyzed. Some papers include more topics such as papers with innovation in their title and also sustainability. The core of these papers is to improve sustainability in ports by implementing innovative solutions, so this belongs to the sustainability theme. The same method of screening keywords was used to determine the topics or themes. The division resulted into nine different topics: efficiency, energy, engineering, environment, finance, geopolitics, policy, safety and sustainability (Figure 2.4).

Figure 2.4: Relevant papers sorted by theme and period



	efficiency	energy	engineering	environment	finance	geopolitical	policy	safety	sustainability
1993-2002	1			2				1	13
2003-2012	1		1		1		1	1	28
2013-2022	5	9		3	2	1	2		42

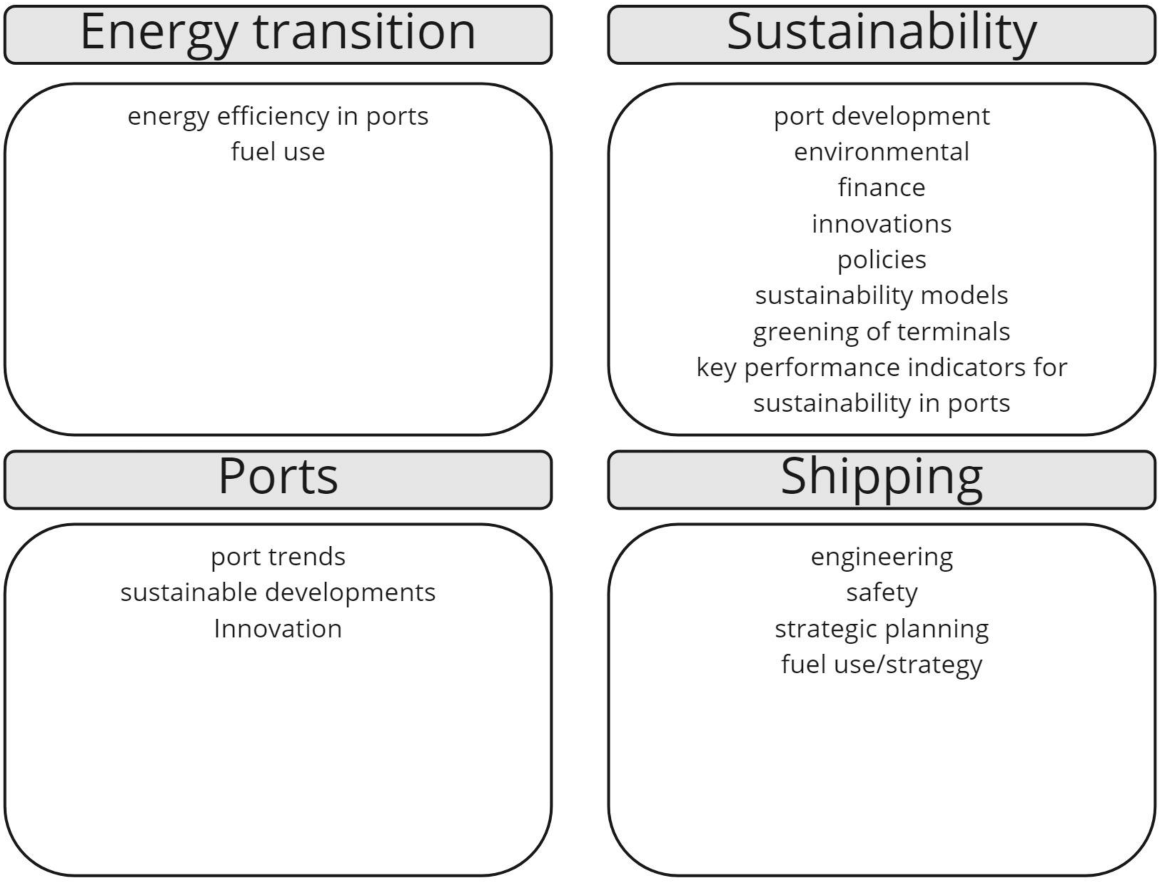
Source: own composition

All irrelevant papers unrelated to the researched topic are deleted in Figure 2.4. Consequently, 114 papers are left. Little attention is paid in the literature to efficiency, energy, engineering, environment, finance, geopolitics, policy and safety. The energy awareness in the liquid bulk segment grows over the researched period from no papers in the first two periods (1993-2002) to nine papers in the last (2003-2022). In all topics, there has been an increase in the number of papers in the last three decades. This is not by coincidence, regulatory institutions such as EU but also more globally such as the IMO are imposing regulation related to reduce greenhouse gas emissions. 83 papers related to sustainability indicate a high awareness of sustainability compared to other topics. The topic of energy only appeared in the last decade, which covers the period from 2013 until 2022, indicating that the energy transition's attention started later than the awareness for sustainability.

2.1.3. Thematic exploration of key research areas

An analysis of the topics related to sustainability, energy transition, ports and shipping is presented in Figure 2.5.

Figure 2.5: Analysis of relevant topics



Source: own composition

Looking into the topics of the papers left, the research looked deeper into what is already researched into these themes. Related to the energy transition, researchers focused mainly on energy efficiency in ports and fuel use for ships. What was stated in the introduction of the research, that much research is related to feasibility of fuels in the shipping industry, was confirmed in the SLR of this paper (i.e. Olamide, 2015, and Ramsay et al., 2022). The papers with sustainability topics focus on port development of all types of ports (e.g. containers, dry bulk) but also environmental impact, finance, innovations, policies, sustainability models, greening of terminals and key performance indicators for sustainability in ports. Examples of papers focusing on sustainability are Helmick et al. (1996), Gilman (2003) and Frederiksen, 2005. These papers focus on technological aspects in the port in general, policy and fiscality. The topics in the remaining 114 papers related to ports focus on port trends, sustainable developments and innovation. Lastly, the topics related to shipping mainly focus on how to implement fuels from an engineering perspective, safety of fuel transition and strategy of fuel choice in shipping. There is little to no research concerning port challenges and energy transition.

Out of the 114 resulting papers, the majority (57%) – 65 papers in total – cover general topics not focused on a specific researched area. The remaining 49 papers are more specific and focus on particular areas, with 16 covering Asia, 19 covering Europe, 7 covering North America and 7 covering Africa. Nevertheless, none of the papers has an area focused on South America which is striking because South America has great potential to export non-carbon energy (IEA, 2024d). The port of Santos alone handles 90 million tonnes of liquid bulk cargo (Santos Port Authority, 2020).

Based on the analysis of the authors from the selected papers, most of the authors appear only one time in the detailed analysis. Nonetheless, certain authors were found to have a higher frequency of appearance, including Roh and Thai, as well as Siddiqui, Szwankowski and Wang. Roh and Thai (2016, 2023) researching sustainability ASEAN Port Development and a case study in Korea. Siddiqui (2013; 2012) conducted research on the tactical planning in maritime transportation of crude oil and route choice in maritime transportation of crude oil, while Szwankowski (Szwankowski, 1998, 2000) focused on spatial and transport aspects related to sustainable development in the port of Gdansk. Finally, Wang (2015; 2018) developed a framework for port sustainability and energy efficiency.

The analysis indicates gaps in the literature related to the combination of low carbon, energy transition, liquid bulk, sustainability, sustainable, tankers, ports, crude oil, maritime, terminal product tanker and liquid tanker. An example of a gap in the literature is the lack of papers addressing the implications of the energy transition on ports and their readiness to accommodate these changes. The list of gaps is inexhaustible but gives an indication for future literature and recommendations.

2.2.Positioning in the academic literature

The systematic literature review of this chapter reveals several significant gaps in the existing research concerning the energy transition in ports, particularly in relation to liquid bulk, low-carbon energy sources, and sustainability. While much of the current literature focuses on general topics such as the greening of ports and sustainability, there is a lack of studies that combine these aspects with the energy transition specific to liquid bulk operations, tankers and related terminal functions. Overall, the liquid bulk market requires more research, as the introduction of this dissertation already illustrated that it will be significantly impacted by the energy transition.

The growing research from the 1990s onwards, as shown in the systematic literature review (SLR), illustrates the growing focus on energy transition, sustainability and technological developments in ports. However, the studies identified in this review show a tendency to focus more on generic port development, shipping fuel transitions and the greening of terminals and their operations. Despite the growing attention to sustainability in ports, relatively few studies have concentrated on the intersection of energy transition and the liquid bulk sector. This is particularly striking given the substantial global trade in liquid bulk and the crucial role that ports have in handling liquid bulk in the wider energy transition. The focus on energy has only emerged in the last researched decade, which is concerning given the urgent need indicated in the introduction chapter for accelerated research to support the energy transition. The following chapters will contribute to this accelertion by examining the storage costs associated with energy transition scenarios and analyzing how these scenarios align with the strategic objectives of the ports.

The researched papers in the in-depth analysis do not address the particular challenges and changes that the liquid bulk sector faces in transitioning to a low-carbon future. Furthermore, the SLR indicates a notable gap in the geographic scope of research. As mentioned in the literature review, there is little to no focus on South America, despite its significant role in liquid bulk trade and their role as a possible future exporter of renewable energy. The Port of Santos in Brazil, for instance, handles a massive volume of liquid bulk cargo, yet no significant research has been conducted on how energy transition impacts this region or its ability to meet future energy demands. This geographical oversight further underscores the importance of this paper's focus for exporting ports of non-carbon energy in regions beyond Europe and Asia. The next chapters will elaborate on the importance of collaboration with exporting energy countries of renewable energy for Europe.

In examining research on sustainability, energy transition and liquid bulk, this chapter identifies a need for greater exploration of specific topics such as the readiness of ports to accommodate low-carbon fuel infrastructure, the effects of energy transition policies on liquid bulk transport, and the adaptation of tankers and terminals to these changes. While earlier studies address energy efficiency and fuel transitions in shipping, previous studies do not sufficiently consider the broader implications for ports, such as storage requirements, fleet adjustments and infrastructure adaptation.

This dissertation intends to contribute to the literature by directly addressing these gaps. By focusing on the implications of energy transition for liquid bulk ports, this dissertation highlights how the shift towards low-carbon energy will affect port storage. Furthermore, it draws attention to the importance of integrating energy transition strategies and how this should align with port objectives to support the uptake of the energy transition, a topic that has been underexplored in current research. The findings suggest that future research should explore how ports can better prepare for these transitions.

In conclusion, while the literature on the energy transition in ports has expanded significantly in recent decades, there remain substantial gaps in understanding the impact on the liquid bulk segment. This dissertation builds on previous research by focusing on these overlooked areas, providing a comprehensive analysis of the challenges and opportunities that lie ahead for ports in the context of a low-carbon future. This will help fill the knowledge gap, offering important insights for both academia and practice in the field of port energy transition. Through its specific focus on the liquid bulk sector and its relation to energy transition, which has not been adequately addressed in existing literature.

2.3.Conclusion

Climate change and energy transition affect the dynamics and trends in maritime shipping. Regulatory authorities such as the International Energy Agency (IEA) and European Commission push the industry to rethink its businesses and become more sustainable. The paper primarily focused on climate change, energy transition and sustainability in ports. This paper answered the research question: *What are the key trends, themes, and research gaps in the academic literature on liquid bulk, energy transition and sustainability in ports?*. The paper investigates earlier research and discovers essential topics and research gaps in research themes in the liquid bulk segment.

The SLR shows that little research has been conducted in the combination of the following key words: low carbon, energy transition, liquid bulk, sustainability, sustainable, tankers, ports, crude oil, maritime, terminal product tanker and liquid tanker. Since 1900 there has been an increase in the number of papers. After 2009, there was a substantial increase; more than 20 papers were published every year. Out of the 1021 papers that remained, 797 were published in the last decade (2012-2022), which shows that interest in these topics is growing. The last part of the systematic review was to organize the relevant papers per topic. The papers were organized into nine topics: efficiency, energy, engineering, environment, finance, geopolitics, policy, safety and sustainability. The research shows that with these keywords, the focus is on sustainability. Only in the last decade (2012-2022) papers related to the energy transition could be found. The European Union introduced several regulations related to climate change (e.g. EIA) which is in line with an increase in the number of papers. Institutions such as the IMO and EU introduced regulations to mitigate climate change and encourage companies to rethink their business.

Building upon the positioning in the academic literature, this chapter highlights that there is a clear underrepresentation of certain critical topics. There is limited research about liquid bulk which is striking for a segment that accounts for 32% of the total cargo transported by sea (maritime transport). The primary focus of the SLR is on liquid bulk terminals, therefore other segments such as container transport fell out of scope. Insights from other sectors could be highly valuable for the liquid bulk segment, to learn from best practices.

Further research is required to investigate how the energy transition and sustainable initiatives will impact ports and how they can make their ports future-proof. Additionally, future research could examine what can be learned or applied from transitions in other industries to ports handling large amounts of liquid bulk products, which could help accelerate the energy transition. This chapter raises important questions regarding who should implement the energy transition, how it can be achieved, which innovations are needed, and which ports are leading this transformation. These insights underline that ports and trade are undergoing a dynamic and uncertain transition, making continued research essential for shaping a resilient and future-proof sector.

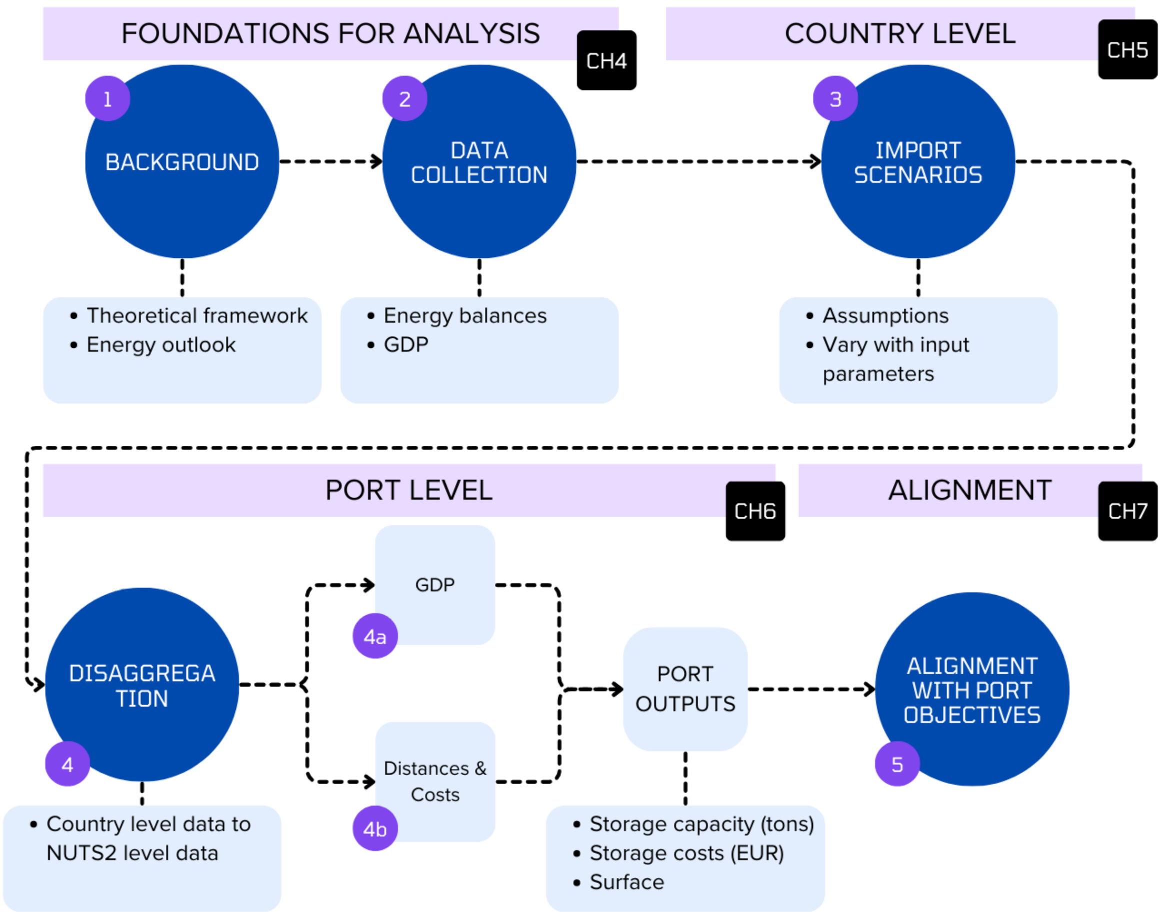
Chapter 3

Methodology

This chapter outlines the methodological approach to this thesis used to address the main research question: *How do European energy transition scenarios impact its major liquid bulk ports with respect to storage investment and their strategic goals for a hydrogen-based economy?*. The main research question is addressed with the help of five sub-questions, the first of which was covered in the previous chapter, the systematic literature analysis. This chapter outlines the methodology used in the next chapters to answer the remaining four sub-questions in the subsequent chapters, ultimately contributing to answering the main research question of this dissertation. A quantitative and qualitative methodological approach is used to answer the research questions. The research will further develop scenarios, calculate vessel and space requirement calculations, storage cost estimates and estimations of import volumes for the analysed ports. Lastly, it will examine the alignment of the non-carbon import flows and port objectives.

Five steps are developed to answer the main research question. Figure 3.1 illustrates the outline and approach of the further research and the coming chapters.

Figure 3.1: Research method



Source: own composition

The black squares in the figure indicate the chapters. The blue circles indicate the steps. First, the foundation for the analysis was built by creating a theoretical framework and looking at energy outlooks. Second, data from Eurostat was collected and analysed. Three qualitative scenarios are developed to reflect potential future orientations of the European energy system. These descriptive scenarios explore how ports may evolve under different energy priorities, infrastructure pathways, and trade dynamics. One of these scenarios is further elaborated through quantitative sub-scenarios to assess its implications for renewable energy uptake and hydrogen flows. Third, sub-scenarios were developed using reliable sources of leading institutions in energy or regulatory institutions to determine the input parameters or assumptions. Input variables are varied in each sub-scenario to assess different outcomes. These include projections for 2030, 2040 and 2050, focusing on energy demand, renewable generation, and emission reduction. Following the sub-scenario development, the fourth step in Chapter 6 involved disaggregating import flows. At this stage, import flows were allocated to NUTS2 regions based on GDP and hinterland connectivity with ports (distances & costs). After the disaggregation of the flows, port key outputs were calculated. The outputs for ports include storage capacity, costs and surface calculations. Building on these findings, Chapter 7 examines the extent to which these projected non-carbon import flows align with port objectives. This final step assesses whether ports are strategically prepared for the large-scale adoption of hydrogen and ammonia, linking import projections to broader port strategies. The last section of this chapter will elaborate on the methodology used to research the alignment.

This chapter is divided into six sections, each focusing on the methodological approach. First, the method for the research foundation is explained for creating countries' energy transition scenarios. Thereafter, the data collection is explained. The country-level section outlines the approach to the data analysis and illustrates the method of calculating the import of non-carbon energy in each sub-scenario. The port-level section disaggregates data from the country to regional level (NUTS2) to assess port-related factors, such as hinterland connections. Thereafter, a section elaborates on the method of the alignment of non-carbon imports and port objectives. Lastly, the conclusions summarize the methodology and discuss how it supports the overall research objectives, preparing for the subsequent application in the next chapters.

3.1.Towards energy transition scenarios for ports

Chapter 4's method combined a qualitative (descriptive scenarios) and quantitative (sub-scenarios) analysis of energy transition scenarios to answer the research question: *What are the energy transition scenarios for Europe?* The method used to answer the research question is a comprehensive review of existing literature, reports and data from global energy outlooks. This methodology establishes a theoretical framework that examines the evolving energy landscape. The analysis includes global energy market trends, the interplay between energy supply and demand and the impact of these transitions on energy flows.

Specifically, this chapter uses a comparative approach to evaluate global energy-supplying countries and their anticipated shifts due to changing demand and supply patterns. It examines the top 10 global energy-supplying countries. Three numbers are analysed: the percentage share in global emissions, the change of their emission share in the global emissions between 2000 and 2022, the percentage share of renewables in the total power generation. This analysis allows for a clearer understanding of how each country in the top 10's contribution to global emissions and renewable energy generation has evolved, providing insight into their role in the global energy transition and their potential impact on future emission reduction targets.

In addition, it employs secondary data analysis to assess the European energy scenario outlook, focusing on current and projected energy flows. The secondary data comes from leading energy institutions and the EU. By synthesizing this information, the chapter builds a foundation for understanding how the energy transition influences liquid bulk handling in ports. Subsequently, Chapter 4 gives an overview of the existing energy flows in Europe, using the data of Eurostat. The data presents the import, production and export of carbon energy in 2022 measured in GWH/year. This data and analysis serve for the selection of analysed European countries further for the scenario development. Furthermore, the port selection was made based on the analysis of the top 20 ports handling in cargo volumes, liquid bulk and the geographic location in the researched countries. These ports are subject for further analysis.

The method includes a scenario-based exploration of ports, providing a descriptive analysis of their potential future state and the associated challenges and opportunities arising from the energy transition. Through this methodology, the chapter provides both a theoretical and practical view of the subject, the foundation for more detailed analyses in the subsequent chapters. The next section illustrates how the country-level scenarios are developed by using the insights of Chapter 4.

3.2.Data information

The next three chapters use data collected through Eurostat and can be found in Appendix B (Eurostat, 2022). Eurostat data is collected from national administrations responsible for energy statistics. The data providers can be national statistical institutes, ministries, energy agencies, and professional associations depending on the country. The data was geographically delineated and limited to all countries that are part of Europe's geographical territory. The data set is collected annually, and our research focuses on 2022. The collected data are expressed in Gigawatt-Hour (GWh). The energy balance of Eurostat is the statistical accounting of energy products and their flow in the economy. In the context of this research, Eurostat's data allows for an in-depth analysis of energy trends in Europe.

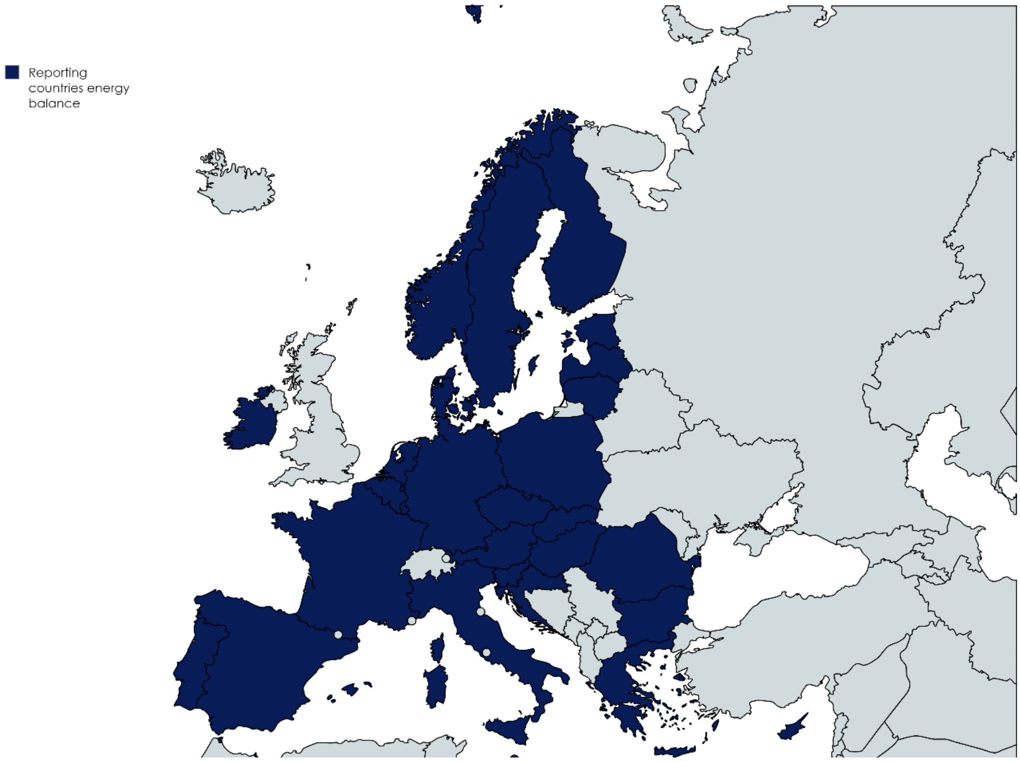
The research of the next three chapter relies on Eurostat data due to its reliability, consistency and comprehensive energy statistics covering many European countries. Eurostat offers a thorough overview of energy products and their flows. These data are sourced from national administrations, including statistical institutes, ministries and energy agencies, ensuring high accuracy. This is essential to establish a solid foundation for the scenario analyses conducted in this research. The research concentrates on 2022, providing the findings reflect the current state of energy flows and consumption across Europe.

A key component involves analysing energy balances to examine energy flow. The dataset includes multiple dimensions of energy supply and demand. Using Eurostat data is essential for answering the research question, as it reveals the underlying energy patterns and flows essential for understanding future scenarios of energy import and consumption in Europe. By encompassing multiple economic sectors, such as transport and industry, the data enables a comprehensive view of the energy needs within the port context. Additionally, focusing on 2022 ensures the analysis is grounded in recent and relevant trends, which is critical for analysing the current dynamics of energy supply chains. With the uncertainty surrounding future scenarios, the reliability and versatility of the Eurostat dataset are key for modelling the complexity of port scenarios and quantifying their potential impact on ports.

The data on energy balances includes primary production, recovered and recycled products, imports, change in stock, gross available energy, international maritime bunkers, gross inland consumption, international aviation and the total energy supply (Eurostat, 2024a). The analysis provides a clear view of energy distribution across the European continent on country level.

There are 28 reporting countries, shown in Figure 3.2. The map shows that the reporting countries are more extended than only the countries that are included in the European Union. The study analyses the 27 EU countries plus Norway. The importance of including Norway is supported by reports from the International Energy Agency (IEA, 2022d), which details Norway's contribution to global energy markets and its efforts to enhance energy sustainability as an energy exporter.

Figure 3.2: Reporting countries



Source: own composition via Mapchart (2024)

The collected data provides a good foundation for the analysis, offering reliability to enable scenario development. The next section outlines the methodology used to calculate the port outputs (costs, surface and storage capacity) with this data in place. In addition to energy data, this study also implements an economic analysis by examining the GDP across European regions. This approach enables to allocate flows to ports at a more disaggregated level.

Furthermore, data from Eurostat (2024a) was collected to analyse European countries' gross domestic product (GDP), including Norway, at current market prices by NUTS2 regions. The detailed breakdown by NUTS2 regions is crucial for understanding regional disparities and distributing import flows across different areas. NUTS2 regions are part of the Nomenclature of Units for Territorial Statistics (NUTS) system, developed by the European Union to classify territorial units for statistical and economic analysis. NUTS2 represents medium-sized regions, often corresponding to provinces, regions, or administrative divisions within a country, depending on its structure (e.g., Flanders in Belgium or Catalonia in Spain) (Eurostat, 2024a). By providing a standardized framework, NUTS2 regions enable consistent comparisons across the EU and help identify disparities between regions, ensuring targeted policy interventions and funding distribution. This dataset is retrieved from Eurostat (2024a) and the specific data can be found in Appendix B.

Chapter 7 uses the homogeneity index H to measure the consistency of the respondents' scoring on the alignment of the implementation of the hydrogen projects (non-carbon imports) and port objectives. Therefore, interviews and a scoring system are used to research the alignment and port objectives. The next section lays the foundation of the development of scenarios.

3.3.Country level

First, the Eurostat data is utilized to develop non-carbon import scenario. Therefore, calculations are needed. This process begins with the extraction of simplified energy balances from the Eurostat database. An overview of all researched countries is made of their imports, exports, production and stock. A division is made between carbon and non-carbon energy. On the one hand, carbon energy includes solid fossil fuels, manufactured gases, peat and peat products, oil shale and oil sands, natural gas and oil and petroleum products. On the other hand, non-carbon energy includes renewables & biofuels, non-renewable waste, nuclear heat and electricity. This categorization is crucial for calculating the total energy supply needed for further analysis of non-carbon energy imports. The total energy supply is needed to calculate further outputs of the import of non-carbon energy.

3.3.1. Energy balance calculations

This section presents the non-carbon energy balance calculations needed for further scenario development. The gross available energy is determined by summing up the primary production, the recovered and recycled products, and the imports while subtracting the exports and adding the change in stock. The international maritime bunkers are deducted to calculate the gross inland consumption. Finally, to obtain the total energy supply, international aviation is also deducted.

Figure 3.3: The total energy calculation

+primary production
+recovered & recycled products
+imports
-exports
+change in stock
=gross available energy
-international maritime bunkers
=gross inland consumtion
-international aviation
=total energy supply

Source: own composition

The primary production includes all forms of domestic energy production, such as coal, oil, natural gas, and renewable energy sources like solar and wind (Eurostat, 2024a). The recovered and recycled products include energy that is recovered from waste. Imports and exports in Europe predominantly comprise natural gas and crude oil. Change in stock refers to the variation in energy reserves or inventories within a given period. This includes any increase or decrease in stored energy resources, such as crude oil, natural gas, or coal inventories and renewable energy sources stored in batteries or other forms. (Eurostat, 2024a)

3.3.2. Non-carbon energy import

To calculate the net import of non-carbon, it is assumed that the energy demand equals the energy available. The output of the scenarios results in the following formula for the net import of non-carbon energy for country (c):

$$\begin{aligned}\Delta\, Import\ of non - carbon - energy_{c,2030} &= \left(import\ non - carbon\ energy_{c,2022} - export\ non - carbon\ energy_{c,2022}\right) \\ &+ \Delta\ in\ production\ and\ recovery\ energy_{c,2022-2030} \\ &+ \Delta\ in\ gross\ energy\ available_{c,2022-2030} \\ &+ \Delta\ in\ carbon\ energy\ imports_{c,2022-2030}\end{aligned}$$

The formula represents the net change in carbon-based energy imports for country c by 2030. It is determined by the balance of non-carbon energy imports and exports in 2022, adjusted for changes in domestic energy production and recovery, shifts in the total energy available for consumption, and variations in carbon energy imports between 2022 and 2030. This formula captures how the evolving energy mix impacts the need for non-carbon-based energy imports over time.

This change is calculated for the years 2030, 2040 and 2050. A positive change indicates an increasing dependency on non-carbon energy imports due to higher imports than exports, insufficient domestic production, or rising energy demands. Conversely, a negative outcome suggests a move toward energy self-sufficiency or an export-oriented strategy resulting from increased domestic production, reduced demand or higher exports. A zero outcome implies stability in the energy trade balance, with no significant change in reliance on non-carbon energy imports since 2022.

In this model, the net import is calculated as the sum of the changes in production, gross energy and carbon imports, along with the difference between imports and exports. The results help to understand how different countries will handle their energy needs in relation to imports and exports, reflecting the overall trends in energy flows and energy dependencies.

To calculate non-carbon energy imports in tonnes per year, the following formula can be used:

$$non - carbon\ energy\ import_c = \frac{\Delta\ in\ non\ carbon\ net\ carbon\ imports_c * \text{estimated \% of non−carbon energy import per year}_c}{Energy\ densitiy} * 10^3$$

The formula of non-carbon energy import in country c represents the total import of non-carbon energy for country c. It is calculated by multiplying the change in net non-carbon energy imports by the estimated annual share of non-carbon energy imports. For the first analysis, the sub-scenarios, a ratio of 25% ammonia and 75% hydrogen was assumed for the sub-scenarios in Chapter 5. This division serves as a hypothetical basis for exploring import needs under specific assumptions. Sensitivity analyses could further examine the impact of alternative ratios (Chapter 6). This value is then divided by the energy density to account for the energy content of the imported fuels, with a conversion factor of 10^3 applied for unit consistency. This formula provides an estimate of the total non-carbon energy imports based on expected fuel distribution and energy content.

In this analysis, non-carbon energy imports for hydrogen and ammonia are quantified for each scenario. This detailed examination allows assessing the trajectory of non-carbon energy imports and their implications for energy policy and strategy in the coming decades. A critical assumption is that all non-carbon energy imports will consist of hydrogen or ammonia, as stated in the introductory chapter.

3.4. Port level

In this section, the country-level calculations are used to calculate port-level needs. First, the transport costs are calculated. Thereafter, the gravitation model is used to distribute the non-carbon energy flows of country level to port level. By using the gravitation model, vessel requirements, space requirements and cost of transport can be calculated.

3.4.1. Transport cost estimation

Distances between ports and end destination need to be calculated to make an estimation of costs. Here, the research uses two approaches, one where all ports are connected with every NUTS2 area, and one based on the existing or considered hydrogen pipeline network. The ports included in the analysis for the Hamburg-Le Havre region are the ports of Antwerp-Bruges, Amsterdam, Rotterdam, North Sea port, Bremen, Hamburg and HAROPA. In the Atlantic region, the analysis focuses on the port of Bilbao. For the

Mediterranean region, the ports analysed are the ports of Cartagena, Valencia, Tarragona, Barcelona, Marseille, Genoa, La Spezia, Civitavecchia and Trieste.

Building out an extensive pipeline network will stimulate the use of hydrogen and must happen fast to be in line with the European goals. Early hydrogen infrastructure enables a competitive European energy transition (European hydrogen backbone, 2023). One of the sensitivity analyses will focus on this pipeline network.

The first approach in the pipeline network sensitivity analysis is one where every port is connected with the NUTS2 level. Port-level data was collected at the NUTS2 level. The first approach involves collecting port-level data at the NUTS2 level through three key steps: determining the coordinates of each port and corresponding NUTS2 zone, calculating distances between ports and their respective NUTS2 zones, obtaining GDP data for each NUTS2 region from Eurostat (2022).

The second approach in the sensitivity analysis in Chapter 6 is the approach in which the existing and considered H_2 network of the European Hydrogen Backbone initiative is used. The map illustrates an accurate view of the hydrogen infrastructure that exists or is planned to be constructed by 2040. The pipeline network connects several European countries, including the Netherlands, Belgium, Germany, France, Spain and Italy. Figure 3.4 illustrates that not every NUTS2 zone will be connected to one of the analysed ports. To establish this comprehensive network, close collaboration is needed, and the establishment of this hydrogen network will depend on future supply and demand dynamics of the integrated energy system. However, more pipelines could be installed and can extend the network; although the network is quite extensive, there are some NUTS2 levels that are not connected through the network, such as Bretagne or Marche. Therefore, the first approach gives a good overview of what could happen when every NUTS2 zone is connected to all ports. Some of the pipelines shown on the map cross the sea, these offshore connections are not included in the analysis. All land-based connections are taken into account for the further analysis.

Figure 3.4: Currently considered H_2 pipeline network -

Source: European hydrogen backbone (2023)

A key reason for prioritizing hydrogen pipelines over ammonia pipelines for hinterland transport is the efficiency and compatibility of existing and planned infrastructure. While ammonia is an effective hydrogen carrier for long-distance transport to ports, its distribution further inland via pipelines is less practical due to its toxicity and the need for specialized materials to prevent corrosion and leakage (European hydrogen backbone, 2023). Instead, ammonia is expected to be converted into hydrogen at importing ports before further transport via the hydrogen pipeline network (Flux50 & Vlaio, 2020). This approach minimizes safety risks, reduces the need for separate ammonia-specific pipelines, and aligns with ongoing hydrogen infrastructure developments that aim to connect industrial hubs across Europe. As a result, the hydrogen pipeline network will play a crucial role in linking ports with inland demand centers, ensuring an efficient and scalable supply chain. (Flux50 & Vlaio, 2020)

The results of the non-carbon energy imports in each scenario are then divided according to the GDP of each NUTS2 zone using the gravitational model (2022). These steps are needed for the subsequent calculations. The results of the import of non-carbon energy in each scenario are used to divide the imports over the NUTS2 areas according to the GDP of each NUTS2 zone (Eurostat, 2022). A gravitation model is used to divide the import demand.

In this dissertation, the shortest distance is used (i.e. the straight-line or 'as-the-crow-flies' distance) rather than the actual length of the pipeline connections. This approach is justified given the numerous assumptions and estimates involved in the analysis, which means that the straight-line distance remains a reasonable approximation. The use of a straight-line distance simplifies the model without significantly affecting the overall accuracy of the results, as the main variations and uncertainties are likely to arise from other factors (i.e. demand).

3.4.2. Gravitation model

A gravitation model is used in economic geography and international trade to predict and explain trade flows between different regions (Anghelache et al., 2019). A simplified gravitation model is used to allocate the import volumes across regions. The gravitation model was employed to handle assumptions and data limitations efficiently. While more complex models could provide finer detail, the gravity model offers an approach suitable for this analysis. Consequently, the distance and costs are calculated based on the possible port.

Due to data limitations, the research assumes that all imports take place via maritime transport. Pipeline imports are not explicitly considered, as no consistent or detailed data is available on the volumes transported via pipeline for all countries involved (e.g., from Eurostat). Furthermore, it is assumed that inland demand is met by domestic production. A simpler gravity model is suitable for this study due to the many assumptions for the uncertainty of the scenarios and the limitation of data. More advanced models, while offering the potential for more precision, would demand additional data and assumptions, which could complicate the analysis without significantly improving accuracy, given the inherent uncertainties in the scenarios and in the evolving energy outlooks. The gravitation model is used in numerous studies to predict crude oil, coal, iron trades (Babri et al., 2017; Boxell, 2015; Shirazi et al., 2020). GDP is also a widely used proxy in gravitation models to reflect economic size and import potential, and has been used in similar studies related to bulk energy flows and trade modelling (Babri et al., 2017; Boxell, 2015; Shirazi et al., 2020). While variables such as industrial production or energy demand profiles could also be used, such data is not consistently available across all NUTS2 regions. GDP, on the other hand, is available at this level of disaggregation and of reliable sources (Eurostat). It reflects both industrial and consumer activity. However, it is important to note that the gravitation model does not account for geopolitical factors that can influence port choices and trade patterns. Recent developments, such as Germany's rapid construction of LNG terminals after the disruption of the Nord Stream pipeline, demonstrate that geopolitical urgency can override pure market logic (Skopljak, 2023). While the model relies on GDP and distance to estimate flows, real-world decisions are also shaped by strategic, political and security concerns. Therefore, this model provides a simplified but adaptable framework that can be updated to reflect such developments when new data or assumptions become available.

The model is inspired by the law of gravity in physics, which states that the gravitational force between two objects depends on their mass and the distance between them. In this model, GDP is considered as “mass” that attracts trade flows. Regions with a higher GDP will have a higher demand for trade and will, therefore, import more. This is because larger economies have more production capacity and a larger consumer base, which in turn requires more raw materials, semi-finished goods and finished products (Anghelache et al., 2019).

The distance between the port and the NUTS2 zone is a barrier or cost. The higher the distance between these two areas, the higher the cost and the lower the expected trade flows between them. By applying the gravity model, the import flows can be distributed across various NUTS2 zones based on their relative economic size (GDP) and their distance from the ports. Zones with a larger GDP and closer proximity to import ports would receive more imports because they have both the capacity and the proximity to receive and distribute goods efficiently.

The share of the import port from export port e to destination j is then calculated as follows:

$$Share\ import\ port_{e,j} = \frac{1/Total\ transport\ cost_{e,i,j}{}^{2}}{\sum_{i=1}^{n} 1/Total\ transport\ cost_{e,i,j}{}^{2}}$$

The $Share\ import\ port_{e,j}$ is the proportion of imports allocated to import port i for destination j. The total transport $cost_{e,j}$ is distance as a proxy for transport costs between export port e and import port i, to destination j. n is the total number of import ports included in the analysis.

The transport cost is determined for both the maritime and the land transport (pipeline). The transport cost per nm for liquid hydrogen and ammonia are based on the transport cost over sea of Sovechea (2024) and the transport cost per km of pipeline (land based) from European Commission (2021a). Table 3.1 and Table 3.2 present the calculation of this cost. In Table 3.1, the cost per tonne per nautical mile for maritime transport is $\$0.193.10^{-6}$/tonne/nm for LH_2 and $\$0.52.10^{-7}$/tonne/nm for NH_3. Table 3.2 displays the cost per tonne per kilometre for pipeline transport (hinterland transport), which is €$0.240.10^{-6}$/tonne/km for LH_2 and €$0.520.10^{-6}$/tonne/km for NH_3. The weigthed cost ratio of the transportation cost for hydrogen and ammonia is obtained by taking the average values from both tables. The cost ratio of 2030 is 2.1229 for LH_2 and 17.1662 for NH_3. The cost ratio for land transport cost over maritime cost is called α, in the calculations a ratio of 75% hydrogen and 25% ammonia is used which will lead to a value of 5.8837. As transport costs can vary depending on infrastructure, distance and technological developments, a sensitivity analysis will be conducted in Chapter 6 to assess the impact of different cost assumptions.

Table 3.1: Transport cost over sea for LH_2 and NH_3

Transport Cost	LH_2	NH_3
Cost	2.09 \$/kg	0.56 \$/kg
Maritime distance from Rotterdam to Australia used in the study of Sovechea	10,850 nm	10,850 nm
Cost per tonne/nm	0.000000113 euro/tonne/nm	0.000000030 euro/tonne/nm

Source: own composition based on Sovechea (2024)

Table 3.2: Hinterland transport cost LH_2 and NH_3

Transport Cost	LH_2	NH3
Cost	0.6 euro/kg	1.3 euro/kg
Distance used in the study of the European Commission	2,500 km	2,500 km
Cost per tonne/km	0.000000240 euro/tonne/km	0.000000520 euro/tonne/km

Source: own composition based on European Commission (2021a)

Furthermore, an assumption is needed for the maximum land-based transport distance, which means the maximum distance in which transporting hydrogen or ammonia via pipeline is more interesting than transporting hydrogen or ammonia by sea. According to the research by d'Amore-Domenech et al. (2023), hydrogen is typically transported via pipeline for distances up to 6,500 km. For distances between 6,500 km and 10,000 km, transporting hydrogen in its liquid form is most effective (Jurišic, 2023). Beyond 10,000 km, the use of Liquid Organic Hydrogen Carriers (LOHCs) is considered the best option (d'Amore-Domenech et al., 2023). As mentioned before, the European pipeline network does not connect a port with every NUTS2 zone. The most suitable alternative for distances up to 3,000 km would be transporting compressed hydrogen (CH_2) by ship, which falls out of the scope of this dissertation (Song et al., 2021).

After collecting the distances between NUTS2 zones and their connecting ports, the total cost of transport between export port e to destination j is calculated by:

$$Total\ transport\ cost_{e,j} = \left(distance\_land_{(i,j)} * \alpha\right) + (distance\_sea_{(e,i)} * 1.853)$$

The $distance\_land_{(i,j)}$ is the distance between the importing port and the final destination (NUTS2) within the country, measured nautical miles. The $distance\_sea_{(e,i)}$ is the distance between the exporting port and the importing port, measured in nautical miles. The formula converts the distance from nautical miles to kilometers by multiplying by 1.853[2].

To calculate the amount of H_2 and NH_3 that goes through an import port (i) is calculated as follows:

$$Amount\ of\ tons\ via\ port_i = \sum_{c=1}^{m}\sum_{j=1}^{L} Share\ port_{(e,i,j)}\ .tons_{j,c}$$

In this formula this dissertation considers c countries (m = 6) and in each country has j. regions (L = number of NUTS-2 zones) to which the energy needs to be distributed. All of these flows will be summed to get a total import volume per region.

Subsequently, the total amount of tonnes required in a hinterland region j (NUTS2 region) is then calculated by distributing the total energy need of a country based on its economic activity per NUTS-2 region, which is proxied by the GDP:

Subsequently, the total amount of tonnes imported in a destination j (NUTS2 region) is then calculated:

$$Tons_{j,c} = Total\ import_c\ * \frac{gdp_j}{\sum_{j=1}^{l} gdp_j}$$

The total amount of tonnes imported into a destination j (a NUTS2 region) in country c is calculated by distributing the total import volume of non-carbon energy in country c proportionally based on the GDP of each region. The formula ensures that economically stronger regions receive a larger share of the total non-carbon energy imports.

To conclude, the gravitation model is used to assign the non-carbon import flows per port. After calculating the non-carbon import flows per port, several port outputs can be calculated. The next sections explain how the vessel requirement is calculated. Thereafter, Section 3.4.4. elaborates on the method applied to calculate the space requirements and the costs of storage.

3.4.3. Vessel requirements

The number of vessels calls to import the required energy per year for each import port can be calculated by determining the import volumes illustrated in the gravitation model. Inputs are needed for the sizes of the vessels and their capacity. Based on the specifications of the first design of a ship to carry liquid hydrogen (LH_2), the vessel has a capacity of 11,200 tonnes per vessel (Parkes, 2022). This vessel, developed

[2] 1 nm = 1852 m

by Kawasaki Heavy Industries, has a total volume of 160,000 m^3 and is comparable in scale to a standard LNG carrier (Parkes, 2022). The development trajectory of this vessel type illustrates the long innovation cycles in the maritime sector: Kawasaki began conceptual work around 2013, and the smaller prototype vessel (Suiso Frontier, 1,250 m^3) only completed its maiden voyage in 2022. The full-scale carrier remains in the early stages of deployment as of 2025. This ten-year development period demonstrates that large-scale shifts in vessel design require significant time and investment, and widespread commercial use of larger or more efficient LH_2 carriers is unlikely before 2030. Therefore, this study uses the current design as a conservative and realistic basis to estimate vessel requirements for future decades, acknowledging that while efficiency gains may emerge over time, their impact on vessel numbers should not be assumed prematurely given the long development timelines and the potential for delays due to trade barriers, regulatory uncertainty, or geopolitical disruptions.

For ammonia (NH_3), following the data of Martin (2023), 1.9 million tonnes of NH_3 were transported between mid-2021 and mid-2023 using 114 vessels, resulting in an average of 16,667 tonnes per vessel (Martin, 2023). The first four vessels will be delivered by the end of 2026 (Martin, 2023). This is a realistic estimate, taking into account current vessel designs and transport trends (Ju et al., 2020). Similar to hydrogen carriers, external factors such as trade barriers or geopolitical issues could affect the pace of fleet expansion or modernization. Using these inputs, the number of vessels calls of ship type k per week in a certain year x in port i is calculated with the following formula:

$$Nvessel\ calls_{i,k,x} = \frac{Amount\ of\ tons\ via\ port_i}{capacity\ per\ vessel_k . 52}$$

The formula for $Nvessel\ calls_{i,k,x}$ calculates the total number of vessel calls required at import port i to transport non-carbon energy to its captured hinterland per week in year x. per vessel type k (H_2 or NH_3). In the calculation the ration between H_2 and NH_3 vessels is set at 75% H_2 and 25% NH_3.

The $capacity\ per\ vessel_k$, refers to the tonnage capacity of the vessel used for transportation (ammonia or liquid hydrogen). This formula, therefore, calculates the total number of vessel calls required at import port i to move the specified amount of non-carbon energy to destination j, accounting for both the vessel capacity and the portion of the energy transported by sea.

3.4.4. Space requirements and costs of storage

The lead time for hydrogen and ammonia at a port can vary with demand, but the lead time is approximately 20 days or three weeks (G. Decan, personal communication, July 9, 2024). Therefore, the created scenarios will assume a storage time of three weeks in the port. An increase in the lead time for hydrogen and ammonia in a port will correspondingly enlarge the requirement for space because the products will stay longer in the port and subsequently, more storage space is needed. The required storage volume per energy carrier k (hydrogen or ammonia) for each importing port is calculated as follows:

$$required\ storage\ volume\ port_{i,k,x} = Nvessel\ calls_{i,k,x} * storage\ time_{i,k} * capacity\ per\ vessel_k$$

The required storage volume for an import port i in a specific year x is calculated by multiplying the number of required vessels to import the required energy per week by the storage time for that energy type in port i and the capacity per vessel. The number of required vessels is determined from the previous calculation, which accounts for the volume of imports and the required fleet. Storage time refers to the amount of time the cargo needs to be stored at the port before it is further distributed. The capacity per vessel represents the maximum amount of cargo a single vessel can carry. This formula estimates the total storage volume needed at the port i to accommodate the imported non-carbon energy while taking into account the required fleet, storage time and vessel capacity.

To determine the amount of storage tanks, inputs are needed about the size of the tanks and the products stored. The energy density of the products is required. The energy density of hydrogen is 33.3 kWh/kg according to different sources such as Cipriani et al., Zou et al., Ratnakar et al. and Aceves et al. (2010; 2014; 2021; 2022). The energy density of ammonia is different according to the scientific sources. Measurement conditions, assumptions in calculations, unit conversions, the physical state of ammonia, and the specific use case or application of ammonia context could explain the differences in the numbers. Table 3.3 indicates the sources used to calculate ammonia's average energy density level. The average of 5.46 kWh/kg will be used in further analysis.

Table 3.3: Energy density value of ammonia

Title	kWh/kg	Source
Progress in green ammonia production as potential carbon-free fuel	6.32	(Chehade & Dincer, 2021)
Using ammonia as a sustainable fuel	4.73	(Zamfirescu & Dincer, 2008)
Ammonia as effective hydrogen storage: a review on production, storage and utilization	5.17	(Aziz et al., 2020)
Handbook of chemistry and physics	4.73	(Lide, 2004)
Hydrogen & fuel cells: advances in transportation and power	5.08	(Hordeski, 2020)
Ammonia (NH3) Storage for Massive PV Electricity	6.30	(Y. Wang et al., 2018)
Ammonia as a renewable energy transportation media	5.88	(Giddey et al., 2017)
average	**5.46**	

Source: own composition

The storage tank assumptions for the measurement for liquid hydrogen are based on a sphere of the study of Ratnakar et al. (2021). This a sphere with a volume of 225 tonnes and a diameter of 22 m for liquid hydrogen storage (Ratnakar et al., 2021). The safety distance around the sphere is assumed to be five meters for an LH_2 tank following the study of Ratnakar et al. (2021). The European Commission (2023d) study assumes that an LH_2 terminal has a utilization rate of 50% and a send-out capacity ratio of 2.5%. The send-out capacity is the ratio between the hydrogen that could be stored and the amount that can be sent out (delivered, consumed or exported) per unit of time.

The total energy content is calculated as follows:

$$Total\ energy\ content\ of\ one\ storage\ tank_k = mass\ of\ one\ storage\ tank_p \times\ energy\ density_p$$

The $Total\ energy\ content\ of\ one\ storage\ tank_k$ is the total energy content of a single storage tank for product p (either ammonia or liquid hydrogen). The total energy content of one storage tank is 7.5 GWh for liquid hydrogen and 2000 GWh for ammonia (Clean Hydrogen Partnership & Deloitte., 2023). The $mass\ of\ one\ storage\ tank_p$ is the amount of stored product in one tank for liquid hydrogen 225 tonnes and for ammonia 36,364 tonnes (Clean Hydrogen Partnership & Deloitte., 2023). $Energy\ density_p$ is the energy density of the product in megawatt-hours per tonne (33.3 MWh/tonne for liquid hydrogen and approximately 5.3 MWh/tonne for ammonia).

The assumptions for ammonia storage are based on a Vopak tank (2022). The capacity of the tank is needed to calculate the size of a storage tank. The capacity of the ammonia tank is 55,000 m^3. By using the energy density of ammonia, 5.46 kWh/kg, the mass for one storage tank is 36,364 tonnes (Vopak, 2022).

The mass per storage tank is calculated by dividing the total energy content by the density. After calculating the mass per storage tank of hydrogen and ammonia further port storage costs can be calculated, starting with the amount of storage tanks required:

$$\# \, storage \; tanks \; required_k = \left. \frac{storage \; volume \; port_{i,k} * energy \; density_k}{10^3} \middle/ Storage \; tank \; size_k \right.$$

Once the number of storage tanks is calculated, the required storage space can be determined using:

$$Storage \; space \; required \; (ha) = \frac{storage \; tanks \; required * required \; area}{10^4}$$

The estimated cost of one LH_2 tank is 12.49 million euros for LH_2 (liquid form of hydrogen). The cost is determined by the size of the tank (7.5 GWh/storage tank) and the storage cost ranging from 0.61 to 2.71 million euros per GWh. For this analysis, the average storage cost of 1.665 million euros per GWh is used for liquid hydrogen, which results in an average cost for a storage tank of $12{,}5.10^6$ EUR (European Commission, 2023f).

The average storage size of an ammonia refrigerated tank is 328 GWh with a CAPEX cost of 0.196 MEUR/GWh, which results in an average cost for a storage tank of $64{,}3.10^6$ EUR. (European Commission, 2023f). With this information the cost for investing in the storage tanks per energy carrier k (storage $cost_k$) can be computed:

$$Storage \; cost_k = \# \, storage \; tanks \; required_k \, . cost \; storage \; tank_k$$

To conclude, after the data was collected and country level calculation were made, the gravitation model is used to assign the non-carbon import flows per port. This quantification of hydrogen and ammonia imports forms the foundation for understanding ports' role in the energy transition. With the import flows determined, the next step is to assess the alignment between these imports and port objectives. In Chapter 7, this dissertation evaluates how the projected hydrogen and ammonia imports integrate into port strategies. By doing so, this dissertation examines to what extent ports are prepared for the large-scale adoption of non-carbon energy and how these imports align with their goals.

3.5.Alignment port objectives

This section outlines the methodology used to examine how the implementation of a hydrogen scenario in European ports contributes to achieving port objectives. The research question of Chapter 7 is formulated as follows: *How well are the strategic plans of port authorities aligned with the ambitions of transitioning towards a hydrogen-powered hub?*. The research approach of this alignment is inspired by the frameworks of Acciaro et al. (2014, 2018) and Acciaro & Sys (2020) and employs a scoring system to evaluate the relevance of port objectives and the success of the transition to a hydrogen-powered hub scenario in meeting these objectives.

The first step involves selecting European ports as the foundation for the analysis. Next, a preliminary list of port objectives is compiled based on a thorough review of the existing literature. This list is validated by port authorities and subsequently refined into a final of objectives. Data collection is carried out through interviews with energy transition experts within port authorities. During these interviews, the hydrogen-powered hub scenario is explained in detail, ensuring that respondents have a clear understanding of the research context before completing the survey.

The survey with likert scale gathers scores that assess two key aspects: the importance of specific port objectives and the potential success of the hydrogen scenario in achieving those objectives. To evaluate the consistency and consensus in scoring, the homogeneity index (H-index) is calculated. This index measures the degree to which respondents agree on their assessments. High values of the H-index indicate strong consensus among participants, while lower values suggest variability in scoring.

The analysis combines these scores to measure the alignment of the hydrogen scenario with port objectives. This provides insights into whether the transition to a hydrogen-powered hub scenario effectively supports the strategic goals of the ports, offering a structured framework to assess the viability of this energy transition in the maritime sector.

3.6.Conclusion

This chapter outlined a structured methodological framework for a scenario-based analysis required to address the research objectives of future import volumes, specifically for hydrogen and ammonia and estimating port-specific requirements. Thereafter, the alignment between the implementation of hydrogen projects and port objectives is researched.

The first part elaborated on the methodology used for the foundation for scenario development both at country level and at port level for their non-carbon imports. The method of the theoretical framework and analysis of the energy outlooks is explained.

The second part explained the data collection. The data illustrates the detailed energy balance calculations; the analysis considers primary production, imports, exports and stock changes to determine gross inland consumption and total energy supply. This allows for scenarios of non-carbon energy imports, particularly for hydrogen and ammonia for 2030, 2040, and 2050. The researched dataset was obtained from Eurostat. The Eurostat data used in this research provides a comprehensive and reliable foundation for scenario development and analysis, covering energy balances across 28 European countries, including the 27 EU member states and Norway. This data, sourced annually from national institutions like statistical agencies and energy ministries, enables detailed insights into primary energy production, imports and consumption patterns across key economic sectors relevant to port operations. Focusing on 2022 ensures that the analysis covers recent trends, capturing current energy flows and market dynamics. Additionally, GDP data for European regions at the NUTS2 level allows for a distribution of import flows, by using a gravitation model.

The third part explained the methodology used at country-level. It uses energy balance calculations, including primary production, imports, exports and stock changes to estimate gross inland consumption and total energy supply. This enables developing scenarios for non-carbon energy imports for ports, focusing on hydrogen and ammonia for 2030, 2040, and 2050.

The fourth step translated the country-level import data into port-level insights. This was achieved through a gravitation model methodology that distributes non-carbon imports across ports based on factors such as GDP and hinterland connectivity. This step enables a detailed understanding of how future import flows are likely to be distributed among ports.

The final section explored the methodology for assessing the alignment between hydrogen projects in ports and their strategic objectives. This involves evaluating the consistency and success of non-carbon energy transition scenarios in meeting port objectives, using scoring systems and analytical tools such as the H-index and Wilcoxon test.

The methodological framework developed in this chapter serves as a basis for the analyses in Chapters 4, 5, 6 and 7. These analyses will quantify the import volumes, spatial requirements and storage costs for hydrogen and ammonia at major European ports under various scenarios. Additionally, the framework facilitates understanding how these energy transitions align with broader port objectives, offering strategic insights into the adaptation of ports to future energy flows. This structured approach enables answering the overarching research question.

Chapter 4

Towards energy transition scenarios for liquid port flows

The introduction chapter illustrated the necessity of shifting away from the coal industry as an energy source is necessary as the world experiences the effects of climate change. Embracing the energy transition is crucial and an enabler in paving the way for a sustainable future. However, much uncertainty is seen in the pathway to decarbonization. Institutions and regulators can be barriers and facilitators of the energy transition. The higher the government cooperation, the more it accelerates the energy transition following the study of Patrahau et al. (2021).

The European energy crisis, starting in 2021, raises interest in the future energy mix. The 2021 energy crisis was driven by a combination of factors, including a recovering global demand for energy following the COVID-19 pandemic and a limited supply of natural gas. Harsh winters and geopolitical tensions, such as Europe's reliance on Russian gas, further intensified pressure on energy markets. In particular, the Russian invasion of Ukraine in 2022 marked a turning point in Europe’s energy policy, exposing vulnerabilities in supply chains and accelerating the shift towards energy independence and diversification. This led to soaring energy prices, supply disruptions and an increased focus on the energy transition and diversification of energy sources. This energy crisis raises a lot of questions. Which energy source is most suitable? Which energy mix is viable in which region? Does one best focus on one or more energy sources?

Also, ports need to be prepared. Infrastructure and logistics systems are required to support the port's competitive position by serving businesses and consumers. Therefore, it is necessary to examine the current and future markets. By analyzing these aspects, the research establishes a foundational understanding that will guide the development of our scenarios for energy transitions in port settings.

This thesis focuses on examining the energy transition in ports, with particular attention to scenarios and the associated requirements for costs, surface calculations and infrastructure needed to support the transition of energy flows within the port. Ports undergo the transition and must ensure that sufficient infrastructure is in place to accommodate new energy flows. A scenario analysis provides a range of potential outcomes, offering insight into what might occur in the future. This tool enhances understanding and allows for more informed decision-making. Importantly, decisions are not derived directly from the scenarios themselves; instead, the scenarios serve as a framework to explore possibilities and better grasp uncertainties associated with specific choices. By using scenarios, more targeted and better decisions can be made. Scenario development is widely recognized as a method for managing high levels of uncertainty when shaping future business strategies and government policies (Snoek, 2003).

The descriptive scenarios will be created from the energy outlooks of prominent institutions (DNV, IEA, Clarkson etc.) in two steps. The first step includes analyzing the existing and future energy market and global carbon-energy-supplying-countries. The second step involves zooming into the European energy market and liquid bulk ports which should adapt to the energy transition to stay competitive. This evaluation serves as the foundation for the development of descriptive energy scenario for ports.

Chapter 2 presented that prior research focused mainly on the adoption of alternative fuels in shipping, aiming to reduce emissions from ships. However, there is a notable research gap concerning the broader energy transition within port environments, specifically in relation to how evolving energy flows, such as the increased handling of hydrogen and ammonia as energy carriers, will impact port competition, port cargo focus, port operations, infrastructure and their strategic positioning as a port. By addressing this gap, the following research question is posed: *What are the energy transition scenarios for Europe?*

This chapter is organized into sections that provide a comprehensive analysis of energy transition concepts and scenarios. Section 1 delves into the theoretical framework for transition scenarios, laying the foundation to build up the scenarios. Section 2 analyzes the global market, looking at the global supply and demand outlook. Furthermore, it analyzes the carbon energy trade, specifically the oil market and discusses global energy countries. In Section 3, the analysis zooms in on the European market. It looks at the supply side outlook and import, export and production flows. Section 4 zooms further into important liquid bulk ports in Europe to give an understanding of key ports in the energy transition. Section 5 includes the development of descriptive energy transition scenarios specifically for European ports. Section 6 provides the discussion of the scenarios described. Lastly, Section 7 entails the conclusion of this chapter. This outline ensures a systematic exploration of the energy transition within port environments.

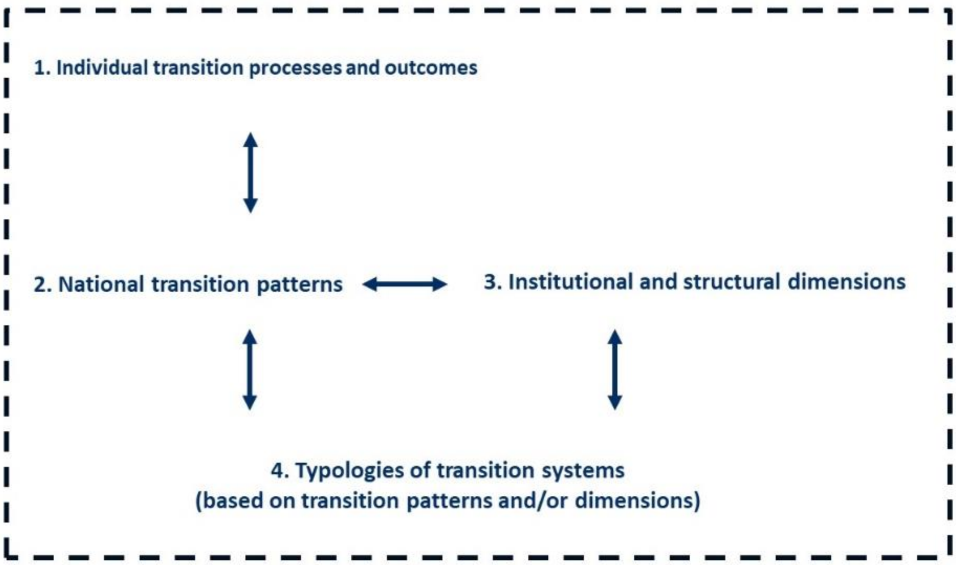
4.1.Theoretical framework for transition scenarios

The theoretical framework for energy transition scenarios in this section offers a structured approach to understanding and addressing the uncertainties of future developments. First, the conceptual framework of transition systems is analyzed and translated to ports. Subsequently, the drivers and factors that shape the energy scenarios will be examined.

4.1.1. Transition systems

A transition entails a comprehensive ecosystem that must adapt accordingly (Raffe, 2008). The framework of a transition system (Figure 4.1) provides an understanding of their dynamics and characteristics. By exploring the framework of transition systems, insights are gained into the different elements interacting with and influencing each other within a transition process. This facilitates the identification of critical points and intervention strategies to drive successful and sustainable transitions in various domains. This will enable the development of more effective strategies and interventions for achieving sustainable and resilient transformations.

Figure 4.1: A conceptual framework of transition systems



Source: own composition based on Raffe (2008)

The first level is the transition processes and outcomes. The individual transition processes and outcomes are measured at the micro-level, which in the port context involves specific actions taken within individual port operations. As an example, these actions could include adopting renewable energy technologies such as wind and solar, implementing green infrastructure for energy storage and increasing low-carbon carriers such as hydrogen or ammonia in port operations. Such micro-level changes represent the building blocks of a broader transition toward sustainability and are often driven by technological advancements, market demand and regulatory requirements. (Raffe, 2008)

The second level, the national transition patterns, is at the macro level and includes aggregate transition processes and outcomes, associations, inequalities, labor-market integration, etc. Level 2 in transition systems for energy transition in ports involves broader trends such as integrating renewable energy into the port energy mix, developing hydrogen infrastructure, or increasing adoption of circular economy principles across ports. These patterns are influenced by national and regional energy policies, such as the European Union's green transition targets, which are designed to reduce carbon emissions and promote the use of renewable energy across various industries, including the maritime sector. National transition patterns also consider factors like the role of ports in the supply chain, regional cooperation, and the alignment of infrastructure development with national energy and climate goals. (Raffe, 2008)

Level 3, institutional and structural dimensions are the independent variables that predict national transition patterns. This includes national regulations, EU directives, and institutional support mechanisms that guide green transition efforts in ports, such as the European Green Deal and the Renewable Energy Directive. The role of public-private partnerships and the involvement of various stakeholders, including port authorities, logistics companies and energy providers, is also critical at this level. These institutional and structural elements help predict the success of national transition patterns and influence the pace of change within the sector. (Raffe, 2008)

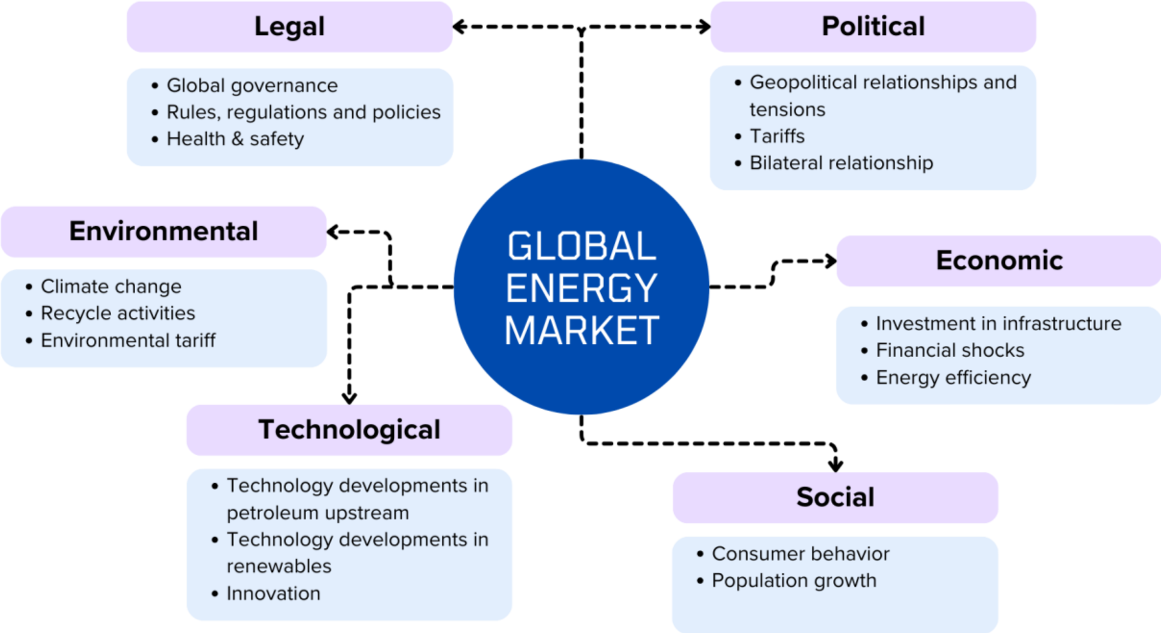
Lastly, at Level 4, typologies help categorize the various pathways and strategies that ports might adopt in their energy transition. These typologies can differentiate ports based on their level of investment in green technologies, their role in energy supply chains, or the extent to which they are integrated into broader sustainability networks. Depending on their progress toward meeting sustainability targets, ports might be classified as innovators, early adopters or laggards. These typologies provide a framework for understanding how different ports may evolve and how they contribute to the overall transition toward a sustainable energy system. (Raffe, 2008)

Several factors and challenges influences the transition of ports to sustainability. According to Geerlings (H. Geerlings, personal communication, February 18, 2023), three main drivers play a crucial role in transitioning ports to sustainable ports. On the one hand, companies and ports must rethink their businesses and eliminate their reliance on fossil fuels to align with climate objectives. Secondly, on the other hand, these companies generate substantial profits from their involvement in the fossil fuel industry. Lastly, the geopolitical landscape significantly impacts on the energy transition, with factors such as wars, conflicts, and trade restrictions exerting a substantial influence (SRM, 2023).

4.1.2. Drivers and factors shaping energy scenarios

Before moving to scenario development, it is essential to note that different drivers and factors shape the energy scenarios. Ghasemian et al. (2020) researched the impact of various factors on global energy scenarios. Figure 4.2 presents these five key factors and some examples of drivers. To further refine this analysis, a PESTEL analysis is used, which examines the political, economic, social, technological, environmental, and legal factors that influence the energy transition. This additional layer will provide a more comprehensive understanding of the external forces shaping the development of energy scenarios.

Figure 4.2: Driving forces of global energy scenarios



Source: Own composition based on Ghasemian (2020) and Mat Yusop (2018)

The study of Ghasemian (2020) identifies five main domains and key factors steering on the global energy markets: social, technological, economic, environmental and political driving forces. The social drivers of global markets include population growth, aging population, urban development, labor force growth, workforce productivity, etc. Technological examples are technology development, remaining technically recoverable natural gas or oil etc. Economic drivers include energy efficiency, financial shocks, world GDP growth, prices etc. Environmental factors such as climate change, chemical pollution, carbon capture and storage significantly influence the energy outlook. Lastly, political drivers such as global governance, national energy policies and geopolitical relationships are essential. (Ghasemian et al., 2020)

The relevant drivers are defined by cross-impact analysis. Cross-impact analysis is a method used to analyze and understand the relation between various factors or events within a system, typically when planning for complex or uncertain futures. According to the cross-impact analysis of Ghasemian et al. (2020) on global energy markets identified the social drivers as population growth and consumer behavior. The technological drivers are developments in renewables and upstream petroleum. The economic drivers are an investment in infrastructure, financial shocks and energy efficiency. The environmental driver is climate change, and the political drivers are geopolitical relationships and tensions as well as global governance (Ghasemian et al., 2020).

However, beyond these five driving forces, the legal aspect significantly impacts the global energy landscape, such as global governance, rules, regulations and policies (Mat Yusop, 2018). The research of Mat Yusop (2018) also also applies the PESTEL analysis to assess the business environment, aiming to enhance understanding of macro-environmental factors. This framework is particularly suitable for identifying influencing factors in the global energy market, as it considers political, economic, social, technological, environmental and legal dimensions. The legal component involves the regulatory frameworks that shape how energy is produced, consumed and distributed. Policies tied to global climate agreements, national energy strategies, and the role of governments in shaping energy transition are pivotal in guiding the energy markets. Although Ghasemian et al. (2020) emphasize only five domains, the inclusion of legal factors provides a more comprehensive understanding of the forces at play. The list of examples for all the drivers is inexhaustible. However, it gives a good view on the important factors influencing global energy markets.

Furthermore, the study of Bazilian et al. (2020) sums up the following fundamental driving forces for energy scenarios: policy, energy technology, disruptive advancement, falling costs or slow progression of energy technology (Bazilian et al., 2020). The study of Erin Bass & Grøgaard (2021) describes the long-term energy transition via low-carbon and renewable energy solutions drivers as the co-evolution and interaction of economic, social, technological and regulatory components.

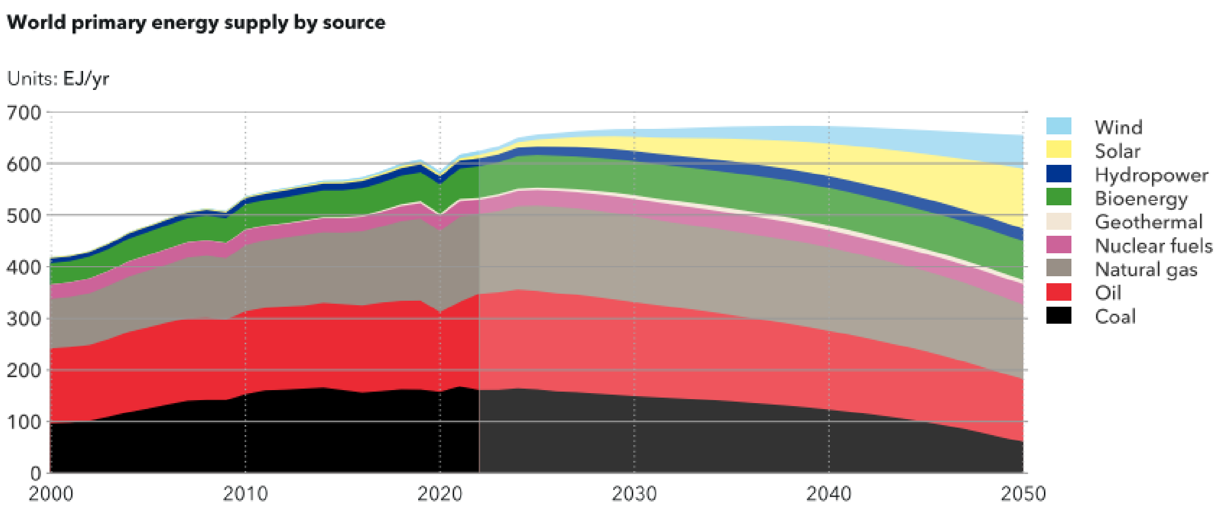
4.2. Global energy market outlook

The global energy market is at a crossroads, as oil-producing companies and nations face significant challenges in aligning with the 2050 climate goals. On the one hand, these companies strive to be as profitable as possible, but on the other hand, they try to satisfy regulatory institutions by reducing their CO_2 emissions. This tension underscores the need for a level playing field that harmonizes climate goals with economic objectives in the energy sector. A level playing field is needed to streamline climate goals with the industry's financial and growth goals (Delbeke, 2023).

4.2.1. Supply and demand

Fossil fuels are the largest source of CO_2 -emissions and must be phased out to meet global climate targets (Calverley & Anderson, 2022). However, despite these goals, more than 80% of our energy comes from fossil fuels (DNV, 2024; Ritchie et al., 2020). Figure 4.3 presents the world's primary energy supply by energy source.

Figure 4.3: World primary energy supply by source



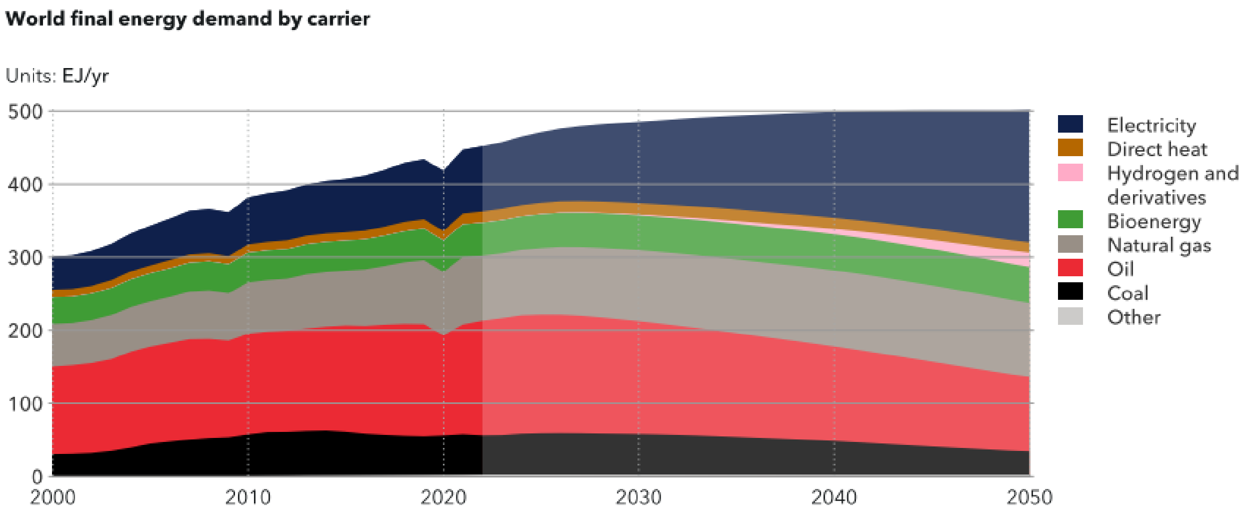
Source: DNV (2024)

DNV forecasts the global energy supply by source until 2050 of wind, solar power, hydropower, bioenergy, geothermal energy, nuclear energy, natural gas, oil and gas. Before the pandemic in 2019, primary energy was at the level of 594 EJ. In 2023, the primary energy supply was 634 EJ. The forecast suggests a peak in 2038 at 673EJ/year, while in 2021 DNV estimated a peak in 2030 at around 617 Exajoule (EJ) (DNV, 2021, 2024) (Appendix A). The primary energy supply mix will change significantly by 2050. The share of fossil fuels will decrease from 80% in 2023 to 50% by 2050. The decline is the highest for coal falling from 25% to 9% over the next 27 years (DNV, 2024). The share of renewables will triple from 15% in 2023 to 44% by 2050. Within the renewable energy share, the largest increase is for solar and wind, which will increase by 14-fold and 9-fold towards 2050. Solar energy will reach 18% and wind energy will be 10% of the total energy supply. (DNV, 2024)

Despite the significant share of bioenergy in DNV's projections, this dissertation does not include it as a central focus as mentioned in Chapter 1. Bioenergy involves distinct logistical chains, lower energy density, and complex sustainability certification, making its large-scale import structurally different from other energy carriers. Bioenergy does not seamlessly integrate with the liquid bulk systems and high-volume energy flows that are the focus of this dissertation. Therefore, the analysis concentrates on energy carriers whose logistical profiles and infrastructural demands more directly match the operational realities and strategic priorities of ports.

Figure 4.4 presents the demand side, it shows a decline in fossil fuels and an uptake of renewable alternatives (electricity, hydrogen etc.) (DNV, 2024). In 2023, electricity represented 20% of the world's final energy use. By the end of the forecast period, electricity will increase up to a share of 36% at 181 EJ. Electricity has a higher efficiency in its end use than other energy carriers such as coal (DNV, 2024). Hydrogen and its derivatives show significant growth in the forecast from a negligible contribution in 2023 to 4% in the final energy demand by 2050. The direct use of oil and coal decline by about 40% by 2050. In contrast, direct use of natural gas increases modestly over the forecast period, driven by growth in the buildings and manufacturing sectors. (DNV, 2024)

Figure 4.4: World final energy demand by carrier



Source: DNV (2024)

Comparing the supply and demand side shows that DNV expects that the total energy supply will be higher than the total energy demand. The total energy supply is expected at 655 EJ/year for the supply and 500 EJ/year for the demand side. The mismatch between energy supply and demand, as predicted by DNV, can be addressed through a combination of policy measures, technological adjustments and market dynamics, focusing on reducing fossil fuel production, scaling up renewable energy, improving storage technologies, and promoting integrated energy markets. The supply of coal (60EJ/year by 2050) is much higher than the demand for coal (40EJ/year) by 2050, highlighting a growing oversupply of coal as demand declines due to shifts towards cleaner energy sources. Conversely, the demand for oil is projected to outpace supply, indicating potential supply constraints or a stronger dependence on alternative fuels in sectors where oil demand remains resilient. These mismatches suggest adjustments will be needed in energy production, infrastructure and policy to align supply with evolving demand patterns.

The energy demand outlook of BP (2024) is twofold, one for the “current trajectory” and one under a “Net Zero” scenario for 2022 by 2050. In 2022, fossil fuels (oil, natural gas, and coal) dominate the energy mix, with renewables and nuclear and hydro power contributing less. Under the "Current Trajectory" forecast for 2050, the share of renewables grows, but fossil fuels still occupy a significant portion of the energy mix. By contrast, in the "Net Zero" scenario for 2050, renewables, nuclear and hydro power make up the majority of the primary energy supply, while fossil fuel consumption declines, particularly for coal and oil. BP's report (2022) shows a decline in fossil fuels and an increase in renewables by 2050 compared to 2020. The total final consumption is higher in the New momentum scenario compared to 2020. In the Accelerated and Net Zero scenarios, the final energy consumption will be shown to be lower in 2050 compared to the levels of 2020.

DNV’s forecast of global energy demand reflects on two potential pathways for meeting future energy needs. The "Current Trajectory" of BP aligns with DNV’s projected gradual increase in renewable energy, though fossil fuels will still play a major role by 2050. However, the "Net Zero" scenario, aiming for carbon neutrality by 2050, requires an intense shift towards renewables, nuclear, hydropower, sharply reducing reliance on fossil fuels (BP, 2024). DNV's (2022) report also includes a roadmap for the energy transition. According to DNV, non-fossil energy is projected to comprise 51% of the energy mix by the year 2050. Following their roadmap, 5% of this energy mix will consist of hydrogen by 2050. By 2045, the solar power supply will be at 35% of the full energy supply.

The energy demand in the world energy outlook of IEA (2024d) confirms the previous reports. From 2013 to 2023, the fossil fuels in the global energy mix decreased from 82% to 80%. Although this does not seem to be a high decrease, the demand for energy has increased by 15% over this period and 40% of this growth has been met by clean energy. Coal has already been in a structural decline for advanced economies since 2008, while oil demand peaked for advanced economies in 2005. In their Stated Policies Scenario (STEPS), 58% of renewables (threefold compared to 2023) is reached, but still falling short of their Net Zero Emissions Scenario, which reaches 90% of clean energy by 2050.

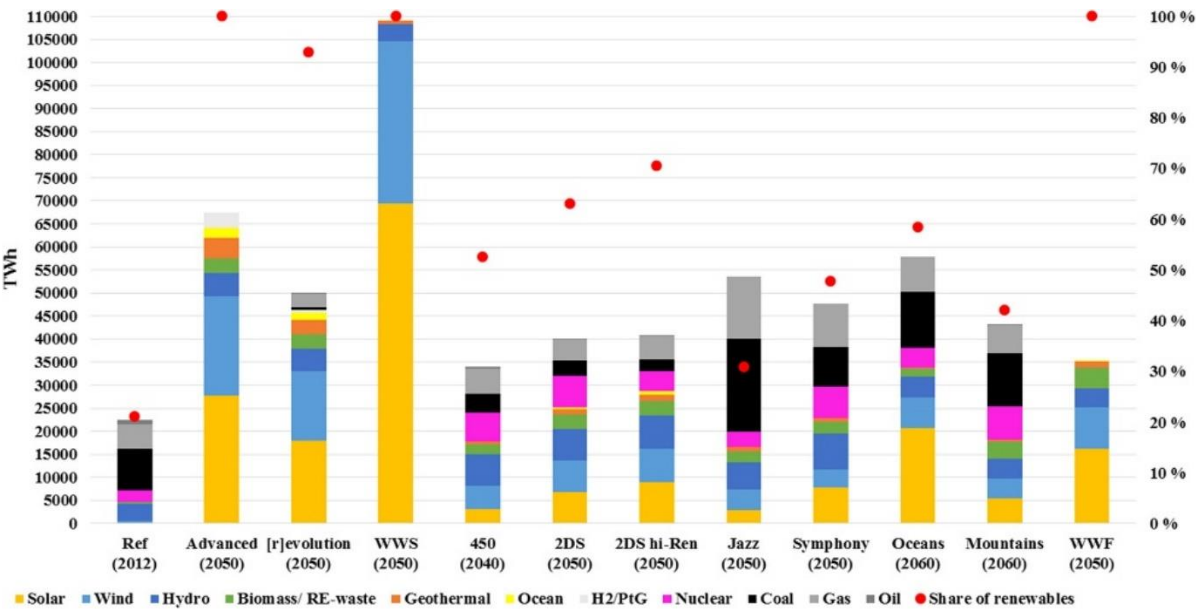
These outcomes are similar to those of Stopford (2022). Stopford also expects a decrease in oil and coal consumption combined with an extensive uptake of renewable consumption from 2020-2050. Stopford sees renewables at approximately 325 exajoules by the end of 2050 (Stopford, 2022).

4.2.1. Global energy scenario comparison

Based on the forecasts of leading institutions, a composite energy outlook is created. The research of Child et al. (2018) compared energy technologies, which shows the diversity of energy outlooks of the supply side, as shown in Figure 4.5.

Figure 4.5 presents the twelve researched scenarios of the paper of Child et al. (2018). The diversity in the different scenarios is considerable. Analyzing the scenarios for 2050 shows that on average 75% of all energy generation will exist out of renewable power (red dots). Three scenarios (Advanced, World Wild Fund and Wind Water and Solar) are more optimistic and estimate a 100% share of renewables in their energy mix. The Wind Water and Solar (WWS) scenario is an outlier in the group since it excludes bioenergy. Furthermore, the Ref scenario estimates the lowest energy generated in 2050, between 20,000 and 25,000 Twh electricity generation from different sources per year. There is not yet a consensus on the role of carbon capturing and storage (CCS) in future energy scenarios.

Figure 4.5: Electricity generation (TWh) from different sources and share of renewable power in total generation (%)



Source: Child et al. (2018)

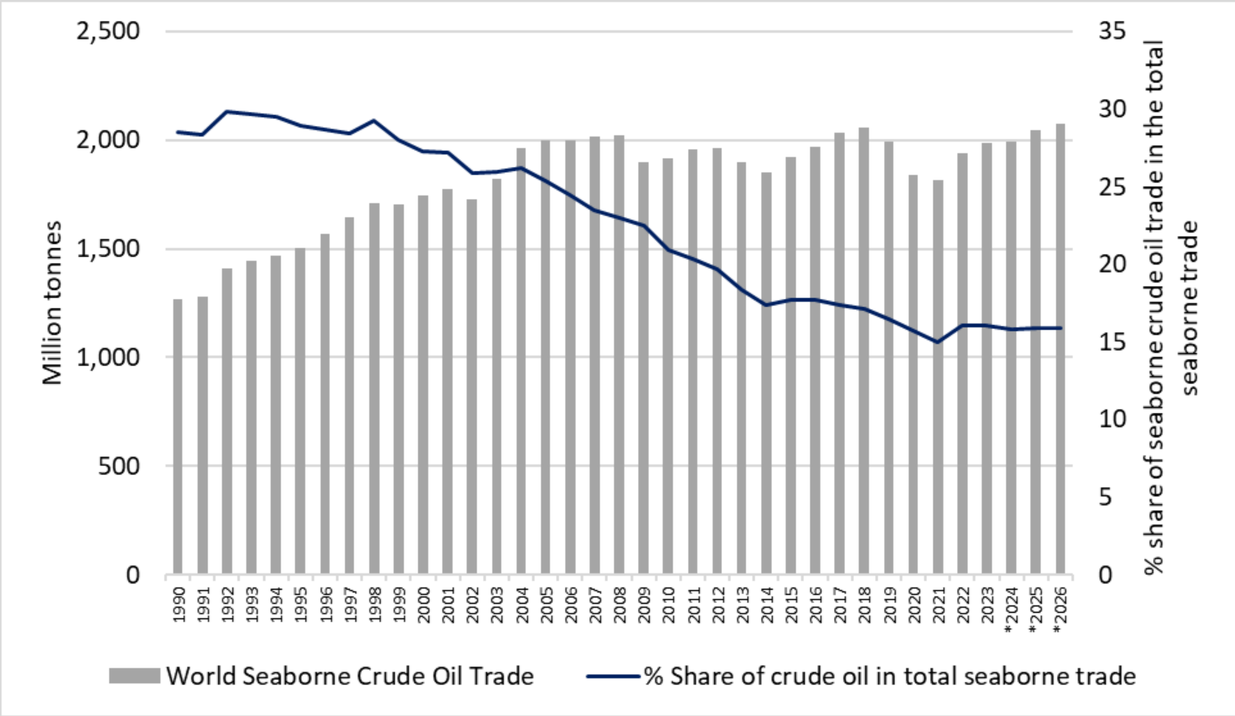
A comparative analysis of different energy outlooks (IEA, DNV, BP and BNEF) shows that, in general, a growth in renewables is estimated and a decrease in coal as a fuel can be seen. BP (2022) estimates that primary energy will decrease, but the extent to which it will fall is still unclear. BP also estimates that fossil fuels will still account for approximately 60% of all primary energy in 2050.

Our research chooses to work with different scenarios to address these uncertainties in future energy flows, enabling a holistic view of different pathways and their outcomes.

4.2.2. Crude oil trade

As part of the global energy supply and demand landscape, crude oil remains a key commodity, with its trade patterns offering insights into market dynamics and strategic interests. Figure 4.6 illustrates the world seaborne crude oil trade.

Figure 4.6: World seaborne oil trade



Source: Clarkson Research (2022)
*forecast

The years 2024, 2025 and 2026 are forecasts made by Clarkson Research. The forecast can give an estimation of how the world seaborne crude oil trade is going to evolve in the coming two years. However, oil is a strategic business. Market economics are influenced by many companies and organizations that control the crude oil trade (Stopford, 2009).

The world seaborne trade in crude oil showed a solid increase from 1990 to 2001. In 2022, there was a decrease, initiated by a slowdown in demand and the effect of the Asian financial crisis (UNCTAD, 2002), followed by a sharp rise. After that, the trade stagnated more or less at the same volume. However, the percentage share of the oil trade in the total world seaborne trade decreased from 1990 to 2022. Since more people live on this planet, the demand for energy and other goods is not reducing over this period. The demand for crude oil must be substituted by sustainable alternatives to compensate for the demand for crude oil. After 2022, the share of oil trade in the total seaborne trade stagnated.

According to DNV, the transition towards more sustainable alternatives is a contributor to the decline in the share of oil (2018b, 2024). The crude oil and oil products peak are expected to be reached around 2030 (DNV, 2018b). The report of TotalEnergies (2022) enforces the phasing-out of crude oil in the maritime industry as a fuel and the shift to renewable energy such as H_2-based fuels, electricity and biofuels.

4.2.3. Overview of global energy supplier countries

The energy transition from fossil fuels to renewable energy sources is a pivotal global challenge. Ports are crucial enablers in this transformation due to their roles in energy imports, exports and technological advancements.

Traditionally, energy trade was dominated by fossil fuels such as coal, oil and natural gas, extracted in a limited number of countries. In contrast, renewable energy sources, such as solar and wind, are more evenly distributed across the globe, allowing more regions to become energy producers. This geographical redistribution of energy production has the potential to transform existing dependencies and reduce the concentration of energy power. While some conventional fossil fuels like coal are being phased out in many parts of the world, others such as liquefied natural gas (LNG) and shale gas have experienced temporary growth due to their lower carbon emissions compared to coal and their role as transition fuels. Shale gas, extracted through hydraulic fracturing (or "fracking"), has notably altered energy markets, particularly in the United States, which became a net energy exporter largely due to its shale revolution (EIA, 2024). However, environmental concerns, including groundwater contamination, methane emissions, and induced seismicity, have led to restrictions or outright bans on fracking in several countries, such as France, Germany, and the Netherlands. This duality highlights the tension within the energy transition: short-term strategies to reduce emissions can sometimes conflict with long-term sustainability goals. Simultaneously, the emergence of green hydrogen and ammonia as potential energy carriers presents new opportunities and challenges. These molecules can be produced in regions with abundant renewable resources and transported globally, enabling a new form of energy trade. However, the required infrastructure, such as electrolysers, storage facilities and specialized ships and terminals, is still under development. (EIA, 2024)

The energy demand of countries is an important factor for attracting flows. The top ten leading total energy suppliers are China, the United States, India, Russia, Japan, Brazil, Canada, Iran, Korea and Germany. The growth in energy production in 2022 was mainly driven by China, the United States (US), Saudi Arabia, India, Indonesia and Brazil (IEA, 2024c). The growth in crude oil production was driven by Saudi Arabia and the United States (Enerdata, 2023). The largest sources of energy in the world in 2022 are oil (30%) and coal (28%) (IEA, 2024c). The total electricity generation in the world has grown by almost 90% over the period of 2000-2022; the downside of this energy is that it's still mainly created with fossil fuels, more specifically coal and natural gas (IEA, 2024c). This section dives deeper into these ten main energy-supplying countries, as presented in Table 4.1. These countries take up a share of 67% of all global emissions.

Table 4.1: Top 10 global energy-supplying countries

NR.	Country	% global emissions	Δ 2000-2022 global emissions	% share of renewables in total power generation
1	China	31.10%	245%	24.20%
2	United States	13.51%	-20%	21.10%
3	India	7.38%	182%	22.00%
4	Russia	4.76%	10%	7.90%
5	Japan	2.85%	-15%	21.50%
6	Brazil	1.21%	40%	87.50%
7	Canada	1.53%	4%	68.50%
8	Iran	2.04%	123%	3.90%
9	Korea	1.61%	32%	7.10%
10	Germany	1.79%	-25%	39.40%

Source: Own composition based on IEA (2024a)

China is the world's largest primary energy supplier in 2022 (IEA, 2024c). Since, China is very reliant on coal (71.4% of its total energy production), their emissions have gone up by 245% in the period from 2000-2022. China accounts for 31.10% of the global emissions. However, it is making significant strides to catch up in hydrogen technology (Chai et al., 2021; IEA, 2024c). The EU is still ahead in terms of technology, especially in terms of technology efficiency (Chai et al., 2021). However, China benefits from lower production costs. Additionally, China leads the world in solar panels and batteries, where it is dominant. In contrast, Europe aims to be a leader in wind energy and electric vehicles. Shanghai, specifically the port of Shanghai, plays a crucial role in the energy transition with its Green Port Development Strategy aiming for carbon neutrality by 2060 (L. Collins, 2022). The port promotes hydrogen as a key energy carrier and supports LNG and methanol usage. Significant investments in LNG infrastructure, solar and wind energy underscore its commitment (L. Collins, 2022). Financial backing includes substantial contributions from the Chinese government and the CMA CGM Group to support clean energy initiatives and achieve net-zero emissions by 2050 (L. Collins, 2022). In 2022, China's renewable share is 24.2% of its total power generation.

North America plays a key role in ensuring global energy security because of two of the world's top ten oil producers in the United States and in Canada and the world's largest natural gas producer in the United States (US) (IEA, 2024a). The United States is the second largest energy producer and consumer.The total energy supply of the United States consists of 36% oil and 35% natural gas (IEA, 2024a). Following EIA (2023), the total amount of petroleum imports to the US rose sharply in the 1970s, more specifically from members of OPEC countries. In the US, it rose until 2005. Thereafter, there is a small decline in petroleum imports (EIA, 2023). There are multiple reasons for the decline in petroleum imports in the US after 2005, such as the US striving towards energy independence and the economic crisis in 2008 (IEA, 2023). In 2024, President Trump was re-elected with his outspoken words, "We will drill, baby, drill." he tends to increase domestic oil production, lower energy prices, and boost the economy regardless of climate change. This clearly illustrates the influence of geopolitical impact on the future of flows in ports (Mampaey, 2024). In 2022, renewables account for 21.1% of US power generation. The US will account for 13.51% of global emissions in 2022; this has gone down by 20% since 2000. (IEA, 2024a)

India has played a significant role in global energy demand, accounting for 11% of the growth since 2010 (IEA, 2024a). India is still highly reliant on coal production; it accounts for 40% of their energy demand in 2020, another 25% of their demand is allocated to oil, and together with gas (6%), it accounts for more than 70% of their total energy demand. In the Stated Policies Scenario (STEPS), which projects the energy sector's trajectory based on current policies, India is anticipated to drive more than 25% of the global energy demand increase through 2035. This reflects India's expanding influence on future energy dynamics under prevailing policy frameworks. India has a higher quality of solar energy due to its hot and dry climatic zones compared to other East-Asian countries, which provide an ideal environment for solar energy generation, making it one of the most promising regions for solar power development. Since 2015 there has been a rapid expansion in their solar power capacity, from 2015 1.9 GW to 80 GW in 2024 (IEA, 2024a).

Russia is the world's second-largest producer of natural gas and has the world's largest gas reserves (IEA, 2024a). Russia has the world's largest gas reserves. In total, it accounts for 4.76% of global emissions in 2022 and has increased with 10% since 2000 (IEA, 2024a). Russia cut off its oil exports to Poland and Finland in 2022 when it launched its military aggression against Ukraine, which affected many countries in Europe (European Council, 2024b). Renewables only account for 7.9% of their total power generation in 2022 (IEA, 2024a). Furthermore, Russia has extended its production of crude oil and coal since 2000 by 69% and 90% in 2022. The production of crude oil, coal, and natural gas accounts for almost 94% of their total energy production. (IEA, 2024a)

Japan is guided by principles of energy security, economic efficiency, environmental sustainability, and safety guided by its energy policy. Japan accounts for 2.85% of the total global emissions, which has decreased by 15% since 2000 by 2022 (IEA, 2024a). Japan is the world's largest importer of LNG and is proactively working towards carbon neutrality (MLIT, 2008). Japan has proposed that the Port of Yokohama survey hydrogen utilization for a carbon-neutral port project. This initiative focuses on upgrading the port function with consideration of decarbonization based on the import, storage and use of large quantities of next-generation energy sources such as hydrogen and ammonia and the concentration of industrial facilities in the waterfront area. The port aims to achieve climate neutrality by 2050 (IAPH, 2021).

Japanese production mainly exists out of nuclear (38.2%), hydro (11.5%), wind and solar (21.5%) and biofuels and waste (24.5%) in 2023. (IEA, 2024a)

Brazil's energy policies are well-aligned with global energy challenges with a high share of renewables, almost exceeding 45% of its primary energy demand (IEA, 2024a). This makes Brazil's energy sector one of the world's least carbon intensive energy countries. Hydropower generates around 80% of Brazil's electricity, making its energy mix one of the cleanest globally, though further expansion is limited by environmental concerns. Solar PV is set to account for nearly 70% of new additions, while natural gas, wind, and bioenergy use are also expanding. As a global leader in biofuels, Brazil's ethanol production is expected to reach 660 thousand barrels per day by 2026. At COP26, Brazil committed to net-zero emissions by 2050 and a 50% emissions reduction by 2030, supported by a ban on illegal deforestation and a developing national hydrogen strategy. (IEA, 2024a)

Canada has set ambitious targets to reduce greenhouse gas emissions by 40-45% from 2005 levels by 2030 and to achieve net-zero emissions by 2050. Energy production and use contribute over 80% of Canada's GHG emissions, with oil and gas production alone responsible for about a quarter. The country's electricity system is already among the cleanest globally, mainly due to its dominant use of hydropower and significant nuclear energy contributions. To meet its climate goals, Canada has implemented several policy measures, including a carbon pricing scheme (carbon tax and emission trading system). Canada, despite its low population density of four people per square kilometre, has a high energy demand due to its vast land area and diverse climate, resulting in significant carbon emissions (Statista, 2020). Canada is one of the highest per capita emitters worldwide, alongside China, the US, India, Russia, and Japan. This high energy demand and emission rate positions Canada as a crucial player in the global energy trade, with the potential to significantly impact energy transition strategies. (Statista, 2020)

Iran's energy mix consists mainly of natural gas (71.8%) and oil (26.2%). 40% of their total energy production consist of crude oil, and another 58.6% consists of natural gas (IEA, 2024a). Renewable energy is gaining importance as Iran seeks to reduce CO_2 emissions and reliance on imported fossil fuels. While renewables mainly generate electricity, they are also being explored for heating and biofuels in transportation. However, the traditional use of biomass for cooking and heating, which causes severe health and environmental damage, is being phased out in line with international climate goals. Their share of renewable energy (2%) in electricity generation is still remarkably low compared to other energy-supplying countries. (IEA, 2024a)

Korea's energy sector is very reliant on fossil fuels, with high industrial energy use and a significant share of coal-fired power generation. However, Korea is driving its energy transition by emphasizing green growth through low-carbon technologies. The private sector's innovation capacity and the population's openness to digitalization play key roles in investments in energy storage, smart grids, and intelligent transport systems. Despite these initiatives, renewables only take up a share of 1.61% of the total electricity generated. Korea's nuclear production accounts for 79.2% of its total energy production. (IEA, 2024a)

Germany's Climate Law outlines a path to net-zero emissions by 2045, with an ambitious energy transition target of 80% renewable electricity by 2030, rising to 100% by 2035, and the complete phase-out of coal. The country has been a leader in offshore wind and solar PV, having also phased out nuclear power by 2023. Major legislative reforms aim for 100-110 GW of onshore wind, 30 GW of offshore wind, and 200 GW of solar by 2030, alongside investments in 10 GW of hydrogen. Additionally, the Energy Efficiency Act targets a reduction of 500 TWh in energy consumption by 2030, around one-fifth of its 2022 energy use. (IEA, 2024a)

The geopolitics of energy supply plays a crucial role in shaping the global transition from fossil fuels to renewable energy, with clear distinctions between countries that remain heavily reliant on traditional energy sources and those taking a leading role in clean energy development. For instance, countries like China and the United States are major fossil fuel producers. China, the largest global energy supplier in 2022, still relies on coal for 71.4% of its energy production but is making significant strides in renewable energy, particularly in hydrogen technology, and solar power continues to dominate the global energy landscape. In contrast, the European Union, particularly Germany, is a forerunner in the energy transition, with ambitious targets for offshore wind and solar energy and plans to achieve 100% renewable electricity by 2035. The geopolitical impact on energy policies is clear in the United States and Russia. It affects the global energy flows. On the other hand, Brazil stands out as a leader in renewable energy, with nearly half of its energy demand already met by clean sources, notably hydropower and biofuels, underscoring its role as a pioneer in sustainable energy practices. Countries have unique resources, challenges, and strategies that determine their approach towards the energy transition. Their strategic investments and policies will significantly shape the future of global energy markets.

4.3.Energy scenario outlook for Europe

The previous general energy outlooks gave insights into the potential future energy mix globally. One thing is sure: the energy mix will change over the years. In this section, the research will zoom in on Europe. The European Commission tries to pioneer the clean energy transition (European Commission, 2019a). The energy system needs to change in the future. However, a lot of uncertainty exists on how it should change. The European Commission sets ambitious goals by imposing regulations such as the Fit for 55. Following the Fit for 55 reports of the European Commission and the European Technology and Innovation Platform (2022b; 2021), renewables-based electrification is the key to delivering climate-neutrality by 2050. According to the European Commission and the European Technology and Innovation Platform (2022b; 2021), electricity will account for 57% of direct and 18% of indirect use through renewable hydrogen and its derivatives. The energy demand by energy carriers is estimated to consist of 57% of electricity, 2% of oil, 1% of natural gas, 8% of heat distributed, 13% of bioenergy, 2% of e-liquids, 7% of e-gas 9% of hydrogen. Wind energy will make up 50% of the EU's electricity mix. Most of the power generation for renewable energy systems (RES) should come from solar photovoltaic (PV) and wind, with solar thermal, tidal and geothermal having small shares (European Commission, 2019a). Offshore wind parks are expected to develop significantly after 2030. The impact of the transition in energy mixes on ports is relevant to decision-making in ports. This chapter zooms in on Europe's energy outlook.

4.3.1. Supply and demand

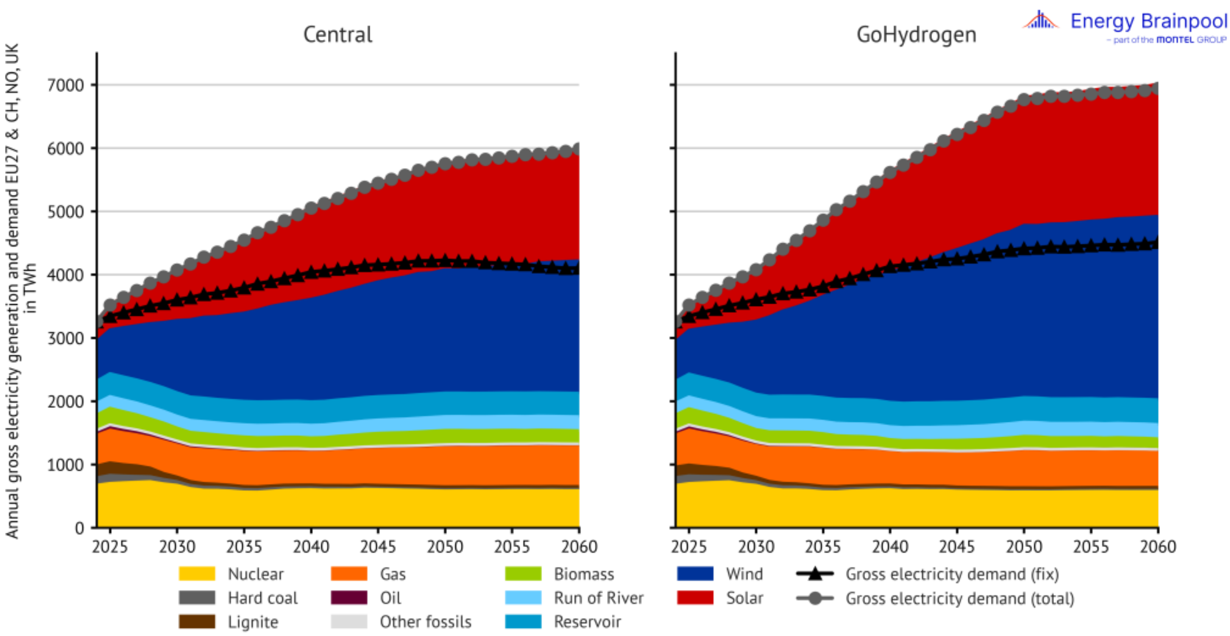
Europe emits 3.2% of the global emissions, which has shown a 30% increase in the period of 2000 to 2022 (IEA, 2024a). The share of renewables is 38.2% of their total power generation (IEA, 2024a). In Europe, a difference between West- and South-Europe regarding the energy transition can be seen. The most significant difference between South and West is onshore and offshore wind energy. Ports in West Europe are investing more in these technologies. In terms of hydrogen, the West currently holds a significant lead. However, according to planned capacities, the South is projected to catch up in hydrogen production (Mauro, 2019). There are also differences in renewable energy share in the total energy mix of countries. Norway and Sweden are the highest in the global ranking, both with a share of almost 60% of renewables in their energy mix in 2021. Malta, Ukraine and Belgium ranked towards the bottom of the list of European countries on the global list, with a share between 8 and 12% in 2021. (IEA, 2024a)

Europe’s reaction to Russia’s cut-off in 2022 was to diversify the imports from gas; Norway and the US take up a large share and the take up of renewables (European Council, 2024b; IEA, 2024a). Europe’s priority was energy security. Norway is a progressive country in renewable energy, heavily investing in offshore wind development to achieve a capacity of 4-6 GW by 2026 and 12-16 GW by 2030 (Skopljak, 2023). Despite its reliance on LNG, Norway is one of the world's largest energy exporters and is shifting towards renewable energy sources like hydropower and enhanced electricity grids (Skopljak, 2023).

The first step is to look at Europe's energy supply and demand. Europe's energy demand or consumption in 2022 mainly exists out of oil products (40.3%) and natural gas (21%). 28% of this demand comes from the transport sector and 25% from the residential sector. (IEA, 2024a). There are no demand forecasts for Europe, as institutions seem to assume that supply will be the determining factor. Supply assumptions often shape the framework for infrastructure planning, especially in renewable energy contexts, as supply capacity is seen as a limiting factor for meeting future demands (Warren et al., 2016).

The supply forecasts by Energy Brainpool, as described by Dahlem (2024) of the electricity generated by 2050 in EU27 include the UK, Norway and Switzerland, based on their Brainpool scenario. Figure 4.7 shows two: the Central scenario and the GoHydrogen scenario.

Figure 4.7: Gross electricity generation EU27 + UK, Norway and Switserland

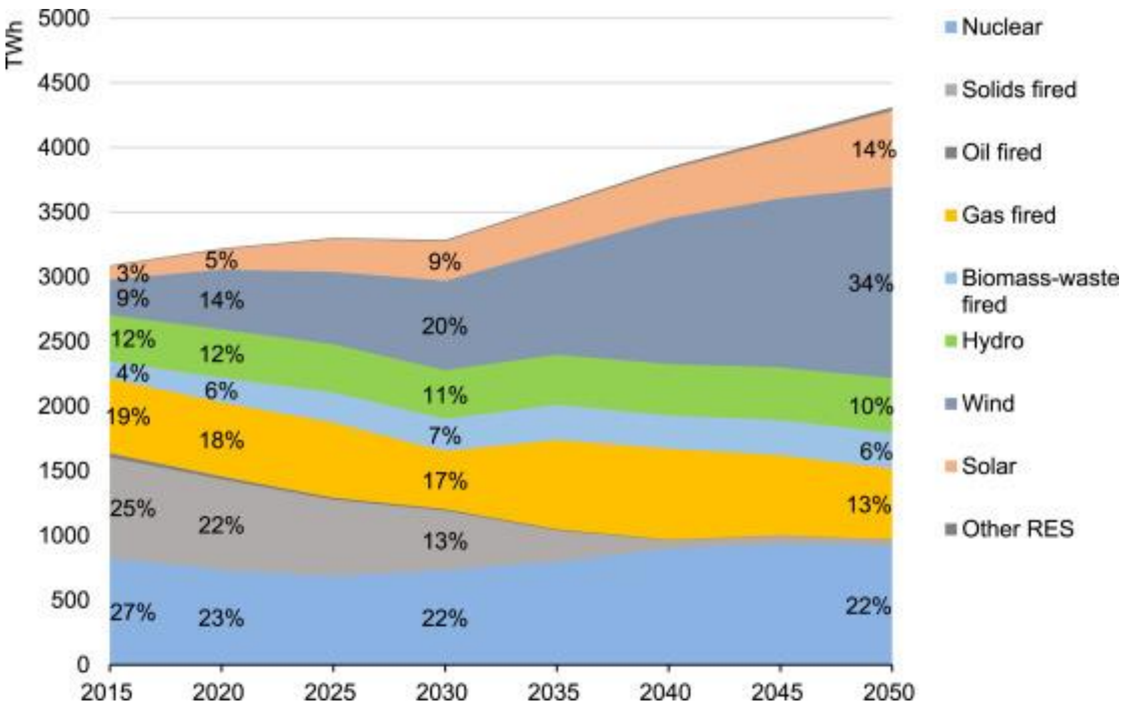


Source: Dahlem (2024)

In the "Central" scenario, fluctuating renewable energy sources are forecast to comprise approximately three-quarters of total supply capacity by 2050. By 2060, renewable energy technologies (excluding hydrogen-powered gas turbines) are expected to represent over 80% of the power plant fleet. In contrast, the "GoHydrogen" scenario envisions a bigger expansion of renewable energy infrastructure. By 2060, installed generation capacities in Europe are projected to surpass 3,500 GW, while in the Central scenario it is projected to be just above 3000 GW. The energy mix will have a significant focus on solar and wind power. By 2050, these sources alone are expected to take a share of more than 80% of the total generation capacity. (Dahlem, 2024; Zhou, 2021)

The research of Capros et al. (2018) estimates the net generated energy mix by 2050 (Figure 4.8).

Figure 4.8: Net generation by plant type in EU28 in the EUCO30 scenario



Source: Capros et al. (2018)

The EUCO30 scenario was made in 2016 by the European Commission. Compared to the above supply and demand scenarios, the EUCO30 scenario is an optimistic scenario. The EUCO30 scenario aims to increase the share of renewables by 30% by 2030 and by 80% by 2050. Following their scenario and estimations, the generated energy mix will consist of 22% of nuclear energy, 1% of other renewable energy sources, 13% of gas-fired fuels, 6% biomass-waste fired, 10% out of hydro-generated energy, 34% wind-generated energy and 14% out of solar energy. (Capros et al., 2018). Based on the scenario of Capros et al. (2018) and assuming a wind turbine produces an average of 3 million kwh per year, the European Union should nearly install 500 million windmills by 2050 across Europe to meet the estimated wind energy generation.

Connolly et al. (2016) present a scenario for 100% renewable energy by 2050. The cost of the smart energy system scenario will be 10-15% higher than in the business-as-usual scenario. The study's results show that if CO_2 reduces by 80% by 2050 compared to 1990, the annual cost of the EU energy system will be approximately 3% higher than the fossil fuel alternative, and it will be 12% higher to reach an energy mix that consists of 100% renewable energy. Enabling the smart energy Europe scenario requires implementing wind power, solar power, electric vehicles, heat savings, individual heat pumps, large-scale thermal storage, district heating, biomass gasification, carbon capture and recycling, electrolysers, chemical synthesis and fuel storage. (Connolly et al., 2016)

Analyzing both the demand and the supply side forecast for 2050 gives more insights into the energy mix of 2050. Although both scenarios include slightly different countries, are from various institutions and have a different starting point (2010 and 2015), the forecasts show similarity. The biggest share in the demand scenario (Zhou, 2021) is for wind (30%), gas (20%), nuclear (17%) and solar (16%). In the supply scenario (Capros et al., 2018) the main shares are slightly differently divided. The most significant share is also wind power but with 34%, more than in the demand scenario. Followed by nuclear power (22%), solar (14%) and gas (13%). The trend in both scenarios is clear, more renewable energy carriers and phasing out fossil fuels (coal, crude oil etc.). RES, such as wind and solar can profit after 2030 from cost reduction and a super-grid connection from the North Sea which enables and stimulates the use of the RES (Capros et al., 2018).

In summary, Europe has ambitious renewable energy targets and expects significant shifts in supply and demand. Demand in 2022 is dominated by oil products and natural gas, with renewables steadily increasing their share over the last decade. Wind and solar power will lead the transition, supported by large-scale infrastructure expansions such as offshore wind parks and super-grid connections after 2030. Supply scenarios emphasize a rapid shift toward renewables, with projections of over 80% of generation capacity from wind and solar by 2050. Regional differences persist, with Western Europe advancing in wind energy and hydrogen development, while Southern Europe shows promising growth in planned hydrogen capacities and solar power. In response to geopolitical disruptions like Russia's gas supply cut, Europe prioritized energy security by diversifying imports and accelerating renewables adoption. The trend is clear: phasing out fossil fuels and fostering renewables will dominate Europe’s energy strategy, requiring massive infrastructure investments and innovative technologies to meet climate-neutrality goals.

4.3.2. Overview of existing energy flows in Europe

The European energy system is transforming due to climate goals and shifting supply and demand dynamics. At the core of the current system lies the refining sector, which plays a pivotal role in ensuring the availability of energy products while adapting to align with future energy objectives. The refining sector plays a crucial role in Europe’s energy supply but must adapt to remain future proof. Refineries, such as those of TotalEnergies and ExxonMobil, are strategically located near petrochemical hubs and can continue contributing to a climate-neutral economy by producing sustainable energy such as advanced biofuels and synthetic fuels (Killemaes, 2024). According to Energia, a sector federation in Belgium, there will still be demand for liquid fuels by 2050, particularly for transport modes that are difficult to electrify (Killemaes, 2024). However, significant investments are required, supported by a stable European regulatory framework and potential government subsidies to mitigate investment risks. Refineries are already working on the energy transition by reducing emissions by decarbonizing existing production processes and embracing new technologies. (Killemaes, 2024)

Europe's energy landscape is shaped by its dependence on imports, notably liquefied natural gas (LNG). It imported 134 billion m3 of LNG in 2023 (Winckelmans, 2024). LNG imports amount to 37% of Europe's total imported gas demand for 2023. In 2021, LNG comprised less than one-fifth of the imported gas demand. Due to its substantial LNG imports, Europe contributes to other nations' economic prosperity. Notably, significant proportions of these imports originate from countries such as the United States (37%), Qatar (12.1%), Russia (11.7%), and Algeria (9.5%) (Winckelmans, 2024). The global LNG demand in 2024 is approximately 405 million tonnes a year. The expectation is that LNG demand will increase by more than 50% by 2040 by Poten & Partners (2023).

In this thesis, non-carbon energy is seen as energy that does not emit carbon dioxide or other greenhouse gas emissions, such as nuclear energy, hydrogen, wind, solar and biomass. Carbon-based energy releases carbon dioxide or other greenhouse gas emissions such as coal, crude oil, unabated natural gas etc.

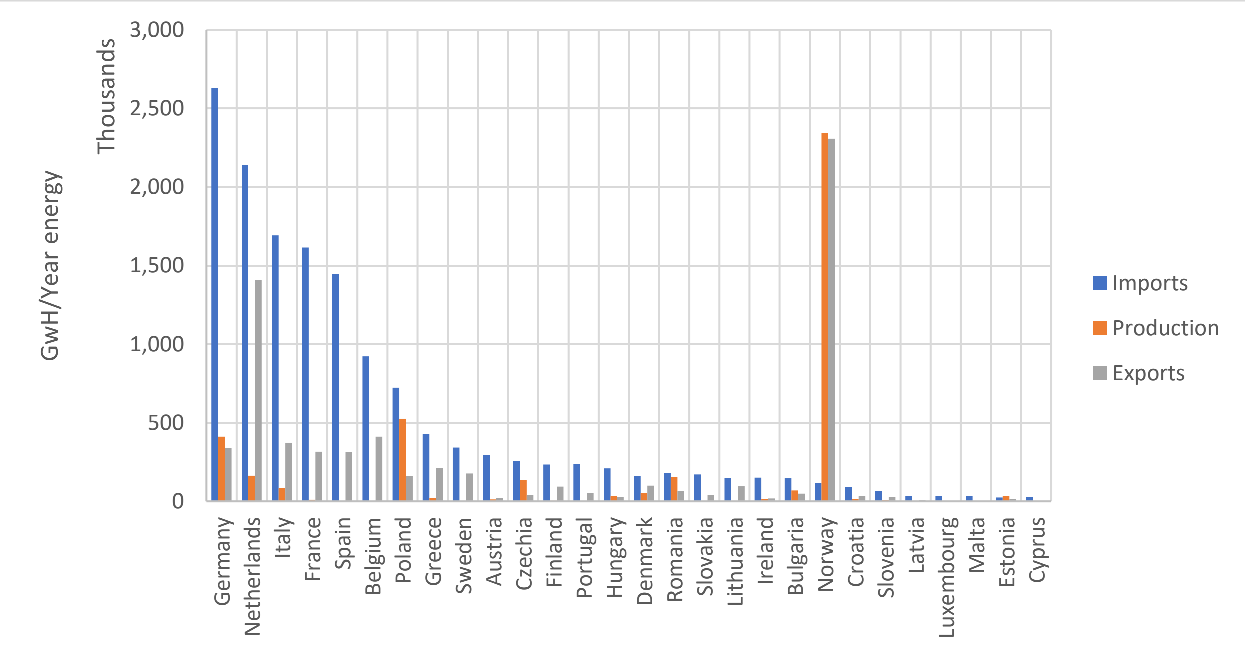
Due to climate change and measures taken to mitigate it, the demand for carbon-based energy needs to switch to low-carbon hydrogen and its derivatives, such as ammonia. Poten & Partners (2023) researched the potential of repurposing LNG terminals. Both ammonia and liquid hydrogen are not a perfect fit for an LNG terminal. However, liquid hydrogen is more favorable than ammonia when re-using selected components with cost savings of 100 million dollars for liquid hydrogen and 300-400 million dollars for ammonia. However, in response to climate change and international efforts to reduce carbon emissions, Europe is shifting its energy focus from fossil fuels to low-carbon alternatives such as hydrogen and ammonia. Following the study of IRENA (2022) and d'Amore-Domenech et al. (2023), the energy trade will shift from carbon energy transport to non-carbon energy.

This shift toward hydrogen, ammonia, and its derivatives is particularly important for European ports, which aim to achieve 100% carbon neutrality. This goal contrasts with the port of Los Angeles, which targets an 85% reduction in emissions by 2050 (The port of Los Angeles, 2023). In light of ambitious CO_2 reduction initiatives in Europe, Europe anticipates a decline in LNG demand by 2030 by 11%. This reduction is aligned with efforts to mitigate greenhouse gas emissions and transition towards more sustainable energy sources. Consequently, there is a forecast surplus of LNG, prompting a strategic shift towards greater emphasis on hydrogen as an alternative energy solution. (Winckelmans, 2024)

Import, production and export

Figure 4.9 shows European countries' import, production and export of carbon-based energy. The countries that import the most carbon-based energy are Germany, the Netherlands, Italy, France, Spain, and Belgium. (Eurostat, 2024a)

Figure 4.9: Countries carbon-based energy overview (2022)



Source: own composition based on Eurostat (2024a)

These six most importing countries show higher imports than their production and export of carbon energy. However, the Netherlands shows a high level of exports compared to other importing countries. It exports 1.2 thousand GWh of oil and petroleum products, which accounts for more than 30% of all oil and petroleum product exports. The geographic location of the Netherlands, combined with the refinery resources, makes it very attractive for exporting oil and petroleum products (Port of Rotterdam, 2024a). This is also known as the "Rotterdam Effect", which refers to the phenomenon where a significant portion of, in this case, crude oil imported into the Port of Rotterdam in the Netherlands is subsequently re-exported to other countries without being refined or consumed in the Netherlands (Kuipers, 2018). Rotterdam's status as one of the largest oil trading hubs globally is facilitated by its strategic location, extensive storage facilities, and advanced infrastructure. Oil tankers often offload their cargo in Rotterdam for storage, blending, or distribution to other European countries. The Port of Rotterdam can accommodate large tankers because it guarantees sufficient draught (Kuipers, 2018).

Besides the Netherlands, Germany also shows high levels of carbon-based energy imports. Germany's main supplier of carbon-based energy is Russia (Wettengel, 2024). The Netherlands and Germany are followed by Italy, France, Spain and Belgium, with Belgium importing almost 1 million GwH in 2022.

Norway is an outlier in production, especially compared to its imports. The reason for Norway's high amount is their LNG production and their production of oil and petroleum products. Poland is a large producer of carbon energy due to its coal production. Poland is a major producer or extractor of coal due to the presence of coal mines. France produces significant amounts of nuclear energy. (Eurostat, 2024a)

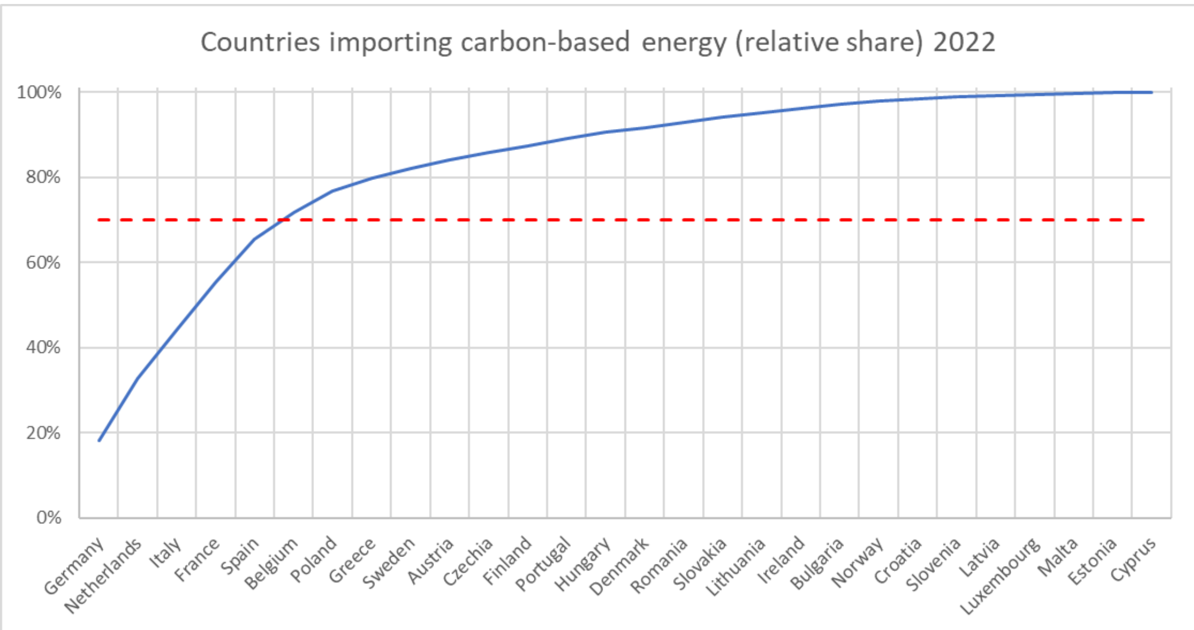
In terms of carbon exports, Norway and The Netherlands are the biggest. The production of carbon-based energy in Norway is high, specifically of natural gas, which translates into high volumes of exports. As discussed above, the "Rotterdam effect" also applies to the exports. The port of Rotterdam serves the ideal conditions to attract oil carriers and enable efficient export to international ports. Rotterdam exports are high in oil and petroleum products. (Kuipers, 2018)

The import and export flows show Europe's dependence on carbon-based energy. The import/production ratio is high for Germany, The Netherlands, Italy, Spain and Belgium. A high ratio indicates high import numbers and low production, which means that they rely a lot on importing carbon energy (transport) and these countries and their ports could eventually play a role as a hub. The countries attracting most of the importing carbon-based flows should switch to renewable alternatives. (Wettengel, 2024)

Share of import carbon-based energy

Figure 4.10 presents the relative share of European country's imports of carbon-based energy. Striking is that the first six countries that import the most carbon-based energy together have a share of more than 70% of all carbon-based energy imports in 2022. These countries play a vital role in the energy transition because they must reduce their carbon imports and replace them with sustainable alternatives.

Figure 4.10: Countries importing carbon-based energy (relative share)

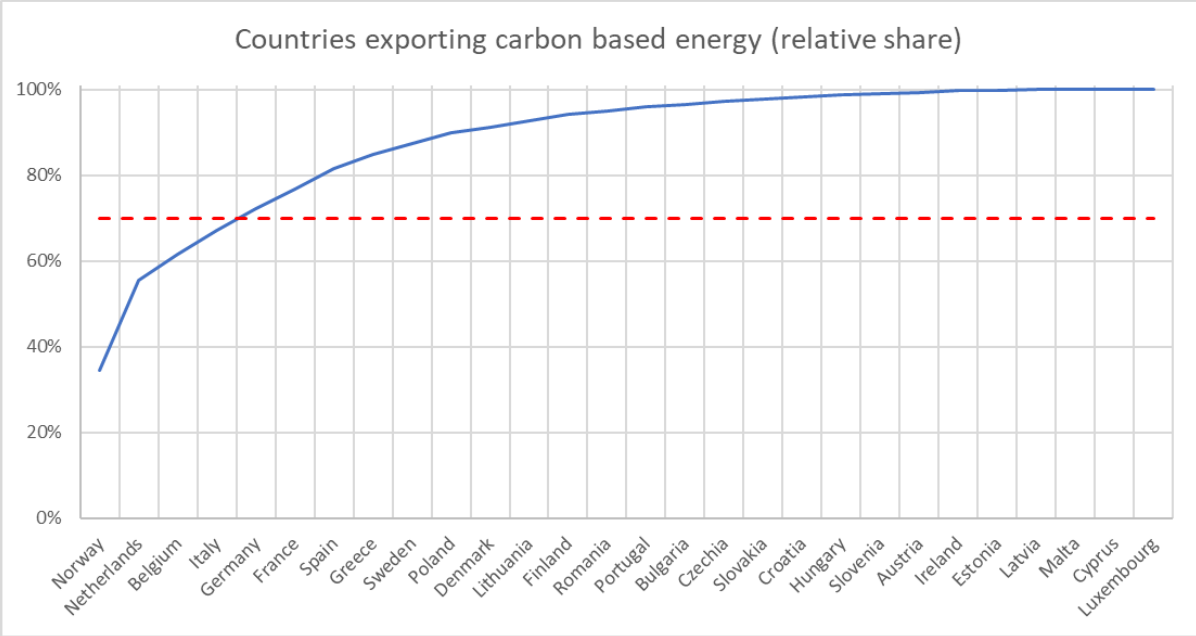


Source: Own composition based on Eurostat (2024)

Share of export carbon-based energy

Figure 4.11 shows the relative export shares of carbon-based energy in European countries, highlighting Norway's significant role in this share. Norway alone contributes over 30% of the overall share of carbon-based energy exports in Europe (geopolitical entity). Norway and the Netherlands bring the export share beyond 50%. Subsequently, Belgium, Italy, Germany, France, and Spain follow in descending order.

Figure 4.11: Countries exporting carbon-based energy (relative share)



Own composition based on Eurostat (2024)

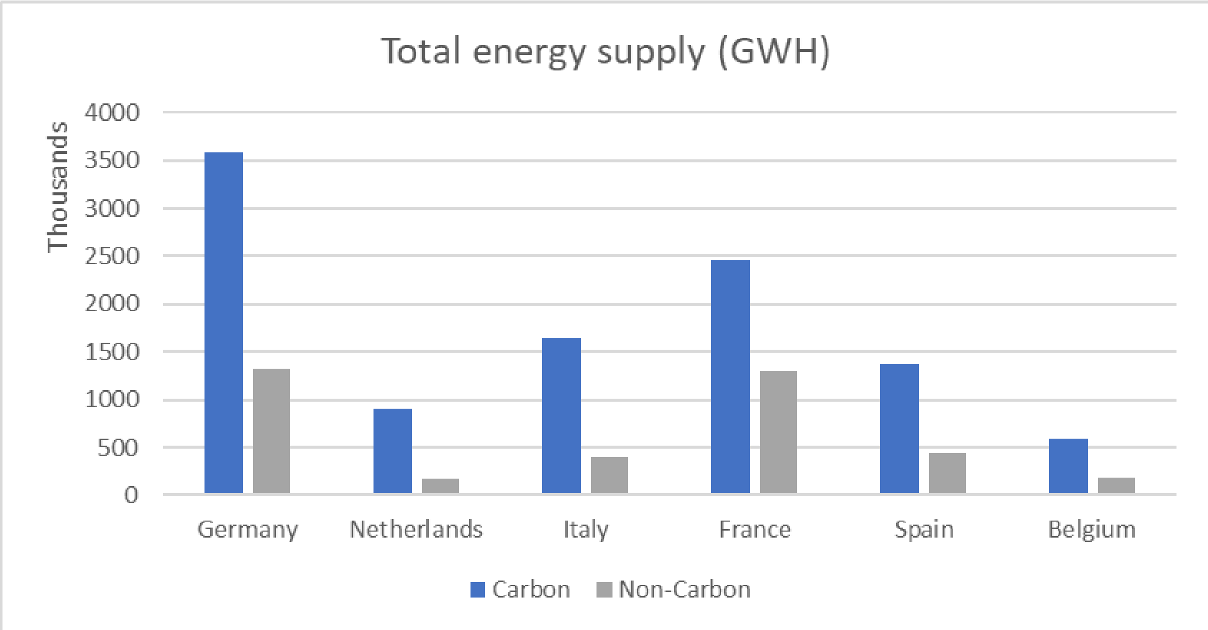
The import and export data derived from the data above of carbon-based energy from European countries indicate that only a select few countries contribute significantly to the overall import and export figures. Germany, the Netherlands, Italy, France, and Belgium consistently rank in the top six for import and export. Furthermore, Spain emerges as an outlier in imports, occupying the seventh position in exporting carbon-based energy. At the same time, despite its prominence in exports, Norway notably lags in imports, positioned at the 21st place.

The analysis of Europe's production, import and export illustrates the importance of six countries: Germany, The Netherlands, Italy, France, Spain and Belgium.

Total energy supply

Figure 4.12 represents the total energy supply of these six countries expressed in GwH. Germany and France have the largest carbon energy supply. Germany's supply of carbon energy will surpass 2,500 thousand GwH in 2022. The non-carbon share of both countries is almost half of their total carbon energy supply, which is relatively high compared to the Netherlands, Italy, Spain and Belgium. Due to its nuclear production, France has nearly reached half of the carbon energy supply with its non-carbon supply. Germany is the leading producer of renewable energy and biofuels in Europe. France is the largest importer of LNG in Europe in terms of volume. Thereafter, Spain, The Netherlands, Italy and Belgium follow in the second, third, fourth and fifth place (ACER, 2024). The graph indicates that these six countries predominantly depend on carbon energy sources rather than non-carbon alternatives.

Figure 4.12: Calculation of total energy supply



Source: Own composition based on (Eurostat, 2024a)

The figures above clearly state the dependence of the six most importing countries of carbon energy. These countries could play an important role in the energy transition because they must change their energy mix to mitigate climate change.

Building on the insights of this section, which emphasizes the crucial role of the six key energy-supplying countries in Europe's carbon energy imports, it becomes important that the focus must now shift from countries to ports. Ports are key enablers of trade and thus of importing non-carbon energy (IAPH, 2024). While these countries are central to the energy transition due to their reliance on carbon-based energy, the ports within these countries serve as the critical nodes for energy import, storage and distribution. Therefore, understanding the dynamics of these maritime hubs is essential for evaluating the infrastructure requirements and regulatory changes needed to support a successful energy transition across Europe. (Notteboom & Haralambides, 2023)

4.3.3. Analysis of key ports in handling liquid bulk in Europe

The ports analysed in this research were chosen to reflect the diversity across Europe in terms of size, regional characteristics, competitiveness, proximity to key markets, cargo handling, and market positioning. Building on the findings from the previous sections, which highlighted six key energy-supplying countries: Germany, the Netherlands, Belgium, France, Spain, and Italy. By understanding the current dynamics of carbon energy imports, the research can better evaluate the necessary infrastructural and regulatory adaptations required for a successful energy transition in these key maritime hubs (IEA, 2023). The research will further focus on identifying the ports that play a pivotal role in energy import, export, storing and handling.

This chapter will delve into the top 20 European ports (Eurostat, 2024b) based on their total cargo volumes, with a specific emphasis on their share of liquid bulk handling. This focus is essential, as ports involved in liquid bulk are significantly impacted by the ongoing energy transition. The ports in these countries will serve as vital nodes in this transition, facilitating the import and distribution of renewable energy such as hydrogen, ammonia, and biofuels. To ensure a comprehensive analysis, additional ports from other countries will be considered based on strategic factors such as geographical location and their role in facilitating energy trade. This approach provides a holistic understanding of how European ports are positioned.

Table 4.2 of Eurostat (Eurostat, 2024b, p. 20) represents the top 20 European ports in total cargo volume, measured in gross weight of goods handled. As the composition of the top 20 ports changes over the analysed years in the data set, the list of included ports of Eurostat is greater than 20 (30). The data includes all cargo types: liquid bulk, dry bulk and containerized cargo. However, Table 4.2 only includes the liquid bulk handled in 2022 of these ports expressed in thousand tonnes.

Table 4.2: Importing amount of liquid bulk in top 20 ports in handling cargo volumes (thousand tonnes)

No.	analysis	Port	2022 (thousand tonnes)	Share of total	Acc. share
1	Y	Rotterdam	211,672	25%	25%
2	Y	Antwerp-Bruges	89,729	11%	36%
3	Y	Amsterdam	44,628	5%	41%
4	Y	Trieste	41,720	5%	46%
5	Y	HAROPA (Le Havre and Rouen)	40,834	5%	51%
6	Y	Marseille	39,380	5%	56%
7	Y	Cartagena	28,011	3%	59%
8	Y	Algeciras	27,287	3%	62%
9	N	Gdansk	25,044	3%	65%
10	N	Sines	24,774	3%	68%
11	Y	Wilhelmshaven	22,612	3%	71%
12	N	Augusta	22,514	3%	74%
13	N	Göteborg	22,130	3%	76%
14	Y	Bilbao	20,483	2%	79%
15	Y	Nantes Saint-Nazaire	20,316	2%	81%
X	Y	North Sea Port	17,600	2%	83%
16	Y	Tarragona	17,341	2%	85%
17	N	Constanta	16,737	2%	87%
18	Y	Barcelona	15,531	2%	89%
19	Y	Genova	14,340	2%	91%
20	Y	Dunkerque	13,927	2%	93%
21	Y	Zeeland Seaports	13,725	2%	94%
X	Y	Castellon	10,300	1%	95%
22	Y	Hamburg	9,906	1%	97%
23	N	Klaipeda	8,291	1%	98%
24	Y	Valencia	5,819	1%	98%
25	N	Tallinn	5,158	1%	99%
26	N	Taranto	2,183	0%	99%
X	Y	La Spezia	1,960	0%	99%
27	N	Riga	1,580	0%	100%
28	Y	Gioia Tauro	1,530	0%	100%
X	Y	Civitavecchia	800	0%	100%
29	N	Peiraias	768	0%	100%
30	Y	Bremerhaven	390	0%	100%
Total			**839,020**		

Source: (Eurostat, 2024b; Ministerio de transportes y mobilidad sostenible, 2024; North Sea Port, 2023; Portmobility Civitavecchia, 2024; Ullyett, 2023)

This table summarizes the total throughput of European liquid bulk ports in 2022, specifically analysing the ports that were ranked in the top 20 by (all) cargo volumes according to Eurostat (2024b) over the period from 2013 to 2022. While the focus is on the year 2022, the analysis includes all ports that appeared in the top 20 during that timeframe, providing an overview of their role in cargo handling volumes and liquid bulk. The "Scope" column indicates whether a port is located in one of the six key carbon-importing countries: Germany, the Netherlands, France, Belgium, Spain and Italy. These six countries were identified as critical in the previous section due to their significant role in carbon energy imports.

Ports marked with an "X" are added in the analysis despite not being in the top 20 of total cargo volumes handled, except North Sea Port which was already in the list under “Zeeland Seaports” which include only the Dutch Ports: Terneuzen and Vlissingen. These ports are added due to their strategic geographical position and their importance in liquid bulk handling. This ensures a comprehensive view of the European energy transition landscape, using data from Eurostat (2024b) and geographical considerations, ensuring representation of areas otherwise unserved, such as La Spezia and Civitavecchia. Additionally, Castellon is added due to its significant amount of liquid bulk throughput, 10,300 tonnes in 2022. La Spezia, Civitavecchia, Castellon and North Sea Port are located into the six primary carbon energy importing countries.

The table ranks European ports based on their liquid bulk handled volumes in 2022. The top five ports in handling liquid bulk in this top 20 list of Eurostat include Rotterdam (211,672 thousand tonnes, 25% of the total), Antwerp-Bruges (89,729 thousand tonnes, 10%), Amsterdam (44,628 thousand tonnes, 5%), Trieste (41,720 thousand tonnes, 5%), and HAROPA (40,834 thousand tonnes, 5%). These five ports handle half of the total liquid bulk trade, demonstrating their significant role in the sector. The accumulated share column reflects the cumulative share of these ports, highlighting the concentration of liquid bulk handling in a few key locations in Europe. The top 5 represents 50% of all liquid bulk volumes handled in the 30 ports in Table 4.2. (Eurostat, 2024b)

The distribution within the top three liquid bulk ports is now examined. The reports of the port of Rotterdam, Antwerp-Bruges and Amsterdam present more detailed division in their liquid bulk segment. In the port of Rotterdam, the total liquid bulk numbers rose by 4% from 2021 to 2022 (Port of Rotterdam, 2023). The crude oil throughput increased by 5.9% because of the transshipment of (Russian) crude oil (Port of Rotterdam, 2023). However, petroleum products saw a 10.8% decline due to a structural decrease in incoming flows and the re-export of fuel oil. In contrast, LNG volumes rose by 63.9%, as it served as an alternative to natural gas. The 15.3% increase in other liquid bulk can be attributed to additional stockpiling caused by container logistics disruptions in 2021 (Port of Rotterdam, 2023). The port of Antwerp-Bruges (2022) reports handling 42 million tonnes of fuels in 2022. Additionally, 13.9 million tonnes of other mineral oil products, such as naphtha, were processed. The port also handled 14.8 million tonnes of LNG, 3.1 million tonnes of LPG, and 16.3 million tonnes of chemicals (Port of Antwerp-Bruges, 2022). The Port of Rotterdam handled 34.5 million tonnes of oil products, which represent the majority of its liquid bulk handling (Port of Amsterdam, 2022). The Ports of Rotterdam, Antwerp-Bruges and Amsterdam play important roles in Europe’s liquid bulk trade, with a strong focus on energy-related products. Rotterdam continues to be the largest hub for crude oil, though its increasing volumes of LNG suggest a shift towards more sustainable energy sources (Port of Rotterdam, 2023). Antwerp-Bruges, while still handling large quantities of fuel and petroleum products, also sees significant LNG and LPG imports (Port of Antwerp Bruges, 2024). Amsterdam’s reliance on oil products highlights its importance in the traditional energy sector, though it also reflects the continued carbon-intensive imports in the region (Port of Amsterdam, 2022). Despite the rise in energy sources like LNG, these ports still manage substantial volumes of carbon-based imports, underscoring the ongoing dependency on fossil fuels while the energy transition gradually unfolds. Currently, there are no available statistics for imports of ammonia or hydrogen, further investigation reveals that the ammonia being imported into the Port of Antwerp is not yet green ammonia (Port of Antwerp Bruges, 2024). Additionally, LNG, while a cleaner alternative to traditional fossil fuels, is still not energy-neutral and continues to contribute to carbon emissions.

The table also presents each port's share of the total throughput and cumulative share ("Acc. share"), illustrating their relative importance in Europe's maritime trade. This selection of ports will serve as the basis for further analysis in the following chapters, emphasizing their role in adapting to changes in the energy mix and handling liquid bulk cargoes.

For further analysis, the selection of ports is based on two primary criteria: the volumes of liquid bulk handled in 2022 and their participation in the interviews outlined in Chapter 7. The ports that participated in the interviews include Bremen, Amsterdam, Rotterdam, Antwerp-Bruges, North Sea Port, HAROPA, Bilbao, Cartagena, Valencia, Castellon, Tarragona, Barcelona and Genoa.

Several ports were excluded from this analysis. For example, Algeciras, despite handling significant volumes of liquid bulk, was considered peripheral to the major energy-importing countries, and Spanish ports were noted for having relatively weak hinterland connections, which limits their capacity to facilitate energy imports effectively. Wilhelmshaven was excluded because Bremerhaven participated in the interviews in Chapter 7, and both ports share a similar geographic location. Additionally, Hamburg was included in the analysis, as it is geographically close to these ports, and its exclusion would not significantly impact on the results.

Some ports with smaller market shares (under 2%) were also excluded, while other ports that participated in Chapter 7 interviews were added. Following this analysis, the final selection of ports for further scenario analysis includes the following 18 ports: Bremen, Hamburg, Amsterdam, Rotterdam, Antwerp-Bruges, North Sea Port, HAROPA, Bilbao, Cartagena, Valencia, Castellon, Marseille, Tarragona, La Spezia, Genoa, Trieste, Barcelona, and Genoa. These ports were selected for their significance in handling liquid bulk and their direct involvement in the study of non-carbon energy imports. This comprehensive selection of ports in the six most carbon importing countries ensures a holistic view of key ports that will play a critical role in the energy transition, providing valuable insights into future energy flows.

4.4.Energy transition descriptive scenarios for ports

To prepare ports for a radically changing energy landscape by 2050, it is essential to explore plausible long-term scenarios. These scenarios do not aim to predict the future but help navigate uncertainties, inform strategic decisions and identify necessary investments. The scenarios will depend on the evolution of global trade, geopolitical tensions, availability of sources, etc. However, thinking about possible scenarios and preparation is crucial. The previous sections show that the energy mix will be various. Extensive use of solar and wind energy is predicted. Therefore, ports must invest further in windmill parks and solar energy generation. However, these energy generators are very vulnerable to the local climate. The feasibility of energy sources such as solar power and wind is highly contingent upon the quantity of wind and solar radiation.

These cases underscore the importance of flexibility and adaptability in planning renewable energy projects. Even mature and well-supported initiatives can face significant hurdles due to shifting economic or regulatory conditions. Such examples highlight the critical need to anticipate and mitigate these challenges when developing a diverse and resilient energy mix.

After analyzing and comparing the supply and demand in the previous sections, three scenarios are created: the renewable energy dominance scenario, the hydrogen-powered hub scenario, and the diverse energy mix scenario.

While there may be some overlap in the use of renewable energy sources such as wind and solar power across different scenarios, several factors differentiate the scenarios from each other. These include the synergy and complementarity of multiple renewable sources, each scenario's specific energy needs and diversification goals, technological differences, scenario-specific objectives, and economic and environmental priorities. While wind, solar and hydrogen can all play roles in sustainable energy strategies, infrastructure and investments can vary significantly based on each scenario's specific goals and context.

4.4.1. Renewable energy dominance scenario

In this scenario, ports prioritize the transition to RES. The energy mix by 2050 includes mainly wind and solar power. The installation of wind turbines must increase significantly along the coast and offshore. Solar panels must be installed on port facilities (parking places, warehouses, etc.). Fossil fuels are phased out, and vehicles in the port will be powered by electric power. Ships also use shore power when berthed in ports. The main challenge of this scenario lies in the sudden power interruptions that could occur.

The renewable energy dominance scenario implies low liquid volumes for ports. Wind and solar power require space for installation. The installation of wind turbines and solar panels will require substantial infrastructure changes. Wind turbines may need offshore platforms, while solar panels will need mounting structures on various port facilities. This infrastructure must be designed to withstand harsh conditions. A lot of wind implies a lot of energy generation, which consequently requires storage capacity for this extra energy.

Furthermore, the electrification of vehicles used in ports and the charging infrastructure are needed. All of these new investments have an initial and operational cost for maintenance. However, ports that transition to the renewable energy dominance scenario can position themselves as frontrunners in long-term sustainable development, potentially boosting economic activity and attracting investments that could give these ports a competitive advantage.

4.4.2. Hydrogen-powered hub scenario

This scenario highlights the long-term strategic use of hydrogen production and distribution. Electrolysis facilities need to be scaled up to produce green hydrogen using renewable energy sources such as wind and solar. Hydrogen is used to reduce GHG emissions by powering vehicles, machinery, ships, etc. Ports will invest in hydrogen storage and distribution infrastructure to supply the port, industry and cities. Hydrogen is a clean and versatile energy carrier that enables various applications. However, the production of green hydrogen is energy-intensive and thus expensive. The use of hydrogen can significantly reduce GHG emissions across various sectors, making it a valuable tool in meeting climate goals.

Ports will need hydrogen storage to ensure a steady supply for various applications. Hydrogen storage tanks and facilities will occupy space within the port and could potentially impact other operations and land use within a port. An extensive network of pipelines must be rolled out to ensure a smooth distribution of hydrogen. The handling and storing of hydrogen require specific safety measures, including adequate ventilation and safety protocols. Ports will need to invest in safety infrastructure and personnel training.

The initial costs in the hydrogen-powered hub scenario for the production of green hydrogen are high because of the energy intensity. Ongoing operational costs will include energy costs for electrolysis, hydrogen production and distribution infrastructure maintenance and safety-related expenses. Nonetheless, in a long-term, hydrogen infrastructure may be essential for port operations and supporting a broad industrial decarbonization strategy toward 2050.

4.4.3. Diverse energy mix scenario

This scenario focuses on diversifying the energy mix to enhance energy resilience and reduce environmental impact in the long term. Besides wind and solar power use in the port, large-scale batteries are used to ensure a stable power supply. Natural gas is used as a transitional fuel parallel with carbon capture and storage (CCS) technologies to minimize emissions. Energy efficiency measures are implemented throughout the port, optimizing energy consumption in lighting, heating and cooling systems.

Sustainable biofuels are explored for ship use and heavy machinery to reduce carbon footprint further. The diverse energy mix can be complex and requires more diversification of infrastructure investments.

Ports must manage various energy sources, including wind and solar power, large-scale batteries, natural gas, carbon capture and storage (CCS) technologies, nuclear power and potentially sustainable biofuels. The diversity of sources requires careful capacity planning to ensure a stable and reliable energy supply. Deploying large-scale batteries is crucial for maintaining a stable power supply, storing excess energy and releasing it when needed. The diversification of energy sources and infrastructure will require significant initial investments. Diversifying the energy mix enhances energy resilience, reducing the risk of disruptions due to fluctuations in energy supply or price volatility.

4.5.The challenges and opportunities of the different scenarios

After reflecting and designing scenarios, evaluating the challenges and opportunities of the scenarios mentioned above is important. In general, technological improvement, geopolitics, finance, environmental regulations, resource availability and public acceptance will lead to the choice of focus for energy sources. (IEA, 2023; IRENA, 2022a)

4.5.1. Renewable energy dominance scenario

In the Renewable energy scenario, sources like wind and solar power offer an effective solution for powering port buildings (Tawfik et al., 2023). Additionally, these renewable sources can support hydrogen production, as wind and solar are intermittent in nature, making hydrogen a key candidate for fuel, energy storage, and as a carrier (Ishaq et al., 2022). Looking at the long-term outlook, it is crucial to recognize that these sources will be integral in decarbonizing port operations and supporting the energy transition up to 2050. A notable example highlighting the challenges in the renewable energy sector is the recent decision by Equinor and BP to terminate the OREC agreement for the Empire Wind 2 offshore wind project in the United States (Equinor, 2024). Despite its potential capacity of 1,260 MW, the project faced economic pressures from inflation, rising interest rates and supply chain disruptions, making the initial agreement financially unviable. These issues underscore the long-term challenges the renewable energy sector faces, including the unpredictability of energy markets and the need for sustained investment to make such projects financially viable over decades. Similarly in Europe, the Princess Elisabeth Zone, a large-scale offshore wind project along the Belgian coast, has faced significant delays and financial concerns. Rising costs and complex regulatory frameworks have posed challenges to its development, despite its strategic importance for Belgium's renewable energy goals. (Equinor, 2024)

Also, inland ports will require careful planning to secure renewable energy, considering their unique challenges such as distance from large-scale renewable energy projects and limited grid capacity. Exploring options like localized renewable energy production (e.g., solar or wind farms near the ports), hydrogen-based solutions, or even partnerships with regional energy providers are essential to support their transition.

A further consideration in the renewable energy scenario is the role of batteries for energy storage. While batteries are often seen as a key technology for storing renewable energy, several challenges must be addressed for their widespread adoption. First, batteries, especially lithium-ion types, can pose significant safety risks, including the danger of fires that can be difficult to control once triggered (Fazey et al., 2018). These fires are typically caused by overheating, leading to dangerous chemical reactions. Furthermore, the disposal of batteries remains an environmental challenge. The cost of disposing of used batteries is high due to the need for proper recycling processes, and the environmental impact of improperly disposed batteries is significant. Additionally, the availability of materials for new batteries—such as lithium, cobalt, and nickel—raises concerns, as these resources are finite, often mined in environmentally sensitive areas, and subject to geopolitical risks. The high demand for these materials may lead to supply chain disruptions or price volatility, further complicating their viability as a long-term solution for energy storage.

4.5.2. Hydrogen-powered hub scenario

In the Hydrogen-powered hub scenario, hydrogen emerges as a pivotal and versatile energy carrier (Neumann et al., 2023; Notteboom & Haralambides, 2023). It produces zero carbon emissions when burned or used. Hydrogen is a good substitute where direct electrification is impractical, such as industrial heating or heavy-duty transport. Moreover, hydrogen is needed to produce ammonia, which further enables its broader application. Looking towards the future, hydrogen will be a key enabler of decarbonization efforts in sectors that are difficult to electrify, with significant potential for growth and integration into the global energy system up to 2050. Its utilization is widely used in various energy, transportation, and industry sectors, making it a key component in the transition towards a sustainable future (Neumann et al., 2023). As a result, hydrogen is expected to play a critical role in the future energy landscape, including industries, transportation and energy storage.

However, it is important to acknowledge that hydrogen production is highly energy-intensive. Most hydrogen today is produced via steam methane reforming (SMR), which has a high carbon footprint unless combined with carbon capture and storage (CCS). Green hydrogen, produced through water electrolysis powered by renewable energy, is a cleaner alternative but requires significant electricity input. For example, producing 1 kg of green hydrogen can require up to 50 kWh of electricity, highlighting the substantial energy demand associated with its production. This poses challenges in scaling up hydrogen use, particularly in areas with limited access to renewable energy sources or grid constraints. (IEA, 2019)

While hydrogen's potential is undeniable, its energy-intensive production underscores the need for strategic planning to ensure that its use aligns with broader sustainability goals and does not inadvertently increase demand for fossil-based energy.

4.5.3. Diverse energy mix scenario

In the Diverse energy mix scenario, the potential lies in its ability to create a flexible and resilient energy system within ports where everything is connected and easily accessible. Ports can significantly increase a countries' energy security and sustainability by integrating multiple energy sources, such as wind, solar, natural gas with carbon capture and storage (CCS), batteries to store energy for later use and biofuels. In the long term, such a diversified energy system can enhance the resilience of ports, providing a stable energy supply, even as renewable sources continue to fluctuate due to their intermittent nature. Using large-scale batteries to store surplus energy ensures a stable supply, even when renewable sources fluctuate due to their intermittent nature. Additionally, adopting sustainable biofuels for ships and heavy machinery addresses a key challenge in decarbonizing the maritime and industrial sectors and reducing reliance on fossil fuels.

Nuclear energy, controversial in terms of sustainability, presents significant opportunities and challenges (IEA, 2022b). A key advantage is its ability to provide a stable and reliable source of low-carbon energy, essential for reducing greenhouse gas emissions in large-scale energy systems. Unlike intermittent renewable sources like wind and solar, nuclear power delivers continuous, baseload power, which is critical for industrial-scale applications, such as ports. However, nuclear energy comes with considerable challenges, including safety risks, the potential for accidents and the long-term management of nuclear waste (IEA, 2022b). The construction costs for nuclear plants are high, and it can take decades to build new plants. Moreover, concerns around nuclear energy and the environmental impact of uranium mining persist. On the opportunity side, advancements in nuclear technologies, such as small modular reactors (SMRs) and reactors that use spent nuclear fuel, are promising. These innovations aim to reduce costs, enhance safety, and make nuclear energy more adaptable to varying energy needs. Additionally, nuclear fusion (still experimental) has the potential to revolutionize the energy sector by providing near-limitless clean energy. Nuclear energy also offers energy independence for nations unable to fully rely on renewable sources due to geographical or infrastructural limitations. Furthermore, institutions such as IRENA will not support nuclear energy programmes due to (i) a long-complicated process, (ii) nuclear energy produces waste and (iii) it is relatively risky. (IRENA, 2022a)

While a diverse energy mix offers numerous advantages, hydrogen and ammonia stand out as pivotal energy carriers in the future energy landscape, particularly for sectors such as heavy industry and maritime transport, where direct electrification is challenging. Hydrogen serves as a sustainable energy carrier when produced via electrolysis powered by renewable energy sources like wind and solar, ensuring zero emissions during its generation. Ammonia, derived from hydrogen, further extends this potential by offering a practical solution for decarbonizing long-distance shipping, underscoring its role as an efficient means of storing and transporting renewable energy. In the following chapters, the role of hydrogen and ammonia in driving the energy transition, as well as their reliance on renewable energy, will be the focus. These energy sources are essential for decarbonizing ports and supporting global efforts toward a low-carbon economy.

4.6.Scenario selection

Before quantifying these scenarios (in sub-scenarios) in the next chapter, it is crucial to first develop a descriptive framework that outlines the key characteristics and the potential of each scenario. This approach ensures a comprehensive, long-term understanding of the foundational infrastructural, economic, and logistical conditions that will shape the future energy landscape. This sequential approach ensures that the quantification of sub-scenarios is based on a contextually relevant evaluation, strengthening the validity of the subsequent calculations and strategic implications over the long term.

Given the European ports' critical role in facilitating the transition to non-carbon energy, the focus in the following empirical sub-scenarios in the next chapters will primarily be on the Hydrogen-powered hub scenario. This decision is driven by the necessity of large-scale hydrogen imports to meet the EU’s climate objectives, particularly in reaching the predefined goals of the European Green Deal and Fit for 55 targets, which require decarbonization across industries and transport. Hydrogen offers a viable pathway for ensuring a stable and scalable energy supply on the long term. Furthermore, European ports, acting as an import hub, are poised to become key entry points for importing hydrogen and ammonia, given their existing infrastructure, logistics expertise and integration into global trade networks (Notteboom & Haralambides, 2023; Port of Antwerp Bruges, 2024; Port of Rotterdam, 2024b). This makes the hydrogen-powered hub scenario the most relevant for evaluating the spatial and economic implications of the energy transition in a port context. By applying an empirical approach in the next chapters. Additionally, as Europe is unlikely to generate sufficient renewable energy domestically, large-scale imports will be inevitable, reinforcing the need to prioritize a sub-scenario that realistically captures the infrastructural and economic shifts required to accommodate hydrogen as a dominant energy carrier (Notteboom & Haralambides, 2023).

4.7.Conclusion

The paper investigated energy transition scenarios for ports. It answers the research question: *What are the energy transition scenarios for Europe?*. The research developed three distinct scenarios illustrating the potential pathways for energy transition within ports. Each scenario presents unique advantages and challenges, offering valuable insights for port authorities and stakeholders. These findings underscore the significance of strategic planning for a sustainable energy future in ports.

Firstly, this chapter investigated the theoretical framework, giving insight into transition systems and the main drivers and factors for shaping the energy market. The global energy market drivers are identified as: social, technological, political, environmental and economic drivers.

Secondly, the global energy market and the European energy market were analyzed. Despite global targets, the data from DNV (2024) presents the slow decline in fossil fuel reliance, predicting a decrease to 50% of the energy mix by 2050. Simultaneously, renewables are expected to triple, driven by exponential growth in solar and wind energy. Countries such as China and the US remain dependent on fossil fuels but are investing in renewables, mainly hydrogen and solar. Meanwhile, Germany and Brazil lead with ambitious renewable energy transition, focusing on offshore wind and hydropower. Geopolitical dynamics, especially between the US and Russia, impact global energy flows. Each country's unique resources and policies will influence future global energy markets.

Thirdly, the research zooms into the European energy market. Europe is progressing towards ambitious renewable energy targets, with oil and natural gas dominating demand in 2022, but renewables are steadily increasing. Wind and solar power will lead the transition, with projections showing over 80% of capacity from these sources by 2050. Regional differences exist, with Western Europe advancing in wind and hydrogen and Southern Europe growing in solar and hydrogen. Geopolitical disruptions, like Russia's gas supply cuts, are driving diversification and accelerating renewable adoption. Europe's future energy strategy will focus on phasing out fossil fuels and massive infrastructure investments.

Analyzing a theoretical framework of energy systems and the market insides gave the input for the descriptive energy scenarios. The first scenario, named as the *Renewable energy dominance scenario* envisions a future in which ports embrace a significant reliance on wind and solar power. This scenario is characterized by substantial investments in renewable energy infrastructure, signaling a strong commitment to sustainable practices. The second scenario, the *Hydrogen-powered hub scenario*, emphasizes the adoption of hydrogen as a primary energy carrier within port operations. This scenario highlights the potential for hydrogen to play a pivotal role in the port's energy transition strategy. Lastly, the *Diverse energy mix scenario* takes a more balanced approach by advocating for a mix of different energy carriers. This strategy promotes sustainability and implies risk diversification, mitigating potential vulnerabilities associated with over-reliance on a single energy source.

The analysis of the scenarios highlights both the challenges and opportunities in the energy transition for ports. The Renewable energy dominance scenario emphasizes the transformative potential of wind and solar power, alongside challenges such as financial viability, supply chain disruptions and resource constraints for battery storage. The Hydrogen-powered hub scenario positions hydrogen as a versatile and critical energy carrier, though its energy-intensive production underscores the need for strategic planning and access to renewable electricity. Lastly, the Diverse energy mix scenario illustrates the flexibility and resilience of integrating multiple energy sources, including emerging options like biofuels, CCS and advanced nuclear technologies, while addressing concerns related to safety, cost and waste. Across all scenarios, hydrogen and ammonia emerge as pivotal elements in the transition, particularly for decarbonizing sectors such as maritime transport and heavy industry. Their integration within ports and reliance on renewable energy will play a central role in shaping a sustainable and low-carbon future, as explored further in the following chapters. Therefore, in Europe the Hydrogen powered hub scenario is promising and will be further used to quantify sub-scenarios.

These scenarios collectively offer ports and stakeholders valuable insights into various avenues for energy transition, each with its unique advantages and challenges. The choice of scenario to pursue will depend on many factors, including technological readiness, regulatory frameworks, and economic considerations. Ultimately, the path to a sustainable energy future for ports will require careful consideration and a strategic approach that aligns with specific port characteristics and goals.

While the qualitative descriptive energy scenarios offer valuable insights into potential pathways for cleaner energy adoption, the subsequent recommendations aim to further elaborate on and quantify our analysis. A quantitative analysis enables quantifying volumes, storage place and costs. However, more data is essential for refining and quantifying the scenarios to make them more precise and accurate. Encouraging companies to share relevant data will be crucial for advancing our understanding of the energy transition in ports.

Chapter 5

Exploring hub allocation for energy flows: a strategic analysis

The allocation of port infrastructure for energy flows is challenging, given the diverse requirements and characteristics associated with different energy types. As ports play a pivotal role in the global energy transition, understanding the dynamics of energy flows becomes essential for optimizing infrastructure and facilitating sustainable energy development. This knowledge not only supports the efficient handling of future energy carriers but also informs critical investment decisions that shape the strategic positioning of ports in the evolving energy landscape.

The growing focus on transitioning to renewable energy sources, such as wind, solar and hydrogen adds complexity to port infrastructure planning. Renewable energy flows often have different logistics and storage needs compared to traditional fossil fuels. Moreover, the predominance of certain energy types in ports necessitates an investigation for strategic decision-making. For instance, ports that have historically handled large volumes of coal or oil face challenges in transitioning to accommodate renewable energy without significant investments and policy support. Europe is a net energy importer, indicating its dependency on other continents and countries. In 2020, 58% of the energy available in the European Union (EU) was produced outside Europe (European Council, 2024a). By quantifying infrastructure strategies and enabling the efficient integration of renewable energy carriers, this study supports the diversification of energy sources and enhances Europe's capacity for domestic energy storage and distribution, thereby reducing dependency on external energy suppliers.

The previous chapter identified the six most carbon importing countries in Europe: Germany, the Netherlands, Belgium, France, Spain and Italy. These six countries are subject to this analysis. This chapter analyses the supply and demand predictions concerning carbon-based and non-carbon-based energy flows in European countries. These assumptions are used as input for the calculation of the non-carbon energy volumes for each country. The last chapter identified three scenarios of which one scenario is further used and split up into sub-scenarios. The scenario that was chosen is the Hydrogen-powered hub scenario. In light of developing towards more hydrogen and its carriers, this chapter delves deeper in quantifying the earlier descriptive scenario. Therefore, the research question is formulated as follows: *How will the energy flows of the major carbon-importing countries in Europe be impacted by the energy transition scenarios?*

Section 5.1 discusses the supply and demand predictions for both carbon-based and non-carbon-based energy sources. These assumptions form the basis for estimating the future non-carbon energy volumes for each of the six identified countries. Section 5.2 develops three non-carbon energy import sub-scenarios. Each sub-scenario reflects a different pathway for the energy transition, highlighting variations in import volumes, energy types and their implications for the six major carbon-importing countries. Section 5.3 evaluates the likely oucomes in the current policy and technological context. Section 5.4 concludes the main findings. Countries, ports, stakeholders, energy companies and investors can use this analysis to make informed decisions on infrastructure investments and strategic planning. Since, ports are crucial enablers of trade, these sub-scenarios will give insights in port planning for storage and costs.

5.1.Assumptions for energy sub-scenarios

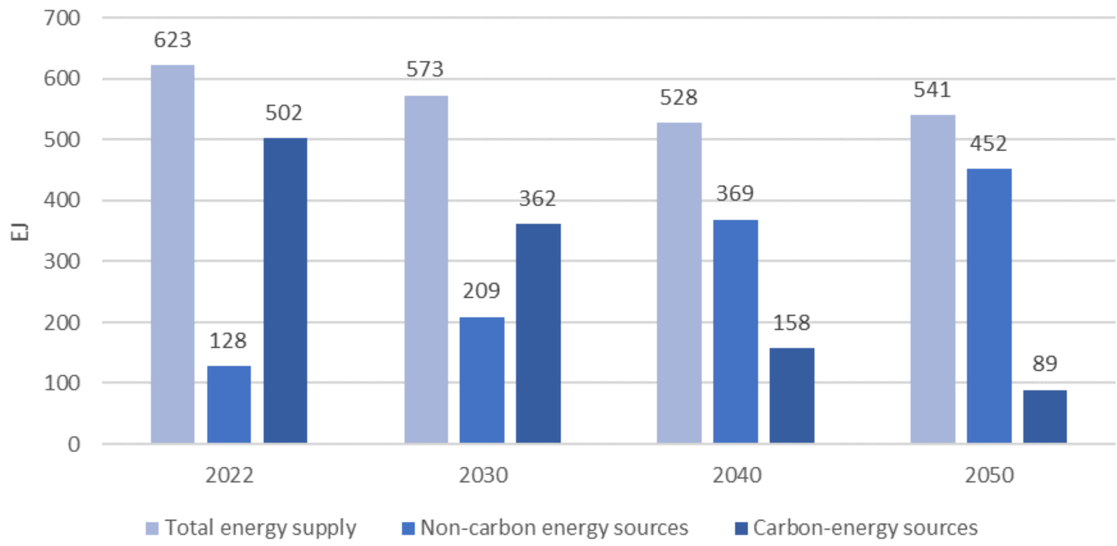
Before developing country-specific sub-scenarios, it is essential to establish underlying assumptions. Based on the global energy outlook in Chapter 4, the Net Zero emission scenario of the International Energy Agency (IEA) is chosen (2022d). The assumptions needed for this analysis, such as demand, import, and domestic production, were derived from both the IEA's Net Zero Emission scenario and the European

Commission's research, as they best aligned with the parameters required for this analysis. This scenario sets out a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050 and to limit the global temperature rise to 1.5°C above preindustrial levels in 2100. The scenario does not rely on emission reductions outside the energy sector (such as industry or agriculture) to achieve its goals. The projections from the IEA serve as the basis for forecasting future non-carbon energy flows for the six selected European countries that are the largest energy importers of carbon energy in Europe. Since the IEA provides detailed numbers and predictions only for the global supply and demand outlook, these projections are applied to our sub-scenarios for the European context. The International Energy Agency (IEA) is a global institution recognized in energy research and policy, providing reliable and comprehensive data. By relying on IEA projections, this chapter presents insights that are applicable to the European context.

5.1.1. Supply

The world energy scenarios of IEA will be used as a basis for input for the calculation of non-carbon energy sub-scenarios. In the net zero emission scenario of the IEA, universal access to reliable modern energy services is reached by 2030, and major improvements in air quality are secured (IEA, 2022d). Figure 5.1 illustrates the world energy supply Net Zero Emission scenario for 2022 and shows the estimations for 2030, 2040 and 2050.

Figure 5.1: total world energy supply Net Zero Emmission Scenario

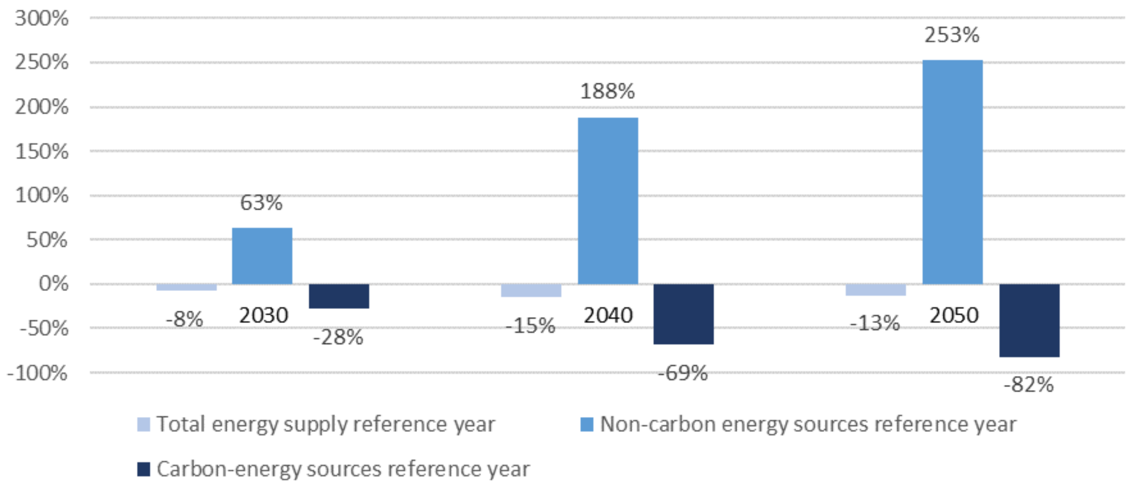


Source: own composition based on IEA (2023)

The graph shows a shift in the energy mix. The total energy supply decreases from 623 EJ in 2022 to 541 EJ in 2050, reflecting improved efficiency and reduced demand (IEA, 2023). Carbon-based energy sources decline sharply, from 502 EJ in 2022 to 89 EJ in 2050, while non-carbon sources, such as renewables and nuclear energy, grow from 128 EJ to 452 EJ in the same period. This transition emphasizes the global shift away from fossil fuels towards sustainable energy systems, requiring significant policy support, investment and infrastructure development to achieve climate goals.

Based on the previous graph, the difference between the reference year 2022 and future estimations is calculated in Figure 5.2. The figure clearly shows an increase in non-carbon energy sources by 253% in 2050 compared to the reference year 2022. On the other hand, the figure shows a decrease in the carbon energy sources by -82% by 2050 compared to 2022. The total energy supply compared to the reference year will decrease by 8% by 2030, 15% in 2040 and 13% in 2050 compared to 2022.

Figure 5.2: The percentage change relative to the reference year 2022



Source: own composition based on IEA (2023)

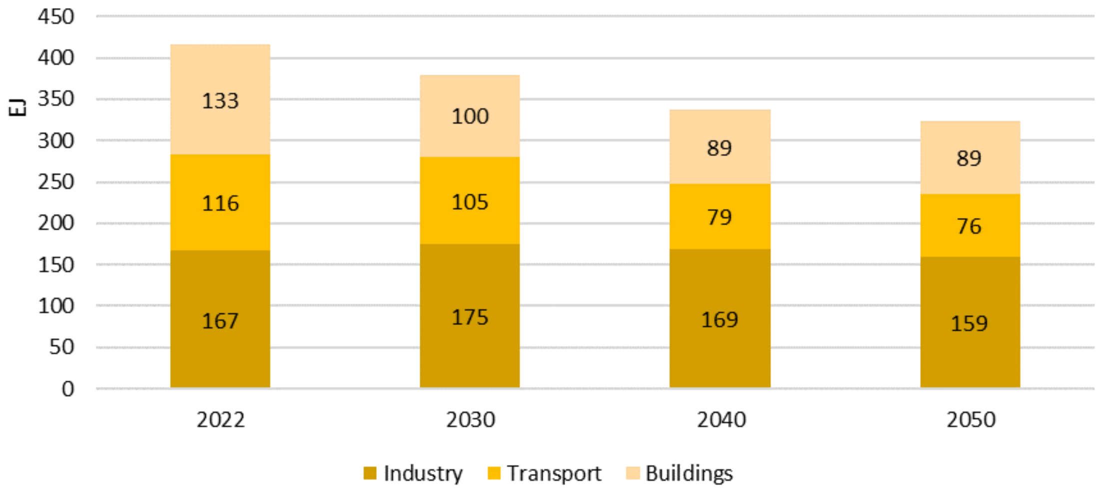
These percentages for supply are used as assumptions for determining each country's future non-carbon energy sub-scenarios.

5.1.2. Demand

Figure 5.3 presents the energy demand per sector: industry, transport and buildings. The year 2022 is historical data, not based on predictions. The years 2030, 2040 and 2050 are estimations from the IEA per sector. The sectors are divided into industry, transport and buildings.

The figure shows a decrease in the energy demand (EJ) across the three sectors in the Net Zero Emission scenario of towards 2030, 2040 and 2050. The industry sector is the largest energy consumer, solid fuels account for the largest share. The transport sector relies mainly on oil for their fuel usage. The buildings sector mainly relies on electricity (46 EJ in 2022). Within the share of solid fuels, coal still accounts for the largest share. In 2022, it accounts for almost 40% of all energy demand in Europe. (IEA, 2023)

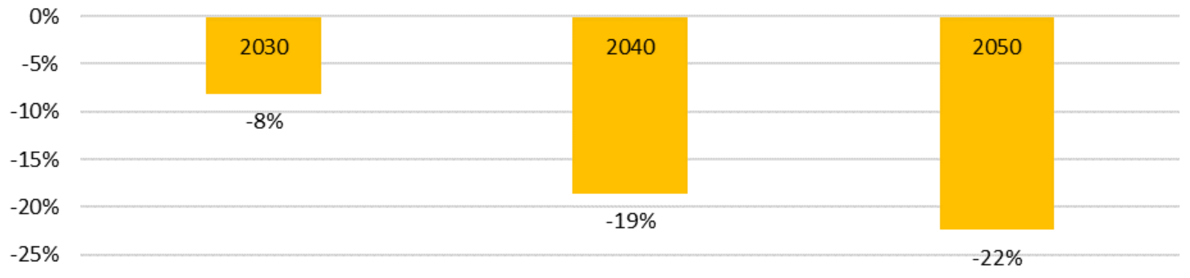
Figure 5.3: World energy demand total and per sector



Source: based on data of IEA (2023)

The previous graph illustrates the different sectors and their worldwide. Figure 5.4 illustrates the total energy consumption worldwide. The percentages below show that, following the study of IEA, the total energy consumption compared with the reference year 2022 will decrease in 2030 by 8%. For 2040, the IEA estimates a decrease by 19% and by 2050 a decrease by 22% in the total energy consumption.

Figure 5.4: Total energy consumption (EJ)



Source: based on data of IEA (2023)

These percent change will be used in the sub-scenarios as input for designing non-carbon energy sub-scenarios for the Netherlands, Belgium, Italy, Spain, France and Germany.

5.2.Energy sub-scenarios of the Hydrogen-powered hub scenario

The previous assumptions of the IEA and the European Commission and will be used as input for developing future non-carbon energy sub-scenarios. The next sections quantify three non-carbon energy sub-scenarios). Furthermore, the inputs require the division expressed in percentage of the import share of hydrogen and ammonia. The IEA (2022a) does not provide an explicit import division between ammonia and hydrogen. For this analysis, a ratio of 25% ammonia and 75% hydrogen was assumed. This division serves as a hypothetical basis for exploring import needs under specific assumptions. Sensitivity analyses could further examine the impact of alternative ratios.

5.2.1. Sub-scenario 1: Accelerated non-carbon growth with fossil stability

This section presents the first sub-scenario assumptions and the results. The first sub-scenario (SS1) involves a decrease of carbon production and recovery. By 2050, there will be a slight increase in natural gas imports and petroleum product imports will remain unchanged. The ratio between imported hydrogen and ammonia remains unchanged over the three periods (2030, 2040 and 2050).

Assumptions

The following table includes all parameters to build Sub-scenario 1. The assumptions of change in demand, increase in carbon production & recovery and increase in non-carbon output & recovery are based on the reports of IEA (2022d). The import parameters of carbon energy were based on data of the European Commission (2013). The IEA estimates the overall demand for energy to decrease by 8% by 2030, by 19% by 2040 and by 22% by 2050. The population is estimated to increase by 2050. Therefore, the energy use should be more efficient to establish that decline in energy usage (Nations, 2024b).

The estimation for solid fossil fuels imports, natural gas import and petroleum products import are based on the predictions of the European Commission (2013). Carbon production and recovery are estimated to decrease by 28% by 2030, 69% by 2040 and 82% by 2050. The chosen parameters show a strong decrease in solid fossil fuel imports (coals and solid products derived from coals). A reduction of fossil fuels of almost 50% is expected by 2050, and gas imports are expected to increase by 23% by 2050. Petroleum products will remain approximately the same across the years 2030, 2040 and 2050 compared to 2022.

Table 5.1: Parameters Sub-scenario 1

	Demand	Production & recovery		Imports		
Year	Energy demand	Carbon	Non-carbon	Solid fossil fuels	Natural gas	Petroleum products
2030	-8.00%	-28.00%	63.28%	-18.37%	10.40%	1.00%
2040	-19.00%	-69.00%	188.28%	-33.18%	16.70%	1.25%
2050	-22.00%	-82.00%	253.13%	-47.98%	23.00%	1.50%

Source: own composition based on IEA (2023) and European Commission (2013)

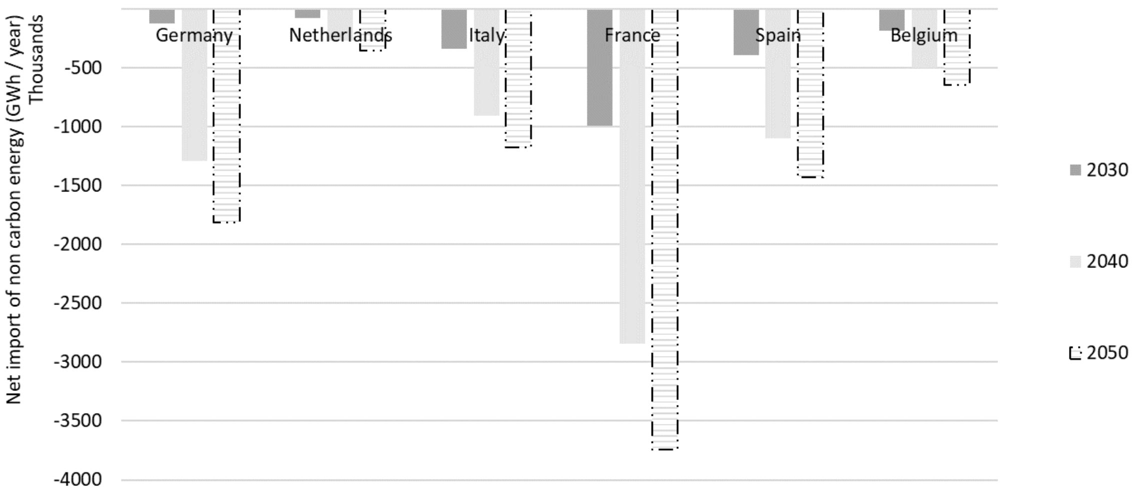
Despite the growth in non-carbon energy domestic production, the continued dependence on carbon-based energy, particularly the increase in natural gas imports and the stable level of petroleum product imports, does not align with EU climate regulations (European Green Deal etc.). This indicates that while Sub-scenario 1 supports a shift towards non-carbon energy, it does not fully meet the EU's objectives for phasing out carbon energy reliance.

Results

The result shows the net import which is calculated with the input parameters of Table 5.1. The net import of non-carbon energy indicates how much non-carbon energy is being imported on a net basis, considering domestic production, recovery and the changes in energy supply and carbon imports. The net import presents the difference between the imported and exported energy. Positive values indicate that a country imports more than its exports. Negative values indicate that a country imports less than it exports.

Figure 5.5 illustrates the outcomes of Sub-scenario 1 of the net import of non-carbon energy.

Figure 5.5: Net import of non-carbon energy SS1



Source: based on (European Commission, 2013; Eurostat, 2024a; IEA, 2023)

The output of Sub-scenario 1 shows a decrease for each country in net non-carbon energy imports expressed in GWh/year by 2030, 2040 and 2050. France's net imports of non-carbon energy decreased the most compared to other countries. A decrease of approximately -3700 GWh/year is seen by 2050 compared to the level of 2022. According to Kolm (2023) Germany imported 63.7% in 2020 of its energy, showing its dependency on other countries for their energy imports. By increasing their domestic production of non-carbon energy by more than 250%, it meets its domestic energy demand. Sub-scenario 1 shows that an increase in local green energy production covers the decrease in the import of solid fossil fuels. Therefore, the net import of carbon-based energy decreases in each of the researched countries over the period of 2030, 2040 and 2050. This sub-scenario shows that no import is needed due to the rising import of natural gas, the slight growth of oil and petroleum products and the growth in non-carbon energy production over 2030, 2040 and 2050.

As analysed in this sub-scenario, with increased renewable energy production in European countries and a decline in the import and storage of solid fossil fuels, there should be enormous investment in infrastructure to accommodate the rise in non-carbon energy production. Additionally, sufficient space must be allocated for the installations required to handle non-carbon energy, and the production of such energy must remain economically viable to ensure its long-term sustainability. The characteristics of the suitability for non-carbon energy production depend on the characteristics of each country that influence the feasibility and efficiency of generating, storing and distribution non-carbon energy. For solar energy, the average sun hours in Spain are double of the hours in Belgium or the Netherlands (Statista, 2021).

5.2.2. Sub-scenario 2: Moderate non-carbon expansion with fossil stability

After the first sub-scenario, where the amount of solid fossil fuels imported decreases heavily, the second sub-scenario (SS2) focuses on less domestic production of non-carbon energy.

Assumptions

The assumptions of demand, carbon production and carbon imports remain unchanged compared to the first sub-scenario in the previous section. The only parameter that changes is the production and recovery, which increases slower than in Sub-scenario 1. The production and recovery become, respectively, by 2030, 2040 and 2050: 20%, 40% and 60%.

Table 5.2: Parameters Sub-scenario 2

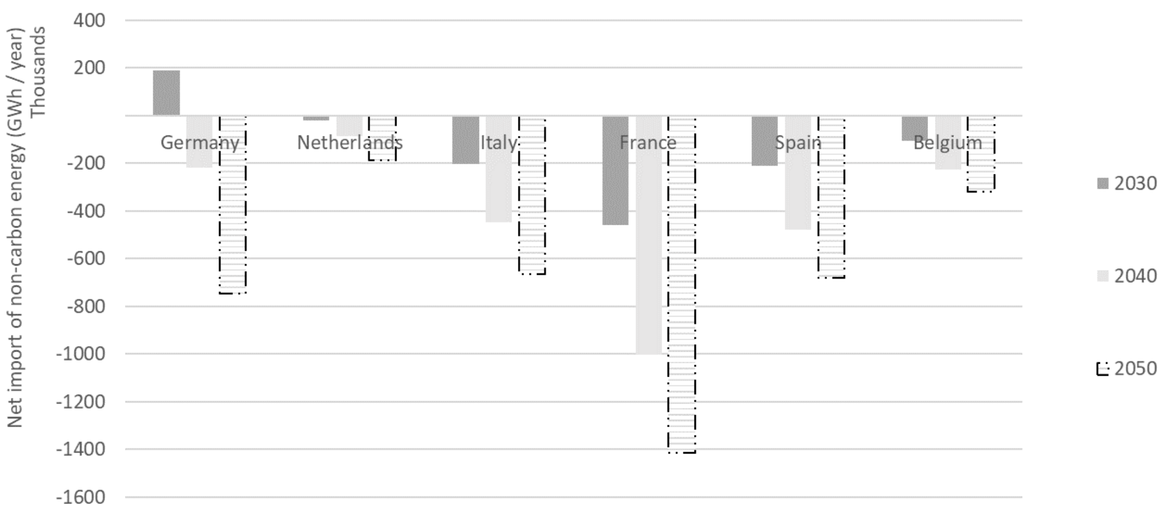
	Demand	Production & recovery		Imports		
Year	Energy demand	Carbon	Non-carbon	Solid fossil fuels	Natural gas	Petroleum products
2030	-8.00%	-28.00%	20.00%	-18.37%	10.40%	1.00%
2040	-19.00%	-69.00%	40.00%	-33.18%	16.70%	1.25%
2050	-22.00%	-82.00%	60.00%	-47.98%	23.00%	1.50%

Source: own composition based on IEA (2023) and European Commission (2013)

Results

Figure 5.6 presents the net import of non-carbon energy of Germany, the Netherlands, Italy, France, Spain and Belgium. The results of Scenario 2 show a different net import of non-carbon energy compared to Sub-scenario 1. Sub-scenario 1 showed that if the EU boosts its non-carbon domestic production by 250%, the net import of non-carbon energy will decrease for every country by 2050. In Sub-scenario 2, the slower increase (+60% by 2050) in non-carbon production, leads to moderate growth in domestic supply, resulting in a less pronounced reduction in imports, with a net non-carbon import figure that is negative but less extreme as in the first sub-scenario. The first sub-scenario illustrates a -3000 GWh/year net non-carbon energy import for France, while Sub-scenario 2 shows a net non-carbon import of -1400 GWh/year. This indicates that France still is a net exporter of non-carbon energy, but the export surplus is smaller compared to Sub-scenario 1. Only Germany will have to import approximately 200 Gwh of non-carbon energy by 2030.

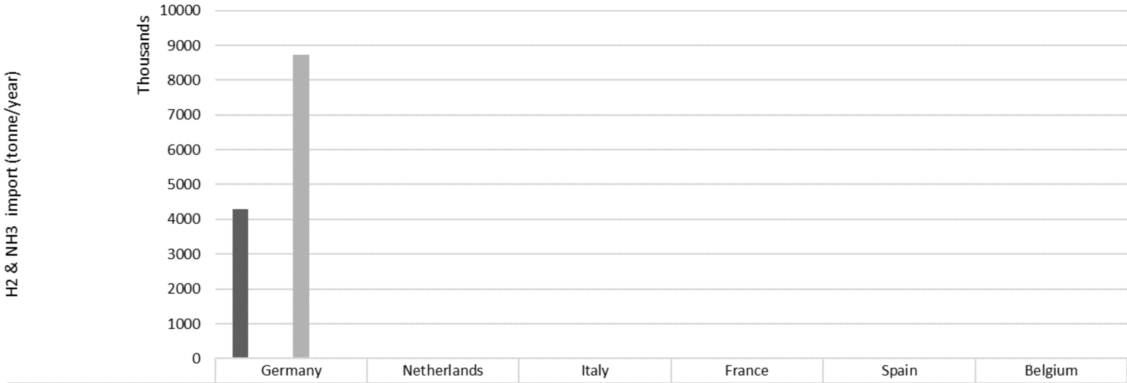
Figure 5.6: Net import of non-carbon energy SS2



Source: based on based on (European Commission, 2013; Eurostat, 2024a; IEA, 2023)

Figure 5.7 presents each country's estimated imports, divided into hydrogen and ammonia import needs. As seen in Figure 5.6, Germany needs to import non-carbon energy by 2030. This results in Germany importing almost 4.3 million tonnes of hydrogen annually by 2030. By 2030, Germany will have to import almost 8.8 million tonnes of ammonia. By 2040 the domestic production will cover the decreased domestic production of carbon energy and imports of carbon energy. Although 75% of the import need will consist of hydrogen and only 25% will be met by ammonia, the required ammonia imports, expressed in tonnes, will be higher than those of hydrogen to compensate for the energy shortage. This is because ammonia has a lower energy density per tonne compared to hydrogen, meaning that a larger volume is required to deliver the same amount of energy.

Figure 5.7: Non-carbon energy import by 2030, 2040 and 2050 SS2



	Germany	Netherlands	Italy	France	Spain	Belgium
2030 H2 75% [tonne/year]	4,285,884	-	-	-	-	-
2040 H2 75% [tonne/year]	-	-	-	-	-	-
2050 H2 75% [tonne/year]	-	-	-	-	-	-
2030 NH3 25% [tonne/year]	8,720,911	-	-	-	-	-
2040 NH3 25% [tonne/year]	-	-	-	-	-	-
2050 NH3 25% [tonne/year]	-	-	-	-	-	-

Source: own composition based on (IEA, 2022a)

5.2.3. Sub-scenario 3: Full decarbonization pathway

In the third sub-scenario, the production and import of carbon energy will decrease sharply. In contrast, the production of non-carbon energy, which will scale up by 300% by 2050 compared to 2022 levels. The next section reveals the specific assumptions for the third sub-scenario (SS3).

Assumptions

Sub-scenario 3 will abandon carbon energy production and carbon imports completely by 2050, as shown in Table 5.3. In contrast, it will increase its non-carbon energy production. By 2030, the production of non-carbon energy must increase by 100%, by 2040 by 200% and by 2050 by 300% compared to 2022 levels. The energy demand will remain unchanged compared to the first sub-scenario. The ratio of hydrogen to ammonia remains constant at 75/25% ratio.

Table 5.3: Parameters Sub-scenario 3

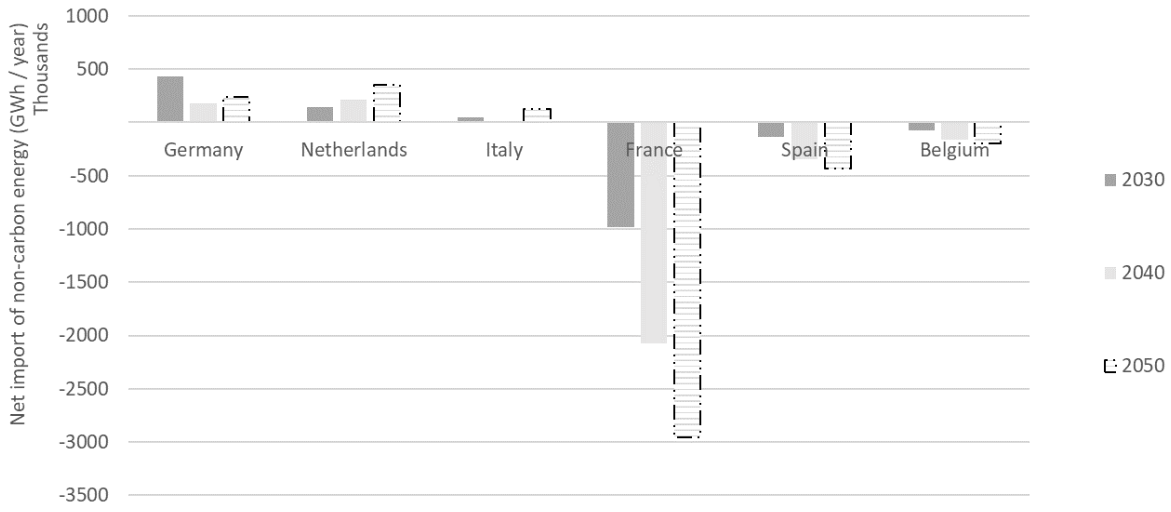
	Demand	Production & recovery		Imports		
Year	Energy demand	Carbon	Non-carbon	Solid fossil fuels	Natural gas	Petroleum products
2030	-8.00%	-33.33%	100.00%	-33.33%	-33.33%	-33.33%
2040	-19.00%	-66.66%	200.00%	-66.66%	-66.66%	-66.66%
2050	-22.00%	-100.00%	300.00%	-100.00%	-100.00%	-100.00%

Source: own composition based on IEA (2023)

Results

Figure 5.8 illustrates the net import of non-carbon energy of Sub-scenario 3 for 2030, 2040 and 2050.

Figure 5.8: Net import of non-carbon energy SS3

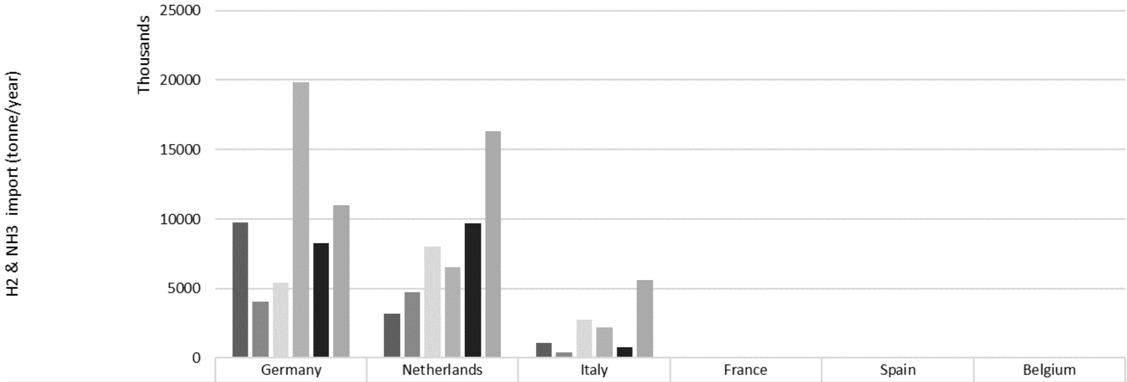


Source: based on based on (European Commission, 2013; Eurostat, 2024; IEA, 2023)

If the parameters of solid fossil fuels, natural gas and oil decrease to -100% by 2050, the net import of non-carbon energy (hydrogen and ammonia) will be positive for Germany, The Netherlands and Italy (Figure 4.8). All countries show an increase compared to Sub-scenario 1 and Sub-scenario 2. France will already produce a large amount of nuclear energy by 2022. The overproduction could be exported. However, it is not efficient to transport nuclear in molecular form. Instead, France could export the oversupply of energy in the form of electricity to other EU countries, such as Germany or the Netherlands via high-voltage networks in the form of electricity. France, in this sub-scenario, could limit their import of H_2 and NH_3. Spain and Belgium have a slightly negative net import of non-carbon energy, which means that they have enough gross energy available and do not need to import non-carbon energy.

Figure 5.9 illustrates the import needed of hydrogen and ammonia by 2030, 2040 and 2050 in Sub-scenario 3.

Figure 5.9: Non-carbon energy import by 2030, 2040 and 2050 SS3



	Germany	Netherlands	Italy	France	Spain	Belgium
2030 H2 75% [tonne/year]	9,746,711	3,211,174	1,088,756	-	-	-
2040 H2 75% [tonne/year]	4,062,179	4,752,547	382,984	-	-	-
2050 H2 75% [tonne/year]	5,386,231	8,024,658	2,746,400	-	-	-
2030 NH3 25% [tonne/year]	19,832,593	6,534,093	2,215,400	-	-	-
2040 NH3 25% [tonne/year]	8,265,717	9,670,475	779,296	-	-	-
2050 NH3 25% [tonne/year]	10,959,895	16,328,563	5,588,372	-	-	-

Source: own composition based on IEA (2022a)

The trajectory of non-carbon imports between 2030 and 2050, initially decline before rising sharply, reflects the interaction of various factors. A decrease in overall energy demand, growth in domestic non-carbon production, and the gradual phase-out of carbon-based energy sources all shape import requirements. Between 2030 and 2040, domestic non-carbon production expands significantly (+100% by 2030, +200% by 2040), while total energy demand declines (-8% by 2030, -19% by 2040), temporarily reducing import needs. By 2050, with carbon-based production and imports fully phased out (-100%), the balance shifts between domestic production and remaining energy demand, driving a renewed increase in non-carbon imports. This fluctuation represents a transitional phase as the energy system adapts to a new mix shaped by evolving parameters.

Germany, The Netherlands and Italy will need hydrogen and ammonia imports by 2030, 2040 and 2050. Germany should import approximately 9.7 million tonnes/year of hydrogen by 2030, approximately 4.1 million tonnes/year by 2040 and 5.4 million tonnes/year by 2050. The import of hydrogen of the Netherlands will grow from 2030 to 2050 from 3.2 million to 8 million tonnes/year. In Italy, the import of hydrogen is lower: from 1.1 million tonnes/year in 2030 to 2.7 million tonne/year in 2050.

The import of ammonia is 20 million tonnes in 2030 for Germany, 6.5 million for the Netherlands and 2.2 million tonnes of ammonia for Italy. In 2040 the imports are lower 8.2 million for Germany, 9.7 million for the Netherlands and 800 thousand for Italy. In 2050, Germany needs almost 11 million tonnse of ammonia, the Netherlands 16.3 million tonnes and Italy 5.6 million tonnes of ammonia.

In the third sub-scenario, Germany, the Netherlands and Italy should prepare their ports for importing hydrogen and ammonia, which means that ports in Germany, the Netherlands and Italy must be ready to store and handle the imported hydrogen and ammonia. Sub-scenario 3 illustrates that although the non-carbon domestic production increased with 300% by 2050 and if these countries have no carbon imports and no carbon production, that non-carbon import is needed.

If these countries aim to address climate change, Sub-scenario 3 shows that achieving net-zero emissions requires a full transition away from carbon-based energy sources. This means that domestic production alone, even with such a large increase of 300% by 2050, will not suffice to meet the energy demands of countries such as Germany, the Netherlands and Italy if no carbon imports are allowed by 2050.

To meet this challenge, these countries must invest heavily in port infrastructure to facilitate the import, storage and handling of hydrogen and ammonia. Ports will need to be equipped with specialized storage tanks, pipelines and facilities to manage these energy carriers with extra awareness for safety and efficiency (Notteboom & Haralambides, 2023). Beyond infrastructure, logistical frameworks and regulatory policies will also need to evolve to ensure a seamless flow of energy imports into the national grids.

This sub-scenario underscores the urgency of immediate action in large-scale investment in non-carbon energy infrastructure. These investments will not only support the import of hydrogen and ammonia but also help to establish a resilient energy supply chain, also to serve the hinterland of a country. Without these critical developments, the energy transition risks stalling, and the climate goals set for 2050 may remain unattainable. Furthermore, space is needed to accommodate the infrastructure required for renewable energy imports and existing infrastructure based on carbon imports must also be adapted to support this shift towards non-carbon energy.

5.3. Evaluating the sub-scenarios in the current policy and technological context

While Sub-scenario 1 presents a scenario of moderate carbon reduction combined with an increase in natural gas imports and stable petroleum product imports, it may face significant challenges in aligning with current EU climate regulations, such as the European Green Deal. The projected continued reliance on natural gas and petroleum products, even with an increase in non-carbon energy production, may be less likely given the EU’s strong carbon reduction goals. Sub-scenario 2, with more gradual increases in non-carbon energy production, may be a more realistic pathway in the medium term, given the technological and economic constraints currently limiting the pace of non-carbon energy expansion. Sub-scenario 3, which envisions full decarbonization by 2050, aligns with the EU's long-term climate objectives but may be difficult to achieve without significant technological advancements and policy shifts, particularly in the energy storage and hydrogen sectors. The likelihood of these scenarios largely depends on the speed of technological innovation, the political will to enforce stricter regulations, and the pace at which infrastructure for non-carbon energy is scaled.

5.4.Conclusion

Chapter 5 analyses the existing energy flows of the largest importing countries of carbon energy in terms of GwH/year in 2022. The countries that were researched are part of Europe's geographical territory and are not limited to the European Union. As the global energy flows evolve, understanding the dynamics of energy imports, exports and production within these key regions becomes increasingly critical. Therefore, the research question was formulated as follows: *How will the energy flows in the six largest carbon-importing countries in Europe be impacted by various transition scenarios?*

Three potential energy sub-scenarios for the years 2030, 2040 and 2050 were constructed, each based on different assumptions. The first sub-scenarios are based on the assumptions of the IEA and the European Union. The second and third sub-scenario include a more extreme or less extreme interpretation of certain assumptions in the first sub-scenario.

The first sub-scenario, *Accelerated non-carbon growth with fossil stability*, focuses on the findings of the International Energy Agency and the European Commission. The first sub-scenario focuses on a slight decrease of the energy demand, a decrease in carbon energy production, a sharp uptake of non-carbon energy (up to 250% by 2050), a reduction by 50% in solid fossil fuel import, an increase of natural gas by 23% by 2050 and a status quo by the import of petroleum products. The results show that there is no need to import non-carbon energy because the demand will be fulfilled by the increase of domestic non-carbon production and a slight decrease in fossil fuel imports and domestic carbon energy production. If the imports of carbon energy remain relatively stable, it suggests that no non-carbon import is necessary.

The second sub-scenario, *Moderate non-carbon growth with fossil stability*, supposes a more moderate production increase in non-carbon energy by 60% by 2050, all other factors remain unchanged. The moderate growth in non-carbon energy production leads to an increased reliance on non-carbon imports. For Germany, these imports are expected to reach approximately 4.2 million tonnes of hydrogen and 8.7 thousand tonnes of ammonia per year by 2030. This sub-scenario shows that Germany must invest in infrastructure for non-carbon energy production and make investments to cover the growth in the import of hydrogen and ammonia by 2030.

The third sub-scenario, *Full decarbonization pathway*, brings the carbon production and import to zero by 2050, assuming that all other factors remain unchanged. In this sub-scenario, Germany, the Netherlands and Italy must import non-carbon energy. Energy imports of hydrogen rose for Germany to 9.7 million, 4.1 million, and 5.4 million tonnes per year by 2030, 2040 and 2050. The Netherlands must import 3.2 million tonnes of hydrogen by 2030, 4.8 million tonnes by 2040 and 8 million tonnes of hydrogen. Italy needs to import 1 million tonnes of hydrogen by 2030, almost 400 thousand tonnes by 2040 and 2.7 million tonnes by 2050. For ammonia, 19 million tonnes must be imported by 2030 for Germany, 6.5 billion tonnes for the Netherlands and 2.2 billion tonnes for Italy by 2030. By 2040 this will be 8.2 billion for Germany, 9.7 billion for the Netherlands and 800 thousand tonnes of ammonia for Italy. In 2050, almost 11 million tonnes of ammonia for Germany, 16.3 billion tonnes for the Netherlands and 5.6 billion tonnes of ammonia for Italy. In Sub-scenario 3, Germany, the Netherlands and Italy need to prepare for non-carbon energy import and make significant investments in infrastructure and policy frameworks to facilitate hydrogen and ammonia import, storage and distribution. These preparations include expanding port facilities capable of handling liquid hydrogen and ammonia shipments, creating extensive pipeline networks to transport this non-carbon energy and ensuring compatibility with existing industrial systems (mostly designed for carbon energy).

The findings underscore the diverse investment strategies required under different sub-scenarios. Given the urgency of climate change, a shift towards renewable energy sources is necessary, resulting in an increased production and import of non-carbon energy to meet rising demand for non-carbon energy. As countries transition to non-carbon energy, their ports must invest in infrastructure to support this shift, including storage, handling and production facilities such as wind turbines and solar panels. The sub-scenarios presented provide valuable insights into potential shifts in energy flows and their implications for non-carbon energy imports, highlighting the need for strategic investments in both import and production infrastructure. Further research is necessary to evaluate the land requirements for ports and industrial zones to support non-carbon energy import and production, as well as to estimate the types and quantities of vessels needed to meet the growing demand for non-carbon energy. These insights will be crucial for guiding future investments and policy decisions, enabling a transition to a sustainable energy future.

Chapter 6

Cost and surface analysis for future ports in the context of the energy transition: a scenario-based approach

The transition to a low-carbon future is a central objective of global efforts to mitigate climate change. Within this energy transition, hydrogen and ammonia have emerged as key renewable energy carriers, offering significant potential to reduce emissions while enabling the large-scale transport and storage of renewable energy. These energy carriers are important for Europe, a region heavily reliant on carbon energy imports, as ammonia and hydrogen offer a pathway to decarbonizing energy systems and meeting the European Union's ambitious climate targets. Therefore, it is important to understand the logistics and economic implications of the supply chain of importing and storing these carriers. It is crucial for optimizing port infrastructure and advancing sustainable energy strategies.

In the previous chapters, an analysis was conducted to determine which countries are likely to require significant imports under three non-carbon energy sub-scenarios based on predefined parameters based on important energy reports from leading institutions. These analyses identified the countries with substantial carbon-based energy imports, underscoring the urgency for these nations to transition to non-carbon energy sources to meet the European Union's climate goals. These countries are Germany, The Netherlands, Belgium, France, Italy and Spain. Chapter 5 developed three energy sub-scenarios for these countries. This chapter builds on the insights of Chapter 4, zooming in from a country-level analysis to a port-level analysis. By examining the outputs of key European ports in those six countries, this chapter provides a more detailed understanding of the implications for port infrastructure and surface needs.

The primary objective of this chapter is to analyse the import volumes for hydrogen and ammonia, storage requirements and storage costs under the three earlier developed sub-scenarios. The analysis addresses how these ports can adapt to facilitate the transition to non-carbon energy imports. Therefore, this chapter addresses the following research question: *What are the storage investment costs and storage requirements linked to the imported volumes of hydrogen and ammonia in key European ports?*

By shifting from a country-level analysis to port-specific outputs, this chapter underscores the critical role of port infrastructure in facilitating the energy transition. The findings provide insights into the storage space and costs required under three potential sub-scenarios for ports. This chapter provides a valuable contribution to understanding how European ports can support a low-carbon economy and meet the EU's ambitious climate targets.

Section 6.1 identifies potential origin or exporting countries for non-carbon exports and evaluates their role in supplying Europe. Section 6.2 investigates how hydrogen and ammonia can be stored, addressing the technical and spatial requirements of these energy carriers which allows further storage calculations. Section 6.3 quantifies the outcomes in terms of import volumes, required storage surface and associated costs. Section 6.4 conducts a sensitivity analysis to explore the impacts of varying key parameters, providing a holistic view of the challenges and opportunities. Finally, Section 6.5 summarises this chapter.

6.1.Supplier country analysis for hydrogen and ammonia

The energy transition implies a shift in trade routes. Countries and ports are looking at bilateral agreements to facilitate hydrogen trade and mention this in their national strategies. Hydrogen becomes affordable in cost-effective locations with the good renewable energy conditions and low project development costs.

Therefore, countries with high potential in the production of renewable energy, ensuring a reliable supply, are ideal for hydrogen supply (IRENA, 2024). Additional factors influencing this choice are land availability, water access (electrolysis) and infrastructure necessary for transporting and potentially exporting energy to meet the demand needs (IRENA, 2024). According to IRENA (2022d), water constraints significantly affect the production of green hydrogen for countries such as Saudi Arabia, Middle East, North Africa and Eastern Asia. Europe, the US, Japan and South Korea as pioneers of implementing state-level strategies for hydrogen. However, China is trying to catch up with a fast pace (World Economic Forum, 2023).

The potential production areas for green hydrogen for Europe must be identified. Hydrogen produced by nuclear energy is left out of the scope. Nuclear electricity does not generate direct emissions but the nuclear fuel cycle of uranium mining, conversion, enrichment and fuel fabrication results in emissions. Table 6.1 illustrates an overview of potential supplier countries for Europe. It is important to note that the list is not exhaustive but provides a good indication of potential production areas. The number of times a country is mentioned across the reviewed sources serves as a proxy for its perceived relevance. While not a definitive measure, a higher frequency of mentions suggests stronger recognition or greater emphasis in current hydrogen studies and strategic outlooks.

Table 6.1: Overview of potential green hydrogen supplier countries for Europe

Source	Australia	Brazil	Morocco	Egypt	Chile	Colombia	China	Norway	Saudi Arabia	South -Africa / Namibia	South America	US/ Canada
Panchenko et al., 2023		X	X	X						X		
IRENA, 2024	X									X	X	
IRENA, 2022c	X		X		X	X	X					
Rikabi, 2024	X		X		X							
Moritz et al., 2023	X		X		X		X	X	X			
Galimova et al., 2023			X		X							
IEA, 2019	X	X	X	X	X		X		X	X	X	X
Collins, 2024			X	X	X			X	X	X		X
# Mentioned	**5**	**2**	**7**	**3**	**6**	**1**	**3**	**2**	**3**	**4**	**2**	**2**

Source: (Panchenko et al., 2023), (IRENA, 2022d), (IRENA, 2024), (Rikabi, 2024), (Moritz et al., 2023), (Galimova et al., 2023), (IEA, 2019) and (P. Collins, 2024)

Australia is mentioned in five studies and stands out as a world leader in hydrogen development. Despite its strong position, the transportation costs to Europe are high. The transportation costs for ammonia from Australia to Rotterdam are \$0.56/kg (in terms of cost of hydrogen) and \$2.19/kg for liquid hydrogen (Panchenko et al., 2023). This strengthens the fact that ammonia is cheaper to transport than liquid hydrogen, which may influence the decision-making process for potential imports. Australia is located approximately 10,000 to 12,000 nautical miles away from Europe, significantly driving up transport costs (TransportguideRotterdam, n.d.).

South America and more specifically countries such as Chile, Colombia and Brazil show great potential to export renewable energy (IEA, 2019; Moritz et al., 2023; Panchenko et al., 2023). Chile, Colombia and Brazil have significant history of investments in renewable energy. This historical focus has positioned them favourably for hydrogen production in the future. Brazil has already a positive trade balance and is prepared for export. Most of its renewable energy generation originates from hydropower (IEA, 2019). 48% of its energy consumption is made up of renewable energy (IEA, 2019). In 2008, Brazil accounted for over 90% of renewable energy investments in Latin America (IEA, 2019). Its historical focus on developing renewable energy projects has driven cost reductions, increased productivity and promoted technological advancements Additionally, Brazil has significant potential for wind power, particularly in the Northeast, and solar power in remote areas of the Amazon (IAPH, 2024; Pereira et al., 2012). Chile is already very export-oriented among these countries. It is mentioned in multiple papers and reports (Moritz et al., 2023; Rikabi, 2024). These countries have a strategic position with numerous ports. Brazil and Chile have already established collaborations with the EU in developing green hydrogen projects, including signing off-take agreements with EU buyers, which positions these countries favorably in the hydrogen market. Furthermore, the study of IEA (2022a) illustrates that Latin Americ, Europe and Australia compared to other regions such as Canada and China, will take the lead in hydrogen electrolysis production by 2030. Additionally, Latin America illustrates that they have already installed the announced capacity that they expected to install for electrolyser capacity by 2030, far ahead of other global regions (IEA, 2022a).

Morocco is mentioned in seven studies and has the advantage of being close to the EU . The costs of shipping green ammonia from Morocco are competitive compared to those from Chile and Australia (Rikabi, 2024). However, it is important to note that Morocco remains reliant on coal and frequently imports electricity, which means it will take time to scale up its production of green hydrogen (IRENA, 2024). South Africa and Egypt have been mentioned less frequently (Galimova et al., 2023; IRENA, 2024). While South Africa and Namibia possess potential, it still requires further development, investments and the current infrastructure may pose a barrier to efficient hydrogen production and export (Dakhling, 2024; IEA, 2019). More than 20 projects with an electrolyser capacity at or above 100 MW have been announced in Kenya, Mauritania, Morocco, Namibia and South Africa.

China, with two mentions (IRENA, 2022d; Moritz et al., 2023), has the potential to produce hydrogen at a large scale but faces significant challenges. China is the largest producer (30% of the world's total) and consumer of hydrogen (IEA, 2022c). In March 2022, China's government set out ambitions to reach 100,000 and 200,000 tonnes a year of annual green hydrogen production capacity by the end of 2025 (World Economic Forum, 2023). In December 2024, these figures were not yet hit, but analysts suggest that China is on its way to meeting these targets. China's reliance on coal for its energy mix raises concerns about the sustainability of its hydrogen production. Its distance from Europe makes it less attractive as a hydrogen supplier than closer alternatives like North Africa. Additionally, the trade relations between Europe and China are complex, marked by expanding economic ties and rising geopolitical tensions.

Norway has only two mentions (IRENA, 2022d) but it could be a significant player due to its existing energy infrastructure and geographic proximity to Europe. Norway is also considered the cheapest supplier of green ammonia in Europe (Moritz et al., 2023). Norway launched Europe's largest green hydrogen operational production plant in 2024. The hydrogen produced at the plant is used to manufacture green ammonia. Despite this significant investment, the production of Norway remains primarily focused on regional applications, in contrast to countries such as Brazil or Morrocco, which target large-scale export markets. Another study of IEA (2022a) on hydrogen stated that in Europe Spain, Denmark, Germany and the Netherlands are front runners in Europe's electrolytic hydrogen production.

Saudi Arabia is mentioned three times (IEA, 2019; IRENA, 2022d) and faces significant challenges, particularly due to water constraints, which affect green hydrogen production. However, desalination technologies could potentially mitigate these challenges, making Saudi Arabia a possible future player in hydrogen exports. The construction of the NEOM green hydrogen project is planned to operate in 2026.

The United States and Canada are preparing for hydrogen production and export, with the U.S. leveraging significant incentives under the Inflation Reduction Act and aiming for 10Mt of clean hydrogen by 2030, of which 3Mt could be exported to Europe. Both countries benefit from strategic access to the Atlantic and Pacific markets. (P. Collins, 2024)

Regions such as Sub-Saharan Africa and parts of South America have also been mentioned for their vast solar and wind potential, making them promise for large-scale green hydrogen production in the future (IRENA, 2024). However, infrastructure and political stability may present obstacles that need to be addressed for these regions to become reliable hydrogen suppliers. (IRENA, 2024)

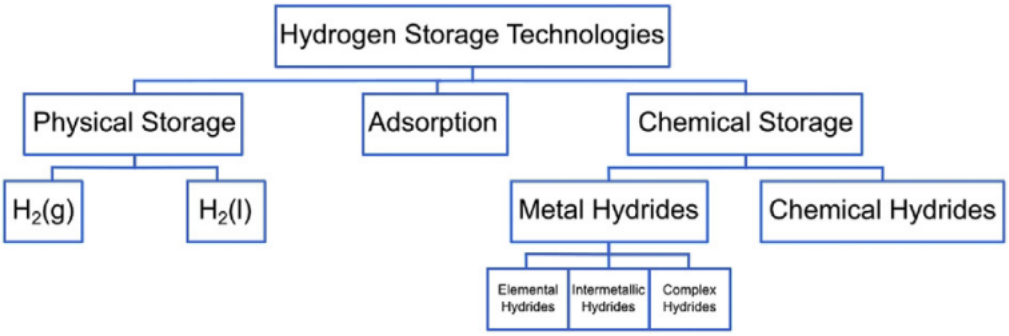
Several key factors influence decision-making beyond transport and storage costs when selecting trade partners for hydrogen imports. Economic factors, the availability of financing, resource quality and proximity to trade partners are important factors (IEA, 2019). Additionally, policy considerations, such as government energy targets and infrastructure regulations, play a significant role in shaping the industrial ecosystem. Technical expertise and research are also an important consideration. Furthermore, geopolitical stability, trade relations and trade dependence are essential factors, as they affect supply chain security and partnership reliability (IRENA, 2024). Another relevant aspect is the expected form in which hydrogen will be exported, which varies between countries (ranging from ammonia and liquid hydrogen to LOHCs or compressed hydrogen). This choice influences the feasibility of trade partnerships, as it affects compatibility with port infrastructure and the level of technological readiness on both the origin and receiving port.

For the further research, the research selected two geographically closer destinations and two more distant ones. The selected exporting countries for green hydrogen are Brazil, Morocco, Egypt and Namibia/South Africa for this analysis. It is based on their strong potential to supply green hydrogen to Europe, supported by favourable renewable energy conditions and strategic positioning. Brazil offers a mature renewable energy landscape, with nearly half of its energy consumption derived from renewables and significant experience in hydropower, wind and solar projects. It has already established partnerships with the EU for green hydrogen development, making it a key player for future imports (IEA, 2019). Morocco, with its proximity to Europe and competitive shipping costs for green ammonia, stands out as an attractive supplier (IRENA, 2022d; Moritz et al., 2023; Panchenko et al., 2023; Rikabi, 2024). Egypt and Namibia/South Africa represent emerging opportunities for hydrogen production. Namibia and South Africa are leveraging its vast solar and wind resources. Both regions (Egypt and Namibia) hold promises but still face challenges related to scaling up production and export capabilities. Both the port of Antwerp and the port of Rotterdam have investments in Namibia for hydrogen and ammonia projects (Van Oost, 2025). These areas, combined, present a diverse mix of hydrogen supply chains, aligning with Europe's need for secure, cost-effective and scalable imports. The selection of these countries or regions reflects a balance between their proximity to Europe, their production potential and long-term strategic partnerships. All these countries are also mentioned in the report of the IEA (2019).

6.2.Storage possibilities for hydrogen and ammonia

The model uses assumptions to calculate costs. It is important to note that storing hydrogen implies significant challenges. One of the main challenges is the high energy cost associated with cooling hydrogen to its liquid state. Hydrogen must be stored at extremely low temperatures (-253°C), which requires substantial energy and increases operational costs (Andersson & Grönkvist, 2019). This also affects the overall efficiency of hydrogen use. There are several ways to store hydrogen, Figure 6.1 presents the storage methods according to Andersson & Grönkvist (2019).

Figure 6.1: Hydrogen storage technologies



Source: (Andersson & Grönkvist, 2019)

There are three main categories of storing. First, hydrogen could be stored as a gas or a liquid in pure, molecular form without any significant physical or chemical bonding to other materials. This storage method, especially in liquid form, can also lead to boil-off losses, where hydrogen evaporates over time, reducing the usable volume. Second, hydrogen could be adsorbed onto or into a material, held by relatively weak physical van der Waals bonds, which are weak intermolecular forces. Lastly, atomic hydrogen may be chemically bonded, also called absorbed.

The latter can be further divided into two sub-categories, the metal hydrides and the chemical hydrides. The storage properties of these materials are different. Metal hydrides contain metal atoms. In these compounds, hydrogen can be directly bonded to the metal atom (elemental and intermetallic hydrides) or part of a complex ion bonded to a metal atom (as in complex metal hydrides). In contrast, chemical hydrides are non-metallic elements, typically involving carbon, nitrogen, boron, oxygen and hydrogen combinations (Andersson & Grönkvist, 2019; Ishaq et al., 2022). Ammonia could be easily reformed via a Haber Bosch reversible process via cracking ammonia back into nitrogen and hydrogen. Chemical hydrogen storage methods are not without challenges. The process of releasing hydrogen from these compounds often results in energy losses, which can reduce the net energy output. Moreover, scaling up these technologies for industrial applications requires further technological advancements and considerable investment. (Andersson & Grönkvist, 2019; Ishaq et al., 2022)

The only form of hydrogen storage currently employed on a significant scale is hydrogen in pure form, gas or liquid (physical storage). The Haber-Bosch process is widely used for large-scale ammonia production, primarily for fertilizers and industrial applications. However, its role as a hydrogen carrier in the energy transition is still in its early stages, with limited large-scale implementation and significant challenges in ammonia cracking and cost efficiency. The physical storage also implies risks associated with the infrastructure needed for safe and efficient storage. Hydrogen is highly flammable, and the tanks used for storage need to be built from specialized materials to prevent leaks. Furthermore, hydrogen can cause embrittlement of metals. (Andersson & Grönkvist, 2019)

Furthermore, there are experimental projects such as the ACES in Utah which will store green hydrogen (gas) converted from renewable energy in underground salt caverns, providing enough energy to power 150,000 households by 2025 (FCW, 2020). It aims to store 1,000 megawatts of clean power. This storage method is more cost-effective than aboveground tanks and is gaining traction in Europe for the clean energy transition (FCW, 2020).

In this dissertation, the non-carbon import (H_2) is transported in the form of liquid hydrogen (LH_2) and ammonia (NH_3).

6.3.Sub-scenarios quantification

The sub-scenarios of Chapter 5 are used to develop port sub-scenarios and further calculations. Based on the method detailed in Chapter 3, the import was divided according to the gravitation model using the GDP share of each NUTS2 region and the distance from the ports to each NUTS2 region. In this chapter, the analysis continues by translating the three developed sub-scenarios for countries to ports. Initially, key assumptions are established: all imports are presumed to originate from Namibia, and the developed sub-scenarios are founded on the premise that each port is connected to every NUTS2 region through dedicated pipelines. Namibia was selected as a reference case for the base scenario because it is one of the most frequently mentioned potential exporters of green hydrogen to Europe, and represents a realistic and data-supported option for initial calculations. This simplification allows for a clear and consistent comparison between ports. Subsequently, sensitivity analyses will be conducted later in this chapter to evaluate the impact of variations in these assumptions. These include alternative exporting countries, in order to assess how import origin influences port infrastructure needs and related costs.

The geometric mean is used to compare the three sub-scenarios. The geometric mean (GM) calculates the average of non-carbon imports for each port covering the period 2030-2050. The geometric mean is used because the values are related multiplicatively or represent growth and change over time. Unlike the arithmetic mean, which averages values by summing them and dividing by the number of data points, the geometric mean accounts for the compounding effects of these values. The geometric mean is useful for time-series data, such as non-carbon outputs in this case. The outputs change over time, the geometric mean helps capture the cumulative effect of these changes, providing a more accurate representation of the average behavior across the years.

The formula for the weighted geometric mean of non-carbon outputs is expressed as:

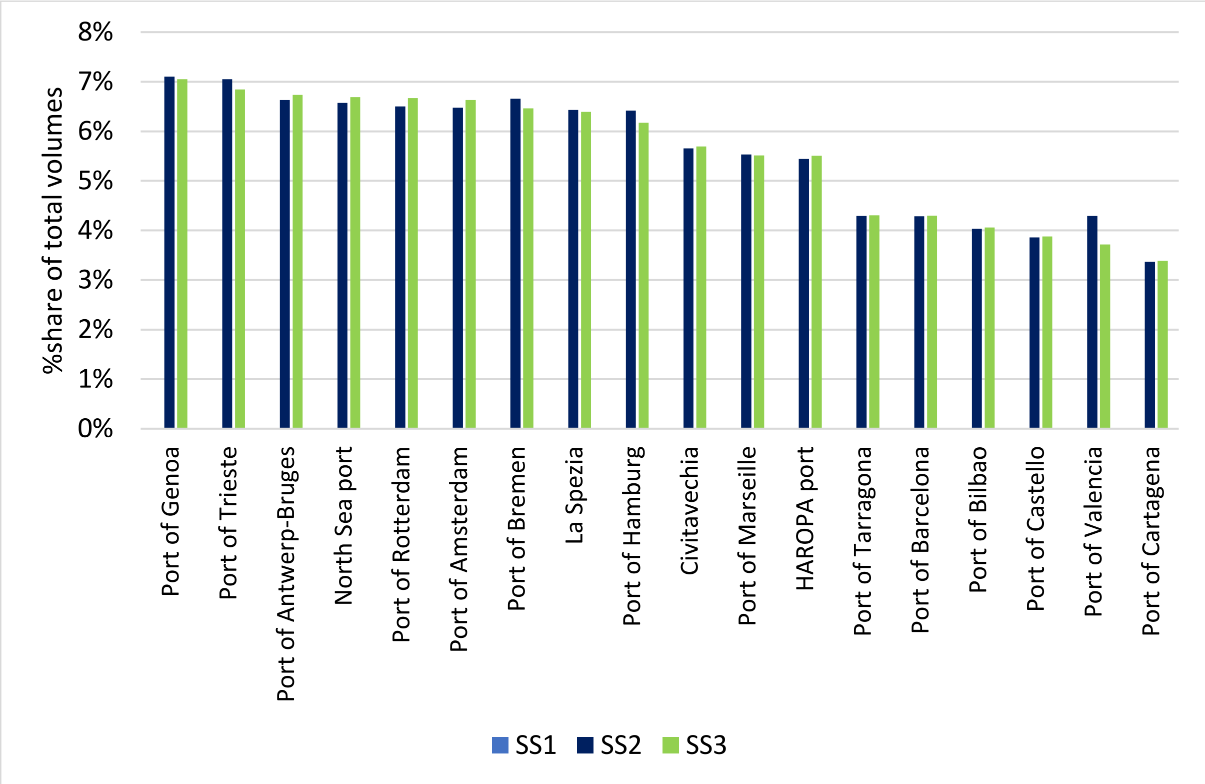
$$GM = \frac{\frac{(2040-2030)*Output_{2030}}{10}+\frac{(2040-2030)*(\frac{Output_{2040}-Output_{2030}}{2})}{10}+\frac{(2050-2040)*Output_{2040}}{10}+\frac{(2050-2040)*(\frac{Output_{2050}-Output_{2040}}{2})}{10}}{20}$$

The formula could be simplified as:

$$GM = \frac{1}{4}Output_{2030} + \frac{1}{2}Output_{2040} + \frac{1}{4}Output_{2050}$$

Figure 6.2 presents the import share for the eighteen ports selected for the analysis for the three sub-scenarios. The figurepresents the geometric average percentage share of H_2 in 2030, 2040 and 2050. The ammonia share through each port is the same as the H_2 share.

Figure 6.2: % average share of H2 import in each sub-scenario per port



Source: own composition

As presented in the previous sections SS1 does not show an output of non-carbon energy, focusing instead on increased domestic production and continued reliance on carbon-based imports. The graph indicates that several ports take the lead in importing non-carbon energy, even though the imports in these three sub-scenarios do not directly originate from the countries where the ports are located. The imports are distributed across the ports, as shown in Figure 6.2, allowing for identifying ports with major roles and those with more minor roles in the import of non-carbon energy in the three sub-scenarios. Nine ports lead in imports of non-carbon energy if there is an import need for non-carbon energy (Sub-scenario 2 and 3): port of Genoa, port of Trieste, port of Antwerp-Bruges, North Sea Port, port of Rotterdam, port of Amsterdam, port of Bremen, port of La Spezia and port of Hamburg. The rest of the ports account for less than 6%. A gap exists between ports; three ports take up an average share of 5-6%: the port of Civitavecchia, Marseille and HAROPA. The ports of Tarragona, Barcelona, Bilbao, Castellon, Valencia and Cartagena have a small share, between 4.5% and 3.4%, in Sub-scenarios 2 and 3.

The first sub-scenario illustrates a 22% decline in energy demand by 2050, a decline by 82% in carbon energy production, and an increase by 188% of non-carbon production by 2050. The assumptions for carbon imports of Sub-scenario 1 indicate a reduction of solid fossil fuels by 54%, an increase of natural gas by 23%, and a slight growth of 2% in oil and petroleum products by 2050. This results in no import need for non-carbon flows in Sub-scenario 1 by 2030, 2040 and 2050 for these six countries and, consequently, no non-carbon throughput on port activities related to these imports.

The second sub-scenario presents a 22% decrease in energy demand by 2050, a decrease by 82% in carbon energy production and an increase of 60% in non-carbon production by 2050. The import assumptions of carbon remain the same as in Sub-scenario 2. This sub-scenario will result in Germany's need to import non-carbon energy by 2030. Figure 6.2 only shows the averages for 2030 because for 2040 and 2050 there are no imports. Sub-scenario 2 shows that the port of Genoa (7.1%) and port of Trieste (7.05%) take up the most significant share of imports by more than 7%, followed by the port of Bremen, Antwerp-Bruges, North Sea Port, Rotterdam, Amsterdam, La Spezia and Hamburg. The port of Civitavecchia, Marseille, HAROPA, Tarragona, Barcelona, Bilbao, Castellon, Valencia and Cartagena have a share between 3.4 % and 5.7%. Italy, Germany, Belgium and The Netherlands will handle most of the imports. Ports in France and Spain will only take on a small portion of this import.

The third sub-scenario assumes a 22% decline in energy demand by 2050, the complete phase-out of domestic production and imports of carbon-based energy and an increase in domestic renewable energy production, doubling by 2030 and tripling by 2050. The outcome indicates a rise in imports for Germany, the Netherlands, and Italy. These findings highlight these countries' significant role in the energy transition. The ports in Italy, Belgium, the Netherlands and Germany- Port of Genoa, Trieste, Antwerp-Bruges, North Sea Port, Rotterdam, Amsterdam, Bremen, La Spezia and Hamburg - tend to play a significant role in Sub-scenario 3. However, Belgium was not on the list of importing countries of non-carbon energy in sub-scenario 3. The port of Genoa accounts for more than 7% of the imports needed to serve the energy needs in these six countries. While Germany requires the largest share of imports, other ports outside of Germany will play a crucial role in facilitating these imports. In this graph, Bremen, the first port of Germany, will take up a share of nearly 6.4%.

The graph Figure 6.2 demonstrates that specific ports lead in non-carbon energy imports across the sub-scenarios. Nine ports play a significant role in two out of the three sub-scenarios focused on non-carbon imports. Thereafter, the share of each port drops below 5.6%. These ports show a consistently high share of non-carbon imports, indicating their strategic importance in the transition towards sustainable energy sources. These ports are well-positioned to facilitate the import and distribution of non-carbon energy resources across Europe. Their high shares across the sub-scenarios highlight their potential roles in contributing to Europe’s energy diversification and resilience, positioning them as possible key ports for further analysis.

For the volume, surface and cost calculations, this research needs to zoom in on ports. The selection of the three ports analyzed in this chapter is based on the data presented in Chapter 4, which emphasized the significance of specific ports in Europe’s liquid bulk handling. According to the ranking of European ports by their handling liquid bulk volumes in 2022, Rotterdam accounted for 25% of the total, Antwerp-Bruges 10% and Amsterdam 5%. These percentages show the importance of these ports, together handling a significant share (40%) of Europe's liquid bulk volumes. These ports are located in two different countries, namely Belgium and the Netherlands. Given their current role in managing large volumes of liquid bulk, these ports are well-positioned to transition towards handling non-carbon energy in the future. This potential transformation aligns with the energy transition goals, making these ports critical for analysis in this chapter.

This section examines the port of Rotterdam, Antwerp-Bruges and Amsterdam within the context of the three previously determined sub-scenarios in Chapter 6. It examines the similarities and differences in the outcomes across the sub-scenarios, as well as between the three selected ports.

6.3.1. Port of Rotterdam

Table 6.2 presents the import requirements of hydrogen and ammonia expressed in tonnes of the port of Rotterdam in 2030, 2040 and 2050.

Table 6.2: Volumes of hydrogen and ammonia (tonnes) port of Rotterdam: 2030, 2040 & 2050

		2030		2040		2050	
		H2	NH3	H2	NH3	H2	NH3
SS1	Share of total volume	0.00%		0.00%		0.00%	
	Total volumes	-	-	-	-	-	-
SS2	Share of total volume	6.50%		0.00%		0.00%	
	Total volumes	1,951,686	3,971,288	-	-	-	-
SS3	Share of total volume	6.52%		6.81%		6.55%	
	Total volumes	2,936,346	5,974,873	1,500,512	3,053,241	2,307,603	4,695,508

Source: own composition

In sub-scenario 1, no imports of non-carbon energy are required for the port of Rotterdam in 2030, 2040 and 2050 due to strong projections of domestic production. However, despite this increase in domestic non-carbon energy production, there will still be a need to import carbon-based energy, which contradicts EU regulations. Therefore, Sub-scenario 1 is not ideal, as it does not account for the necessary transition to non-carbon energy imports to meet demand.

Sub-scenario 2 indicates a decrease in carbon production and imports of fossil fuels and a slower increase in domestic production growth of 60% by 2050 in non-carbon energy, which causes Germany to import non-carbon energy. The import need can be explained as follows. The gradual growth of non-carbon production will increase by 100% by 2030. This growth is insufficient to compensate for the 28% decrease in carbon imports during the same period. As a result, the shortfall created by the decline in carbon imports must be addressed through additional imports of hydrogen and ammonia to meet demand. This translates into a need for importing almost 2 million tonnes of hydrogen and almost 4 million tonnes of ammonia via the port of Rotterdam in 2030. The port of Rotterdam takes a share of approximately 6.5% of all imports in Sub-scenario 2 and 3.

Sub-scenario 3 uses the same 300% increase in domestic production as Sub-scenario 1 but decreases its carbon production and imports by 100% by 2050, which causes a greater need for non-carbon imports. By 2030, the port of Rotterdam must import almost 3 million tonnes of hydrogen and almost 6 million tonnes of ammonia. In 2040, these volumes are projected to decrease to 1.5 million tonnes of hydrogen and approximately 3 million tonnes of ammonia. However, by 2050, the import requirements are expected to increase again, reaching 2.3 million tonnes of hydrogen and 4.7 million tonnes of ammonia. This temporary dip in import volumes in 2040 can be explained by a sharp increase in domestic renewable production capacity by 2040, combined with a still moderate decrease in total energy demand and a slower decrease of carbon energy imports (by -66%), temporarily reduces the need for non-carbon energy imports. However, by 2050, the complete phase-out of carbon-based energy sources results in a significantly higher demand for non-carbon energy. As domestic production cannot fully cover this need, import volumes rise again.

The trend in non-carbon imports, with an initial decrease followed by a significant rise, reflects the interplay of the different parameters. The declining energy demand, increasing domestic non-carbon production, and the phasing out of carbon-based energy sources influence the non-carbon import needs. Between 2030 and 2040, domestic non-carbon production expands significantly (+100% by 2030, +200% by 2040), which, combined with a lower total energy demand (-8% by 2030, -19% by 2040), reduces the need for imports during this period. By 2050, as carbon production and imports are fully phased out (-100%), the balance between domestic non-carbon production and the remaining energy demand shifts, leading to a renewed increase in non-carbon imports. This trend or dip illustrates a transitional phase where the system adjusts to a new energy mix determined by the changing parameters.

Table 6.3 presents the output parameters for the port of Rotterdam.

Table 6.3: Output parameters sub-scenarios for port of Rotterdam

		2030		2040		2050	
		H2	NH3	H2	NH3	H2	NH3
	Required fleet (#vessels/week)	-	-	-	-	-	-
	Storage volume (tonne)	-	-	-	-	-	-
	Storage tanks required (#)	-	-	-	-	-	-
	Storage space required (ha)	-	-	-	-	-	-
SS1	Storage cost (MEUR)	€ -	€ -	€ -	€ -	€ -	€ -
	Required fleet (#vessels/week)	3.35	0.45	-	-	-	-
	Storage volume (tonne)	112,597.28	22,744.65	-	-	-	-
	Storage tanks required (#)	501	1	-	-	-	-
	Storage space required (ha)	43.03	2.75	-	-	-	-
SS2	Storage cost (MEUR)	€ 6,256.24	€ 392.00	€ -	€ -	€ -	€ -
	Required fleet (#vessels/week)	5.04	0.68	2.58	0.35	3.96	0.54
	Storage volume (tonne)	169,404.59	34,219.73	86,568.03	17,486.74	133,130.95	26,892.45
	Storage tanks required (#)	753	1	385	1	592	1
	Storage space required (ha)	64.67	2.75	33.07	2.75	50.84	2.75
SS3	Storage cost (MEUR)	€ 9,403.09	€ 392.00	€ 4,807.69	€ 392.00	€ 7,392.60	€ 392.00

Source: own composition

After analyzing the non-carbon import for SS1, SS2 and SS3, the different port output sub-scenarios are calculated. As SS1 has no output, there are also no output parameters for the port of Rotterdam. SS2 requires a fleet of 3.4 and 0.5 vessel calls per week in the port of Rotterdam by 2030. The storage requirements in the Port of Rotterdam by 2030 are 112.6 thousand tonnes of hydrogen and 22.7 thousand tonnes of ammonia, needing 501 storage tanks for hydrogen storage and only one storage tank for ammonia. This results in a 43 hectare storage space required for hydrogen and 2.75 ha's for ammonia. The storage cost is 6.3 billion euros and 392 million euros respectively. Sub-scenario 3 shows that the weekly fleet requirement is five vessels for hydrogen in 2030, 3 for 2040 and 4 for 2050. Hydrogen accounts for 75% of the total non-carbon energy imports in these three sub-scenarios, meaning that ammonia makes up the remaining 25%, with corresponding fleet parameters. The storage volume requirements in the Port of Rotterdam for 2030 are 169 thousand tonnes, consisting of 34 thousand tonnes of ammonia and 87 thousand tonnes of hydrogen with an increasing demand for storage of both energy carriers in the future. The storage capacity needed for hydrogen is substantial, with 753 storage tanks required by 2030, while only one storage tank is needed for ammonia, highlighting the difference in storage needs. The required storage space is 65 hectares for hydrogen and only 3 hectares for ammonia. In terms of storage costs, there is a clear contrast, with storage for hydrogen costing approximately €9.4 billion, while ammonia storage costs €392 million. This highlights the significantly higher costs of hydrogen storage in Sub-scenario 3.

The projected dynamics of hydrogen imports through the port of Rotterdam align closely with the sub-scenarios developed in this research. Initial imports of green or blue hydrogen are expected between 2024 and 2025 at the Port of Rotterdam (Port of Rotterdam, 2024b). Ammonia has already been shipped to the port of Rotterdam and produced from green hydrogen via renewable energy (Port of Rotterdam, 2024c). The hydrogen is then transformed via the Haber Bosch method to ammonia to transport. The Port of Rotterdam believes that they can have a port throughput of 20 million tonnes of hydrogen by 2050, the port of Rotterdam itself can only produce domestically a maximum of 10% of that amount by offshore wind (Port of Rotterdam, 2024c). That means that 90% needs to be imported, which is about 18 million tonnes (Port of Rotterdam, 2024c). Two-thirds of the imports via the Port of Rotterdam are destined for the German market, which aligns with and reinforces our research outcomes (Port of Rotterdam, 2024c). The second sub-scenario also identified the Port of Rotterdam as one of the critical hubs for Germany's imports. This highlights Rotterdam's strategic role in facilitating energy import flows to the German market and underscores its importance within the broader European energy supply chain. If SS3 is compared to the 2 million tonnes predicted of domestic non-carbon energy, then SS3 is extremely positive because it expects a domestic production of 14.86 million tonnes of hydrogen for the Netherlands. So then the domestic production by 2050 should rise with only 100%, which is already double. This translates in 13.1 million tonnes of hydrogen and 26.7 million tonnes of ammonia, which equals approximately 17.85 million tonnes of hydrogen equivalent. This outcome aligns well with the projected demand by 2050, which is estimated at around 18 million tonnes of hydrogen imports.

For the port of Rotterdam, three different groups of exporting countries for hydrogen are categorized (Port of Rotterdam, 2024c). The first group, the OECD countries, are the developed countries that have the willingness to pay, whose technology is ready, and who have a dynamic environment. However, these OECD countries have a large local marketplace that they must satisfy first. The second category of focus for the OECD countries is the Middle East and India. They have good renewable energy sources such as wind and solar power, capital strength and knowledge. The third category is South America and Africa, which have great resources but have more financial risks. Ports are looking at supporting them with knowledge and support them financially. In 2021, the Port of Rotterdam has agreements with 25 countries such as Norway, Spain, Scotland, Canada, the United States, Namibia and Australia. Some of these countries, such as Australia, have the downside of being far from the port of Rotterdam. According to the Port of Rotterdam, it could be viable because the transport cost of ammonia or hydrogen only accounts for 5-6% of the total cost of hydrogen, which means that distance should not limit its use. The first fully commercial ammonia-ready supply chains are expected to be ready by 2026. The Delta-Rhine Hydrogen Pipeline, which will connect the Port of Rotterdam to the German hinterland, is expected to be operational by 2032–2033 (Port of Rotterdam, 2024d). This pipeline is included in our projections as it forms a key part of the European Hydrogen Backbone network, enabling large-scale hydrogen transport across borders and strengthening Rotterdam’s role as a key import and transit hub for Germany (European hydrogen backbone, 2023). There is still a lot of work in terms of building pipelines. However, there will be no pipeline connection in 2024 from the Port of Rotterdam to Germany. (Port of Rotterdam, 2024c)

6.3.2. Port of Antwerp-Bruges

The Port of Antwerp-Bruges accounts for a share of 10% in 2022 of the liquid bulk ports researched in Chapter 4 (30 ports). Table 6.4 illustrates the total import volumes of non-carbon imports through the port of Antwerp-Bruges.

Table 6.4: Volumes (tonnes) of hydrogen and ammonia port of Antwerp-Bruges: 2030, 2040 & 2050

		2030		2040		2050	
		H2	NH3	H2	NH3	H2	NH3
SS1	Share of total volume	0.00%		0.00%		0.00%	
	Total volumes	-	-	-	-	-	-
SS2	Share of total volume	6.63%		0.00%		0.00%	
	Total volumes	1,989,218	4,047,659	-	-	-	-
SS3	Share of total volume	6.62%		6.85%		6.61%	
	Total volumes	2,982,668	6,069,129	1,511,297	3,075,185	2,326,689	4,734,344

Source: own composition

No non-carbon imports are required in Sub-scenario 1 for the port of Antwerp-Bruges for 2030, 2040 and 2050 due to strong domestic projections for non-carbon energy production.

Sub-scenario 2 projects a 28% reduction in carbon production and an 18% decrease in fossil fuel imports by 2030 compared to 2022. There is a 10.4% rise in natural gas imports and a modest 1% increase in overall energy consumption by 2030. However, the sub-scenario highlights slower growth in domestic non-carbon energy production, which is expected to increase by 20% by 2030 compared to 2022. This gradual growth is insufficient to fulfil the decline in carbon imports, creating a shortfall in the energy supply. As a result, Germany's energy demand necessitates imports of non-carbon energy, including hydrogen and ammonia. For the port of Antwerp, this results in a need to import almost 2 million tonnes of hydrogen and 4 million tonnes of ammonia in 2030. These volumes in the port of Antwerp-Bruges represent 6.63% of all imports required for the six researched countries, specifically for Germany. By 2040 and 2050, the port does not require additional imports under Sub-scenario 2, as domestic production is expected to catch up by 60% by 2050 and there will be still some production and import of carbon energy.

Sub-scenario 3, which assumes a 300% increase in domestic production by 2050 compared to 2022 alongside a complete phase-out of carbon-based energy imports (-100% by 2050), leads to a higher demand for non-carbon imports. For the port of Antwerp, this results in importing almost 3 million tonnes of hydrogen and 6 million tonnes of ammonia in 2030. These volumes decrease in 2040 to 1.5 million tonnes of hydrogen and 3 million tonnes of ammonia due to domestic production increases and reduced overall energy demand (8% by 2030 and -19% by 2040). However, by 2050, as carbon imports are entirely eliminated, the import needs rise again to 2.3 million tonnes of hydrogen and 4.7 million tonnes of ammonia, representing 6.61% of all imports needed for Germany, Italy and the Netherlands. The trend in non-carbon imports at the port of Antwerp, characterized by a decline by 2040 followed by a substantial increase by 2050, reflects the same patterns to those identified in the Port of Rotterdam. This trend demonstrates the dynamic interaction of several factors, including decreasing overall energy demand, increasing domestic non-carbon production, and the phased elimination of carbon-based energy sources.

Table 6.5 presents the output parameters for the port of Antwerp-Bruges.

Table 6.5: Output parameters sub-scenarios for port of Antwerp-Bruges

		2030		2040		2050	
		H2	NH3	H2	NH3	H2	NH3
	Required fleet (#vessels/week)	-	-	-	-	-	-
	Storage volume (tonne)	-	-	-	-	-	-
	Storage tanks required (#)	-	-	-	-	-	-
	Storage space required (ha)	-	-	-	-	-	-
SS1	Storage cost (MEUR)	€ -	€ -	€ -	€ -	€ -	€ -
	Required fleet (#vessels/week)	3.42	0.46	-	-	-	-
	Storage volume (tonne)	114,762.60	23,182.05	-	-	-	-
	Storage tanks required (#)	511	1	-	-	-	-
	Storage space required (ha)	43.89	2.75	-	-	-	-
SS2	Storage cost (MEUR)	€ 6,381.11	€ 392.00	€ -	€ -	€ -	€ -
	Required fleet (#vessels/week)	5.12	0.70	2.59	0.35	4.00	0.54
	Storage volume (tonne)	172,077.02	34,759.56	87,190.23	17,612.43	134,232.08	27,114.88
	Storage tanks required (#)	765	1	388	1	597	1
	Storage space required (ha)	65.70	2.75	33.32	2.75	51.27	2.75
SS3	Storage cost (MEUR)	€ 9,552.94	€ 392.00	€ 4,845.15	€ 392.00	€ 7,455.04	€ 392.00

Source: own composition

The different port output sub-scenarios are calculated after analysing the non-carbon import for SS1, SS2 and SS3. As SS1 has no output, there are also no output parameters for the Port of Antwerp-Bruges.

Sub-scenario 2 results in an import of almost 2 million tonnes of hydrogen and 402 thousand tonnes of ammonia in 2030. It has a required fleet of 3.4 and 0.5 weekly vessel calls in the Port of Antwerp-Bruges. The storage requirements in the Port of Antwerp-Bruges by 2030 are 114,763 tonnes of hydrogen and 23,182 tonnes of ammonia, needing 511 storage tanks for hydrogen storage and only one storage tank for ammonia. This results in a 44 hectares storage space required for hydrogen and 2.75 ha for ammonia. This storage costs €6.4 billion for hydrogen and €392 million for ammonia.

In sub-scenario 3, the outputs are higher compared to SS2. By 2030, the Port of Antwerp-Bruges will handle almost 3 million tonnes of hydrogen and 603 tonnes of ammonia, requiring 5.12 and 0.70 weekly vessel calls, respectively. This will require 765 hydrogen storage tanks and one ammonia storage tank, covering 66 ha for hydrogen and 3 ha for ammonia storage surface. Storage costs in 2030 for SS3 are estimated at €9.6 billion for hydrogen and €392 million for ammonia. By 2040, the import volumes and infrastructure requirements decrease slightly. The Port of Antwerp-Bruges will handle 1.5 million tonnes of hydrogen and 305 thousand tonnes of ammonia, with a fleet of 2.59 hydrogen vessel calls and 0.35 ammonia vessel calls per week. The number of hydrogen storage tanks needed would rise to 388 by 2040, and ammonia would still require one tank. Hydrogen storage would occupy 33.32 hectares, and ammonia storage would remain at 2.75 hectares. The storage costs in 2040 are projected at €4.8 billion for hydrogen and €392 million for ammonia.

The estimations for 2050 show growth in import volumes under SS3, with a required fleet of 4 hydrogen vessel calls and 0.54 ammonia vessel calls per week by 2050. Storage volumes are projected to reach 134,232 tonnes of hydrogen and 27,115 tonnes of ammonia. The storage infrastructure would require 597 hydrogen tanks and one ammonia tank, utilizing 51.27 ha for hydrogen storage and 2.75 ha for ammonia. Storage costs are estimated at €7.4 billion for hydrogen and €392 million for ammonia in 2050.

These sub-scenarios emphasize the Port of Antwerp's strategic importance in supporting Europe's transition to green energy and import of non-carbon energy, especially in Sub-scenario 3, by facilitating the storage and import of hydrogen and ammonia at scale.

Belgium expects to import 45 TWh per year of non-carbon energy, the majority of this import is experted to be imported via the Port of Antwerp-Bruges (Air Liquide, 2023). This import can be is translated in 6-10 million tonnes of ammonia by 2030 or 1.2-1.5 million tonnes of hydrogen (Air Liquide, 2023; Lancaster, 2023). These predictions are in line with the predictions of SS3 made in this chapter. Following the Belgian Federation of hydrogen strategy this 45 TWh per year is going to increase towards 200-350 TWh in 2050 (Air Liquide, 2023). If this 200-230 TWh per year is translated to a 75% hydrogen and 25% ammonia, it results in 4.5-7.9 million tonnes of hydrogen and 8.5-15 million tonnes of ammonia. The SS3 scenario shows that it is a quite positive scenario and if the domestic carbon-production is brought to 250% by 2050 instead of 300%, the results show us that there is a need for 4.9 million tonnes of hydrogen and 10 million tonnes of ammonia.

The Port of Antwerp-Bruges is looking at countries with a surplus of wind and solar, such as Chile, Oman, Egypt, Brazil and Namibia, for their green hydrogen import. The port of Antwerp-Bruges has the advantage of having two platforms, Antwerp and Bruges, which have complementary benefits. Bruges can accommodate and store hydrogen carriers by sea. Antwerp can accommodate hydrogen carriers by pipeline and by sea. Hydrogen carriers can be further processed into hydrogen, which can then be used for various purposes such as electricity generation, fuel, and heat and as a feedstock for industrial processes. (Port of Antwerp Bruges, 2024). The Port of Antwerp-Bruges plans to have the local infrastructure for producing hydrogen, ammonia, and other hydrogen carriers ready by 2025-2026. The first import of hydrogen and its carriers is expected in 2027-2028 and at a large scale in 2030. By supporting projects in the Port of Antwerp-Bruges, Europe enhances the import capabilities for non-carbon energy, highlighting Antwerp's crucial role in the import of sustainable energy. For instance, Air Liquide received a €110 million grant from Europe to develop the first large-scale project for producing, liquefaction, and distributing renewable hydrogen from ammonia (Air Liquide, 2024). Such projects and grants promote the import of non-carbon energy and underscore the strategic importance of the Port of Antwerp. (Port of Antwerp Bruges, 2024)

6.3.3. Port of Amsterdam

The port of Amsterdam accounts for 5% of the total liquid bulk imported into Europe in 2022 (Eurostat, 2024b, p. 20). Table 6.6 illustrates the total volumes of non-carbon energy imports expressed in tonnes for the port of Amsterdam.

Table 6.6: Volumes (tonnes) of hydrogen and ammonia port of Amsterdam: 2030, 2040 & 2050

		2030		2040		2050	
		H2	NH3	H2	NH3	H2	NH3
SS1	Share of total volume	0.00%		0.00%		0.00%	
	Total volumes	-	-	-	-	-	-
SS2	Share of total volume	6.48%		0.00%		0.00%	
	Total volumes	1,943,388	3,954,403	-	-	-	-
SS3	Share of total volume	6.49%		6.77%		6.50%	
	Total volumes	2,921,060	5,943,768	1,492,148	3,036,221	2,290,746	4,661,206

Source: own composition

The table provides an overview of the projected imports of non-carbon energy, specifically hydrogen (H_2) and ammonia (NH_3), for the Port of Amsterdam under three sub-scenarios (SS1, SS2, and SS3) for the years 2030, 2040, and 2050. Additionally, it indicates the share of these imports relative to the total import requirements of Europe's six main carbon-importing countries in 2022.

In Sub-scenario SS1, the port of Amsterdam does not import hydrogen or ammonia in any analysed years.

In Sub-scenario SS2, the port of Amsterdam is projected to import 1.9 million tonnes of hydrogen and almost 4 million tonnes of ammonia in 2030. These volumes represent 6.48% of the total import needs of the six carbon-importing countries. However, no imports of hydrogen or ammonia are required for 2040 and 2050 under this sub-scenario.

In Sub-scenario 3, the port of Amsterdam is more prominent in non-carbon energy imports. In 2030, the port is expected to handle 2.9 million tonnes of hydrogen and 5.9 million tonnes of ammonia, corresponding to a 6.49% share of total import needs. By 2040, this share will increase to 6.77%, with imports reaching almost 1.5 million tonnes of hydrogen and 3 million tonnes of ammonia due to the interplay of the different input parameters such as demand and carbon imports. In 2050, the port's share slightly decreases to 6.5%, with projected imports of almost 2.3 tonnes of hydrogen and approximately 4.7 million tonnes of ammonia.

These results highlight the varying levels of involvement of the port of Amsterdam in future non-carbon energy imports, with Sub-scenario S3 depicting the port as a significant hub for hydrogen and ammonia importation over time.

Table 6.7 presents the output parameters for the three different sub-scenarios for 2030, 2040 and 2050 for the port of Amsterdam.

Table 6.7: Output parameters sub-scenarios for port of Amsterdam

		2030		2040		2050	
		H2	NH3	H2	NH3	H2	NH3
SS1	Required fleet (#vessels/week)	-	-	-	-	-	-
	Storage volume (tonne)	-	-	-	-	-	-
	Storage tanks required (#)	-	-	-	-	-	-
	Storage space required (ha)	-	-	-	-	-	-
	Storage cost (MEUR)	€ -	€ -	€ -	€ -	€ -	€ -
SS2	Required fleet (#vessels/week)	3.34	0.45	-	-	-	-
	Storage volume (tonne)	112,118.53	22,647.94	-	-	-	-
	Storage tanks required (#)	499	1	-	-	-	-
	Storage space required (ha)	42.86	2.75	-	-	-	-
	Storage cost (MEUR)	€ 6,231.26	€ 392.00	€ -	€ -	€ -	€ -
SS3	Required fleet (#vessels/week)	5.02	0.68	2.56	0.35	3.93	0.53
	Storage volume (tonne)	168,522.67	34,041.58	86,085.48	17,389.27	132,158.40	26,696.00
	Storage tanks required (#)	749	1	383	1	588	1
	Storage space required (ha)	64.33	2.75	32.89	2.75	50.50	2.75
	Storage cost (MEUR)	€ 9,353.14	€ 392.00	€ 4,782.71	€ 392.00	€ 7,342.65	€ 392.00

Source: own composition

The table outlines the projected requirements for various parameters related to hydrogen (H_2) and ammonia (NH_3) imports for the Port of Amsterdam under three sub-scenarios (SS1, SS2, and SS3) for the years 2030, 2040, and 2050. These parameters include the required fleet size, storage volume, number of storage tanks, storage space, and associated storage costs.

In sub-scenario 1, no imports of hydrogen or ammonia are expected in any of the assessed years. Consequently, all values for the required fleet, storage volume, storage tanks, storage space and storage costs result in no output.

In sub-scenario 2, moderate import volumes lead to limited infrastructure requirements. In 2030, the Port of Amsterdam would require 3.34 vessels per week for hydrogen and 0.45 for ammonia. The associated storage volume is projected at 112 thousand tonnes for hydrogen and 23 thousand tonnes for ammonia, necessitating 499 storage tanks for hydrogen and 1 for ammonia. The storage space required is estimated at 43 hectares for hydrogen and 2.75 hectares for ammonia, with storage costs of €6.2 billion and €392 million, respectively. No non-carbon imports or infrastructure needs are projected for 2040 or 2050.

In sub-scenario 3, the Port of Amsterdam plays a more significant role, with substantial infrastructure requirements. In 2030, 5.02 vessels per week would be needed for hydrogen imports, alongside a storage volume of 168 thousand tonnes, requiring 749 storage tanks and 65.33 hectares of space. Storage costs are estimated at €9.4 million. Imports of ammonia are expected to require 0.68 vessels per week, a storage volume of 34,041.58 tonnes, one storage tank, 2.75 ha of storage space and a storage cost of €392 million in 2030. By 2040, 2.56 vessels per week are projected for hydrogen imports and 0.35 for ammonia, with storage volumes of 86,085 tonnes for hydrogen and 17,389 tonnes for ammonia. This requires 383 storage tanks for hydrogen and one for ammonia, with storage spaces of 33 hectares and 2.75 hectares, respectively, and storage costs of €4.8 billion and €392 million. In 2050, the required fleet will increase to 3.93 vessels per week for hydrogen and 0.53 for ammonia, with storage volumes reaching 132,158 tonnes for hydrogen and 26,696 tonnes for ammonia. The infrastructure needed includes 588 storage tanks for hydrogen and one for ammonia, 51 hectares of storage space for hydrogen and 2.75 hectares for ammonia, with storage costs amounting to €7.3 billion and €392 million, respectively.

The Port of Amsterdam is working to establish the necessary infrastructure for hydrogen transport and storage to support industrial use and regional supply. The infrastructure includes underground pipelines and above-ground storage tanks. A key project involves collaboration in the North Sea Canal region to develop a regional hydrogen network linking IJmuiden and the Amsterdam port area to the national hydrogen grid. The long-term goal is to create a more integrated port network that allows companies to connect directly to this infrastructure. (Port of Amsterdam, 2024)

6.4.Sensitivity analysis

The previous section presents a cost and surface area analysis for the future role of ports in the energy transition, focusing on the import of hydrogen and ammonia through a scenario-based approach. The analysis includes calculations for the required fleet, storage capacity, storage costs and surface area needs of the port of Rotterdam, Antwerp-Bruges and Amsterdam. This section will extend this analysis with a sensitivity analysis to examine changes in key parameters. This section discusses (i) the impact on output port parameters when imports consist exclusively of ammonia, (ii) the effects of limited pipeline connections between the port and hinterland regions, (iii) the consequences of changes in the origin of non-carbon exporting countries,(iv) the implications for storage capacity requirements and costs under increased storage durations and (v) an increased or decreased transport cost. The sensitivity analysis strengthens the findings and help reflect on parameters and outcomes which provides a holistic view for future port infrastructure planning.

6.4.1. Ammonia scenario

Exploring a scenario focused entirely on ammonia imports instead of hydrogen is valuable to understanding its potential advantages in specific contexts. For countries with limited solar resources and high costs for ammonia production, a balanced strategy combining partial domestic production with diversified import sources can optimize energy security and capture economic benefits. Conversely, solar-rich regions can use local production to meet their energy needs while boosting revenue streams by trading on international markets (Galimova et al., 2023). Such an analysis helps evaluate the strategic trade-offs and benefits of relying on ammonia as a central energy carrier in varying regional conditions. Since ammonia is already widely traded and transported globally, while liquid hydrogen shipments are still in an early, experimental phase, incorporating an ammonia-focused scenario offers a practical basis for assessing near-term feasibility and infrastructure readiness.

The main sub-scenario (3), as outlined in section 6.4, is resumed. The non-carbon imports consist only of ammonia. The results are shown in Table 6.8.

Table 6.8: Port outputs non-carbon imports SS3: ammonia

	2030		2040		2050	
Port of Rotterdam						
Required fleet (#vessels/week)	-	27.58	-	14.09	-	21.67
Storage volume (tonne)	-	1,378,817	-	704,594	-	1,083,579
Storage tanks required (#)	-	4	-	2	-	3
Storage space required (ha)	-	11.00	-	5.50	-	8.25
Storage cost (MEUR)	€ -	€ 1,568.00	€ -	€ 784.00	€ -	€ 1,176.00
Port of Antwerp-Bruges						
Required fleet (#vessels/week)	-	28.01	-	14.19	-	21.85
Storage volume (tonne)	-	1,400,568	-	709,658	-	1,092,541
Storage tanks required (#)	-	4	-	2	-	3
Storage space required (ha)	-	11.00	-	5.50	-	8.25
Storage cost (MEUR)	€ -	€ 1,568.00	€ -	€ 784.00	€ -	€ 1,176.00
Port of Amsterdam						
Required fleet (#vessels/week)	-	27.43	-	14.01	-	21.51
Storage volume (tonne)	-	1,371,639	-	700,666	-	1,075,663
Storage tanks required (#)	-	4	-	2	-	3
Storage space required (ha)	-	11.00	-	5.50	-	8.25
Storage cost (MEUR)	€ -	€ 1,568.00	€ -	€ 784.00	€ -	€ 1,176.00

Source: own composition

In the ammonia-only scenario, the weekly fleet demand across the three analysed ports ranges between 14 and 29 vessels per week in each port in 2030, 2040 and 2050. This is higher than the mixed (base) sub-scenario, where the combined fleet requirements for liquid hydrogen and ammonia range from 2.56 in 2040 to 7 in the highest scenario for 2030. The ammonia-only scenario requires storage capacities of approximately 1.38 million tonnes of ammonia in 2030 for the three ports to approximately 704 thousand tonnes in 2040, reducing to approximately 1.1 million tonnes in 2050 across all ports.

In contrast, the mixed scenario (sub-scenario 3) demands significantly higher storage for hydrogen and ammonia, with total storage volumes for the port of Rotterdam, Antwerp-Bruges and Amsterdam exceeding 500 thousand tonnes for ammonia and hydrogen in 2030, 250 thousand tonnes in 2040 and dropping to 400 thousand tonnes in 2050. The ammonia-only scenario requires more volume (around 700 thousand to 1.3 million tonnes) but its storage is more efficient in terms of storage requirements. The ammonia-only scenario requires fewer storage tanks and less space than the mixed scenario although the volumes are higher. For example, the ammonia-only scenario needs 2–4 tanks per port for the Ports of Rotterdam, Antwerp-Bruge and Amsterdam, translating to 5.5–11 hectares of storage space. In contrast, the mixed scenario for hydrogen alone necessitates up to approximately 750 tanks in 2030, reflecting hydrogen storage's logistics and spatial challenges. Storage costs in the ammonia-only scenario are significantly lower, totalling approximately between €780 million and €1.6 billion. By contrast, the mixed scenario has much higher storage costs, especially for hydrogen storage, totalling approximately €9.4 billion for hydrogen alone in 2030, with an additional cost of approximately €400 million for ammonia. The ammonia-only scenario offers a more economically sustainable pathway for non-carbon imports.

Overall, the ammonia-only scenario offers a more feasible outcome with a less resource-intensive and more cost-effective approach for non-carbon imports compared to the 75%-25% hydrogen-ammonia mix.

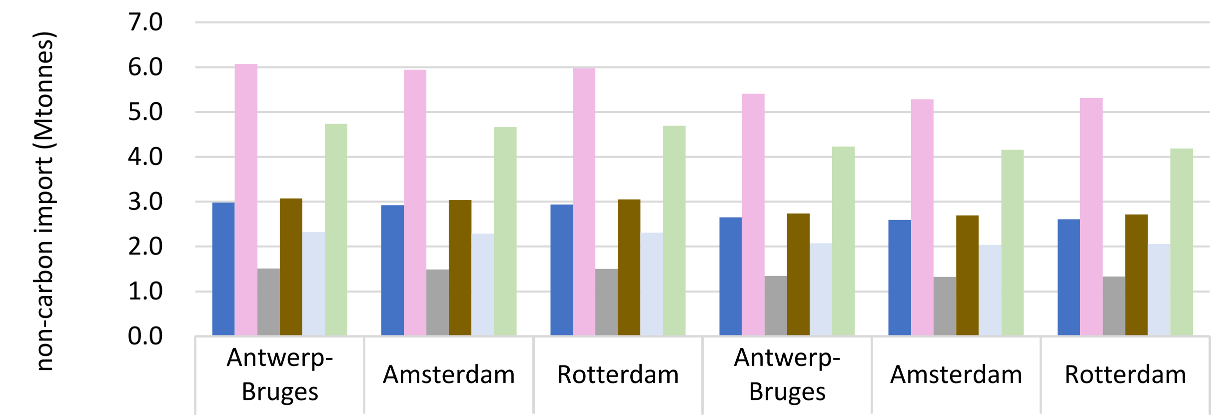
6.4.2. Considered pipeline connection

As explained in Chapter 3, the previously developed sub-scenarios are based on the assumption that each port is connected via pipeline to each NUTS2 region, which seems unlikely to occur. In this section, the research explores whether bringing back the pipeline network to the considered pipeline network by

European Hydrogen Backbone would impact on the import of non-carbon energy to ports (European hydrogen backbone, 2023).

The main scenario (Sub-scenario 3), as outlined in section 6.4, is resumed, building on the assumptions established therein. Figure 6.3 compares Sub-scenario 3 of the ports of Antwerp-Bruges, Amsterdam and Rotterdam.

Figure 6.3: Complete pipeline infrastructure versus considered pipeline network SS3



	Antwerp-Bruges	Amsterdam	Rotterdam	Antwerp-Bruges	Amsterdam	Rotterdam
	all areas are connected to the ports			considered pipeline network		
2030 H2	2.98	2.92	2.94	2.66	2.60	2.61
2030 NH3	6.07	5.94	5.97	5.40	5.29	5.32
2040 H2	1.51	1.49	1.50	1.34	1.33	1.33
2040 NH3	3.08	3.04	3.05	2.74	2.70	2.71
2050 H2	2.33	2.29	2.31	2.08	2.04	2.06
2050 NH3	4.73	4.66	4.70	4.23	4.16	4.19

Source: own composition

The volumes for these three ports decrease when connecting only the considered pipeline network, although only a few areas could not be served, such as Kassel. The volumes switch from 2.98 million tonnes of hydrogen for the Port of Antwerp-Bruges in a full connected hinterland pipeline network for 2030 to 2.66 million tonnes with the considered network, a difference of 320 thousand tonnes of hydrogen. The trend is similar from the for the Port of Amsterdam and Rotterdam. The ammonia trade by 2030 will decrease by 67 thousand tonnes from the All areas are connected scenario to the Considered pipeline network scenario. There are no significant differences between the three ports overall. In 2040, the volumes of hydrogen and ammonia are lower when only the considered pipeline network is used, compared to the fully connected hinterland pipeline network. For hydrogen, the Port of Antwerp-Bruges sees a reduction of approximately 170 thousand tonnes, from 1.51 million tonnes in the fully connected scenario to 1.34 million tonnes in the considered network. Amsterdam and Rotterdam both experience a similar decrease of around 160 to 170 thousand tonnes for hydrogen. For ammonia, all three ports (Antwerp-Bruges, Amsterdam and Rotterdam) see a reduction of approximately 35 thousand tonnes, with ammonia volumes decreasing from 3 million tonnes to 2.7 million tonnes in the considered pipeline network scenario. The trend shows a significant volume decrease when only the considered pipeline network is available, although the relative difference between the three ports remains relatively consistent.

The volumes of all ports are lower in the Considered pipeline network scenario (SS3). The decrease of connections immediately results in a decrease in volumes. This decline is primarily due to the exclusion of several NUTS2 regions that are not covered in the considered European Hydrogen Backbone network.

These include industrial and semi-industrial regions such as Niederbayern, Gießen-Kassel, Dresden, Arnsberg, Sachsen-Anhalt and Marche, as well as more remote or insular territories such as Sicilia and Martinique.

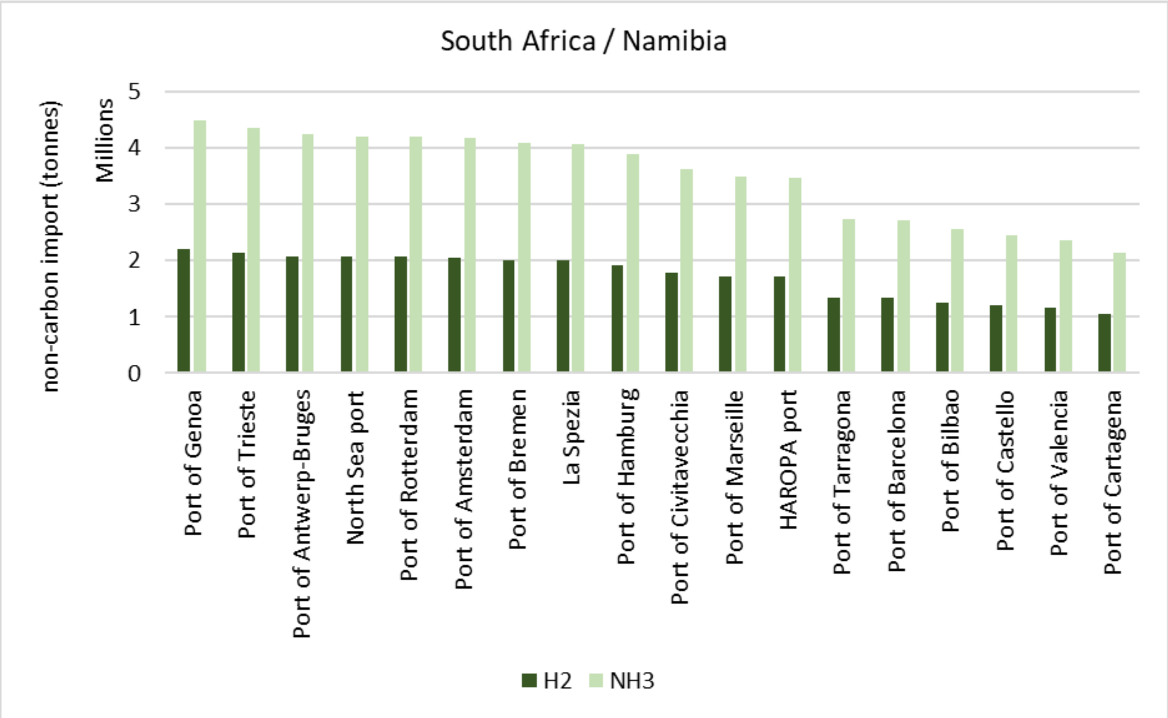
While the major industrial clusters in North-Western and Central Europe remain connected and continue to drive the core of the demand, the excluded regions still represent non-negligible hydrogen and ammonia demand. This includes smaller industrial users, decentralized energy systems, and future mobility applications. Their aggregate demand contributes to the overall import needs in the fully connected scenario. Therefore, the decrease in total port volumes reflects the loss of the demand. This scenario presents the importance of hinterland infrastructure to attract more demand.

6.4.3. Non-carbon exporting countries

The model allows changing the origin of the non-carbon exporting countries to the European ports. The main scenario (Sub-scenario 3), as outlined in section 6.4, is resumed. This section compares four exporting countries: South Africa (through the Port of Durban), Morocco, Brazil and Egypt.

Figure 6.4 illustrates the non-carbon energy imports of hydrogen and ammonia for the researched European ports from South Africa and Namibia.

Figure 6.4: South Africa/Namibia non-carbon import



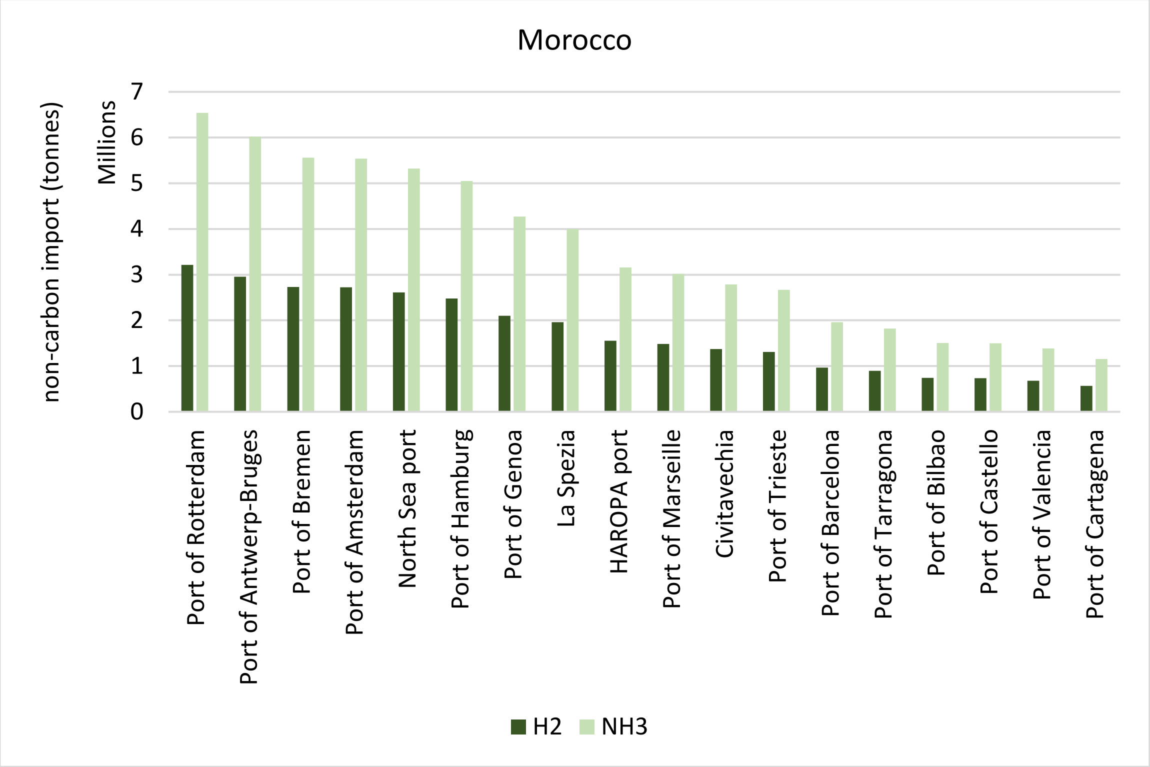
Source: own composition

If the non-carbon export comes from South Africa or Namibia, the port of Genoa, Trieste, Antwerp-Bruges, North Sea Port, Rotterdam, Amsterdam and Bremen will import more than 2 million tonnes of hydrogen and 4.5 million tonnes of ammonia. These ports will take the lead in importing non-carbon energy if the non-carbon energy is imported from South Africa and Namibia, followed by the Port of La Spezia, Hamburg, Civitavecchia, Marseille and HAROPA. The rest of the researched ports will take up a minor role, with imports ranging below 1.5 million tonnes of hydrogen and 2 to 3 million tonnes of ammonia.

A clear pattern emerges where Northern-European ports, particularly those in the Netherlands, Belgium, and Germany, import most non-carbon energy. Southern European ports, especially those in Spain, handle considerably smaller quantities, reflecting lower regional demand or limited capacity. Italian ports like Genoa and Trieste are notable exceptions, serving as key entry points for hydrogen and ammonia into the Mediterranean area, likely due to their strategic location and integration into more extensive energy networks.

Figure 6.5 presents the non-carbon imports via European ports imported from Morocco transported via the Port of Tangier.

Figure 6.5: Morocco non-carbon import



Source: own composition

The Port of Rotterdam imports the largest volumes, with 3.2 million tonnes of hydrogen and 6.5 million tonnes of ammonia. Close behind are the port of Antwerp-Bruges (2.95 million tonnes of hydrogen and 6 million tonnes of ammonia), the port of Bremen (2.7 million tonnes of hydrogen and 5.6 million tonnes of ammonia), and the port of Amsterdam (2.7 million tonnes of hydrogen and 5.5 million tonnes of ammonia). These ports, located in Belgium, the Netherlands, and Germany, are among the top importers of non-carbon energy.

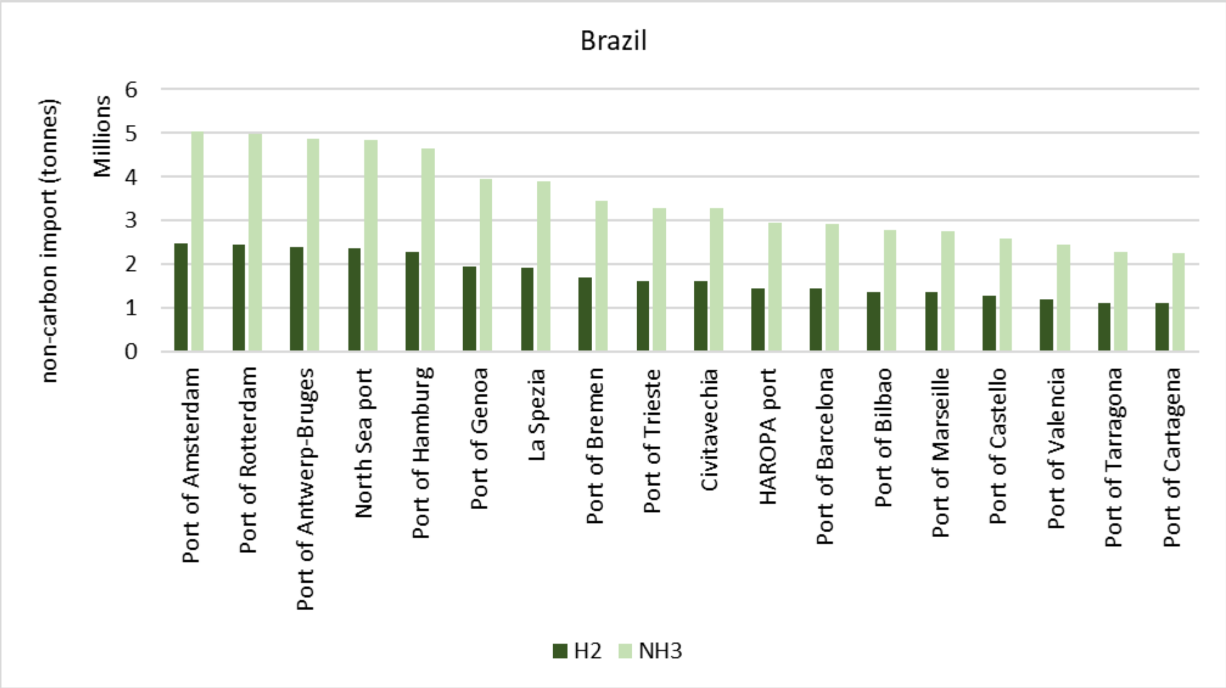
North Sea Port and the Port of Hamburg are also major importers, reflecting the central role of ports in Germany and the Netherlands. Other significant importers include the Port of Genoa and the Port of La Spezia, both in Italy.

Other ports such as the port of Marseille (1.48 million tonnes of hydrogen and 3 million tonnes of ammonia), port of Civitavecchia and port of Trieste handle more modest import volumes. Ports in Spain, such as the port of Barcelona and the port of Tarragona, also import lower quantities. The port of Cartagena (568 thousand tonnes of hydrogen and 1.16 million tonnes of ammonia) imports the smallest amounts of non-carbon energy in this scenario.

Compared to South Africa or Namibia, Morocco's proximity to Europe, leads to higher import volumes in ports nearer to Morocco, such as those in Belgium, the Netherlands and Germany. Although Morocco is geographically close to the Spanish ports, their import volumes remain relatively low, as the scenario prioritizes non-carbon energy imports for Italy, Germany and the Netherlands. In the case of Germany and the Netherlands, imports are directed primarily through the northern ports, while Italy directly imports through its ports. France positions itself in the middle, with its ports serving as intermediary points for both northern and southern European destinations.

Figure 6.6 presents the division of non-carbon import if non-carbon energy is imported from Brazil via the Port of Rio de Janeiro.

Figure 6.6: Brazil non-carbon import



Source: own composition

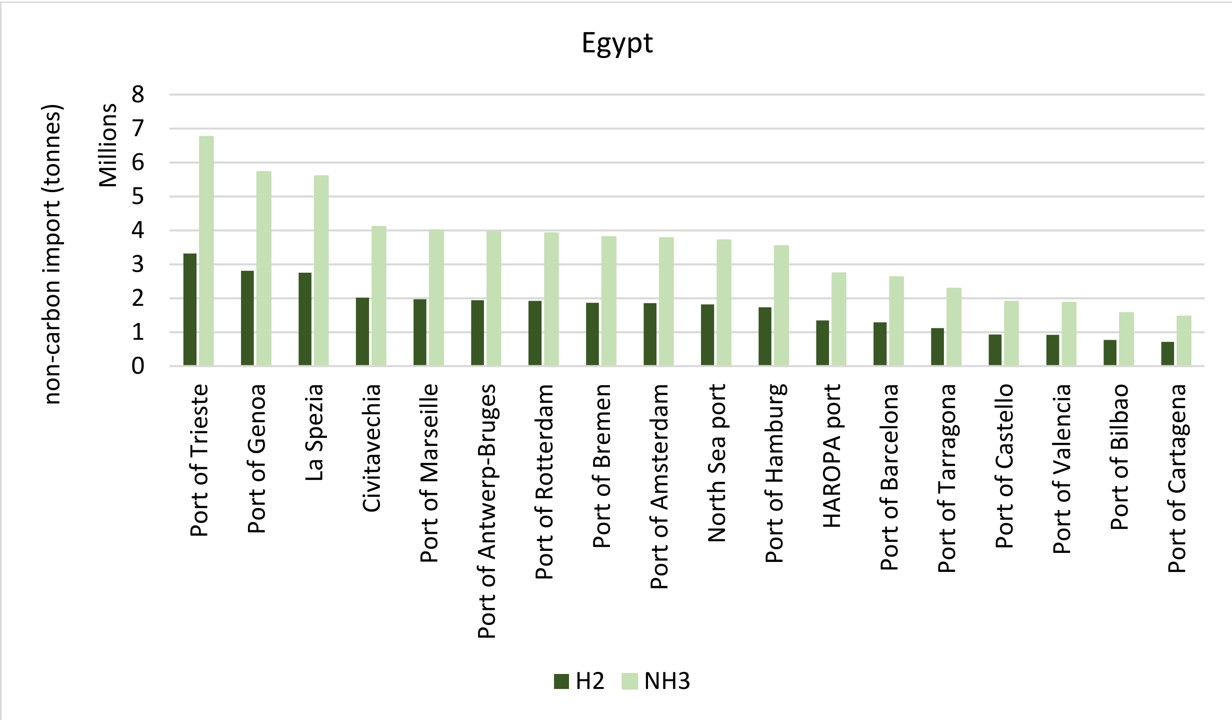
The port of Amsterdam and the port of Rotterdam import the largest volumes of non-carbon energy, with each port receiving almost 2.5 million tonnes of hydrogen and around 5 million tonnes of ammonia from Brazil. These are closely followed by the port of Antwerp-Bruges and the North Sea Port, importing just under 2.4 million tonnes of hydrogen and nearly 5 million tonnes of ammonia. Ports in the Netherlands, Belgium, and Germany account for most hydrogen and ammonia imports, reflecting their central role in the distribution of non-carbon energy in Europe.

Ports such as the port of Genoa and La Spezia also receive significant volumes, with hydrogen imports exceeding 1.9 million tonnes and ammonia imports near 3.9 million tonnes. While handling smaller volumes compared to their northern counterparts, the ports in Italy maintain a consistent share of the non-carbon imports. Meanwhile, French and Spanish ports, including the port of Marseille and the port of Barcelona, see moderately lower volumes of imports, with hydrogen imports between 1.3 and 1.4 million tonnes.

The port of Cartagena imports the smallest quantities, with just over 1.1 million tonnes of hydrogen and approximately 2.2 million tonnes of ammonia, highlighting the limited role of certain southern ports in this scenario. Brazil's position as an exporting country demonstrates a clear trend where Northern-European ports dominate the import of non-carbon energy. In contrast, Southern-European ports play a more secondary role in this trade.

Figure 6.7 shows the import of non-carbon energy from Egypt through the Port of Said.

Figure 6.7: Egypt non-carbon import



Source: own composition

Non-carbon export from Egypt will cause the ports in Italy (Trieste, Genoa, La Spezia and Civitavecchia), to have the largest share of imports. The port of Trieste will import over 3.3 million tonnes of hydrogen and approximately 6.7 million tonnes of ammonia, making it the leading importer in this scenario. The port of Genoa follows with 2.8 million tonnes of hydrogen and around 5.7 million tonnes of ammonia, and the port of La Spezia imports a comparable 2.75 million tonnes of hydrogen and 5.6 million tonnes of ammonia. The port of Civitavecchia handles slightly smaller volumes, importing just over 2 million tonnes of hydrogen and 4 million tonnes of ammonia.

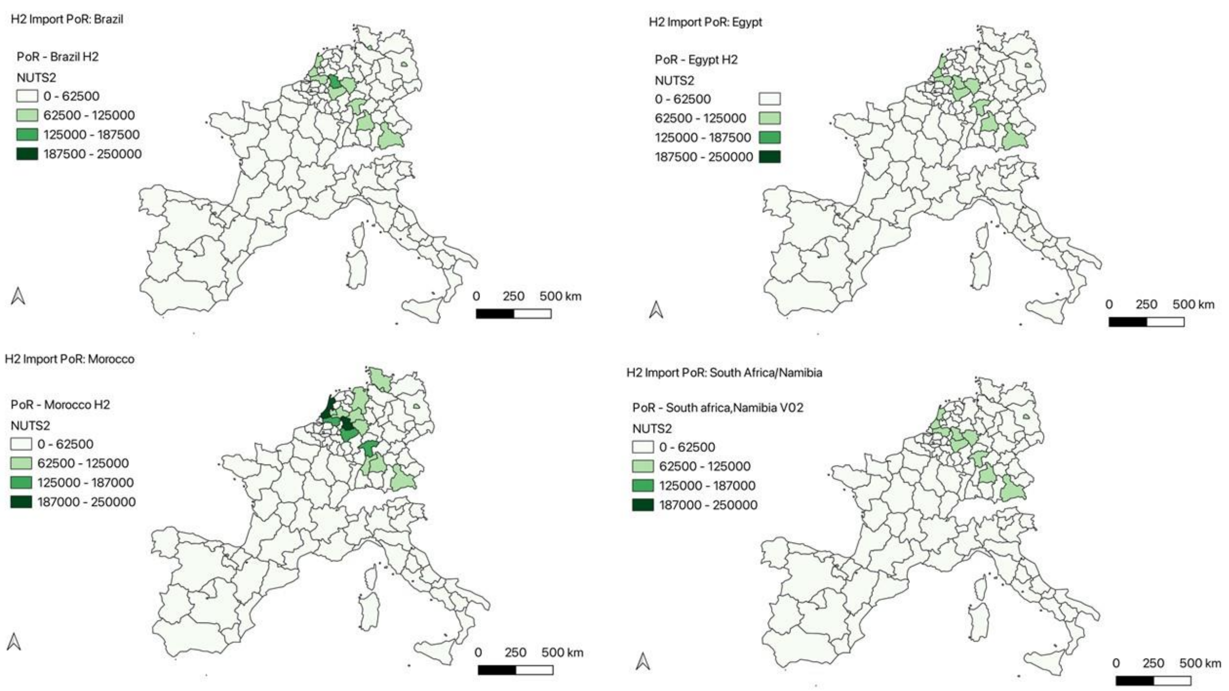
French ports, such as the port of Marseille, also play a notable role, importing nearly 2 million tonnes of hydrogen and just under 4 million tonnes of ammonia. Meanwhile, Northern-European ports, including the ports of Antwerp-Bruges, Rotterdam and Bremen, import similar volumes, between 1.8 and 1.9 million tonnes of hydrogen and approximately 3.7 to 3.9 million tonnes of ammonia.

Ports in Spain, such as the ports of Barcelona and Tarragona, see moderate imports, handling between 1.1 and 1.3 million tonnes of hydrogen and approximately 2.2 to 2.6 million tonnes of ammonia. The port of Cartagena has the smallest import share, receiving about 715 thousand tonnes of hydrogen and 1.45 million tonnes of ammonia.

Egypt's proximity to Southern Europe, more specifically brings the Italian ports at the forefront of non-carbon energy imports, while Northern- and Western-European ports handle moderate volumes, reflecting their role in broader regional distribution networks. The comparison of non-carbon energy exports from South Africa/Namibia, Morocco, Brazil and Egypt shows distinct regional trends in the distribution of imports across European ports. For South Africa and Namibia, Italian ports such as Genoa and Trieste dominate the imports, while for Morocco and Brazil, researched Northern-European ports, the Netherlands, Belgium, and Germany, handle the largest volumes. The port of Cartagena repeatedly records the lowest volumes in all four exporting origins, highlighting a clear geographical pattern where proximity and trade routes influence the distribution of non-carbon energy imports. The farther away from Europe (Brazil and South Africa/Namibia), the more equal non-carbon imports are between the researched ports.

Figure 6.8 presents the spatial distribution of hydrogen imports through the port of Rotterdam originating from Brazil, Egypt, Morocco and South Africa/Namibia. The geometric mean is taken for 2030, 2040 and 2050.

Figure 6.8: Comparison H2 output through PoR from different exporting countries (tonnes)



Source: own composition

The map presents the differences in hydrogen import volumes at the NUTS2 regional level, illustrating the varying demands in terms of tonnages for H_2 across Germany, Italy and the Netherlands. Regions are categorized into four equal distinct classes based on import volumes, ranging from 0 to 250,000 tonnes. Mainly the import is concentrated in the Netherlands and Germany when the throughput port is going through the port of Rotterdam. Especially in the case of Morrocco, the import is concentrated in the South of The Netherlands and West Germany. The imports from Brazil, South Africa and Egypt are distributed more evenly.

In summary, the analysis of non-carbon energy imports from South Africa/Namibia, Morocco, Brazil, and Egypt reveals patterns in how the researched European ports handle imports of hydrogen and ammonia. Northern European ports, such as those in the Netherlands, Belgium and Germany, consistently lead in the volume of imports, particularly when the energy comes from Morocco or Brazil. Italian ports, such as Genoa and Trieste, take the lead when energy is exported from South Africa or Namibia. Southern European ports, particularly those in Spain, tend to handle lower volumes of non-carbon energy imports, with the Port of Cartagena importing the smallest amount across all scenarios. The proximity of certain ports to their respective exporting countries influences these trends, with Southern European ports being more focused on imports from geographically closer countries, such as Egypt. As a result, Southern European ports typically play a more localized role, while Northern-European ports serve as central hubs for the distribution of non-carbon energy across Europe. Exporting areas, Egypt and Morocco, which are closer to the importing countries, attract higher import volumes to the leading ports, making them more prominent compared to farther exporting areas like South Africa and Brazil where the imports are more evenly distributed across the importing ports.

6.4.4. Storage time

The model allows for variations in storage time to assess the impact on the output of non-carbon imports. The main scenario (Sub-scenario 3), as outlined in section 6.4, is resumed. This section explores how shorter and longer storage times influence the output of non-carbon imports in 2030, 2040 and 2050 of hydrogen and ammonia.

In Sub-scenario 3, a storage time of 3 weeks is assumed. In the first case, the storage time is doubled (to 6 weeks) compared to Sub-scenario 3, Table 6.3, Table 6.5 and Table 6.7 illustrates the differences in the required fleet, storage volume, storage tanks required and storage costs for the ports of Rotterdam, Antwerp-Bruges and Amsterdam.

Table 6.9: 6 weeks storage volumes and costs

	2030		2040		2050	
	H2	NH3	H2	NH3	H2	NH3
Port of Rotterdam						
Required fleet (#vessels/week)	5.04	6.89	2.58	3.52	3.96	5.42
Storage volume (tonne)	338,809	689,408	173,136	352,297	266,262	541,789
Storage tanks required (#)	1,506	2	770	1	1,184	2
Storage space required (ha)	129.34	5.50	66.13	2.75	101.69	5.50
Storage cost (MEUR)	€ 18,806.18	€ 784.00	€ 9,615.38	€ 392.00	€ 14,785.20	€ 784.00
Port of Antwerp-Bruges						
Required fleet (#vessels/week)	5.12	7.00	2.59	3.55	4.00	5.46
Storage volume (tonne)	344,154	700,284	174,380	354,829	268,464	546,270
Storage tanks required (#)	1,530	2	775	1	1,194	2
Storage space required (ha)	131.40	5.50	66.56	2.75	102.54	5.50
Storage cost (MEUR)	€ 19,105.88	€ 784.00	€ 9,677.81	€ 392.00	€ 14,910.08	€ 784.00
Port of Amsterdam						
Required fleet (#vessels/week)	5.02	6.86	2.56	3.50	3.93	5.38
Storage volume (tonne)	337,045	685,819	172,171	350,333	264,317	537,831
Storage tanks required (#)	1,498	2	766	1	1,175	2
Storage space required (ha)	128.65	5.50	65.79	2.75	100.91	5.50
Storage cost (MEUR)	€ 18,706.28	€ 784.00	€ 9,565.43	€ 392.00	€ 14,672.81	€ 784.00

Source: own composition

Table 6.9 needs to be compared to Sub-scenario 3 of Table 6.3, Table 6.5 and Table 6.7. The figure clearly illustrates the importance of short storage times for reducing storage capacity needs and costs. An increase in storage duration from 3 weeks to 6 weeks increased storage volume, storage tanks, space requirements and costs, while the required fleet remains unchanged. For instance, at the Port of Rotterdam in 2030, halving the storage duration elevates the storage volume of hydrogen from 169 thousand tonnes to 339 thousand tonnes, with a increase in storage tanks from 753 to 1,506 and storage space from 65 hectares to 129 hectares. Similar trends are observed across all ports and years.Storage costs also show increases with longer storage durations. At the port of Antwerp-Bruges in 2050, costs increased from €7.5 million for 3 weeks to almost €15 million for 6 weeks. In summary, longer storage times significantly increase storage capacity needs and costs, while fleet requirements remain unaffected. These findings emphasize the importance of optimizing storage times to enhance the efficiency and cost-effectiveness of port operations.

An important remark is that the assumed average storage time of twenty days was verified by the port authority of the Port of Antwerp-Bruges. However, storage durations can vary significantly depending on the specific role of the terminal and market dynamics. For instance, in environments where traders are active (i.e. crude oil), storage times can fluctuate throughout the year depending on trading strategies. Conversely, if hydrogen or ammonia is primarily used as industrial feedstock, storage durations tend to be shorter due to steady, continuous offtake. Nonetheless, in the context of increasing strategic autonomy and supply security concerns, it is possible that governments or companies will opt to maintain larger buffer stocks, which would extend the average storage duration beyond what is currently observed. Furthermore, infrastructure bottlenecks (i.e. pipeline capacity limitations) can extend storage durations if products cannot be transported inland immediately (IEA, 2024b; Neumann et al., 2023). This means that while the 20-day assumption is valid for current operational realities, future conditions could justify longer storage durations such as indicated with these extended storage durations.

6.4.5. Transport cost

While the sub-scenarios assume constant transport costs based on current estimates, it is important to recognize that these costs are unlikely to remain static over time. Several factors can influence future cost developments. Technological innovation can improve efficiency and reduce costs of compression, liquefaction and transport, particularly for emerging carriers such as liquid hydrogen and ammonia. Economies of scale play a role, as the expansion of global supply chains and infrastructure can lead to lower unit costs (European Commission, 2020a; IEA, 2019). At the same time, infrastructure development, such as pipelines, terminals, and storage facilities, may initially increase costs but eventually bring long-term reductions.

However, not all trends point toward cost reduction. As mentioned by the European Commission (2020a) and IRENA (2020), several factors increase the transport costs. Geopolitical tensions, supply chain disruptions and price volatility (such as electricity for electrolysis) may significantly increase production and logistics expenses. Additionally, evolving regulatory frameworks, including carbon pricing mechanisms or stricter safety standards, can lead to additional costs and investment uncertainties.

To reflect this uncertainty, a sensitivity analysis is conducted. A deliberate distinction is made between maritime and hinterland transport, as the import potential of hydrogen and ammonia is expected to be strongly influenced by the relative cost competitiveness of each mode (maritime and pipeline). A key assumption in the sensitivity analysis is that maritime transport will become increasingly cost-attractive compared to pipeline-based hinterland transport. This is based on the expectation that continued innovation, scaling effects and international cooperation in maritime logistics will lead to large cost reductions in seaborne transport. (IRENA, 2022c)Table 6.10 shows the decrease of maritime transport. IRENA predicts the maritime transport for LH_2 to decrease with almost 57%. The same decrease is applied for ammonia which result in.

Table 6.10: Transport cost predictions 2050

	Transport Type	Sub-scenarios value (2024)	Predicted value (2050)	Source
LH_2	Maritime	2.09 USD/kg ≈ 1.92 €/kg	0.9 USD/kg ≈ 0.83€/kg	(IRENA, 2022c)
NH_3	Maritime	0.56 USD/kg ≈ 0.52 €/kg	0.24 USD ≈ 0.74€/kg	(IRENA, 2022c)

Source: (IRENA, 2022c) & (IEA, 2019)

Returning to Sub-scenario 3, maritime transport cost assumptions are adjusted in line with long-term projections of IRENA (2022c) indicating a significant decrease. All other assumptions remain consistent with those of the original sub-scenario (SS3). The exporting non-carbon port remains South Africa, as in the initial configuration.

To investigate the implications of these cost changes, the Port of Rotterdam is selected as a case study. With a maritime distance of approximately 9,500 kilometers (straight-line distance) between the Port of Durban and Rotterdam, the focus of the analysis is on long-distance transport routes. As the largest liquid bulk port in Europe, the Port of Rotterdam provides a relevant and representative case for analysing the implications of reduced maritime transport costs. Table 6.11 presents the implications of reduced maritime transport costs on the logistical and infrastructural requirements for hydrogen and ammonia imports at the Port of Rotterdam. The data demonstrate how lower shipping costs affect key logistical parameters.

Table 6.11: PoR decreased maritime costs

	2030		2040		2050	
	H2	NH3	H2	NH3	H2	NH3
Required fleet (#vessels/week)	6.1	8.3	3.2	4.4	4.9	6.7
Storage volume (tonne)	203,835	414,763	108,058	219,877	163,731	333,160
Storage tanks required (#)	906	2	481	1	728	1
Storage space required (ha)	78	6	41	3	63	3
Storage cost (MEUR)	€ 11,313.68	€ 784.00	€ 6,006.49	€ 392.00	€ 9,090.90	€ 392.00

Source: own composition

A key observation is the increase in required fleet size in comparison with SS3. In 2030, the number of hydrogen vessels per week rises from 5.0 in the baseline to 6.1 under lower cost assumptions. For ammonia, the fleet grows from 6.9 to 8.3 vessels/week. This upward trend is consistent in all timeframes, reaching 4.9 (hydrogen) and 6.7 (ammonia) vessels/week by 2050, compared to 4.0 and 5.4 in the baseline. Furthermore, storage volumes and infrastructure requirements also rise slightly. For hydrogen in 2030, volume increases from 169,405 to 203,835 tonnes, requiring 906 tanks instead of 753, and 78 hectares instead of 65. Similar trends are observed for ammonia. While the number of ammonia storage tanks remains stable (mostly one or two large tanks), the storage volume and space increase modestly. The most noticeable difference lies in the storage costs for hydrogen. In 2030, costs increase from €9.4 billion in the baseline to €11.3 billion under reduced maritime costs. By 2050, costs rise from €7.4 billion to €9.1 billion. This increase is attributed to higher volumes and more extensive infrastructure needs. For ammonia, storage costs remain stable at €392 million across both scenarios, indicating a lower cost sensitivity to maritime transport changes in a scenario where only 25% of all non-carbon import needs consists of ammonia. Finally, the share of total volume allocated to the Port of Rotterdam increases slightly from 7% to 8%, suggesting that lower maritime costs enhance the port's attractiveness as an import hub for hydrogen and ammonia.

In conclusion, although lower maritime transport costs reduce per-unit shipping expenses, they lead to increased traffic, higher import volumes and more infrastructure demand. These decrease in maritime transport costs result in the need for strategic planning in port development to accommodate hydrogen and ammonia imports.

6.5.Conclusions

In conclusion, transitioning to a low-carbon future is essential in addressing global climate challenges, with hydrogen and ammonia playing pivotal roles as renewable energy carriers. Understanding the logistic and economic difficulties of importing and storing these energy carriers is key to optimizing port infrastructure and supporting sustainable energy strategies.

This chapter focused on examining the import volumes, storage requirements and costs for hydrogen and ammonia in key European ports, building upon the insights developed in the previous chapters. The following research question was formulated: *What are the storage investment costs and storage requirements linked to the imported volumes of hydrogen and ammonia in key European ports?* By shifting the focus from country-level to port-level, this chapter explored the essential role of port infrastructure in supporting the energy transition and ensuring that European ports can accommodate the growing demand for non-carbon energy imports.

The first part of this chapter focused on the economic, logistics and technical aspect of the transportation of non-carbon energy. The first part researched which countries could be key players for Europe to import non-carbon energy. Countries with abundant renewable energy resources, such as Morocco, Brazil, and Chile, are emerging as potential hydrogen and ammonia suppliers for Europe. Transportation costs are a concern. Therefore, ammonia emerges as a more cost-effective option compared to liquid hydrogen. In terms of storage, hydrogen presents challenges with various technologies available, including gas or liquid storage, adsorbed materials and chemical hydrides. Ammonia, through the Haber-Bosch process, offers an easier and more efficient alternative for storage and transport. These findings indicate the challenges and opportunities of hydrogen and ammonia in storage and transportation.

The analysis of port sub-scenarios (Figure 6.2) reveals that nine key ports - Genoa, Trieste, Antwerp-Bruges, North Sea Port, Rotterdam, Amsterdam, Bremen, La Spezia and Hamburg - are central to the import of non-carbon energy across the three sub-scenarios. These ports consistently lead in energy imports, with particularly significant roles in sub-scenarios focused on Germany, Italy and the Netherlands. The volume, surface and cost calculations for the Port of Rotterdam, Antwerp-Bruges and Amsterdam show that especially in Sub-scenario 3 when extra non-carbon import is expected, extra space and costs are needed to accommodate the non-carbon import. The volumes in 2030 of the non-carbon import hit almost 3 million tonnes for hydrogen and 6 million tonnes of ammonia for the port of Rotterdam, Amsterdam and Antwerp-Bruges. This results in a storage cost by 2030 for these ports of around 9 billion euros for hydrogen and 4 billion euros for ammonia.

A sensitivity analysis was conducted to obtain a holistic approach. First, the sensitivity analysis highlights that an ammonia scenario presents a more cost-effective and resource-efficient approach for non-carbon imports compared to a mixed hydrogen-ammonia scenario. In the ammonia only scenario, the required fleet, storage capacity and storage costs are significantly lower, with weekly vessel demands ranging from 2 to 4 per week for ammonia and storage capacities between 1.37 million tonnes in 2030, 705 thousand tonnes in 2040, and 1 million tonnes in 2050. Storage costs for ammonia alone are lower, totalling €780 million to €1.6 billion, compared to the higher storage costs of up to €9.35 billion for hydrogen alone in the mixed scenario (Sub-scenario 3). The ammonia scenario also requires fewer storage tanks and less space, making it a more feasible and economic pathway for non-carbon energy imports, offering a more feasible, resource-efficient and cost-effective pathway for non-carbon energy imports. By requiring fewer vessels, reduced storage volumes, fewer tanks and significantly lower costs, this scenario highlights the practicality of focusing on ammonia as a central energy carrier. Its established global trade infrastructure contrasts with the experimental phase of liquid hydrogen, further reinforcing ammonia's near-term feasibility and readiness. For regions with limited renewable resources, combining imports with domestic production optimizes energy security, while solar-rich regions can capitalize on local production and international trade.

Second, the sensitivity analysis reveals that limiting the pipeline network to the considered European Hydrogen Backbone (EHB) significantly reduces the volumes of hydrogen and ammonia imported to ports. In 2030, the port of Antwerp-Bruges has a reduction of 300 thousand tonnes of hydrogen, with similar decreases for Amsterdam and Rotterdam. The ammonia trade also decreases by approximately 67 thousand tonnes across all three ports. By 2040, hydrogen volumes decrease further by 170 thousand tonnes, while ammonia imports drop by 34 thousand tonnes in the considered pipeline scenario. While the overall import volumes decrease, the relative shares of ports shift, with ports in Spain and Italy increasing their share due to improved connections, while ports in Belgium, the Netherlands, and Germany experience a slight decrease.

Third, the sensitivity analysis of non-carbon energy imports from South Africa/Namibia, Morocco, Brazil and Egypt highlights significant regional differences across European ports. Ports in the Netherlands, Belgium and Germany, handle the largest volumes when energy is exported from Morocco or Brazil. Italian ports, such as Genoa and Trieste, take the lead when imports originate from South Africa or Namibia. Conversely, Southern-European ports import lower volumes, especially those in Spain, with the Port of Cartagena consistently receiving the smallest amounts across all scenarios. Proximity to the exporting countries plays a key role in these trends, as Southern-European ports import more from geographically closer regions, such as Egypt. In contrast, Northern-European ports act as major hubs for broader distribution across Europe. Ports closer to exporting countries like Egypt and Morocco have higher import volumes. In contrast, distant origins such as Brazil and South Africa result in more even distribution of imports among the ports.

Fourth, the sensitivity analysis is the extension of storage time. In sub-scenario 3, where a storage time of three weeks is assumed, doubling the storage time to six weeks results in a marked increase in storage volume, storage tanks and space requirements. For example, when the storage duration is extended from 3 weeks to 6 weeks, the Port of Rotterdam sees an increase in storage volume from 169 thousand tonnes to 339 thousand tonnes, along with a rise in the number of storage tanks and space required. Similarly, storage costs increase with longer durations, such as at the Port of Antwerp-Bruges, where costs rise from €7.5 million to €15 million by 2050 for hydrogen. These findings highlight the importance of managing storage times to avoid unnecessary increases in costs and space requirements, which can affect the efficiency of port operations.

Lastly, the last sensitivity analysis, the decrease of maritime transport costs. While the sub-scenarios assume constant transport costs based on current estimates, it is important to acknowledge that these costs are unlikely to remain static over time. Several factors may drive future cost reductions, such as technological innovations, emerging carrier technologies, economies of scale etc. The decrease in maritime transport costs reveals that lower maritime transport prices increase the attractiveness of the Port of Rotterdam as an import hub for hydrogen and ammonia. This results in higher weekly vessel arrivals, greater import volumes and a modest rise in infrastructure requirements, especially for hydrogen (75% of the non-carbon energy import demand). While storage costs for ammonia remain relatively stable, hydrogen storage costs increase significantly due to larger volumes and associated infrastructure needs. As a result, shipping hydrogen and ammonia over long distances may become increasingly viable, reinforcing the strategic importance of major ports such as Rotterdam.

These results highlight the need for future energy infrastructure. Efficient and well-managed storage capacity, combined with a strategic selection of exporting countries, will be crucial for the success of Europe's energy transition. The findings are a valuable foundation for policymakers and port authorities to take actions towards a more sustainable and economically viable future.

Chapter 7

Assessing hydrogen energy projects in relation to the objectives of port authorities of major European carbon energy importing countries

The world is facing environmental challenges. The need to shift towards sustainable and renewable energy sources shapes the energy balances. Countries and ports strive to reduce their carbon footprint and mitigate the impacts of climate change. The traditional energy mix should be replaced by renewable energy as shown in the previous chapters. This fundamental energy shift affects how people power their homes and industries and changes throughout crucial infrastructural hubs, particularly ports. Ports are hubs for enabling trade.

In the European context, the maritime industry plays an important role in meeting the ambitious objectives the European Commission (EC) set forth. The EC has articulated a comprehensive framework, including initiatives such as the Green Deal (European Commission, 2022a), Renewable Energy Directive (RED II) (European Commission, 2023d), Energy Efficiency Directive (EED) (European Commission, 2023a), Fit For 55 (European Commission, 2022b), The FuelEU Maritime (European Commission, 2023b) initiative are crucial to stimulating actions that mitigate the impact of climate change. These European initiatives focus on achieving climate neutrality by 2050 and setting mandatory targets for EU Member States. One of the objectives is to incorporate a minimum of 32% renewable energy into the EU Member States energy consumption by 2030 (European Commission, 2022a, 2023d). Recent geopolitical tension and vulnerabilities in energy supply chains have underscored the risks of dependence on external sources for energy, especially in times of conflict, natural disasters or political tensions.

Port authorities can capitalise on the import of non-carbon energy by preparing their ports and facilities for new liquid flows, such as hydrogen (IAPH, 2024). Port objectives are identified to ensure a port functions properly and become future proof. The port objectives are applicable for short and long term. First, it is necessary to understand what is meant by port objectives. A port objective represents concrete, measurable goals or activities that contribute to the broader vision and mission of the port. These objectives, whether short-term or long-term, are essential for the overall success and operational efficiency of the port, and port objectives play a crucial role in its journey towards sustainability. This research emphasizes the long-term objectives and visions of ports. (Barba, 2023)

This chapter focuses on hydrogen as a central component of a port's future energy mix. Hydrogen is by far the most mentioned of all renewable fuel options (Puliti, 2022). Hydrogen, identified as a key enabler of global sustainability goals (IEA, 2019), offers diverse applications, including industrial use, transportation, power generation, and building energy needs. Transitioning ports to prioritize hydrogen within their operations can significantly contribute to reducing their carbon footprint. While ammonia has proven successful as a hydrogen carrier, this research focuses on hydrogen, for which ammonia could serve as the energy carrier. However, given ammonia's role as an efficient storage and transport medium for hydrogen, its implications and relevance are indirectly addressed within the scope of the analysis, ensuring a comprehensive approach to hydrogen-related strategies for ports. (IEA, 2019)

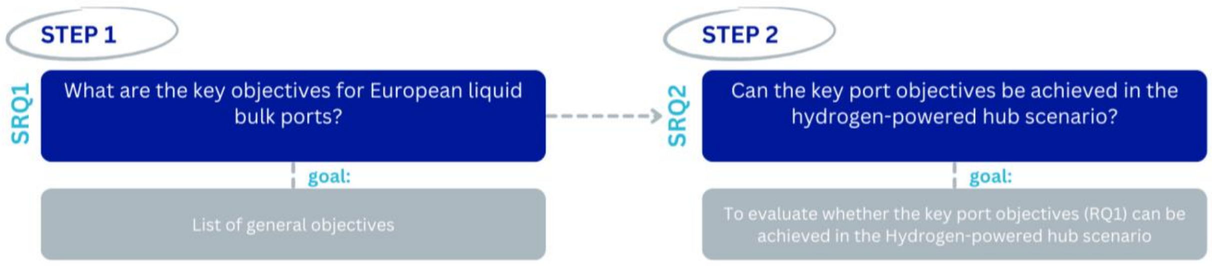
In this background, this chapter investigates the alignment of a non-carbon energy flow transition, more specifically hydrogen, with predefined port objectives. The chapter examines general port objectives related to the shift towards alternative and greener energy sources, in this case, hydrogen. It investigates the importance of port objectives and measures the success of implementing hydrogen solutions in responding to each formulated port objective. Hence, the research question is formulated: *How well are the strategic plans of port authorities aligned with the ambitions of transitioning towards a hydrogen-powered hub?*

To address the main research question of this chapter, two sub-questions (SRQ) are used:

- *What are the key objectives for European liquid bulk ports?*
- *Can the key port objectives be achieved in the hydrogen-powered hub scenario?*

The sub-research questions will be handled as shown in Figure 7.1. Step one and sub-research question one focus on identifying the key objectives for European liquid bulk ports. This step results in a list of general objectives, which serves as a foundation for the next stage of the analysis. Step two and sub-research question two build upon these objectives by assessing their feasibility within the hydrogen-powered hub scenario. The goal of this step is to evaluate whether the key port objectives (SRQ1) can be achieved in this scenario. These steps and sub-research questions will help to address the main research question.

Figure 7.1: Sub-research questions and goals



Source: own composition

This study focuses on the six most carbon energy-importing countries in the European Union, identified in the previous chapters. The selected ports of Chapter 4 are crucial for liquid energy import and will undergo significant changes as the global shift to sustainable energy unfolds. The selected ports are Bremen, Hamburg, Amsterdam, Rotterdam, Antwerp-Bruges, North Sea Port, HAROPA, Bilbao, Cartagena, Valencia, Castellon, Marseille, Tarragona, La Spezia, Genoa, Trieste, Barcelona, and Genoa. The significance of this research extends to various stakeholders, including policymakers and investors, offering them valuable insights. By analysing the outcomes, stakeholders can make informed decisions about potential investments and initiatives to align with their port objectives.

The objectives that ports should prioritize to align with future goals have been collected through a literature review, analysis of port reports and expert interviews. Chapter 4 outlines the hydrogen-powered hub scenario which will be used as an assumption in the interviews for this chapter, ensuring that all interviewees have a common starting point. Subsequently, experts in liquid bulk and energy transition of the analysed ports score the importance of the port objectives. Thereafter, the experts score to which extends the switch to alternative energy contributes to the port objectives.

The following sections unfold the research. Section 1 delves deeper into the role of a port authority and port objectives. Section 2 outlines the hydrogen-powered hub scenario. Section 3 expounds on the methodology. Section 4 presents the data collection and Section 5 discusses the results of the analysis. Section 6 synthesizes the conclusion for stakeholders, policymakers and investors.

7.1.Port authority roles and objectives in energy matters

This section analyses different port authority roles and the objectives of ports. Port authorities are responsible for setting and achieving these objectives to guide the development and operational functioning of the port. The definition of a port authority depends on their roles described below. In general, the function of a port authority can be described as "*the body with statutory responsibilities that manages a port's water* *and land-side domain"* (Verhoeven, 2010). A port authority is an entity responsible under national law or regulations for managing and overseeing the port's infrastructure, as well as coordinating the activities of various operators or stakeholders within the port (Notteboom & Haralambides, 2023). The next section elaborates on the different port authority roles.

7.1.1. Port authority roles

A port authority, whether public or private, plays a vital role in the administration, development and effective management of port operations (Panjako et al., 2020). Depending on its role, it may also be involved in infrastructure improvement, operational coordination and oversight of various port-related activities (Pallis, 2020). In port management, the role of a port authority is essential in shaping the objectives and operations of a port. Verhoeven's (2010) research present the conceptual framework for port authority roles. Ports can be privately or publicly operated. As delineated by the World Bank (2007), these models encompass four fundamental types: public service port, tool port, landlord port or private service port.

Figure 7.2 provides a concise overview of these basic port management models, highlighting the key aspects such as infrastructure ownership, superstructure management, port labour control and the ownership of other functions within the port ecosystem. Understanding these management models is crucial to understand the government and the functioning of ports and how they set their objectives. (Worldbank, 2007)

Table 7.1: Basic port management models

Type	Infrastructure	Superstructure	Port Labour	Other functions
Public service port	Public	Public	Public	Majority Public
Tool port	Public	Public	Private	Public/Private
Landlord port	Public	Private	Private	Public/Private
Private service port	Private	Private	Private	Majority Public

Source: Worldbank, 2007

As Table 7.1 illustrates, the different types of port management go together with different ownership (World Bank, 2007). If a port's spatial domain is privately owned, a port authority does not have a significant influence on the management of infrastructure, superstructure and port labour. Consequently, the type of port management model impacts the delineation of objectives within a port environment.

The most prevalent model among European ports is the landlord model. Most port managing bodies in Europe are publicly owned. The landlord port model is applied in ports such as Le Havre, Rotterdam and Antwerp-Bruges. Here, the infrastructure, including essential port assets such as docks and terminals, remains publicly owned, while the superstructure (e.g., warehouses, facilities) and port labor are typically under private operation (Verhoeven, 2010). For port authorities with a landlord function, their financial foundation primarily relies on port dues and concession fees (Notteboom & Haralambides, 2023). The administration of other functions within the port can exhibit a mix of public and private ownership or operation (Worldbank, 2007). This study focuses on ports located in The Netherlands, Belgium, Italy, France, Germany and Spain.

Understanding the management models of ports is important for assessing how well they are positioned to facilitate the energy transition. The type of port management model directly impacts a port's ability to implement sustainable energy projects, including hydrogen infrastructure and to which level. For instance, the landlord model, prevalent in European ports and in this chapter, offers a balance between public ownership of infrastructure and private sector involvement in operations (Worldbank, 2007). With publicly owned infrastructure, port authorities hold a pivotal role in steering the industry and port stakeholders toward sustainability. Port authorities can drive the transition by investing in green infrastructure, designing policies to incentivize clean technologies and enabling public-private partnerships for large-scale projects. This enables ports to act as catalysts for decarbonization and support industries to reduce emissions and position themselves as leaders in the renewable energy supply chain. However, aligning public goals with private operators' investments remains a key challenge, requiring balanced regulatory frameworks and incentives. By leveraging their unique position, landlord ports can not only adapt to but actively shape the shift to a sustainable energy future.

7.1.2. Port objectives analysis

This section analyses port objectives that should be prioritized by ports to align with future goals. The list of port objectives includes general strategic and green objectives. The list of green objectives cannot be separated from the general objectives of a port. A port authority must address public and private agendas. For example, a port must mitigate climate change while simultaneously maintaining its competitiveness with other ports. Balancing these agendas requires an understanding of the objectives that enable port authorities to remain resilient while pursuing future goals. The list of port objectives derived from the literature was reworked and evaluated by port authorities involved in this research.

The research of Acciaro et al. (2014) formulated the objectives according to the functions of a port authority (Meersman et al., 2005; Meersman & Van de Voorde, 2010; Verhoeven, 2010): landlord function, regulatory function, operator function and the community manager role. Reviewing these port objectives with the port objectives formulated by port authorities on their websites and in annual reports, the list was adapted. Objectives can vary from one port to another, depending on various factors such as geographic location, economic priorities, strategies, type of cargo it handles, etc. The weight of importance of these goals can also change over time, depending on for example the urge for climate change. While ports may have unique objectives based on their circumstances and priorities, they share some common themes and objectives.

Most researched ports mention their objectives in their year report or in their sustainable report. The vision, strategy and mission of a port mostly reveal their core focus. However, to reach a consensus about port objectives, the objectives were validated by experts, which allowed discussion of port objectives with stakeholders and experts within the port authority to cluster and confirm the port objectives. First, a preliminary list of objectives was drafted. Second, the list was reworked to a final list of port objectives and definitions. To enhance response accuracy and maintain participant engagement, the objectives of Acciaro et al. (2014) were constrained to ten general port objectives and precisely defined. Table 7.2 presents the final list of port objectives and their corresponding definitions.

Table 7.2: Port objectives final

	Objectives	Definition
1	Environmental stewardship	Protecting port ecosystems, complying with environmental regulations, climate adaptation and controlling pollution.
2	Sustainable infrastructure	Building and managing infrastructure with a focus on sustainability and efficiency.
3	Resource management	Managing resources, including energy, circular economy for sustainability and reducing dependence on fossil fuels.
4	Economic competitiveness	Enhancing the port's competitive position, attracting sustainable businesses, industries, and client relationships.
5	Operational efficiency	Minimizing operational impacts, improving energy efficiency, nautical services and optimizing processes.
6	Regulatory compliance	Adhering to national and international regulations and standards.
7	Innovative leadership	Spearheading technological advancements and driving the development and adoption of renewable energy technologies and innovations to maintain a leading role.
8	Community engagement	Involving stakeholders, increasing environmental awareness, and encouraging sustainable practices.
9	Communication and marketing	Sharing information on environmental measures, enhancing the visibility of green initiatives, and positioning as a green port.
10	Safety and security	Ensuring the well-being of personnel and maintaining a secure working environment.

Source: own composition adapted from Acciaro et al. (2014)

This final list consists of ten port objectives to ensure the ports are aligned with future goals. These objectives encompass a comprehensive set of goals, each accompanied by its definition, ensuring a clear understanding of their relevance and application. The ten objectives that ports should prioritize to align with future goals are: environmental stewardship, sustainable infrastructure, resource management, economic competitiveness, operational efficiency, regulatory compliance, innovative leadership, community engagement, communication & marketing and safety & security. Collectively, these objectives form a holistic framework for achieving future goals of a port while ensuring competitiveness, meeting demands of stakeholders and addressing public and private agendas.

7.2. Hydrogen-powered hub scenario

Before starting the empirical part, the analysis further in the paper is based on a fixed future scenario to ensure coherent and relevant insights. This chapter focuses on the hydrogen scenario as the envisioned future for ports. Aligning this scenario enables a comprehensive assessment of how ports can transition towards hydrogen as a primary energy source. This consistency is essential for accurately answering the questions about the importance and success of evolving toward a hydrogen-powered hub scenario on port objectives.

The transition of a port to hydrogen underscores a fundamental shift in energy supply. Ports, serving as pivotal nodes in global trade, are confronted with the imperative to secure and manage a sustainable energy supply. This necessitates a strategic overhaul of traditional energy infrastructures to efficiently accommodate the sourcing, storage and distribution of hydrogen. Chapter 4 elaborated on the challenges included in a port mainly focussing hydrogen. To produce green hydrogen, electrolysis facilities need to be scaled up. Additionally, hydrogen storage facilities must be developed to ensure a steady supply. There are several main challenges to overcome such as rolling out an extensive pipeline network. Furthermore, storage and handling of hydrogen requires specific safety measures, including ventilation and safety protocols.

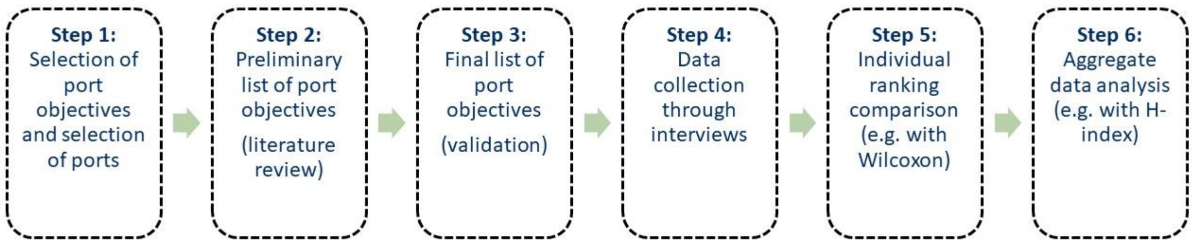
Based on the research conducted in the previous chapter, hydrogen emerges as one of the most reliable options to fulfil energy needs, it will play a significant role in the energy balance that passes through ports. Since ammonia can be produced indirectly through the Haber-Bosch process using hydrogen, it is also considered within the scope of the hydrogen-powered hub scenario. Therefore, ammonia is indirectly included in the analysis alongside hydrogen.

7.3.Methodology

This chapter investigates the implementation of a hydrogen scenario in European ports and the alignment with port objectives. The research uses a scoring system to assess the importance of port objectives and the success of alignment of transition to a hydrogen-powered hub scenario and the set of predefined port objectives. The methodology of this chapter is based on research earlier conducted by Acciaro et al. (2014), Acciaro et al. (2018) and Acciaro & Sys (2020). Six steps will be used to answer the research question: *How well are the strategic plans of port authorities aligned with the ambitions of transitioning towards a hydrogen-powered hub?*

The homogeneity index H is a way to measure the consistency of the respondents' scoring. The scoring, the H-index and Wilcoxon test will be used to answer the research questions. The following six steps are followed:

Figure 7.2: Methodology approach H-index



Source: adapted from Acciaro & Sys, 2020

The initial phase involves the selection of European ports, serving as the foundation for subsequent steps. The first step was done in chapter 4. The second step entails compiling a preliminary list of port objectives based on a literature review validated by port authorities. The third step contains a refined final list of port objectives. The fourth step is collecting data through interviews (Appendix C). Within the port authority, personal online interviews were conducted with energy transition experts. In some cases, these interviews involved a single expert, while in others, the entire department was included to gather a holistic perspective. These experts provided valuable insights into the integration of non-carbon energy sources such as hydrogen.

Before the scoring exercise, each interview started with a clear explanation of the research context. The Hydrogen-powered hub scenario was introduced, and the interviewee was walked through all port objectives one by one. This ensured that the interviewee fully understood each objective's meaning and relevance in the context of the hydrogen transition. Only after this structured clarification and contextual framing, the scoring was requested. This step was essential to improve the consistency and validity of the answers and ensure that each interviewee interpreted the objectives and the scenario in the same way.

The interviews serve to explain the research to the experts, more specifically, the hydrogen-powered hub scenario was explained and the survey to collect the scores was clarified. The survey was filled in after the interview was conducted with the interviewee, to make sure that the interviewees were properly informed about the context of the research. While this method provided in-depth insights from port stakeholders themselves, it is acknowledged that such sources may be subject to top-down or commercially driven perspectives. To mitigate this, the insights from interviews were supported by sometimes multiple interviewees and the list of port objectives was obtained by researching reports and earlier studies. Moreover, the objective of the chapter was not to produce an independent performance ranking of the different interviewed ports, but to identify which port objectives are perceived as most critical by stakeholders involved in hydrogen infrastructure development.

The fifth step makes the individual scoring comparison using the H-index (Appendix D) and the Wilcoxon test (Appendix E). The Wilcoxon signed-rank test is used due to the potential non-normal distribution of our data, which could violate the assumptions required by traditional statistical tests like the t-test. With the obtained data two scores are calculated: the relevance of the objectives and the success scoring of the transition to a hydrogen-powered hub scenario with the alignment of port objectives (step 6). The success score is used to measure the extent to which the implementation or potential implementation of a hydrogen scenario contributes to port objectives. The implementation of hydrogen flows could be seen as successful if it aligns with the related objective (Acciaro et al., 2014).

The H-index will be calculated to compare those two scorings. The H-index is the relative homogeneity index. First, the h_i needs to be calculated. It is calculated by taking the square sum of the percentage frequencies of the scorings given by the interviewees. This means that f_{ij} signifies the percentage of interviewees that ranked the same score to objective i with value j, whereof $j = 1,\dots,5$. Value 1 means very unimportant or not successful at all, value 5 means very important or very successful.

The value of h_i can be calculated as follows (Acciaro et al., 2014):

$$h_i = \sum_j f_{ij}^2$$

h_i has value 1 when all interviewees gave an equal score for the importance of a port objective in the objectives scores or gave an equal score for the success score of the implementation of the hydrogen scenario in aligning with port objectives. The value 1 stands for maximum homogeneity in the answers of the interviewees. If all interviewees rank an objective as very important and assign it a score of 5, the value will display 1. This means that there is a perfect consensus in answering. In contrast, if there is an equal number of people for each ranking (1-5), the value is $0.2 = 5 \text{ x } (0.2)^2$ (maximum heterogeneity). This means that there is less consensus in answering the scores. The h_i then serves to calculate the homogeneity index H_i

$$H_i = \frac{h_i - \min(h_i)}{\max(h_i) - \min(h_i)} = \frac{h_i - 0.2}{0.8}$$

The higher the H_i the more it suggests that the analyzed port authority experts provided consistent scorings for the objective. Conversely, lower values of H_i signify a lack of consensus in scoring the objective. This score has a ranking between zero and one.

7.4.Data collection

After having approached twenty ports in the six most carbon importing countries of Europe, thirteen ports responded positively: Bremen, Amsterdam, Rotterdam, Antwerp-Bruges, North Sea Port, HAROPA, Bilbao, Cartagena, Valencia, Castellon, Tarragona, Barcelona and Genoa. The map in Figure 7.3 illustrates the thirteen analysed ports for this Chapter.

Figure 7.3: Map of interviewed ports

Source: own composition via GIS

The scores given by thirteen experts in energy transition within port authorities are assembled, portraying a future where hydrogen dominates the renewable energy mix (a hydrogen-powered hub scenario). The focus lies on the implementation of hydrogen facilities in ports.

7.5.Results

This section shows the outcomes of the analysis. It is interesting to examine which objectives are deemed important and whether these crucial objectives are aligned with port objectives when transitioning to a hydrogen-powered hub scenario.

7.5.1. Importance and success scoring

Table 7.3 shows the relevance of the objectives scored by the interviewees. Overall, all objectives prevailing scores are between 4 and 5, which means that they are seen as important to very important. Objectives ranked with very important are environmental stewardship, sustainable infrastructure, economic competitiveness, operational efficiency, regulatory compliance, innovative leadership, community engagement and safety and security. Especially economic competitiveness is seen as very important by 92% of the interviewees. It reflects its important role in the decision-making process. Additionally, safety and security are ranked by 77% of the interviewees as very important. Environmental stewardship is highly valued, with 62% of participants ranking it as very important.

Table 7.3: Objectives relevance scoring

	1	2	3	4	5	Prevailing score
Environmental stewardship	0%	0%	0%	38%	62%	5
Sustainable infrastructure	0%	0%	23%	31%	46%	5
Resource management	0%	0%	15%	46%	38%	4
Economic competitiveness	0%	0%	0%	8%	92%	5
Operational efficiency	0%	0%	15%	31%	54%	5
Regulatory compliance	0%	0%	0%	46%	54%	5
Innovative leadership	0%	8%	31%	23%	38%	5
Community engagement	0%	0%	23%	23%	54%	5
Communication and marketing	0%	0%	8%	62%	31%	4
Safety and security	0%	0%	8%	15%	77%	5

Source: own composition

Table 7.4 shows the success scoring of the implementation of transitioning towards a Hydrogen-powered hub scenario related to the objectives. Environmental stewardship, resource management, economic competitiveness and safety & security illustrate high scores, indicating that interviewees rank that the transition to a hydrogen-powered hub scenario aligns effectively (very successful) with these objectives. Sustainable infrastructure, regulatory compliance and innovative leadership objectives seem to be less aligned according to the experts with the hydrogen scenario. The majority of the interviewees ranked these objectives as moderately successful (score 3 to 4). This may be due to the fact that the experts view regulation and infrastructure more broadly than the impact of the implementation of hydrogen flows.

Table 7.4: Objectives success scoring

	1	2	3	4	5	Prevailing score
Environmental stewardship	0%	8%	15%	38%	38%	4; 5
Sustainable infrastructure	0%	8%	38%	38%	15%	3; 4
Resource management	0%	0%	31%	31%	38%	5
Economic competitiveness	0%	0%	15%	38%	46%	5
Operational efficiency	0%	15%	0%	69%	15%	4
Regulatory compliance	0%	15%	31%	31%	23%	3; 4
Innovative leadership	8%	0%	46%	23%	23%	3
Community engagement	0%	8%	15%	46%	31%	4
Communication and marketing	0%	0%	38%	46%	15%	4
Safety and security	8%	0%	23%	31%	38%	5

Source: own composition

While the overall perceived relevance of the port objectives is high, with prevailing scores of 4 or 5 across all categories, the success ranking of hydrogen adoption in relation to these objectives reveals several areas where alignment could be improved. Particularly for objectives such as sustainable infrastructure, regulatory compliance and innovative leadership, the success scores were notably lower than their relevance scores. This discrepancy suggests that although these objectives are considered very important by stakeholders, the current implementation of hydrogen initiatives is not yet perceived to fulfill them sufficiently.

To enhance the alignment between hydrogen adoption and the strategic objectives of ports, a number of targeted actions can be considered. First, with respect to sustainable infrastructure, it is important to move beyond the existing assets. Instead, efforts should be directed towards actively involving current industrial actors, particularly those linked to fossil fuel activities (i.e. crude oil). These actors often control critical infrastructure and locations within the port area (i.e. refineries). By engaging them in the redevelopment and repurposing of their existing assets for hydrogen-related activities, ports and government can accelerate the implementation of hydrogen while simultaneously advancing the objective of sustainable infrastructure. Establishing a shared roadmap with port stakeholders (i.e. refineries) to prioritize infrastructure needs can further support long-term planning and ensure that the transition is aligned with broader port development strategies.

Second, regulatory compliance remains a challenge, as existing frameworks are often not fully adapted to the specificities of hydrogen handling and distribution. Involving port authorities and stakeholders more actively in national and European hydrogen policymaking processes can help ensure that regulations reflect more on the operational needs. In addition, closer collaboration between government and key port stakeholders, such as terminal operators, energy companies, and logistics providers, is essential to ensure that hydrogen adoption aligns more closely with the strategic objectives of ports. Governments can support this alignment by establishing dedicated working groups or pilot programs that give ports the opportunity to experiment with hydrogen technologies under temporary, more flexible regulatory conditions. These types of initiatives allow ports to test new practices while collecting data to inform permanent regulations. Moreover, Europe can reinforce this process through targeted subsidies and financial support, such as those already provided under European programs such as the Important Projects of Common European Interest (IPCEI) and the Clean Hydrogen Partnership, which demonstrate how strategic funding can accelerate compliance and adoption simultaneously (European Commission, 2020b).

Third, in terms of innovative leadership, hydrogen adoption can support innovation, but therefore convincing all stakeholders of the value of hydrogen adoption in successfully contributing to innovative leadership is needed. Collaboration between stakeholders, port authority and government accelerate the development and application of innovative hydrogen solutions but also strengthens the port's leadership role in the energy transition. By actively promoting these partnerships and showcasing the outcomes, ports can further solidify their position as innovation hubs within the maritime industry. An example of this is the HyPACT project, which focuses on developing an efficient process for cracking green ammonia into hydrogen (WaterstofNet, 2022).

In summary, the findings indicate that the hydrogen adoption can be significantly enhanced by addressing gaps in sustainable infrastructure, regulatory compliance and innovative leadership. By aligning hydrogen initiatives more closely with the broader objectives of ports, stakeholders are more likely to be convinced of the role they can play in advancing these port objectives. The alignment is important for driving the uptake of hydrogen within ports, which can accelerate the pace of the energy transition. This alignment will help ports actively meet their objectives, supporting an acceleration of hydrogen adoption as an element of their future strategies.

Table 7.5 presents the H-scores concerning the relevance and success assessments. Elevated scores are seen for economic competitiveness and safety and security for the relevance H-index, indicating consistency in answering the importance of the objectives. The lowest score in the relevance scoring pertains to innovative leadership, suggesting heterogeneous scoring for this objective.

Table 7.5: Comparison table

	H-index relevance	H-index success ranking
Environmental stewardship	41%	16%
Sustainable infrastructure	20%	16%
Resource management	23%	17%
Economic competitiveness	82%	23%
Operational efficiency	26%	41%
Regulatory compliance	38%	8%
Innovative leadership	13%	16%
Community engagement	25%	17%
Communication and marketing	35%	23%
Safety and security	53%	13%

Source: own composition

Comparatively, the H-scores for the success rankings are generally lower compared to the H-index relevance scores for importance, indicating a lower consistency in respondents' answers. Remarkably, operational efficiency demonstrates the highest consistency in the success ranking, surpassing its own H-index score for relevance, indicating greater consistency in answering in assessing the success of operational efficiency by implementing the transition to a hydrogen-powered hub scenario. There is a low score for environmental stewardship, sustainable infrastructure, resource management, regulatory compliance, innovative leadership, community engagement and safety & security for the success scoring. Regulatory compliance, for example, shows low consistency in the success-scoring which means that the experts were not consistent in how successful the implementation of the hydrogen scenario will contribute to national and international regulations and standards. A possible explanation for these discrepancies may be the broader definition of the objectives and the specific focus on a hydrogen scenario. For example, comparing both the relevance and success ranking of safety and security shows a relatively high score of the consistency of the importance which is lower when answering the question if the transition contributes to safety and security. The definition of safety and security also implies the well-being of personnel. The experts may rank the contribution of a hydrogen-powered hub scenario low to well-being of personnel. Furthermore, hydrogen can be considered highly flammable, necessitating stringent safety measures to prevent potential risks associated with its handling and storage. However, hydrogen also offers safety benefits in terms of enhancing environmental quality and contributing to a sustainable living environment.

7.5.2. Evaluating differences: a Wilcoxon analysis

The Wilcoxon rank test (Appendix E) enables to compares two related or independent scores to assess whether they are different, based on the ranks of the data rather than the raw values. In this case, the test is applied to related scores, as it compares the importance and success ratings given by the same group of experts. Acciaro et al. conducted their study with a sample size of 7 (n = 7) and adopted a significance level of 0.01. Given that the sample size in this chapter is 13 (n = 13), the same significance level of 0.01 is applied.

The Wilcoxon rank test rejects the null hypothesis ($M_{imp}=M_{succ}$) that the median of the two scorings (importance and success) is similar, which means that the two scorings are significantly different at the 0.01 significance level (Acciaro et al., 2014). The results show that the importance scoring (how important experts consider certain port objectives) is consistently higher than the success scoring (to what extent experts perceive that transitioning to a hydrogen-powered hub scenario contributes to achieving these selected objectives). This indicates that, while experts indicate port objectives as highly important, they are less convinced about the extent to which the Hydrogen-powered hub scenario effectively supports the success of achieving these objectives. This could be due to the fact that the objectives are broad and general port objectives, not solely focused on the greening of the port. Enhancing the alignment of hydrogen implementation with key port objectives may strengthen stakeholder trust and support, enabling faster hydrogen adoption and promoting sustainability in the ports and their energy flows.

7.5.3. Differences between ports in the North and South

This section examines potential regional differences between the northern and southern ports studied. The analysis first focused on comparing the importance rankings of port objectives between northern and southern ports. Following this, the study explored whether there were differences in the perceived success of hydrogen adoption in achieving these objectives across the two regions. To explore whether the lack of significant differences is consistent across regions, the sample was divided into six northern ports (North Sea Port, Port of Amsterdam, Port of Antwerp-Bruges, Port of Bremen, Port of Haropa, and Port of Rotterdam) and seven southern ports (Port of Barcelona, Port of Bilbao, Port of Cartagena, Port of Castello, Port of Genoa, Port of Tarragona, and Port of Valencia) for a more detailed comparison.

To test these regional differences, the Wilcoxon signed-rank test was applied to both the importance and success rankings (Appendix F). While this test is suitable for small sample sizes, it is important to acknowledge that splitting the already limited dataset into two regional groups further reduces statistical power. The analysis revealed no statistically significant differences between the northern and southern ports in terms of their importance rankings ($\alpha > 0.01$). Similarly, no significant differences were found in the success rankings between the two regions. These findings suggest a consistent alignment between the perceived importance of port objectives and the expected success of hydrogen adoption in achieving them, regardless of the region, although the limited sample size warrants caution when interpreting these results.

The analysis of regional differences between northern and southern ports found no significant disparities in either the importance or success rankings of hydrogen adoption and port objectives. Both rankings were consistent across regions, suggesting that the perceived importance of port objectives and the expected success of hydrogen adoption and port objectives are similarly aligned, regardless of whether the ports are located in the North or South.

7.6. Conclusion

In conclusion, this chapter successfully identified and verified a concise list of ten port objectives. The port objectives were analysed and verified by port authorities. This chapter assesses how the hydrogen-powered hub scenario aligns with these port objectives by answering the following research question: *How well are the strategic plans of port authorities aligned with the ambitions of transitioning towards a hydrogen-powered hub?*

To address the main research question of this chapter, two sub-questions are used: *What are the key objectives for European liquid bulk ports ? & Can the key port objectives be achieved in the Hydrogen-powered hub scenario?*

First, port objectives were identified by analyzing reports and literature and subsequently verified with experts from port authorities. This process resulted in a final list of ten key port objectives which ports should prioritize to align with future goals. These ten objectives are: environmental stewardship, sustainable infrastructure, resource management, economic competitiveness, operational efficiency, regulatory compliance, innovative leadership, community engagement, communication & marketing and safety & security.

Following this, thirteen port authorities from the six European countries with the highest carbon imports participated in the research through interviews and surveys. This chapter examined both the perceived importance of these objectives and the extent to which the implementation of the hydrogen-powered hub scenario successfully aligns to achieving the identified port objectives. By applying the H-index methodology, the research revealed disparities between the importance of the objectives and their level of success in practice.

The findings indicate significant importance attributed to the formulated objectives, with particularly high prevailing scorings for all formulated objectives. Notably, assuming the hydrogen-powered hub scenario emerges as a contributor to enhancing environmental stewardship, resource management, economic competitiveness and safety & security, which showed high importance scores and high success scores. This is shown by the high success prevailing scores. However, the alignment between hydrogen implementation and certain key port objectives, such as sustainable infrastructure, regulatory compliance and innovative leadership, appears to be lower. While these objectives are scored as highly relevant, the hydrogen-powered hub scenario is not yet perceived to sufficiently align with these objectives. Improved stakeholder involvement, flexible regulatory frameworks and active repurposing of fossil infrastructure are essential steps towards better alignment. Enhancing this alignment could increase stakeholder support and accelerate hydrogen adoption in ports.

The H-index measures the consistency in answers. Elevated scores in economic competitiveness and safety and security for the relevance H-index indicate consistent recognition of the importance of these objectives. Conversely, the lowest relevance score pertains to innovative leadership, suggesting varied assessments for this objective.

The Wilcoxon rank test rejects the null hypothesis at a 0.01 significance level. The results show that the median difference ($M_{imp} = M_{succ}$) between the two scores is significantly different at the 0.01 significance level. These findings reveal a misalignment between the perceived importance of port objectives and the perceived success of the hydrogen-powered hub scenario in achieving the port objectives. Aligning hydrogen implementation more closely with key port objectives could enhance stakeholder confidence and support, facilitating faster adoption of hydrogen technology and advancing sustainability in ports. This could be due to the fact that the objectives are broad port goals, not solely focused on the greening of the port.

The comparison between northern and southern ports showed no significant differences in either the importance of port objectives or success rankings of hydrogen adoption and port objectives.

This research and findings underscore the critical role of hydrogen in the energy transition in fostering the sustainable development of ports. These findings have implications for port management and decision-making. Port authorities and decision-makers can use these insights to inform strategic planning and investment decisions, prioritizing initiatives that align with identified objectives and show the greatest (potential) impact. Moreover, this chapter highlights that while the hydrogen-powered hub scenario contributes to multiple relevant port objectives, experts perceive a misalignment between its potential success and the overall importance of these objectives. Addressing this gap could enhance stakeholder confidence and accelerate adoption. This chapter serves as a stepping stone towards enhancing the sustainability and competitiveness of ports, thereby contributing to broader efforts towards a greener future.

Moving forward to future research, it is recommended to broaden the scope of respondents, encompassing a more extensive geographical range, particularly in France, Germany and Italy. By diversifying the sample, a more comprehensive understanding of regional variations in port objectives and alternative future scenarios could enrich the research's overall findings. Additionally, increasing the sample size would enhance the generalizability of the results, providing deeper insights into the dynamics of sustainable port development across Europe. Furthermore, the objectives could be narrowed down to greening objectives and the study could reveal if the implementation of the hydrogen powered hub scenario aligns more with which would allow the study to explore whether the implementation of the hydrogen-powered hub scenario aligns more closely with the environmental sustainability goals of ports or even broader to European regulations.

Chapter 8

Conclusions

This dissertation studied the energy transition and its effects on European ports, focusing on liquid bulk, renewable energy imports and the strategic role of ports in adapting to these changes. Specific focus was placed on the potential of hydrogen and ammonia as critical energy carriers, with scenario-based sensitivity analyses to evaluate costs and spatial demands.

8.1.Findings

This concluding chapter presents the main findings of the dissertation. The main objective of the dissertation was to develop energy scenarios to calculate non-carbon energy import volumes, required storage capacity and storage costs for ports located in the six most carbon-importing countries of Europe. Subsequently, the alignment between the implementation of these hydrogen import flows and port objectives was researched. The following sections present the conclusions from the different chapters to answer the main research question: *How do European energy transition scenarios impact its major liquid bulk ports with respect to storage investment and their strategic goals for a hydrogen-based economy?* Sub-questions were formulated and addressed in the six core chapters to address the main research question.

This chapter summarizes the findings following the order of the research questions addressed in the earlier chapters. Chapter 2 of the dissertation, addressing research question 1, provided a systematic literature review that presents earlier research, research pathways, and the research gap. Subsequently, Chapter 3 described the method used to answer the main research question with sub-questions which were addressed in the following chapters. Chapter 4, which addressed the second research question, explored energy transition systems and energy outlooks to develop descriptive port scenarios and present their associated challenges. Thereafter, Chapter 5 quantified three non-carbon energy sub-scenarios at a country-level for six European countries that import most carbon energy. Chapter 5 adresses research question 3. Then, Chapter 6, addressing research question 4, quantifies non-carbon energy sub-scenarios at port level and quantifies port import volumes, storage capacity needs and storage costs. Finally, Chapter 7, addresses research question 5 and analyses how the non-carbon import flows, more specifically hydrogen, align with port objectives.

8.1.1. What are the key trends, themes and research gaps in the academic literature on liquid bulk, energy transition and sustainability in ports?

Ports play an essential role in facilitating trade, of which the tanker segment faces unique challenges related to the energy transition. As the liquid bulk market has a significant role in transporting alternative energy and aims to phase out the crude oil to mitigate climate change and to align with predefined global and European regulations. The first sub-question was formulated as follows: *What are the key trends, themes and research gaps in the academic literature on liquid bulk, energy transition and sustainability in ports?*

Little research was conducted concerning the combination of liquid bulk, low carbon, energy transition, sustainability, tankers, ports, crude oil, maritime and terminals. Interest in these topics has grown significantly, with a notable rise in publications since 2009. Almost 80% of the papers concerning these keywords were published between 2012 and 2022.

The papers that were obtained by using the selected keywords were organized into nine key topics: efficiency, energy, engineering, environment, finance, geopolitics, policy, safety, and sustainability. A notable finding is that sustainability dominates the topics. Energy transition research began gaining prominence only in the last decade (2013-2022), driven by climate-focused regulations and policies coming from the EU and leading institutions such as IEA.

The academic literature on liquid bulk, energy transition and sustainability in ports reveals a strong focus on energy efficiency, sustainability in port development and the transition to alternative fuels in shipping, with research often addressing environmental impacts, policy innovations and key performance indicators. Regional studies concentrate on Asia, Europe, North America and Africa, while South America, despite its possibly significant role in non-carbon energy exports, remains underrepresented. The systematic literature highlights gaps in port-specific challenges and infrastructure readiness for the energy transition. The findings underscore the need for further research into the energy transition's implications for ports and their adaptation towards a sustainable future.

8.1.2. What are the energy transition scenarios for Europe?

Chapter 4 provided essential insights to address the research question: *What are the energy transition scenarios for Europe?* The chapter established a theoretical framework for understanding energy transition by examining the drivers and factors shaping energy scenarios. Then, global and European energy outlooks were analysed and used for further scoping the dissertation. Next, Chapter 4 discussed the existing energy flows in Europe, which is crucial to identifying the critical importing carbon countries in Europe. These countries will be subject for further analysis. Furthermore, it analysed the key ports in handling liquid bulk, which was subject for further analysis in Chapter 5 and 6. The last part was dedicated to describing possible port flow scenarios and to analyse challenges and opportunities. The findings of Chapter 4 formed the foundation for developing and quantifying specific sub-scenarios in Chapters 5 and 6, ensuring a comprehensive exploration of Europe's energy transition pathways.

The theoretical framework entails a conceptual framework that must adapt accordingly to establish a successful energy transition in which collaboration between stakeholders is crucial. The findings of the drivers and factors illustrate five essential drivers for the global energy market, which could influence the scenarios: social, technological, political, environmental and economic factors.

The global energy market outlook section shows that the global energy market is at its crossroads, as oil-producing companies and nations face significant challenges in aligning with the 2050 climate goals. Coal has been phaced out already since 2008. The oil peak is expected just before 2030. Renewable energy, such as wind and solar power, is expected to increase by 2050. This shift underscores the urgent need for ports to adapt their infrastructure and operations to support renewable energy imports and production. According to DNV, the transition towards more sustainable alternatives contributes to the decline in the share of oil. Furthermore, an overview of the top 10 global energy-supplying countries is presented. The top 10 energy supplying countries globally are China, United States, India, Russia, Japan, Brazil, Canada, Iran, Korea and Germany. The geopolitics of energy supply shapes the global shift to renewables, highlighting contrasts between fossil-fuel-dependent nations and clean energy leaders. China and the US remain major fossil fuel producers, with China advancing in renewables like hydrogen and solar. China leads the world in solar panels and batteries. Germany targets 100% renewable electricity by 2035, while Brazil leads with nearly half its energy demand covered by clean sources like hydropower and biofuels. Brazil's share of renewables in their total power generation is almost 88%, Canada is second in the top 10 with 69%. Geopolitics heavily influences energy policies and global flows, with nations' resources and strategies shaping future energy markets. These geopolitical dynamics present both opportunities for innovation and challenges related to energy security and international collaboration.

The European energy market outlooks illustrate that Europe emits 3.2% of global emissions. The European energy market is pressured by the regulations of the European Commission, which strives to be climate-neutral by 2050. Demand in 2022 is dominated by oil products and natural gas, with renewables steadily increasing their share over the last decade. Wind and solar power are identified as the primary drivers of this transition, requiring large-scale infrastructure investments such as offshore wind parks and grid connections after 2030. Supply scenarios emphasize a fast shift toward renewables, with projections of over 80% of generation capacity from wind and solar by 2050. Regional differences persist, with Western Europe advancing in wind energy and hydrogen development, while Southern Europe shows promising growth in planned hydrogen capacities and solar power. In response to geopolitical disruptions like Russia's gas supply cut, Europe prioritized energy security by diversifying imports and accelerating renewables adoption. These findings highlight Europe's potential as a leader in renewable energy but also underscore the need for strategic investment and policy alignment to address regional disparities.

When zooming in on the carbon and non-carbon import, production and export of Europe, the findings show six main importing countries of carbon energy: Germany, The Netherlands, Italy, France, Spain and Belgium. Together, they import 75% of the total import of carbon energy in 2022. France is a large producer of nuclear energy and Germany is the leading producer of renewable energy and biofuels in Europe in 2022. Norway and the Netherlands are the largest exporters of carbon energy. Norway because it is the largest producer of LNG in Europe and the Netherlands due to their hub function as ports.

The key ports in handling liquid bulk are researched and the findings show that the Port of Rotterdam, Antwerp-Bruges, Amsterdam, Trieste and HAROPA take a leading role (top 5) and have an accumulated share of 50%. The ports taken into account for further analysis for the sub-scenario development are Rotterdam, Antwerp-Bruges, Amsterdam, Trieste, HAROPA, Marseille, Cartagena, Bilbao, North Sea Port, Tarragona, Barcelona, Genoa, Castellon, Valencia, La Spezia, Civitavecchia, Bremen and Hamburg. Focusing on these ports provides a strategic lens for understanding how Europe's key hubs can evolve within different energy transition scenarios.

Three qualitative descriptive scenarios were developed to indicate the challenges and opportunities of energy transition pathways for ports. In the Renewable energy scenario, wind and solar power present an opportunity to power port buildings sustainably and support hydrogen production. However, their intermittent nature poses a challenge, requiring complementary energy storage solutions like hydrogen to ensure reliability. In the Hydrogen-powered hub scenario, hydrogen offers opportunities as a zero-emission energy carrier, especially in industrial heating, heavy transport and ammonia production. The challenge lies in scaling up infrastructure, securing renewable energy sources for electrolysis, and addressing economic feasibility. In the Diverse energy mix scenario, integrating wind, solar, CCS, batteries and biofuels provides a flexible and resilient energy system, enhancing energy security and reducing dependency on fossil fuels. The challenge is managing the complexity of combining multiple sources and ensuring seamless connectivity while addressing the higher initial investment costs. Given European ports' critical role in facilitating the transition to non-carbon energy, the focus of the empirical sub-scenarios in the next chapters will be on the Hydrogen-powered hub scenario. This decision is driven by the necessity of large-scale hydrogen imports to meet the EU's climate objectives, particularly in achieving the European Green Deal and Fit for 55 targets. Hydrogen and its carriers (i.e. ammonia) offer a viable pathway to ensuring a stable and scalable energy supply. Furthermore, European ports are well-positioned to become key entry points for hydrogen and ammonia, due to their infrastructure and logistics expertise. As Europe is unlikely to generate sufficient renewable energy domestically, large-scale imports will be essential, reinforcing the need to focus on this scenario to evaluate the necessary infrastructural and economic shifts.

In summary, Chapter 4 identified critical drivers, evaluates global and European energy trends and outlined key countries and ports for further analysis. These findings established a foundation for sub-scenario development and cost-surface analyses in the subsequent chapters, addressing the research question and contributing to an understanding of Europe's energy transition pathways.

8.1.3. How will the energy flows of the major carbon-importing countries in Europe be impacted by the energy transition scenarios?

The insights and findings of Chapter 4 facilitated quantifying country-level sub-scenarios of non-carbon energy for Europe's six most carbon-importing countries. Building on these insights, Chapter 5 explored how energy flows in these countries are impacted on by varying energy transition, addressing the research question: *How will the energy flows of the major carbon-importing countries in Europe be impacted by the energy transition scenarios?*

Three sub-scenarios were developed for 2030, 2040, and 2050, using the Eurostat data of 2022. Each sub-scenario is based on different assumptions regarding energy demand, carbon reduction and domestic production of non-carbon energy.

The first sub-scenario aligns with the assumptions of the International Energy Agency (IEA) and the European Commission. It envisions a transition characterized by a slight decrease in energy demand, a sharp uptake in non-carbon energy domestic production (up to 250% by 2050), and a reduction of 50% in solid fossil fuel imports by 2050. While petroleum product imports remain stable, natural gas imports increase by 23% by 2050. In this sub-scenario, all six countries achieve energy self-sufficiency as domestic production meets demand, resulting in no need for non-carbon energy imports. However, the continued need for carbon-based energy imports, particularly natural gas, does not fully align with EU climate regulations, indicating that this sub-scenario may not be ideal for meeting long-term decarbonization goals.

The second sub-scenario adopts a more conservative perspective, assuming a moderate increase in non-carbon energy production of 20% by 2030, 40% by 2040 and 60% by 2050. All other factors remain the same as in Sub-scenario 1. The slower growth in domestic non-carbon energy production leads to an increased reliance on hydrogen and ammonia imports, with Germany needing to import approximately 4.3 million tonnes of hydrogen and 8.7 million tonnes of ammonia annually by 2030. This sub-scenario highlights the urgency for Germany to develop infrastructure for green energy production and expand its capacity to handle hydrogen and ammonia imports. Germany is highly dependent on carbon energy sources. After 2030, there will be no need to import non-carbon energy because domestic production will fulfil the energy needs.

The third sub-scenario represents the most ambitious energy transition, eliminating carbon energy production and imports by 2050. This drastic shift results in the need for non-carbon energy imports from countries such as Germany, the Netherlands, and Italy. By 2050, Germany would need to import 5.3 million tonnes of hydrogen annually, while the Netherlands and Italy would require 8 million and 2.7 million tonnes by 2050, respectively. By 2030, Germany will need to import 19 million tonnes of ammonia annually, while the Netherlands and Italy will require 6.5 million and 2.2 million tonnes, respectively. By 2040, Germany's ammonia imports are projected to reach 8.2 billion tonnes, the Netherlands 9.7 billion tonnes, and Italy 800 thousand tonnes. By 2050, ammonia imports are expected to rise to nearly 11 million tonnes for Germany, 16.3 billion tonnes for the Netherlands, and 5.6 billion tonnes for Italy. This sub-scenario underscores the necessity for significant investments in infrastructure, including port facilities for hydrogen and ammonia, extensive pipeline networks and industrial systems compatible with non-carbon energy sources.

These findings demonstrate how varying energy transition sub-scenarios profoundly impact energy flows in Europe’s major carbon-importing countries, especially the dependence of non-carbon imports for countries such as Germany, Italy and the Netherlands. The findings emphasize the critical need for strategic planning, infrastructure investments and policy adjustments to ensure a successful transition to a non-carbon energy future.

8.1.4. What are the storage investment costs and storage requirements linked to the imported volumes of hydrogen and ammonia in key European ports?

Using the methodology developed and explained in Chapter 3 and the further findings of Chapter 4 and 5, Chapter 6 was able to zoom in from country-level non-carbon import to port-level non-carbon imports. The primary objective of this chapter was to analyze the import volumes for hydrogen and ammonia, storage requirements and storage costs under the three earlier developed sub-scenarios. The analysis addressed how these ports can adapt to facilitate the transition to non-carbon energy imports. Therefore, Chapter 4 answered the following research question: *What are the storage investment costs and storage requirements linked to the imported volumes of hydrogen and ammonia in key European ports?* Shifting the analysis from a country-level perspective to port-specific sub-scenarios and outputs highlighted the critical role of port infrastructure in ensuring that European ports can accommodate the growing demand for non-carbon energy imports.

The findings show that nine key ports for importing non-carbon energy, including Antwerp-Bruges, Rotterdam and Amsterdam, will serve as central hubs for non-carbon energy imports in the developed sub-scenarios. With hydrogen and ammonia imports, especially in scenarios with high import volumes (such as Sub-scenario 3), additional storage space and higher costs will be required. The Port of Rotterdam for example, requires an import of almost 3 million tonnes of hydrogen and nearly 6 million tonnes of ammonia by 2030 in Sub-scenario 3, resulting in a storage cost of 9.4 billion euros for hydrogen and 400 million euros for ammonia. The storage requirements in Sub-scenario 3 range from 385 storage tanks in 2040 to 753 storage tanks in 2050, and only one tank is needed to store ammonia for 2030, 2040 and 2050. This higher import needs require new and large-scale approaches for transporting and storing hydrogen and ammonia. Ammonia emerges as a more cost-effective and resource-efficient option, offering lower storage and transportation costs compared to liquid hydrogen.

The sensitivity analyses further underlined the complexity of port planning. Compared to a mixed hydrogen-ammonia approach, the ammonia-only scenario offers a more practical efficient and cost-effective pathway for non-carbon energy imports. The ammonia-only scenario requires fewer vessels, less storage and lower costs. Ammonia's established global trade infrastructure further underscores its near-term feasibility.

Limiting the pipeline network from a full connection from the researched ports to each NUTS2 region to the considered pipeline connection of the European Hydrogen Backbone program significantly reduces import volumes at ports in Belgium, the Netherlands and Germany while increasing the share of Southern European ports (more evenly distributed non-carbon imports).

Additionally, proximity to exporting countries, such as Morocco and Egypt, influences trade flows within the model, with ports closer to these regions handling larger volumes. Longer storage durations (e.g., three to six weeks) increase storage costs and space requirements, emphasizing the importance of managing storage efficiently.

These findings underscore that the successful integration of hydrogen and ammonia into Europe's energy systems will depend on strategic investments in port infrastructure, efficient storage management and collaboration with key exporting countries. Ports will play a pivotal role in the energy transition, acting as logistical and economic hubs that enable Europe to achieve its sustainability goals.

8.1.5. How well are the strategic plans of port authorities aligned with the ambitions of transitioning towards a hydrogen-powered hub?

The global imperative to transition toward sustainable energy sources has placed ports at the forefront of energy transition efforts. As critical infrastructural hubs, ports face the dual challenge of reducing carbon emissions while aligning with broader climate goals. In Europe, the climate goals are prior. Initiatives such as the Green Deal and Renewable Energy Directive shape the path to climate neutrality by 2050. Among alternative energy sources, hydrogen emerges as a pivotal element in achieving these ambitions, offering diverse applications across industries and transportation.

In the previous chapters, sub-scenarios for non-carbon energy imports, both at country and port level, were developed to quantify the potential role of hydrogen and ammonia in reshaping the European energy landscape. These sub-scenarios outlined how non-carbon imports could meet future energy demands, focusing on storage capacity, infrastructure and associated storage costs. Building on this foundation, chapter 7 focused on how these non-carbon imports align with the strategic objectives of port authorities. Specifically, it assessed whether transitioning to hydrogen as a port aligns with predefined port objectives. The research question guiding this analysis was: *How well are the strategic plans of port authorities aligned with the ambitions of transitioning towards a hydrogen-powered hub?*

Port objectives, essential for guiding ports toward sustainable development, have been identified and verified, with input from port authorities across Europe. These ten researched objectives are environmental stewardship, sustainable infrastructure, economic competitiveness, operational efficiency, regulatory compliance, innovative leadership, community engagement, resource management, and safety and security.

By employing the hydrogen-powered hub scenario, this research examined how transitioning to hydrogen could contribute to achieving these ten objectives. Interviews and surveys conducted with thirteen port authorities in the liquid bulk segment revealed the importance and the success of implementing these objectives. The analysis highlighted significant alignment between the hydrogen scenario and key objectives such as environmental stewardship, economic competitiveness, safety & security, and resource management. These objectives consistently ranked highly in terms of both importance and implementation success.

The H-index methodology demonstrated consistency in respondents' assessments, with a powerful alignment on economic competitiveness and safety & security objectives. Conversely, objectives such as innovative leadership displayed more variability in perceived relevance. The Wilcoxon rank test rejected the hypothesis that the median ($M_{imp} = M_{succ}$) difference between the two scores is not significantly different at the 0.01 significance level. These findings reveal a gap between the perceived importance of port objectives and the perceived effectiveness of the Hydrogen-powered hub scenario in achieving them. Improving the alignment between hydrogen implementation and key port objectives could enhance stakeholder confidence and support in the hydrogen transition, accelerating hydrogen adoption and advancing sustainability within ports.

The study underscored the critical role hydrogen plays in fostering the sustainable development of ports. The Hydrogen-powered hub scenario was shown to be a valuable strategy, not only in reducing carbon emissions but also in advancing broader port objectives, enhancing sustainability and maintaining competitiveness in a rapidly evolving maritime industry.

8.1.6. How do European energy transition scenarios impact its major liquid bulk ports with respect to storage investment and their strategic goals for a hydrogen-based economy?

This section addresses the main research question with the help of sub-research questions. The central question guiding this dissertation is: *How do European energy transition scenarios impact its major liquid bulk ports with respect to storage investment and their strategic goals for a hydrogen-based economy?*

The energy transition scenarios impact the need for space and investments in energy-storing facilities within major European liquid bulk ports. The parameters of energy demand, carbon energy import and domestic carobon and non-carbon energy production determine the requirement for non-carbon energy imports (hydrogen and ammonia). The extent to which carbon energy imports and domestic carbon energy production are restricted by regulators and their regulations plays a crucial role in shaping future energy needs. In 2022, Germany, France, Spain, Italy, the Netherlands and Belgium had significant carbon energy imports. These countries are dependent on external suppliers, including major exporters such as Russia. These carbon importing countries require substantial efforts to meet the European Union's climate objectives, such as those outlined in the European Green Deal, Fit for 55 and RePowerEU Plan.

In sub-scenario 1, Accelerated non-carbon growth with fossil stability, a high level of non-carbon domestic energy production combined with a decline in domestic carbon production by 82% by 2050, a decline of fossil fuel imports by 50% by 2050, a slight increase of natural gas import, and a stable petroleum production, eliminates the need for non-carbon energy imports in the six researched countries. However, the continued reliance on carbon energy (domestic production and imports) contradicts EU regulations, making this sub-scenario less viable. If Europe wants to meet their predefined environmental goals, then non-carbon import is needed.

Sub-scenario 2, Moderate non-carbon expansion with fossil stability, projects a 60% increase in non-carbon production by 2050, the importing parameters of carbon energy remains the same as in SS1 and an 82% decrease in carbon production by 2050. By 2030, only Germany requires additional non-carbon energy imports. Germany very reliant on carbon energy imports, particularly of solid fossil fuels. For ports such as Rotterdam, Antwerp-Bruges and Amsterdam, this translates to 2 million tonnes of hydrogen and 4 million thousand tonnes of ammonia, with associated costs of 6 billion euros for hydrogen and 400 million euros for ammonia. Despite these efforts, the sub-scenario still falls short of EU regulatory targets for 2050 due to insufficient decarbonization.

Sub-scenario 3, Full decarbonization pathway, aligns most closely with EU regulations. The sub-scenario targets a 100% reduction in carbon production and import, along with a 300% increase in non-carbon domestic production. This extensive reliance on domestic production introduces risks, if countries fail to achieve their production targets, additional non-carbon imports will be required. By 2050, Germany, the Netherlands and Italy will require 5.3 million, 8 million and 2.7 million tonnes of hydrogen. For ammonia Germany needs nearly 11 million tonnes, the Netherlands 16 million tonnes and 2.7 million tonnes of ammonia for Italy. The costs for hydrogen imports for the Port of Rotterdam rises from 9.4 billion euros in 2030 to 7.3 billion euros in 2050, while ammonia costs remain at 400 million euros. Storage space requirements range between 30 and 68 hectares for hydrogen and ammonia for the Port of Rotterdam, Antwerp-Bruges and Amsterdam.

A sensitivity analysis revealed that ammonia storage is significantly more efficient in terms of both cost and space. Transitioning to an ammonia-only scenario reduces costs from approximately 7.4 billion euros in 2050 for the port of Rotterdam, Antwerp-Bruges and Amsterdam (in the mixed scenario, hydrogen and ammonia) to approximately 1.2 billion euros for each port. Storage space requirements decrease from 33–

68 hectares to 5.5–11 hectares. Pipeline infrastructure plays a critical role in import volume, when all NUTS2 areas are connected to the ports, the NUTS2 regions attract higher volumes compared to the considered network by 2030-2040. A fully integrated network results in 3 million tonnes of hydrogen imports, whereas partial pipeline connectivity reduces this to 2.7 million tonnes. For ammonia, volumes decline from 6 million to 5.4 million tonnes under similar conditions. The geographic proximity of exporting countries also impacts import patterns, with closer exporters attracting larger volumes through closer ports. For instance, if Egypt is the primary exporter and Italy is one of the importing countries among Germany and the Netherlands, Italian ports and Marseille would handle between 2 and 3.3 million tonnes of hydrogen and 4-6 million tonnes of ammonia. Storage duration is another critical factor. Extending storage time from three to six weeks increases required space from 60 to 130 hectares in 2030 for example, drives cost up from 7.7 billion to 15.5 billion euros for hydrogen and ammonia by 2050.

The second part of the research question researched the alignment of non-carbon energy import strategies with port objectives. This research is essential for ensuring that hydrogen implementation contributes to broader port development goals. If this Hydrogen-powered hub does not align with port objectives, ports are far less likely to invest in hydrogen development. This dissertation identified ten key objectives of European port authorities, which all showed high importance scores: environmental stewardship, sustainable infrastructure, resource management, economic competitiveness, operational efficiency, regulatory compliance, innovative leadership, community engagement, communication & marketing and safety & security.

By adopting the Hydrogen-powered hub scenario, this dissertation assessed the extent to which hydrogen transition aligns with the identified port objectives. Interviews and surveys conducted with thirteen port authorities in the liquid bulk segment highlighted strong alignment between hydrogen adoption and objectives such as environmental stewardship, economic competitiveness, safety & security and resource management. These objectives ranked highest in both importance and implementation success.

The H-index methodology confirmed consistency in respondents' assessments of the importance ranking, with notable agreement on economic competitiveness and safety & security. However, innovative leadership exhibited greater variability in perceived relevance and success in aligning with the Hydrogen-powered hub scenario. The results reject the null hypothesis, indicating a significant difference between the importance and success scores at the 0.01 significance level. Importance scores (how experts view port objectives) are consistently higher than success scores (how experts perceive hydrogen transition's contribution to these objectives). Strengthening this alignment could enhance stakeholder confidence and support for hydrogen adoption, thereby accelerating the transition and reinforcing sustainability within ports. To conclude, this dissertation underscores the pivotal role that ports play in Europe's energy transition, positioning them as central hubs for non-carbon energy imports such as hydrogen and ammonia. Given the escalating demands for non-carbon energy to meet the EU's climate goals, it is evident that ports must invest in advanced infrastructure, enhance their operational capacity and prioritize regulatory alignment to accommodate future energy flows. The findings clearly demonstrate that the energy transition is not only a matter of technological change but also of strategic alignment between energy import strategies and port objectives.

Ports must proactively address infrastructure bottlenecks by investing in storage facilities and transport networks to manage the forecasted increase in hydrogen and ammonia imports. International cooperation and cross-border integration are essential for streamlining energy flows. Strategic planning should align with regulatory frameworks and long-term sustainability goals, promoting investment in clean energy technologies.

The research highlights the importance of aligning hydrogen-powered hubs with the broader sustainability objectives of European port authorities. This alignment is crucial for meeting EU climate targets and positioning ports as leaders in the global transition to a carbon-free economy. Strengthening these connections will support investment in hydrogen infrastructure and collaboration, ensuring a sustainable energy future for Europe. The next section will present recommendations to enhance ports' roles in the energy transition, focusing on infrastructure, collaboration and regulatory alignment to prepare for future challenges.

8.2. Recommendations

The recommendations of this section build upon the findings from previous chapters, addressing the challenges and opportunities that ports face in the transition to non-carbon energy flows. With the European energy transition necessitating substantial changes in ports, particularly in accommodating hydrogen and ammonia imports, these recommendations provide actionable insights for port authorities, policymakers and stakeholders. By aligning port infrastructure investments with the broader goals of sustainability, economic competitiveness and energy security, this section outlines strategic pathways to ensure ports remain critical enablers of Europe’s energy transition while meeting their operational objectives.

The dissertation illustrates the urgent need for action in advancing the integration of non-carbon energy imports, such as hydrogen and ammonia, within liquid bulk ports. While significant research has focused on the feasibility of non-carbon energy as fuels in general, the specific implications for ports remain underexplored. To address this, port authorities, industry stakeholders and policymakers must prioritize investments in dedicated infrastructure, including specialized storage facilities, transport networks and handling systems designed to manage the specific requirements of hydrogen and ammonia. Additionally, operational strategies must be updated to incorporate safety protocols, regulatory compliance and logistics solutions that align with the unique characteristics of non-carbon fuels. Only through these targeted investments and strategies can effectively support ports in the transition to non-carbon energy systems and position themselves as key players in Europe's energy future.

Port authorities should consider offering long-term concessions to private companies investing in hydrogen and ammonia infrastructure, fostering a stable investment environment. In doing so, port authorities can enforce strict sustainability criteria when granting these concessions, ensuring that storage infrastructure aligns with the broader decarbonization goals. This approach will encourage companies to innovate in creating sustainable storage solutions, while also accelerating the development of the required infrastructure for the energy transition. For example, The Port of Antwerp-Bruges is already advancing hydrogen projects through its NextGen district. Additionally, stimulating collaboration is crucial. The Port of Rotterdam for example is realising a hydrogen ecosystem to import green energy (wind farms), produce green hydrogen and import terminals for hydrogen and hydrogen carriers.

A key recommendation is the urgent need for unified regulations to guide the transition to non-carbon energy in ports, which was indicated in the interviews. Current regulatory frameworks vary across countries, creating inefficiencies and uncertainties for investors and operators. For example, while the Netherlands and Germany have developed comprehensive hydrogen strategies with clear safety and technical guidelines, some Southern and Eastern European countries have less defined regulatory frameworks, leading to fragmented infrastructure development. Without such harmonization, ports in different countries may face delays in permitting, additional costs for adapting to multiple regulatory systems, and difficulties in establishing cross-border hydrogen corridors. This regulatory alignment is critical to accelerating the transition, reducing inefficiencies, and enabling ports to adapt swiftly to the growing demand for non-carbon energy imports while maintaining competitiveness and operational coherence.

It is clear that a global approach (Chapter 4) is essential to navigating the energy transition, particularly within the context of ports. While this dissertation focuses on Europe, developments in other parts of the world play a crucial role in shaping the global energy landscape. For instance, China, as the world's largest emitter, has already taken significant steps in addressing this issue. Its investments in solar energy are among the highest globally, positioning it as a key player in the transition to non-carbon energy sources. However, it also highlights the need for a global effort to address emissions and stay competitive, with an emphasis on international cooperation and strategic planning. Ports must adapt and specialize to meet these challenges, capitalizing on their regional strengths.

Ports in Northwest Europe, such as Rotterdam and Antwerp-Bruges, should take the lead in investing in hydrogen and ammonia infrastructure, areas where they benefit from a combination of geographic location, existing industrial clusters and well-developed (or potential) hinterland connectivity. These ports already function as major gateways for fossil-based liquid bulk (Chapter 4), and the transition toward non-carbon molecules is essential to maintain their relevance and competitiveness. Their proximity to major demand centers for non-carbon energy, such as Germany, France, and Italy, gives them a logistical advantage in distributing large energy volumes efficiently. Moreover, planned and existing pipeline infrastructure reinforces their strategic role in ensuring the reliable inland transport of hydrogen and ammonia. These investments will be crucial for enhancing the region's position in the global energy transition. Meanwhile, Southern Europe has the potential to capitalize on the rapid growth of solar energy, using its geographical advantage to enable renewable energy generation and export. This abundance of solar power creates opportunities for ports in the region to develop into strategic hubs for the export of renewable energy carriers, such as hydrogen and ammonia. By investing in the necessary infrastructure, these ports can position themselves as critical links in Europe’s energy transition, reducing reliance on imports from other continents. These investments and strategies are crucial for ports to stay competitive.

In this context, the descriptive scenarios presented in this dissertation of Chapter 4 offer valuable insights for port strategic planning for infrastructure. They highlight the challenges and opportunities ports face in the transition to non-carbon energy. Ports should prioritize collaboration with countries that have a surplus of non-carbon energy such as Morocco, Brazil, Egypt and Chile, investing in energy infrastructure that allows for long-term benefits. This can help ensure that countries are not reliant on a single energy source, as recent geopolitical tensions (such as those surrounding Russia's gas supply cuts in 2022) have demonstrated the risks associated with energy dependence. Minimizing vulnerabilities associated with over-reliance on a single energy source will be key to ensuring the resilience and sustainability of ports in the future. To mitigate these vulnerabilities, ports must also work towards energy independence or try to diversify their energy sources by forming strategic partnerships with multiple countries. Such collaborations can contribute to a more stable and sustainable energy supply, supporting the successful integration of renewable energy and fostering resilience in the face of geopolitical disruptions. Moreover, policies should be put in place to support the scalability of renewable energy production at the global, national and regional levels.

Ports prior in importing non-carbon energy (following the sub-scenarios used in this dissertation), such as Germany, the Netherlands and Italy, must prioritize strategic investments in infrastructure to support non-carbon energy imports, particularly hydrogen and ammonia. This includes expanding port facilities, creating storage solutions and building pipelines to ensure efficient transport and distribution of these fuels. Future planning should involve strengthening and expanding the pipeline network to ensure more efficient and consistent energy distribution across ports.

Some ports will need to examine the potential for expanding their facilities or, as in the case of Antwerp-Bruges, consider mergers. The platform of Antwerp in the Antwerp-Bruges port faces space shortages, but with the merger with Bruges, this issue has been temporarily solved. Their complementary strengthens their competitive position, also to accelerate the energy transition. Many European ports are already reaching the limits of their expansion potential and will need to explore the transition from carbon infrastructure to non-carbon infrastructure.

The results of the sensitivity analysis highlight the complexity of managing storage times and capacity. Ports must work together to develop standardized protocols for ammonia and hydrogen storage, optimizing storage durations and minimizing space and cost inefficiencies. Given the space constraints in many ports, ammonia (NH_3) presents a more viable option than liquid hydrogen (LH_2), as it requires less demanding storage conditions, is cheaper and is easier to handle at large scales.

In addition, governments have a key role to play in aligning port objectives with national and regional hydrogen adoption strategies. Ports often operate with their own commercial and spatial priorities, which may not fully align with broader energy transition goals. To address this, governments should develop frameworks that include policy goals across energy, spatial planning and port development. This includes establishing clear roadmaps, allocating funding and facilitating intergovernmental cooperation to ensure that port developments are future-proof and compatible with national hydrogen strategies. Governments and supranational institutions have to create policy coherence between different governance levels (i.e. European and national levels).

8.3.Future research directions and limitations

This section identifies key areas for future research and examines the limitations encountered throughout the dissertation. While the research comprehensively analyzed the spatial and investment requirements for hydrogen and ammonia imports in European ports, this dissertation could not include certain aspects due to data accessibility. These future research pathways will help refine the strategies outlined in this dissertation, ensuring ports can adapt effectively to the evolving energy landscape.

This dissertation highlights several key areas requiring further research to complement its findings. One of the most critical gaps identified in the literature is the limited understanding of how the energy transition specifically impacts ports, particularly those handling liquid bulk cargoes such as oil, chemicals and future energy carriers such as hydrogen and ammonia. While much research has been conducted on container transport, the liquid bulk sector, which is critical for handling hydrogen and ammonia flows, remains underexplored. Additionally, the role of geopolitics in shaping non-carbon energy flows needs deeper investigation, as global political dynamics significantly influence the sourcing, transport and storage of these energy carriers.

Moreover, an essential aspect that has not been fully addressed is the role of commodity traders in shaping the flow of non-carbon fuels through ports. Traders play a pivotal role as mentioned in the introduction in determining where and when energy carriers such as hydrogen and ammonia are stored and traded. Their influence is significant in a volatile energy market, as they help drive logistical decisions, manage storage facilities and interact with port authorities on infrastructure needs. Future research should explore how traders' strategic decisions impact the needed port infrastructure and the non-carbon energy supply chain.

This dissertation uses a gravitation model to estimate the distribution of hydrogen and ammonia flows across ports, based primarily on GDP and distance to hinterland areas. While this approach is suitable for high-level strategic assessments and offers flexibility in a data-limited context, it does not capture key geopolitical influences. For instance, recent geopolitical shifts, such as Germany’s rapid construction of LNG terminals following the Nord Stream pipeline disruption, show that political urgency and strategic considerations can override purely market-based logic. Therefore, future research should consider integrated models that explicitly incorporate geopolitical drivers of port development and trade flows. However, some geopolitical reasoning is already reflected in the earlier assumptions on demand, imports, and domestic production. The model remains adaptable and can be updated as new data becomes available, making it a flexible tool for future analyses.

Another crucial area for research is determining the most effective strategies to accelerate the energy transition in ports. Understanding this interplay could offer valuable insights into policy design and implementation. Moreover, further exploration of emerging non-carbon energy carriers and the sustainability of nuclear energy is essential, particularly in evaluating whether the benefits of nuclear power outweigh its associated safety risks nowadays. These research directions will help bridge critical knowledge gaps and provide a more comprehensive framework for navigating the energy transition in ports.

Additionally, further research is needed in pipeline transportation for hydrogen and ammonia. If more data were available on pipeline transportation costs and more consensus around transportation costs in general, it would be possible to refine the model used in this dissertation and improve its accuracy. Understanding the cost structures associated with different transport options, such as pipelines versus other methods, could significantly enhance the strategic planning for energy flows in ports. Furthermore, investigating the feasibility of additional pipelines for transporting hydrogen and ammonia could make their transportation more efficient and cost-effective. More pipelines (accessibility) would have important implications for the scalability of non-carbon energy infrastructure in ports and could increase the attractiveness of hydrogen and ammonia as energy carriers. Therefore, research into pipeline expansion, its economic feasibility, and its logistics challenges will be critical to ensure the energy transition in the future.

The model used in this dissertation offers flexibility and can be expanded into other sectors, such as dry bulk. If a new non-carbon energy carrier were to emerge, the model allows for adjustments, as shown in the sensitivity analysis in Chapter 6. This adaptability makes the model a helpful tool for assessing future developments and preparing for potential shifts in energy flows. Most of the calculations in this dissertation are based on current knowledge and technologies. However, technological advancements in renewable energy, transportation and storage systems could influence the feasibility of these options in the future. The strength of the model lies in its flexibility, meaning that as new technologies emerge, the model can easily be adapted to incorporate these innovations, ensuring its continued relevance and accuracy in future research.

Ammonia is currently more cost-effective and feasible for storage and transportation (sensitivity analysis. Although ammonia is positioned as a more resource-efficient option, future research into its environmental impacts, particularly during transportation and storage, will be critical. Ongoing technological advancements in energy carriers, transporting vessels and storage systems can further reduce costs and improve efficiencies. As ports in different European regions will play varying roles in non-carbon energy imports based on geographical proximity to exporting countries, there is a need for region-specific studies on port adaptation strategies. It should also align with their domestic non-carbon energy production.

A transcontinental hydrogen pipeline, such as one connecting Morocco to Central Europe, is considered technically and economically feasible according to several recent studies . However, such projects require a long-term vision, political commitment, substantial investment and a certain degree of confidence in future offtake. These factors explain why progress on such infrastructure has been relatively slow. Moreover, current projections indicate that a pipeline of this scale would only become operational after 2050, placing it outside the temporal scope of this research. In contrast, intra-European pipeline initiatives, such as the planned Mediterranean hydrogen corridor, are included in this study, as they are expected to be realised within the 2050 timeframe.

The alignment of the Hydrogen-powered hub scenarios with port objectives could be extended to other scenarios in future research. For instance, examining a fossil fuel-based scenario would provide insights into the extent to which it still aligns with port objectives. Additionally, future research could refine the focus from general port objective to more specific objectives related to sustainability. In this dissertation, the goal was to research the alignment with the general objectives, acknowledging that while climate change is one of the most ambitious and critical goals, ports also pursue other significant objectives beyond meeting climate and sustainability targets. Also, long-term studies could evaluate the alignment in a decade. These findings will give more insights into the energy transition's effect on port objectives and if this effect has changed over time.

A potential limitation for future research, not addressed in this dissertation, is the public acceptance of ammonia transport, particularly near urban port city areas (i.e. port of Antwerp-Bruges, port of Rotterdam etc.). As ammonia can be hazardous and may raise concerns among local communities, this issue could become a major port-related challenge in the future. Future research could explore how to address these concerns, incorporating public perception and social acceptance into port planning strategies. For example, in 2022 in Groningen, the Netherlands, there were concerns when an ammonia transport train was planned to pass through densely populated areas. This brought public concern about the risks of transporting hazardous materials through such areas. Furthermore, as shown in Chapter 7, safety and security are seen as important port objectives, making it essential to address these issues. Future research could explore how to address these concerns. Another limitation is the repurposing of the existing infrastructure and terminal facilities for carbon energy use. While this dissertation outlines the surface requirements for green energy carriers, it does not assess in depth how current oil and gas terminals could be converted or adapted to accommodate hydrogen and ammonia flows. This presents a significant research opportunity, as reusing infrastructure could reduce transition costs, minimize spatial conflicts, and accelerate the transformation of port areas into renewable energy hubs.

The dissertation could be expanded to include other continents, such as Asia, North America and Africa, where hydrogen-related projects are being implemented, applying the model and interview methodology to a broader range of ports, enabling analysis across diverse geographical and operational contexts. Such expansion would provide a more comprehensive understanding of global non-carbon imports and the universal applicability of hydrogen and ammonia initiatives to achieve port objectives.

Ultimately, this dissertation enables a deeper understanding of ports' role in the energy transition. It addresses key aspects of hydrogen and ammonia imports. These future research suggestions will be crucial for refining the strategies and the extent of the model’s applicability. By integrating geopolitical factors, improving data availability on pipelines and inland demand and refining the modeling approach beyond GDP and distance-based assumptions, future studies can ensure that ports are prepared for the ongoing energy transformation and well-positioned to lead the development of non-carbon energy infrastructure. Such research will contribute to a more resilient, adaptive and future-proof global energy network.

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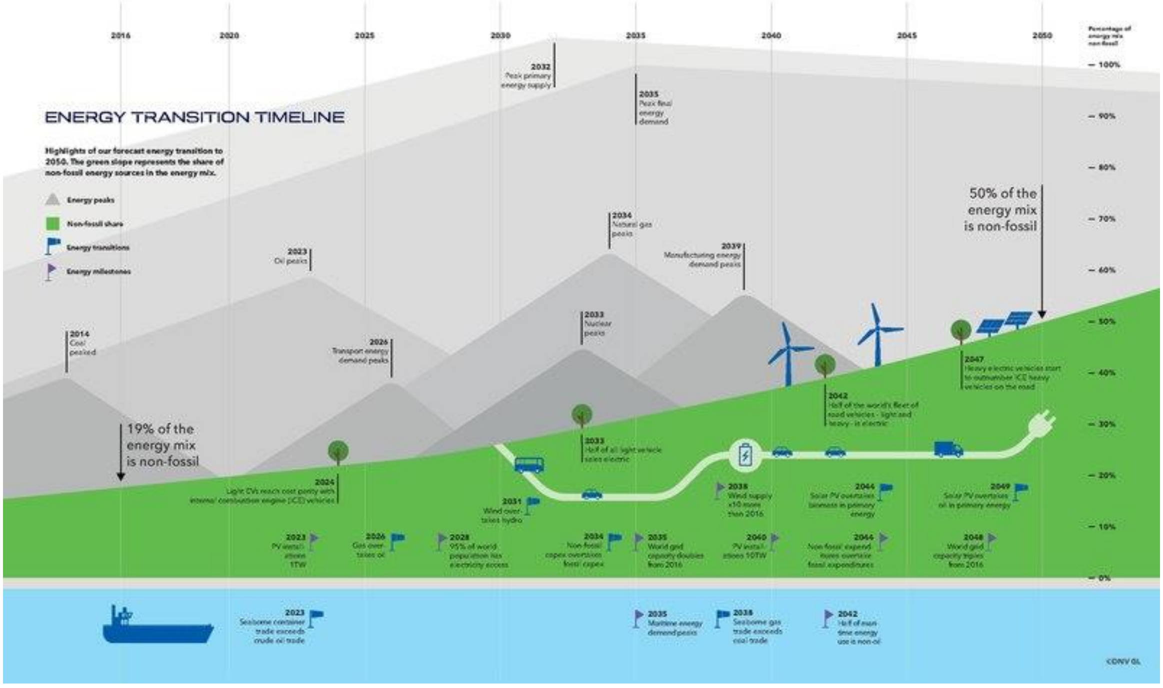
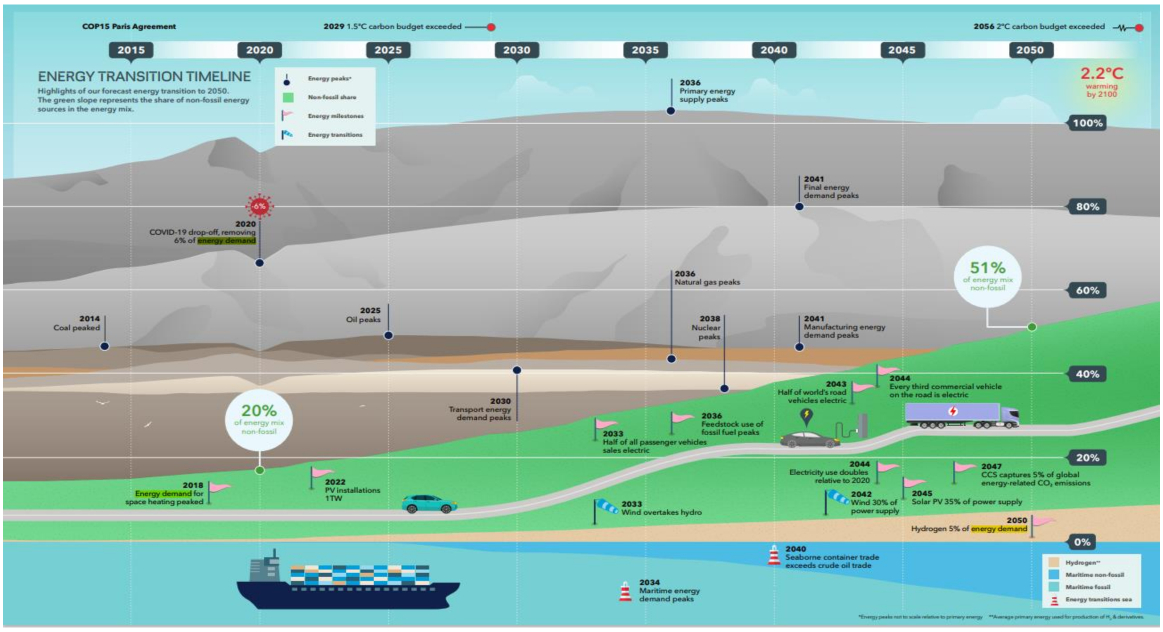
Appendix A – Energy transition timeline



Source: (DNV, 2020)



Source: (DNV, 2022)

Appendix B – Data collected

Energy balances - Source: (Eurostat, 2024a)

Time frequency	Energy balance	Standard international energy product classification (SIEC)	Unit of measure
Annual	Primary production	Total	Gigawatt-hour
Annual	Primary production	Solid fossil fuels	Gigawatt-hour
Annual	Primary production	Manufactured gases	Gigawatt-hour
Annual	Primary production	Peat and peat products	Gigawatt-hour
Annual	Primary production	Oil shale and oil sands	Gigawatt-hour
Annual	Primary production	Natural gas	Gigawatt-hour
Annual	Primary production	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Primary production	Renewables and biofuels	Gigawatt-hour
Annual	Primary production	Non-renewable waste	Gigawatt-hour
Annual	Primary production	Nuclear heat	Gigawatt-hour
Annual	Primary production	Electricity	Gigawatt-hour
Annual	Primary production	Heat	Gigawatt-hour
Annual	Recovered and recycled products	Total	Gigawatt-hour
Annual	Recovered and recycled products	Solid fossil fuels	Gigawatt-hour
Annual	Recovered and recycled products	Manufactured gases	Gigawatt-hour
Annual	Recovered and recycled products	Peat and peat products	Gigawatt-hour
Annual	Recovered and recycled products	Oil shale and oil sands	Gigawatt-hour
Annual	Recovered and recycled products	Natural gas	Gigawatt-hour
Annual	Recovered and recycled products	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Recovered and recycled products	Renewables and biofuels	Gigawatt-hour
Annual	Recovered and recycled products	Non-renewable waste	Gigawatt-hour
Annual	Recovered and recycled products	Nuclear heat	Gigawatt-hour
Annual	Recovered and recycled products	Electricity	Gigawatt-hour
Annual	Recovered and recycled products	Heat	Gigawatt-hour
Annual	Imports	Total	Gigawatt-hour
Annual	Imports	Solid fossil fuels	Gigawatt-hour
Annual	Imports	Manufactured gases	Gigawatt-hour
Annual	Imports	Peat and peat products	Gigawatt-hour
Annual	Imports	Oil shale and oil sands	Gigawatt-hour
Annual	Imports	Natural gas	Gigawatt-hour
Annual	Imports	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Imports	Renewables and biofuels	Gigawatt-hour
Annual	Imports	Non-renewable waste	Gigawatt-hour
Annual	Imports	Nuclear heat	Gigawatt-hour
Annual	Imports	Electricity	Gigawatt-hour
Annual	Imports	Heat	Gigawatt-hour
Annual	Exports	Total	Gigawatt-hour
Annual	Exports	Solid fossil fuels	Gigawatt-hour
Annual	Exports	Manufactured gases	Gigawatt-hour
Annual	Exports	Peat and peat products	Gigawatt-hour
Annual	Exports	Oil shale and oil sands	Gigawatt-hour
Annual	Exports	Natural gas	Gigawatt-hour
Annual	Exports	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Exports	Renewables and biofuels	Gigawatt-hour
Annual	Exports	Non-renewable waste	Gigawatt-hour
Annual	Exports	Nuclear heat	Gigawatt-hour
Annual	Exports	Electricity	Gigawatt-hour
Annual	Exports	Heat	Gigawatt-hour
Annual	Change in stock	Total	Gigawatt-hour
Annual	Change in stock	Solid fossil fuels	Gigawatt-hour
Annual	Change in stock	Manufactured gases	Gigawatt-hour
Annual	Change in stock	Peat and peat products	Gigawatt-hour
Annual	Change in stock	Oil shale and oil sands	Gigawatt-hour
Annual	Change in stock	Natural gas	Gigawatt-hour
Annual	Change in stock	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Change in stock	Renewables and biofuels	Gigawatt-hour
Annual	Change in stock	Non-renewable waste	Gigawatt-hour
Annual	Change in stock	Nuclear heat	Gigawatt-hour
Annual	Change in stock	Electricity	Gigawatt-hour
Annual	Change in stock	Heat	Gigawatt-hour
Annual	Gross available energy	Total	Gigawatt-hour
Annual	Gross available energy	Solid fossil fuels	Gigawatt-hour
Annual	Gross available energy	Manufactured gases	Gigawatt-hour
Annual	Gross available energy	Peat and peat products	Gigawatt-hour
Annual	Gross available energy	Oil shale and oil sands	Gigawatt-hour
Annual	Gross available energy	Natural gas	Gigawatt-hour
Annual	Gross available energy	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Gross available energy	Renewables and biofuels	Gigawatt-hour
Annual	Gross available energy	Non-renewable waste	Gigawatt-hour
Annual	Gross available energy	Nuclear heat	Gigawatt-hour
Annual	Gross available energy	Electricity	Gigawatt-hour
Annual	Gross available energy	Heat	Gigawatt-hour

(continued)

Time frequency	Energy balance	Standard international energy product classification (SIEC)	Unit of measure
Annual	International maritime bunkers	Total	Gigawatt-hour
Annual	International maritime bunkers	Solid fossil fuels	Gigawatt-hour
Annual	International maritime bunkers	Manufactured gases	Gigawatt-hour
Annual	International maritime bunkers	Peat and peat products	Gigawatt-hour
Annual	International maritime bunkers	Oil shale and oil sands	Gigawatt-hour
Annual	International maritime bunkers	Natural gas	Gigawatt-hour
Annual	International maritime bunkers	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	International maritime bunkers	Renewables and biofuels	Gigawatt-hour
Annual	International maritime bunkers	Non-renewable waste	Gigawatt-hour
Annual	International maritime bunkers	Nuclear heat	Gigawatt-hour
Annual	International maritime bunkers	Electricity	Gigawatt-hour
Annual	International maritime bunkers	Heat	Gigawatt-hour
Annual	Gross inland consumption	Total	Gigawatt-hour
Annual	Gross inland consumption	Solid fossil fuels	Gigawatt-hour
Annual	Gross inland consumption	Manufactured gases	Gigawatt-hour
Annual	Gross inland consumption	Peat and peat products	Gigawatt-hour
Annual	Gross inland consumption	Oil shale and oil sands	Gigawatt-hour
Annual	Gross inland consumption	Natural gas	Gigawatt-hour
Annual	Gross inland consumption	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Gross inland consumption	Renewables and biofuels	Gigawatt-hour
Annual	Gross inland consumption	Non-renewable waste	Gigawatt-hour
Annual	Gross inland consumption	Nuclear heat	Gigawatt-hour
Annual	Gross inland consumption	Electricity	Gigawatt-hour
Annual	Gross inland consumption	Heat	Gigawatt-hour
Annual	International aviation	Total	Gigawatt-hour
Annual	International aviation	Solid fossil fuels	Gigawatt-hour
Annual	International aviation	Manufactured gases	Gigawatt-hour
Annual	International aviation	Peat and peat products	Gigawatt-hour
Annual	International aviation	Oil shale and oil sands	Gigawatt-hour
Annual	International aviation	Natural gas	Gigawatt-hour
Annual	International aviation	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	International aviation	Renewables and biofuels	Gigawatt-hour
Annual	International aviation	Non-renewable waste	Gigawatt-hour
Annual	International aviation	Nuclear heat	Gigawatt-hour
Annual	International aviation	Electricity	Gigawatt-hour
Annual	International aviation	Heat	Gigawatt-hour
Annual	Total energy supply	Total	Gigawatt-hour
Annual	Total energy supply	Solid fossil fuels	Gigawatt-hour
Annual	Total energy supply	Manufactured gases	Gigawatt-hour
Annual	Total energy supply	Peat and peat products	Gigawatt-hour
Annual	Total energy supply	Oil shale and oil sands	Gigawatt-hour
Annual	Total energy supply	Natural gas	Gigawatt-hour
Annual	Total energy supply	Oil and petroleum products (excluding biofuel portion)	Gigawatt-hour
Annual	Total energy supply	Renewables and biofuels	Gigawatt-hour
Annual	Total energy supply	Non-renewable waste	Gigawatt-hour
Annual	Total energy supply	Nuclear heat	Gigawatt-hour
Annual	Total energy supply	Electricity	Gigawatt-hour
Annual	Total energy supply	Heat	Gigawatt-hour

GDP – Source:(Eurostat, 2024a)

eurostat

Gross domestic product (GDP) at current market prices by NUTS 2 regions [nama_10r_2gdp]

Open product page   Open in Data Browser

Description: -

Last update of data: 19/02/2024 23:00
Last change of data structure: 19/02/2024 23:00

Institutional source(s)

Eurostat

Contents	Time frequency	Unit of measure
Sheet 1	Annual	Million euro
Sheet 2	Annual	Euro per inhabitant
Sheet 3	Annual	Euro per inhabitant in percentage of the EU27 (from 2020) average
Sheet 4	Annual	Million units of national currency
Sheet 5	Annual	Million purchasing power standards (PPS, EU27 from 2020)
Sheet 6	Annual	Purchasing power standard (PPS, EU27 from 2020), per inhabitant
Sheet 7	Annual	Purchasing power standard (PPS, EU27 from 2020), per inhabitant in percentage of the EU27 (from 2020) average

Appendix C – fill in form

When filling in the input table below, please make sure to assume that ports are evolving toward the hydrogen-powered hub scenario:

2. Hydrogen-powered hub scenario

- Electrolysis facilities need to be scaled up to produce green hydrogen
- Hydrogen storage facilities
- Main challenges:
  - An extensive pipeline network needs to be rolled out
  - Storage and handling need specific safety measures: ventilation and safety protocols
  - High initial costs for the production of green hydrogen because of the energy intensity

Input table

Importance ranking: How important is every objective (apart from switching to a hydrogen-powered hub scenario?

1. very unimportant
2. unimportant
3. neutral
4. important
5. very important

Success ranking: To what extent does implementing more sustainable energy flows in your port contribute to achieving this goal?

1. not at all successful
2. unsuccessful
3. neutral
4. successful
5. very successful

Port Objectives	Importance ranking	Success ranking
Environmental stewardship		
Sustainable infrastructure		
Resource management		
Economic competitiveness		
Operational efficiency		
Regulatory compliance		
Innovative leadership		
Community engagement		
Communication and marketing		
Safety and security		

More info about the objectives:

Environmental Stewardship: Protecting port ecosystems, complying with regulations, and controlling pollution.

Sustainable Infrastructure: Building and managing infrastructure with a focus on sustainability and efficiency.

Resource Management: Managing resources, including energy, for sustainability and reducing dependence on fossil fuels.

Economic Competitiveness: Enhancing the port's competitive position, attracting sustainable businesses and industries.

Operational Efficiency: Minimizing operational impacts, improving energy efficiency, and optimizing processes.

Regulatory Compliance: Adhering to national and international environmental regulations and standards.

Innovative Leadership: Spearheading technological advancements and driving the development and adoption of renewable energy technologies to maintain a leading role in environmental sustainability within the port industry.

Community Engagement: Involving stakeholders, increasing environmental awareness, and encouraging sustainable practices.

Communication and Marketing: Sharing information on environmental measures, enhancing the visibility of green initiatives, and positioning as a green port.

Safety and security: Ensuring the well-being of personnel and maintaining a secure working environment

Appendix D – H-index

^2 objective relevance

	1	2	3	4	5	
Environmental stewardship	0	0	0	0.14793	0.3787	0.53
Sustainable infrastructure	0	0	0.05325	0.09467	0.21302	0.36
Resource management	0	0	0.02367	0.21302	0.14793	0.38
Economic competitiveness	0	0	0	0.00592	0.85207	0.86
Operational efficiency	0	0	0.02367	0.09467	0.28994	0.41
Regulatory compliance	0	0	0	0.21302	0.28994	0.50
Innovative leadership	0	0.00592	0.09467	0.05325	0.14793	0.30
Community engagement	0	0	0.05325	0.05325	0.28994	0.40
Communication and marketing	0	0	0.00592	0.3787	0.09467	0.48
Safety and security	0	0	0.00592	0.02367	0.59172	0.62

^2 success relevance

	1	2	3	4	5	
Environmental stewardship	0	0.00592	0.02367	0.14793	0.14793	0.325443787
Sustainable infrastructure	0	0.00592	0.14793	0.14793	0.02367	0.325443787
Resource management	0	0	0.09467	0.09467	0.14793	0.337278107
Economic competitiveness	0	0	0.02367	0.14793	0.21302	0.384615385
Operational efficiency	0	0.02367	0	0.47929	0.02367	0.526627219
Regulatory compliance	0	0.02367	0.09467	0.09467	0.05325	0.266272189
Innovative leadership	0.00592	0	0.21302	0.05325	0.05325	0.325443787
Community engagement	0	0.00592	0.02367	0.21302	0.09467	0.337278107
Communication and marketing	0	0	0.14793	0.21302	0.02367	0.384615385
Safety and security	0.00592	0	0.05325	0.09467	0.14793	0.301775148

	H-index relevance	H-index success ranking
Environmental stewardship	41%	16%
Sustainable infrastructure	20%	16%
Resource management	23%	17%
Economic competitiveness	82%	23%
Operational efficiency	26%	41%
Regulatory compliance	38%	8%
Innovative leadership	13%	16%
Community engagement	25%	17%
Communication and marketing	35%	23%
Safety and security	53%	13%

H-waardes	0.20
	0.80

Appendix E – Wilcoxon rank test

Importance ranking

	Median
Environmental stewardship	**5**
Sustainable infrastructure	**4**
Resource management	**4**
Economic competitiveness	**5**
Operational efficiency	**5**
Regulatory compliance	**5**
Innovative leadership	**4**
Community engagement	**5**
Communication and marketing	**4**
Safety and security	**5**

Difference	Abs. Diff.	Ranking
1	1	4
0	0	0
0	0	0
1	1	4
1	1	4
1	1	4
1	1	4
1	1	4
0	0	0
1	1	4

Succes ranking

	Median
Environmental stewardship	**4**
Sustainable infrastructure	**4**
Resource management	**4**
Economic competitiveness	**4**
Operational efficiency	**4**
Regulatory compliance	**4**
Innovative leadership	**3**
Community engagement	**4**
Communication and marketing	**4**
Safety and security	**4**

alpha	**0.01**
T-	**0**
T+	**28**
Wstat	**0**
Wcrit	**9**
n	**13**

H0: Mimp =Msucc
H1: Mimp/= Msucc

Appendix F – Wilcoxon rank test (N&S)

Importance (N&S)

diff	abs diff	value
0	0	
-2	2	3.5
0	0	
0	0	
-2	2	3.5
1	1	1
-2	2	3.5
-2	2	3.5
0	0	
0	0	

alpha	**0.01**
T-	**1**
T+	**14**
Wstat	**1**
Wcrit	**9**
n	**13**
p	**0.125**

H0: Mimp =Msucc
H1: Mimp/= Msucc

Success (N&S)

diff	abs diff	value
-1	1	3.5
-1	1	3.5
1	1	3.5
-2	2	7
0	0	
-1	1	3.5
0	0	
0	0	
-1	1	3.5
-1	1	3.5

alpha	**0.01**
T-	**24.5**
T+	**3.5**
Wstat	**3.5**
Wcrit	**9**
n	**13**
p	**0.078**

H0: Mimp =Msucc
H1: Mimp/= Msucc