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DECISION-MAKING AND LOGISTICS FOR ENERGY-RELATED LIQUID BULK WITHIN THE PORT

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Abstract

The energy transition is reshaping global trade flows, introducing uncertainty into energy-related liquid bulk logistics, particularly within ports. Despite the significance of liquid bulk in global supply chains, existing port choice models are primarily developed for containerized cargo. This study investigates the key determinants of decision-making in liquid bulk logistics within the context of sustainability transitions. Using a multi-case study approach, including stakeholder interviews and qualitative analysis, we identify factors shaping infrastructure planning, port selection, storage, and transportation modes. The findings reveal that logistical choices in liquid bulk are highly interdependent, shaped by supply chain structures, stakeholder dynamics, and regulatory frameworks. As ports might evolve into multi-energy hubs, new actors and uncertainties emerge, particularly regarding the role of hydrogen and biofuels. Understanding these evolving dynamics is crucial for optimizing logistics strategies and ensuring efficient, sustainable energy supply chains.

1. Introduction

The global energy transition is reshaping trade flows, leading to significant uncertainty in liquid bulk The global energy transition is reshaping trade flows, leading to significant uncertainty in liquid bulk logistics, particularly within ports and their hinterlands [1],[2], [3]. As energy demand shifts and uncertainty about the liquid bulk flow grows, long-term infrastructure planning becomes increasingly complex.

Traditionally, port choice models have analyzed cargo flows based on factors such as cost, transit time, and service quality [4], [5], [6]. However, most studies focus on containerized cargo, while liquid bulk logistics remain underexplored. Unlike containers, liquid bulk consists of raw materials such as crude oil, refined petroleum products, and biofuels, which are deeply intertwined with global trade and energy markets [7]. The decision-making processes governing liquid bulk flows, particularly in the context of the energy transition, require further investigation.

Faced with increasing pressure to reduce emissions and adapt to shifting energy demands, ports, as crucial hubs in energy supply chains, must navigate these changes while balancing efficiency and sustainability [8]. While green port initiatives focus on improving efficiency and adopting alternative fuels [9], most research remains limited to port operations rather than their broader impact on the industries they facilitate. A more comprehensive understanding of how sustainability developments shape liquid bulk logistics is essential for developing effective capacity distribution analysis.

This study aims to bridge these gaps by examining the key factors shaping decision-making in liquid bulk logistics and assessing how sustainability considerations influence these processes. The central research question is: What are the key determinants driving the port-related logistics of present and future energy-related liquid bulk?

Understanding these determinants is essential for multiple reasons. From a societal perspective, identifying key stakeholders and their roles enhances coordination and accountability, ensuring that the right actors are involved in shaping sustainable logistics solutions. For industry, insights into evolving trade flows and infrastructure needs are valuable for transport and infrastructure managers, helping them anticipate future demands and optimize capacity planning. Scientifically, this research fills a critical gap in the literature by examining the interaction between decisionmaking, logistics processes, and sustainability in liquid bulk supply chains, offering new perspectives on an evolving sector.

The subsequent structure of this paper is as follows: Initially, Chapter 2 delves into the relevant literature concerning energy-related liquid bulk and port logistics. Subsequently, the employed methodology is explained in Chapter 3. Thereafter, the findings of the existing logistical chain are examined in Chapter 4, while Chapter 5 addresses the projections for the future logistics chain. Finally, a comprehensive discussion along with the conclusions is discussed in Chapters 6 and 7.

2. Modeling SU and IRI

Seaports constitute a fundamental component of the global transportation infrastructure, playing a pivotal role in international trade by connecting maritime routes with inland transportation networks [10]. In historical contexts, seaports functioned as isolated nodes for the entry and exit of goods. However, in contemporary settings, they have evolved into vital elements of complex supply chain networks that extend across continents [11], [12], [13], [10].

2.1 The Liquid Bulk Sector: Trends, Challenges, and Market Dynamics

The liquid bulk sector, distinguished by materials transported in tanks and handled by specialized pumping systems, is a critical segment of global maritime trade. It accounts for approximately one-third of global shipping volumes [14], [15]. This sector includes energy-related liquids such as LNG, petroleum products, and crude oil [14], [15]. Among these, crude oil dominates, with about 59% of global oil production being transported by sea [14], [16]. This underlines the vital role of maritime transport in global energy security and economic activities [14], [16]. The oil transportation industry is characterized by its high mobility, ease of market entry, fragmentation, and the homogeneity of tanker technology, which influences freight rates and market dynamics [14].

Liquid bulk volumes have seen fluctuations influenced by geopolitical factors, economic growth, and energy transitions [16]. In 2024 and 2025, maritime gas trade is expected to outpace oil trade growth [17]. Both gas and oil ton-miles are likely to increase due to rerouting caused by disruptions in key transit routes like the Panama Canal and Suez Canal [17]. Simultaneously, stricter environmental regulations are reshaping the sector [17]. Measures such as double-hulled tankers, cleaner fuel technologies, and policies like the EU Emissions Trading Scheme (ETS) and IMO's Energy Efficiency Existing Ship Index (EEXI) aim to reduce emissions but require substantial investment, affecting operational costs and market competitiveness [18], [19], [20]. As sustainability goals drive change, the sector face the challenge to balance economic feasibility with the need for lower emissions and alternative fuel adoption.

The oil supply chain is conventionally divided into three categories: upstream, midstream, and downstream [21], [22]. The upstream segment involves exploration and extraction, where crude oil is recovered through drilling techniques and transported via pipelines or tankers [23], [21], [22], [24]. In the midstream phase, crude oil is moved to refineries or storage facilities, where it undergoes initial processing to remove impurities and stabilize its composition [23], [21], [22], [24]. The downstream segment includes refining, where crude oil is transformed into various petroleum products through distillation and chemical processing, followed by distribution to end-users through pipelines, ships, and terminals [23], [21], [22] [24]. LNG logistics involves different steps, including liquefaction, cryogenic transport, and regasification [25] [26], [27]. The transition toward biofuels and hydrogen introduces new challenges, necessitating specialized infrastructure and handling procedures to ensure efficient and sustainable energy flows [28].

Port choice modeling is a critical component of freight transport analysis, reflecting broader supply chain decision-making rather than isolated port selection [6], [4]. From the perspective of shippers, factors influencing port choice are based on cost, efficiency, and connectivity [4]. This encompass both qualitative aspects, such as service quality and reputation, and quantitative components, including freight rates, transit time, and hinterland accessibility [4]. O'Connor et al. (2020) advanced the research by integrating AIS data for the evaluation of congestion impacts, thereby clarifying the influence of hinterland connectivity as a factor [29]. Port and terminal choice differ in influencing factors, with terminal efficiency and handling costs playing a more significant role in terminal choice [30], [31].

While much of the existing research on port choice focuses on developed regions, studies in emerging markets reveal additional factors influencing decision-making. Souza et al. (2021) highlighted the significance of taxation and cargo theft in Brazil, alongside more common considerations such as hinterland connectivity [32]. Similarly but also differentiating in the cargo type, Tapia et al. (2019) examined soy export logistics in Argentina, incorporating mode choice and emphasizing the relevance of Free Alongside Ship (FAS) pricing in their model [33]. The modelling of port choice illustrates the complex nature of the global freight system, wherein regional determinants, variations in cargo type, and dynamics of Theo supply chain influence the decision-making process.

2.2 Port Dynamics and Energy transition

The global reliance on fossil fuels has led to significant environmental challenges, prompting a shift towards cleaner energy alternatives, such as biofuels, hydrogen, and renewable energy sources (RES), to align with the Paris Agreement's climate goals [34], [35], [36]. Biofuels obtained from biomass, such as biodiesel and bioethanol, are essential contributors to this transition. Moreover, hydrogen, when produced from renewable sources, is increasingly recognized as a potential clean energy carrier [37], [38]. Despite these advances, uncertainties in hydrogen's growth remain, with challenges in scaling infrastructure and technology diffusion [39]. Meanwhile, the renewable energy sector is expanding rapidly, offering both opportunities and challenges, particularly in emerging economies [40].

Ports, as vital logistics centers, are increasingly central to the energy transition. They are shifting from traditional transport roles to complex energy hubs involved in the transport, transformation, and generation of energy [9], [41]. The integration of renewable energy and alternative fuels such as hydrogen and biofuels into port operations is critical for enhancing sustainability and reducing carbon emissions [8], [42]. As ports evolve, new infrastructure for energy storage and distribution is required, alongside strategies to optimize energy management [43]. Studies on hydrogen infrastructure emphasize the need for strategic planning and robust frameworks to facilitate smooth integration into port logistics [44], [45].

The energy-related liquid bulk sector within ports involves a diverse range of stakeholders, each playing a unique role in the complex logistics chain. Port authorities, once primarily focused on managing infrastructure and ensuring safety, have transformed into more dynamic entities [46]. These authorities now engage with a variety of stakeholders, from private companies to government agencies, to address the multifaceted challenges of modern maritime logistics [46], [47]. At the heart of port operations, terminal and storage operators manage the complex processes of cargo handling, which require specialized infrastructure and equipment [9]. These operators ensure the efficient transfer of goods between ships and shore, coordinating with various stakeholders to keep the logistics process running smoothly [9].

Logistics service providers oversee the entire or parts of the supply chain process, integrating transport, storage, and distribution to enhance coordination and sustainability across various stages of logistics [48]. Energy companies, especially the major oil and gas firms, play an integral role in both traditional energy operations and the ongoing transition to renewable energy, helping to meet the growing demand for cleaner energy solutions [49]. Commodity traders play an essential role in optimizing the transformation of raw materials and managing the flow of energy-related products, leveraging their expertise in identifying opportunities for spatial, temporal, and processing arbitrage [7], [50]. Additionally, various Directorates-General from the European Commission, national ministries, and regional and local authorities all play their part in regulating, guiding, and supporting this sector [51], [52]. Together, these stakeholders navigate the complexities of managing energy-related liquid bulk in ports.

2.3 Case Study

Research on port choice models for liquid bulk remains limited, with a particular gap in understanding the role of governance structures and actor interactions. Addressing this gap requires a deeper examination of the decision-making processes in liquid bulk logistics. Therefore, a case study methodology is adopted, as detailed in section 3, to analyze the European liquid bulk sector and its evolving dynamics.

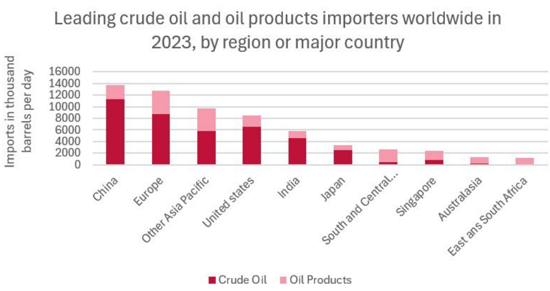


Fig.1: Import Oil based on [53]

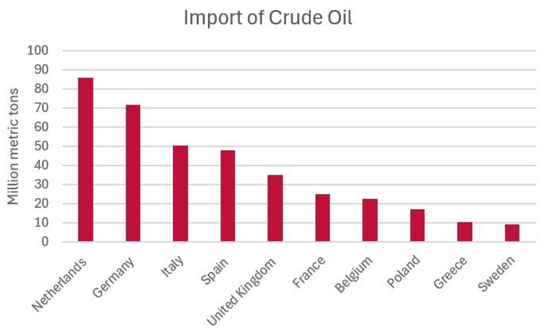


Fig.2: Import Crude Oil EU based on [54]

Europe is the second-largest importer of crude oil and petroleum products, with total EU imports reaching 479.6 million metric tons in 2023 worldwide [54]. The Netherlands, as the leading EU importer, accounted for 86.07 billion metric tons [53]. The ARA (Amsterdam-RotterdamAntwerp) region plays a central role, with Rotterdam recognized as the primary hub for liquid bulk throughput [55]. Additionally, the region is a focal point for hydrogen initiatives, with ports such as Rotterdam, Antwerp, and Groningen Seaport striving to become future hydrogen hubs [56], [57], [58]. However, delays in these projects create both opportunities and uncertainties, making the ARA region an ideal case study for examining the interplay of trade patterns, governance structures, and the ongoing energy transition.

3. Method

This research utilizes a multiple case study methodology to analyze the liquid bulk logistics chain. Through the integration of qualitative research techniques, including interviews, stakeholder analysis, and literature study, the study investigates interactions, decision-making processes, and the effects of the energy transition on port logistics.

A multiple case study design was chosen to provide a comprehensive understanding of the logistics chain, where each stakeholder interview represents a distinct case, allowing for comparative analysis and pattern identification. Considering each stakeholder interview as an individual case aligns with the replication logic articulated by Yin (2009) [59]. Stakeholders were selected based on the literature study.

Semi-structured interviews were used to collect primary data. Semi-structured interviews allow for flexibility in exploring themes while ensuring consistency across respondents [60]. Interview questions were developed based on gaps identified in the literature. The process of conducting semi-structured interviews is consisting of six distinct steps: selecting stakeholders, designing the interview structure, conducting interviews, summarizing and verifying responses, and analyzing the collected data [60], [61]. A visual tool was developed to facilitate discussion and improve data reliability.

The use of visualization is a known technique in qualitative research, where it has been utilized for generating data, analyzing findings, and sharing knowledge [62]. Visual methods allow abstract concepts to become more tangible, fostering deeper insights and understanding [63]. Given the absence of an existing tool tailored to this case, a new tool was designed featuring icons representing the processes in the logistics chain of energy-related liquid bulk, based on literature findings. The tool includes icons for all transportation modes except air transport, which was deemed irrelevant to this logistics chain, along with blank squares for interviewees to add additional elements. A key advantage of this tool is its ability to address inconsistencies in terminology. This challenge has been identified in the literature, where different terms are used for the same processes. By relying on visual representations, interviewees clarify the meaning of icons or request general icons for specific processes, ensuring consistency across interviews and improving the reliability of findings.

Lastly, a stakeholder analysis is conducted to gain insights into the participants in the energyrelated liquid bulk logistics chain, focusing on their actions, goals, relationships, and priorities. Stakeholders are broadly defined as individuals, groups, organizations, institutions, or even the natural environment that may have an impact or interest in the system [64]. The analysis employs a Power-interest grid, where stakeholders are categorized based on their interest in the logistics system and their capacity to affect events. Through the categorization of stakeholders based on their power and interest, this approach facilitates the identification of individuals and entities with substantial influence on decision-making, as well as those significantly impacted by alterations within the logistics chain. Consequently, it provides a thorough perspective on their roles and interactions [65].

4. Current logistic Chain of Energy related liquid bulk

Figure 3 illustrates the logistics chain for energy-related liquid bulk, developed from a combination of interviews and literature. The legend in the bottom left of the figure provides definitions for the icons, most of which were identified early on. There is the addition of a blending icon based on feedback from interviewees who emphasized its importance. Although the study focuses on port processes, earlier stages of the logistics chain are also included due to their strong interconnections and impact on port activities.

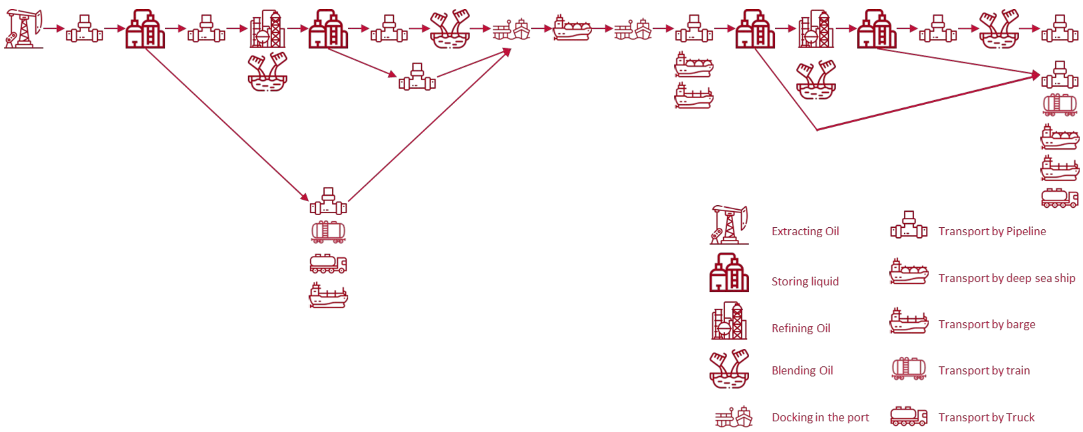


Fig.3: Current Liquid Bulk energy related Logistic Chain

The illustrated logistics chain corresponds with established logistic chain models present in the literature. Firgure 3 incorporates differentiations such as the inclusion of recurrent processes, the blending procedure, and the flexibility in the refinement operation locations. While conventional literature typically situates refining at the destination port, the interviews disclosed that refining may occur at various points along the chain. Additionally, interviews identified a trend towards earlier refining. This trend is motivated by the increasing value of refined products and the impact of varying sustainability policies across regions. Consequently, refining occurs in areas with more favorable regulations.

4.1 Choices in the current logistic chain

The logistics chain has evolved through past decisions that continue to shape its efficiency and flexibility. Understanding these choices is crucial for optimizing operations and making informed future decisions.

Refinery and storage locations Choice Refinery and storage locations are determined by logistical efficiency, regulatory constraints, and supply chain interdependencies. Given the close ties between refineries and storage facilities, their placement is typically considered together. The location selection balances access to multimodal transport infrastructure and distance to production and consumption hubs. Storage near refineries enhances supply chain efficiency, ensuring a steady supply of raw materials and uninterrupted operations.

The location decisions are also influenced by zoning regulations and environmental permits mandated by local authorities. Companies leasing land from port authorities must comply with predefined zoning plans, potentially requiring municipal or provincial approval for modifications. Citizen participation is increasingly impacting these procedures. In addition to regulatory and strategic considerations, the location decisions for refineries and storage facilities are also influenced by the high interdependency and long-lasting relationships within the supply chain. Companies in logistics, terminals, and storage sectors frequently align with the requirements and preferences of their clients, establishing infrastructure in locations that favor their partners.

Refining and Blending Choice When and where to Refining and blending depend on product owners, typically energy majors or traders, who are constrained by available refining and blending facilities within the supply chain. Blending is often postponed to maintain flexibility in meeting regional fuel specifications. Some logistics and storage operators integrate refining steps into their services, enhancing efficiency and creating optimization opportunities.

Port Choice The selection of ports represents a dynamic decision-making process influenced by market conditions, infrastructure, and geography. Within the spot market, oil is allocated to the highest bidder, whereas long-term contracts facilitate stable supply arrangements. Ownership may be transferred during transit, permitting redirection in response to market fluctuations. Furthermore, infrastructure constitutes a crucial determinant, as not all ports possess the specialized facilities necessary for managing liquid bulk. Geographical constraints also play a role in port selection. Coastal ports with fewer proximate urban areas are favored for safety considerations, while inland ports are subject to more stringent regulatory measures and environmental considerations.

Storage Choice Storage serves to balance supply and demand over time. The decision on location and time period is influenced by market conditions and available capacity. Cargo owners determine storage duration and location based on strategic objectives, utilizing a mix of long-term contracts and spot agreements to optimize flexibility and cost-efficiency.

Mode Choice Transport mode selection depends on cargo volume, infrastructure availability, and cost efficiency. Pipelines are preferred for large volumes due to their efficiency, while other modes such as tankers, rail, or trucks are used where pipelines are unavailable. In some cases, transport options are limited by infrastructure constraints, making availability a primary determinant in decision-making.

Overall, the logistics chain is shaped by an interplay of strategic, regulatory, and operational factors, where decisions at each stage influence supply chain efficiency and flexibility.

4.2 PI Grid

The energy-related liquid bulk logistics chain is characterized by its complexity and the involvement of multiple stakeholders. To systematically analyze their roles, interactions, and influence, a PI grid has been developed shown in firgure 4. This framework provides insights into decision-making processes, dependencies, and the power dynamics within the logistics network.

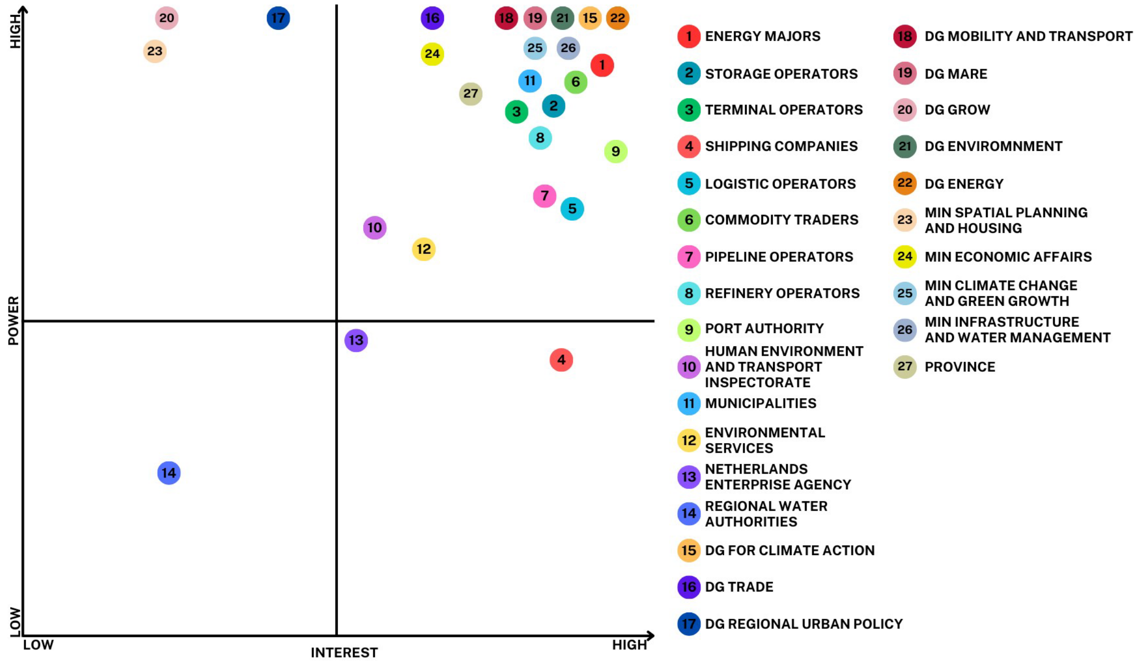


Fig.4: PI Grid

The first group, stakeholders with low interest and low power, primarily consists of regional water authorities responsible for maintaining water quality and safety. While they regulate waterways used for transport, their direct involvement in logistical decisions is minimal. Conversely, actors with high interest but low power, such as shipping companies and the Netherlands Enterprise Agency (RVO), closely monitor developments in the sector. Shipping companies own and operate tankers but rely on energy majors and traders for contracts. Similarly, RVO, focused on sustainable economic growth, ensures regulatory compliance despite its limited direct influence over logistics decisions.

The third category includes stakeholders with high power but low interest, such as DG Mare, the Ministry of Spatial Planning and Housing, and the DG Regional Urban Policy. These entities have the authority to implement policies that may impact the logistics chain; however, their primary responsibilities lie elsewhere. Maintaining engagement with these actors is essential to prevent unintended disruptions arising from policy changes. The most influential group consists of those with both high power and high interest, including various Directorates-General, ministries, and energy majors. These stakeholders shape logistics through policymaking, regulation, and financial investments. Energy majors exert substantial influence due to their economic stakes and lobbying activities, directly affecting logistical decision-making.

Additional stakeholder such as storage operators, terminal operators, refinery operators, and commodity traders, possess high interest but varying degrees of power. They maintain operational independence while collaborating closely with energy majors to ensure alignment with market demands. Traders, in particular, play an increasing role due to vertical integration strategies that expand their control within the supply chain. The port authority also holds significant influence, although constrained by municipal decisions. Its role is primarily facilitative, responding to market and regulatory demands rather than dictating them. In contrast, municipal governments wield considerable power, balancing economic, environmental, and social factors to optimize urban development. Pipeline and logistics operators similarly exhibit varying levels of power, with pipeline operators often holding monopolistic control over the infrastructure, while logistics operators gain leverage through vertical integration. Regulatory bodies, such as environmental agencies and transport inspections, have limited direct power but play a crucial role in ensuring compliance and shaping regulatory frameworks. Their oversight remains integral to maintaining a functional and sustainable logistics network.

5. Future logistic Chain of Energy related liquid bulk

The future of energy-related liquid bulk remains uncertain, with different groups envisioning distinct dominant energy carriers. Some emphasize hydrogen as the primary future energy source, while others prioritize biofuels. Additionally, smaller alternative liquid energy sources and wind energy in logistics are recognized by certain stakeholders. This study only examines hydrogen and biofuels as primary liquid energy carriers, comparing the emerging supply chains, actor fields, and uncertainties.

5.1 Logistic Chain

To gain a comprehensive understanding of critical decisions and their variations, the logistics chains of hydrogen and biofuels must be outlined.

Hydrogen Logistic Chain The future hydrogen logistics chain differs from the current oil logistics chain in some steps, as can be seen in figure 5. Hydrogen production begins with renewable energy sources, such as wind turbines or solar panels, and the utilization of an electrolyzer. The produced hydrogen is transported as liquid hydrogen under extremely low temperatures and pressures or chemically bound to a carrier. Transportation requires specialized ships and pipelines. Upon arrival at a port, hydrogen can either be transported inland while still attached to the carrier or converted into a gaseous form for grid injection.

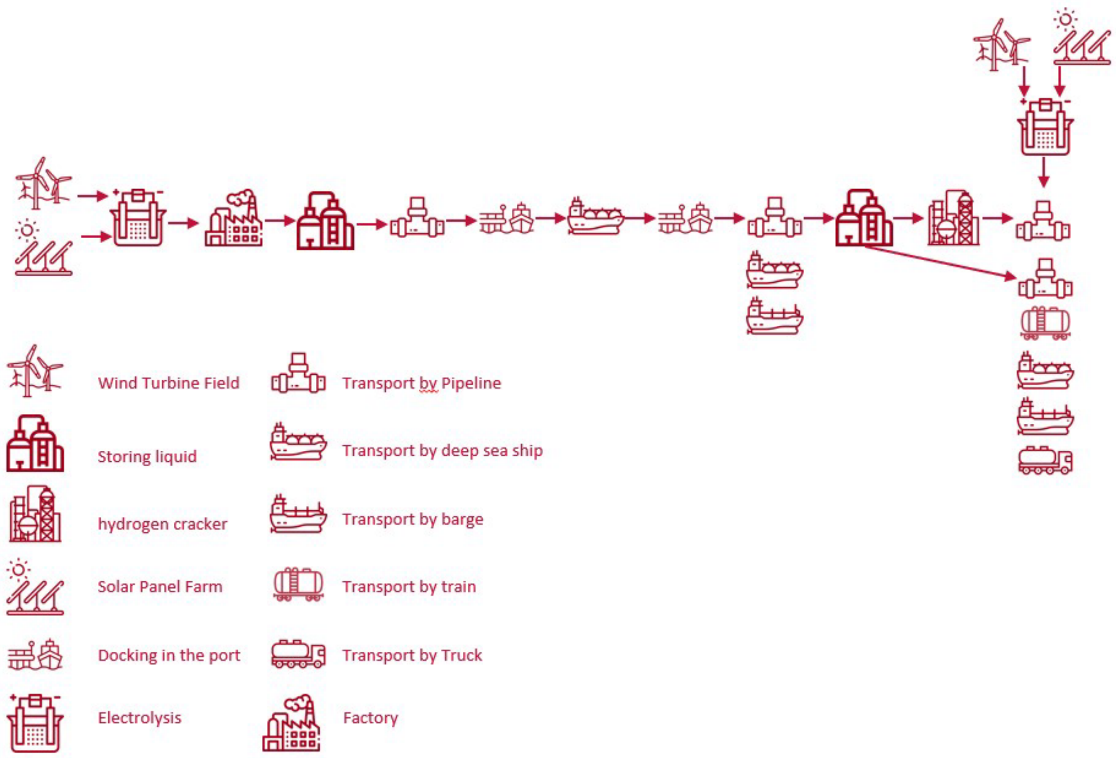


Fig.5: Hydrogen Logistic Chain

Biofuels Logistic Chain Compared to hydrogen, biofuels require fewer new technologies and infrastructure.The logistic chain of biofuels is shown int figure 6. Biofuels are derived from renewable resources such as plant-based materials or waste. These resources are stored and transported similarly to bulk transportation currently. Post-refinement, biofuels follow traditional crude oil logistics, utilizing existing pipelines, ships, and storage facilities, reducing the need for extensive new infrastructure.

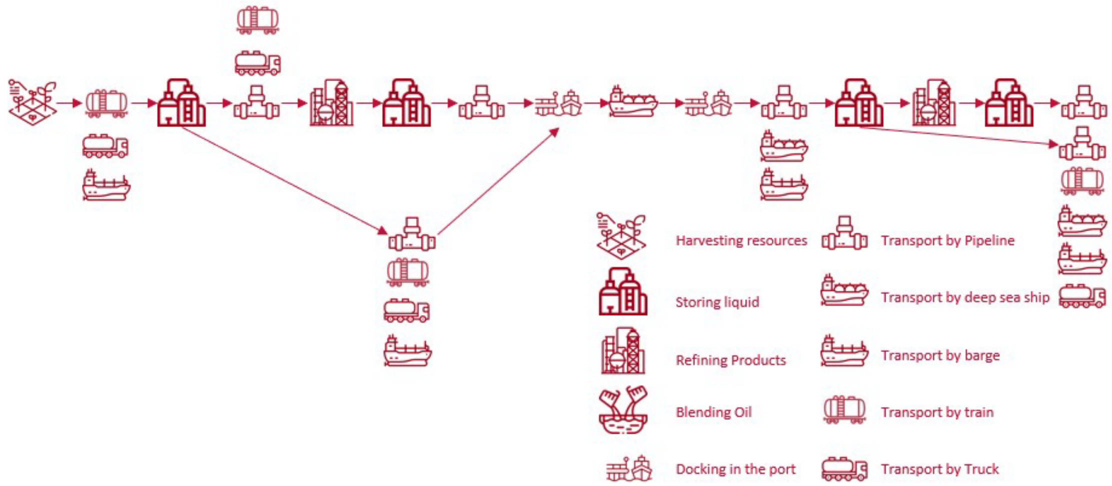


Fig.6: BioFuels Logistic Chain

5.2 Choices

Examining the two future supply chains reveals similarities, but also requires new decisions.

Energy Carrier and Biofuel Type Choice This decision-making category is distinct from conventional fuel logistic decisions. Within the hydrogen supply chain, transport methods vary significantly; hydrogen may be conveyed as pure liquid hydrogen or attached to a carrier, each impacting the logistical framework. The choice of carrier directly affects required port facilities and infrastructure investments. Additionally, the choice of biofuel feedstock must be made, as different raw materials influence production and overall supply chain logistics. While this decision may have a smaller impact on infrastructure needs compared to the differences between hydrogen carriers, it remains an essential decision in biofuel logistics.

Industry Location Choice Similar to crude oil, biofuels are expected to be processed in existing facilities. Since they do not require new infrastructure or introduce additional risks, they can integrate into established industrial locations. Some hydrogen carriers can follow this approach, but others, like ammonia, present safety concerns. The presence of residential areas in ports complicates decision-making, necessitating careful consideration of storage and transport risks.

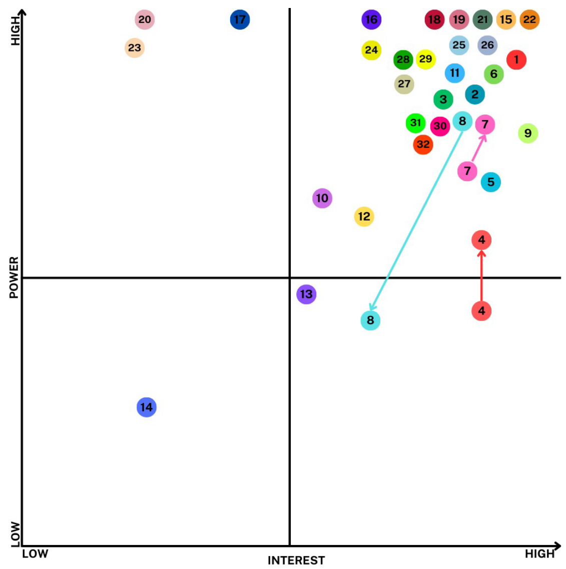
Refining / Cracking / Dehydrogenation Choice This choice is expected to resemble decisions in the oil sector. A market for hydrogen is anticipated, similar to the current oil market, where supply and demand dictate this decision. Initially, decisions may be constrained by available facilities, but ultimately, traders and energy majors will drive the process.

Port Choice Port selection remains crucial in energy logistics. Import locations are influenced by supply and demand, available infrastructure, and policy measures. The existing logistics chain is largely dictated by energy majors and commodity owners, and this trend is expected to continue.

Mode Choice Mode choice will remain largely the same as in the current liquid logistics chain, except that for hydrogen, the available options depend on the chosen carrier. Due to the composition of certain carriers, some transport modes may not be suitable. This highlights how interdependent the chain's decisions are, starting with the initial choice of carrier or feedstock.

5.3 Stakeholder Landscape

The transition to hydrogen and biofuels will shift the roles of stakeholders in energy-related liquid bulk, this is highlighted in Figure 7 Figure 8, Figure 9 and Figure 10. Hydrogen will require new actors such as electrolysis operators, hydrogen cracker operators, and dehydrogenation plant operators, this will reduce the role of refinery operators. Renewable energy park operators may also gain influence in hydrogen production. Shipping companies and pipeline operators are expected to see increased importance due to the expected increasing demand for these transport modes. In contrast, the biofuel supply chain will remain more similar to existing logistics, with the addition of feedstock providers as stakeholders.



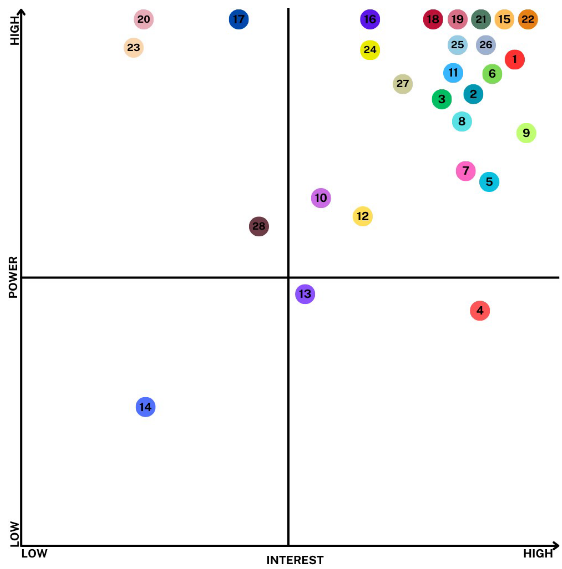


Fig.7: Hydrogen PI-Grid

Fig.8: Biofuels PI-Grid

Fig.9: Stakeholders Hydrogen

Fig.10: Stakeholders Biofuels

5.4 Uncertainties

The transition towards future energy scenarios introduces several uncertainties that influence stakeholder decisions throughout the supply chain. These uncertainties impact various aspects of the energy landscape, and understanding them is essential for navigating the evolving market. Nine uncertainties, identified through interviews, provide insight into how stakeholders perceive and address challenges in the transition.

The most significant uncertainties identified are Capital Investment and Market Demand. With Market Demand ranked as the most critical by some stakeholders. This relationship between capital investment and market demand highlights the interdependence between securing financial resources for infrastructure and ensuring sufficient demand for new energy products. The viability of the transition depends partly on these two factors.

Political Stability is also a concern, emphasized by stakeholders for its role in ensuring a predictable regulatory environment. Without stable politics, businesses face the risk of sudden policy changes that could disrupt long-term planning. While other uncertainties, such as Permitting and Competitive Position, are mentioned but rank lower in importance, they remain relevant in the broader context of market dynamics and regulatory approval processes.

Finally, uncertainties like Safety, Raw Materials availability, Geopolitical Tensions, and Interdependency are recognized but are considered secondary to the primary concerns of Capital Investment and Market Demand. These factors, though important, are viewed as less pressing in comparison, suggesting that stakeholders prioritize financial and market-related uncertainties when making strategic decisions in the transition to new energy systems.

6. Conclusion

Bringing these findings together, the key determinants driving port-related logistics for present and future energy-related liquid bulk are a combination of market forces, infrastructure availability, regulatory conditions, and stakeholder dynamics. Historically, port logistics have been shaped by geographical positioning, infrastructure capacity, regulatory frameworks, and long-term business relationships. The development of chemical clusters and vertical integration strategies has further reinforced logistical patterns by creating synergies between storage, transport, and processing.

Looking ahead, the energy transition introduces new uncertainties and infrastructure demands. Market demand remains a major factor, with hydrogen and biofuels requiring significant capital investment while facing uncertain adoption rates. Political stability, permitting challenges, and geopolitical tensions further complicate long-term decision-making. The role of the stakeholders is evolving, with new players such as hydrogen cracking operators and renewable energy producers gaining influence, while traditional energy majors and traders must adapt to remain competitive.

The future logistics of energy-related liquid bulk will depend on the energy carriers adopted, leading to new infrastructure needs, including hydrogen cracking units, dehydrogenation facilities, and carbon capture systems. Ports will also require specialized docking connections and pipeline adaptations. While these developments introduce complexity, they also build upon existing logistical foundations, enabling a more structured transition.

Ultimately, the evolution of port logistics is shaped by the interplay between private sector investment and port authorities' facilitation. While companies are responsible for adapting their facilities, port authorities play a crucial role in fostering collaboration and ensuring infrastructure aligns with industry needs. The transition may also redefine port functions, with some maintaining industrial processing roles while others shift towards import-export hubs. This transformation will reshape trade flows, supply chain structures, and the balance of power among stakeholders in the logistics chain of energy-related liquid bulk.

7 Discussion and Recommendations

The findings of this research provide new insights into the evolving logistics of energy-related liquid bulk and the role of various stakeholders. However, some aspects require further reflection.

The starting point of this research was to assess whether existing port choice models, primarily developed for containerized cargo, could also be applied to energy-related liquid bulk. Previous studies on dry bulk have demonstrated that the influencing factors differ from those associated with containerized cargo. Most port choice models rely on Multinomial Logit (MNL) models, which turn out to be unsuitable for liquid bulk. The unique characteristics of this sector, including strong dependence on market demand and specialized infrastructure requirements, create uncertainty. This makes traditional modeling approaches less effective. Alternative methodologies, such as agent-based modeling or scenario-based forecasting, may offer better insights. The uncertainty surrounding the future energy mix—whether dominated by hydrogen carriers, ammonia, or biofuels, further complicates predictive modeling, as the key decision on energy transition pathways has yet to be made.

Another consideration is the generalizability of the findings derived from the case study methodology. Previous literature on port choice models has shown that influencing factors can vary by region, suggesting that geographic context plays a role in decision-making. This research has identified key factors influencing the liquid bulk logistics chain, and while the methodology supports broader applicability, validation through studies in different regions would strengthen these conclusions. Additionally, it would be valuable to assess whether these findings hold for ports primarily functioning as import-export hubs rather than industrial processing clusters, as most ports examined in this study fall into the latter category.

For the interviews, stakeholders from various companies were consulted, with most interviews conducted with a single representative per company. However, within organizations, different departments or individuals may hold varying perspectives on the liquid bulk supply chain. This study does not account for potential internal differences in viewpoints, which may have influenced the findings by capturing only a single perspective rather than a more comprehensive companywide outlook. Future research could benefit from engaging multiple representatives within each organization to capture a broader and more nuanced understanding of decision-making processes.

A serious game has been developed to address the complexities of transitioning to new energyrelated liquid bulk logistics. This interactive tool provides a structured environment for stakeholders to engage in decision-making, navigate interdependencies, and experiment with cooperation strategies. By simulating real-world bottlenecks, the game highlights how misalignment, hesitation, and regulatory constraints can hinder progress. It also demonstrates the impact of incentives and penalties, offering valuable insights into how policies influence investment decisions. The results of the game can be analyzed to better understand stakeholder behavior, coordination challenges, and effective negotiation strategies. This makes it a useful tool for both learning and policymaking, helping to foster more efficient and collaborative approaches to liquid bulk logistics.

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