Zero-emission Fueling Infrastructure for IWT: Optimizing the Connection between Upstream Energy Supply and Downstream Energy Demand

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Abstract
A key challenge in the energy transition for Inland Water Transport is the functional design of bunker networks and first-order dimensioning of individual bunker stations. A fundamental ingredient for this is an improved understanding of how upstream energy supply ('well-to-bunker-station') and downstream demand ('bunker-station-to-tank') may interconnect. In this paper we discuss an approach to the design of bunkering networks that takes logistic modelling to estimate network scale energy demand as a starting point. Depending on the vessels that use the network and the anticipated fuel mix for the overall fleet, logistical modelling may be used to estimate the magnitude of the energy demand along the network. Estimates of the operational range of vessels per energy carrier help to estimate maximum bunker station inter-distances. Insight into the potential supply chains that connect the source of each energy carrier to a physical bunker facility is needed to close the loop. Energy carriers may be needed on board in a gaseous or liquid form, or in the form of electrons. Transfer may take place in the form of loading (e.g., filling the fuel tank, charging the battery pack) or swapping (e.g., exchanging fuel containers, exchanging battery containers). Depending on the energy carrier, transfer method(s) and demand quantities, functional designs of bunker stations (in terms of required system elements and their order-of-magnitude dimensions) can be made. Depending on service level requirements both the dimensions of individual bunker stations and their spread over the network may be optimized. Key contribution of this work is a thorough overview of aspects that play a role in the design of bunker infrastructure for the decarbonisation of inland shipping. Based on this overview steps for further research are recommended.

Keywords: Inland Water Transport, Bunkering, Well-to-Bunker-Station, Bunker-Station-to-Tank.

1. INTRODUCTION

In line with the Climate Act and Paris Agreement, representing significant global efforts to combat adverse impact of climate change through mitigation, governments are actively working towards reducing greenhouse gas emissions to ensure a global temperature rise below 2ºC by 2030 [1]. In this regard, a commitment to a sustainable future includes a shift from fossil fuels to more clean and renewable energy resources. Inland shipping is a promising sector for reducing emissions in transportation, exhibiting higher energy efficiency and lower pollutant emissions compared to road or air transport. With the promotion and expansion of inland shipping, countries can leverage its potential to mitigate the environmental impact of transportation and carbon emissions. Furthermore, this shift can alleviate road congestion and reduce dependence on long-haul trucking, further aiding in emissions reduction.

Exploiting renewable resources as alternative fuels presents several challenges. One key challenge involves the construction of new facilities and infrastructures necessary to support the use of alternative fuels. This endeavor often requires significant investment, both in terms of financial resources and planning efforts. It involves establishing charging or refueling stations, upgrading existing ports and terminals, and adapting vessels to accommodate new fuel and propulsion systems. These considerations are closely intertwined with the Supply Chain Network (SCN) of bunkering, playing a crucial role in understanding the flow of fuels, associated costs, and other influential factors that contribute to the success of the network.

In order to achieve optimal network planning, strategic considerations play a crucial role. These considerations include factors such as the number, location, capacity levels, and technology employed

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in network facilities. These aspects directly impact the efficiency and responsiveness of the network. Designing bunkering infrastructure for inland shipping within a supply chain involves determining the location of bunkering facilities and devising strategies for fuel supply from resources to production locations, then to bunkering infrastructure, and finally connecting to downstream vessels. The choice of the location, capacity, and the type of bunkering are controlled by factors such as demand congestion, the amount of demand, the state of the waterway, the state of the fleet from the downstream side and the production, distribution, and resource locations from the upstream side. Availability and accessibility of alternative fuels, the feasibility in terms of production, distribution, the adequacy of supply facilities, and safety regulations are also of paramount importance.

The extensive literature on the location of bunkering infrastructure for different fuel types is noteworthy. However, it is crucial to highlight that these studies frequently overlook the condition of waterways and fleets in their analyses. Additionally, many of these studies tend to exclusively focus on a single fuel type, which limits their ability to offer comprehensive insights for future planning and decision-making processes. In 2022, Vilchez [2] conducted a comprehensive examination of the ongoing initiatives in Europe aimed at mitigating greenhouse gas emissions arising from navigation activities. Their focus was on the deployment of low- and zero-emission vessel technologies, with particular attention to alternative fuels such as electricity, hydrogen, and natural gas. The study also identified a range of policy measures and research and development actions put forth by European governments to facilitate these environmental efforts. In 2021, Grosso [3] assessed European research and innovation projects using the TRIMIS system and highlights the need for a combination of innovations to achieve carbon reduction goals. These potential innovations include lightweight materials, hull repair methods, wind-assisted propulsion, engine efficiency, hydrogen, and alternative fuels, emphasizing both technological and non-technological solutions to mitigate environmental impacts. Moreover, Prussi [4] explored the maritime industry's environmental concerns and its transition towards alternative fuels to meet decarbonization targets. This study proposed sector segmentation to assess fuel consumption and availability in Europe, highlighting factors like cost, GHG savings, safety regulations, and infrastructure reliability play vital roles in fuel adoption. Amaph [5] utilized bibliometric analysis to examine research trends in cleaner alternative marine fuels for reducing emissions in the shipping industry. He believed that the research field is growing significantly, with the USA as a major contributor, and Liquified Natural Gas being the most studied alternative fuel. However, recent trends indicate increased attention to methanol, ammonia, and hydrogen fuels, offering insights for future research on shipping industry decarbonization. Additionally, Moirangthem [6] highlighted the importance of alternative fuels in reducing emissions in the marine transport sector, driven by MARPOL regulations and stricter emission standards. Their report provided an overview of various alternative fuels, including methanol and LNG, while addressing sustainability and safety concerns. Furthermore, the report suggested the development of testing standards and policies to further promote the adoption of cleaner fuels in the shipping industry.

A comprehensive understanding of the upstream and downstream components of the SCN, along with the interdependencies, enables more efficient infrastructure planning. By connecting infrastructure and network levels, stakeholders can better respond to current energy needs and anticipate future demand, thereby facilitating a smoother transition to alternative fuels.

Considering the importance of inland shipping and connecting the upstream and downstream of the supply chain network, this paper examines three different forms of fuel (i.e., liquid, gaseous, and electricity) in order to demonstrate the challenges faced in developing the SCN of bunkering infrastructure for various kinds of fuel. Furthermore, a comprehensive assessment of the respective supply chains is presented. By analyzing the upstream and downstream elements, the paper aims to provide a comprehensive understanding of the complexities involved. Then, the challenges associated with considering the use of these alternative fuels in inland shipping are discussed, allowing for a realistic appraisal of the situation. Finally, the paper concludes with recommendations based on the findings, highlighting potential strategies to overcome the identified challenges and accelerate the transition towards sustainable inland shipping.

2. FOCUS ON THE SUPPLY SIDE

To gain a comprehensive understanding of the bunkering infrastructure, it is crucial to delve into the upstream side of the fuel SCN for inland shipping. This involves focusing on bunkering infrastructure located at terminal stations, which act as vital links between the upstream and downstream parts of the fuel supply chain. For a fuel type to be made available to inland shipping, important decisions (and investments) need to be made in the upstream supply chain to facilitate adequate supply. To analyze the upstream part of the fuel SCN for bunkering, it is essential to consider the feedstock and raw materials of alternative fuels, suppliers, and the distribution between different parts of the supply chain. Zero-emission fuels predominantly depend on renewable energy sources for production, including solar power, wind energy, hydroelectric power, geothermal energy, and biomass. The availability of resources, scalability, accessibility, sustainability, and the feasibility of production are crucial factors to be considered. Additionally, resources capacity, regulations, and safety issues should be considered.

The environmental impact of alternative fuels also holds significant importance. Zero-emission fuels must exhibit minimal to no emissions of greenhouse gases throughout their entire life cycle, including extraction, production, distribution, and utilization. It is necessary to consider the total life cycle emissions of a particular fuel, including indirect emissions from upstream processes. The energy density is also an important factor to consider. Fuel with a higher energy density allows for longer sailing ranges and reduces bunkering frequency, making it more desirable for use.

Existing infrastructure and compatibility with current vessels and engines are other key parameters that should be identified. The shift to alternative fuels may require substantial investments in infrastructure both economically and technically, comprising investments in refueling stations, bunkering equipment, charging points, distribution facilities, storage facilities, supplier plant as well as modifications to vehicles and engines.

Alternately, government policies, incentives, and regulations are of paramount importance in promoting the widespread adoption of zero-emission alternative fuels. By implementing supportive policies, governments can stimulate investments, research, and development in alternative fuels, while fostering a favorable market environment

Furthermore, it is critical to consider economic viability of alternative fuels. Assessing the cost of production, distribution, and utilization of fuels is crucial in determining competitiveness on the market. Factors such as economies of scale, technological advancements, and market demand control fuel cost-effectiveness.

Fuel suppliers also play a crucial role in the SCN of bunkering infrastructure for inland shipping. A well-established infrastructure for procuring, storing, and distributing the required fuels, meeting the demands of inland vessels, should be available. In terms of fuel procurement, suppliers engage in sourcing fuels from diverse sources, establishing relationships with fuel producers to ensure a reliable supply. The production technology used to convert feedstock into alternative fuels should be efficient, scalable, and environmentally friendly. Different technologies are utilized based on the type of fuel involved. For example, biofuel production involves fermentation or chemical processes, while hydrogen production relies on electrolysis. Storage facilities and infrastructure should be maintained to store and handle the fuels. These facilities typically consist of large tanks or storages designed for storing different types of fuels. The infrastructure includes systems for fuel quality testing, blending, and customization based on customer requirements. Suppliers manage the logistics and transportation aspects of fuel delivery from resources to plants or from storage to bunkering terminals and vessels. They coordinate the movement of fuel through various modes of transportation, such as pipelines, train, trucks, trailers, container trailers, cables, or dedicated fuel barges, depending on the fuel types. If production sites have access to either inland or seaports, choosing short sea or inland waterway transportation can be a cost-effective and environmentally friendly choice. Alternatively, truck transportation is a flexible option with excellent connectivity, particularly suitable for smaller ports that lack multimodal connections to the hinterland. Even though pipeline transport does not currently appear to be viable for all fuel types, it should not be ruled out as an option. It might be a good business case to build one.

Efficient logistics planning and optimization of transportation routes are essential to ensure timely and cost-effective fuel delivery. It is important to note that the costs incurred by fuel suppliers in their SCN can affect the price of fuel at bunkering stations. The capital and operational expenditures encompass various components, including supply costs, distribution costs, construction costs, maintenance and operational costs, handling costs, inventory costs, shortage costs, raw material prices, and fuel prices.

Suppliers of alternative fuels can be categorized as centralized or on-site. Centralized suppliers utilize existing infrastructure, while on-site suppliers are employed in situations where distribution is impractical or expensive, or when building a plant incurs significant investment. On-site suppliers ensure fuel accessibility and convenience for vessels by establishing an adequate number of production sites near stations.

This paper examines three types of fuels based on their physical appearance: gaseous, liquid, and electricity. The assessment of the technological feasibility of a fuel SCN is vital to determine the viability of each fuel type. It is important to note that zero-emission fuel alternatives, such as green hydrogen, electric batteries, biofuels, and methanol, have distinct infrastructure requirements. To ensure efficient implementation of the necessary bunkering infrastructure, it is crucial to analyze the SCN for each type of fuel.

2.1 Gaseous fuels

Figure 1 illustrates the Green Hydrogen supply chain, which involves the process of electrolyzing water using electricity that could be derived from renewable sources such as wind farms, solar panels, hydropower, biomass energy, geothermal energy, or tidal energy. To enable this process, electrolyzing plants need to be constructed. The feasibility of establishing these expensive plants depends significantly on the availability and accessibility of natural resources [7].

The output of the electrolysis process is hydrogen gas, which has a low energy density and occupies a considerable amount of space. Therefore, specialized storage technology is required to facilitate its storage. Gas can be transferred through pipelines, trailer trucks, or swappable containers. Pipelines are suitable for gas and liquid forms but require high levels of safety measures and initial investments in materials. It is important to note that if the distance between the stations and plants is significant, the cost of pipeline construction and maintenance increases due to the amount of material needed. However, pipelines are more convenient for distribution and provide significant capacity [8].

Gas trailers or swappable containers have lower initial costs compared to pipelines since they do not require additional infrastructure. However, they are typically used for short-term storage and rely on road infrastructure, which can increase hazards on the road. When using swappable containers, it is crucial to consider container dimensions, equipment for container displacement (such as cranes) to ship, loading and unloading times, and charging schedules. Station facilities should be designed to accommodate the containers adequately or provide specific storage facilities if containers require special handling properties. Additionally, optimizing the timing of distributing container transfers to charging facilities and charging time minimizes waiting times and network shortages.

Different storage and charging facilities can be constructed near stations, plants, or even between plants and stations. The choice of capacity of these facilities depends on the pressure and temperature requirements for storing gaseous fuels. Direct dispensing of this fuel to ships requires high-pressure compressors, and temporary storage necessitates low-pressure buffer storage. Bunkering operations can be carried out using hoses from gas trailers, storage facilities, or fuel-containing trucks.

The main challenges associated with gaseous fuels include the production or supply risks from limited renewable resources, the need for sufficient bunkering infrastructure and suitable ports, the relatively low energy content and price volatility influenced by the upstream part of the SCN.

2.2 Liquid fuels

Figure 1 also illustrates the fuel SCN of liquid hydrogen, which is obtained through the liquefaction of gaseous hydrogen and offers improved energy density compared to its gaseous form. Currently, there is a scarcity of infrastructure for liquefaction plants, making it economically impractical due to the high fuel costs until the installation of such facilities begins. Liquid hydrogen resembles LNG (liquefied natural gas) and holds promise for mid-term applications. Its transportation can be achieved through specialized liquid trucks that account for boil-off losses,

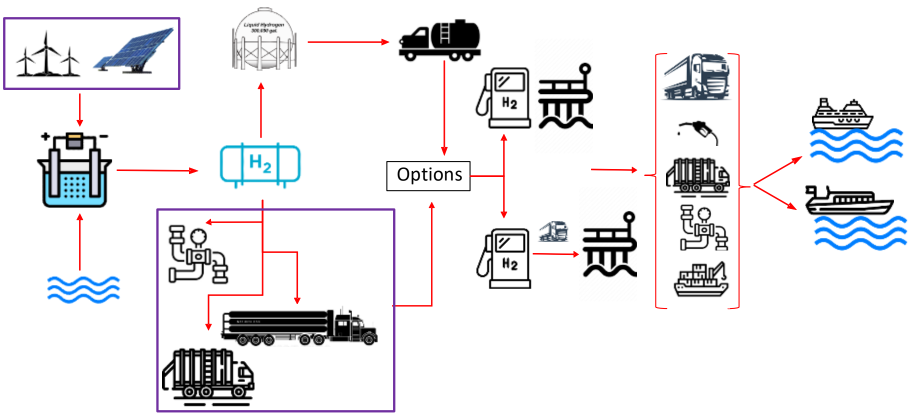

Figure 1 Green hydrogen supply chain network

necessitating the construction of dedicated facilities at a high cost. Bunkering operations can be conducted using hoses connected to trucks, fixed stations, or even bunker barges.

Biofuel is a liquid fuel, depicted in Figure 2, that can be derived from various sources including natural gas, gasified biomass, renewable sources (such as residual plant and animal fractions), and rapeseed oil. It offers several advantages as an alternative fuel. Firstly, it is non-toxic to humans and the environment. Secondly, there are no specific policies governing its usage, and finally, the infrastructure changes required for implementing biofuel usage are relatively minor, with costs negligible compared to other alternative fuels, making it a convenient option for replacing traditional fuels. However, it is important to note that biofuel is not a completely emission-free solution and only reduces greenhouse gas (GHG) emissions by approximately 60% [9].

It is similar to diesel/gasoil, and primarily utilized in heavy road vehicles. It exhibits comparable energy density and storage characteristics to diesel fuel. Storage of biofuel is recommended at ambient temperature and atmospheric pressure. In terms of energy density, viscosity, volume, and refueling time, biofuel is comparable to other alternative fuels. Currently, bunkering operations for biofuel can be conducted using trucks or direct drum transfers. There are, however, several challenges associated with biofuel usage. Ensuring long-term availability is one such challenge, as well as addressing competition between transportation modes and other industrial sectors. Additionally, the production rate of biofuel is relatively low, and it still contributes to emissions. Consequently, biofuel is considered a transitional fuel rather than a zero-emission solution.

Figure 3 presents an overview of the Methanol supply chain, which is more widely available compared to hydrogen and electricity. Methanol can be produced through four primary pathways: grey methanol (derived from fossil sources), bio methanol (obtained from wet biomass), carbon-recycled methanol (generated from fossil-based solid waste through gasification), and e-methanol (produced using green hydrogen and carbon sources). To achieve future greenhouse gas (GHG) targets, the transition to carbon-neutral fuels like bio-methanol and e-methanol is crucial. However, during the ongoing shift to methanol-based maritime transport, grey methanol may still be necessary in the short-term and medium-term.

The infrastructure costs associated with Methanol are comparable to diesel/gasoil and lower than other alternative fuels. It can also be used in various applications with minimal modifications. Methanol distribution can be carried out by train, which is cost-effective; trailers, although expensive and suitable for low volumes and short distances; barges; and pipelines, which are suitable for transporting large volumes and offer energy and cost efficiency during operation. Bunkering options for Methanol include ship-to-ship, shore-to-ship, and truck-to-ship methods. Currently, these methods are available for ferries in inland shipping, but they face challenges such as limited demand, high costs, and inadequate infrastructure [10].

While methanol does not face significant technological barriers and is considered a climate-neutral fuel, one of the main challenges is the high cost of producing methanol from renewable resources. Additionally, methanol has a lower energy density compared to gasoil and diesel, and it also exhibits higher toxicity. Furthermore, it requires more frequent bunkering stops compared to conventional fuels.

2.3 Battery Electric

Figure 4 illustrates a battery electric supply chain, which offers a lower energy density compared to diesel and gasoil, making it suitable for short-distance transportation. The charging stations within this chain should be capable of serving vessels with distances up to 100 km. There are two types of vessels that utilize batteries: fixed battery vessels and vessels with exchangeable batteries.

For fixed battery vessels, the charging time and capacity of the charging points are crucial factors. Therefore, charging facilities should be available at the stations to accommodate these requirements. The majority of vessels are charged during midnight hours, and the charging points should be located near the electricity grid. However,

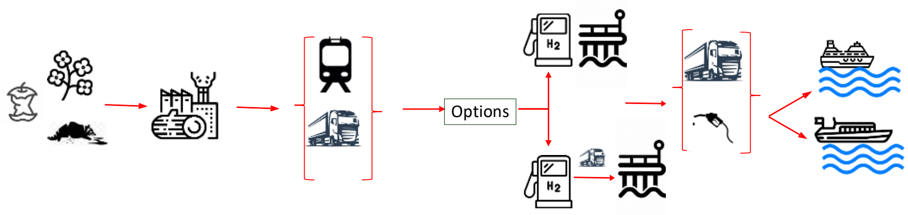

Figure 2 Biofuel supply chain network

distribution is necessary in areas without grid congestion. It is also possible to consider modifying the grid if necessary vessels with pre-installed electric batteries can be charged either through a cable or by induction.

Alternatively, exchangeable power packs or swappable batteries can be employed, which offer benefits such as time savings, reduced potential loss of revenue, and lower initial investment for the shipper. However, the infrastructure cost associated with exchangeable power packs is high, with limited economies of scale, requiring the development of entirely new infrastructure. Currently, this approach is restricted due to certain drawbacks, including longer charging times and time-consuming processes. The existing capacities do not support long or medium routes, necessitating a significant amount of power. While the risk of battery fires is generally low, if they occur, they can lead to significant issues.

3. FOCUS ON SPECIFYING DEMAND

In order to identify suitable locations for bunkering infrastructure for zero-emission inland shipping, it is crucial to conduct an analysis of the demand for alternative fuels. This analysis entails evaluating the current and future traffic flow requirements of vessels operating on inland waterways. By understanding patterns of demand, planners can prioritize the placement of bunkering facilities along specific waterways or regions. The placement of refueling points is determined based on the minimum sailing range of the representative fleet in the corridor. This ensures that all types of ships in the corridor can reach the next refueling point, with the maximum distance between two refueling points not exceeding this minimum range.

Estimating the required capacity of each refueling point can be done by considering the total energy consumption at various time scales, and the allocation of energy supply can be based on the direction of energy consumption. Accurately quantifying the energy demand for the entire route and corridor network necessitates reliable estimation of energy demand, taking into account variations in sailing conditions such as water depth, which affect energy demand [11]. It is also important to examine the potential effects of alternative fuels on a vessel's sailing range, payload capacity, and sailing velocity. Accordingly, if the sailing range is the only aspect impacted, the primary effect on transport efficiency would be an increased frequency of bunker stops. On the other hand, if the range remains unchanged but the payload capacity is affected, the main impact on transport efficiency would be the need for more trips to transport the same cargo volume [12].

Additionally, factors such as vessel types, their energy requirements, and the anticipated growth of the shipping industry should be taken into consideration. Two commonly used methods for estimating global bunker demand are the top-down and bottom-up approaches. To estimate energy consumption, information on transport demand (including volumes, origins, and destinations), waterway network conditions (such as water depths and currents), and fleet characteristics (such as composition and engine ages) is necessary. Vessel resistance algorithms can be utilized for this estimation [13-16].

Algorithms for energy consumption calculations, both at the individual ship and corridor network levels, have been implemented in the Python package OpenTNSim. Aggregating the results from multiple vessels allows for mapping the energy consumption of the corridor network and determining energy consumption at different time scales. The state of the waterway, including water depth and current, directly impacts the energy demand and congestion for transportation. The classification of waterways determines the maximum vessel size that can be used. It is important to note that alternative fuels have a lower energy density compared to diesel, which may require larger tanks or more frequent refueling [11].

Understanding the state of the available fleet for transportation on the waterway network, as defined by PIANC and RVW [12], is crucial. Factors such as available air draught, maximum width, length, and draught, as well as bottlenecks related to width and depth, typically impose limitations on the maximum vessel class allowed on a waterway.

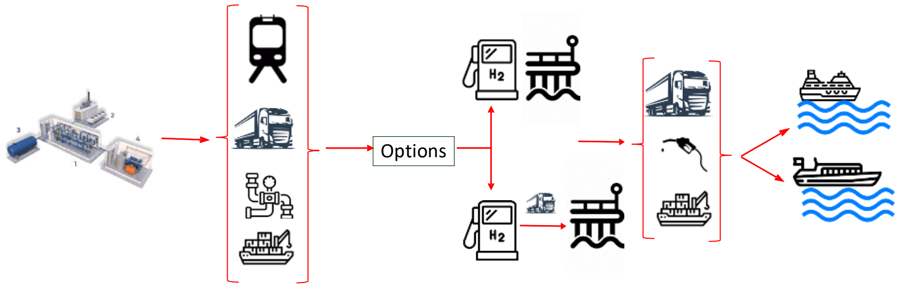

Figure 3 Methanol supply chain network

Traffic intensity and environmental conditions such as reduced water levels due to low discharge extremes can also influence the assessment [17,18]. It should be recognized that not all vessels in the fleet will be of maximum size, and smaller vessels will require more trips to transport the same cargo volume compared to larger ships. Older vessels might have outdated engines that perform less efficiently in terms of emissions. Additionally, evaluating the availability of alternative modes of transportation, such as road, rail, and pipelines, is important. If these alternatives can accommodate a significant shift in transportation, it will increase the pressure on the inland shipping sector to adopt or transition to other energy solutions [12].

4. MATCHING SUPPLY AND DEMAND

The bunkering terminal plays a crucial role as a key node within the inland shipping fuel SCN. These terminals are strategically located along inland waterways to facilitate efficient distribution of fuel. Upon receiving fuel shipments from suppliers, bunkering terminals store them temporarily before transferring them to vessels. Bunkering operations involve the transfer of fuel from storage facilities to vessels or direct supply from a grid (either available fuel pipelines or electricity).

The upstream side of the inland shipping SCN focuses on the production of fuel using various feedstocks and production methods, as well as the transportation of these fuels to bunkering stations or transferring fuel to vessel without using bunkering stations. This analysis considers feedstock suppliers, transportation companies, and fuel handling procedures. It also considers emerging trends in fuel production, such as the use of renewable energy sources or the adoption of cleaner fuel technologies, to align with environmental sustainability goals. Furthermore, the decision-making process regarding fuel selection and sourcing involves assessing the availability and reliability of different renewable resources. Evaluating the scalability and long-term viability of these resources is crucial, as it impacts the stability and resilience of the bunkering network. Additionally, the production plants and suppliers capable of producing and supplying the desired fuel with the best feasible distribution to bunkering stations need to be identified. Collaboration with renewable energy providers, research institutions, and regulatory bodies can help identify emerging technologies and advancements in renewable energy production, ensuring the availability of sustainable fuel sources for bunkering operations.

However, the capacity of these renewable resources is limited, necessitating careful decision-making regarding the quantity and type of fuel to be used and where it should be deployed. This decision also affects the selection of suppliers and production sites, which can be categorized into on-site and centralized facilities. Conversely, the downstream side addresses the efficient transfer of fuel from bunkering stations or other bunkering methods to end consumers, which are the vessels. This analysis involves commodity traders or brokers, transportation companies, storage facilities, bunkering operators, and vessels. It also considers the evolving needs and regulations in the shipping industry, such as the transition to low-emission vessels or the implementation of stricter fuel quality standards.

Efficient planning and coordination of the fuel SCN from the perspective of decision-makers at the bunkering station side are crucial to finding an acceptable trade-off between the upstream and downstream sides of the supply chain. This requires careful consideration of factors such as fuel production, transportation logistics, storage facilities, and bunkering operations to ensure the smooth flow of fuel from suppliers to end consumers. Additionally, assessing the availability and accessibility of bunkering locations, as well as the infrastructure requirements, plays a vital role in optimizing the bunkering network for inland shipping. Effective collaboration among stakeholders, including government bodies, shipping companies, fuel suppliers, and terminal operators, is essential to develop sustainable and resilient bunkering solutions.

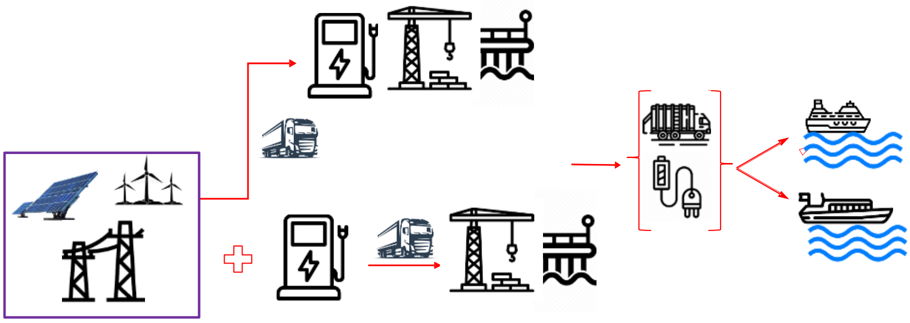

Figure 4 Electric battery supply chain network

In addition to cost considerations, the design of bunkering locations for inland shipping requires a comprehensive analysis of various factors to ensure an efficient and sustainable supply chain. This analysis includes evaluating the accessibility and proximity of potential bunkering sites to key shipping routes, as well as considering the infrastructure requirements for fuel storage, handling, and transfer operations. By integrating these factors, the bunkering network can be designed to support the seamless flow of fuels, promote environmental sustainability, and contribute to the overall growth and resilience of the inland shipping industry.

When determining the bunkering transfer method to be used, a combination of factors comes into play. These factors include the location of bunkering sites, which define the availability of infrastructure and the rules and regulations specific to each fuel and bunkering procedure. The amount of fuel to be bunkered and the operating costs of the vessel being fueled are also crucial considerations. Additionally, time and capacity considerations are important in determining the desired service level, aiming to minimize unmet demand, bunkering time, waiting time at the station, and traveling time. Factors such as traffic on waterways and demand congestion need to be carefully considered to optimize the bunkering process.

The bunkering type selected significantly impacts the required infrastructure. Ship-to-ship bunkering, for instance, is a flexible solution suitable for a wide range of fuel volumes, but only for liquid fuels. In this case, storage or production sites should be located within a certain distance of the port to support the bunkering barge. Ship-to-ship bunkering can take place at various locations, including along the quayside, at anchor, or at sea. Compared to other bunkering methods, ship-to-ship bunkering offers greater flexibility in terms of capacity and bunkering location.

Truck-to-ship bunkering, on the other hand, has capacity limitations due to the truck's capacity. However, it offers the lowest investment costs, making it suitable for short-term phases or smaller fuel volumes. For truck-to-ship bunkering, the location of the truck (either at a station or along the river) should be carefully determined, taking into account the availability of safe mooring places for vessels. Fixed bunkering stations enable bunkering volumes of any size and support multi-fuel bunkering, where a bunker vessel can carry multiple fuels or grades to serve several vessels. These fixed stations can be located specifically for bunkering purposes or serve other functions as well. They may incorporate storage facilities for handling swappable containers or charging facilities for electric vessels. Other components related to bunkering operations, such as cranes for container swapping, compressors, fuel quality testing facilities, and fuel blending facilities, may also be present. Fixed bunkering stations should be constructed to accommodate multiple fuels since other bunkering types are limited to supporting only one type of fuel.

In addition to carefully considering the selection of bunkering methods, various costs need to be calculated, including equipment, construction, distribution, installation, land, legal, and bunkering maintenance, and operations expenses. By integrating cost considerations, environmental sustainability, technological advancements, and regulatory compliance, the design of bunkering locations for inland shipping can contribute to establishing a robust and future-proof fuel SCN. This enables the seamless flow of fuels, supports the transition towards cleaner

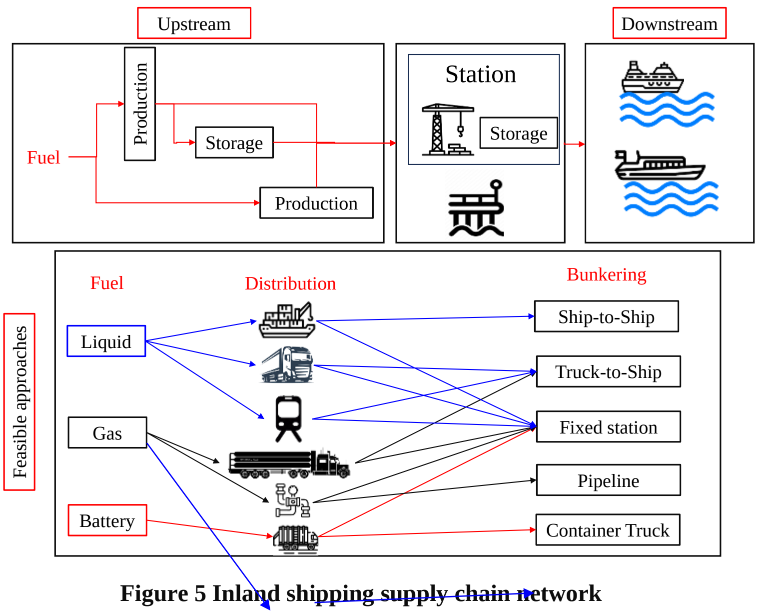

Figure 5 Inland shipping supply chain network

energy sources, and fosters the overall growth and sustainability of the inland shipping industry. Furthermore, it is important to assess whether the entire corridor has the necessary infrastructure and fleet capabilities to support vessels using the same type of fuel at the corridor's origin. These factors, including waterway infrastructure and fleet characteristics, influence the demand and feasibility of different bunkering types and distribution methods.

In designing bunkering locations for inland shipping, the distribution between components of the upstream side (resources, production plants, storages) and bunkering stations should be carefully considered based on the feasibility of different distribution types for fuels. Distribution options include truck, trailer, gas trailer, container trailer (utilizing road infrastructure and currently suitable for liquid, gas fuels), pipeline (suitable for gas and liquid fuels), train (using rail infrastructure and currently suitable for liquid fuels), container trailer (use road infrastructure and currently is suitable for fuels in the form of gas and electricity) and barges (utilizing waterway infrastructure and suitable for liquid fuels). Assessing the accessibility of distribution infrastructure in relation to waterway infrastructure and its feasibility for the desired fuels is crucial.

Distributing fuels by road can be employed for both centralized and on-site production with limited capacity. After distributing the fuels, bunkering can be done either by truck-to-ship transfer or by storing the fuels in fixed stations. Container trailers are suitable for distributing gas fuels and battery electricity, which need to be transferred to stations. These stations should have storage facilities to handle the containers. Another distribution option is by train, which is suitable for liquid fuels. If the rail infrastructure is not located near waterways, an additional distribution method, such as trucking the fuel to ports, needs to be considered. The third distribution type, which is pipeline, is more suitable for on-site production, reducing the huge costs of needed infrastructure. After distribution, the fuel can be stored in fixed stations, and bunkering can be done through pipelines. Another distribution option is by barges, suitable for liquid fuels. It allows for shipping fuels from both on-site and centralized production. After distribution, bunkering can be conducted either by ship-to-ship transfer or by storing the fuel at fixed stations. Fixed bunkering stations offer another option, where vessels can moor at jetties or pontoons, and storage facilities can be incorporated within the station. The capacity of these stations may vary depending on the demand. Additionally, swapping containers is another distribution option worth considering. This method offers lower delivered costs, eliminates the need for expensive land-based infrastructure, reduces bunker time, and allows for charging facilities to be co-located with loading operations. This can be achieved by utilizing cranes and similar port infrastructure, or the containers can be transported to separate charging facilities [12]. So, the selection of the most appropriate distribution method depends on factors such as fuel type, infrastructure availability, cost considerations, and the specific requirements of the bunkering operation.

Cargo owners often prioritize cost over greener transport options if cheaper conventional alternatives are available. However, higher costs that affect the entire industry can potentially be passed on to customers, leading to a shift in price willingness for greener transport [10]. Bunker prices significantly impact ship owners, operators, and charterers, and high bunker prices incentivize the adoption of alternative energy sources in the shipping industry. Fuel prices for shipping are influenced not only by production costs but also distribution costs and sellers. Additionally, bunker prices depend on the availability of the product in the market. Quay operators generally prefer to avoid occupying their premises with vessels that require truck-based bunkering. This is due to limited space availability for loading/unloading activities and environmental permit restrictions. As the market demand increases, ship-to-ship transfers become more attractive for vessels with a fuel demand of 200 metric tons or more (equivalent to more than four tank trucks). Compliance with regulations governing fuel quality, safety, and environmental standards is a vital aspect of the bunkering supply chain. Fuel suppliers, bunkering terminals, and transportation entities must adhere to relevant regulations to ensure safe and sustainable bunkering operations. Emphasis on compliance with emission regulations and the use of low-emission or alternative fuels is increasingly important to promote environmental sustainability.

The objective of the inland shipping supply chain analysis is to compare multiple scenarios and address the following key questions:

1. What can evaluate the essential changes or expansions needed in the current bunkering infrastructure to facilitate a seamless shift from traditional fuels to alternative fuels?
2. How can it be determined whether there is a need for new bunkering locations or if optimizing existing facilities is sufficient?
3. What are the key determinants influencing the bunkering supply chain network components in order to achieve zero emissions and how can they influence?

4. How can a bunkering network effectively incorporate multiple alternative fuels, and what would be the logistical and operational considerations in managing such a mixed fuel within the network?
5. How do waterway and fleet properties, including fleet composition, water depth, route traffic, waiting times, and bunkering procedures, influence the design and optimization of a sustainable bunkering network for inland shipping?
6. Which bunkering types are currently suitable and feasible, and how will their suitability evolve over time?

By examining these questions and conducting a comprehensive supply chain analysis, we aim to provide valuable insights into the design and optimization of bunkering locations for inland shipping.

5. CHALLENGES

Designing bunkering locations for inland shipping involves several challenges. Construction costs, facility location planning, and relocation projects require long-term investments. To ensure profitability, decision-makers should prioritize long-term facilities designed to remain operational for extended periods. It is crucial to select locations with sufficient capacity to accommodate not only the current demand for alternative fuels but also the future transition towards achieving net-zero emissions. Therefore, assessing the demand location and its congestion level is critical in estimating the required supply volume to prevent shortages within the network. Major waterways, such as core ports and main corridors, are expected to experience higher demand and may necessitate additional resources compared to other areas. Consequently, the network should aim to maintain the capacity of new facilities while meeting all demands. For the primary steps towards zero-emission, instead of constructing new plants near resource sites, investing in distribution is often more economically viable.

Additionally, reliability is a vital aspect to consider in the bunkering supply chain. Road congestion, weather conditions, and maintenance can significantly increase travel time for road transport. Rail transport generally operates on fixed schedules but can experience delays due to train failures or track repairs. River transport may face obstacles during the dry season when shallow sections become impassable. Addressing bottlenecks is crucial to improve the reliability of inland shipping. Road transport, favored by small transport companies, can be more competitive due to fuel subsidies and the preference for smaller trucks. Rail transport tends to have more cost but allows larger volumes per shipment, while river transport is generally the most cost-effective option for carrying significant cargo volumes.

Moreover, for swappable containers, the duration for which containers should remain on-site at fixed bunkering stations is an important consideration as their storage capacity in stations can change over time. Additionally, considering the capacity of suppliers is crucial. Centralized supply chains offer advantages, with suppliers benefiting from economies of scale, large-scale storage facilities, and well-established logistics networks to efficiently serve high-demand areas. However, transportation costs for centralized suppliers can increase due to longer distances and lead times to reach bunkering stations. On the other hand, on-site production may face challenges in scaling up production and meeting increased demands if existing infrastructure has limited capacity. The choice between on-site and centralized production depends on factors such as operational scale, geographic distribution, cost considerations, infrastructure availability, and responsiveness requirements. A combination of both approaches can be adopted to optimize the bunkering supply chain. Finding the right balance between centralized and on-site production, along with considering distribution factors such as lead time, transportation feasibility, and investment costs, is crucial for optimizing the bunkering supply chain and ensuring efficient fuel delivery to meet the demands of inland shipping.

6. DISCUSSION AND CONCLUSION

The following discussion focuses on key aspects related to the design of bunkering infrastructure for inland shipping. One crucial consideration is the exploration of alternative storage options derived from natural resources, particularly temporal or unconventional options. For example, utilizing salt caverns as storage facilities for gases like hydrogen offers a secure and efficient means of storing alternative fuels. This approach reduces costs and expedites the implementation of alternative fuels for inland shipping. Additionally, modifying or extending existing infrastructure can facilitate the integration of alternative fuels into the current system, minimizing the need for significant investments in new facilities, albeit at the expense of functionality for other fuels.

The distribution of bunkering locations should be guided by vessel traffic density to ensure that high-traffic areas receive adequate service without overinvesting in low-traffic regions. Implementing these design considerations involves establishing fuel production capacities, adhering to specific policies and regulations, and accounting for uncertainties and resilience within the supply chain network. It is crucial to consider fuel diversity to accommodate the varying needs of inland vessels, as different vessels may require different fuel types. Therefore, a range of fuels, including traditional and alternative options, should be available at bunkering locations.

Uncertainties within the supply chain network present challenges for bunkering infrastructure design. Fluctuating fuel prices, changes in demand, and potential disruptions in the supply chain must be taken into account. Building resiliency into the network, such as incorporating redundant storage capacities or diversifying fuel sources, helps mitigate the impact of uncertainties and ensures a reliable and continuous fuel supply. It is worth noting that prioritizing factors in the supply chain network is crucial due to the time and cost involved.

The first step involved projecting demand to determine if the existing infrastructure described in the literature could meet current and future needs, and whether there were any fluctuations in demand. This assessment considered not only the quantity of demand but also the specific requirements for alternative fuels. Additionally, demand can vary daily and weekly, as well as across different corridors within a day. Such variability can also impact the supply side. In their research, Momenitabar [19] utilized machine learning methods, including Random Forest, Extreme Gradient Boosting Method, and Ensemble learning algorithms, to project bioethanol demand. In 2022, Kazi and Eljack [20] employed an RNN-LSTM prediction model to identify future hydrogen demand from the maritime sector. To forecast demand, various approaches such as time series analysis and machine learning algorithms can be applied based on historical data patterns.

Among the available methodologies, utilizing real-time data in an agent-based simulation proves to be a more reliable approach. This simulation method focuses on the development, capacity, and interactions within the waterway system. By employing agent-based simulation, it becomes possible to examine interactions between social systems, stakeholders, and the natural environment. This approach is particularly useful for identifying key stakeholders, such as vessel operators, port authorities, fuel providers, and regulatory bodies. Agents represent different vessel types, routes, schedules, fuel requirements, and decision criteria for selecting bunkering locations. The multi-agent simulation simulates vessel movements, routes, and stops for bunkering, while capturing data on fuel consumption, emissions, and operational costs for various vessel scenarios. Additionally, a framework should be designed to identify the trade-offs between dynamically changing scenarios. This Digital Twin could provide detailed information regarding waterway conditions, traffic patterns, vessel types, and sizes. To identify potential locations for bunkering infrastructure within the digital twin of the network, it is necessary to conduct an assessment using the results obtained from the multi-agent simulation. In addressing the questions about alternative fuels outlined in section 4, it is crucial to acknowledge that numerous factors influence decision-making regarding them. However, at this stage, determining which factors are superior remains uncertain. To gain a better understanding of these influential factors and to identify the trade-offs among them, the techniques mentioned earlier can be instrumental. These methods enable decision-makers to explore design scenarios, simulate the behavior of the supply chain, evaluate feasibility, identify bottlenecks, and optimize configurations. By leveraging these techniques, a resilient and efficient bunkering infrastructure can be achieved.

In conclusion, this paper explores the challenges and complexities associated with developing the supply chain network of bunkering infrastructure for alternative fuels in inland shipping, focusing on three different fuel forms: liquid, gaseous, and electricity. By analyzing the upstream and downstream components of the supply chain, this study establishes a comprehensive understanding of the interdependencies and considerations for infrastructure planning, including influential factors.

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