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Baltic Sea Region

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SMART GREEN MOBILITY
BSR HyAirport

Supply Chain

Report on

WP 1.2 Supply Chain 1.2.3 Transport

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Content

Glossary

Abbreviation	Full Term	Explanation
BSR	Baltic Sea Region	The area around the Baltic Sea, including Germany, Poland, Lithuania, Latvia, Estonia, Finland and Sweden.
BSR HyAirport	BSR Hydrogen Air Transport – Preparation of Baltic Sea Region Airports for Green Hydrogen	Project to prepare airports in the Baltic Sea Region for the use of green hydrogen in aviation.
EHB	European Hydrogen Backbone	A planned cross-border hydrogen pipeline network in Europe.
GH_2	Gaseous hydrogen	Hydrogen in its gaseous state, used for transport and storage.
HRS	Hydrogen refuelling station	A facility that stores and dispenses hydrogen.
LCOHT	Levelized cost of hydrogen transport	The average cost per kilogram of transporting hydrogen, accounting for all relevant expenses over time.
LH_2	Liquid hydrogen	Hydrogen in its liquid state, requiring cryogenic storage.
MEGC	Multi-Element Gas Container	A special container used for transporting gases, such as hydrogen, by rail or road.
WG	Working group	A team within the project focused on a specific aspect.
WP	Work package	A major section of a project, with specific objectives and deliverables.

Executive Summary

This report contains an in-depth analysis of hydrogen transport solutions for airports in the Baltic Sea Region (BSR) as part of the BSR project HyAirport. The main objective is to evaluate cost-effective hydrogen logistics strategies to support the early adoption of hydrogen-powered aviation.

The key findings show that, due to the relatively low initial demand at airports and the currently decentralised hydrogen infrastructure, transport by truck is the most practical and flexible solution for the short-term introduction phase. As hydrogen demand increases and infrastructure expands, options such as rail and pipeline are also expected to gain importance, particularly with the expansion of the European Hydrogen Backbone (EHB).

The report highlights the importance of site-specific factors in determining the optimal means of transport, such as airport size, proximity to hydrogen hubs and existing infrastructure. A guide and decision tree are provided to help airports select the most appropriate logistics solution based on demand, distance and infrastructure availability.

Recommendations include:

- Prioritising hydrogen delivery by truck for initial rollout at most airports.
- Planning for future integration into rail and pipeline networks once demand and infrastructure are mature.
- Early engagement with local stakeholders to address infrastructure gaps and regulatory requirements.
- Regularly updating cost models and logistics strategies in line with developments in market conditions and hydrogen technologies.

Overall, the results support a step-by-step approach to hydrogen logistics, enabling airports to adapt flexibly to the development of the hydrogen economy in the Baltic Sea Region.

1. Project context and objectives of the work package Transport

The following section provides an overview of the BSR HyAirport project as well as the objectives of the work package (WP) 1.2.3 Transport. WP 1.2.3 Transport is one of the individual sub-packages within the overall WP 1.2 Supply Chain, which also includes WP 1.2.1 Demand Analysis, WP 1.2.2 Local Production and WP 1.2.4 Storage.

1.1 The BSR HyAirport project

The project "BSR Hydrogen Air Transport – Preparation of Baltic Sea Region Airports for Green Hydrogen," in short referred to as "BSR HyAirport," is a transnational cooperation in the framework of the Interreg Baltic Sea Region Programme aimed at promoting the use of hydrogen in the aviation sector. It seeks to facilitate the early adoption of hydrogen-powered aircraft by preparing airports for storing, handling, and delivering green hydrogen as a future energy source in aviation.

The integration of gaseous hydrogen (GH_2) as an energy source in aviation presents a transformative opportunity to reduce the carbon footprint of air travel. As climate change pressures industries to adopt cleaner technologies, initiatives like the BSR HyAirport project are crucial. By preparing airports for hydrogen-powered aircraft, the BSR HyAirport project aims to establish a framework that promotes sustainable aviation and aligns with broader environmental goals in the Baltic Sea Region. The project focuses on facilitating the adoption of hydrogen technology by creating the necessary infrastructure for storing, handling, and delivering green hydrogen. It fosters regional cooperation among partners from multiple countries, develops practical solutions for hydrogen usage in aviation, and tests and pilots these solutions to ensure their operational suitability, ultimately supporting the aviation sector's transition to more sustainable practises.

BSR HyAirport is an initiative of the Lead Partner, Hamburg Airport. Hamburg Airport developed the project and applied for co-funding by the Interreg Baltic Sea Region Programme in March 2023. The Interreg Baltic Sea Region Programme is a cooperation and funding instrument designed by the European Union to promote cross-border regional development and enhance collaboration among countries in the Baltic Sea Region area. As part of the European Union's Interreg initiative it focuses on addressing common challenges faced by the region, such as environmental sustainability, economic growth, and social inclusion and fosters collaboration across borders. Key areas of focus include promoting innovation, sustainable development, climate change adaptation, and improving accessibility within the region. By facilitating cooperation and sharing best practises, the Interreg Baltic Sea Region Programme aims to create a competitive, environmentally friendly, and inclusive region.

The BSR HyAirport project features transnational cooperation across seven countries in the Baltic Sea Region, including Germany, Poland, Lithuania, Latvia, Estonia, Finland, and Sweden. It benefits from a broad partnership comprising 16 project partners and 24 associated organisations across the aviation value chain, including airports, airlines, industry partners, aviation suppliers, public authorities, research and education institutions, and NGOs.

Figure 1.: Map of project partner locations.

Hamburg Airport operates as the leading partner, with the other project partners being:

- Poznan Airport, Poland
- State company Lithuanian Airports,Lithuania
- SJSC Riga International Airport, Latvia
- Tallinn Airport, Estonia
- Finavia Cooperation, Finland
- Swedavia AB, Sweden
- Växjö Smaland Airport AB, Sweden
- Latvian Hydrogen Association, Latvia
- Sylt Airport, Germany
- Sylt Air, Germany
- Lübeck Airport, Germany
- SIA Gulfstream Oil, Latvia
- Latvia University of Life Sciences and Technologies, Latvia
- RISE Research Institutes of Sweden, Sweden
- Gulfstream Oil, Latvia

Project Partners

The project partnership is representing a very high percentage of airports in the Baltic Sea Region as project partners Finavia, Lithuanian Airport and Swedavia operate between 3 and 20 airports in their home countries.

The project creates a unique platform for joint development, implementation, and testing of practical solutions addressing the common challenges and specific needs related to hydrogen usage. With a total duration of 36 months, the project commenced in November 2023 and will conclude in October 2026.

The BSR HyAirport project is divided into three work packages: WP 1 – Preparing Solutions; WP 2 – Piloting and Evaluating Solutions; and WP 3 – Transferring Solutions.

WP 1 **Preparing solutions**

Elaborating solutions for the use of hydrogen at Baltic Sea Region airports

- WP 1.1 Legal Framework
- WP 1.2 Supply Chain
- WP 1.3 Aircraft Handling
- WP 1.4 Airport Equipment
- WP 1.5 Business Case

WP 2 **Piloting and evaluating solutions**

Piloting and evaluating concept solutions for use of hydrogen at Baltic Sea Region airports

- WP 2.1 Supply Chain
- WP 2.2 Aircraft Handling
- WP 2.3 Airport Equipment
- WP 2.4 Business Case

WP 3 **Transferring solutions**

Enabling target groups to get ready for hydrogen powered aircraft / vehicles aircraft

- WP 3.1 Communication
- WP 3.2 Durability Plan

Figure 2.: BSR HyAirport work packages 1 – 3.

The project focuses on applications using gaseous hydrogen as proposed smaller aircraft with up to 80 seats will use gaseous hydrogen and will be ready for production and operation much earlier compared to larger aircraft. First scheduled flights with gaseous hydrogen-powered aircraft could already operate at the end of the decade. Larger aircraft, e.g. the Airbus A320 family and Boeing 737 family that currently dominate intra-European air transport, will most likely use liquid hydrogen (LH_2) and not enter scheduled operations before 2035.

1.2 Objective of the report

This report documents the results of work package 1.2.3 Transport as part of the BSR HyAirport project. The aim of the report is to make concrete statements on possible transport solutions that are relevant for airports in the Baltic Sea Region based on scientific principles and project-specific analysis. In particular, the evaluation of economic efficiency is the centre of interest. The transport scenarios serve as practical examples to give the target audience a first impression of the hydrogen network in the Baltic Sea Region.

In addition, the report also provides a transferable basis for airports outside the project context. The decision-making principles presented can serve as a practical and initial guide for airports considering the introduction of hydrogen technology at their airport and help them to determine the most cost-effective transport method.

It is important to emphasize that the results presented here are not a final prognosis but are intended to serve as a guide and orientation aid.

2. Method

The following chapter presents the approach of the working group (WG) Transport and discusses collaboration with other working groups.

2.1 Methodology of the working group Transport

The approach taken by the working group Transport was to systematically evaluate the most suitable options for hydrogen transport for airports in the Baltic Sea region. The process began with a comprehensive literature review to understand the fundamentals and current state of hydrogen transport, as well as to gather reliable data on transport costs. However, the review revealed significant variations in reported transport costs, primarily due to differing assumptions and methodologies across studies. This variability made direct cost comparison challenging.

To address this issue, the team developed a special criteria system tailored to the context of the BSR HyAirport project, which enables the selection of studies with similar parameters and applications. Key factors influencing hydrogen transport cost were identified. This includes transport distance, storage methods and hydrogen demand. The value ranges for these parameters were determined based on real-life conditions at airports in the Baltic Sea region, as specified by project partners. Additionally, relevant data on airport infrastructure and hydrogen hubs collected to inform the assessment of transport options. In the project context, hydrogen hubs include production facilities, central storage facilities, import terminals and hydrogen refuelling stations (HRS).

For the scope of this analysis, only the direct costs of hydrogen transport were considered. Costs related to hydrogen production (e.g. electrolysis), on-site storage and refuelling infrastructure were deliberately excluded. This demarcation was intended to allow for a clear, isolated comparison of transport costs, unaffected by other variables that could otherwise hinder comparability. Using the established criteria, the most relevant study was identified.

A study by the Fraunhofer Institute for Factory Operation and Automation and Hamburg University of Applied Sciences (Solomon et al. 2023) was selected as it closely aligns with the project's context and requirements. The authors of this study were consulted directly to gain deeper insights into their research, and their cost calculation model was adapted to fit the specific parameters of airports in the region. The outcomes from this tailored model formed the foundation for the cost estimates of hydrogen transport to BSR airports. Subsequently, the analysis enabled the identification of the most cost-effective transport routes for each participating airport.

The results from this work package were used to develop a practical guide for airports, offering a structured tool for determining the most appropriate hydrogen transport method based on local conditions. To facilitate decision-making, a step-by-step decision tree was created, guiding users through the critical thresholds to identify the most cost-efficient transport solution.

2.2 Collaboration with other working groups

The evaluation from the WG Demand analysis was used to determine the initial hydrogen demand at the BSR airports for the cost calculation scenario in this report. This data-based approach makes it possible to get more accurate results.

The results from WG Transport are closely related to those of the WG Local production. Their findings help airports decide whether to invest in local production or decide for a hydrogen delivery model.

The outcomes from WG Transport contribute to the development of a business case, which is processed in the WG Business case. Determining transport costs is an essential component for establishing the financial framework.

3.Fundamentals of hydrogen transport

Hydrogen transport plays a crucial role in enabling the widespread adoption and integration of hydrogen as an energy carrier. The selection of the appropriate means of transport depends on various factors, including distance, volume, infrastructure availability and economic considerations.

This chapter examines the hydrogen state (gaseous/liquid) and their impact on transport needs. Furthermore, it provides an overview of the technological, infrastructural and economic foundations of hydrogen transport. The project looks at the three land-based transport options: truck, pipeline and rail. Understanding their characteristics is important to understand their suitability for hydrogen transport in different contexts. Shipping has been excluded as it is primarily used for high-volume international flows over long distances, whereas the focus of this project is on regional supply routes.

Regarding the economic dimension, it must be noted that several studies provide initial estimates of the transport costs of hydrogen, however, the results of these studies differ greatly from ~ 0.10 - 14 €. The reason for this lies in the different framework conditions and assumptions made when calculating costs. Factors such as the means of transport, the selected transport distance, the form of hydrogen considered, and the assumed demand have a major influence on the calculated costs. The literature review revealed that the great varieties in those factors make it difficult to define a generally valid transport price. The distances considered vary greatly in length, which ranges from about 25 km to 3,000 km. Furthermore, the demands considered differ in the studies depending on the scenario selected, up to 30 tonnes a day. Most available studies examine scenarios with a rather high hydrogen demand. As the demand of the BSR airports is expected to be low initially, this made it difficult to identify realistic short-term cost scenarios. Moreover, there are different selections for the means of transport (ship, train, truck and/or pipeline). In addition, in some studies the production price of hydrogen was considered whereas others include the costs for compression while ignoring the cost of production. The fact that hydrogen can be transported in different physical states also leads to many different prices that cannot be compared with each other or brought to a consensus. In order to be able to make reliable statements on transport costs for the BSR region in this project, the most cost-influencing indicators were defined, and the most suitable cost calculation was selected. The criteria system, cost calculation models and results are provided in Chapter 6.

It should also be noted that the simplifications taken by the authors influence the outcomes. While they are often necessary for mode tractability, they must be carefully considered when looking at the results. Common simplifications include assumptions such as neglect of certain variables like geographical factors and differences in labor costs, use of idealized models like no loss during and after transport and the exclusion of certain complexities in the system like jams or construction time.

3.1 Form of hydrogen

Hydrogen can be transported in its physical form in two states of aggregation: gaseous and liquid hydrogen. The choice of state has a direct impact on the technical design of transport infrastructure, energy efficiency, and financial implications. The (Energy Transitions Commission 2021) concludes that the volume of hydrogen and the travelled distance have the strongest influence on which form of hydrogen is most economical for transport.

Compression is required for the transport of gaseous hydrogen, which allows larger quantities to be transported at higher pressures, up to 1,000 bar (Energy Transitions Commission 2021). Therefore, the compressed hydrogen must be transported in special pressure-resistant containers. Throughout this report, the term GH_2 also includes compressed gaseous hydrogen. These can consist of:

- only a metal wall (type 1)
- a metal wall with a coating of resin-impregnated glass or carbon fiber composite reinforcement (type 2)
- a lining of metal, usually aluminum, and typically a reinforcement of carbon or glass fiber (type 3)
- or a lining of plastic, usually polyamide or polyethylene, and usually a carbon fiber reinforcement (type 4) (EMCEL 2020).

The conversion requires a considerable amount of energy (Energy Transitions Commission 2021). Transport can be conducted by pipeline, truck, rail or ship. The State Energy Agency of Hesse concludes that the transport of gaseous hydrogen in normal tank cars at low pressure is technically possible but not economically viable, as only small quantities could be transported (Milella et al. 2020). The transport by sea is not considered in this report.

Liquid hydrogen must be cooled to -253 °C and kept permanently cold (Ohmstede et al. 2023). The conversion process also requires a lot of energy. Well-insulated cryogenic tanks are essential for keeping hydrogen in its liquid state and preventing evaporation. The tank structure typically consists of a double-walled container. The inner wall stores LH_2, while the outer wall provides insulation and protection. The inner wall is usually made of materials such as stainless steel or aluminum alloys to provide tightness and resistance to corrosion caused by LH_2. The outer wall consists of insulating materials and protective layers to reduce heat transfer and external environmental influences. Despite these precautions, evaporation losses of around 1–5% per day can occur (Xie et al. 2024). Key challenges are the evaporation losses and the complex technology required. Liquid hydrogen can be transported by truck, train and ship. The Ministry of Energy Security states that transport via pipelines would be theoretically possible but is currently not feasible for technical, economic, and infrastructural reasons (Department of Energy Security & Net Zero 2023). Transport by ship is not considered in this report. Table 1. summarises the means of transport options for gaseous and liquid hydrogen:

Form of hydrogen	Means of transport			
	Truck	Pipeline	Train	Ship
GH_2	X	X	X	X
LH_2	X		X	X

Table 1.: Means of transport options for gaseous and liquid hydrogen.

Alternatively, hydrogen can be transported in the form of derivatives such as ammonia or methanol, which is already happening worldwide. Finally, hydrogen can also be transported in the form of hydrogen carriers such as liquid organic hydrogen carriers (Energy Transitions Commission 2021). Neither of these options will be considered further in this report.

3.2 Means of transport

This chapter provides an overview of the transport options truck, pipeline and train. Each method presents distinct advantages and challenges, shaped by technical, logistical and cost-related parameters. By examining these key transport modes, this chapter aims to support informed decision-making for efficient and cost-effective hydrogen supply chains.

3.2.1 Truck

Transporting hydrogen by truck is already an established method and currently the most flexible option for hydrogen distribution. The infrastructure is easy to set up, as the extensive road network can be used (Department of Energy Security 2023).

Gaseous hydrogen transported by truck is under high pressure of 200 to 500 bar, with 200 to 300 bar being the most used. The typical capacity of a truck loaded with gaseous hydrogen is between 400 and 1,100 kg. Liquid hydrogen has a higher energy density than compressed hydrogen (Xie et al. 2024). Trucks loaded with can transport between 2,000 and 4,500 kg. The pressure in the tanks is currently between 1 and 12 bar.

The fact that truck transport does not require complex infrastructure represents a cost advantage. The investment costs for truck transport depend on the number of trucks and trailers required and are based on transport capacity and travel time. Operating costs include maintenance, fuel, and personnel (Ohmstede et al. 2023). Trucks are most cost-effective for short distances and small volumes. This is due to the low energy density of hydrogen. The lower payload due to the heavy tanks remains a key challenge. This limits the amount of hydrogen that can be transported, making long-distance transport costly (Xie et al. 2024). By increasing the loading capacity of GH_2 trailers, total costs can be reduced by spreading the fixed costs over more hydrogen, thereby lowering the cost per unit transported (Department of Energy Security 2023). According to (Solomon et al. 2023), compression costs account for over 50 % of the total cost of transporting gaseous hydrogen by truck over short distances. As distance increases, the cost priorities shift: while compression costs remain largely constant, truck-related costs such as fuel, personnel, and maintenance increase significantly. The importance of transport costs therefore increases with distance, while compression costs become relatively less important. The (Energy Transitions Commission 2021) concludes as well that the cost of transporting hydrogen by truck increases with the distance travelled.

Many studies conclude that LH_2 trucks are more economical for long transport distances. The studies cite different distances, but these do not vary greatly and range from 200 - 400 km. For example, the Energy Transitions Commission and the University of Augsburg suggest distances of over 300 - 400 km, in the TransHyDe project they propose distances of over 200 km with a delivery volume of over 1 ton (Energy Transitions Commission 2021, Universität Augsburg n.d., Alekseev et al. 2023). The turning point is due to the higher energy density of liquid hydrogen compared to compressed hydrogen. This enables the delivery of larger quantities of hydrogen per trip (Xie et al. 2024). It is advised to take the different investment costs for gaseous or liquid hydrogen storage facilities into account. This report is purely focused on the costs of transport, excluding the infrastructure or production costs of the different versions of hydrogen (gaseous or liquid). In the end it is essential to find the optimal spot for the individual supply scenario, including investment costs, production costs of G/L H_2, demand, resulting in the different amounts of trucks and trailers needed and routes/km driven, and the transport costs.

For the contemplation and economic comparison of liquid hydrogen versus gaseous hydrogen transport, it is necessary to take the different costs for storage into account. The configuration and way of distribution at place needs to be individually considered, as it is dependent on the individual demand for hydrogen. As well the surrounding synergy effects need to be considered, if liquid hydrogen is used in other applications, or if only gaseous hydrogen is needed. It is possible to store the hydrogen in liquid form and re-gasify for the usage, or regasify it at delivery and store it in gaseous, compressed form. Both considerations come with higher cost, than an infrastructure based on gaseous hydrogen delivery.

In order to be able to find the real economic tipping point between transport in liquid or gaseous form of hydrogen, additionally to the needed receiving infrastructure, the costs for production of hydrogen of course need to be taken into account, as the production costs for liquid hydrogen are higher than gaseous hydrogen due to the increased energy demand for liquefaction. As described above, this report mainly focusses on the transport costs, neither on costs for production nor on the costs for the receiving infrastructure. It should be noted that liquid hydrogen is more cost efficient to scale up, especially for transport and refuelling. In the future, the delivery of liquid hydrogen could also be more advantageous when it is introduced as fuel for aircrafts.

3.2.2 Pipeline

Hydrogen can be transported via pipelines. They are already a central component of the energy infrastructure. However, there is a lack of comprehensive pipeline infrastructure for transporting hydrogen. There are three main types: gathering pipelines, transmission pipelines, and distribution pipelines (Department of Energy Security 2023). Gas transmission pipelines typically range in diameter of 20 - 48 inches and operate at a pressure of 50 - 80 bar. The width of the pipeline and the pressure influence the volume that can be transported through the pipeline (Wang et al. 2021).

Technically, the system is based on the principle of the existing pipeline network used for natural gas, but the physical properties of hydrogen make special demands. Two major issues in terms of materials and construction are permeation and material embrittlement. Hydrogen molecules are very small and can pass through pipeline walls, which can lead to potential gas losses. Material embrittlement can be caused by hydrogen, which weakens materials such as steel, which are often used in pipelines, making them susceptible to cracks and leaks (Department of Energy Security 2023).

The proposal to repurpose existing natural gas pipelines for hydrogen transport has generated a great deal of interest as it could reduce transport costs. However, the special properties of hydrogen pose a particular challenge compared to natural gas and require necessary modifications. Significant adjustments must be made, such as upgrading the material, improving the sealing and adapting the pressure management. This complicates the conversion process and can be costly (Xie et al. 2024). (Koops 2023) additionally states that the repurpose of natural gas pipelines would lead to an increasement of operating costs, due to friction-induced pressure loss implied by the surface structure of the old natural gas pipelines. This pressure loss leads to increased energy demand for the compressors while the repurposing of pipelines would lead to a decrease of capital costs by 75 - 90 %. A more detailed cost analysis of repurposing pipelines would help to evaluate this method. In conclusion, while existing pipelines for hydrogen transport are a viable and potentially cost-effective option for low to medium ranged transport (Koops 2023), it requires careful planning and significant modifications to the infrastructure. These factors must be considered when assessing the overall feasibility and cost-effectiveness of transporting hydrogen via pipelines (Wang et al. 2021).

The investment costs for new pipelines are mainly determined by the length and diameter of the pipeline. Operating expenditure, on the other hand, is primarily driven by maintenance work and electricity consumption, which varies depending on throughput and distance (Ohmstede et al. 2023) but will be far less than the operational costs of repurposed natural gas pipelines, which range up to a higher operational cost of 35 % (Koops 2023). Pipelines are generally not practical for low hydrogen demand due to the high investment costs. For large quantities of hydrogen, the higher capital costs for pipelines can be offset by lower operating costs. This suggests that economies of scale for pipelines lead to greater cost reductions than, for example, trucks (Collis et al. 2020). Some study results show that for hydrogen demand of more than 10 t/day, it makes sense to invest in the necessary expensive infrastructure for a pipeline (Energy Transitions Commission 2021, Solomon et al. 2023).

It needs to be noted that hydrogen transported by pipeline may not have the purity needed for Fuel Cell applications, that generally need a hydrogen quality of 5,0 (impurities of less than 10 ppm/ Purity of 99.999 Vol %). If hydrogen for Fuel Cell applications is directly taken from a pipeline, a purifier most probably would be needed to reach the required purity of hydrogen. This additional infrastructure may influence the operational and investment costs for this transport mode negatively.

3.2.3 Train

Although hydrogen transport by train is still in the development phase, it represents a promising option due to relatively low technological and regulatory barriers (Bregulla/ Kittler 2023). The current state of knowledge on hydrogen transport by rail is still limited compared to established methods such as pipeline or truck transport.

The already well-developed European rail network can be used to transport hydrogen by rail. A prerequisite for hydrogen delivery is a fully functional rail connection to the end customer. Investments in a comprehensive infrastructure specifically designed for this mode of transport are therefore generally not necessary. However, costs for transshipment, pickup, and storage at the origin and destination may arise. Otherwise, the last mile would have to be covered by truck (Bergulla/Kittler 2023).

In technical terms, hydrogen transport by rail is an expanded form of truck transport but is based on larger quantities per trip. That is why transport by train is particularly suitable for medium quantities and medium distances (Bregulla/ Kittler 2023). DB Cargo, for example, is actively involved in the development of hydrogen logistics. They are contributing to the further development of innovative hydrogen containers and testing logistics concepts for the transport of pure hydrogen. Special multi-element gas containers are used for the transport of gaseous hydrogen by train (DB Cargo n.d.). In a case study commissioned by the Landesenergie Agentur Hessen in which they investigated the potential of hydrogen transport via rail, a flat wagon of the type “Lgns 581” was used, which is designed to transport a 40 ft standard container with a maximum loading capacity of 26.6 tonnes. This has a capacity of 1,108 kg of hydrogen at 500 bar (Bregulla/ Kittler 2023). In June 2025, DB announced that the project partners DB Cargo BTT, Hexagon Purus, Endress+Hauser, Infraserv Höchst and Fraunhofer IML had developed a Multi-Element Gas Container (MEGC) for the multimodal transport of gaseous hydrogen by rail. The new MEGC is the first 500 bar container approved for rail use, with an increased load capacity of 1,223 kg. The container is specially designed for transport by rail using flat wagons. The tank has advanced sensors that enable continuous monitoring of pressure, temperature and vibration, thus enabling new safety standards. The container is scheduled to be tested on rail as part of a pilot project at the end of 2025 (DB Cargo 2025).

The transport of liquid hydrogen by rail is fundamentally possible, but there are currently no approved transport containers for this purpose in the EU (Universität Augsburg n.d.). In the USA, for example, they are already in use. Due to the low temperature required, special containers are also required for the transport of liquid hydrogen (DB Cargo, n.d.).

In terms of economic analysis, factors such as track access fees, personnel costs and container costs must be considered. Rail transport is the more sustainable hydrogen transport option due to its lower emissions and environmental impact. While trucks may face rising fees soon, rail transport could benefit from additional targeted government subsidies (Bregulla/ Kittler 2023).

3.3 Summary

Hydrogen transport relies significantly on the physical form of hydrogen. GH_2 is typically handled under high pressure, while LH_2 requires cryogenic temperatures, offering higher energy density at the cost of more complex logistics and specialized containers.

Pipelines are the most efficient solution for transporting large amounts of hydrogen over long distances, due to low operational costs and strong economies of scale but require significant capital investment. Trucks, both for GH_2 and LH_2, are adaptable options for small- to medium-scale deliveries and short-to-moderate distances. They involve lower upfront costs but have higher operating and environmental costs. Rail transport is emerging as a promising solution for medium quantities and distances. It leverages the existing rail network, usually requires little additional infrastructure, and new container innovations like high-pressure MEGCs are increasing capacity and safety. Economic considerations include infrastructure, maintenance, and operational costs for each mode. Table 2. summarises the key factors regarding the means of transport considered.

Criteria	Means of transport				
	Truck GH_2	Truck LH_2	Pipeline	Train GH_2	Train LH_2
Investment cost	Low	Medium	Very high	High	High
Operational cost	Medium	Medium	Low	Low	Low
Cost efficiency	Low (Better for smaller demands and shorter distances)	Medium (Better for medium to high demands and longer distances)	Very high (Better for higher demands and longer distances)	High (Better for medium demands and medium to longer distances)	High (Better for medium to high demands and medium to longer distances)
Scalability	Low	Medium	Very high	High	High
Transport volume	Low	Medium	Very High	Medium	Medium
Infrastructure Requirements	Low	Medium	Very high	High	High

Table 2.: Means of transport in comparison.

4. Integration of Hydrogen Logistics into Airport Infrastructure

The integration of hydrogen logistics into airport infrastructure presents a complex set of challenges and requirements. This section addresses special conditions influencing the selection of transport modes for hydrogen at airports.

4.1 Framework conditions and requirements at airports

From the comparisons of hydrogen transport options conducted so far, it can be concluded that the choice of a suitable mode of transport heavily depends on the specific usage context and thus also on the individual airport context. The choice of a suitable mode of transport for hydrogen at airports must be closely linked to the specific conditions of each airport. Factors such as the size of the airport, its geographical location, the expected hydrogen demand and the existing infrastructure play an important role in deciding which transport solution is practical and efficient. Airports are also characterised by special conditions that influence the selection and implementation of hydrogen logistics, including:

- High safety standards
- Strict access and control regulations
- Limited space availability, especially for new infrastructure (e.g. storage or production facilities)
- High requirements for supply security and reliability
- Fluctuating hydrogen demand (e.g. seasonal)
- Integration into existing logistics processes such as kerosene supply

It should also be noted that transport solutions at airports are significantly influenced by technological developments and the legal framework. The implementation of hydrogen logistics also requires cooperation with stakeholders such as energy suppliers, logistics service providers and regulatory authorities.

4.2 Evaluation of transport modes for airport applications

This section evaluates the transport options for trucks, pipelines and trains. It highlights their strengths and limitations and suitability for different airport environments.

4.2.1 Truck

Transporting hydrogen by truck is particularly suitable for testing hydrogen aircraft, as well as for the beginnings of hydrogen use at airports and for smaller airports.

It does not require the construction of large-scale infrastructure such as pipelines or rail stations, thus enabling a comparatively rapid and cost-effective market entry. Since airports already have secure and well-organised logistics zones, where kerosene is also typically delivered by truck, existing processes and safety precautions can be applied to hydrogen requirements. Moreover, truck transport allows for flexible scaling of delivery volumes, which is a decisive advantage when demand is initially low or fluctuating.

Hydrogen transport by truck is reaching its capacity limit as demand increases. The low energy density per truck unit requires a high number of trips, which significantly increases logistical effort and operating costs. From piloting activities, it can be suggested that deliveries should not exceed one truck per day if there is no central storage facility at the airport and the applications are solely run by trailer swap. From an ecological perspective, this could also be problematic if most transport is not carried out with emission-free vehicles, thus generating additional emissions.

4.2.2 Pipeline

For airports with consistently high hydrogen demand as well as for airports with direct or planned connections to the hydrogen pipeline network, pipeline transport offers the most efficient and economical supply option in the long term.

A key advantage for airport operation is that the transport of hydrogen via pipelines enables a continuous and stable hydrogen supply. Another advantage is the space-saving integration on the airport grounds, as no large storage capacities are required. Additionally, while the construction of a pipeline involves high initial investments, these are amortized through comparatively low operating costs, if the demand remains high. From an ecological perspective, the ongoing operation of the pipeline represents a very low-emission transport option.

The challenges lie in the complex and lengthy planning, approval and construction of pipelines on airport grounds. The effort increases when airports have no existing or planned connection to the external hydrogen network. Furthermore, the pipeline supply is less flexible when demand fluctuates significantly.

4.2.3 Train

Possible application scenarios for hydrogen transport by rail include medium-sized airports with direct connections to the freight rail network, as well as airports with seasonally fluctuating hydrogen demand.

Logistical integration is efficient when airports with existing or nearby rail connections and a growing medium-term hydrogen demand can utilize the existing infrastructure. For airports with seasonally fluctuating hydrogen demand, rail offers a good balance between flexibility and capacity, unlike pipelines or trucks. Rail delivery can be planned according to demand, so costs only arise when needed. Furthermore, rail transport can represent a useful intermediate stage between truck supply and pipeline infrastructure, as operationally relevant quantities can be delivered efficiently. Finally, transport by rail is very low in emissions.

A major obstacle, however, is the lack of freight rail connections at most airports. The "last mile" would require transfer to trucks, which would significantly increase logistical costs.

4.3 Summary

In summary, hydrogen supply at airports is constantly evolving. Requirements vary depending on the phase an airport is in. As hydrogen demand increases, some airports may change their transport methods (Aerospace technology institute 2022). During the rollout phase, the focus is on flexibility. Initial hydrogen demand is low and no significant initial investment is advantageous. During this phase, transporting gaseous hydrogen by truck is the most economically and operationally viable solution. This option allows for a quick start without the need to implement extensive infrastructure measures on the airport site. After the initial phase, during which road transport is likely to be the preferred transport method, other transport methods may be preferred as demand increases and the frequency of tanker deliveries becomes unsustainable (Aerospace technology institute 2022), meaning that more reliable and scalable systems will be required over time. These decisions are determined by local infrastructure conditions, regional supply corridors and a careful assessment of current and future demand. Table 3. compares the three transport methods in terms of their suitability, strengths, weaknesses and their role in supply evolution.

Transport method	Best suited for	Strength	Weakness	Role in supply evolution
Truck	Airports in rollout phase with low initial demand	High flexibility, low initial investment, quick deployment, no extensive infrastructure needed	Unsuitable for sustained high demand, frequency of deliveries becomes unsustainable over time	Preferred in early phase, enables rapid start and operational flexibility
Pipeline	Airports with high sustained demand and pipeline network access	Continuous, stable supply, space-saving, low operating costs, low emissions	High initial investment, complex planning and construction, less flexible if demand fluctuates, limited to airports with network access	Long-term solution for mature, high-demand airports
Train	Medium-sized airports with rail access, airports with seasonal/variable demand	Flexible scheduling, uses existing infrastructure, efficient for operationally relevant quantities, low emissions	Most airports lack direct freight rail links, "last mile" transfer to trucks increases costs	Intermediate solution as demand grows, balances flexibility and capacity

Table 3.: Transport methods for airport applications in comparison.

5. Assessment of infrastructure conditions at BSR airports and scenario definition

To assess the suitability of different modes of transport, it is important to understand the local and regional conditions at the airport locations. These are crucial for short-term and long-term planning and decision-making. Key factors include, on the one hand, the hydrogen hubs around the airport, as they determine the transport distance.

All project partners examined the regional developments of existing and planned hydrogen hubs, such as production and storage facilities, HRS and import infrastructure. This assessment was crucial for understanding the spatial distribution and availability of hydrogen supply sources around BSR airports. Connectivity to such hubs influences the choice of transport mode. It is particularly important to understand which airports need to be integrated into emerging supply corridors due to a lack of nearby hubs. Furthermore, the connection to the freight rail or pipeline network is crucial for the short-term feasibility of this transport option. If this is not available, it must be examined whether appropriate infrastructure is planned or could be implemented in the future.

Therefore, an overview of the current, under construction and planned infrastructure at the BSR airports has been provided. The results of this analysis are presented in Figure 3. The information presented in the map is based on data provided by the project partners and the hydrogen infrastructure map from ENTSOG, EUROGAS, GIE, GEODE, GD4S, and CEDEC in collaboration with the EHB (Entsog Aisbl n.d.). Current information can be found on the website: https://www.h2inframap.eu/#map.

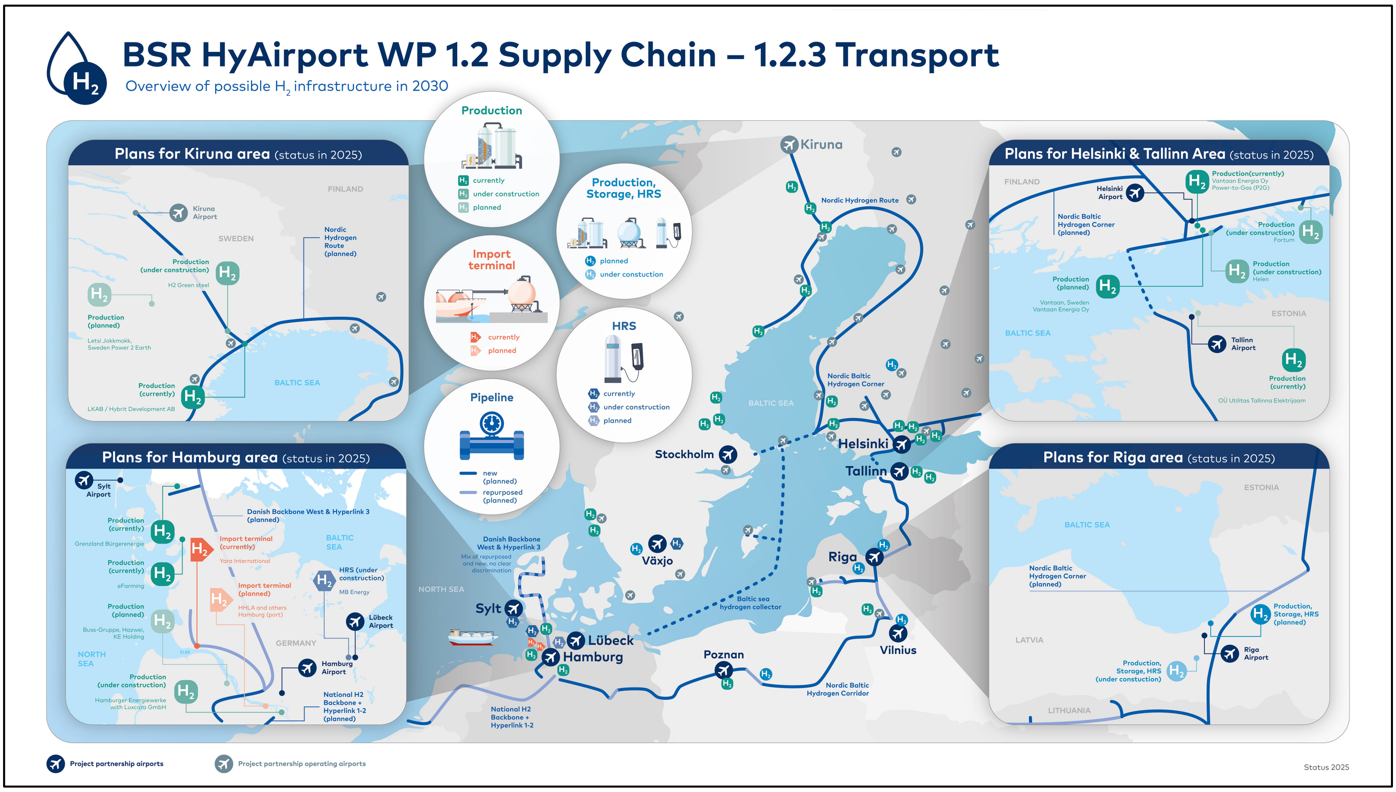

Figure 3.: Map – Framework conditions for participating BSR airports.

NOTE: The map in Figure 3. shows a preliminary overview and makes no claim to completeness. It shows a selection of hydrogen infrastructure in the Baltic Sea region. The decision as to which hydrogen hubs are classified as relevant for the BSR airports lies with the decision-makers of the respective airport partners. For example, the shortest travel distance to the nearest regional hydrogen hub or a highly relevant large-scale hydrogen production facility can serve as the basis for the decision. Furthermore, this map shows those pipelines that run in the region of BSR airports and therefore offer increased potential for future connections. Further pipeline connections are planned in Europe. It should also be noted that ultimately it cannot be verified whether the hydrogen hubs and pipeline connections built or planned will actually go into operation, as it has not been confirmed by the respective operators to the project partners. That is why the map represents a selection of possible hydrogen infrastructure in the Baltic Sea Region in the future.

5.1 Hydrogen hub

Figure 3. shows that the Baltic Sea Region already has a moderate number of hydrogen hubs, but there is still considerable potential for development. Hydrogen hubs include in this project context production facilities, central storage facilities, import terminals and hydrogen refuelling stations. Some airports are already relatively close to a hydrogen hub, often within a radius of around 150 to 200 kilometres. This indicates that at least a basic infrastructure is in place. Växjö Airport, for example, is particularly well positioned, as there are already two hydrogen hubs in their vicinity. Both are less than 70 kilometres away from the airport. The nearest hydrogen hub is the production site in Ljungby by Strandmöllen AB. Växjö Airport therefore benefits from a certain degree of security of supply. Airports such as Umeå and Kiruna are located within a medium distance range of 250 to 350 kilometres.

Despite these existing structures, the expansion of central hydrogen production centres is still in the planning phase in many countries. These planned projects could make a significant contribution to shortening the distances between airports and hydrogen infrastructure in the future. One example of this is the region around Poznan Airport, which currently has no hydrogen infrastructure. However, there are already concrete plans to build a hydrogen hub near the airport, which would significantly facilitate future supply.

At the same time, many of these projects are still subject to uncertainty. Successful implementation depends on multiple factors. In Sweden, for example, the implementation status of individual projects is unclear. The example of Sylt also illustrates that just being close to a hub doesn't automatically guarantee a secure supply: despite the short distance to a hydrogen hub, there's currently no way to transport hydrogen from the mainland to the island. This example shows that if there are no transport options, local production solutions should be considered early on.

Overall, it can be said that the Baltic Sea Region already has a solid foundation in terms of hydrogen hubs, but that targeted infrastructure measures are needed to secure the hydrogen supply. The early involvement of local stakeholders is crucial for the development of location-specific solutions.

5.2 Pipeline

Figure 3. shows as well that currently, none of the airports are connected to a hydrogen pipeline system, and no pipelines are under construction. Furthermore, no pipeline connections are planned for almost any airport. As an exception Hamburg Airport plans to connect to the city's pipeline network in future, which is currently under construction. In 2019, the airport signed a letter of intent with the local gas network operator. The actual construction of the pipeline to Hamburg Airport depends on the future demand for hydrogen at the airport. Other airports have not yet made such efforts.

With the European Hydrogen Backbone, this could change in the future. The EHB Initiative is a group of European gas network operators who want to build a cross-border hydrogen transport network. The initiative plans to build a hydrogen network and proposes five main hydrogen corridors: the North Sea Corridor, the Nordic and Baltic Corridor, the Southwest Corridor, the North Africa-Italy Corridor, and the (South)Eastern European Corridor. The various major hydrogen transport corridors are to be connected into a central European network by 2040. The network is to be expanded to 53,000 km by 2040, with approximately 60 % of the planned network consisting of repurposed natural gas pipelines and up to 40 % of the pipelines to be newly built (Van Rossum et al. 2022). These existing strategies provide a good framework for future development. They form the basis for the development of a hydrogen infrastructure that can be expanded in the future. Since hydrogen demand at larger airports will increase significantly, it makes sense to supply airports with these pipelines in the future, which should be considered in the planning process today. One of the most important recommendations would therefore be to extend the European hydrogen backbone to major airports.

The lack of a pipeline connection, however, highlights that pipelines are not a realistic option for transporting hydrogen to airports in the short term due to the construction time. This could change in the medium to long term, especially if the European hydrogen network is further expanded, which could be possible with the planned European Hydrogen Backbone.

5.3 Railway connection

The availability of rail infrastructure is a key factor in assessing rail-based hydrogen delivery. A suitable connection to freight transport is crucial in this regard. There are significant differences in the connection of Baltic Sea Region airports to the rail network for passenger and freight transport. Table 4. shows the railway connections currently and planned for passengers and cargo for the BSR airports. Some airports already have an extensive rail connection, some are still in the planning and development phase, and some airports have no plans at all for a future rail connection. Vilnius Airport is very well connected, as it has a railway connection for passengers and a railway connection directly to the airport's fuel storage facilities to the city. Additionally, another major rail connection is currently being reconstructed as part of the Rail Baltica project, which will link Lithuania to the broader European rail network. Hamburg, Helsinki, and Stockholm currently have a rail connection, but it is only intended for passenger transport. In Hamburg, for example, the S1 line provides a direct train connection between the airport and the city centre with a travel time of less than 30 minutes. Stockholm has a high-speed train between the airport and the city centre with the Arlanda Express. There is a freight connection about 10 km from Arlanda Airport. Stockholm is currently supplied with Jet-A1 via this connection, with the last mile delivered by pipeline. Most airports participating in the project currently have no rail connection. Riga, Kaunas and Gothenburg are currently the only airports planning a connection to the rail network for passengers. For Kaunas airport, besides the plans for the railway connections for passengers, there are also plans for a railway connection for cargo. For Riga airport, in October 2025, the Latvian government approved regulations proposed by the Ministry of Transport to implement the Riga railway node connecting infrastructure project. This includes building a new railway link between Imanta station and Riga International Airport, funded by the Cohesion Fund. The project aims to improve mobility in the Riga metropolitan area by connecting key transport hubs—Riga Airport, Riga Central Station, and the Aizkraukle direction. It will be implemented by Latvian Railways in cooperation with the national Rail Baltica implementer, European Railway Lines, with a total budget of 264.17 € million. It will include construction of a 1,520 mm gauge railway branch from Rail Baltica station at the Riga airport to Imanta. However, most airports show no planned developments towards rail connections. Even airports with existing passenger connections, including Stockholm, Helsinki, and Hamburg, are not planning any freight connections.

Overall, it can be said that the small number of airports with rail connections, especially for freight transport, and the lack of plans for their expansion significantly limit the role of rail as a transport option for hydrogen at airports in the Baltic Sea Region. At almost all airports in the Baltic Sea Region, targeted investments in rail terminals for freight transport would be necessary to transport hydrogen by rail.

Airport	Railway connection currently		Railway connection planned	
	Passengers	Cargo	Passengers	Cargo
Helsinki	Yes	No	Already exist	No
Tallinn	No	No	No	No
Riga	No	No	Yes, early stage	No
Vilnius	Yes	Yes	Already exist	Already exist
Kaunas	No	No	Yes (in 2030)	Yes (2030)
Palanga	No	No	No	No
Poznan	No	No	No	No
Hamburg	Yes	No	Already exist	No
Lübeck	No	No	No	No
Sylt	No	No	No	No

Stockholm	Yes	Approx. 10 km from airport	Already exists	Approx. 10 km from airport
Gothenburg	No	No	Yes, early stage	No
Umeå	No	No	No	No
Kiruna	No	No	No	No
Växjö	No	No	No	No

Table 4.: Railway connections currently and planned at BSR Airports (Status 10/2025).

5.4 Summary

These findings provide a basis for strategic planning and infrastructure development for BSR airports. They show where existing hydrogen logistics can be used and where limitations arise.

The analysis of the existing infrastructure shows that most airports currently have neither a direct pipeline nor a rail freight connection. This limits the immediate feasibility of large-scale hydrogen deliveries via these modes of transport. Short- to medium-term supply strategies are likely to rely on hydrogen deliveries by truck, which require minimal local infrastructure. Geographical analysis shows that most airports are currently located at an average distance of around 200 km from hydrogen hubs. The proximity of hydrogen hubs to airports already reduces the logistical effort and is advantageous given the relatively low initial demand for hydrogen at airports. The number of hydrogen hubs is expected to increase in the future, further reducing the distances between airports and hydrogen supply points and enabling efficient supply by truck. The lack of fixed infrastructure highlights the need for investment planning and policy coordination if airports switch to more scalable means of transport such as pipelines or trains in the future. This underscores the need for coherent policy interaction at EU and national level for the development of transport infrastructure in Europe.

The expansion of the pipeline network in Europe is creating an increasingly well-connected supply system, the implementation of which suggests that a secure supply of hydrogen from countries with strong export capabilities can also be guaranteed in the future. Airports could thus be reliably supplied with the hydrogen required as aviation fuel. Figure 3. also shows that, thanks to the existing infrastructure, supply is already possible in many places during the introductory phase.

In addition to analysing the airport infrastructure, it should be noted at this point that the use of hydrogen at the BSR airports is currently in the introduction phase or will be in the future. Therefore, as explained in the previous chapters, the use of hydrogen trucks in the early phase with initially low demand currently appears to be the most pragmatic and strategically sensible solution to gain initial operational experience and gradually advance the development of a viable hydrogen infrastructure.

6. Calculation of transport costs for BSR airports

To conduct a comparable assessment of hydrogen transport options for airports in the Baltic Sea Region, several assumptions and framework conditions were defined. These were derived from a combination of insights gained through literature review and discussions within the project’s working group.

6.1 Criteria system and input parameters for cost calculations

Based on the assumptions of the study research, a system of criteria for calculating transport costs was developed. These variables include means of transport, transport distance, hydrogen demand, physical state of hydrogen (mode) and scope and boundaries of the cost analysis. These are used as primary input parameters for cost calculations and decision tools developed in the project.

1. Means of transport
   The analysis considers trucks, pipelines and rail transport. These options are generally recognized in the literature as suitable for regional and national delivery routes. Shipping is excluded from the assessment because the project focuses on last mile delivery to airports rather than transcontinental supply chains.
2. Transport distance
   For each airport, the distance to a hydrogen hub that either already exists, is under construction, or is planned was determined. This data was used to define the distance range analysed in the project. The analysis shows that the scenario primarily considers distances to 400 km.
3. Hydrogen demand
   The hydrogen demand for airports was estimated based on the results of the project's working group 1.2.1 Demand Analysis. Assumptions were made for possible routes in 2030 and 2035. A tool was developed to define the demand for aircraft and vehicles for these scenarios. The assessment of the transport sector also focuses on the short- to medium-term demand volumes that can be expected within the next 10 years. Demand is initially estimated at around 1 ton per week, which is realistic for regional air traffic and ground handling vehicles in early introduction scenarios.
4. Physical state of hydrogen (mode)
   The project focuses primarily on the transport of gaseous hydrogen, as this form is currently considered the most accessible and scalable option for early hydrogen applications in aviation, especially for regional routes and smaller aircraft. Liquid hydrogen is considered a secondary scenario, as it could be relevant in the future for larger aircraft and long-haul flights, as well as for specific secondary locations where distance and hydrogen demand could lead to a tipping point between the preference for transporting gaseous or liquid hydrogen.
5. Scope and boundaries of cost analysis
   To ensure comparability between the different modes of transport, the cost model focuses exclusively on transport-related costs. The costs of hydrogen production, on-site storage, or refuelling infrastructure at airports are not included in the calculation, as other working groups within the project have addressed these aspects. Only the costs of delivering hydrogen to the airport are evaluated.

Criteria	Project-related assumptions
Means of transport	Truck, pipeline and train
Travel distance	0 – 400 km
Hydrogen demand	1 ton per week
Hydrogen mode	GH_2 (LH_2 considered as secondary scenario)
Scope and boundaries of cost analysis	Transport-related costs only

Table 5.: Overview criteria system for determining transport costs in project context.

6.2 Methodological basis for cost estimation

To estimate the costs of transporting hydrogen to airports, this section presents and evaluates an important reference study that provides relevant data, assumptions, and methodological approaches. This reference study serves as the basis for the subsequent cost calculations.

This basis is provided by the reference study “Cost optimization of compressed hydrogen gas transport by truck and pipeline” by the Fraunhofer Institute and HAW Hamburg. The assumptions made are closely aligned with the framework conditions of the BSR HyAirport project. The aim of the study is to optimize the hydrogen supply chain and improve the cost efficiency of transport. The authors examine various key factors that influence transport costs, including pressure level, transport capacity, trailer capacity, pipeline diameter, pressure drop, and transport distance. Overall, the study provides a detailed methodological basis for evaluating economical transport options. The study considered pressurized gas trucks with 350 and 540 bar and pipelines with three different diameters of 100 mm, 150 mm and 200 mm as means of transport. Costs were calculated for distances of 25 - 500 km and a hydrogen demand of 2 - 30 tonnes per day. The levelized cost of hydrogen transport (LCOHT) in the study ranges from 0.30 to 3.44 € per kg. The study examines the costs associated with hydrogen supply in a European context (Solomon et al. 2023).

While most parameters such as means of transport, type of transport and distance were in line with the project requirements, the hydrogen demand assumed in the original study was significantly higher than necessary. Within the framework of BSR HyAirport, a weekly hydrogen requirement of only 1 ton per week was considered appropriate. Based on this revised requirement, the Fraunhofer Institute recalculated the relevant cost values, resulting in project-specific transport costs.

6.3 Evaluation of optimal transport routes and cost estimations for BSR airports

This chapter presents suggestions for the optimal means of transport for hydrogen supply to the BSR airports and the transport costs based on the previously defined criteria and reference study.

The determination of the optimal transport mode is therefore based on factors such as transport distance and hydrogen demand. The adapted analysis conducted from the Fraunhofer Institute considers only gaseous hydrogen, other transport forms such as liquid hydrogen were excluded. The scenario assumes a weekly delivery of 1 ton of hydrogen, representing the expected initial demand at the Baltic Sea Region airports. Based on these parameters, transport by truck using a 350-bar trailer is identified as the most cost-efficient solution for supplying hydrogen to BSR airports, which can be seen in Figure 4. Most airports in the BSR region are located within a 200 km radius of a hydrogen hub, making the delivery of gaseous hydrogen by the truck the most economically viable option. For Umeå and Kiruna transporting liquid hydrogen by truck could be advantageous due to the greater distances to the next hydrogen hub. In these cases, a switch to liquid hydrogen should be considered depending on actual demand.

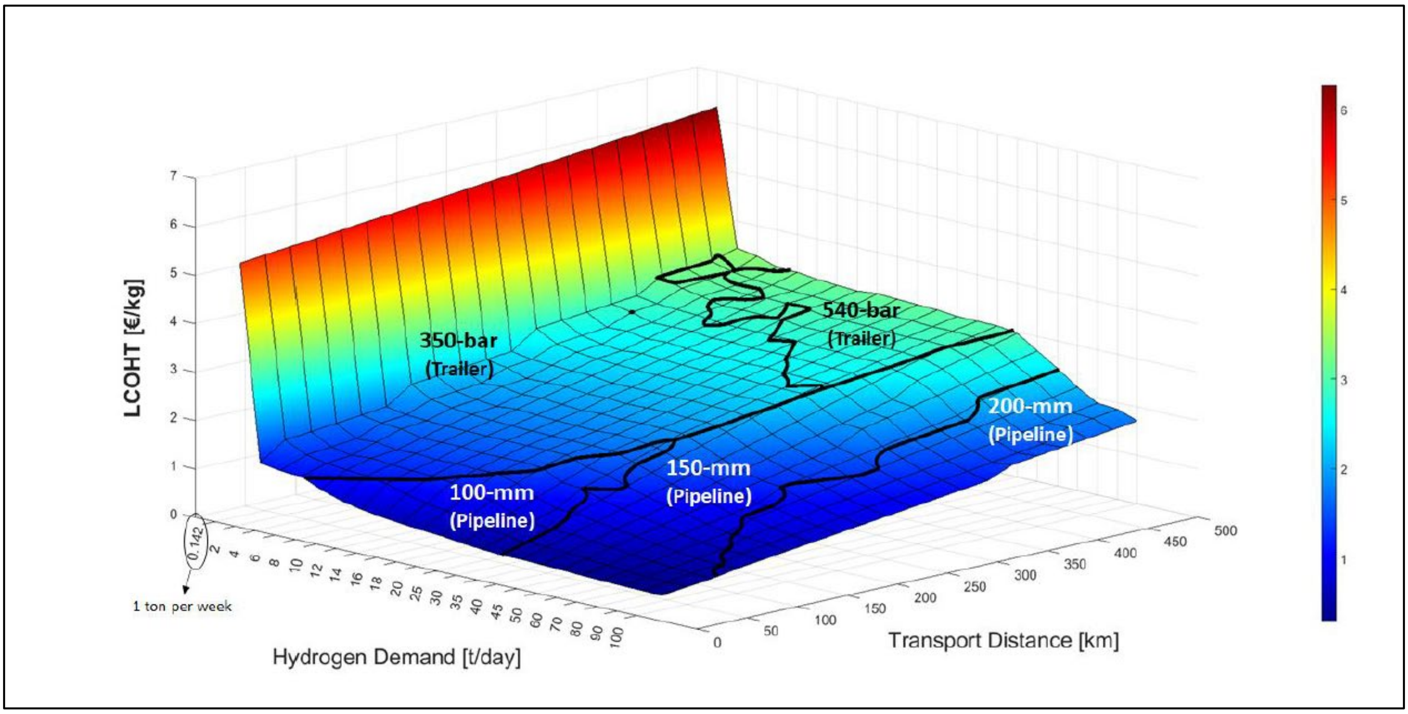

Figure 4.: Least LCOHT as a function of hydrogen demand and transport distance created by Fraunhofer IFF.

The transport costs for the 350-bar trailer, which is the optimal means of transport, are listed below in Table 6. Based on a demand of 1 ton per week, the levelized cost of hydrogen transport is given for distances from 25 to 500 kilometers. These values represent an indicative cost baseline from which BSR airports can estimate the delivery cost per kilogram of hydrogen for their cases. The results show a clear advantage of using regional hydrogen hubs.

350-bar Trailer	
Distance (km)	LCOHT (€/kg)
25	5.23
50	5.29
75	5.34
100	5.40
125	5.45
150	5.51
175	5.56
200	5.61
225	5.66
250	5.72
275	5.77
300	5.83
325	5.88
350	5.94
375	5.99
400	6.05
425	6.10
450	6.16
475	6.21
500	6.27

Table 6.: LCOHT for transport distance from 25 – 500 km for 350-bar Trailer for a fixed demand of 1 t/week.

Using Hamburg airport as an example for a transport cost scenario, the hydrogen hubs closest to the airport were selected to serve as the supply start. Transport costs were calculated based on the project-determined LCOHT. Hamburg is currently already benefiting from the presence of nearby hydrogen hubs and it is expected that further hubs will be added soon. Currently, the Ammonia import terminal in Brunsbüttel is the closest hydrogen hub with an approximate distance of ~ 85 km to Hamburg airport. The transport costs by truck would be 5,362.54 € for this scenario. Assuming the current market price of around 10 € for 1 kg of green hydrogen, transport costs have a share of 1/3 of total expenditure, representing a substantial share. Therefore, they must be carefully considered during the planning process to ensure economic efficiency. A hydrogen hub that is under construction is the production site at Hamburg Moorburg operated by Hamburger Energiewerke with Luxcara GmbH. With ~ 30 km to the airport, the transport cost would be reduced to 5,242.06 € in total. If Hamburg Airport were to source hydrogen from the Port of Hamburg in the future, the distance to the airport would be even shorter with only ~ 20 km travel distance and the transport costs would further decrease to 5,218.98 €.

The results suggest that GH_2 supply via road transport is realistic and optimal for most locations. However, location-specific supply strategies, especially for remote areas—where alternative forms of hydrogen, such as liquid hydrogen, become necessary, always must be considered. For some regions with various possible smaller customers, the transport costs may influence the price too much with the consequence that it is not viable for every customer. With the existence of a larger customer (e.g. airport), that might function as a so-called anchor-customer, the hydrogen delivery price can be influenced through the any-way existing delivery schemes of this larger customer. It might also be worthwhile to build larger storage systems for the aforementioned customer (e.g. airport), than needed, to function as bufferstorage / depot for local supply, which would influence the overall costs, as bigger volumes can be transported initially. In this case it makes sense to estimate if a liquid or gaseous storage would be viable. Influencing factors besides the resulting transport price through liquid or gaseous transport, are for example resulting investment costs for storage and peripheral infrastructure (different for the different physical states of hydrogen) as well as the different needs of special planning (size).

Due to the lack of data on the transport of gaseous hydrogen by rail, a cost calculation was not conducted for this transport option. However, for airports with existing or potential rail connections, a future shift to rail could be reasonable option as the volume increases. The synthesis report of the TransHyDE project LNG2Hydrogen, part of the German flagship project TransHyDE, examined the transport of liquid hydrogen by rail and provides a reference point for initial insights. This analysis considered larger transport volumes of 6 tonnes per container, which, compared to the Frauenhofer Institute cost calculation scenario of 1 ton per week results in economies of scale and thus lower specific transport costs. The report estimates transport costs of approximately 0.60 - 1.25 €/kg for distances between 100 and 1,000 km (Hydrogen flagship project TransHyDE 2025).

In general, there is currently a research gap regarding the costs of liquid hydrogen in smaller quantities. This is primarily since the transport of small volumes of liquid hydrogen is associated with disproportionately high specific costs compared to gaseous hydrogen. Assuming rising demand in the future, this situation could change. In this context, the study "Liquid hydrogen distribution to refuelling stations – comparison with other options" published by the Research Institute of Sweden is worth mentioning as it provides initial insights into how transport costs for gaseous and liquid hydrogen could develop and what developments can be expected. In the study, the use of liquid hydrogen (including liquefaction) for transport to and regasification at hydrogen refuelling stations was compared with the compressed hydrogen gas option. The study also compares safety and regulatory aspects. The study compares three stages in the supply chain: 1) liquefaction or compression at the distribution hub, 2) transport of LH_2 or GH_2 to the hydrogen refuelling station (HRS) and 3) the use of LH_2 or GH_2 at the HRS providing 700 bar gaseous hydrogen. The study, although with many uncertainties, shows that in a developed market with a low-cost scenario, the higher liquefaction cost (than compression) in stage 1 is compensated for by the lower transport and HRS cost, especially for longer distances (e.g. 500 km). For the transport stage LH_2 costs are 2.95 and 6.73 SEK/kg (0.26 and 0.60 €) for 200 and 500 km, respectively (based on 10 t/day transport quantity). For GH2 the corresponding values are 9.58 and 21.53 SEK/kg (0.86 and 1.92 €) (Gopalakrishnan et al. 2025).

It's important to note that the scenarios are based on theoretical distance analysis and indicative cost models derived from scientific studies. In practice, real-world conditions - such as market fluctuations, supplier availability, and seasonal demand - can lead to deviations from the modeled cost-optimal delivery paths. Furthermore, logistical challenges such as the availability of delivery trucks can significantly impact costs. Discussions with industry experts suggest that actual hydrogen delivery cost, especially in early market phase, could be relatively higher than model-based estimates. These deviations are often attributed to currently low delivery volumes, immature logistics chains, and uncertainties regarding long-term demand commitments.

It is reasonable to expect that as demand for hydrogen powered aircraft increases, airports may have to adapt their transport option to meet the rising need for hydrogen supply and to be able to operate economically. This could involve a shift to more scalable transport options such as pipelines. The numerous hydrogen strategies already established in the Baltic Sea countries and across Europe provide a solid foundation for building the necessary infrastructure, as they include national and regional plans for hydrogen production and distribution. The European Hydrogen Backbone is becoming particularly important in this context: as a cross-border pipeline system, it is an essential component of a sustainable energy infrastructure in Europe and plays a key role in the secure and large-scale supply of hydrogen. Therefore, it is expected that the necessary infrastructure will be put in place to ensure that airports can efficiently meet the growing hydrogen demand in aviation.

6.4 Summary

The analysis, using Hamburg Airport as a reference, demonstrates a direct correlation between hydrogen transport costs and the proximity of supply hubs. Transporting hydrogen from the Brunsbüttel ammonia terminal (~ 85 km) incurs a cost of 5,362.54 € for a demand of 1 t/week, while closer sources such as Hamburg Moorburg (~ 30 km) and the Port of Hamburg (~ 20 km) reduce costs to 5,242.06 € and 5,218.98 €, respectively. Given the current market price for green hydrogen is approximately 10 €/kg, transport expenses form around one-third of the total delivery cost. This substantial share highlights the need for careful planning around hub selection and delivery logistics to ensure economic efficiency. For remote areas, alternative hydrogen forms such as liquid hydrogen may be necessary, and supply strategies should be tailored accordingly. The presence of a large customer can help stabilize delivery prices and logistics. Building larger storage systems for such customers can serve as buffer storage or depots for local supply, potentially reducing overall costs by enabling initial bulk transport. Planning should include an assessment of whether liquid or gaseous storage is more appropriate, factoring in investment costs for storage and peripheral infrastructure and the specific requirements for each hydrogen state.

In summary, the cost-optimal strategy for airport hydrogen supply hinges on minimizing transport distances, leveraging economies of scale through anchor customers and central storage, and adapting infrastructure as demand grows. Real-world market and logistical factors must be considered alongside model estimates.

7. Guidelines for planning hydrogen logistics at airports based on project results

Building upon the adapted cost analysis, a guidance- and a decision tree model was developed to provide a first orientation for selecting suitable hydrogen transport modes for airports.

The guidance provides a structured record of the geographical location and proximity to hydrogen hubs, the availability and suitability of existing infrastructure, the type and scope of hydrogen requirements and the framework conditions for implementation. The aim is to obtain well-founded information for the planning of hydrogen transport to the desired destination airport.

Figures 5. – 7. show the decision tree, divided into 3 subtrees, which serves as a practical guide to determine the most suitable transport solution based on the most important influencing factors such as distance to the hydrogen hub, weekly demand and existing infrastructure connections at the airport. It provides a systematic framework for stakeholders to make planning decisions at an early stage. However, the optimal delivery strategy depends on several factors: transport distance, amount of hydrogen to be transported, availability of existing infrastructure, and end use. The decision tree attempts to reflect this, but it is too rigid to make concrete statements about the best transport option.

Guidance for planning hydrogen logistics to airports

1. Geographical location
    a. *Hydrogen hubs*
    Where are the nearest hydrogen hubs? What is the distance between the hub and the airport? (Hydrogen hubs can be e.g. production sites, import terminals, storage facilities and/or HRS)
2. Existing infrastructure
    a. *Railway connection*
    Does the airport have a railway connection? Can it be used for hydrogen transport? If not, could it be adapted for hydrogen transport?
    b. *Pipeline connection*
    Does the airport have access to a hydrogen pipeline system? Is there potential to connect it to one in the future (any planned infrastructure projects)? If yes, what needs to be considered in the planning process so the airport can be connected to the pipeline network?
    c. *Road infrastructure*
    Is the road infrastructure on and around the airport capable of handling hydrogen transport?

3. Hydrogen demand
    a. *Form of utilization at airport*
       Which mode of hydrogen is needed at the airport?
    b. *Estimate hydrogen demand*
       How is the demand of hydrogen in the short term and how will the demand increase in the long term (per day, week and month)?
       Is the hydrogen demand depending on seasonal fluctuations? Are there peaks?
       → For calculation aid check report from the working group 1.2.1 Demand analysis
4. Framework conditions
    a. *Timeframe for realization*
       What is the target timeline for implementing hydrogen transport solutions?
       Are there deadlines given by the government?
    b. *Willingness to invest in infrastructure*
       What short- and long-term financial resources are available for the construction of a hydrogen infrastructure at the airport?
    c. *Stakeholders in the hydrogen field*
       Who are the stakeholders in the region that the airport should collaborate with?

Decision tree

With the information collected in the guidance list, the decision tree can be used to identify the optimal means of transport. The decision tree is divided into 3 subtrees shown below in Figures 5 – 7. It is based on the following criteria: Demand for hydrogen, distance between hydrogen hub und airport, location-dependent pricing structure and infrastructure availability.

The decision tree has so far only proven to be effective and meaningful to a limited extent. This is mainly due to two factors: firstly, the lack of data and secondly, the currently still low demand, which is, however, considered plausible and expected in the first project phase. The current lack of data on transport costs, particularly for rail, means that the decision tree cannot yet provide reliable and broadly supported results. Informed decisions based on this model will probably only be possible once more data is available. However, it is to be expected that the combination with the working group 1.2.2 Local production will help to improve the informative value of the decision tree as the project progresses. The input from this working group and the resulting expansion of the information base will enable the integration of a further use case. This should provide well-founded recommendations for action for the hydrogen supply chain in the future.

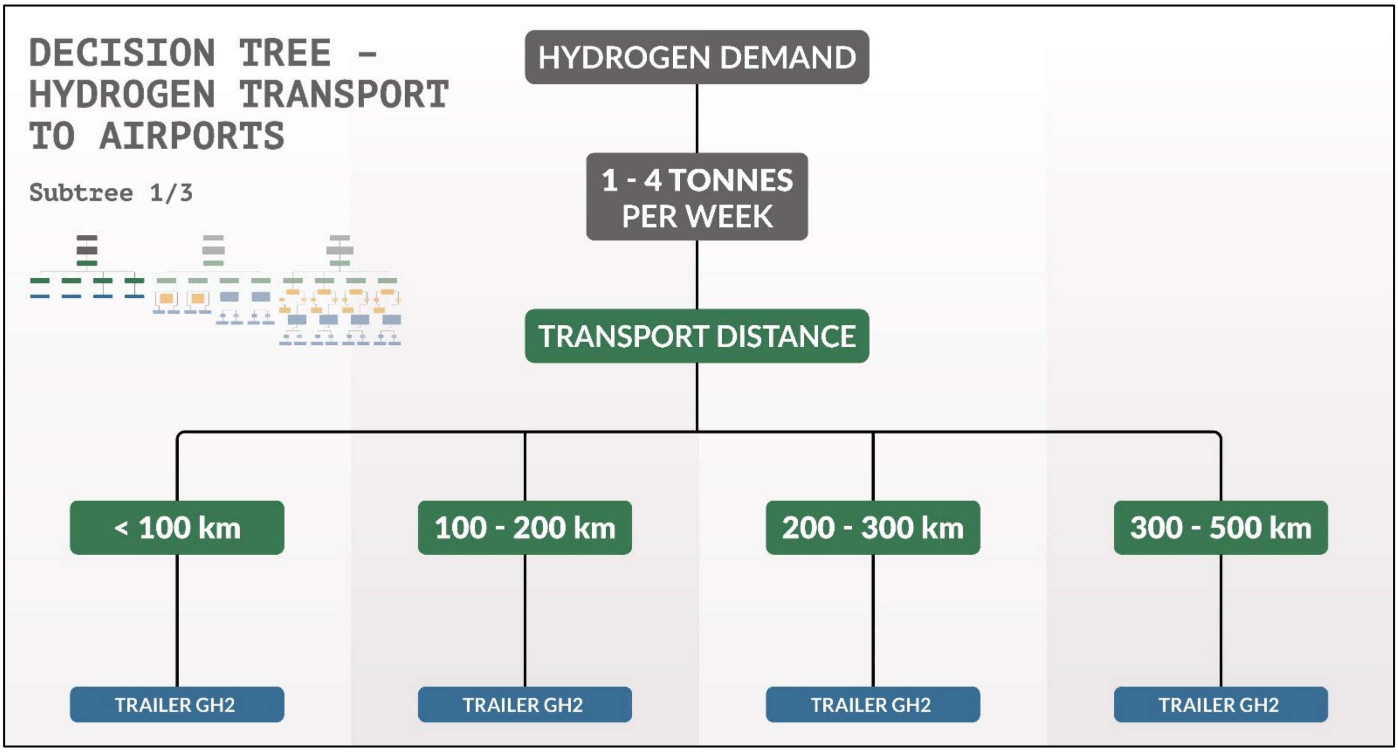

Figure 5.: Decision tree to identify the optimal means of transport. Subtree 1/3.

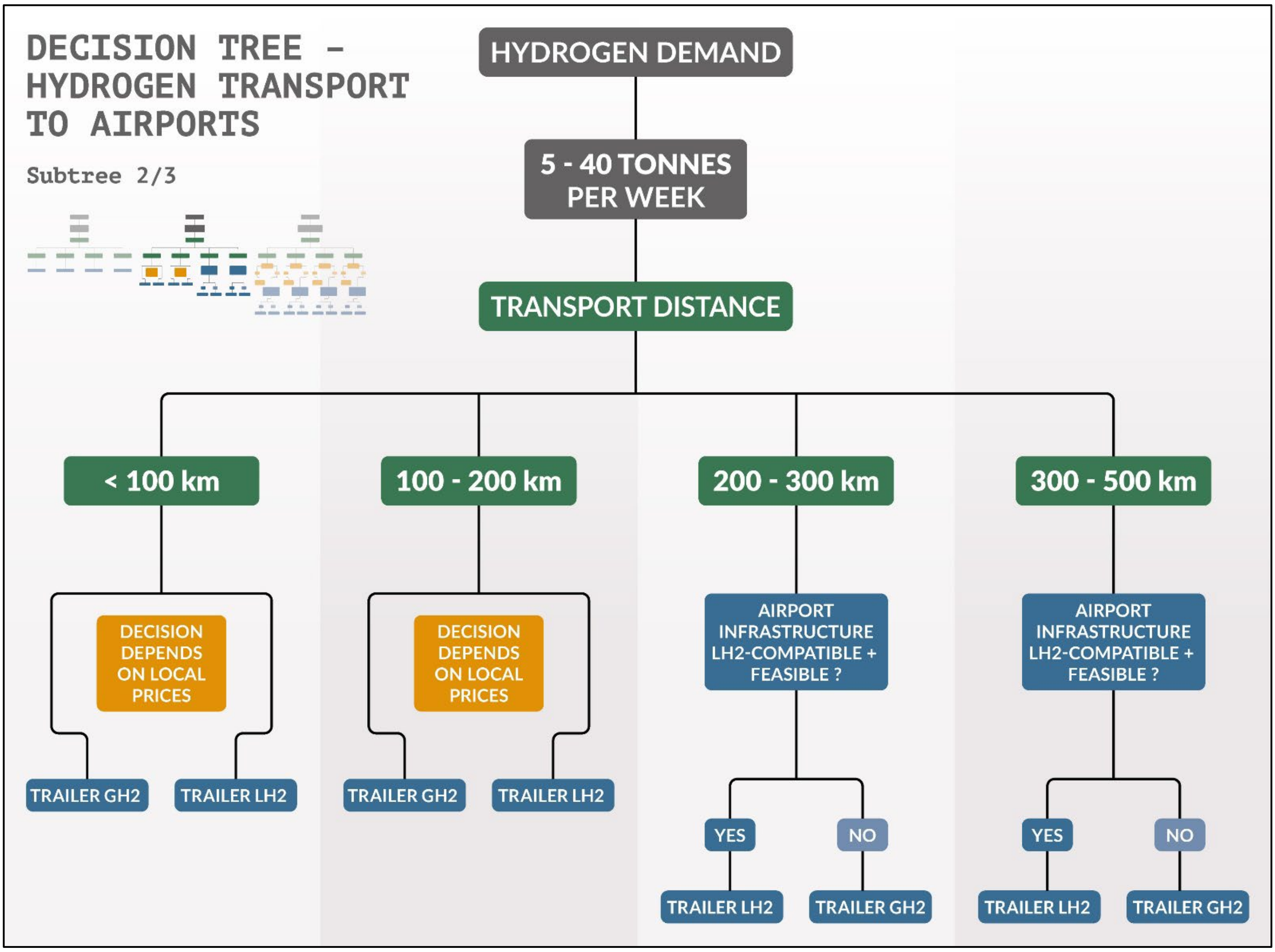

Figure 6.: Decision tree to identify the optimal means of transport. Subtree 2/3.

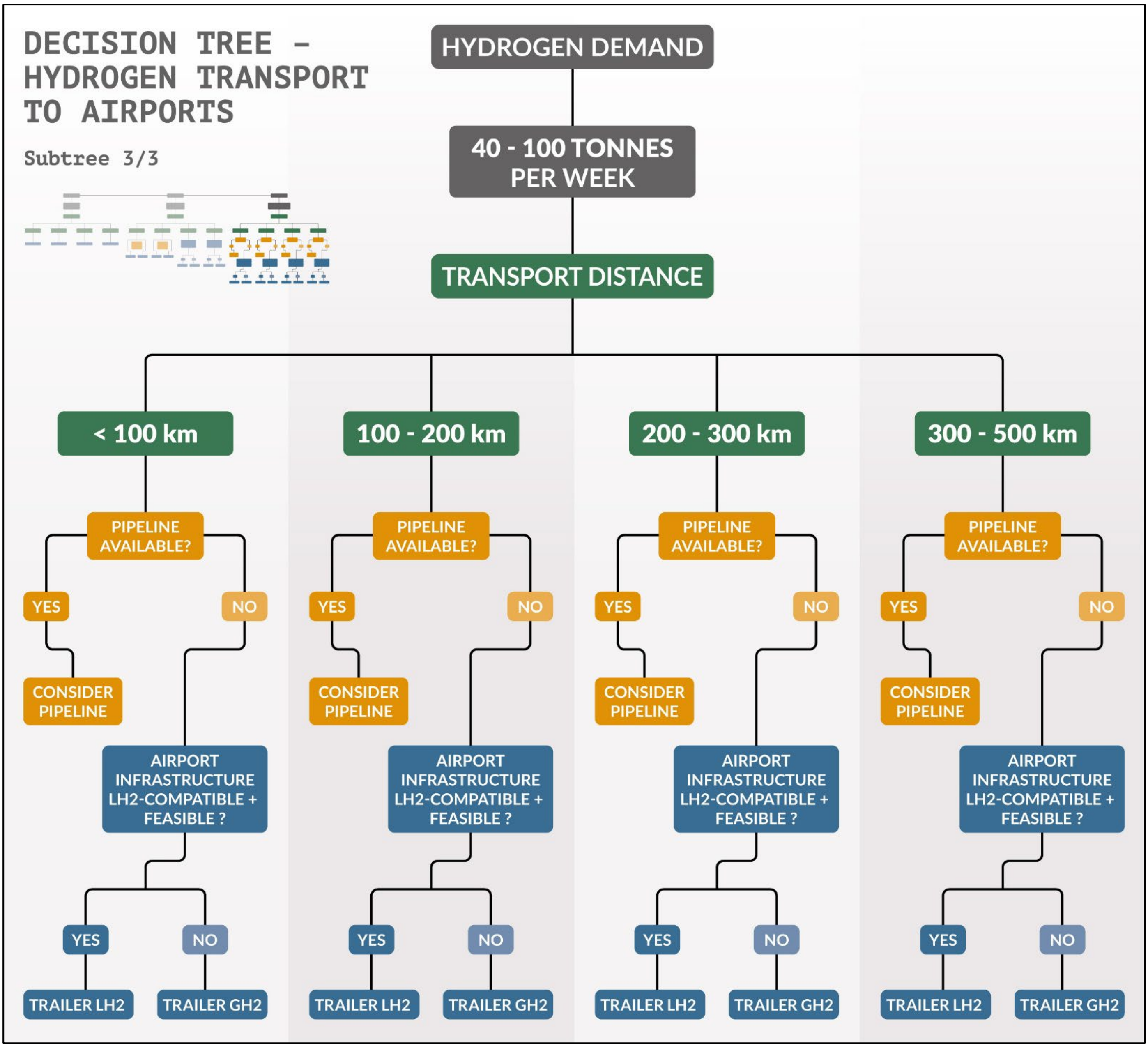

Figure 7.: Decision tree to identify the optimal means of transport. Subtree 3/3.

8.Summary

There are currently several technical options for transporting hydrogen to airports. These technologies are either already in use or at an advanced stage of development and are technically feasible in principle. It is not possible to give a general answer as to which transport solution makes the most sense in each case but rather depends essentially on several site-specific factors: the expected hydrogen demand, the existing infrastructure at the airport and in the surrounding area, the distance to the nearest hydrogen hub and the regulatory and safety-related framework conditions.

The assessment of infrastructure conditions at BSR airports showed that the hydrogen infrastructure in Europe is currently organised on a decentralized basis. Production and distribution take place primarily via numerous smaller, regionally distributed locations. In this situation, road transport by truck would currently be the most practicable and flexible solution - especially in view of the initially low demand for hydrogen. Truck transport thus enables a demand-oriented supply and forms a basis for the short-term introduction phase until the further development of hydrogen logistics in Europe.

With the further development of hydrogen technologies, other logistics solutions such as rail transport and pipelines are expected to gain in importance alongside truck transport in the medium to long term – especially as part of the European hydrogen backbone. By then, the volume of demand is also likely to increase, so that corresponding customers for larger quantities and an increase in production facilities (gaseous in the short to medium term, liquid in the long term) can be expected.

It became clear that reliable cost data for hydrogen transport, especially under real conditions with low initial demand, is still limited. Although there are a number of scientific studies on the costs of hydrogen transport, their results vary widely. This variability is mainly due to different assumptions, methodological approaches and the consideration of different supply scenarios. They are mostly theoretical in nature and do not directly reflect operating conditions. Given project-specific conditions such as decentralized supply structures, short to medium transport distances, and low demand, the available literature is very limited. Nevertheless, for a demand of 1 ton per week and travel distances from 25 to 500 kilometers, it seems reasonable to assume an indicative cost range of approximately 5–7 €/kg H_2 for the transport of GH_2. While these values represent a plausible cost range for initial planning, it must be emphasized that these are only indicative estimates.

In practise, airports are ultimately subject to market prices set by the hydrogen industry, which are influenced by a variety of external factors such as production costs, energy prices, infrastructure availability, and the evolving regulatory environment. Due to these dynamics, the above-mentioned deviations from the estimated price range must be considered in the planning process.

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