RE-Chain study

Building **R**esilient **E**nergy-Supply **Chain**s for the Ports of Duisburg and Amsterdam

Conducted by Fraunhofer UMSICHT on behalf of the Port of Duisburg (duisport) and the Port of Amsterdam
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Agenda

Four working packages (WP) of the RE-Chain study

	General Information about the RE-Chain study
WP 1	System Definition and Questionnaire
WP 2	Spatial Analysis
WP 3	Identification of Off-takers
WP 4	Cost Estimation & Risk Analysis

Introduction

Necessities, Possibilities, and Challenges

- **Hydrogen** is needed to achieve climate neutrality in processes that cannot otherwise be decarbonized, or only with great difficulty. This primarily includes sectors with material and energy applications as chemical industry, steel production, refining, glass, ceramics, brick products, high temperature process heat and long-term energy storage. The quantities of hydrogen likely to be required here have been determined in various studies, allocated to the different economic sectors, classified spatially and temporally, and divided into amounts to be imported and those to be produced domestically.
- The **value chain** from production through logistics to application is long and involves numerous stakeholders, each of whom must develop and implement their own suitable business models. Significant investments are required on all sides. At the same time, there are mutual dependencies between these new business models that need to be established.
- The **technologies required** for hydrogen production and logistics are essentially available and technically feasible. However, the transition to new processes presents particular challenges, especially for end-users: Here, trade-offs between process alternatives must sometimes be made, and the development of new technologies must continue to be advanced.
- The **price of green hydrogen** is currently extremely high. Studies show how it is expected to evolve in the coming years and decades against the backdrop of the emerging global market. A price reduction of approx. 50 % is expected. The **shared challenge** is to develop and establish this new market in competition with the established and low-cost fossil fuel market, so that new sustainable and economically viable processes can emerge in the medium and long term.
- For individual countries, **this means that** production of hydrogen must be prepared, infrastructure expanded, supply chains established, and applications implemented. Each stakeholder must make a series of decisions, which are not about whether to proceed, but rather about when, how, where, and with whom. In this context, it is essential that **different stakeholders from all areas of the value chain** set out early, drive planning forward in a targeted manner, and thus **jointly reduce uncertainties**, so that the necessary investment decisions along the value chain are facilitated.
- For the ports of Amsterdam and Duisburg, this means that they must **develop and implement the supply chain** for the import and redistribution of hydrogen. Potential routes, transport and storage options, transshipment and conversion steps can already be well described and are technically feasible. The **main challenge** here is that binding offtake agreements for the incoming hydrogen must be found in quantities sufficient to enable investment in the supply chain.
- In this role, **the ports of Amsterdam and Duisburg see themselves as critical enablers and trusted partners for all actors in the emerging hydrogen value chain**, actively building the infrastructure and logistics backbone that makes new, resilient supply chains possible.

European ports are evolving into central nodes of the global energy transition. As logistics hubs and energy distributors, they provide the operational backbone for sustainable and reliable supply chains delivering green molecules to European, German, and specifically NRW industry. The ports of Amsterdam and Duisburg are investing ahead of demand to create supply security for the hydrogen market ramp-up.

Introduction
Strategic context

The ports of Amsterdam and Duisburg are actively developing terminal infrastructure, storage capacity, and multi-modal distribution networks to enable the import and inland delivery of significant hydrogen volumes from 2030 onwards – serving as critical enablers for Europe's hydrogen market ramp-up.

SPAIN/MENA-REGION
OVERSEAS PRODUCTION HUB

- Bilbao / Duqm as export hubs – leveraging low-cost renewable energy for competitive hydrogen production (electricity costs 10-30 €/MWh_{el})
- >10 Mt H_2 EU-import target by 2030 [1]

AMSTERDAM
IMPORT HUB

- LH_2 and LOHC terminals under development (operational start ~2030) – enabling 50–200 kt H_2/a import volumes from day one with quad-modal connectivity (barge, rail, truck, pipeline)
- Ramp-up 1 Mt H_2/a hydrogen capacity [3]
- Rhine waterway access to DE and EHB pipeline
- >6 Mm^3 storage volume (oil) [2]
- Adjacent industry: Tata Steel, Nouryon…

DUISBURG
DEMAND CENTER & INLAND DISTRIBUTION HUB

- World's largest inland port – positioned as Germany's primary inland H_2 distribution hub with quad-modal connectivity (barge, rail, truck, pipeline)
- LH_2, LOHC and NH_3 import
- Major off-takers in the Rhine-Ruhr Region
  - e.g., steel and chemical industry
- GET-H2 pipeline connection

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[1]: REPowerEU (2022): https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131 // [2]: Leitprojekt TransHyDE: Europas Seehäfen im Wandel – Drehkreuze für Energie und Industrie , ISBN Number: 978 3 89746 246 5
[3]: Port of Amsterdam: *https://www.portofamsterdam.com/en/business/cargo-flows/liquid-bulk/hydrogen*

General information

RE-Chain study

Overall Scope

Scientific evaluation of the hydrogen supply chain to support both ports - *duisport (DU)* and *Port of Amsterdam (AM)* - in establishing a local hydrogen infrastructure to enhance supply chain resilience and support energy security in Europe → **feasibility study**

System Boundaries

- Considered liquid hydrogen (LH_2) and liquid organic hydrogen carriers (LOHC)
- Evaluating the transport from the port of production to the off-taker
- Oman (Duqm) / Spain (Bilbao) → Amsterdam → Duisburg → Off-takers
  - focus on maritime transport routes and usage in Germany (Rhine Ruhr)
- Different time periods for ramp up are considered

Methodology

- Literature analysis and modelling
- Expert interviews with companies in the hydrogen supply chain
- Scenario analysis

Considered Aspects

RE-Chain study

Considered aspects to evaluate the resilience

- Economy (costs of individual services)
- Quantity of hydrogen (availability, supply and demand)
- Technology options
  - production, transport, conversion processes and storage
  - limited to LOHC and LH_2 as transport technologies
- Energy efficiency of the value chain
- Technical Infrastructure
- Transport modalities: maritime shipping to Amsterdam and inland transport to Duisburg via barge, rail, road, and pipeline → quad-modal assessment
- GIS-Data
- Relevant off-takers
- Scenarios for different developments
  - 2025 (baseline), 2030, 2035, 2040, 2045, and 2050
- Uncertainties / other necessary framework conditions

AI-generated content

Regions involved

Segments of the supply chain

Production

- Spain: (Port of Bilbao in Spain)
- MENA-Region (Port of Duqm in Oman)

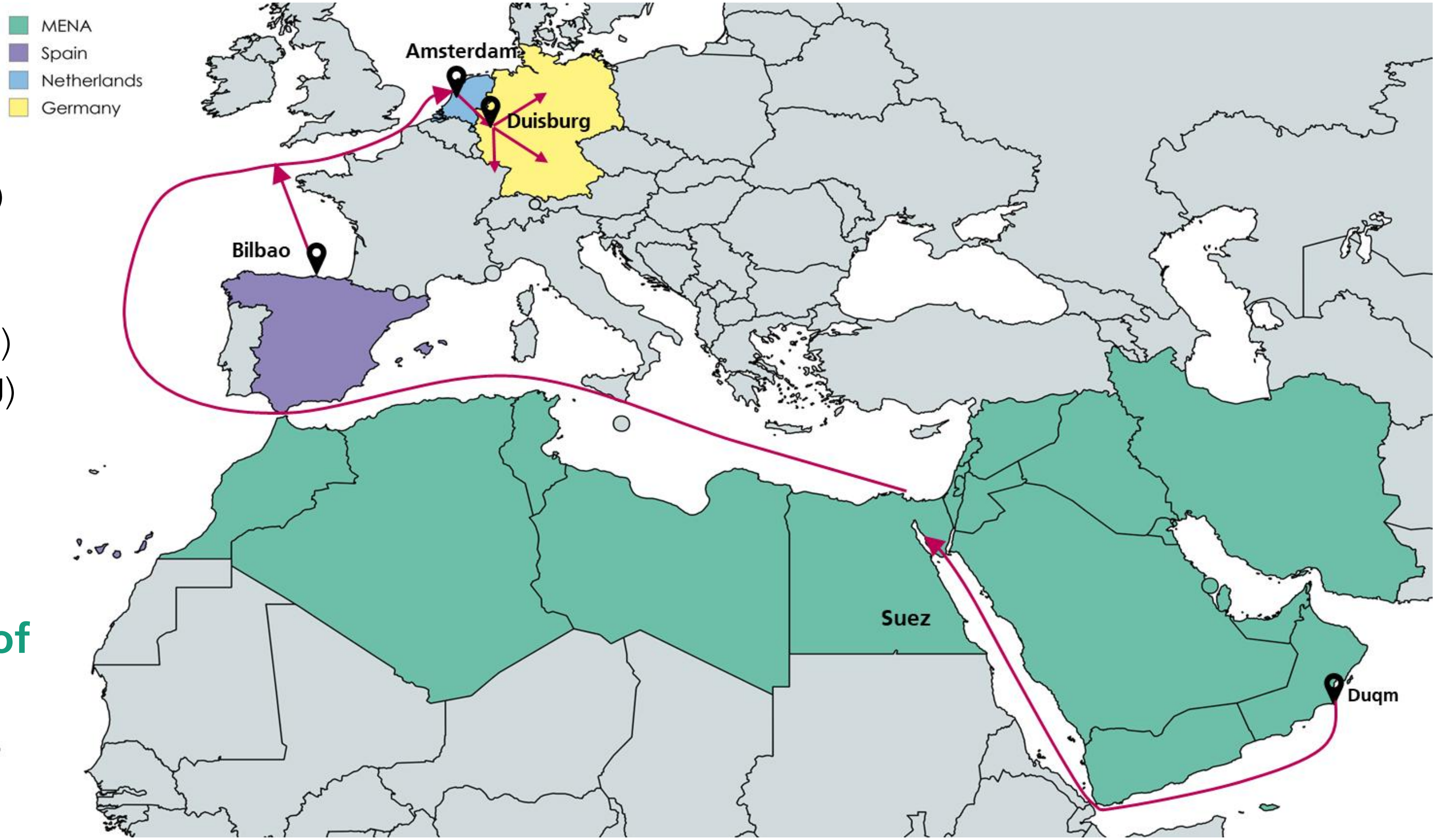
Transport

- Maritime transport to Amsterdam (AM)
- Quad modal transport to Duisburg (DU)

Utilization

- From DU to off-takers in Germany

→ Different services (segments) of the supply chain are considered



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Summary of the four working packages (WP1 to WP4)

Executive Summary of the Results from the RE-Chain study

Fraunhofer UMSICHT

Executive Summary WP1: Technology & Infrastructure Readiness

The technology is proven – key infrastructure is under active development

- **Distinct technical profiles:** LH_2 and LOHC differ fundamentally in energy requirements (cryogenic vs. thermal), handling conditions (–253 °C vs. ambient), infrastructure needs (purpose-built vs. existing), and storage characteristics (time-limited vs. unlimited) – **this complementarity enables route-, demand-, and infrastructure-specific optimization**
- **Technology readiness:** Both LH_2 and LOHC have been demonstrated in international reference projects (Kawasaki Suiso Frontier, Chiyoda SPERA…) – all core components for conversion, transport, storage, and reconversion of the carriers are **commercially proven and reaching operational readiness in the next two years**
- **Infrastructure under development:** LOHC leverages >1 Mm³ existing tank storage in Amsterdam and proven chemical barge fleet on the Rhine. LH_2 cryogenic infrastructure (40,000 m³ storage, 30,000 m³ vessel capacity) are under construction – **both on track for targeted operational start**
- **Quad-modal inland corridor:** The Amsterdam → Duisburg link offers four transport modalities – barge, rail, truck, and future pipeline (GET H_2 / Delta Rhine Corridor) – providing **built-in redundancy** for that hydrogen import corridor
- **Resilience confirmed by industry:** All interviewed companies rank **supply security and committed offtake** as the #1 priority – the ports are de-risking the supply chain through carrier-neutral terminal design, strategic storage buffers, and established international partner networks

All core technologies for LH_2 and LOHC are proven – the Amsterdam–Duisburg corridor provides the infrastructure base and quad-modal connectivity to bring them to commercial scale from 2030.

Executive Summary WP1: Market Entry from 2030 & Scale-Up Path

From 50 to 1000 kt H_2/a – Amsterdam and Duisburg as enablers for Europe's hydrogen ramp-up

- **Targeted operational start ~2030:** Hydrogen import volumes in Amsterdam are targeted at **50–200 kt H_2/a** from day one, reflecting individual terminal capacities of 200 kt H_2/a for LH_2 and 50 kt H_2/a for LOHC (250 kt H_2/a total capacity) as part of a deliberate **dual-carrier strategy** that maximizes flexibility and supply chain resilience
- **Scalable ramp-up:** Combined capacity can grow to **~1000 kt H_2/a by 2045** (~33 TWh_{th}/a), covering a significant share of Rhine-Ruhr industrial hydrogen demand across mobility, steel, chemicals, glass, and data center sector
- **No need to wait for the pipeline:** LOHC can be **barged to Duisburg** today using the existing chemical fleet. For LH_2, a formal permit application for bulk barge transport on the Amsterdam–Duisburg route has been filed – EU-wide approval expected before terminal operations begin. **Hydrogen transport via Rail and Truck is also possible**
- **Growing demand signals:** Industrial off-take from thyssenkrupp, HKM, major truck OEMs plan LH_2 fuel cell trucks, and the broader Rhine-Ruhr chemical cluster. **The demand base for both carriers is robust and diversified**
- **Enabling role of the ports:** Amsterdam and Duisburg act as critical enablers – providing terminal infrastructure, large-scale storage capacity, multi-modal logistics coordination, and a growing ecosystem of international supply, technology, and off-take partners to **unlock Europe's hydrogen market ramp-up**

The ports of Amsterdam and Duisburg are ready to enable large-scale hydrogen delivery from 2030 – infrastructure is under development, transport modalities are available, and demand is confirmed.

Executive Summary WP2: Spatial Analysis

Evaluation of the Ports, Infrastructure and Transport Routes

- **Amsterdam emerges as a resilient route option**: The port combines deep-sea import capability, established liquid-bulk infrastructure, and direct access to Duisburg, enabling **initial import volumes of 50-200 kt H_2/a ramp-up to 1000 kt H_2/a**
- **Two supply corridors were assessed**: The **Duqm–Amsterdam** route enables long-distance PtX imports from Oman, while the **Bilbao-Amsterdam** route offers a shorter European route linked to the Basque Hydrogen Corridor
- **Multimodal inland transport is available**: Hydrogen carriers can be transported from Amsterdam to Duisburg via **barge, rail and truck** over approximately 200-220 km, enabling market entry before pipeline completion
- **Future infrastructure strengthens the route**: The **Delta-Rhine Corridor** and the **European Hydrogen Backbone** will further increase the scalability, while storage and **terminal expansion** remain key requirements
- **Port infrastructure and storage remain decisive enablers**: Both import and inland hub locations require targeted investments in terminal handling, storage, safety distances, permitting and **carrier-specific infrastructure**, especially for LH_2

Amsterdam serves as the strategic hydrogen gateway, combining maritime access, multimodal inland logistics and future pipeline integration to supply industrial end-users in Duisburg and the Rhine-Ruhr region.

Executive Summary WP3: Off-taker Potential in Rhine-Ruhr Region

Off-taker

Large offtake potential in Rhein-Ruhr region

- Projected demand of 870 – 1170 kt by 2030; 3870 – 5370 kt by 2045 with high reliance on imports
- Planned import capacity in Amsterdam could supply significant share of demand in Rhein-Ruhr region
- A highly interconnected region with ambitious hydrogen goals and numerous concrete projects across the value chain
- Existing infrastructure as well as high concentration of planned infrastructure projects
- However, current regulatory and economic conditions lead to wait-and-see approach by companies

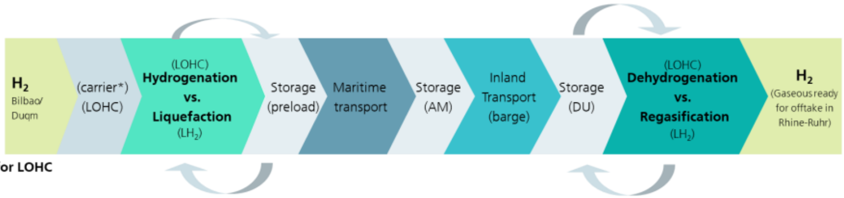
Points of reference for future planning

- Ongoing activities by inter-institutional groups look to combine and focus efforts towards advancing hydrogen utilization -> ports could play an important role in steering the plans
- Hydrogen storage already planned in NRW with open capacities for supply
- Conversion of gas fired power plants from natural gas to hydrogen

Decisions are not about whether to proceed, but rather about when, how, where, and with whom. It is essential that different stakeholders from all areas of the value chain set out early, drive planning forward in a targeted manner, and thus jointly reduce uncertainties to facilitate the necessary investment decisions.

Executive Summary WP4: Levelized Costs of Transport Service (LCOTS)

Key findings of the hydrogen supply chain costs



*Only for LOHC

- **Cost Estimation Approach:** Cost estimation is made with literature data and validated cost data provided by the companies in the maritime hydrogen supply chain with the **Levelized Costs of Transport Service (LCOTS)**
  - **LH2 (five segments):** Liquefaction, storing (preload, AM and DU), maritime transport, inland transport and regasification
  - **LOHC (six segments):** carrier loading, hydrogenation, storing (preload, AM and DU), maritime transport, inland transport and dehydrogenation
  - Unsubsidized prices shown – policy support (CfDs, auctions) would reduce costs further
- **The main cost drivers:**
  - **LOHC:** depends on dehydrogenation (40-45%) maritime transport (10-20%) and hydrogenation (~15%)
    - → strongest lever: waste heat utilization for dehydrogenation can reduce costs up to 40%
  - **LH_2:** depends on liquefaction (30-45%), storing (25-30%) and maritime transport (10-25%)
    - → strongest lever: electricity costs for liquefaction can reduce costs up to 30%
- **Both carrier options are competitive – no single option dominates across all cases**
  - Costs for LOHC and LH_2 are in the same order of magnitude
  - **Bilbao** has lower transport costs due to faster maritime transport
  - **Duqm** has a stronger cost reduction potential due to more renewables and scaling

Bilbao (Transport costs)

- **2030: 3.75–4.50 €/kg (baseline)**
- 2035: 3.15–4.15 €/kg
- 2040: 2.50–3.80 €/kg
- 2045: 2.10–3.60 €/kg
- 2050: 1.70–3.30 €/kg → **Trending to 2.5 €/kg**

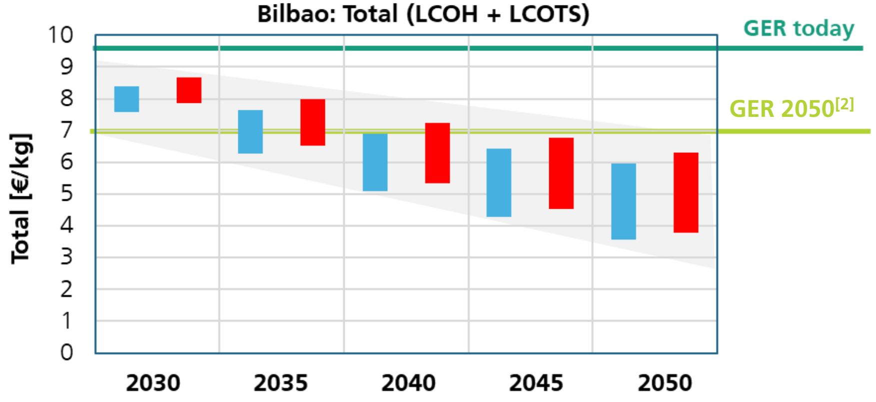
Duqm (Transport costs)

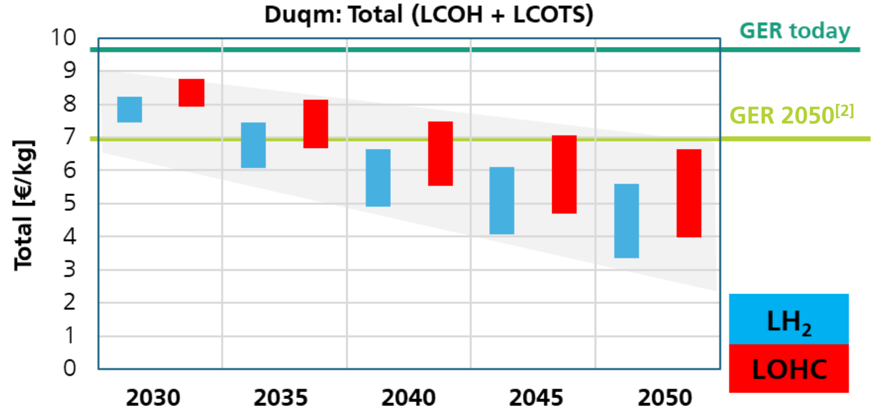
- **2030: 4.10–5.10 €/kg (baseline)**
- 2035: 3.40–4.75 €/kg
- 2040: 2.80–4.40 €/kg
- 2045: 2.30–4.10 €/kg
- **2050: 1.85–3.75 €/kg → Trending to 3 €/kg**

A reduction of LCOTS by up to 50 % by 2050 appears achievable for both carriers – driven by infrastructure scale-up and declining renewable energy costs.

Executive Summary WP4: Total Costs of Imported Hydrogen (LCOH+LCOTS)

Total costs of hydrogen at Duisburg (DPU, Delivered at Place Unloaded)





- **Carrier Options:** Both LH_2 and LOHC achieve comparable total costs across the entire time horizon, no single carrier option dominates, supporting a diversified supply strategy
- **Hydrogen production costs (LCOH):** Between 4 €/kg (in 2030) and 2 €/kg (in 2050) [1]
- **Cost competitiveness of both routes and carrier options:**
  - Bilbao has lower maritime transport costs
  - Duqm has lower hydrogen production costs
  - → Total costs are in the same order of magnitude

By 2030, DPU at duisport reach about 7,5-8,5 €/kg from both options
2040: DPU reach about 5-7 €/kg // 2050: DPU reach about 3,5-6,5 €/kg

Resilience is also ensured in terms of costs, as several options (import ports and carrier options) in a similar price range are available

- **More cost-effective than domestic production:** Imported hydrogen supply from Amsterdam to Duisburg from Bilbao and Duqm can become more effective than domestic green hydrogen production in Germany itself

Both hydrogen carrier options are cheaper than domestic green hydrogen production in Germany.
→ Scaling up the hydrogen infrastructure chain has a clear economic benefit for the EU and Germany

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[1]: Fraunhofer IEE (2026), *Global PtX Atlas*, https://maps.iee.fraunhofer.de/ptx-atlas/#user

[2]: Forschungsstelle für Energiewirtschaft e. V. (2025), *Warum ist Wasserstoff in der Praxis teurer als bisher häufig angenommen?*

Executive Summary WP4: Minimizing Risks Along the Hydrogen Value Chain

Key Takeaways from a macro-perspective

Upstream

- Easing of RFNBO requirements through the postponement of electricity procurement criteria regarding additionality and hourly correlation
- Enabling the use of hourly GHG accounting

Midstream

- Standardized, tradable hydrogen products and contract frameworks are an essential prerequisite for the ramp-up and development of a market
- Consistent implementation of the Hydrogen Acceleration Act
- Development of the hydrogen core network

Downstream

- Government guarantees and sureties as well as price difference mechanisms (CfDs) during the development and ramp-up phase
- Establishment of binding lead markets and demand anchors
- OPEX subsidies as well as transparent, possibly index-linked cap/floor price ranges

Source: BDEW (2026) - Risikominimierung entlang der Wasserstoff-Wertschöpfungskette

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Working Package 1a of the RE-Chain study

System Definition:

Including Literature Analysis of the Technologies and the Process Chain

Liquid Hydrogen (LH_2)

Introduction

Basic Principles

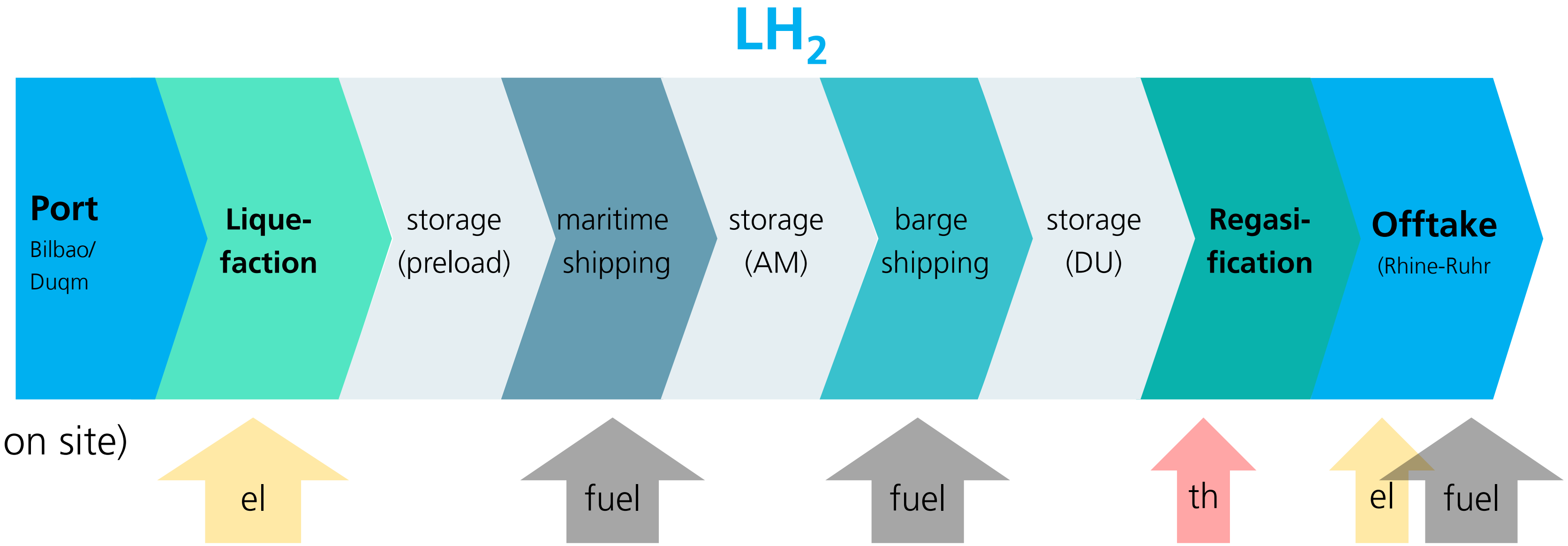
- Hydrogen is liquefied at –253 °C (20 K)
- Volume is reduced to ~1/800 of gaseous H_2 at ambient conditions
- **Volumetric Density: 70.8 kg/m³**
- Energy density: ~2.36 kWh/L (vs. 0.003 kWh/L for GH_2 at 1 bar)

Advantages

- High volumetric density
- High purity
- No carrier = no return transport
- Emerging demand from heavy-duty mobility

Disadvantages

- Energy-intensive liquefaction (at production site)
- Risk of boil-off losses
- Dedicated cryogenic infrastructure required across the entire chain



Liquid-Organic-Hydrogen-Carrier (LOHC)

Introduction

Basic Principles

- Hydrogen is chemically bound to and released from an organic molecule
- Carrier circulates in a closed loop: loaded carrier is shipped to destination, unloaded carrier is returned to origin
- Two primary carrier systems – both liquid at ambient temperature and pressure:
  - MCH system: Toluene (C_7H_8) $\rightleftarrows$ Methylcyclohexane (C_7H_{14})
  - DBT system: Dibenzyltoluene (H_0-DBT) $\rightleftarrows$ Perhydro-Dibenzyltoluene (H_{18}-DBT)
- **Volumetric H_2 Density: 47–57 kg/m³**
- Gravimetric H_2 content 6–7 wt.-%

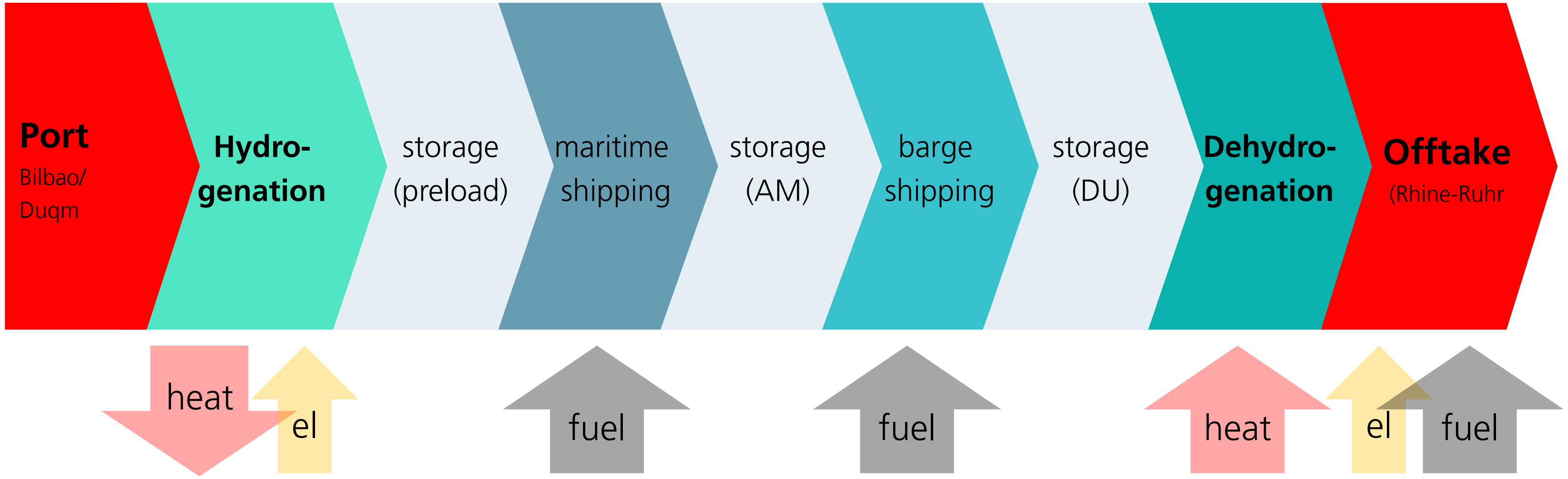
Advantages

- Transport & storage at ambient conditions
- Uses existing infrastructure
- No boil-off – unlimited storage duration

Disadvantages

- Heat-intensive dehydrogenation
- Return transport of empty carrier doubles shipping volume
- Low H_2 content (~6 wt.-%) → ~15-16 kg carrier per kg H_2

LOHC



Technical Process Assessment

LH_2 vs. LOHC-MCH vs. LOHC-DBT

🟢 Positive
🟠 Medium
🔴 Negative

Technical criteria	LH_2	LOHC (MCH)	LOHC (DBT)
Energy penalty at export (Liquefaction / Hydrogenation)	🔴 **10–13 kWh$_{el}$/kg**	🟢 ~1 kWh$_{el}$ + 12–13 kWh$_{th}$ released	🟢 ~1 kWh$_{el}$ + 9–10 kWh$_{th}$ released
Energy penalty at import (Regasification / Dehydrogenation)	🟢 ~0.5 kWh$_{el}$/kg	🔴 **12–15 kWh$_{th}$/kg at 300–400 °C**	🟠 **10–12 kWh$_{th}$/kg at 280–320 °C**
Transport losses over distance	🟠 0–0.5 %/d boil-off, mitigable to near-zero for voyages up to ~4 weeks via advanced storage management	🟢 ~0 % (negligible VOC)	🟢 0 % (zero boil-off)
Carrier mass overhead & return transport	🟢 **No carrier, no return**	🔴 **~16 kg/kg H_2 + return shipment**	🔴 **~15–16 kg/kg H_2 + return shipment**
Volumetric H_2 density	🟢 70.8 kg H_2/m³	🟠 47 kg H_2/m³	🟢 57 kg H_2/m³
Regulatory aspects for transport	🟠 Permit for LH_2 bulk barge transport on Amsterdam–Duisburg route filed; positive decision expected 2026, ADN approval anticipated by 2029 – in time for terminal start	🟢 no limitations	🟢 no limitations

- LH_2 and LOHC represent a fundamental trade-off: energy penalty at export (LH_2) versus energy penalty at import (LOHC)
- Route durations considered here (Bilbao, Duqm) remain within the ~4 weeks threshold where LH_2 boil-off can be managed to near zero – transport losses are not a distinguishing factor between the two carriers in this study

Both technologies achieve promising scores across all categories → a diversified approach is advisable

TRL Overview: LH_2 vs. LOHC-MCH vs. LOHC-DBT

Results from literature analysis

Criteria	LH_2	LOHC (MCH)	LOHC (DBT/BT)
Conversion (Liquef. / Hydrog.)	8–9 (stationary approved)	8–9	7–8
Maritime transport	7–8 one demo vessel with 1,250 m³, next-gen 30,000-40,000 m³ contracted – operation feasible till 2030	9 (conventional oil tanker)	9 (conventional oil tanker)
Storage	8–9 (cryogenic tanks)	9 (conventional oil tanks)	9 (conventional oil tanks)
Reconversion (Regas. / Dehyd.)	9 (vaporization trivial)	6–7 (demo scale, technical feasible so scaling is possible)	6–7 (demo scale, technical feasible so scaling is possible)
Inland barge (Rhine)	7–8 → Permit for bulk LH_2 barge transport (Amsterdam–Duisburg) formally filed; decision expected 2026, ADN European-wide approval targeted before 2029	9 (conventional oil barges)	9 (conventional oil barges)
Integrated supply chain	**7–8 → feasibility demonstrated**	**7–8 → feasibility demonstrated**	**6–7 → feasibility demonstrated**
Key reference project	Kawasaki Suiso Frontier (2022): Australia → Japan, 1,250 m³ / ~75 t H_2	Chiyoda SPERA (2020): Brunei → Japan, 13 t H_2	Hydrogenious: pilot plants DE, no international chain yet

- **LH_2** today's bottleneck is **vessel availability** – however, large vessels (maritime transport) and barges (inland waterways) are under development ready for operation till operation in 2030
- **LOHC:** today's bottleneck is **large-scale dehydrogenation** (>10 t H_2/d) – but the technology will be ready for operation in 2030

The technology is proven and key infrastructure building blocks are already under development – committed offtake and regulatory clarity will unlock the next phase of scale-up

Working Package 1b of the RE-Chain study

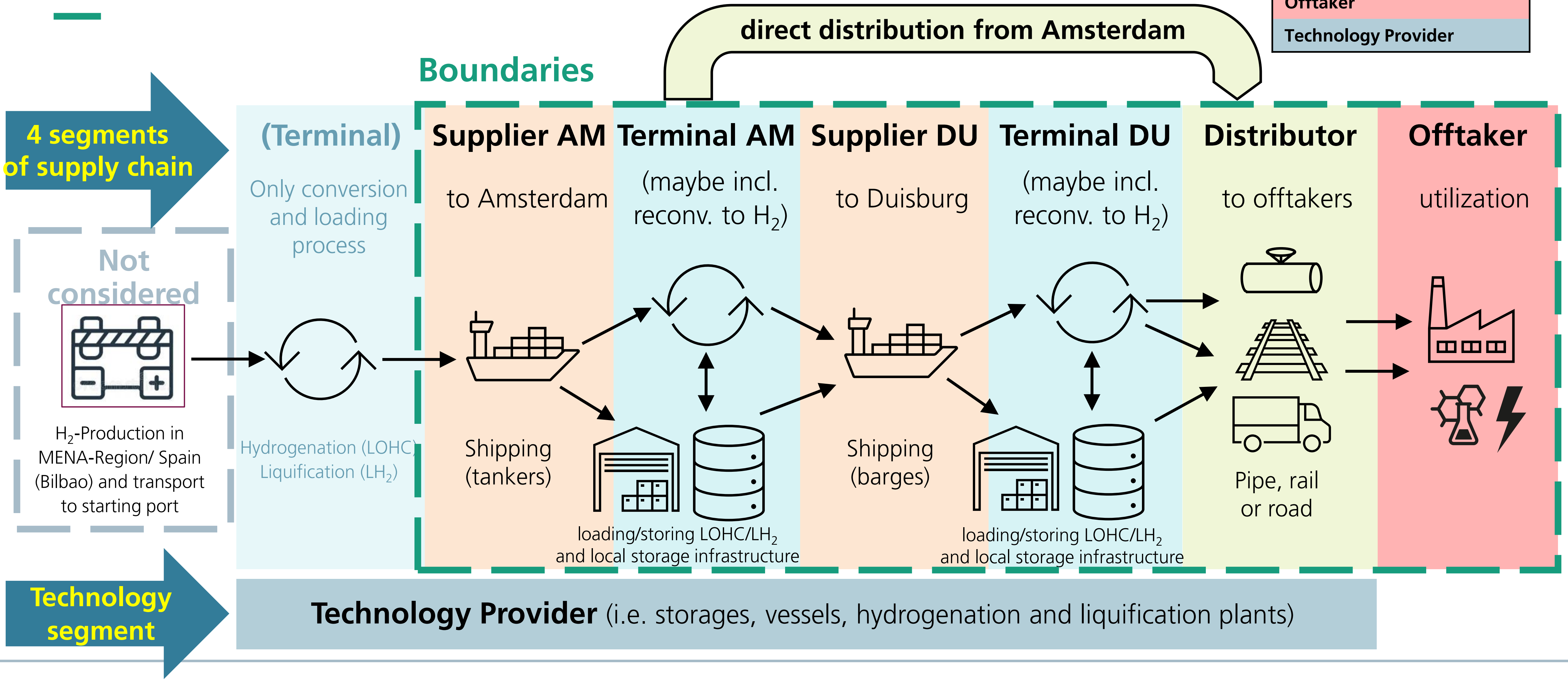
Company Questionnaire:

Insights from Potential Stakeholders in the Hydrogen Supply Chain

WP1: Evaluated five segments in the H_2 supply chain RE-Chain

System boundaries: Transport from the port of origin to the utilization point

- 🟧 **Supplier (AM and DU)**
- 🟦 **Terminals (AM and DU)**
- 🟨 **Distributor**
- 🟥 **Offtaker**
- ⬜ **Technology Provider**



4 segments of supply chain

Not considered

H_2-Production in MENA-Region/ Spain (Bilbao) and transport to starting port

(Terminal)

Only conversion and loading process

Hydrogenation (LOHC)
Liquification (LH_2)

Boundaries

direct distribution from Amsterdam

Supplier AM

to Amsterdam

Shipping (tankers)

Terminal AM

(maybe incl. reconv. to H_2)

loading/storing LOHC/LH_2 and local storage infrastructure

Supplier DU

to Duisburg

Shipping (barges)

Terminal DU

(maybe incl. reconv. to H_2)

loading/storing LOHC/LH_2 and local storage infrastructure

Distributor

to offtakers

Pipe, rail or road

Offtaker

utilization

Technology segment

Technology Provider (i.e. storages, vessels, hydrogenation and liquification plants)

WP1: Companies surveyed for the study (expert interviews)

Designing of the questionnaire

- **Questionnaire:** Created for each of the five segments (see Tab. 01)
  - approx. 50 questions for every segment
  - mostly general resilience (7 key factors) + technical and economical questions
  - runtime from June 2025 till October 2025

- **Companies**
  - Contact to >15 companies who are involved in the hydrogen supply chain
    - Company list was provided by the ports
    - 11 companies agreed to participate
    - 8 companies completed the questionnaire
    - (Some companies are active across multiple segments)

  → 11 completed questionnaires were received

Tab. 01: Companies who answered the questionnaire from the five segments

Nr	Supplier	Terminal	Distributor	Offtaker	Technology
1	🟩				
2	🟩	🟩			
3	🟩	🟩			
4		🟩			
5		🟩	🟩		
6				*WP3*	
7				*WP3*	
8					🟩

→ Sample size in some segments limits statistical significance – results should be interpreted as expert-informed qualitative insights

→ generally limited technology and cost data (*due to confidentiality constraints and the early planning stage of most projects*)

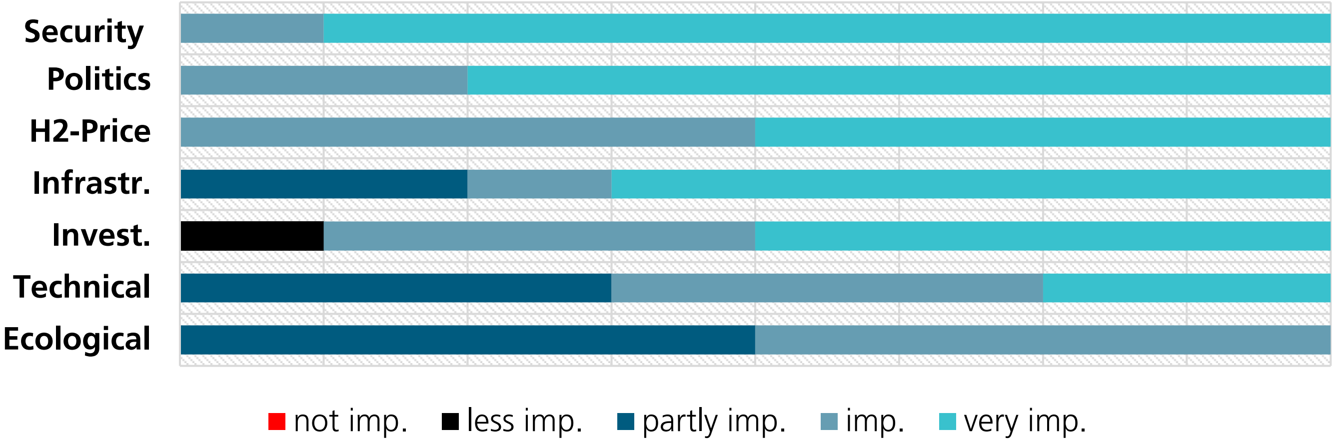
WP1: Questionnaire results of the expert interviews

Importance of the seven resilience factors for the companies in the hydrogen supply chain

Resilience key factors (descending order)

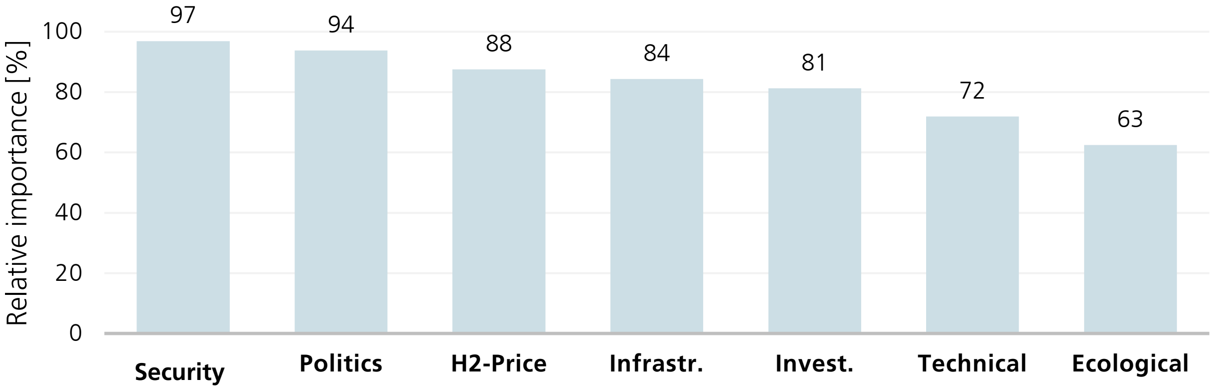
- 1. Security of Supply and Offtake **(Security)**
- 2. Policy Framework and Regulation **(Politics)**
- 3. Hydrogen Price Stability **(H_2-Price)**
- 4. Existing Infrastructure **(Infrastr.)**
- 5. Investment Costs **(Invest.)**
- 6. Technical Standards **(Technical)**
- 7. Ecological Production and Transport **(Ecological)**

Importance (imp.) of the individual factors (sorted in descending order)



Results

- In general, all seven considered factors are important for the resilience (between 63–97%)
- Guaranteed purchase volumes and assured availability are the top priorities for the companies (factor: Security=97%)
- Regulations, price stability und ramp up velocity of the infrastructure is important for planning certainty
- Ecological production ranks the lowest (63%)
- Companies identify regulatory clarity as a key enabler for investment decisions



WP1: Technical Synthesis

Key Results from Industry Interview Results

- **Enabling large scale import and distribution via Amsterdam – Duisburg Corridor (2030):** Both LH_2 and LOHC terminals target operational start ~2030, with a **combined terminal capacity of ~250 kt H_2/a** in Amsterdam, scaling to ~1000 kt H_2/a by 2045
- **Quad-modal corridor:** The Amsterdam–Duisburg link offers barge, rail, truck, and future pipeline connectivity – providing built-in redundancy and flexibility as core resilience features
- **Infrastructure in development:** LOHC leverages existing liquid bulk assets at both ports and LH_2 cryogenic infrastructure is under construction – all building blocks are on track for 2030 operations
- **#1 enabler for scale-up:** Committed offtake and supply security were ranked the top priority by all interviewed stakeholders – the ports actively de-risk the chain by providing storage buffers, logistics coordination, and multi-carrier optionality:

Key Finding: All essential technologies for LH_2 and LOHC are technically proven – what is needed now is committed offtake, regulatory clarity, and investment to scale from demonstration to commercial operation.

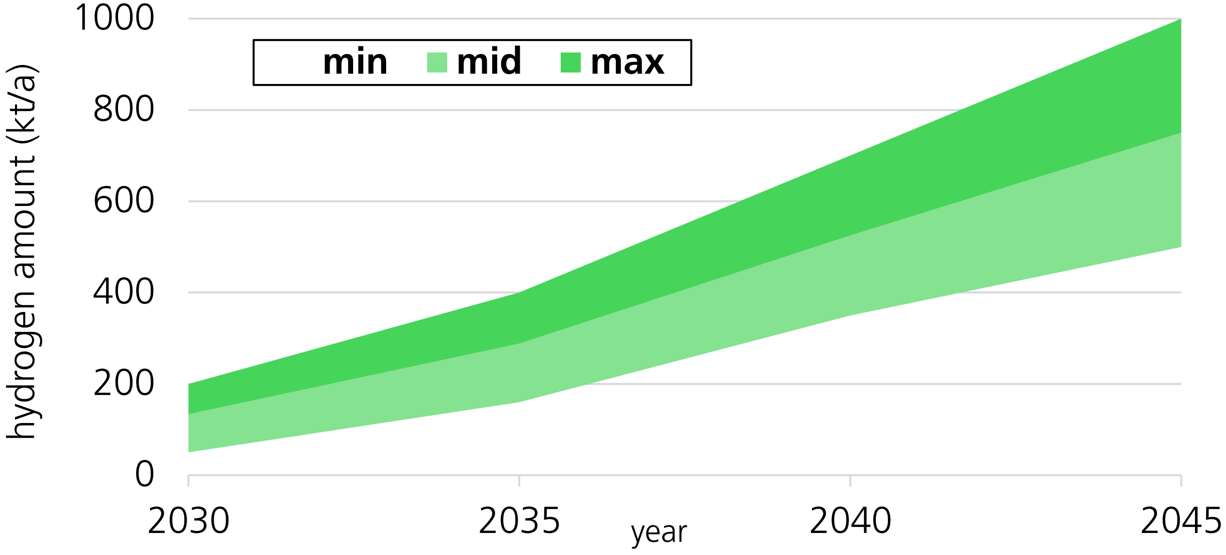
WP1: Scenarios for Terminal Capacities in Amsterdam

Ramp up till 2045 to 1 Mt H_2/a

Hydrogen amounts

- Scenarios ***min*, *mid* and *max*** of terminal capacity utilization
- Starting operation in 2030
  - Projected import volumes: ~50–200 kt H_2/a
  - Total terminal capacity: ~250 kt H_2/a
- Exponential ramp-up till 2045
- In 2045: Total volumes up to 500–1000 kt H_2/a
  → target of 1 Mt/a[1]

Funnel of estimated hydrogen import volumes to Amsterdam



→ Amsterdam pursues a dual-carrier strategy, with LH_2 and LOHC start operations ~2030
  → Starting terminal capacity: LH_2 ~200 kt H_2/a and LOHC ~50 kt H_2/a
  → LH_2 long-term capacity ramp up projected to at least ~600 kt H_2/a
→ Most capacity is deployed after 2030 → FIDs in the next 2–3 years are critical to stay on trajectory
→ At full scale (~1 Mt H_2/a by 2045), Amsterdam could provide a meaningful contribution to Germany's projected H_2 import needs[2], especially for the Rhine-Ruhr-Region

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[1]: Port of Amsterdam: https://www.portofamsterdam.com/en/business/cargo-flows/liquid-bulk/hydrogen
[2]: BMWK, Importstrategie für Wasserstoff und Wasserstoffderivate (2024): https://www.bundeswirtschaftsministerium.de/Redaktion/DE/Publikationen/Energie/importstrategie-wasserstoff.pdf?__blob=publicationFile&v=12

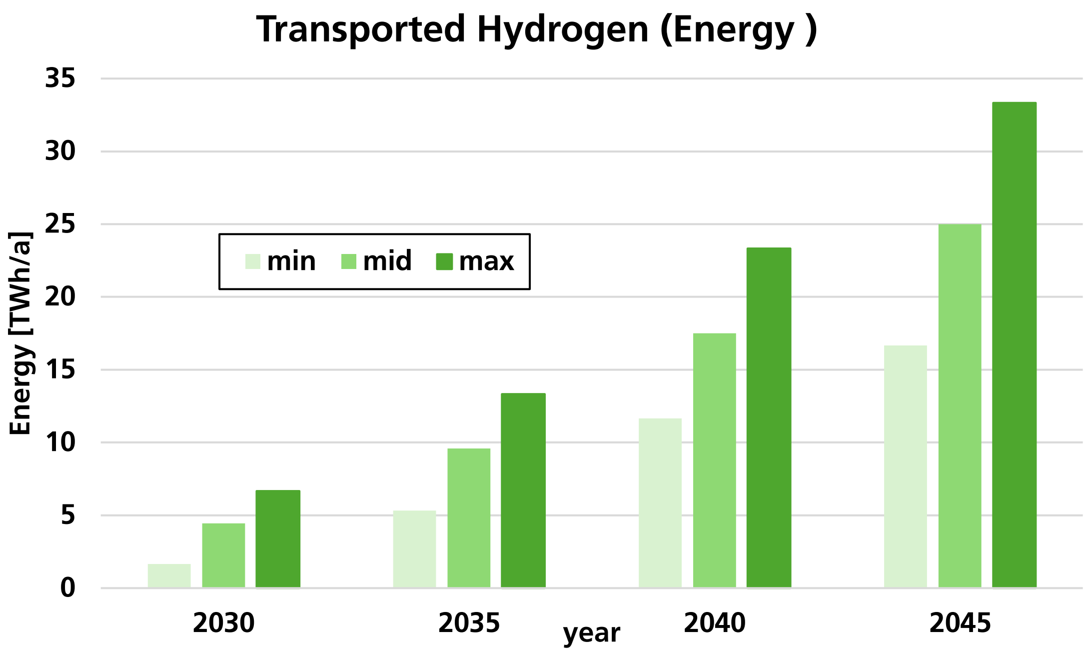
WP1: Transported Energy Amounts to Amsterdam

Ramp up till 2045 to 33 TWh_{th}/a

Note: 1 t $H_2 \triangleq 33.3\ MWh_{th}$ (LHV)

Imported energy

- Scenarios ***min*, *mid* and *max*** of capacity utilization
- Starting 2030
  - with ~2–7 TWh_{th}/a
- Exponential ramp up till 2045
- 2035: 5–13 TWh_{th}/a
- 2040: 12–23 TWh_{th}/a
- 2045: Total amount between 17–33 TWh_{th}/a
  - For reference: Germany's projected import volume is between 560–700 TWh_{th}/a by 2045 [1]
- **Transport from Amsterdam with pipeline, barge, trailer and train is possible**



→ Amsterdam's throughput (~17–33 TWh_{th}/a by 2045) represents ~3–5 % of Germany's total projected import need
→ This corresponds to an estimated ~30–35% projected Rhine-Ruhr industrial H_2 demand

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[1]: BMWK, Importstrategie für Wasserstoff und Wasserstoffderivate (2024): https://www.bundeswirtschaftsministerium.de/Redaktion/DE/Publikationen/Energie/importstrategie-wasserstoff.pdf?__blob=publicationFile&v=12

Working Package 2 of the Re-Chain study

Transport Routes and Spatial Analysis

Route Comparison

Possible hydrogen supply routes by sea

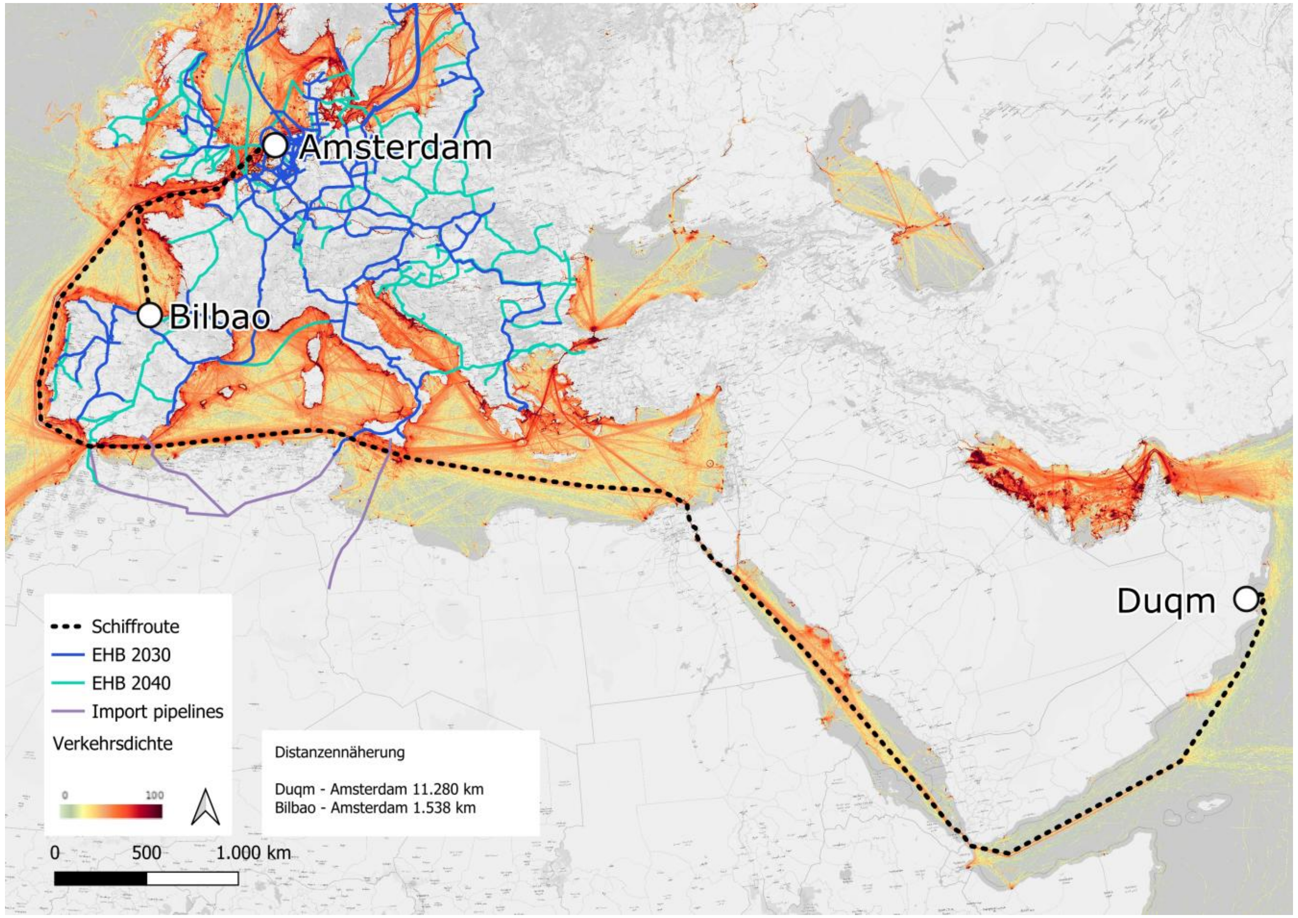
Using the global maritime traffic density data for September 2024 (GMTDS.MAPLARGE), the routes from the Port of Duqm (Oman) to the Port of Amsterdam (Netherlands) and from the Port of Bilbao (Spain) to the Port of Amsterdam were estimated.

Duqm – Amsterdam 11 280 km

Bilbao – Amsterdam 1 538 km

The figure on the right shows these routes, along with traffic density and the planned European hydrogen infrastructure for the target years 2030 and 2040.

Transit fees for the Suez Canal vary by vessel type, cargo and volume, and are difficult to estimate due to a 15% fee increase from 2025 and special LNG discounts. For a typical 170 000–180 000 cbm LNG tanker, a single transit is estimated at $450 000 – 550 000.



Source: [8,9,10]

WP2: Spatial Analysis

Port of Bilbao

Annual cargo throughput: 34.4 million t
↗5% compared to 2023 (Spain ↗2.7%)

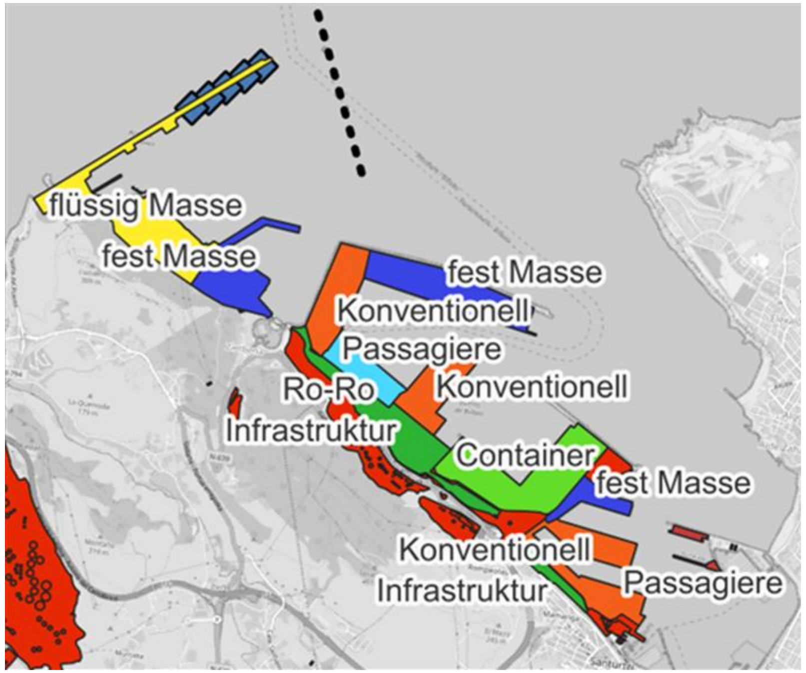
Container traffic: 458 928 TEUs
Main cargo: Crude oil, diesel, gas, iron and steel products, chemicals, machinery

Countries of origin and destination: United Kingdom, Netherlands, Belgium, USA, China, Brazil

Revenue in 2024: 76.7 million € (↗11.6%)

Investments in infrastructure and energy: 32.1 million €

Expansion of the port facility through the second phase of Espigón Central, which will create a new 1 011 m quay frontage on a 310 000 m² site. In addition, wind power capacity will be expanded in collaboration with Haizea Wind Group and Siemens Gamesa.



Legend – Site Map Port of Bilbao

- ● **Containers** → Container handling
- ● **Conventional** → Handling of conventional general cargo that is not transported in containers
- ● **Liquid bulk** → Handling of liquid bulk cargo
- ● **Solid bulk** → Handling of solid bulk cargo
- ● **Ro-Ro** → "Roll-on/Roll-off" (mobile cargo)
- ● **Passengers** → Passenger terminals
- ● **Industry and Port Infrastructure**
- ◆ **Wind turbine**

Source: [4]

WP2: Spatial Analysis

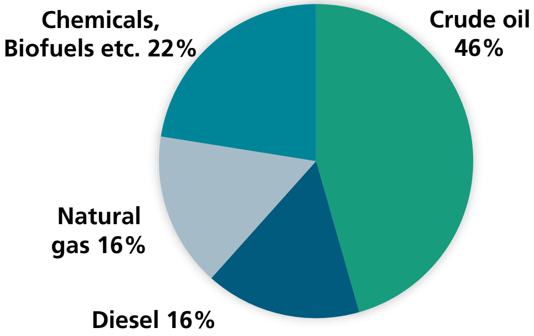
Port of Bilbao

Ship calls (2024)

2 766 (Cargo ships, ferries, and cruise ships)

➔ **7 to 8 ships per day**

281 932 passengers (mainly ferries and 81 cruise ships), which accounts for a small portion—with a strong focus on freight transport.



Liquid Bulks 21.57 Mio. t/a

Estimate: Number of tanker calls per day

Small tankers: 10 000–30 000 t
of chemicals, bunker oil, diesel → **n_{small} = 415 /a**

Medium-sized tanker: 50 000 t
of petroleum products, crude oil (regional)

Suezmax/VLCCs: 150 000 – 300 000 t
crude oil (long-haul) → **n_{VLCC} = 44 /a**

Standard LNG tankers: 70 000–100 000 t
of natural gas → **$n_{standard}$ = 40 /a**

➔ **1.4 tankers/ day**

Port of Bilbao – Sustainability projects

The **BilbOPS project** aims to supply the port's berths with shore power, thereby significantly reducing emissions from port operations. To this end, Onshore Power Supply (OPS) systems with a total installed capacity of approximately 30 MW will be installed at the quays. In **Phase 1** (2024–2026), 4.7 million € in investments are planned for the pilot phase, and in **Phase 2** (2025–2027), an additional 50.1 million € is earmarked for full electrification and grid coverage.

In addition, as part of an Environmental Partnership Agreement, **private environmental investments** totaling 7.34 € million will be made in photovoltaic systems, heat pumps, energy-efficient lighting, and vehicles with alternative drive systems.

Source: [4]

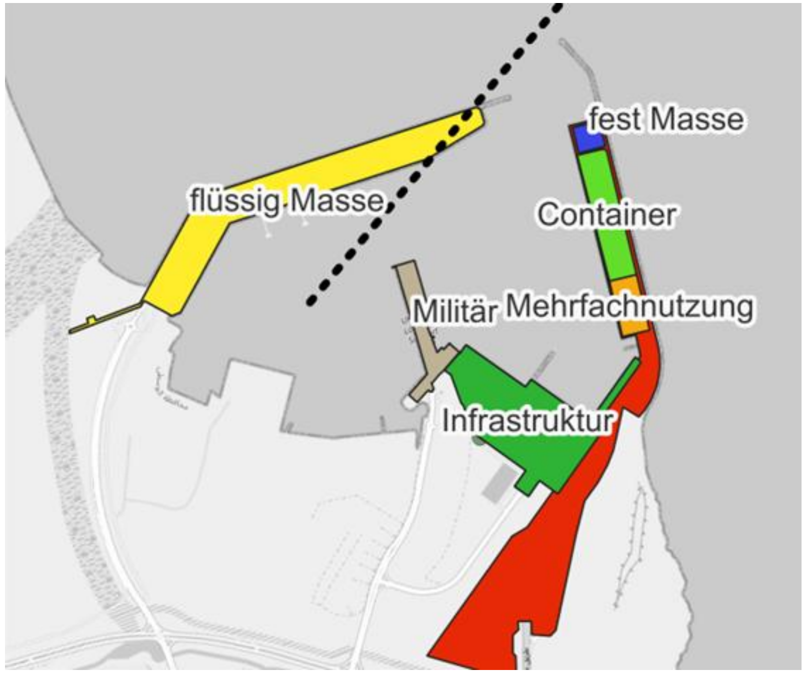
WP2: Spatial Analysis

Port of Duqm

The Port of Duqm has been undergoing expansion in two phases since 2012.

- **Phase 1** (through 2019) involved the construction of basic (terminal) infrastructure.
- **Phase 2** includes the expansion of the liquid bulk terminal (+40 ha), the container terminal, and a new fishing port.

In the immediate vicinity of the port are various industrial sites in the **mineral processing, oil and petrochemical** (Duqm Refinery), **fishing** (accounting for 70% of Oman’s market volume), **pipe and pipeline construction** (Middle East Tubular Services Duqm LLC (METS)), and **heavy industry sectors**.



Legend – Site Map Port of Duqm

🟢 **Containers** → Container handling (1.7 million TEU/year)

🟠 **Multi-purpose** → Handling of breakbulk, project cargo, containers, and other goods

🟡 **Liquid bulk** → Handling of liquid bulk cargo 7 berths with a focus on oil/petrochemicals

🔵 **Solid bulk** → Handling of solid bulk cargo (5 Mt/year) Primarily export of dolomite and limestone

● **Military** → Supply and service for naval vessels

Source: [5,,6]

WP2: Route Comparison

Possible hydrogen supply routes inland

Using specialized route-planning apps, the shortest possible routes between the Port of Amsterdam and Duisport were identified – Shown in the figures below.

With the appropriate infrastructure, hydrogen containers can also be transported by cargo trains. The distance between the two ports by rail is estimated to be 200 – 215 km.

Inland waterway vessel

Truck via highway

Routing setup for inland waterway route for vessels with the following dimensions:
T: 2.80 m, H: 7.70 m, L: 110.00 m, B: 11.40 m

Widths, heights and regulations for the inland waterway route

Amsterdam-Rhine Canal: 72.37 km, waterway class VIb, 34 bridges with a clearance height of 9.05 m above the canal water level NAP-0.40 m, three locks, Legal basis *Rijnvaartpolitiereglement* (RPR)

Rhine (Duisburg-Emmerich): Bridges over the Rhine between Koblenz and Emmerich have a clearance height of at least 9.10 m above the highest navigable water level (HSW), Legal basis *Rheinschifffahrtspolizeiverordnung* (RheinSchPV)

Waal: The Waal is part of the international waterway E10 (Rhine) and is classified as CEMT Class VIb/VIc in the UNECE classification → Minimum bridge height: 9.10 m.

Navigable channel widths on these sections are generally estimated at 70–115 m, based on the CEMT Class Vib/Vic classification. Actual widths may in some cases be greater.

Locks: There are three main lock complexes on the Amsterdam-Rhine Canal; Zuidersluis Nieuwegein, with a width of 12 m and a length of 120 m, is the smallest among them.

Source: [11,12, 21-23]

WP2: Centralized hydrogen supply

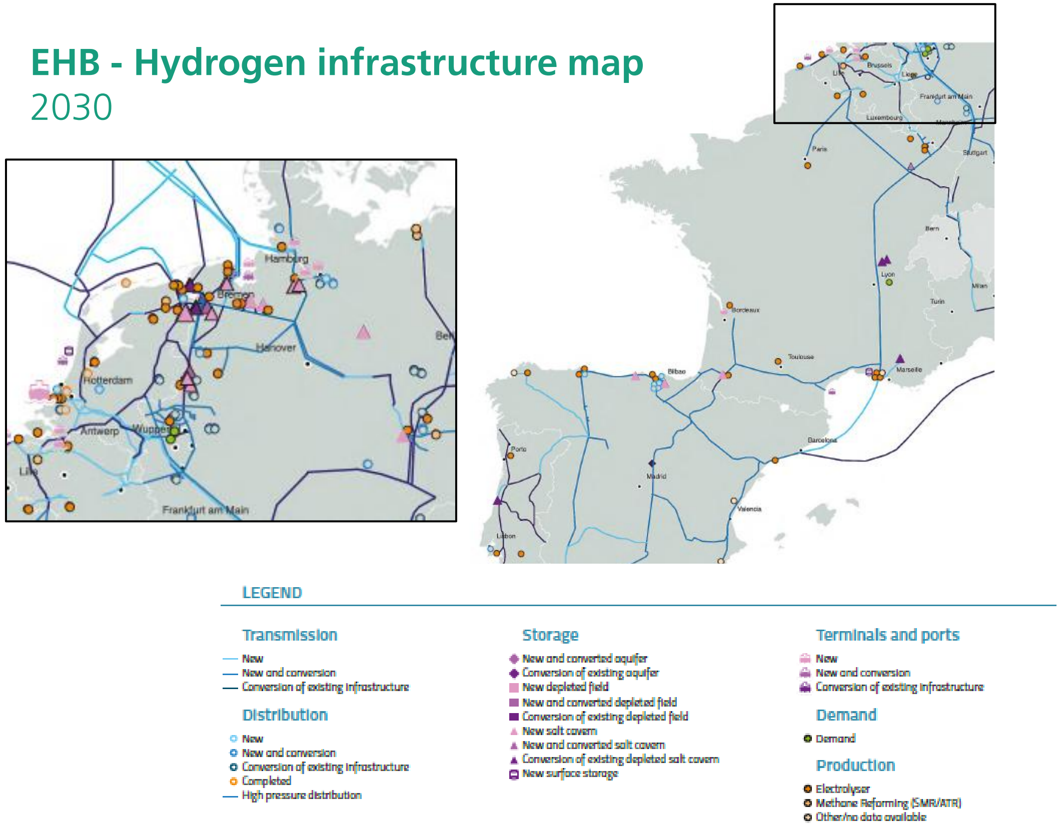
EHB and DRC as a future intra-European solution

European Hydrogen Backbone (EHB): Retrofit/construction of H_2 pipelines for European interconnection. Due to the slow pace of network expansion, interim solutions are necessary. The planning documents set out milestones for 2030 and 2050.

Delta-Rhine Corridor (DRC): Planned H_2/CO_2 pipeline network between the Netherlands and Germany (Shell, BASF, Gasunie, OGE), capacity ~4 300 t/d H_2 (~144 GWh/d); approval and planning procedures are underway in both countries. Here, too, implementation efforts are slow:

Status NL:
since 05/2023: Approval process
03/2024: Expression of Interest launched
from 09/2025: Feasibility study/approval for the Boxtel section
Status DE:
Q1/2024: Cooperation agreement, implementation in planning

EHB - Hydrogen infrastructure map
2030



DRC – Infrastructure map

Source: [13,14]

WP2: References

[1] Tongtong Zhang et al. 2023, Hydrogen liquefaction and storage: Recent progress and perspectives https://doi.org/10.1016/j.rser.2023.113204
[2] Ortiz Cebolla, Rafael ; Dolci, Francesco ; Weidner Ronnefeld, Eveline: Assessment of hydrogen delivery options. https://publications.jrc.ec.europa.eu/repository/handle/JRC130442
[3] Peecock, Anna et al. 2024, Techno-economic assessment of liquid carrier methods for intercontinental shipping of hydrogen: A case study, doi: 10.1016/j.ijhydene.2024.11.205
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[22] https://de.wikipedia.org/wiki/Amsterdam-Rhein-Kanal
[23] https://rheinspange.nrw.de/question/wie-hoch-ist-die-durchfahrtshoehe-der-geplanten-bruecke-fuer-die-rheinschifffahrt/

The website was last accessed on April 9, 2026.

Working Package 3 of the RE-Chain study

Identification of Off-takers in Rhine-Ruhr-Region / NRW

WP3: Objective and Methodology of the Company Analysis

H_2 Offtake potential in the Rhine Ruhr region

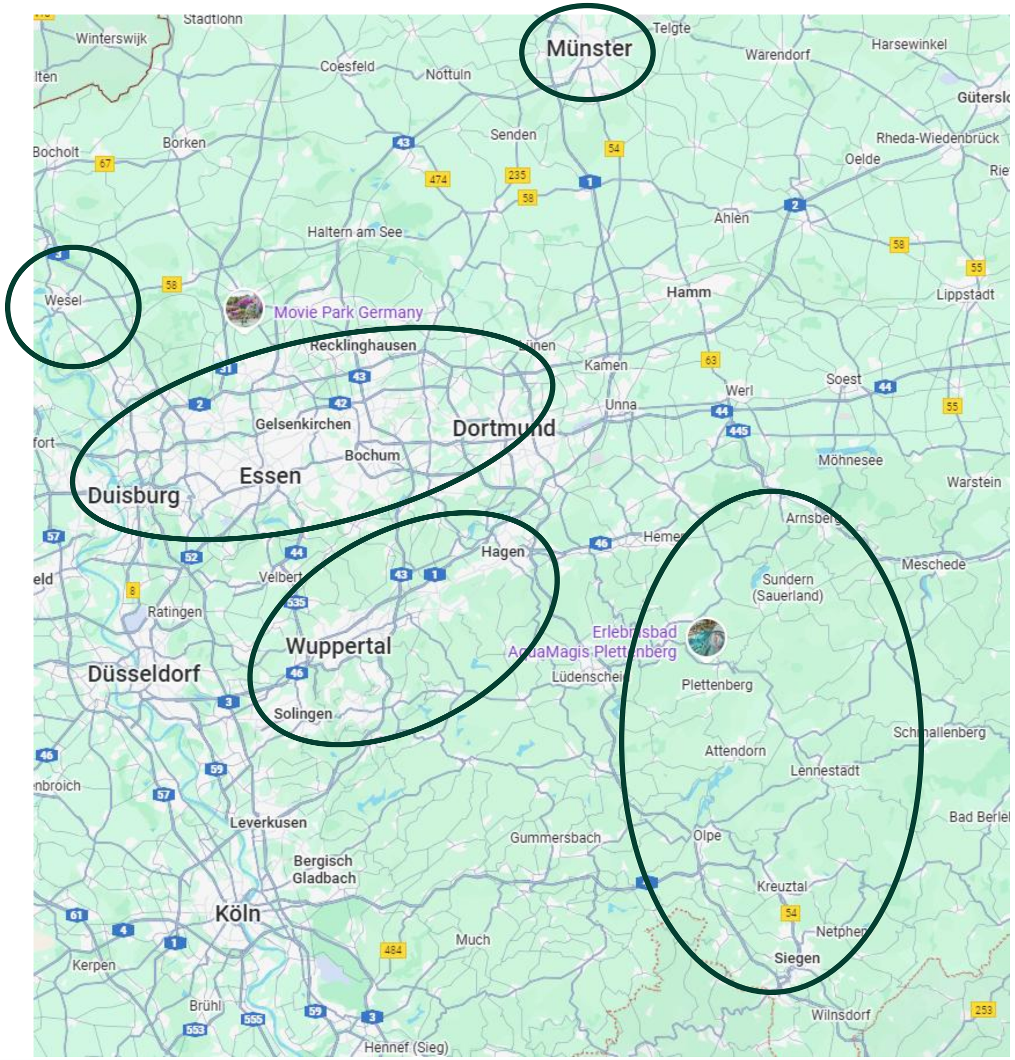
- Intended procedure
  - Assessment of requirements of 10 major off-takers (5 liquified H_2, 5 LOHC if available) served by clients
  - Analysis of existing regional studies (maximum of 5 freely available specific studies)

- Company survey
  - Interviews with off-takers suggested by ports
  - Identification of additional potential off-takers in the region and conduction of a questionnaire-based survey

- Adjustment of the procedure due to hesitation of the surveyed companies
  - Interviews with several IHKs for general overview of companies in specific regions
  - Extended literature review regarding hydrogen demand forecasts for North Rhine-Westphalia

WP3: Study areas

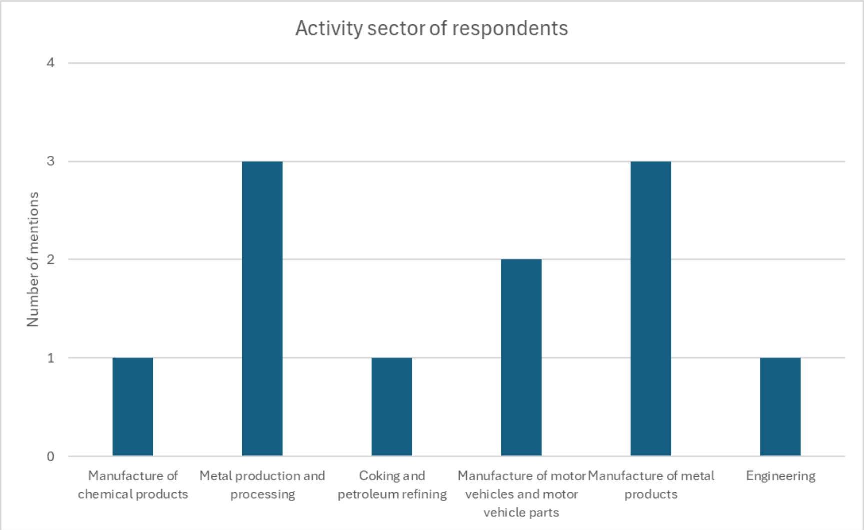
- Initially, the study areas were defined as the Ruhr region, the Rheinberg/Wesel area and the area south of the Ruhr region to identify the ten major offtakers to be evaluated.
- In the course of the work, the region under investigation was extended to South Westphalia. In addition to the companies, the Chambers of Industry and Commerce (IHK) were included in the analysis as potential sources of information.
  - **Rheinberg:** chemical and logistics location (Solvay and Amazon), otherwise characterized by SMEs
  - **Wesel:** port site with establishment of chemical industry (including BYK) as well as SME companies from various sectors (metal and steel processing, construction, ceramics, food, healthcare).
  - **Münster:** small and medium-sized enterprises with a wide variety of industries (mechanical engineering, food, logistics, healthcare, knowledge-based services).
  - **Urban triangle Wuppertal, Solingen, Remscheid:** sites of medium-sized companies (chemical, electrical, plastics industries, metal products, tools, food), including many global market leaders
  - **South Westphalia:** sites of medium-sized global market leaders ((automotive, electrical industry, mechanical and plant engineering, metal products)

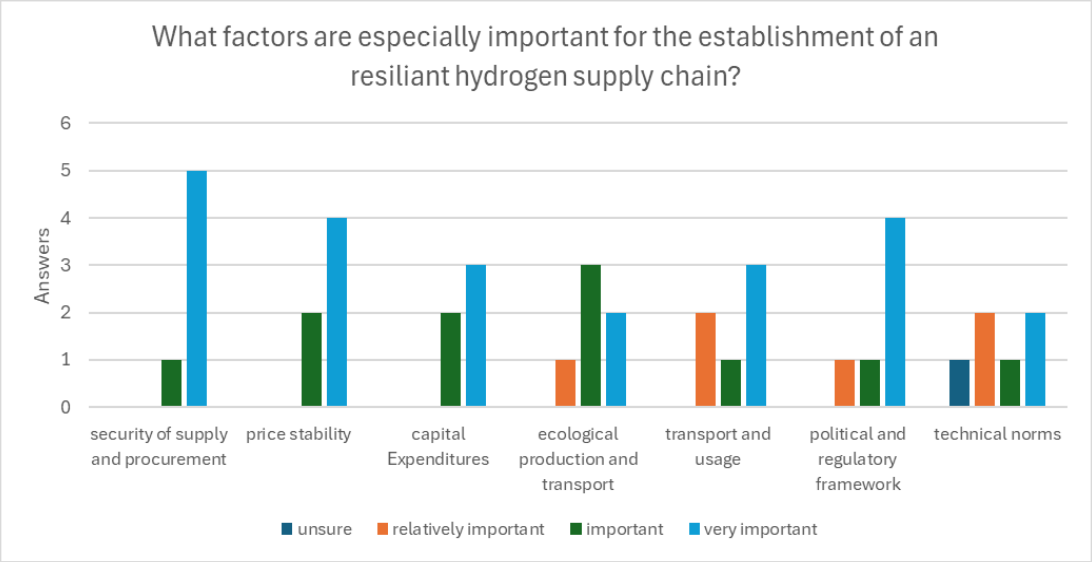


WP3: Questionnaire: Results of the survey

Overview of results

- Infrastructure as well as economic and regulatory conditions named as main hurdles for implementation
- Hydrogen suppliers want security through long contracts – Large industrial companies cannot sign due to financial risk
- Economically viable hydrogen prices are given between **1.5–5 €/kg** in 2035
- Hydrogen demand varies strongly between respondents and years (two at lower end:
  75 t/year + 480 t/year, two large consumers:
  100,000 – 200,000 t/year)
- Spatial constraints at the sites limit delivery of LOHC and LH_2
- For big consumers direct delivery through pipeline is the only option





→ More information in WP4: Cost Estimation

WP3: Literature review: Hydrogen Ramp-Up NRW

Opportunities for hydrogen in Rhein-Ruhr region

NRW status quo and planned initiatives

- 35 MW installed electrolysis capacity
- Up to 220 MW in advanced planning
- Hydrogen infrastructure (storage & transport) planned and partly in use
- Lighthouse projects for large scale use of hydrogen (tkH2steel, hydrogen fired brick making)
- High activity and connectivity with large connection between different stakeholders (Energy4Climate,In4Climate, H2BMR, Klima Diskurs NRW)

Year	H_2-demand	Imports
2030	29-39 TWh	48-70 %
2045	129-179 TWh	>90%

Hurdles

- High cost
- Limited capacity of renewable electricity
- Regulatory restrictions for green hydrogen certification
- Economic and regulatory uncertainty
- Companies choose to delay investment decisions due to regulatory and economic uncertainty
- Hesitation of company's further halts infrastructure development

Sources: In4Climate.NRW, 2026, Wasserstoff auf Kurs bringen: Produktionskosten senken und Nachfrage anreizen, Düsseldorf; MWIKE, 2024, Wasserstoff-Importkonzept Nordrhein-Westfalen

WP3: Conclusion

Opportunities for hydrogen in Rhein-Ruhr region

Opportunities

- **Planned import capacities can significantly contribute to hydrogen demand in NRW**
- **The region is characterized by strong interconnectedness and diverse exchange formats among stakeholders along the hydrogen value chain.**

	2030	**2045**
H_2-demand [kt]	870 – 1170	3870 – 5370
Imports [kt][1]	418 – 819	3483 – 4833
Import volumes Amsterdam [kt]	50 – 200	1000
Possible share of expected imports	6 – 48 %	29 – 21 %

[1]: calculated with import rates of 48 – 70% for 2030 and 90% for 2045, taken from In4Climate.NRW, 2026, Wasserstoff auf Kurs bringen: Produktionskosten senken und Nachfrage anreizen, Düsseldorf and MWIKE, 2024, Wasserstoff-Importkonzept Nordrhein-Westfalen

Working Package 4 of the RE-Chain study

Cost Estimation and Risk Analysis

Working Package 4 of the RE-Chain study

Cost Estimation

Hydrogen supply chain costs: From the port of origin to the port of Duisburg

WP4: Introduction to Cost Estimation

Cost Estimation – Why imported Hydrogen?

*The **Levelized Costs of Hydrogen (LCOH)** are critical for potential off-takers who need price certainty to commit volumes and convert their production processes. At the same time, infrastructure investors require guaranteed off-take to justify their capital expenditure – creating a chicken-and-egg problem that can only be resolved through reliable cost transparency.*

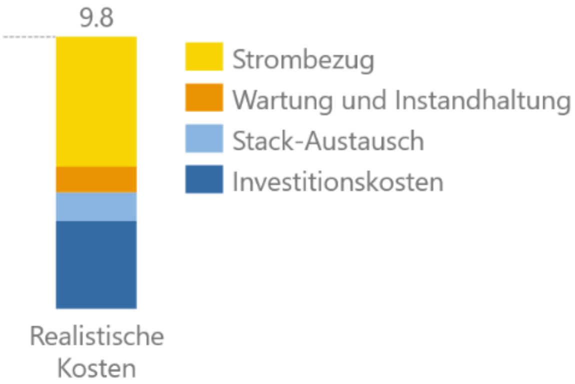
Germany

- Realistic LCOH for green hydrogen are **~10 €/kg today[1]** and so significantly higher than commonly cited in public reports
  - Projections indicate fall to **~7 €/kg by 2050[1]**
- Electricity costs account for ~50 % of total LCOH – this is the single most effective lever for cost reduction [12,13]

Spain/MENA-Region

- Regions offer substantially lower renewable electricity costs due to superior solar irradiation and wind resources
  - ~15–35 €/MWh_{el} vs. ~60–80 €/MWh_{el} in Germany

Central question: Can the lower electricity costs overseas compensate for the additional conversion and transport costs – and at what price does H_2 arrive at the point of use?



Levelized Cost of Hydrogen (LCOH) in Germany of green hydrogen in 2025. Figure copied from[1]

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[1]: Forschungsstelle für Energiewirtschaft e. V. (2025), Warum ist Wasserstoff in der Praxis teurer als bisher häufig angenommen?

WP4: Hydrogen Production Costs in Oman and Spain

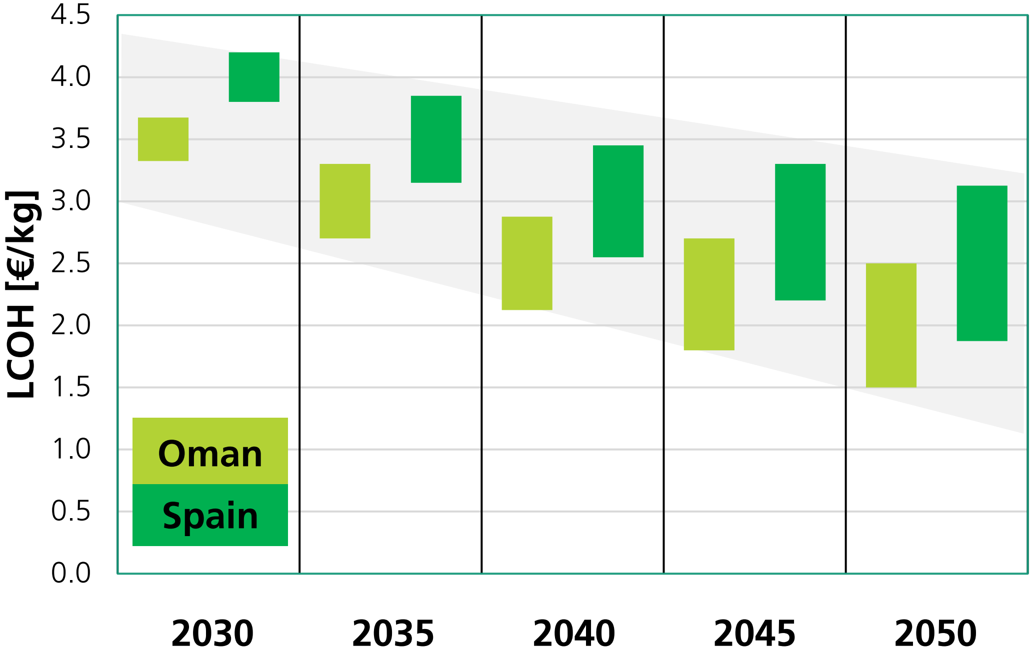
Assumed LCOH in the RE-Chain study

Assumptions in REChain study

- Oman is cheaper (0.5 €/kg) than Spain
- 2030: 3.5 €/kg in Oman (~4 €/kg Spain)
- **2050: Cost reduction to 2 €/kg in Oman (PtX-Atlas [1])**
- Uncertainty of ± 5% for every further 5-years-step

Region	Scenario	2030 [€/kg]	2035 [€/kg]	2040 [€/kg]	2045 [€/kg]	2050 [€/kg]
Oman	Negative	3.68	3.30	2.88	2.70	2.50
	Trend	3.50	3.00	2.50	2.25	2.00
	Positive	3.33	2.70	2.13	1.80	1.50
Spain	Negative	4.20	3.85	3.45	3.30	3.13
	Trend	4.00	3.50	3.00	2.75	2.50
	Positive	3.80	3.15	2.55	2.20	1.88

Cost corridors for hydrogen production



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[1]: Fraunhofer IEE (2026), *Global PtX Atlas*, https://maps.iee.fraunhofer.de/ptx-atlas/#user

WP4: Cost Estimation - System Boundaries for the Supply Chain

Defining the Levelized Cost of Transport Services (LCOTS)

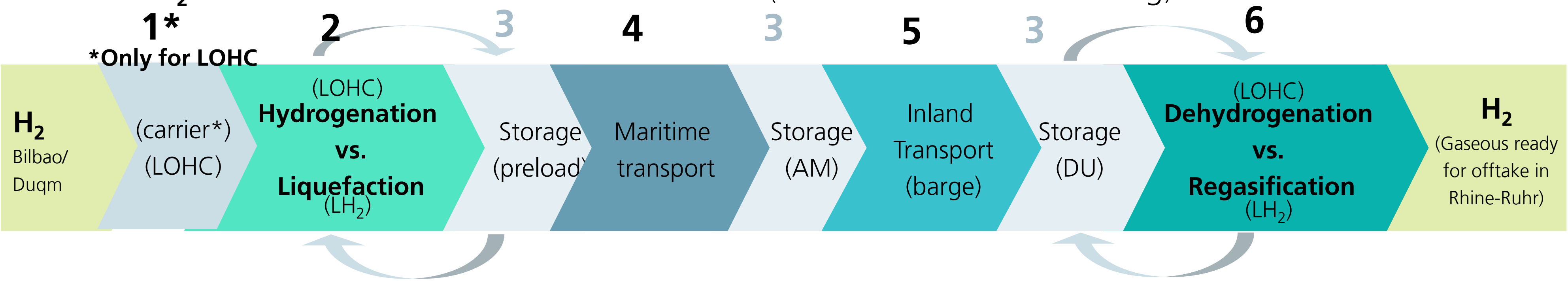
System Boundaries

- The cost estimation in REChain covers the full conversion and transport chain from gaseous H_2 at the port of origin (Bilbao or Duqm) to gaseous H_2 at the gate in Duisburg
- No subsidies are considered (CfDs, auctions, CAPEX, OPEX…) are considered → maximum price ranges
- Excluded: upstream H_2 production and downstream distribution to offtakers beyond the port gate

→ This ensures a technology-neutral comparison – all pathways start and end with the same product (gaseous H_2 in Duisburg, DPU)

Definition of the LCOTS

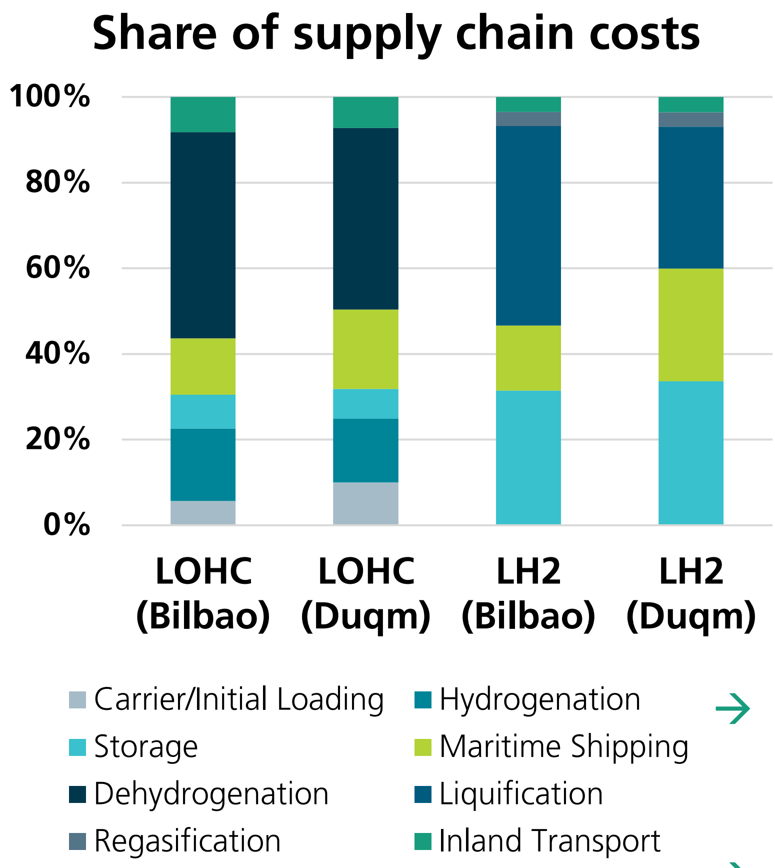
- The costs of the supply chain are defined as **Levelized Costs of Transport Services (LCOTS)**
- LCOTS are the sum of all services in the chain
- The three storing services at ports are clustered as "*Storage*" due to individual marginal costs in the chain
- Results in **five services in the LH_2-Chain and six services in the LOHC-Chain** (additional *initial carrier loading*)



→ With literature analysis and the provided company data from the interviews, Fraunhofer UMSICHT estimated the future LCOTS for both carrier options (LH2 and LOHC) and supply regions (Spain and Oman)

WP4: Cost Breakdown of the LCOTS

Cost comparison of LH_2 and LOHC for short- and long-distance transport



	LOHC (Bilbao)	LOHC (Duqm)	LH_2 (Bilbao)	LH_2 (Duqm)
Carrier/Initial Loading	**4-6 %**	**6-8 %**	**-**	**-**
Hydrogenation	**14-16 %**	**14-16 %**	**-**	**-**
Liquefaction	**-**	**-**	**40-44 %**	**28-32 %**
Storage (incl. boil-off)	**6-8 %**	**6-8 %**	**26-30 %**	**28-32 %**
Maritime Shipping	**11-13 %**	**17-19 %**	**12-16 %**	**22-26 %**
Dehydrogenation	**42-46 %**	**40-44 %**	**-**	**-**
Regasification	**-**	**-**	**2-4 %**	**2-4 %**
Inland Transport	**7-8 %**	**6-8 %**	**2-4 %**	**2-4 %**

**storage costs are summarized across the ports (production, Amsterdam and Duisburg)*

→ For LOHC, **dehydrogenation** is the main cost driver
  → Industrial waste heat from adjacent facilities (*Tata Steel Amsterdam*, *thyssenkrupp* Duisburg) could reduce LOHC reconversion costs by 30–40 %

→ For LH_2, the largest shares come from **liquefaction** and **storage**
  → low-cost renewable electricity can reduce these costs by 30–50 %

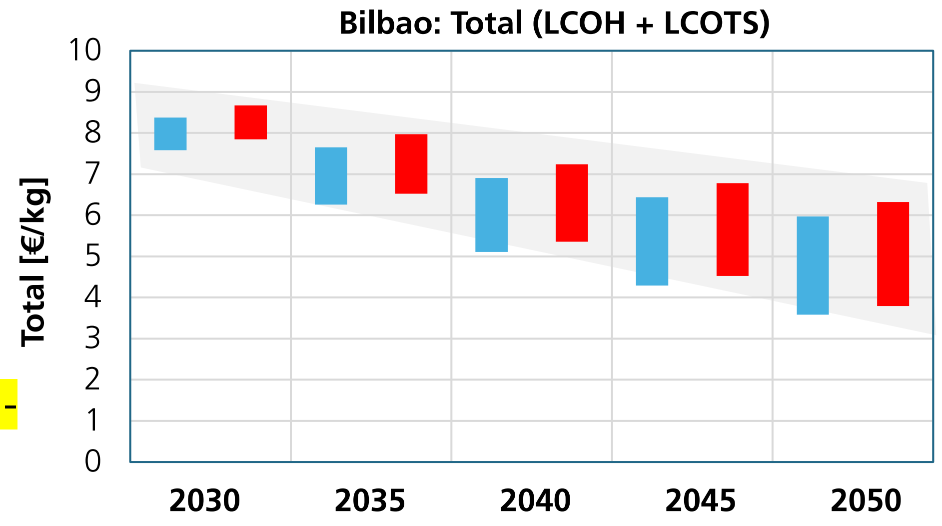
WP4: Comparison of both Routes and Carrier Options

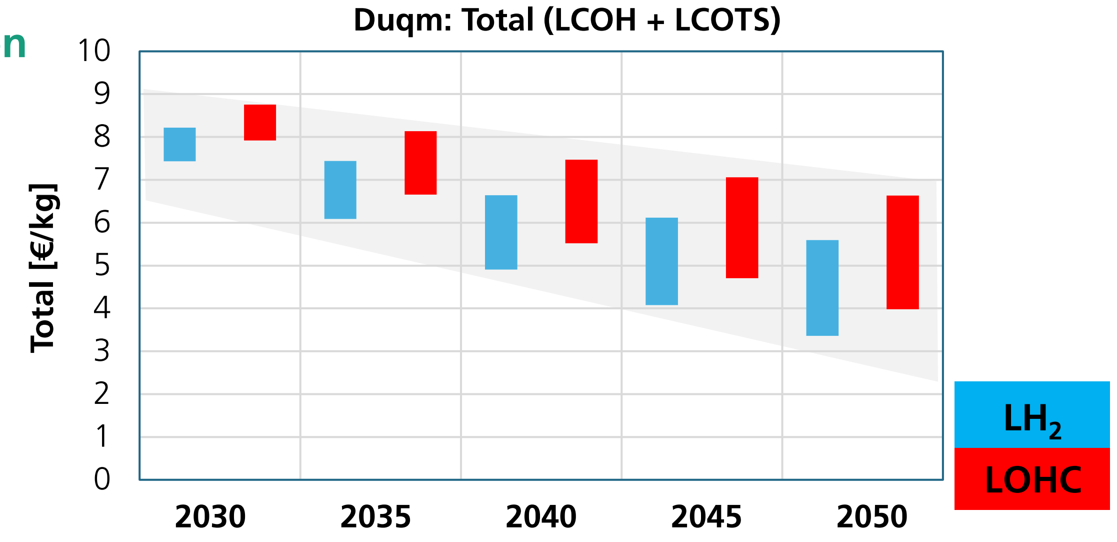
Total Costs (DPU) at Duisburg (LCOH + LCOTS)

- The costs for hydrogen from both regions are comparable
  - Bilbao: lower maritime transport and carrier return costs
  - Duqm: lower hydrogen costs and higher RE availability
- LH_2 cost reduction is driven by economies of scale in cryogenic liquefaction, storage and transport infrastructure
- LOHC cost reduction is supported by the potential use of existing liquid-bulk logistics infrastructure (e.g., tanks and tankers)

→ Both carriers converge towards 3,5–6,5 €/kg by 2050, creating a viable business case for industrial off-take in the Rhine-Ruhr region

Year	Bilbao (LH_2) [€/kg]	Bilbao (LOHC) [€/kg]	Duqm(LH_2) [€/kg]	Duqm (LOHC) [€/kg]
2030	**7.6-8.4**	**7.8-8.7**	**7.4-8.2**	**7.9-8.8**
2035	**6.3-7.7**	**6.6-8.0**	**6.1-7.4**	**6.6-8.0**
2040	**5.1-6.9**	**5.4-7.3**	**4.9-6.6**	**5.4-7.3**
2045	**4.3-6.4**	**4.6-6.9**	**4.1-6.1**	**4.5-6.8**
2050	**3.6-6.0**	**3.9-6.4**	**3.4-5.6**	**3.8-6.3**





WP4: Comparison with production in Germany

Total Costs (DPU) at Duisburg (LCOH + LCOTS)

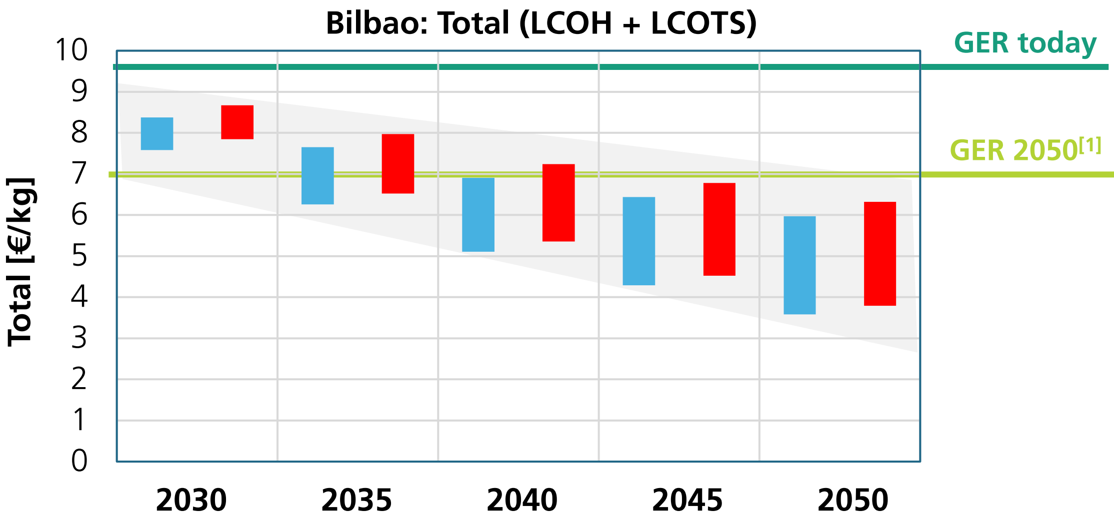
- LCOH in Germany are ~10 €/kg for green hydrogen today
- 2050 Germany **~7 €/kg** [1]
- 2050 Bilbao: LH_2 3.6–6.0 €/kg and LOHC 3.9–6.4 €/kg
- 2050 Duqm: LH_2 3.4–5.6 €/kg and LOHC 3.8–6.3 €/kg

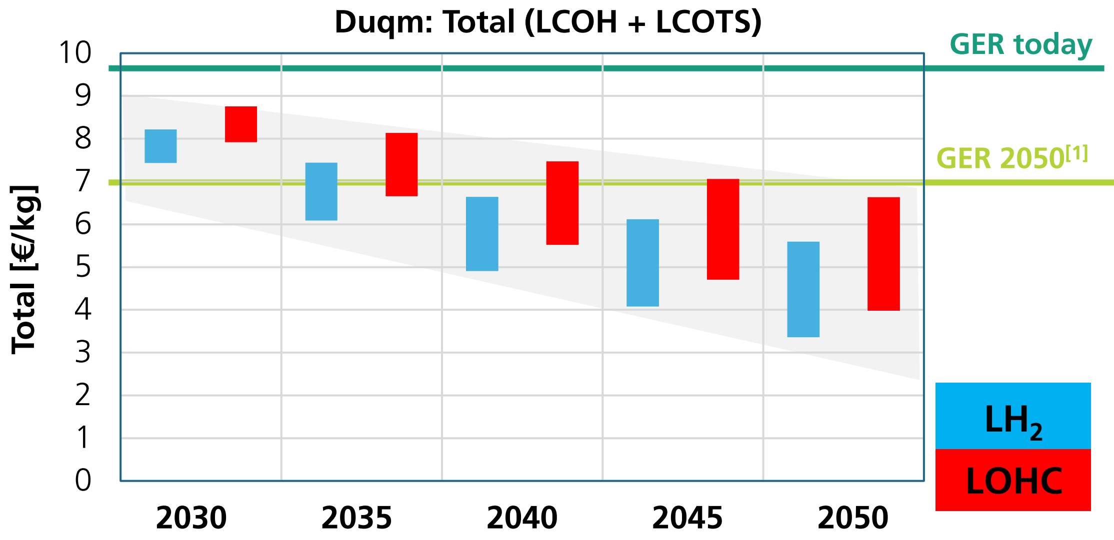
Both carrier options are cheaper than domestic production in GER

Comparison to Off-taker expectations

- **Off-taker price expectations (1.5–5 €/kg in 2035, WP3 results) reflect aspirational targets** in a pre-commercial market – actual market prices will be shaped by carbon pricing and supply security → trend is upward
- **A transitional cost gap of ~2–4 €/kg is expected in 2035** – comparable to early phases of LNG and offshore wind markets, where targeted policy support (CfDs, auctions) successfully bridged similar gaps within 5–8 years
- **Cost convergence is projected for 2040–2045**, driven by infrastructure scale-up, declining RE costs, and increasing CO_2 prices – **positioning early movers at a decisive competitive advantage**

Targeted EU and national funding instruments (CfDs, H_2 auctions…) can further narrow the cost gap – positioning imported hydrogen within off-taker price range before 2040 can be another lever





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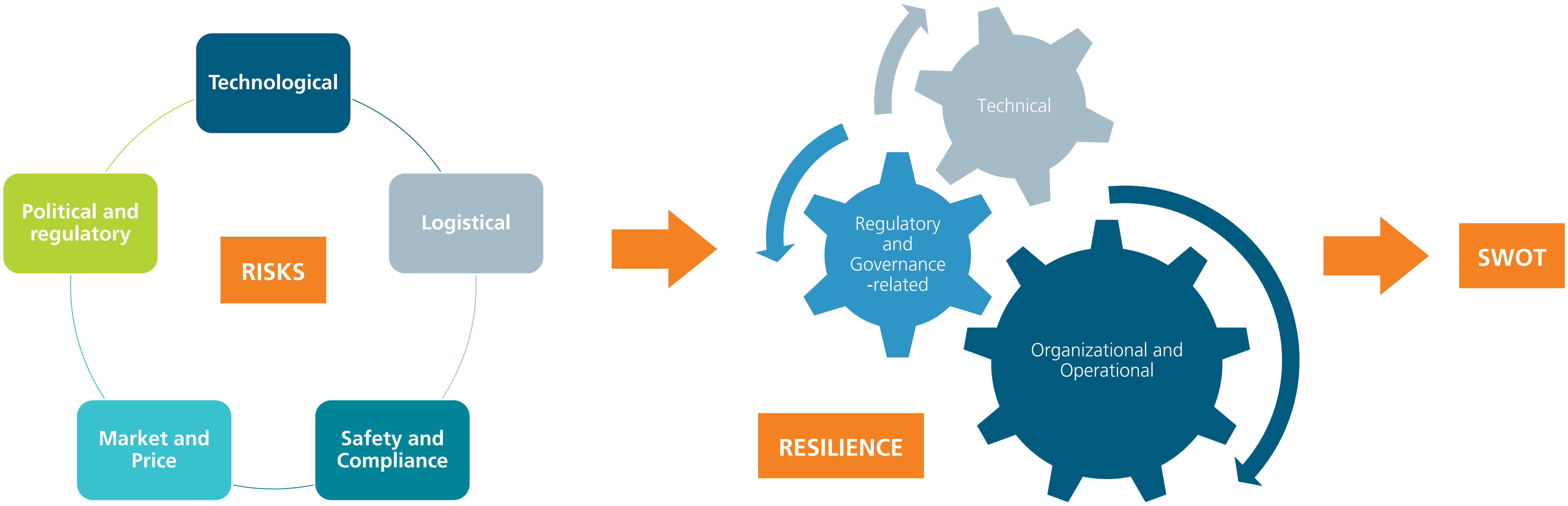
[1]: Forschungsstelle für Energiewirtschaft e. V. (2025), *Warum ist Wasserstoff in der Praxis teurer als bisher häufig angenommen?*

Working Package 4 of the RE-Chain study

Risk Analysis

WP4: Risk & Resilience Analysis

Investigation of risks and derivation of suitable resilience strategies



Technological

Political and regulatory

Logistical

RISKS

Market and Price

Safety and Compliance

Technical

Regulatory and Governance -related

Organizational and Operational

RESILIENCE

SWOT

WP4: SWOT Analysis

LOHC in terms of resilience and risks

Strengths

- potential compatibility with established liquid-bulk transport and storage infrastructure
- high chemical stability and low explosion risk
- high scalability for the transport of large energy volumes

Weaknesses

- energy-intensive dehydrogenation as a systemic bottleneck
- carrier return logistics increase transport demand and system complexity
- dependence on catalysts and process heat

Opportunities

- potential integration with established liquid-bulk logistics
- integration into industrial waste heat utilization
- regional dehydrogenation hubs could serve concentrated industrial hydrogen demand

Threats

- regulatory delays in terminal-adjacent facilities
- market uncertainties regarding the carrier material
- disruptions in dehydrogenation facilities have direct system-critical impacts

WP4: SWOT Analysis

LH_2 in terms of resilience and risks

Strengths

- high energy density and efficient delivery of large volumes
- no carrier return logistics required
- direct compatibility with applications requiring gaseous H_2

Weaknesses

- stringent safety requirements and technological sensitivity
- boil-off management required
- limited large-scale infrastructure and low buffering capacity

Opportunities

- expansion of cryogenic port infrastructure generates economies of scale
- application in mobility & industry enables broad demand
- synergies with LNG expertise and technology

Threats

- political and regulatory uncertainties
- dependence on a limited number of technological suppliers
- delays in infrastructure scale-up could constrain large-volume deployment

WP4: Minimizing risks along the hydrogen value chain

Key Takeaways from macro-perspective

Upstream

- Easing of RFNBO requirements through the postponement of electricity procurement criteria regarding additionality and hourly correlation
- Enabling the use of hourly GHG accounting

Midstream

- Standardized, tradable hydrogen products and contract frameworks are an essential prerequisite for the ramp-up and development of a market
- Consistent implementation of the Hydrogen Acceleration Act
- Development of the hydrogen core network
- Government guarantees and sureties as well as price difference mechanisms (CfDs) during the development and ramp-up phase

Downstream

- Establishment of binding lead markets and demand anchors
- OPEX subsidies as well as transparent, possibly index-linked cap/floor price ranges

Source: BDEW (2026) - Risikominimierung entlang der Wasserstoff-Wertschöpfungskette

WP4: Funding

Most relevant currently available funding options to support LOHC and LH_2 Terminal Infrastructure

DEI+: Waterstof en groene chemie (Netherlands)

- Objective: Supports pilot, demonstration, and test infrastructure projects for hydrogen and hydrogen carriers with a conversion step, with the aim of reducing CO_2 emissions in the Netherlands
- Total budget of 134 million €, up to 30 million € for demonstration projects and 25 million € for test infrastructure. **Closed on 30 July 2026**

Connecting Europe Facility - CEF Energy: Projects of Common/ Mutual Interest Call (European Union)

- Objective: Supports strategic cross-border energy infrastructure projects in Europe, including hydrogen pipelines, storage, import terminals, and related infrastructure
- Total CEF Energy budget of 5.8 billion € for 2021-2027. Expected deadline: end of **September 2026**

Versnelde klimaatinvesteringen Industrie – VEKI (Netherlands)

- Objective: supports CO_2-reduction investments in industry, including hydrogen infrastructure
- Total budget of 125 million €, up to 25 million € for specific hydrogen infrastructure and storage projects. **Open until 28 January 2027**

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