Identification and Testing of Resilience Strategies for Inland Waterway Transport

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ResC4EU RESILIENT SUPPLY CHAINS FOR EUROPE

RENEW

Introduction

Resilience has become a key priority in transport and supply chain systems due to increasingly frequent and severe disruptions. However, Inland Waterway Transport (IWT) remains underrepresented in resilience research and strategy development.
This study was supported by two projects ResC4EU (Resilience for Supply Chains in Europe) and ReNEW (Resilience-centric Smart, Green, Networked EU Inland Waterways). This research features following items:

- Rising disruption pressure
  - Climate-related events (heatwaves, floods, droughts)
  - Labour disputes and operational interruptions
- IWT: critical but highly vulnerable
  - Essential part of Europe's multimodal transport system
  - Strong dependence on water levels, locks, and infrastructure
- Research gap
  - Lack of IWT-specific resilience strategies
  - Existing approaches are mostly generic and not context-sensitive
- Research contribution
  - Literature-based identification of resilience strategies
  - Scenario-based serious gaming to test disruptions
  - Development of a validated resilience framework for IWT

Methodology - Setting

A combined method bridges theory and practice: Part I provides a structured pool of resilience strategies and Part II stress-tests and identifies measures under realistic IWT disruption conditions, which can be linked to the pool of strategies of Part I.

Part I: Literature Review (ResC4EU)
Actionable resilience strategies from existing literature and the ResC4EU project through a post hoc review were derived:

- Foundation: ResC4EU and supply chain resilience literature
- Approach: Post hoc review of key resilience capabilities
- Capabilities → Strategies
  - Flexibility, visibility, digitalisation, financial strength
  - Reframed as actionable strategies
- Outcome: Initial strategy pool for further analysis

Part II: Scenario-based serious gaming methodology (ReNEW)
A scenario-based serious gaming approach within the ReNEW Living Labs was used to identify and refine resilience strategies in real-world IWT contexts:

- Rationale
  - Business games increase practitioner engagement and discussion
  - Safe environment to test measures without real-world risk
- Foundation:
  - Four Living Labs addressing key IWT resilience challenges
- Approach
  - Adapted serious game involving ReNEW Living Lab stakeholders
  - Scenario-based discussion on disruptions and strategies following Serious Gaming approach
  - Six disruption scenarios: heatwave, drought, storm, high water, flooding, strike
  - Role-based interaction reflecting real supply chain actors
- Elicitation of measures
  - Immediate actions using existing measures
  - Long-term strategies to prevent future disruptions
- Outcome
  - Identification of practical and forward-looking resilience measures
  - Integration of practitioner knowledge into strategy development

The adapted approach was carried out with these Living Labs (LL):

- Living Lab LL1 (Ghent): resilient city logistics hub
  - Smart terminal development
  - Floating modular platform for emergency transport & energy supply
- Living Lab LL2 (Douro River): infrastructure & environmental resilience
  - Digital twin for ship performance and emergency planning
  - Real-time wastewater monitoring to prevent illegal dumping
- Living Lab LL3 (EU network): digital planning & mitigation
  - Route-planning app with real-time adjustments (routes, speeds)
  - Enhances network-wide resilience and capacity
- Living Lab LL4 (Autonomous barges): fleet innovation
  - Development of automated, zero-emission vessels (X-barge)
  - Strengthens system adaptability and robustness

Results

Capability-Based Strategy Pool (Part I)
A capability-based pool of resilience strategies from literature, forming the theoretical foundation for further testing was identified:

- Foundation
  - Derived from supply chain resilience literature
  - Capabilities reframed as actionable strategies
- Resilience strategies (strategy pool)
  - **Flexibility** (sourcing & delivery): switch suppliers, routes, or transport modes to maintain flows under disruption
  - **Capacity**: adjust production, storage, and transport volumes to absorb demand and supply shocks
  - **Efficiency**: maintain performance with minimal resources, even under stressed conditions
  - **Visibility**: real-time monitoring of assets, flows, and external conditions for informed decision-making
  - **Adaptability**: reconfigure operations and processes in response to changing environments
  - **Anticipation**: capability to discern potential future events or situations
  - **Recovery**: skill to restore from events
  - **Dispersion**: distribute assets and infrastructure geographically to reduce concentration risks
  - **Collaboration & trust**: share information and coordinate actions across supply chain partners
  - **Security**: protect systems against disruptions, including physical and cyber threats
  - **Financial strength**: ensure liquidity and financial buffers to withstand shocks
  - **Digitalisation**: use digital tools (e.g., data analytics, platforms, digital twins) to enhance resilience
  - **Risk culture**: proactively identify, assess, and manage risks and uncertainties
  - **Sustainability (social & ecological)**: ensure workforce well-being and environmentally sustainable operations
- Outcome
  - Structured strategy pool as theoretical basis
  - Input for validation and refinement in Part II

Scenario-Based Measures (Part II)
Scenario-based measures were identified in the Living Labs and mapped them to the resilience strategy pool from Part I.

Heatwave	Drought	Storm	High Water	Flooding	Strike	Measures mentioned by LLs	Mapped strategy
■		■	■	■		Suspending operations	Flexibility
■						Adjusted operating hours	Flexibility
■	■		■		■	Alternative routes	Flexibility
□					□	Vessel Planning System	Flexibility
	■					Reducing vessel loads	Flexibility
	■		■		■	Adjusting schedules	Flexibility
	■		■	□	■	Alternative transport	Flexibility
					■	Implement contingency plans	Flexibility
					□	Operational adjustments: Use Hubs	Flexibility
■	■	■	■	■	■	Inform clients	Information visibility and exchange
□	■	□	■	■	□	Alternative vessel	Adaptability
	□	□	■	■		Resilient infrastructure: Dredging and maintenance	Adaptability
	□	□	■	■		Resilient infrastructure: Infrastructure improvements	Adaptability
□					□	Invest in automation and technology	Adaptability
■		□	■	■		Monitoring river conditions & weather	Anticipation
■	□					Weather forecast analysis	Anticipation
□						Resilience planning and training	Recovery
□						Community engagement and public awareness	Recovery
■		■	■	■		Securing vessels and equipment	Recovery
■	■	□	□	□		Contracts to cover costs	Collaboration and trust
■	■	■	■	■	□	Build strategic partnerships	Collaboration and trust
□	□	□	■	□		Digital Twin: Advanced monitoring and forecasting	Digital capabilities
		□	■	□		Digital Twin: Hydrological model	Digital capabilities

Key: Existing Strategy ■ Future Strategy □

Figure 1 Measures identified by the LLs and mapped strategy

Figure 1 outlines the measures identified for each LL and how they map to the respective strategies:

- Approach
  - Six disruption scenarios analysed: heatwave, drought, storm, high water, flooding, strike
  - Measures mapped to resilience strategies
- Cross-scenario patterns
  - Strong reliance on operational flexibility and visibility in the short term
  - Increasing importance of digitalisation, infrastructure resilience, and collaboration for long-term adaptation
- Outcome
  - Empirically grounded set of measures linked to resilience strategies
  - Validation and refinement of the strategy pool across scenarios

Results

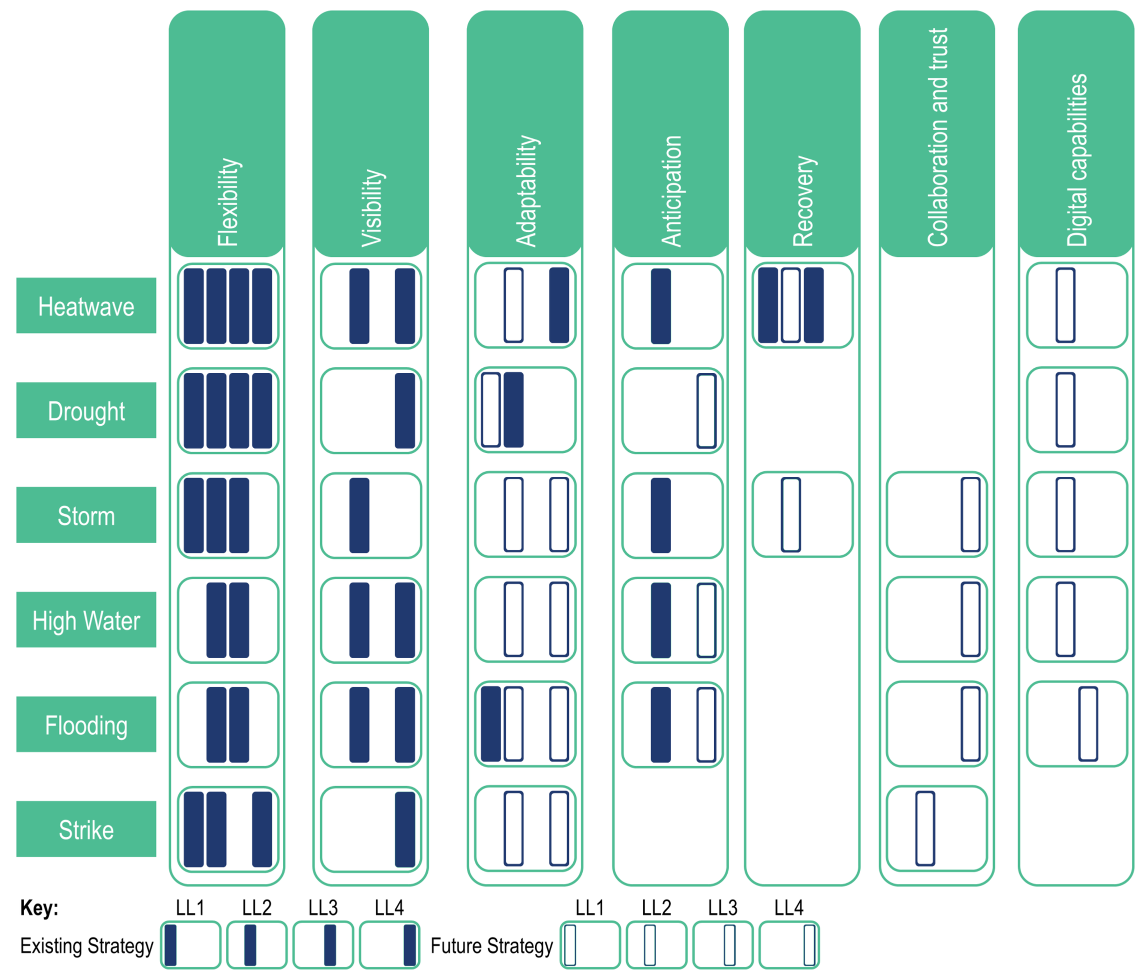

Figure 2 Responses of LL on existing and future measures for scenarios

Figure 2 describes the identified measures by each LL (already mapped to strategies):

- Dominant strategies in practice
  - Flexibility widely applied (e.g., routing, scheduling, loading adjustments)
  - Visibility used selectively (monitoring, client/public information)
- Limited or emerging strategies
  - Adaptability & anticipation: partly applied (e.g., alternative vessels, prediction models)
  - Recovery: few measures (mainly resilience plans and drills)
  - Digitalisation & collaboration: mainly future-oriented (e.g., digital twins)
- Key insight
  - Existing strategies provide a strong foundation
  - IWT-specific challenges (e.g., strikes) remain insufficiently addressed

Conclusions

This study combines literature-based strategy development with scenario-based validation to advance resilience in Inland Waterway Transport (IWT):

- Key findings
  - Strong alignment between theory and practice
  - Core strategies: flexibility, adaptability, anticipation, digitalization
  - Gaps remain, especially for labour-related disruptions
- Main insight: Resilience strategies must be context-specific and scenario-tested
- Limitations
  - Based on simulated scenarios
  - Living Labs represent experimental settings
- Future research
  - Validation with broader IWT stakeholders
  - Integration into digital decision-support tools
  - Testing under real-world disruption conditions
- Contribution & relevance
  - Bridges gap between theoretical capabilities and operational strategies
  - Supports practitioners in improving resilience
  - Provides a reusable serious gaming methodology for research

Acknowledgements

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Bremen's Approach to Hydrogen and PtX Applications - a Comprehensive Overview

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Introduction

Bremen, Germany's smallest federal state, consists of the city Bremen with about 585,000 inhabitants and, just 57 kilometres to the north, the city of Bremerhaven on the mouth of River Weser with about 119,000 inhabitants and one of the world's largest container terminals. Bremen as well is a leading hub in the space as well as aviation and aerospace sector, featuring an international airport and renowned companies such as Airbus, Ariane Group, and OHB Space Systems. Additionally, the city is home to the ArcelorMittal Bremen steel plant. Bremen occupies a strategically vital position within the Trans-European Transport Network (TEN-T). With their strategic location and advanced multimodal infrastructure, Bremen and Bremerhaven serve as essential hubs for European freight transport, further strengthening Bremen's role as a key logistics and transport centre in Europe. As the second largest port location in Germany, the Bremen and Bremerhaven ports in 2024 moved 62 million tonnes of cargo. In total, 4.4 million standard containers were shipped.

In 2020, the total CO_2 emissions from final energy consumption in the state of Bremen amounted to 7.972 million tonnes. The largest share was attributed to steelworks, which accounted for 4.042 million tonnes. Actually, the city is home to the steel plant ArcelorMittal Bremen, a major industrial site that emits roughly 50% of Bremen's total annual CO_2 emissions. The mobility sector as a whole contributed 1.202 million tonnes (15%), with road transport being the dominant source at 1.054 million tonnes. Other mobility-related emissions included 58,000 tonnes from coastal and inland shipping, 36,000 tonnes from aviation, and 54,000 tonnes from rail transport.

Hydrogen Activities in Bremen

Hydrogen is already being utilized on a smaller scale across various industries in the state of Bremen. Looking ahead, hydrogen's potential as an energy source will be expanded across multiple sectors. The transition to a hydrogen economy will be prioritized in industries where replacing fossil fuels with renewable electricity is not feasible. In Bremen, this applies particularly to the steel industry, which is expected to have a significant hydrogen demand. Additionally, hydrogen will play a crucial role in decarbonizing the shipping, aviation, and heavy goods vehicle (HGV) sectors, which are key pillars of Bremen's economy. In this context, the Bremen Hydrogen Strategy integrates various initiatives into a comprehensive framework aimed at decarbonizing hard-to-abate sectors such as steel production, maritime and aviation industries, logistics, and transportation. Furthermore, Bremen together with relevant stakeholders is part of the following ongoing Important Projects of Common European Interest (IPCEI) and other projects:

- In order to reduce the mentioned CO_2 emissions, the state of Bremen in November 2019 adopted the North German Hydrogen Strategy in conjunction with the other four North German states.
- The Bremen senate in December 2021 adopted the "State of Bremen Hydrogen Strategy".
- Furthermore, the current Innovation Strategy of the State of Bremen "Key to Innovations 2030 – Strategy for Innovation, Services and Industry" identified hydrogen technology as an innovation driver and central element for sustainable economic management and efficient use of resources.
- This has led to the deployment of new hydrogen production units. In particular the Hy.City.Bremerhaven initiative has established two 1 MW PEM and alkaline electrolysers, which contribute significantly to green hydrogen production in the region.
- Additionally, the Fraunhofer Institute for Wind Energy Systems (IWES) in Bremerhaven hosts an electrolyser test field, currently featuring two electrolysers with a total production capacity of 2 MW. Both electrolysers serve a variety of off-takers, including seven hydrogen busses, a pilot scale e-methanol plant currently under construction and expected to produce green methanol for maritime purposes, and a publicly accessible hydrogen refuelling station.
- The IPCEI DRIBE focuses on decarbonizing steel production through hydrogen-based processes, utilizing an electrolyser planned at the steel plant and implementing Direct Reduced Iron (DRI)-technology in the steelmaking process.
- The IPCEI Clean Hydrogen Coastline aims to establish a comprehensive hydrogen infrastructure along the northern coast, facilitating large-scale production, distribution, and utilization of green hydrogen.
- The IPCEI WopLin initiative is dedicated to integrating hydrogen into aviation infrastructure in Northern Germany, promoting sustainable air travel.
- The German national project hyBit aims to accelerate Bremen's hydrogen economy by fostering innovation and collaboration across industries.
- The German national project MariSynFuel aims at implementing a local production of synthetic methanol as marine fuel for shipping in Bremerhaven.

Drivers of the Green Energy Transition in Bremen

- DRIVER 1: Availability of strategic logistics assets and infrastructures within Bremen, being at the cross of three TEN-T corridors. Furthermore, Bremerhaven features the eighth busiest EU container port, and Bremen is home to an international airport and features an extensive network of companies operating in international logistics. As potential hydrogen importer as well as producer, the state of Bremen will play a crucial role in transporting green hydrogen to industrial centres across Germany.
- DRIVER 2: Renewable energy production based on locally available resources - Bremen is actively involved in the successful use and development of on- and offshore wind energy capacities to support and implement the ambitious expansion targets set by the German government.
- DRIVER 3: Fertile industrial ecosystem with key actors in particular in the steel industry, aviation, heavy transport, and other industries attracting new businesses and investments. Hydrogen has the potential to be utilized both as energy source and as feedstock in different industries with high need to be decarbonized.
- DRIVER 4: Well established public-private partnership facilitating the development of new business and governance models to turn decarbonization challenges into a great opportunity for socio-economic territorial growth.
- DRIVER 5: Driving Emission-Free Transport: Bremen is raising relevant interest from road, air and waterway transport operators towards free emissions transport. With port capabilities and ongoing naval fleet expansion, hydrogen is positioning more and more as a viable alternative to meet the demands from the evolving landscape.
- DRIVER 6: Exploiting high-quality knowledge: Bremen owns extensive knowledge and experience on safe transport, fire safety and management, store, process and transit fuels, including excellent R&I facilities, clusters and hubs working on hydrogen.

H2B:IMPACT – The Bremen Hydrogen Valley

To support this process, the state of Bremen together with a respective consortium in spring 2025 submitted the H2B:IMPACT project proposal to the Clean Hydrogen Partnership, which was approved in August 2025. H2B:IMPACT has the strategic objective to create a Hydrogen Valley centred in the state of Bremen as depicted in Fig. 1. The setup of the Hydrogen Valley comprises renewable energy sources, hydrogen production and storage, transportation/distribution, and end use. Within H2B:IMPACT, three new value chains will be demonstrated, integrating three hydrogen production systems, related distribution infrastructure and five test-beds with innovative use cases, demonstrating a newly built green regional hydrogen production and innovative offtake in the industrial, heavy transport, maritime logistics, and construction sectors.

H2B:IMPACT will provide advanced balancing infrastructure in the form of a mobile refuelling station, allowing artificial intelligence (AI)-based logistics optimization ensure interoperability. The ports of Bremen pursue continuous improvement measures beyond the statutory environmental standards to develop and implement innovative environmentally friendly technologies and processes in the industrial sectors of ports and shipping. Ongoing activities aim to further decrease emissions to reduce the proportion of compensation certificates required. To this end, it is planned to convert facilities, vehicle fleets, and port vessels to emission-free propulsion and renewable energy supplies with the goal of making the ports of Bremen a CO_2-neutral and low-emission port location by 2035.

H2B:IMPACT aims to drive large-scale demonstration efforts from both the public and private sectors through an industry-led flagship initiative strategically focused on establishing a Hydrogen Valley ecosystem centred in the state of Bremen. The Bremen Hydrogen Valley will be developed as an integrated hydrogen ecosystem, connecting industrial, mobility, construction, and logistics sectors through a coordinated network of hydrogen production, distribution, and storage facilities feeding many end-use applications. By leveraging Bremen's existing infrastructure, industrial base, and ongoing hydrogen initiatives, the project will serve as a scalable and replicable model for hydrogen deployment, supported by key industrial players, demonstrating added value in terms of upscaling potential and improvement of EU industrial competitiveness.

The H2B:IMPACT project will present three value chains, demonstrating five innovative test beds beyond the state of art in the industrial, construction, transport and logistics sectors. The ambition is to accelerate the transition to a hydrogen-based economy, while enhancing energy security, competitiveness, and sustainability, providing key knowledge and roadmaps for further upscaling across the EU and the rest of the world. The project will include a scaling and replication strategy, engaging new stakeholders and expanding hydrogen adoption across additional industrial and transport sectors and will confirm the testbed at final technology readiness level (TRL) 8. The H2B:IMPACT testbeds are interwoven through a network of infrastructure, production sources, and shared innovation goals, creating a circular and mutually reinforcing hydrogen ecosystem in the Bremen Valley.

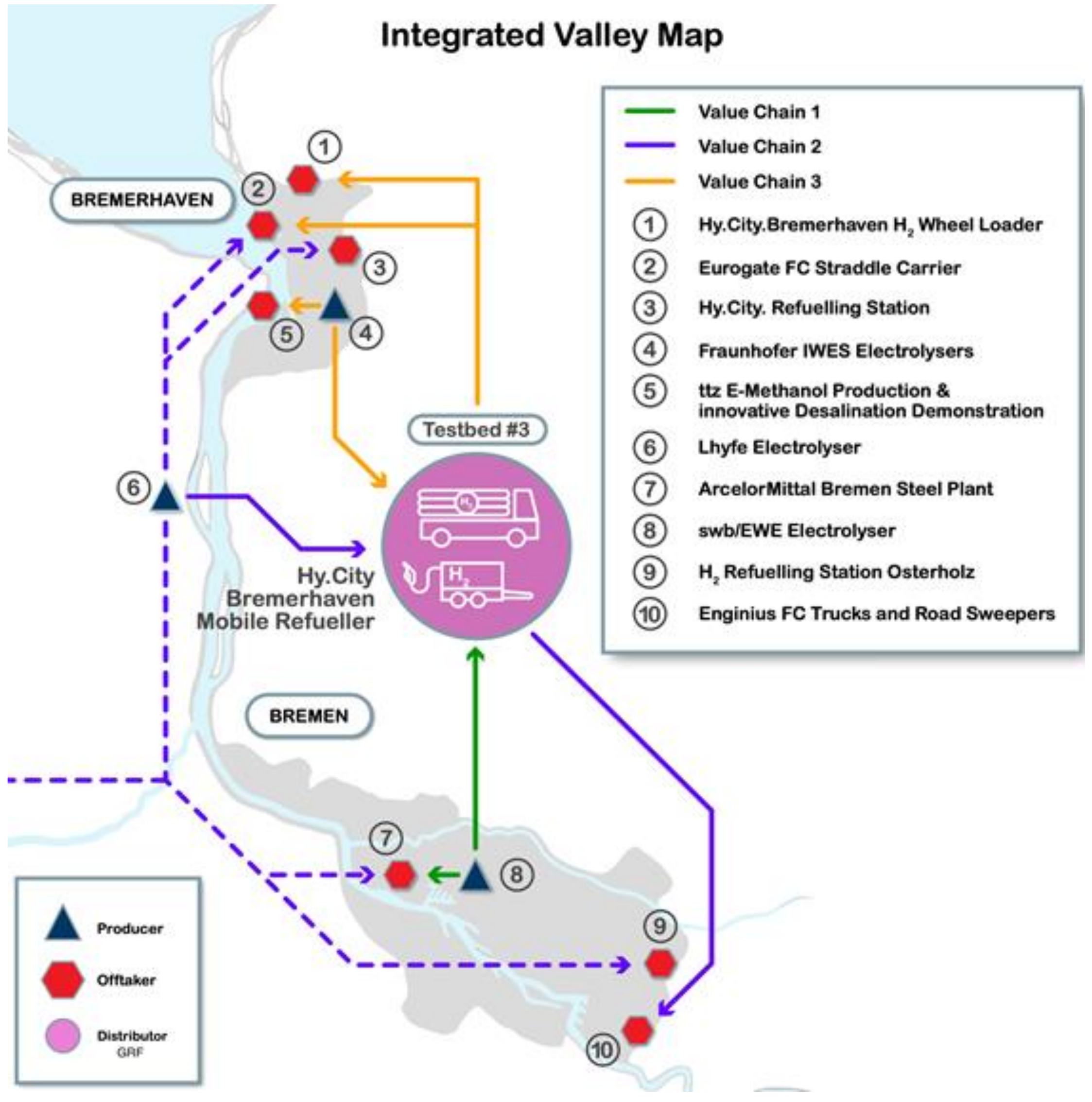

Figure 1 Overview of the Bremen Hydrogen Valley

The synergies emerge not only through common supply chains - such as the shared usage of electrolytic hydrogen from different producers - but also through technological interdependencies that drive efficiencies across applications.

A clear example of cross-sector interaction is the linkage between hydrogen producers and downstream applications. As an example, hydrogen produced and stored at the production sites is routed to the e-methanol facility, where it is synthesized into carbon-neutral fuel. This fuel then powers vessels, thereby completing a closed energy loop. Moreover, the CO_2 required for e-methanol synthesis is captured from a wastewater treatment plant, forming a perfect instance of circularity. Mobile refuelling infrastructure developed under testbed 3 further binds the ecosystem together. The mobile unit not only refuels hydrogen powered trucks (testbed 1) and hydrogen powered construction equipment (testbed 4) but also serves future port operations needs (testbed 2), effectively connecting de-centralized applications to centralized hydrogen sources.

Conclusion

This paper gives an overview over hydrogen-related initiatives in the German federal state of Bremen based on a literature analysis, and identifies six drivers of the green energy transition in Bremen following a qualitative content analysis approach. The latter were found to be related mainly to Bremen's strategic geographical position at the cross of three TEN-T corridors, featuring the eighth busiest EU container port and an international airport, as well as access to renewable energy production provided by on- and offshore wind energy production on the North Sea coast. Furthermore, Bremen features a well established public-private partnership and a fertile industrial ecosystem comprised of steel industry, aviation, heavy transport and other industries attracting new businesses and investments, thus facilitating the development of new business and governance models to advance decarbonization efforts. A raising interest from road, air, and waterway transport operators towards carbon free emissions transport supports this development as well. A sound basis for this process is provided by extensive knowledge and experience in green technologies by Bremen's industry as well as research communities. These facts highlight the promising strategic situation of the German Federal State of Bremen with regard to the green energy transition and especially the establishment of a Hydrogen Valley. The paper as well introduces the new Bremen Hydrogen Valley to be implemented within the H2B:IMPACT project. It briefly describes project activities, value chains, and testbeds foreseen in the project, which during the writing of this paper was expected to start in February 2026. More detailed information is to be provided in additional papers during the runtime of the project.

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Applications in Port Logistics: Mapping Global Use Cases to Support the Transition of North Sea Ports

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Interreg North Sea
Co-funded by the European Union
North Sea Hydrogen Valley Ports

Introduction

As international trade continues to expand, ports have become significant sources of greenhouse gas emissions and other pollutants, not only from transport but also from terminal, warehousing and other logistical activities.

This research is conducted within the Interreg project North Sea Hydrogen Valley Ports (NS H2V Ports), which develops hydrogen strategies for four ports:

- Brest (France)
- Esbjerg (Denmark)
- Bremen/Bremerhaven (Germany)
- Den Helder (Netherlands)

These strategies will be translated into concrete roadmaps that form the foundation for establishing a maritime Hydrogen Valley.

The initial phase of the project → the identification of potential hydrogen use cases in port environments, which will be further assessed and developed in the four selected ports.

Methodology

Potential hydrogen applications in ports were investigated through:

- Desk research and expert consultations with participating ports
- Identification of key hydrogen use cases:
  - On-shore power supply
  - Congestion management and grid balancing
  - Cargo handling equipment and heavy-duty machinery
  - Other port applications

The analysis focuses on hydrogen-based solutions.

The resulting insights form the basis for developing implementation scenarios tailored to four North Sea ports: Bremen/Bremerhaven, Esbjerg, Brest, and Den Helder.

On-shore Power Supply

- Ships at berth typically use diesel auxiliary engines.
- Shore power enables connection to the land-based grid → reduces emissions
- Hydrogen-based systems can provide clean electricity where grid capacity is limited.
- Example: Port of Esbjerg
  - Hydrogen-based shore power using surplus offshore wind
  - Conversion via fuel cells → 100% CO_2-neutral electricity
- Challenges:
  - High investment and operating costs
  - Grid and infrastructure requirements
  - Retrofitting of vessels

Congestion Management and Grid Balancing

Increasing electrification and renewable energy integration make grid management more complex.

Grid congestion and real-time balancing are key challenges in ports.

Example: Port of Den Helder → severe grid congestion limits further electrification

Role of hydrogen:

- Flexible, local power generation (fuel cells / H_2 engines)
- Supports peak demand (e.g., multiple ships on shore power)
- Acts as energy storage (via electrolysis → reconversion to electricity)

Key insight:

- Hydrogen enables grid stability where battery storage or grid capacity is insufficient
- Ports can act as energy hubs (production, storage, use of H_2)

Cargo Handling Equipment

Ports rely on energy-intensive equipment → resulting in high emission levels

Example: Bremen/Bremerhaven → high cargo volumes and intensive terminal operations result in high energy demand and emissions from cargo handling equipment.

Electrification status:

- Tethered equipment → largely electrified
- Untethered equipment → still diesel-based

Hydrogen vs Battery (see Figure 1):

- Battery-electric:
  - Cost increase +14-34%
  - Suitable where grid access is available
- Hydrogen-electric:
  - Cost increase +52-105%
  - Fast refueling & longer operating time
  - Suitable for heavy-duty and continuous operations

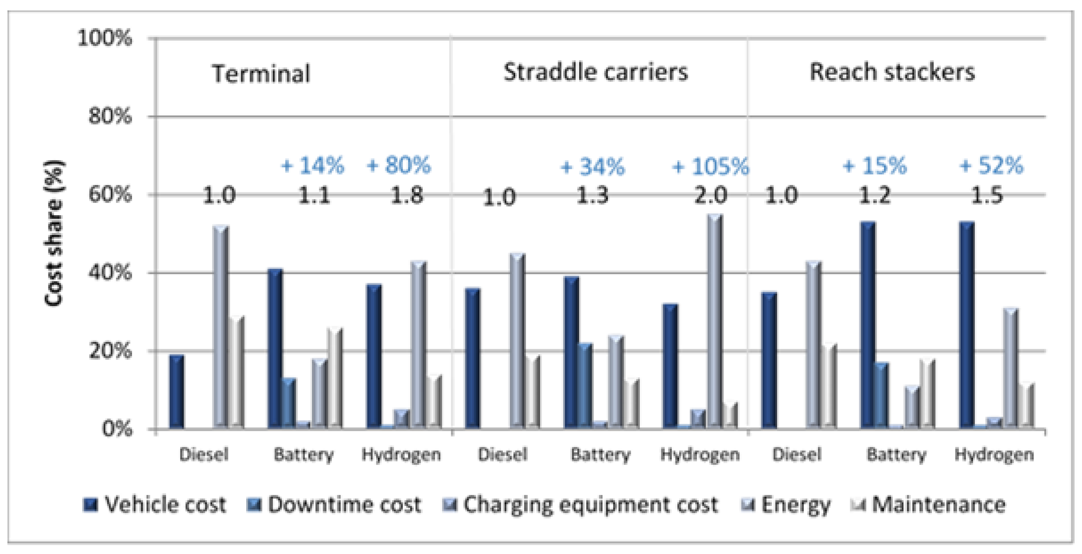

Figure 1: Cost Comparison of Diesel, Battery-Electric, and Hydrogen-Electric CHE by Equipment Type, adapted from APM Terminals, DP World: White paper "Reaching a tipping point in battery-electric container handling equipment". (2023)

Other Hydrogen-Powered Port Applications

Additional use cases:

- Tugboats
- Pilot vessels
- Barges
- Dredging
- Hydrogen refueling infrastructure

Example: Brest → Development of H_2 refueling stations for trucks (TEN-T network requirements)

Hydrogen-Powered Vessels

Tugboats → essential for port operations (maneuvering, towing)
Currently diesel-based → high emissions

Hydrogen potential:

- Fuel cell and dual-fuel solutions enable low/zero-emission operations
- Retrofitting of existing vessels possible

Discussion and Conclusion

Hydrogen use cases in ports were identified as part of the project's initial phase, focusing on applications in port operations and energy systems.

Hydrogen can complement electrification, particularly where grid congestion and infrastructure constraints limit further electrification.

Key Findings

- Battery-electric solutions are currently preferred due to cost-efficiency and higher maturity
- Hydrogen is most relevant for:
  - Heavy-duty and energy-intensive equipment
  - Continuous operations with high energy demand
  - Grid-constrained environments
- Hydrogen also provides additional flexibility through energy storage and grid balancing

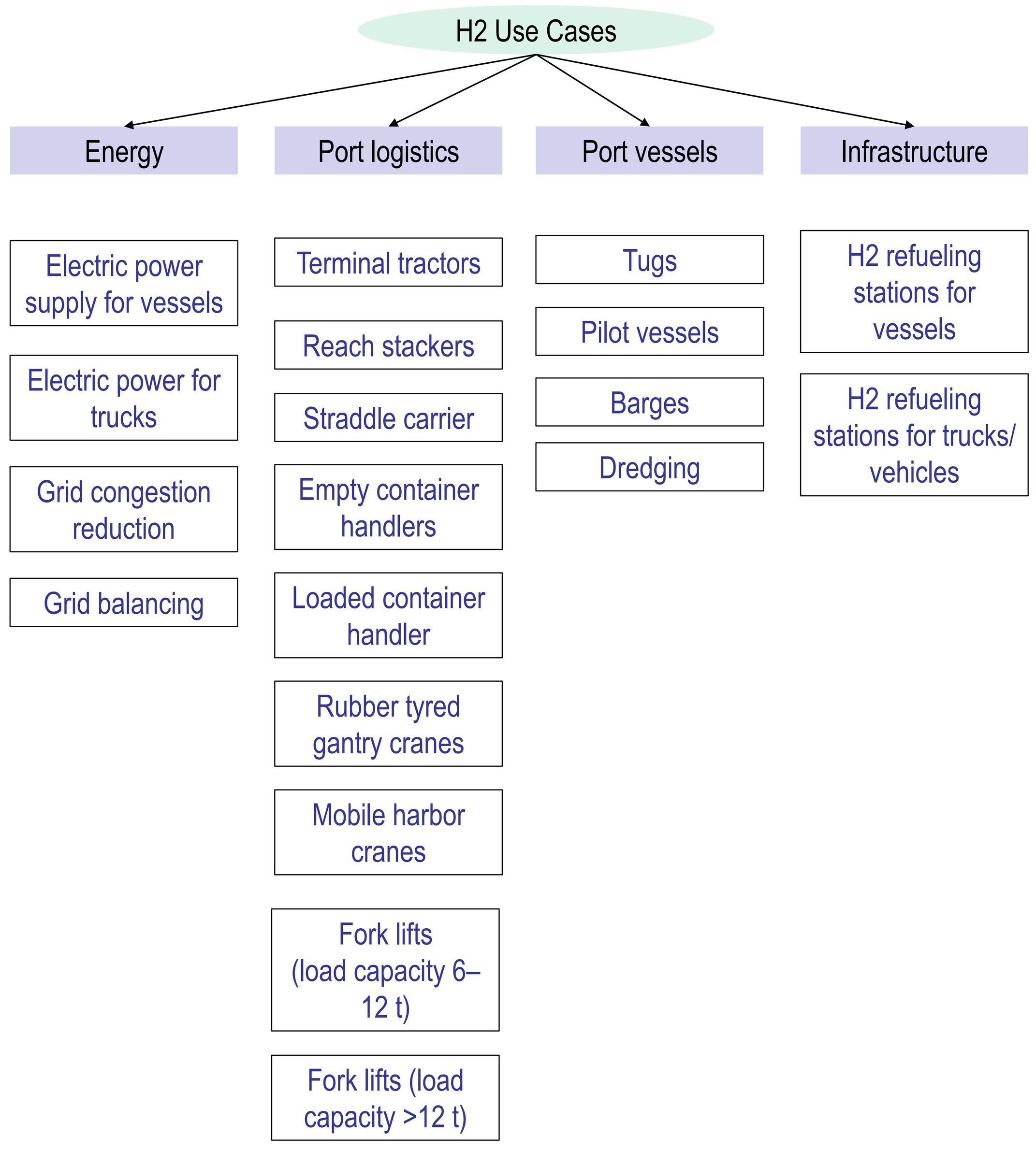

Figure 2: Potential Uses of Hydrogen in Port Operations

Port-Specific Insights

- The suitability of hydrogen applications strongly depends on local conditions, including:
  - Grid capacity
  - Access to renewable energy
  - Operational characteristics
- Example: Den Helder → severe grid constraints (no additional capacity until 2039) limit electrification. A hybrid system combining battery storage and hydrogen fuel cells enables shore power and grid balancing.

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