# Report 3

## Study on hydrogen in ports and industrial coastal areas

Case studies

December 2023

Clean Hydrogen Partnership
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EUROPEAN PARTNERSHIP

Co-funded by the European Union

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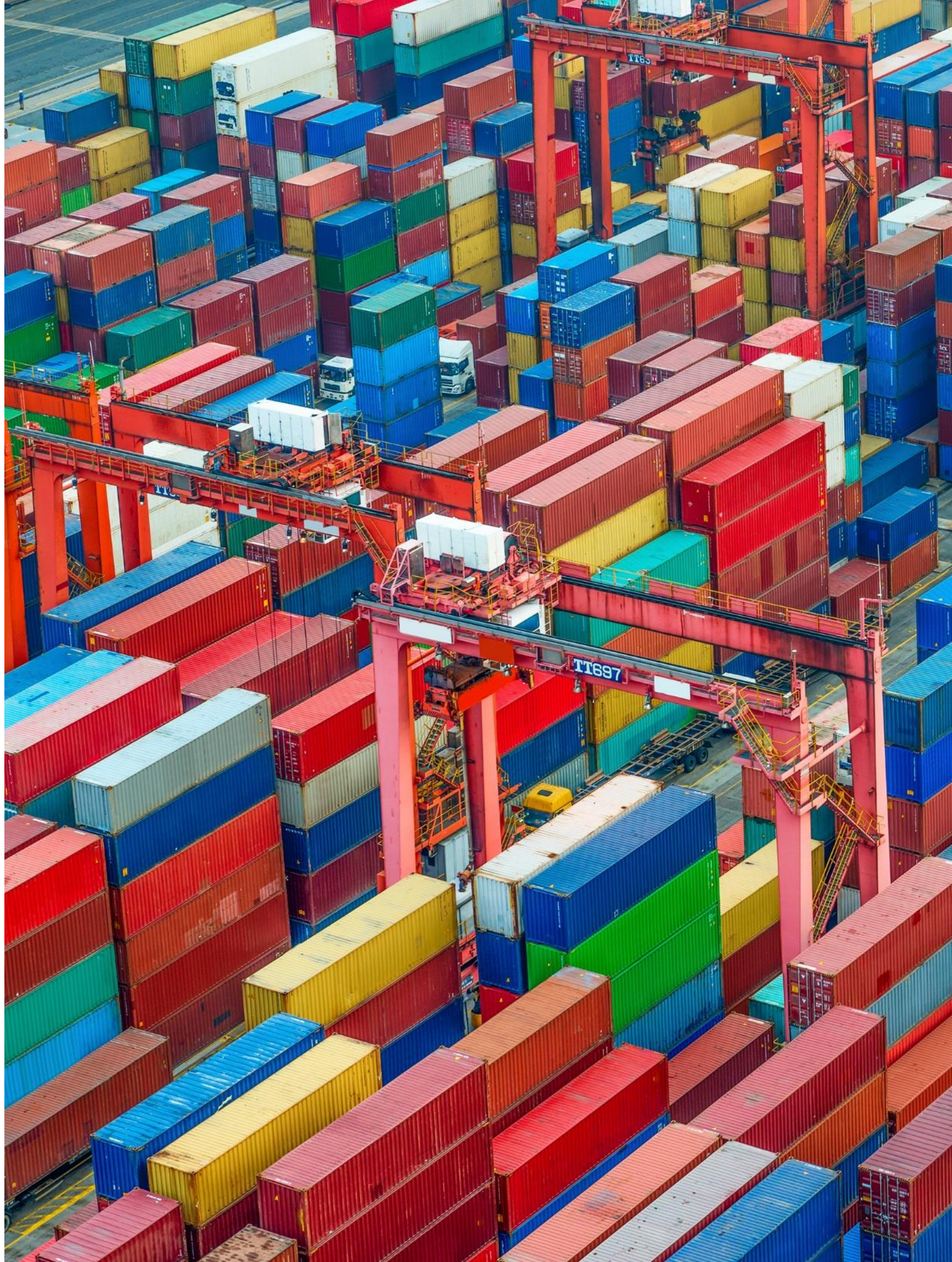

# Content

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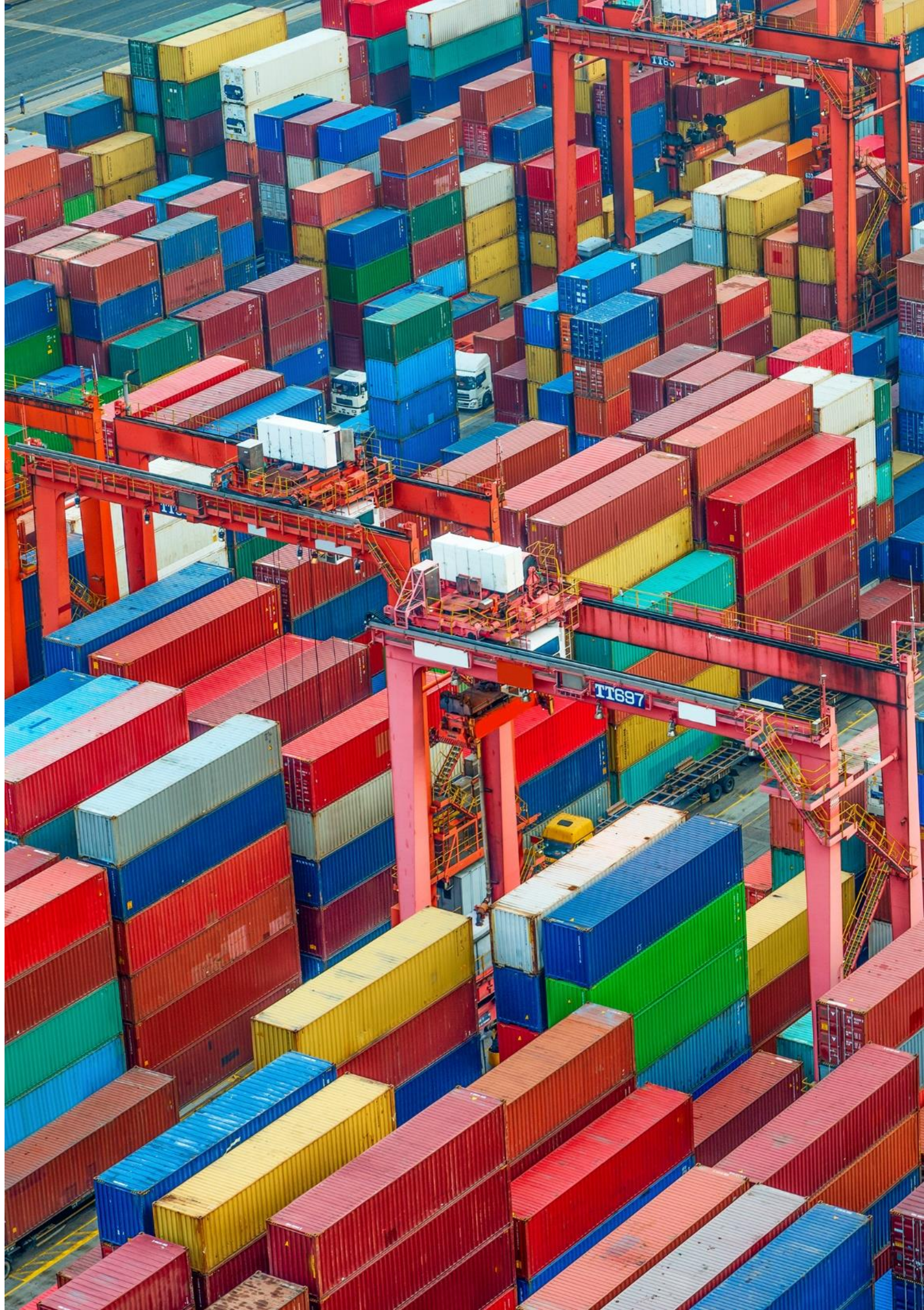

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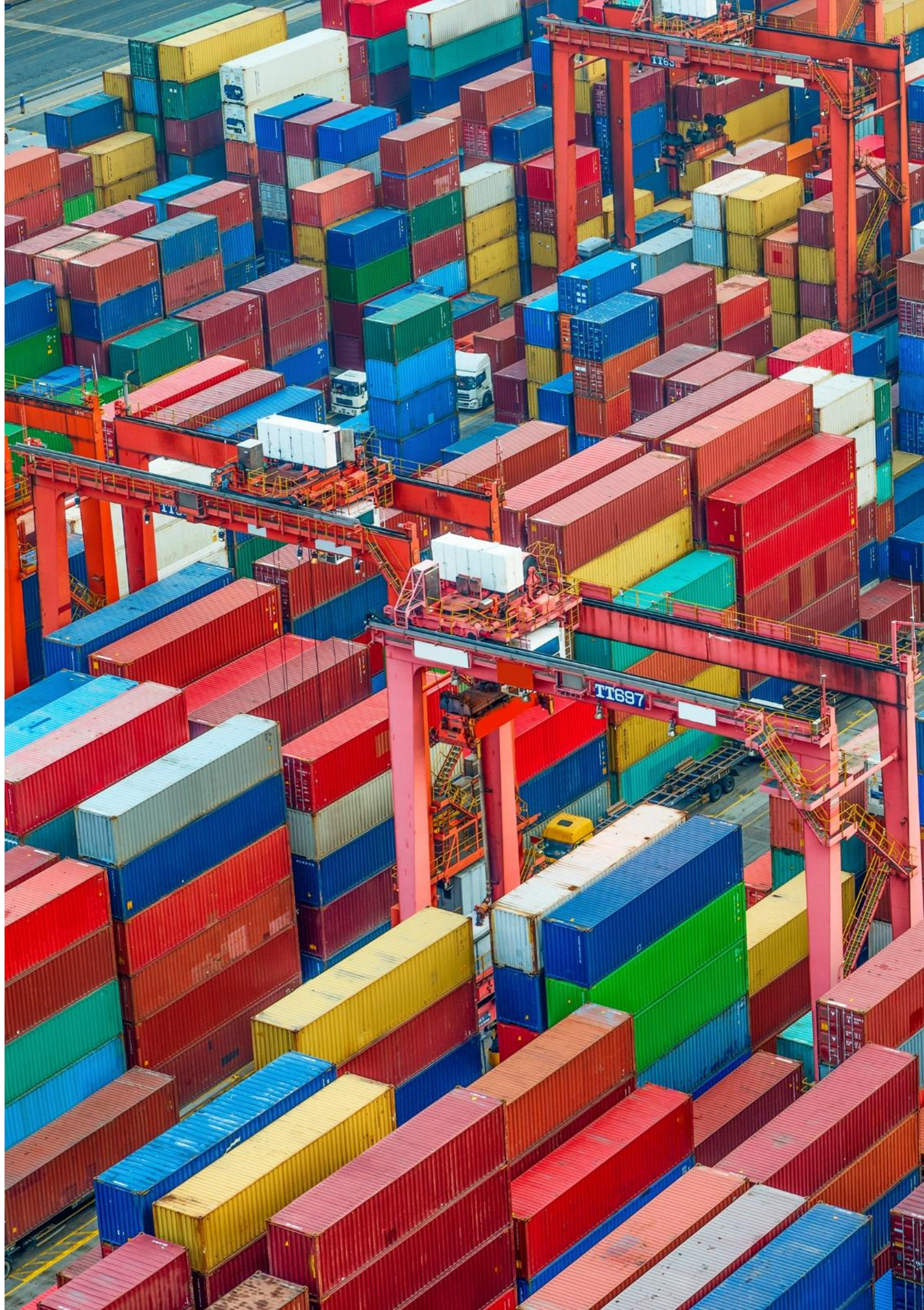

# Context and objectives

# Objectives and tasks of study on hydrogen in ports and industrial coastal areas

## Commissioned by

Clean Hydrogen Partnership

EUROPEAN PARTNERSHIP

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## Performed by

Deloitte.

## Objectives

**Foresight:** visibility on the market potential of hydrogen in ports, and a clear roadmap to implement it.

**Community building:** collaborative resolution of common issues and developing case studies that can act as blueprints to accelerate take-up of financial assistance for hydrogen plans in ports.

## Overview of tasks

| Task | Description | Date |
|---|---|---|
| Task 1 | Hydrogen demand and market potential | July 2022* |
| Task 2 | Hydrogen supply, storage and distribution | July 2022 |
| Task 3 | Definition of business models | July 2022 |
| **Report 3** | | |
| Task 4 | Case studies | November 2023 |
| Task 5 | Recommendations on future activities with particular focus on R&I in the short term | December 2022 |
| Task 6 | Coalition building | November 2023 |

The study feeds into the work of the **Global Hydrogen Ports Coalition**, launched at the latest Clean Energy Ministerial (CEM12). This important international initiative brings together ports from around the world to work together on hydrogen technologies.

* Dates refer to delivery date of final reports

# Content case studies

**Case study description**

- Context, objectives and scope
- Partners of the case study

**Economic analysis**

- Total cost of ownership analysis or investment case (including IRR[1])

**Constraints**

- Technological barriers
- Non-technological barriers and safety considerations

**Work plan and governance**

- Roadmap case study
- Governance and RACI matrix for key actors

**Anticipated benefits**

- Environmental
- Societal
- Economic

**Conclusions & recommendations**

- Conclusions
- Recommendations

Notes: 1) Internal Rate of Return (IRR) is often used in investment projects to calculate the profitability of the project. This number reflects the annual rate of growth that an investment is expected to generate. See next slide

# Overview case studies

## Case study 4

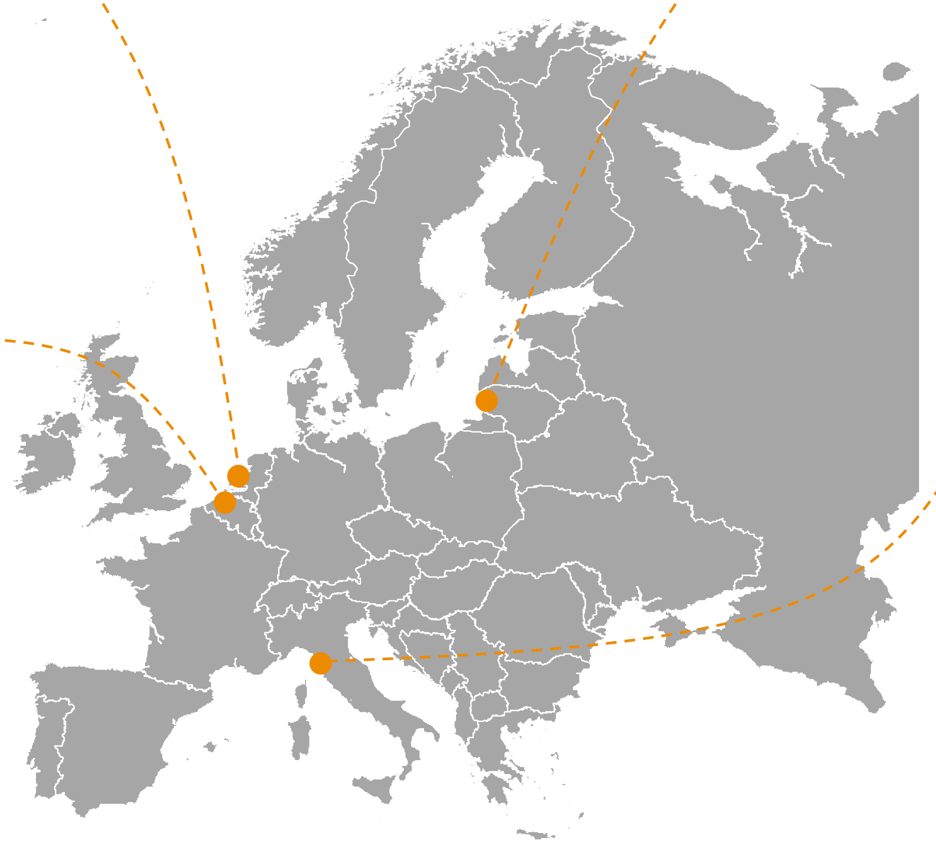
### Key characteristics

- **Port(s) involved**: Port of Pecém, Port of Rotterdam
- **Country**: Brazil, the Netherlands
- **Topic**: Hydrogen import
- **Role of port in the project**: Landlord and enabler

## Case study 2

### Key characteristics

- **Port(s) involved**: Port of Antwerp-Bruges & Port of Duisburg
- **Country**: Belgium, Germany
- **Topic**: Decarbonization of port equipment
- **Role of port in the project**: Landlord, enabler and investor



## Case study 1

### Key characteristics

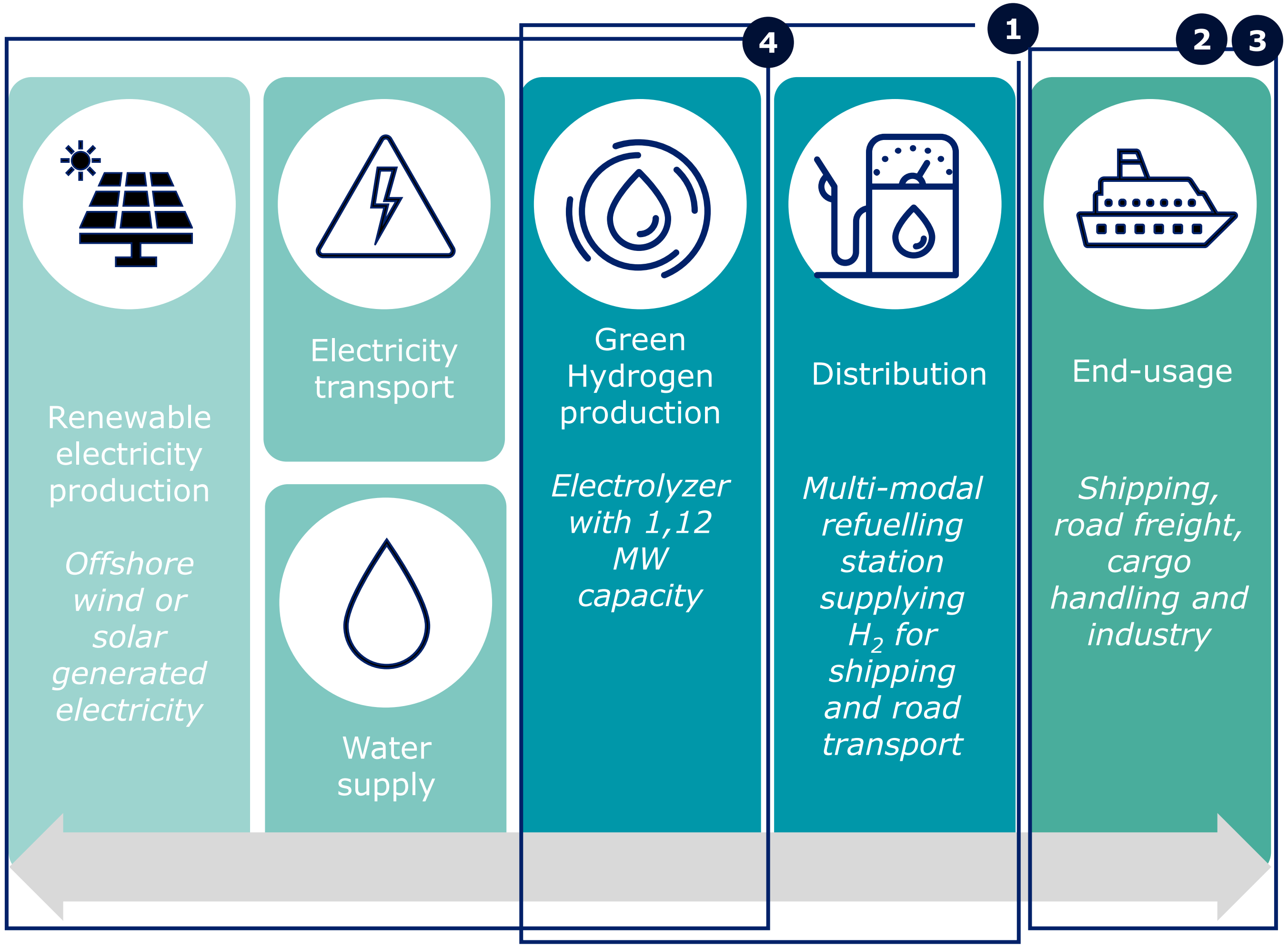
- **Port(s) involved**: Port of Klaipeda
- **Country**: Lithuania
- **Topic**: Hydrogen production
- **Role of port in the project**: Enabler and investor

## Case study 3

### Key characteristics

- **Port(s) involved**: The North Tyrrhenian Port Network Authority (Port of Livorno, Piombino and Portoferraio)
- **Country**: Italy
- **Topic**: Hydrogen consumption (shipping)
- **Role of port in the project**: Landlord and enabler

# Overview case studies – scope




## Scope

**Case study 1:**

- Port of Klaipeda
- *Hydrogen production – electrolyser*

**Case study 2:**

- Port of Antwerp-Bruges
- Duisport
- *Hydrogen consumption - port equipment*

**Case study 3:**

- Port of Livorno
- *Hydrogen consumption - transport (shipping)*

**Case study 4:**

- Port of Rotterdam
- Port of Pecém
- *Hydrogen import*

*Link with archetypes: **industrial**, **logistics and transport**, **bunkering** and **urban.***

# Calculating the Internal Rate of Return and corresponding sensitivity tables

## IRR calculation

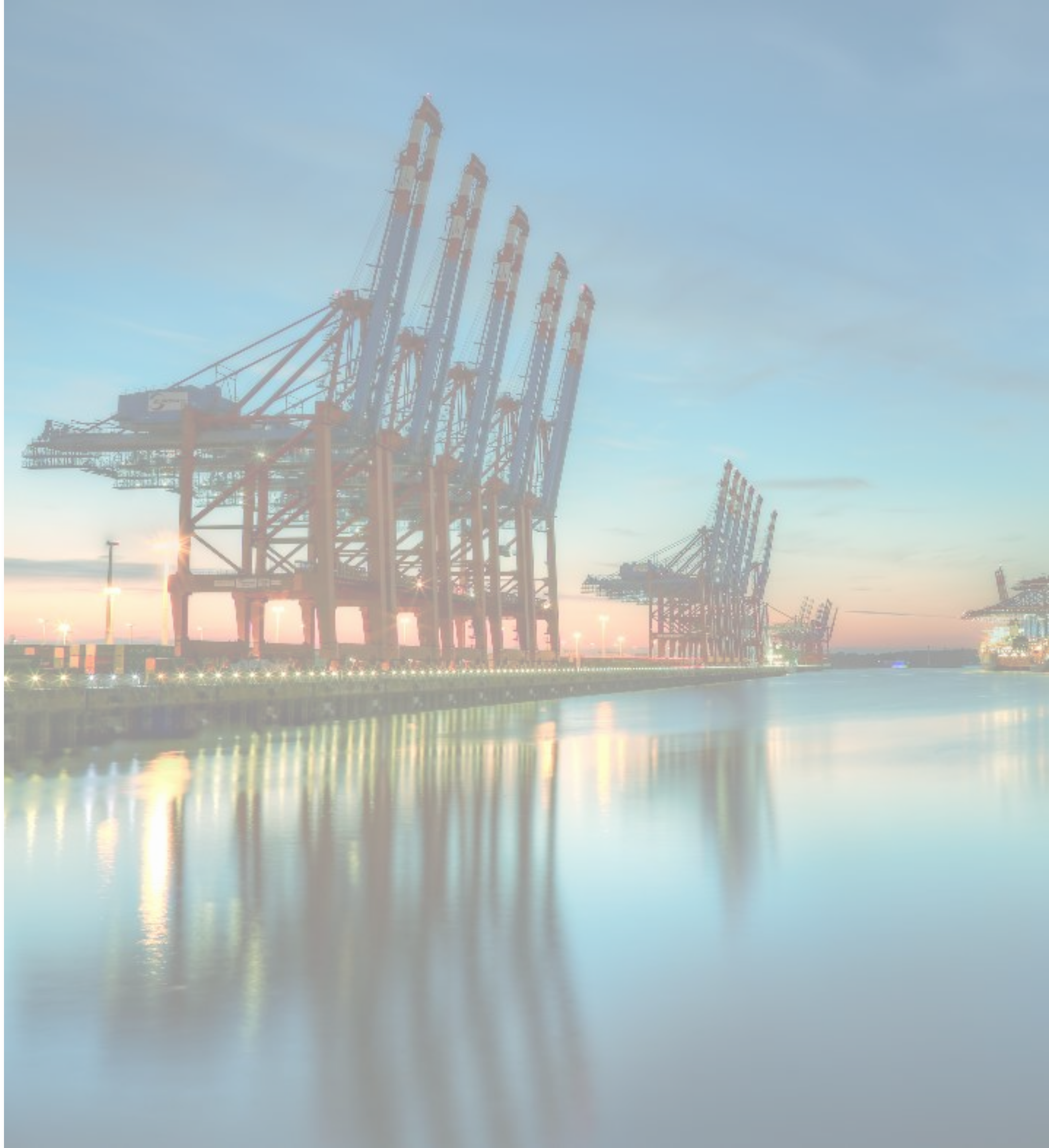
For each case study, detailed financial models have been developed, presenting financial statement and net free cashflow calculations. One of the outputs of these models is the Internal Rate of Return, which is compared to a target IRR based on similar risk-return projects; showcasing the estimated return on investment, and how its compares to similar investments

## IRR sensitivity tables

To provide additional insights, and because of high uncertainty towards 2050, the key levers impacting the IRR are put in sensitivity tables to showcase impact on the IRR in case of percentual divergences from assumptions (because of policy decisions, market evolutions, etc.)

## How is this information used?

The comparison between the modelised IRR and target IRR, as well as the sensitivity tables, provide insights in how to increase the return on investment of the respective projects. This, by looking at the key levers influencing profitability; by on the one hand potentially boosting revenues, and on the other hand reducing the cost base of the researched projects. Finally, the impact of public funding is also included, to showcase its influence on the IRR



# Executive summary

# Port of Klaipeda

PORT OF KLAIPĖDA

- ***Context**: Klaipeda aims to become a green hydrogen hub;* to decarbonize shipping, road freight, port activities and local industry. In a first stage, focus will be on serving local hydrogen demand, which may be upscaled in the future to supply inland industry
- ***Objective**: assess the viability of a business case for green hydrogen production in Klaipeda.*

## Economic analysis

Development of a business case for a pilot plant which includes an electrolyzer to produce hydrogen and a multi-modal refuelling station to supply ships and road transport (of passengers and cargo) :

- Construction of the site and refuelling station will start **mid 2025.** Maximum production capacity of this pilot plant will amount to **193 tonnes annually**, to be gradually scaled up towards 2033
- The total CAPEX investment for a green hydrogen production plant of 1,12 MW and corresponding refueling station is estimated at almost **10 million EUR**
- **Net free cashflows become positive from 2029 onwards**, due to increased incoming cash from the scaling up of hydrogen sales
- The internal rate of return for this project is estimated at **6,63%.** Electricity is the main cost driver. Negotiating a favorable PPA, will therefore significantly improve the IRR

## Constraints

**Technical constraints**: The coordination of intermediate supply of renewable electricity and intermediate demand of a multi-modal refueling station necessitates storage. The overall supply chain efficiency benefits from standardization of the offtake condition (pressure, temperature) and consideration of the offtake condition in the design of the electrolyzer and buffer storage.

**Safety constraints:** It is of paramount importance to involve the Ministry of Environment of the Republic of Lithuania, local authorities and other relevant stakeholders at an early stage to aid the permitting process, as this is new territory. Jointly tackling issues and ‘unknowns’ early will accelerate the permitting process as this can involve a steep learning curve for all entities involved. A detailed QRA and the (compulsory) environmental impact assessment are good starting points.

## Anticipated benefits

**Environmental benefits**: Hydrogen adoption in the port is projected to enable an average emission reduction of 13,6 kg of CO2 per kg of hydrogen produced

**Societal benefits:** Reduced energy dependence through heterogeneous energy carriers. Improve citizens health by reducing emissions and air pollution

**Economic benefits**: Develop Klaipeda as a green industry cluster attracting business downstream in the H2 value chain and (foreign) financial investments in the local economy

The pilot plant is positioned as first hydrogen development, with the aim of increasing knowledge and derisking future investments:

1. Off-take agreements need to be negotiated, and will be key to determine the viability of the business case in an early stage, and to decide on further upscaling or additional production sites
2. Collaboration among the hydrogen value chain will be crucial; to share learnings among producers, distributors, off-takers, facilitators and contributors
3. A steering board will be set up to coordinate hydrogen developments, of which the development of this production and refueling site is a first initiative

# Port of Antwerp and Duisport

- ***Context***: *Terminal operators use port equipment for transporting containers or cargo at their terminal, and consider hydrogen as an opportunity to reduce the emissions of hard-to-electrify port equipment like straddle carriers, reach stackers, terminal tow tractors, large forklifts, etc.*
- ***Objective***: *assess the practical implications, readiness, and next steps required to fuel port equipment on hydrogen.*

## Economic analysis

A total cost of ownership analysis projects the following outcomes:

- Straddle carriers on **electricity** are projected to be the most **cost-efficient option**. However, there are still a **lot of uncertainties** (e.g. not yet fully developed, technical hurdles, availability is still uncertain, biggest impact on the current operations)
- Also **dual fuel straddle carriers** are projected to be a **cost-efficient option,** specially **in the transition since current straddle carriers can be retrofitted**.
- When looking into **hydrogen fuelled straddle carriers, fuel cells are projected to be the most economically interesting** If the fuel cell efficiency would increase to 90%, hydrogen fuel cells become cost competitive with electric straddle carriers
- CAPEX and OPEX are the biggest cost components, followed by the cost for the energy (fuel cost)

## Constraints

**Technical constraints**: Although fuel cells may offer the most efficient fuel conversion, the performance of fuel cells has not yet been tested with straddle-carrier specific load curves (lifting, lowering and transversing)

**Safety constraints:** The size of the hydrogen storage may legislatively present a constraint. From 5 tonnes the SEVESO guidelines are applicable. Below that there is no uniform legislation as of yet, although several initiatives have and are being executed to deal with this.

The hydrogen-fueled straddle carriers must include features to prevent, detect, and extinguish fires. With the dual-use straddle carriers, the safety aspects of the combination of electricity and hydrogen become prominent.

## Anticipated benefits

**Environmental benefits**: avoided CO2 emissions of 94,500-ton $CO_2$ per year if all 350 straddle carriers at PSA are using clean hydrogen as a fuel and avoided air pollution

**Societal benefits:** improved citizens health, job creation, new market opportunities, building knowledge and becoming an innovation hub

**Economic benefits**: avoiding CO2 taxes and attracting business throughout the H2 value stream

The different technologies are still developing, which brings **a lot of uncertainties** towards the future:

1. Continue to invest in research and development
2. Maintain continued contact with different stakeholders so technological advancements can be benefitted from widely
3. Set up contacts and contracts to ensure the availability of hydrogen
4. Work towards shared infrastructure for other port equipment

# The North Tyrrhenian Port Network Authority

AdSP MTS

- ***Context***: *The north Tyrrenian region aims to develop a green hydrogen hub, leveraging its existing know-how and capabilities throughout the value chain to decarbonize* various industrial end-applications
- ***Objective***: *Assess the viability of decarbonizing shipping through a hydrogen powered ferry and ammonia fueled container ship.*

## Economic analysis

The investment requirements and feasibility of a business case are assessed for a green hydrogen powered ferry and green ammonia fueled container ship:

- There is a **40% investment gap** between a hydrogen- and diesel-powered ferry, which is compensated for through lower maintenance costs and decreasing hydrogen price. The Internal rate of return of this pilot-project is 8,89%
- The estimated retrofit cost for an ammonia powered containership with capacity of TEU 1914 amounts to **20 million EUR**, with a TCO 10% higher than its diesel alternative. This pilot project would generate an Internal rate of return of 8,48%
- Pricing a **green premium** to customers for sustainable transportation can significantly increase the attractiveness of the business case. To successfully implement this, the willingness to pay of customers for this green premium should be further investigated

## Constraints

**Technical constraints**: The challenges in retrofitting of vessels for hydrogen or ammonia mainly centers expanded fuel storage requirements, additional safety requirements and fuel handling (in both bunkering and conditioning for the prime mover)

**Safety constraints:** The toxic nature of ammonia requires guidelines to avoid the impact of this substance on aquatic life, the environment and people for different spill scenarios, without making handling of this material arduous. The impact is different for the two states of ammonia (liquid versus gaseous). Related to this are emissions due to the incomplete combustion of ammonia in a harbor environment.

The safe swapping of fuel containers (predominantly for hydrogen) and under which circumstances that is allowed needs to be regulated.

## Anticipated benefits

**Environmental benefits**: A green ammonia powered container ship brings forth an average emission reduction of 152 kg of $CO_2$ per km sailed. A hydrogen powered ferry generates an average emission reduction of 0,018 kg of $CO_2$ per passenger per km

**Societal benefits:** Develop Livorno as a key energy import hub to play a facilitating role in supplying energy to the Italian and European hinterland

**Economic benefits**: Reinvent legacy industry by developing a green industry cluster to sustain economic growth in the Livorno region

The port of Livorno is well positioned to serve as a gateway for imported hydrogen and derivatives, to be further transported to the European hinterland. Moreover, it also acts as a logistical hub within the Mediterranean sea, connecting the Middle East and (Northern-)Africa with Europe. This creates opportunities to facilitate the decarbonization of (international) shipping :

1. Investments to retrofit a ferry and containership towards clean fuel technologies are significant, increasing the cost base of operating these vessels
2. The cost of doing nothing should however also be considered, with rising regulatory pressures, reflected in the maritime shipping industry being gradually added to the EU Emission Trading System (gradually initiated in 2024, to completely fall under ETS as of 2026).

# Port of Rotterdam and Port of Pecém

- ***Context***: *the Port of Rotterdam is exploring both local production and import to meet the hydrogen demand. The Port of Pecém is strategically located in Brazil, with abundant sun and wind energy, access to water, high standard universities, and a well-educated labor force.*
- ***Objective***: *assess the competitiveness, practical implications, readiness, and next steps required to import hydrogen from the Port of Pecém in Brazil to the EU*

## Economic analysis

Hydrogen imported from the Port of Pecém to the Port of Rotterdam is **cost competitive with import from other regions**.

The business case for the hydrogen import value chain could improve by:

- Having concrete **off-taker agreements**
- Policy levers such a green **subsidy** for the H2 price or a capex subsidy
- An increasing **carbon tax** to bridge the gap between hydrogen or ammonia and natural gas prices for consumers
- The **direct use of ammonia** so the expensive reconversion step is avoided

## Constraints

**Technical constraints**: The main technical constraints in hydrogen through ammonia value chain centers on the reforming of ammonia to hydrogen. Especially in nitrogen emission restricted regions, the design of the purification system and the heat supply are the main constraints.

**Safety constraints:** Existing standards for the maximum permissible safety risk as determined for the environmental risk apply unaffectedly to hydrogen. Where such a standard is still lacking, the rule is that an activity must be at least as safe as the equivalent technology based on fossil energy sources.

It is of paramount importance to involve local authorities and other relevant stakeholders at an early stage to aid the permitting process, as this is new territory. Jointly tackling issues and 'unknowns' early will accelerate the permitting process as this can involve a steep learning curve for all entities involved.

## Anticipated benefits

**Environmental benefits**: 1 Mton of hydrogen imported leads to up to 26 Mton of avoided CO2 emissions by 2030.

**Societal benefits:** improved citizens health, job creation, new market opportunities, building knowledge and becoming an innovation hub

**Economic benefits**: avoiding CO2 taxes and attracting business throughout the H2 value stream

The following recommendations can be made:

1. Continue to invest in research and development to mature technologies and bring costs down
2. Maintain continued contact with different stakeholders so the hydrogen value chain is enabled and infrastructure is timely available
3. Set up contacts and contracts to ensure a positive business case for the investment in the hydrogen value chain infrastructure

# Case study 1
Port of Klaipeda

# Case study description

# Case study concerning hydrogen production in the Port of Klaipeda

## Location

## Partners

- Port of Klaipeda

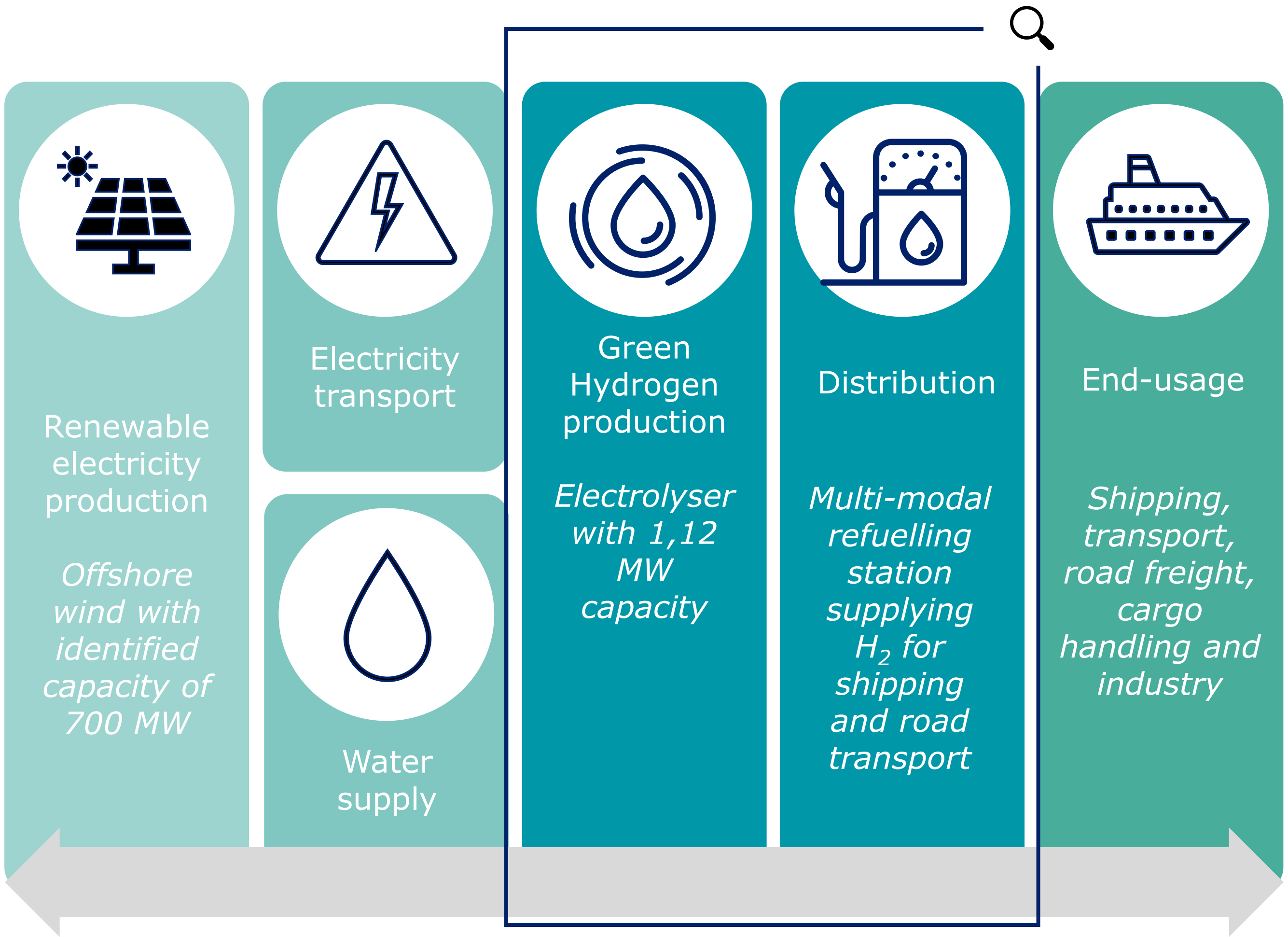
*Link with archetypes: **industrial**, **logistics and transport**, **bunkering** and **urban.***

## Topic

**Hydrogen production**:

*This case study assesses the viability of a business case for green hydrogen production in Klaipeda.*

# The scope and hydrogen plan for this case study




## Objectives and scope

- The Klaipeda Port Authority will start operating an **electrolyser producing green hydrogen** throughout the 2025-2050 period
- Electricity production and supply
  - Power Purchase Agreement to use **offshore wind energy and/or solar energy**
- In a **first stage** (2025-2029), produced hydrogen will be supplied to:
  1. A waste collection ship operated by the Port Authority consuming 43,8 tonnes of $H_2$ per year
  2. Busses in the city of Klaipeda scaled up gradually towards 15, each consuming 2,4 tonnes of $H_2$ per year
- In a **second stage** (2030-2050) hydrogen will be supplied to four end-markets:
  1. Domestic shipping (e.g., ferry and inland shipping)
  2. Road transport (e.g., busses and heavy-duty transport)
  3. Cargo handling (e.g., powering port equipment)
  4. Industry

## Snapshot 2030: hydrogen plan

**Electricity generation**
- A capacity of 24.125 MW of offshore wind energy would be required

**Water supply**
- 3.356 liters of pure water are needed

**Green H2 production**
- 193 tonnes of $H_2$

**Refueling station**
- 193 tonnes of $H_2$

**Shipping**
- 43,8 t $H_2$/year

**Road freight**
- 36,2 t $H_2$/year

**Cargo handling**
- 8 t $H_2$/year

**Industry**
- 3 t $H_2$/year

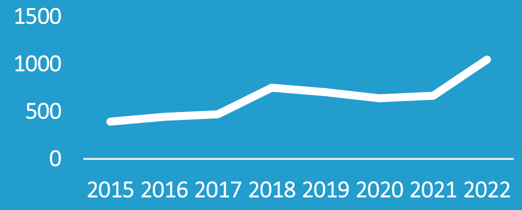
Case study description

# This case study focuses on the hydrogen ecosystem of Klaipeda in which the port operates as facilitator

## Port of Klaipeda

- Located in western Lithuania
- Green Port Policy with the objective of becoming a zero-emission port, to be achieved through its sustainable port development plan in which hydrogen plays an important role

**Overall container traffic**
*2015-2022, historical data ('000 TEU)*

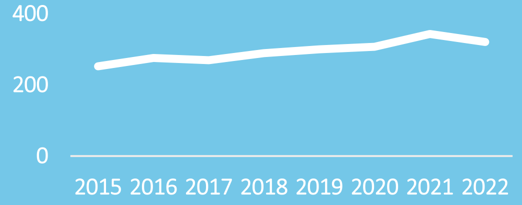



**Cargo turnover**
36.120.000

**Operational multi-purpose terminals**
33

**Port calls**
5.605

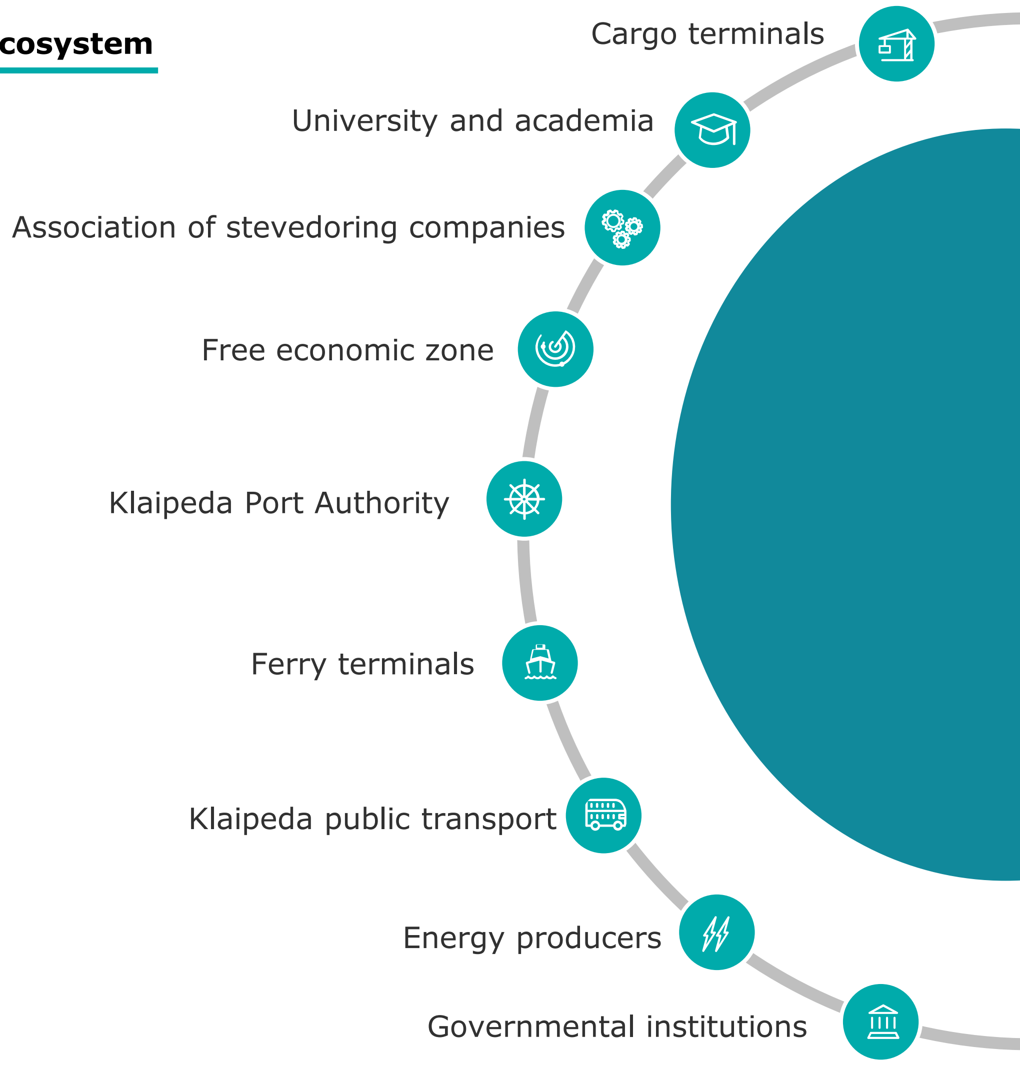
**Ro-Ro cargo handling**
*2015-2022, historical data ('000 units)*




**Contribution to Lithuanian GDP and employment**
6,18%
58.000 (in)direct jobs

**Cruise passengers**
46.853

## Hydrogen ecosystem



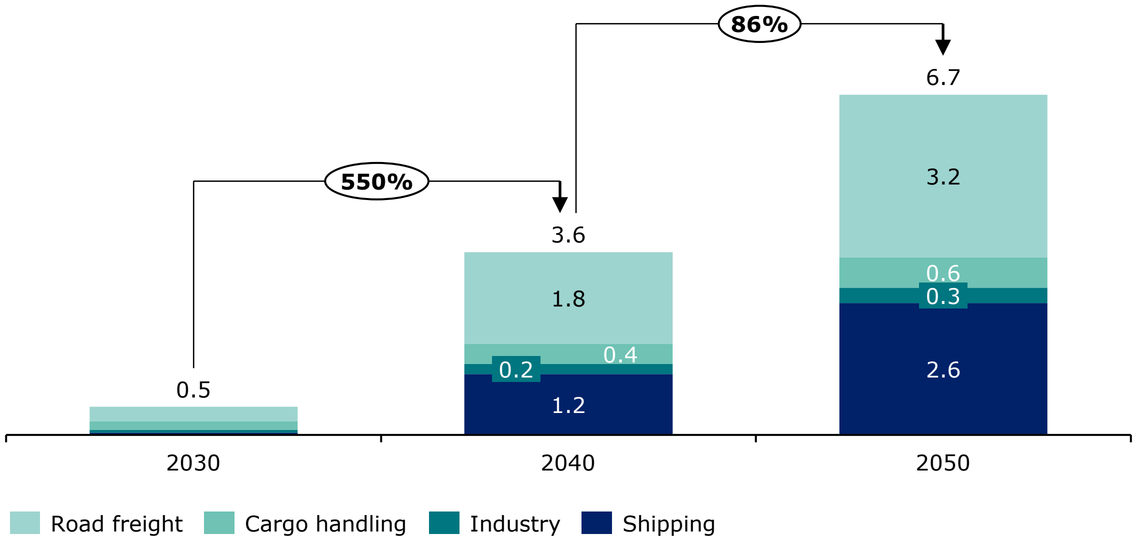



*Source: port of Klaipeda*

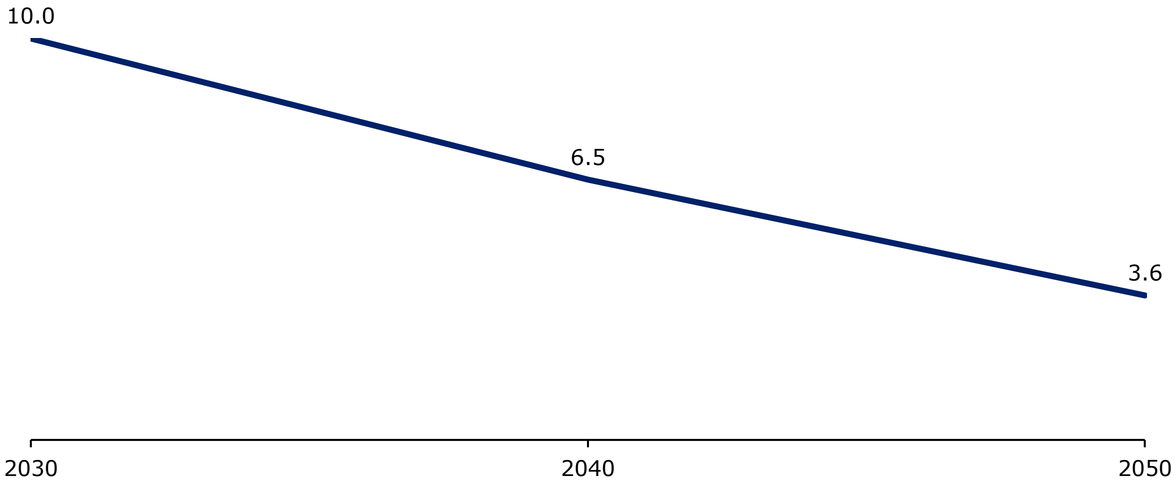
# Economic analysis

# Potential hydrogen demand and price in the Klaipeda area

Hydrogen demand port of Klaipeda
*2030-2050, estimates ('000 tonnes $H_2$)*[1]




Base case hydrogen price port of Klaipeda area
*2030-2050, estimate (EUR)*[1]




## Key takeaways

- $H_2$ demand in the port of Klaipeda area is estimated at 554 tonnes in 2030, mainly driven by **road freight and cargo handling.**
- Between 2030 and 2040 demand is expected to rapidly scale up, accelerated by **road freight and shipping end-markets,** to reach 3.600 tonnes of hydrogen demand in 2040
- In 2050, hydrogen demand is forecasted to be at 6.700 tonnes, an increase of 86% compared to 2040

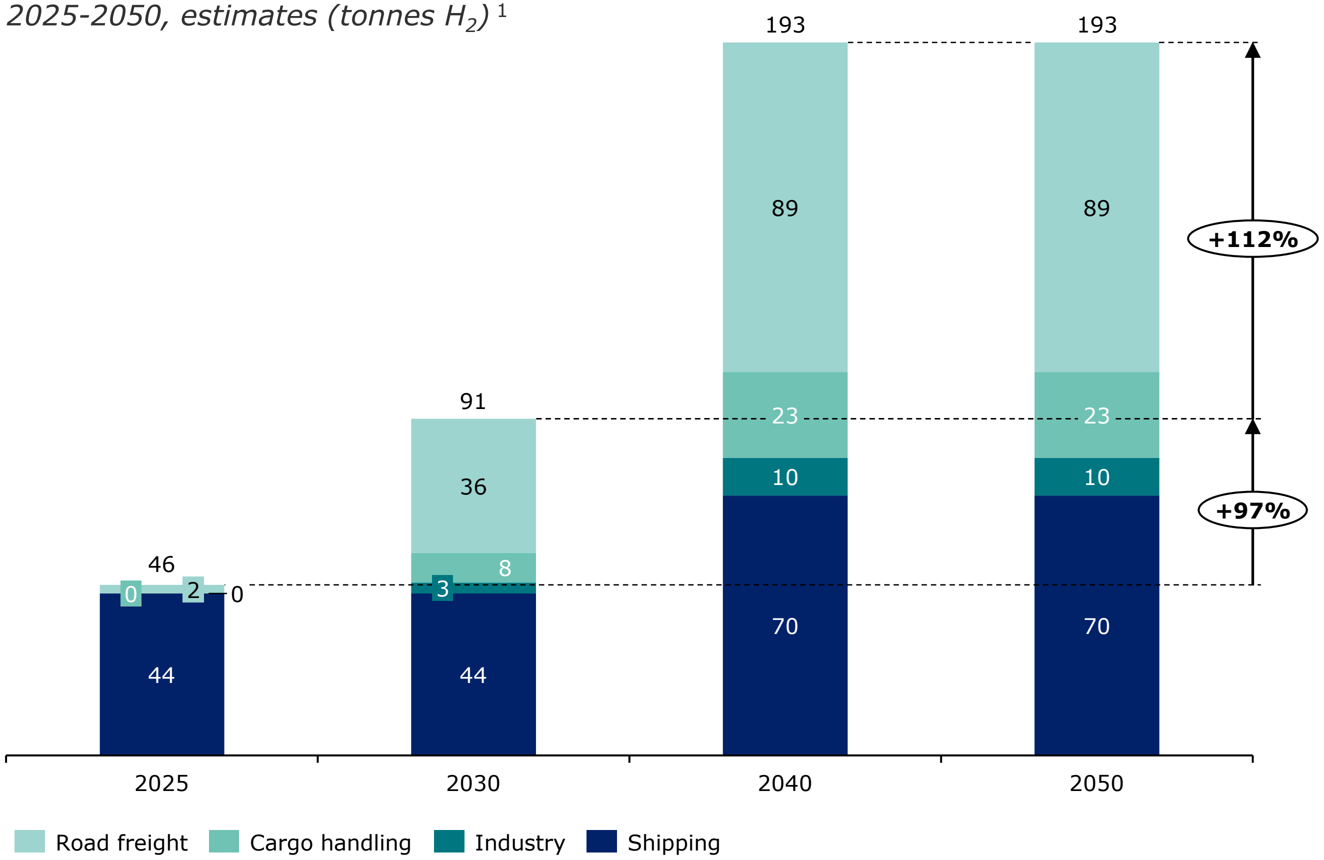
## Key takeaways

- The price at which hydrogen will be sold in the Klaipeda area is expected to remain **constant between now and 2030** at 10 EUR/kg
- **Beyond 2030, the $H_2$ price is projected to fall with around 35%,** reaching 6,5 EUR/kg in 2040
- Towards 2050, the price of hydrogen in the Klaipeda area is estimated to reach **3,6 EUR/kg**

[1]*Expert interviews and Study on hydrogen in ports and industrial coastal areas (2023)*

# Hydrogen sales from production at the pilot plant in the port of Klaipeda

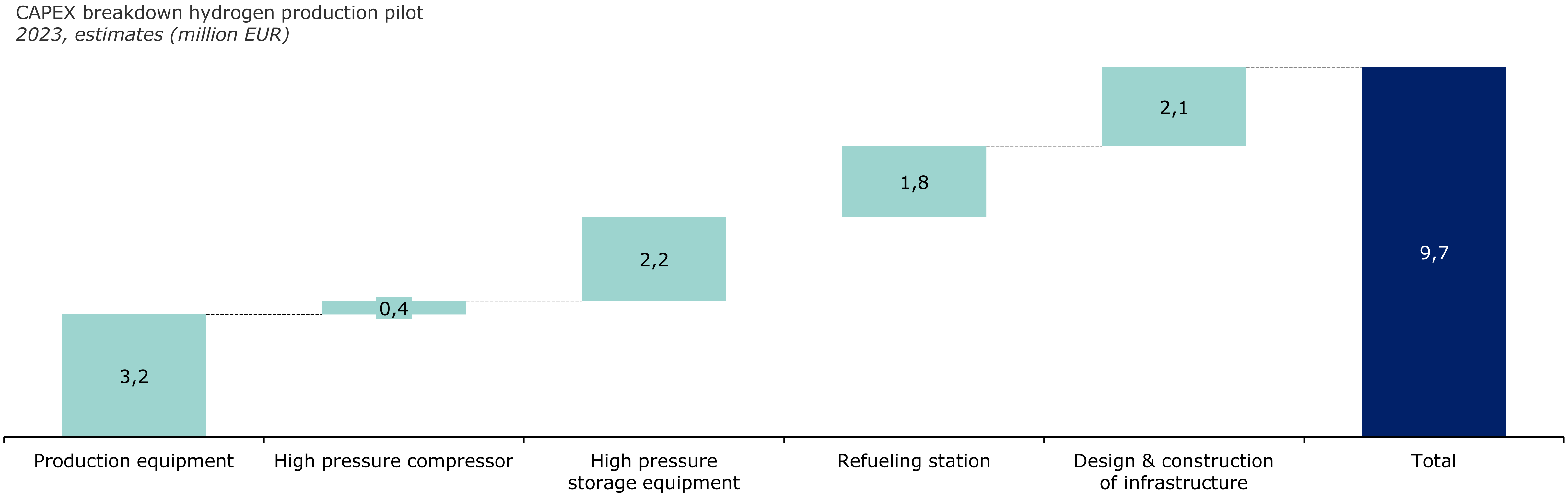
Hydrogen produced for each end-market
*2025-2050, estimates (tonnes $H_2$)* [1]




## Key takeaways

- In 2025 the production site will become operational, with its first 46 tonnes (25% of capacity) being produced. These 46 tonnes will be supplied to **one hydrogen bus** (consuming 2,4 tonnes per year) **and a waste collection ship from the Klaipeda Port Authority** which requires 44 tonnes of $H_2$ per year
- Increasing market demand allows $H_2$ sales to grow towards 2030, reaching an annual production capacity of 91 tonnes (37% of capacity). **Growth will be mainly in road freight and cargo handling end-markets**
- Beyond 2030 hydrogen production is expected to rapidly scale-up, to tap into existing $H_2$ demand, **reaching full capacity (193 tonnes produced per year) in 2033**
- Beyond 2033 the hydrogen production site will operate at full capacity, with **road freight and shipping being the main off-taking end-markets**
- Remaining $H_2$ demand in the Klaipeda area can be covered by **scaling up capacity, other local hydrogen production facilities or through imports**

# CAPEX breakdown of the hydrogen production pilot

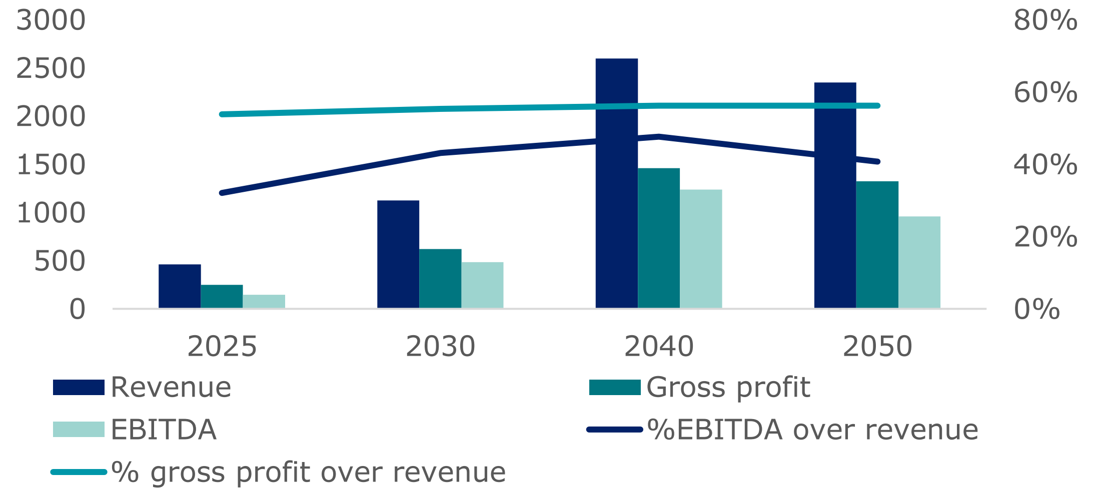



## Key takeaways

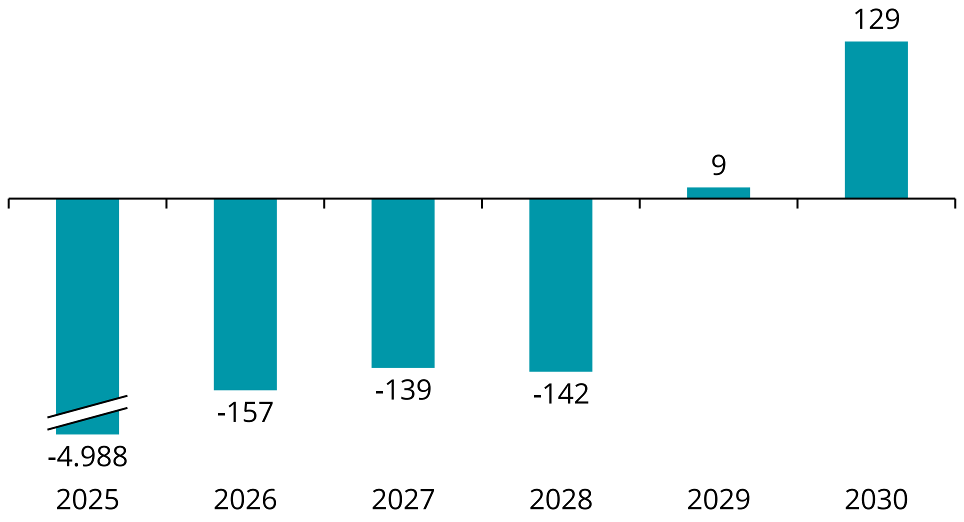
- The total CAPEX investment for a green hydrogen production plant and refueling station is estimated at almost **10 million EUR**
- More than 60% of the total investment in the pilot will go to the **hydrogen production plant** (production equipment, compressor and storage)
- The hydrogen **refueling station** accounts for almost 20% of total investments.
- **Design and construction** of the infrastructure is the third biggest expense, at 2,1 million EUR
- 50% of the CAPEX investment will be covered through an **EU grant**

# Income statement and net free cashflows of the hydrogen production pilot

Income statement overview
*2025-2050, estimates ('000 EUR, %)*




Net free cashflows
*2025-2030, estimates ('000 EUR)*




## Key takeaways

- Towards 2030, **hydrogen sales are gradually scaled up through the increased adoption of hydrogen busses**, going from 1 hydrogen bus in 2025 to 2 in 2027. As of 2029, 10 hydrogen busses are expected to be driving around the Klaipeda area.
- Between 2030 and 2033 gradual scaling of hydrogen sales is continued to reach full production capacity. This translates into **revenues peaking in 2040 at 2.6 MEUR, whereafter a slight decrease sets in due to a declining hydrogen price and the production site remaining at the same capacity**. A potential additional revenue stream that could be assessed are the sales of oxygen as a by-product of hydrogen production
- We assume a **CAPEX subsidy of 50%** in 2025, leading to a net free cashflow of -4.9 MEUR
- **Net free cashflows become positive from 2029 onwards**, due to increased incoming cash from the scaling up of hydrogen sales
- **Attracting clients at an early stage will be key** to strengthen the commercial viability of the business case ( e.g., by closing partnerships and giving incentives for off-take agreements)

# Key levers for a favorable IRR are the hydrogen price, CAPEX subsidy and electricity price

Sensitivity analysis of IRR with Hydrogen price and CAPEX subsidy variables
*2025-2050, estimates (%)*

| Capex subsidy \ Hydrogen price | -10,00% | -5,00% | 0,00% | 5,00% | 10,00% |
|---|---|---|---|---|---|
| 6,63% | | | | | |
| 20,00% | -1,63% | -0,64% | 0,26% | 1,10% | 1,87% |
| 35,00% | 1,35% | 2,27% | 3,12% | 3,92% | 4,67% |
| 50,00% | 4,90% | 5,79% | 6,63% | 7,42% | 8,18% |
| 65,00% | 9,68% | 10,61% | 11,49% | 12,34% | 13,15% |
| 80,00% | 17,84% | 18,96% | 20,05% | 21,10% | 22,13% |

Sensitivity analysis of IRR with Hydrogen price and electricity price variables
*2025-2050, estimates (%)*

| Electricity price \ Hydrogen price | -10,00% | -5,00% | 0,00% | 5,00% | 10,00% |
|---|---|---|---|---|---|
| 6,63% | | | | | |
| 0,00% | 4,90% | 5,79% | 6,63% | 7,42% | 8,18% |
| -5,00% | 6,25% | 7,13% | 7,96% | 8,76% | 9,51% |
| -10,00% | 7,48% | 8,36% | 9,20% | 9,99% | 10,76% |
| -15,00% | 8,63% | 9,51% | 10,35% | 11,16% | 11,93% |
| -20,00% | 9,71% | 10,59% | 11,44% | 12,26% | 13,04% |

Base case

## Key takeaways

- **Due to the low technology maturity of hydrogen and its corresponding risk profile, a double-digit Internal Rate of Return (IRR) would be advisable**. As the aim for the project is not primarily a commercially viable project, but rather gathering knowledge and derisking future projects, lower IRR's could be justified
- **Fixed offtake agreements** could be an option to mitigate the risk of a hydrogen price below the one projected
- Access to **public funding for CAPEX investments drastically improves the business case** and corresponding IRR, as portrayed in the sensitivity analysis
- Electricity costs amount to almost half of revenues (46%). A **favorable electricity price can significantly reduce the Cost of Goods Sold**, and therefore improve your gross profit. This could be achieved by negotiating a discount on your PPA or work with Contracts for Difference

# Constraints

# Technical considerations

## General

The Klaipeda case has a 1.2 MW containerized PEM cell providing compressed hydrogen for road fright and cargo handling. The value chain consist of hydrogen production, compression, storage and fueling station.

## Current technology readiness

The majority of the hydrogen production value chain is commercially available, however the hydrogen produced is typically not commercially attractive.

## Technical considerations to hydrogen production

- The operational pressure of the electrolyser can be increased to decrease the number of compression stages required. This improves the overall chain efficiency by limiting low pressure compression of hydrogen.
- The integration of storage and compression when cascade refueling is utilized at the refueling station. Storage of hydrogen at different pressures increases the overall energy efficiency of the value chain.
- The location of the hydrogen production facility: a location near power infrastructure hubs (e.g. offshore wind) to reduce the impact on infrastructure at small scale and future expansion.

**Sources**:

# Safety considerations

## Description of situation

The value chain in Klaipeda consists of hydrogen production, compression, storage and fueling station. In terms of safety the goal is an inherently safe design of a green hydrogen production pilot with adjacent refueling station in a port setting, while considering the intermittent production behaviour due to the corresponding availability of renewable energy.

## Safety considerations

- The hazardous effect of a puncture (worst case rupture) in the membrane separating the oxygen and hydrogen inside the electrolyser stack.
- Mitigating measures to avoid a potential deflagration inside the electrolyser stack transitioning into a destructive detonation phenomenon.
- Mitigation measures to avoid the formation of a flammable hydrogen/air mixture as a result of loss of containment inside the facility housing the electrolyser.
- The intermittent availability of renewable electricity leads to frequent starts and stops, as well as changes in load. This may have an impact on hydrogen cross over (via the membrane) and other safety issues.
- Cyclic thermal and pressure effects on durability and integrity of intermediate storage tanks.
- Safety distances of the pilot plant, refueling station and crash mitigation measures especially for heavy duty vehicles.
- Ventilation requirements to avoid the accumulation of flammable atmospheres at refueling station, location of detection systems and positioning of venting lines.
- Executing the (compulsory) environmental impact assessment.

## Recommendations

- Involve the Ministry of Environment of the Republic of Lithuania, the local authorities and other relevant stakeholders at an early stage to aid the permitting process.
- With the Ministry of Environment providing the permit, a detailed QRA needs to be executed to ensure that the nearby residential areas are safe for all potential scenarios.
- This applies also for the compulsory environmental impact assessment.
- The chemical industry has decades of experience in the production (not green), handling and storage of hydrogen. Make use of the (safety) lessons learned.

# Breakdown of actions and governance

# Timeline with key milestones to turn Klaipeda in a hydrogen hub and develop hydrogen production at the port

**Go live of green $H_2$ production plant**

| Today | 2024 | 2025 | 2026 | 2027 |
|---|---|---|---|---|
| Set up steering board bringing key stakeholders together on continuous basis | Secure financing | Accelerate off-take of hydrogen through incentives | Upscale electricity distribution infrastructure | Assess the role the production facility played in kick-starting the Lithuanian hydrogen economy |
| Develop hydrogen strategy for Klaipeda Sea Port | Initiate close contact with permitting authorities, to ensure smooth permitting process | Develop wind farm | Assess mobile fueling stations | Assess need to further scale up hydrogen production capacity |
| Execute feasibility studies for hydrogen off-take | Develop value proposition towards clients and secure off-take agreements | | | Assess structural hydrogen distribution infrastructure (from production to end-use) |
| Select partner to operate hydrogen production site | **Take final investment decision** | | | |
| Select partner to operate refuelling station | Release tender for offshore wind farm | | | |
| Final selection of site and execution of environmental impact assessment | Construct $H_2$ production site and refuelling station | | | |

# Governance and RACI-matrix for key stakeholders

| Task / Stakeholders | Port Authority | Klaipeda University | Public transport companies | Green energy producers and distributors | Companies part of port ecosystem | Manufacturing companies | Klaipeda municipality | Lithuanian ministries (transport, energy and finance) |
|---|---|---|---|---|---|---|---|---|
| Set up steering board | A | R | R | R | R | R | R | R |
| Develop hydrogen strategy | A | C | C | C | C | C | R | C |
| Execute feasibility studies hydrogen off-take | I | I | A | C | A | A | I | I |
| Select hydrogen production and refueling station operator | A | I | I | I | I | I | R | C |
| Select final site | A | I | C | I | C | I | C | I |
| Initiate permitting | A | I | I | I | I | I | C | C |
| Secure financing | A | C | C | C | C | C | C | C |
| Develop value proposition | A | I | C | C | C | C | C | I |
| Take final investment decision | A | I | C | I | C | I | C | I |
| Release tender for offshore wind farm | A | I | I | I | I | I | C | C |
| Construct production and refuelling site | A | I | I | I | I | I | R | C |
| Accelerate H2 off-take through incentives | A | I | C | I | C | C | I | C |
| Develop wind farm | I | I | I | A | I | I | C | I |
| Upscale electricity distribution infrastructure | I | I | I | A | I | I | C | C |
| Assess mobile fueling stations | I | C | A | C | C | C | I | I |
| Assess added value of project in kick-starting Lithuanian H2 economy | A | C | C | C | C | C | R | C |
| Assess need to further scale up hydrogen production capacity | A | C | C | C | C | C | R | C |
| Assess structural hydrogen distribution infrastructure | A | C | C | R | C | C | R | R |

## Key takeaways

- The **Klaipeda Port Authority will play a key role in establishing the hydrogen hub**, for which the development of a hydrogen production facility is a key first initiative
- **Continuous collaboration and information sharing among the various stakeholders will be crucial** in the further success of this project, due to high interdependencies ( e.g., securing off-take and governmental support)
- Setting up a **hydrogen steering board ensuring structured governance by bringing together all stakeholders will be essential**, and should remain a continual focus throughout the development of hydrogen projects

## RACI

**R - Responsible**
The organization who takes action to get the task done. They are responsible for part of the work that needs to be executed.

**A - Accountable**
The organization which owns the task or deliverable. They might not get the work done themselves, but they are responsible for making sure it is finalized. To avoid confusion and the diffusion of responsibility, it's best to have one accountable stakeholder per project task.

**C - Consulted**
The stakeholder who will help complete the task. They will have two-way communication with the people responsible for the task by providing input and feedback over the task completion.

**I - Informed**
The stakeholder that needs to be up to date on the task's progress. They will not have two-way communication, but it's essential to keep them informed since they will be affected by the final outcome of the task.

# Anticipated benefits

# Anticipated environmental, societal and economic benefits in the Klaipeda area

## Environmental benefits

- Avoid **$CO_2$ emissions**, thereby contributing to reaching the EU's climate objectives
- Avoid **air pollution** (O3, $NO_2$, $SO_2$)
- Improve living conditions of **marine life** and water quality by reducing spillage of fuels
- **Lead by example**, fostering other stakeholders to take climate action

## Societal benefits

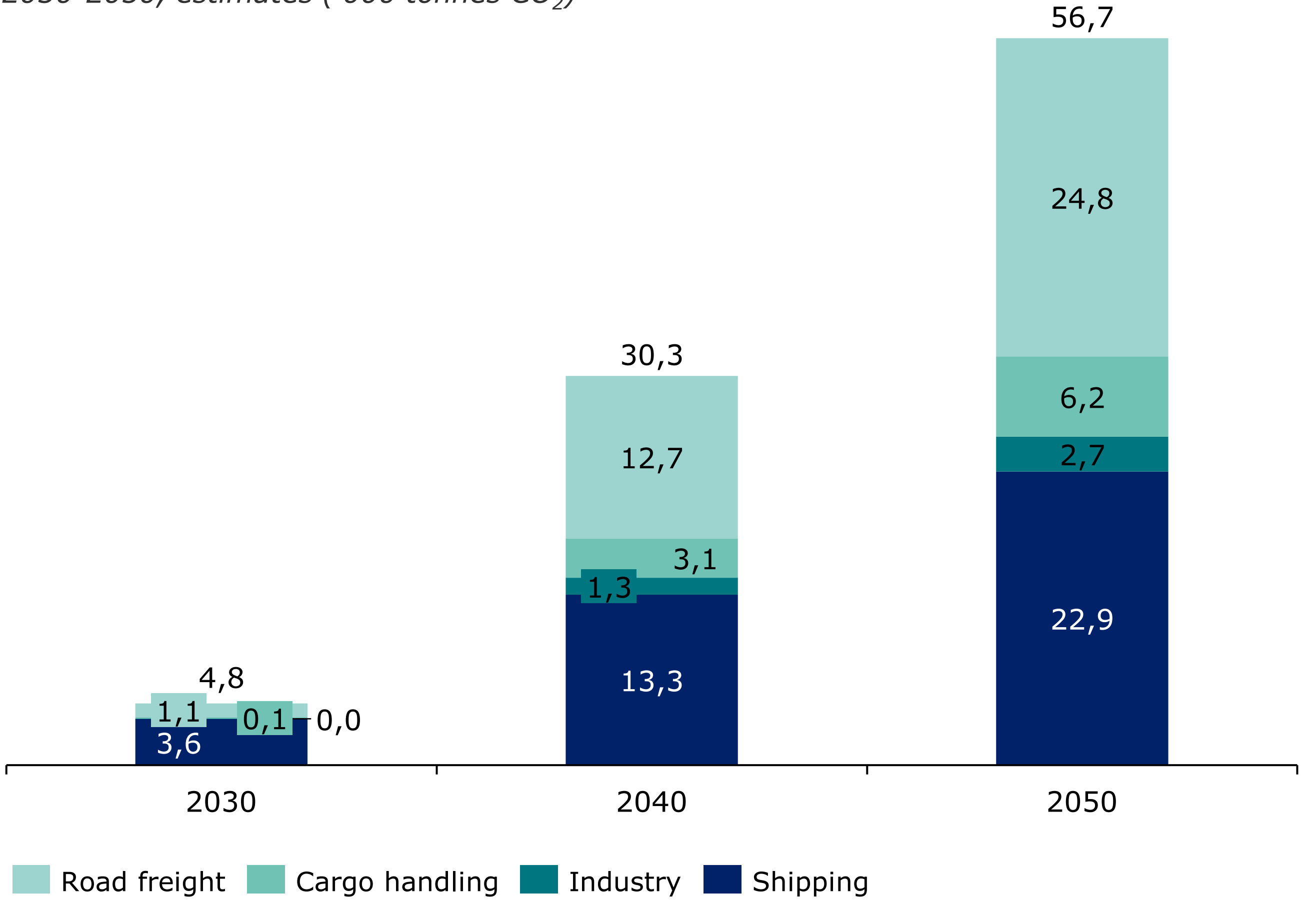
- Reduce **energy dependence** through heterogeneous energy sources and carriers
- Improve **citizens health** by reducing emissions and air pollution
- Put Klaipeda on the map as a front-running **innovation hub** with national and international exposure
- **Build knowledge** on hydrogen production and usage in end-applications
- Prepare the **workforce of the future** through tangible knowledge transfers via the development of specific university courses as part of the Maritime Academy and Klaipeda University
- Develop Klaipeda as an **energy import hub** to play a key role in the Lithuanian energy system

## Economic benefits

- Attract (foreign) **financial investments** in the local economy
- Reduce **environmental taxes**
- Attract **top talent** and further improve reputation of Klaipeda university and Maritime academy as knowledge hubs
- **Move up the value chain** by developing hydrogen technology manufacturing capabilities
- Develop Klaipeda as a **green industry cluster** attracting business downstream in the $H_2$ value chain
- Enable **export of clean technologies** to EU and the world
- Create direct and indirect **jobs**

# Estimated cumulated greenhouse gas emission avoided through the development of this hydrogen production pilot

Cumulated avoided greenhouse gas emissions[1]
*2030-2050, estimates ('000 tonnes $CO_2$)*




## Key takeaways

- The hydrogen produced through this project is estimated to **avoid approximately 56.703 tonnes of $CO_2$ emissions** by 2050
- Hydrogen adoption in the port is projected to enable an **average emission reduction of 13,6 kg of $CO_2$ per kg of hydrogen produced**
- **The highest volume of $CO_2$ emissions are abated in the transport sector**, with road freight and shipping being responsible for respectively 24.837 and 22.889 tonnes of $CO_2$ emissions avoided

[1]*Study on Hydrogen in Ports and Industrial Coastal Areas (2023)*

# Conclusions and recommendations

# Conclusions and recommendations for hydrogen production in Klaipeda

## Conclusions

1. Projections show there will be sufficient hydrogen demand to off-take local production. Beyond 2030, there will be a shortage of hydrogen supply to satisfy demand.
2. This can be mitigated by increasing the capacity of the pilot plant, constructing additional production sites or through imports
3. Off-take agreements still need to be negotiated, and will be key to determine the viability of the business case in an early stage, and to decide on further upscaling or additional production sites
4. The hydrogen production pilot has the potential to play a key role in kick-starting the hydrogen economy in Lithuania by derisking future investments needed through a pilot plant

## Recommendations

### Klaipeda as hydrogen hub

1. Develop overarching hydrogen strategy for city of Klaipeda and the port aligned with the Lithuanian hydrogen strategy as framework for hydrogen related pilot projects
2. Create actionable roadmap with concrete initiatives and milestones to achieve the strategic objectives put forward in the hydrogen strategy, in which the hydrogen production pilot should be embedded
3. Set up joint collaboration platform to consult and inform stakeholders involved in hydrogen related topics

### Hydrogen production pilot

4. Attract off-takers at an early stage of the project to strengthen the commercial viability of the business case. This can be done through partnerships and incentives for long-term off-take agreements
5. Negotiate a favorable electricity price as part of your PPA, since electricity costs amount to almost half of revenues, and therefore have a significant impact on your overall business case
6. Look into potential oxygen off-takers to create and additional revenue stream from oxygen as a by-product of hydrogen production

# Case study 2

Port of Antwerp-Bruges & Duisport

# Case study description

# Case study on decarbonizing port equipment with hydrogen in the Port of Antwerp-Bruges and Duisport

## Location

## Partners

- Port of Antwerp-Bruges
- Duisport
- PSA
- WaterstofNet

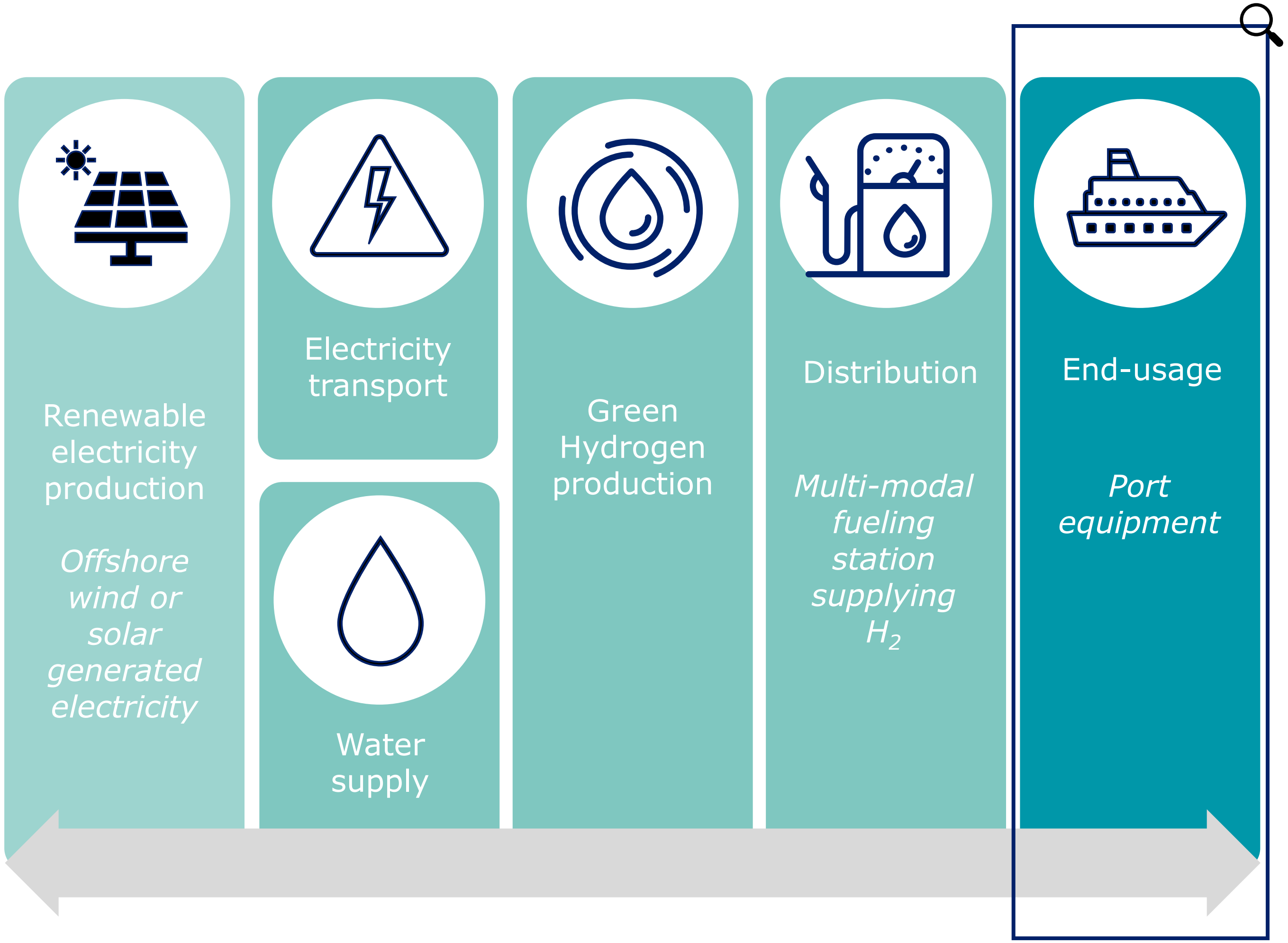
*Link with archetypes:* ***industrial****,* ***logistics and transport****,* ***bunkering*** *and* ***urban.***

## Topic

**Port equipment:**


*This study investigates the potential role of hydrogen as an opportunity to reduce the emissions of hard-to-electrify port equipment like straddle carriers, reach stackers, terminal tow tractors, large forklifts, etc.*

# The objectives and scope of this case study




## Objectives and scope

**Objectives:**

- The objective of this case study is to assess the economic viability, practical implications, readiness and next steps required to fuel port equipment on hydrogen[1].

**Scope:**

- Both a **seaport and an inland port** are involved. Although the type of port equipment is different, similarities can be found in the barriers slowing down the greening of port equipment and the way the business case is developed.
- The study **evaluates the decarbonization routes for port equipment**, focusing on straddle carriers. Straddle carriers are large mobile cranes used in ports for stacking and moving shipping containers. Other port equipment can be assessed analogical.

**Note**: (1) Most terminal operators have a focus on electrification of cargo handling applications. However, not every type of application can be electrified. Equipment with a high power demand, often combined with a challenging use profile may need other solutions than electrification.

# Partners of the case study – Duisport

## Duisport

- The **Port of Duisburg** is the **largest inland port of Europe** and the leading logistics hub in Central Europe, located at the banks of the Rhine.
- The port is located in the heart of Europe's largest consumer market with more than 30 million consumers over a radius of 150 kilometers. Per year, Duisport processes 20,000 ships and 25,000 trains.
- Almost 60% of the $CO_2$ emissions caused by handling equipment in inland ports is attributable to reach stackers in inland ports in Germany
- The port has 2 terminals: 1) DRT (logport III, Duisburg-Hohenbudberg) and 2) MTD (logport VI, Duisburg-Walsum)

**DRT**
- Container bridge: 2
- Reach stacker: 3
- Terminal tractor: 2

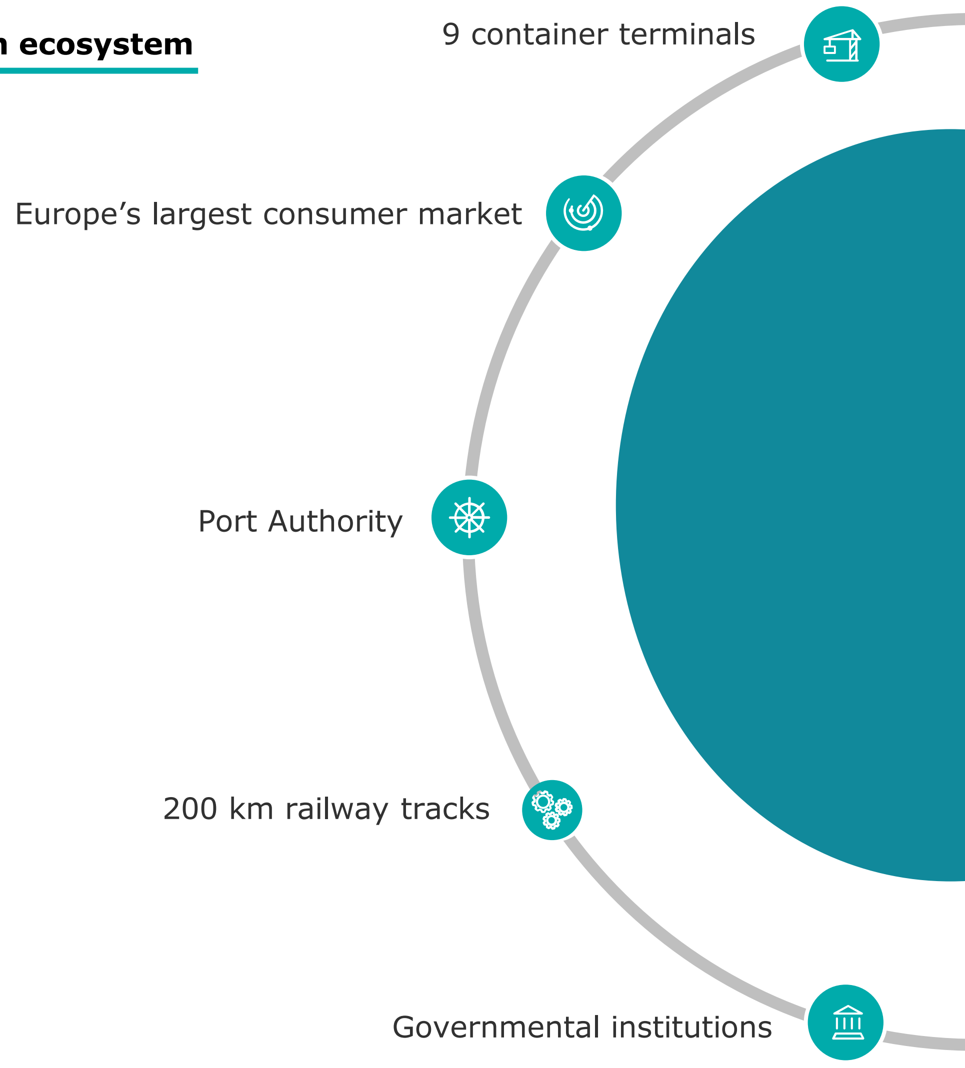
**MTD**
- Container bridge: 2
- Reach stacker: 1
- Terminal tractor: 1
- Container handler: 1

**Cargo turnover**
58.2 Mt

**Container handling**
4.3 million TEU

**Total handling volumes**
111.1 Mt

## Hydrogen ecosystem



# Partners of the case study – Port of Antwerp-Bruges

## Port of Antwerp-Bruges and PSA in Antwerp

- The Port of Antwerp-Bruges is a **coastal port** (sea connection through the river Scheldt) and **one of the largest in Europe**. Further, the port is home to the **largest integrated chemical cluster in Europe**.

- International connections and sustainable growth play an important role for the port. They recognize that the future of transportation is net zero and encourage their customers and concessionaires to engage in their sustainable transition.

- **PSA in Antwerp is the largest container handler in the Port of Antwerp and operates 3 container terminals**: 1) MPET at Deurganck dock (a joint venture between PSA and TIL), 2) Noordzee Terminal and 3) Europa Terminal. Over 80% of all containers coming into Antwerp, pass through one of these terminals.

- A joint venture between MSC PSA Europe Terminal (MPET) and PSA Antwerp (PSAA), Antwerp Terminal Services (ATS), has launched the **world's first hydrogen dual fuel straddle carrier** in the Port of Antwerp-Bruges. Straddle carriers account for over 95% of the CO2 emission caused by port equipment at PSA in Antwerp.

| MPET | Noord-zee | Europa |
|---|---|---|
| Quay crane: 41 | Quay crane: 14 | Quay crane: 9 |
| Reach stacker: 21 | Reach stacker: 9 | Reach stacker: 6 |
| Straddle carrier: 225 | Straddle carrier: 75 | Straddle carrier: 50 |

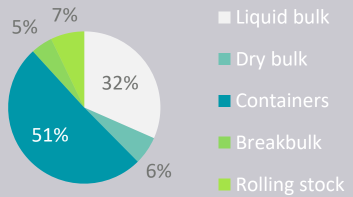
**Overall throughput**

**289 Mt**

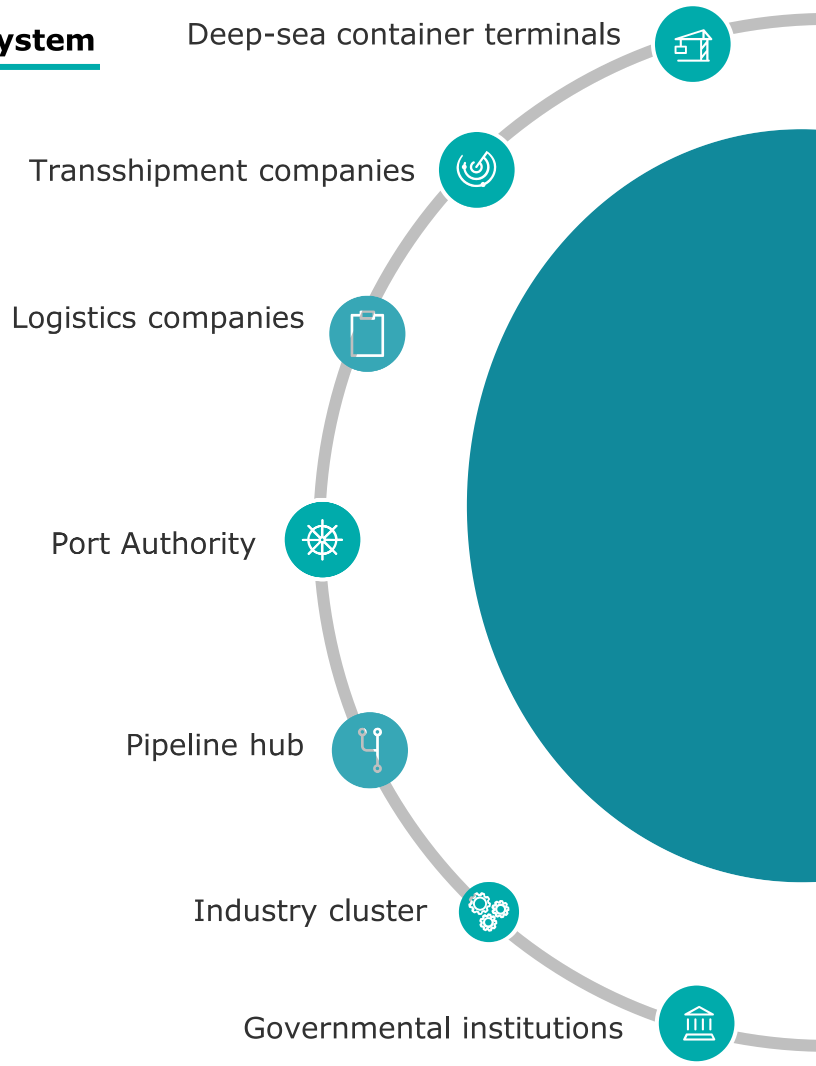
**Container handling**

**12 million TEU**

**Breakdown of tonnes moved**
*2022, historical data (%)*




## Hydrogen ecosystem



# Technological comparison

# Each type of straddle carrier has its own set of advantages and disadvantages (1/2)

| | Diesel ICE[1] (stage IV) | Electric | Hydrogen ICE | Hydrogen Fuel cell | Hybrid diesel | Dual fuel | HVO ICE |
|---|---|---|---|---|---|---|---|
| **Energy carrier** | Diesel | Electricity | Hydrogen | Hydrogen | • Diesel<br>• Surplus energy generated during braking/lowering load is stored in batteries | Diesel (30%)<br>Hydrogen (70%) | Hydrotreated Vegetable Oil (HVO100) produced by using sustainably sourced vegetable and animal matter |
| **Net zero compatible** | ✗ | ✓ | ✓ | ✓ | ✗ | ✗ / ✓ | (✓) |
| **GHG emissions (SOx, NOx, PM)** | • NOx, SOx and PM<br>• Noise emissions | • No GHG emissions if renewables based | • NOx emissions, but aftertreatment is possible<br>• Almost no CO emissions and very little particulates | • No GHG emissions with clean hydrogen | • Reduced noise emissions | • NOx, SOx and PM<br>• Noise emissions<br>• No GHG emissions as of full transition to clean hydrogen | • NOx, SOx and PM<br>• Noise emissions |
| **Technology and infrastructure availability** | Established technology | • Established technology, but integration in vehicle is still challenging<br>• On fleet level infrastructure implications<br>• Charging infrastructure and possible grid upgrade required<br>• Availability of batteries is a concern | • Not yet operational<br>• Existing equipment can be retrofitted<br>• Lack of hydrogen refueling and distribution infrastructure | • Not yet operational<br>• Lack of hydrogen refueling and distribution infrastructure | Established technology | Lack of hydrogen refueling and distribution infrastructure | Equal to diesel ICE |

**Notes**: (1) Internal Combustion Engine

# Each type of straddle carrier has its own set of advantages and disadvantages (2/2)

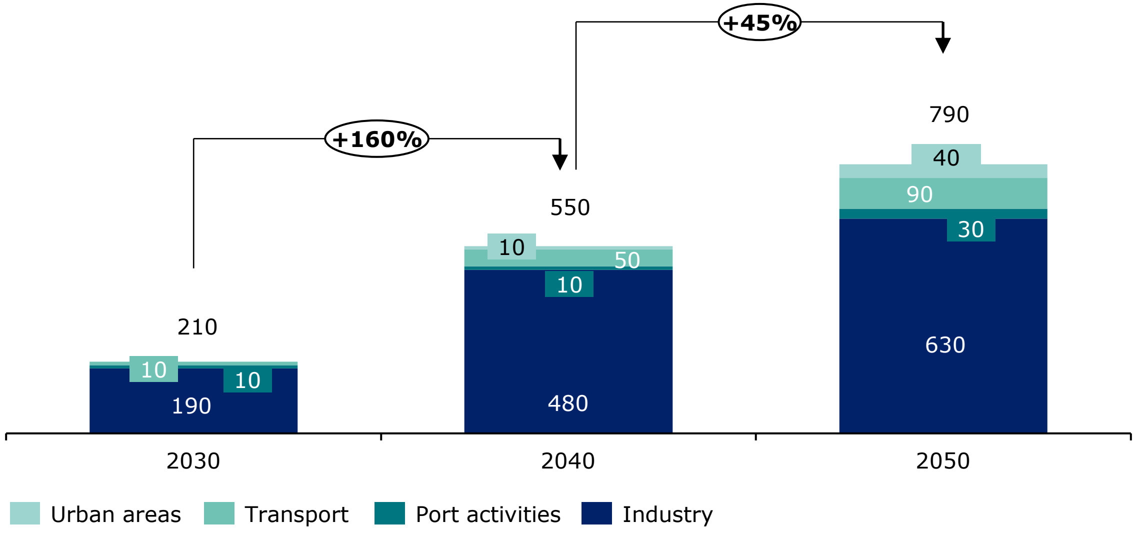
| | Diesel ICE (stage IV) | Electric | Hydrogen ICE | Hydrogen Fuel cell | Hybrid diesel | Dual fuel | HVO ICE |
|---|---|---|---|---|---|---|---|
| **Autonomy/ refueling time (shift of 8 hours)** | • Refueling time of 2 min/shift | Refueling time of 2 x 40 min/shift[2,3] | Refueling time of 12 min/shift[4] | Refueling time of 10 min/shift[3] | Refueling time of 1.5 min/shift | Refueling time of 8 min/shift | Equal to diesel ICE |
| **Change to operation** | / | Significant change: difference in loading times influences the current operation | Limited change | Limited change | / | Limited change | None |
| **Other** | | • Very heavy battery causes stability risks | • Lower fuel efficiency than fuel cells<br>• Quality of hydrogen required is 98%<br>• Availability of spare parts due to similarity to traditional straddle carriers | • Higher investment cost, but lower maintenance cost due to removal of the engine and mechanical-driven components<br>• Needs more space<br>• Quality of hydrogen required is 99.99%, to reach this a purifier and extra measurement installation is required | • Less fossil energy, so fewer costs and reduced emissions<br>• Basis for the future | • Requires a smaller buffer per energy carrier (less reliable on hydrogen), which will be an advantage in the transition<br>• Extra insertion point on top of hybrid diesel straddle carrier | • Similar structure as diesel and thus a substitute without much impact<br>• Availability of HVO (and the amount) is uncertain |

**Notes**: (2) Kalmar also offers the possibility of high power batteries with fast charging. The cycle is then different. (Source). (3) This has an implication on the equipment required. For 7 straddle carriers in operation, 1 will be charging. (4) Charging rate of 4 kg/min at a pressure of 350 bar

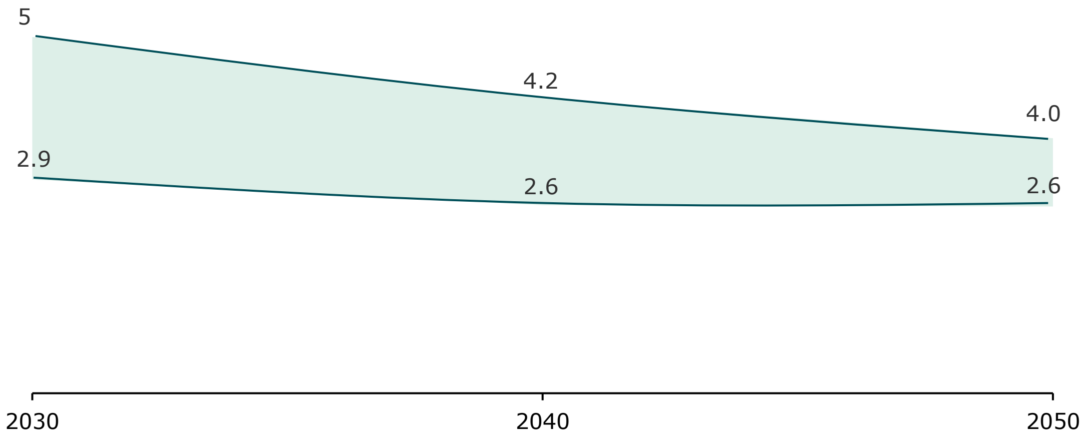
# Economic analysis

# Potential hydrogen demand and price in the Duisport area

Projected hydrogen demand Duisport
*2030-2050, estimates ('000 tonnes $H_2$)*[1]




Base case projected hydrogen cost Duisport area
*2030-2050, estimate (EUR/kg)*[1]




## Key takeaways

- $H_2$ demand in the Duisport area is projected at 0.4 million tonnes in 2030, mainly driven by **industry.**
- Between 2030 and 2040 demand is expected to rapidly scale up, accelerated by **industry and transport,** to reach 0.5 million tonnes of hydrogen demand in 2040
- In 2050, hydrogen demand is forecasted to be at 0.8 million tonnes, an increase of 45% compared to 2040

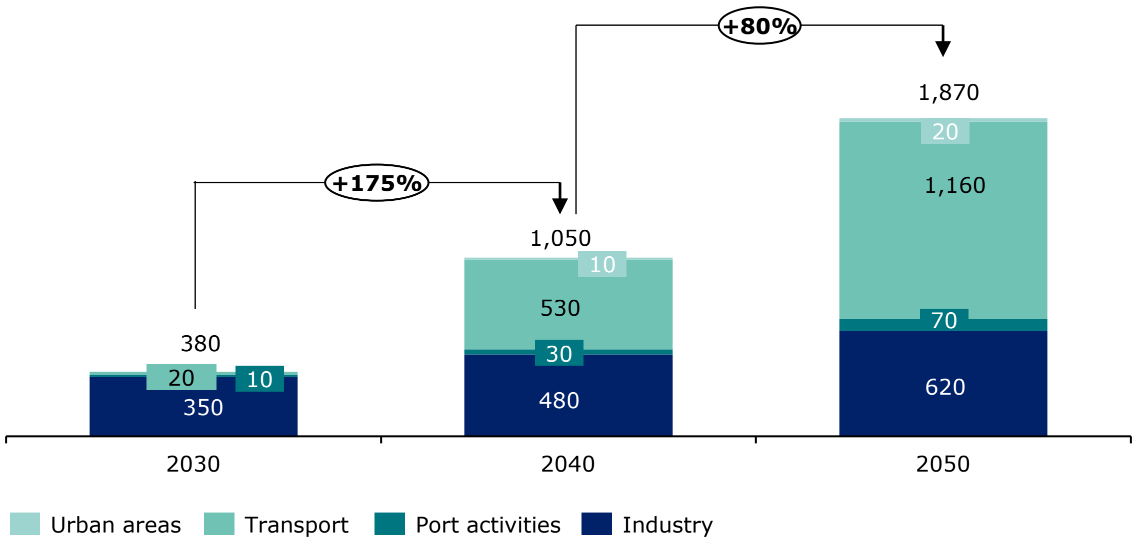
## Key takeaways

- The projected cost of hydrogen in the Duisburg area is expected to be between **2.9 and 5 EUR/kg in 2030**
- **Beyond 2030, the $H_2$ cost is projected to fall,** reaching 2.6 – 4.2 EUR/kg in 2040
- Towards 2050, the cost of hydrogen is estimated to reach **2.6 – 4 EUR/kg**

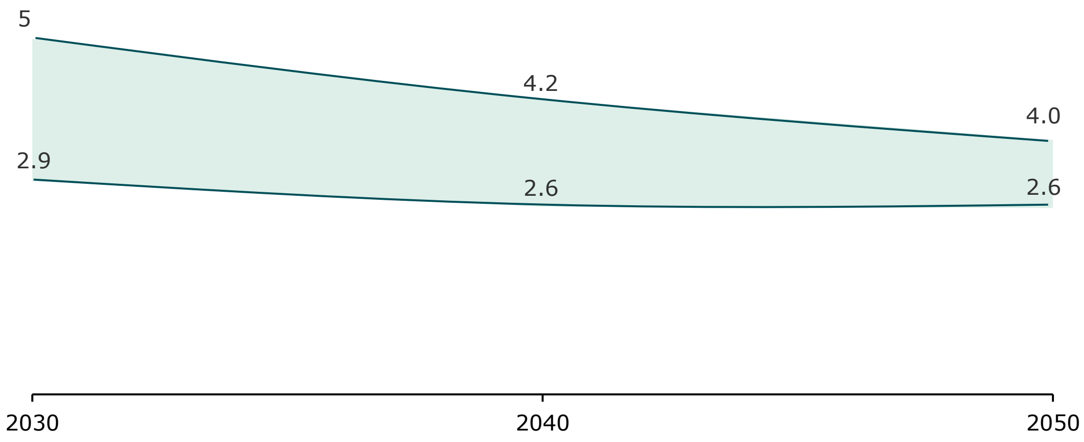
[1]*Study on Hydrogen in Ports and Industrial Coastal Areas, Report 1 (2023). Own port projections might be different*

# Potential hydrogen demand and price in the Port of Antwerp-Bruges area

Projected hydrogen demand in Port of Antwerp-Bruges
*2030-2050, estimates ('000 tonnes $H_2$)*[1]




Base case projected hydrogen cost Port of Antwerp-Bruges area
*2030-2050, estimate (EUR/kg)*[1]




## Key takeaways

- $H_2$ demand in the Port of Antwerp-Bruges area is projected at 0.4 million tonnes in 2030, mainly driven by **industry.**
- Between 2030 and 2040 demand is expected to rapidly scale up, accelerated by **road freight and shipping end-markets,** to reach 1 million tonnes of hydrogen demand in 2040
- In 2050, hydrogen demand is forecasted to be at 1.9 million tonnes, an increase of 80% compared to 2040
- The values are a projection based on a bottom-up approach and methodology taken for all ports identically (see report 1 of the study). Transit is not taken into account.

## Key takeaways

- The projected cost of hydrogen in the Antwerp-Bruges area is expected to be between **2.9 and 5 EUR/kg in 2030**
- **Beyond 2030, the $H_2$ cost is projected to fall,** reaching 2.6 – 4.2 EUR/kg in 2040
- Towards 2050, the cost of hydrogen is estimated to reach **2.6 – 4 EUR/kg**

[1]*Study on Hydrogen in Ports and Industrial Coastal Areas, Report 1 (2023). Own port projections might be different*

# TCO assumptions

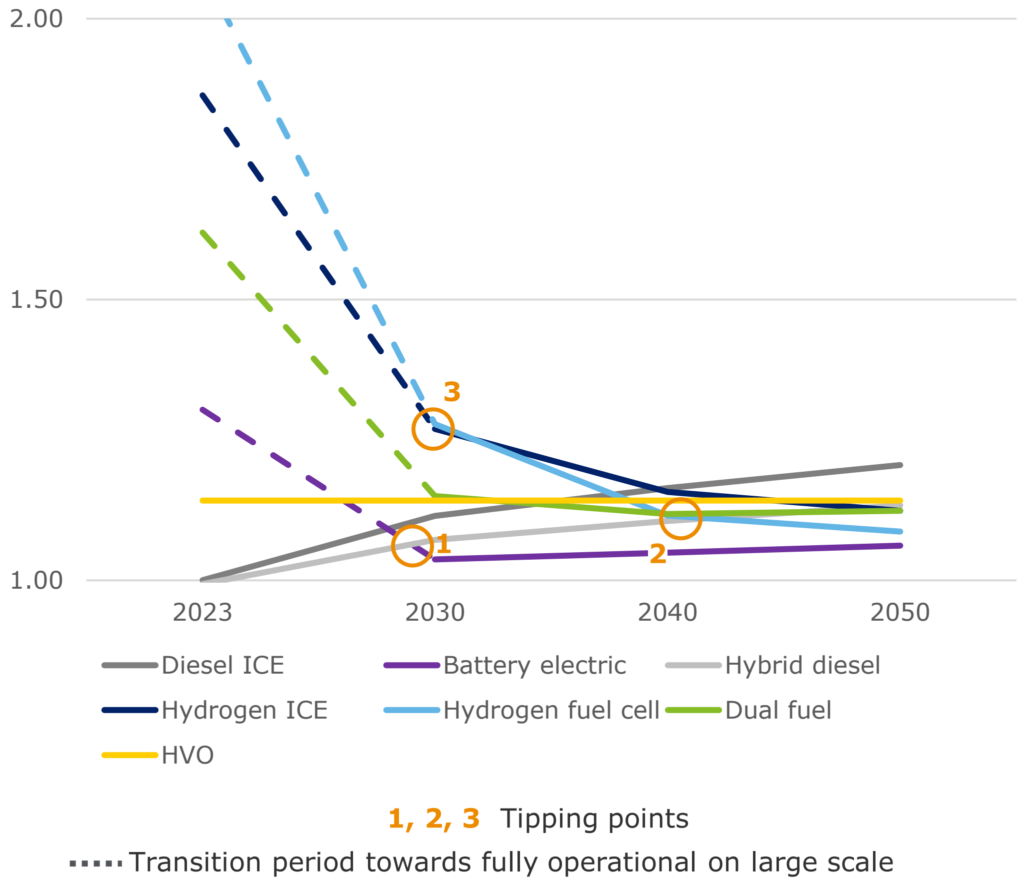
## Key points

Assumptions:

- The **costs of straddle carriers vary widely**, depending on several factors such as size, features, manufacturer, capacity, operating speed, location, etc. An average cost is assumed in this analysis for traditional straddle carriers. A surplus investment cost is considered for all other types of straddle carriers.
- The analysis considers **all direct costs** related to the straddle carriers, **as well as indirect costs and** related to infrastructure required (i.e. for energy storage and refueling stations, required capacity changes to the electricity grid and additional costs for hydrogen grids). All assumptions can be found in the appendix.
- Carbon taxation is considered, since it will play an import role in decarbonizing different sectors. Due to **carbon taxation**, the TCO of straddle carriers running (partially) on diesel will increase in the future. Relatively speaking this improves the business case for more sustainable options on hydrogen and electricity. Also **other taxation rules might change** (i.e. diesel taxation and hydrogen taxation). Due to its high uncertainty concerning timing and values, this is not taken into account in the analysis.
- There is still a **high uncertainty** about the availability and price of **hydrogen** in the future.
- For **electric straddle carriers**, the refueling pace is expected to be a total of 80 min/8-hour shift. In other words, **16% of the time a straddle carrier is recharging**. To compensate for this loading time, extra capacity will have to be in place. For 7 straddle carriers in operation, one will be charging. The TCO accounts for the additional CAPEX and OPEX.
- Technological improvements lead to cost reductions over time. These and all other assumptions and parameter values can be found in the **appendix**.

# Battery electric straddle carriers will most likely be the cheapest option, however due to practical constraints also hydrogen can play a role in decarbonizing straddle carriers

Projected total cost of ownership of straddle carriers
*2023 – 2050, EUR/year normalized for the straddle carrier types compared to the ICE diesel in 2023*




## Key takeaways

**Results:**

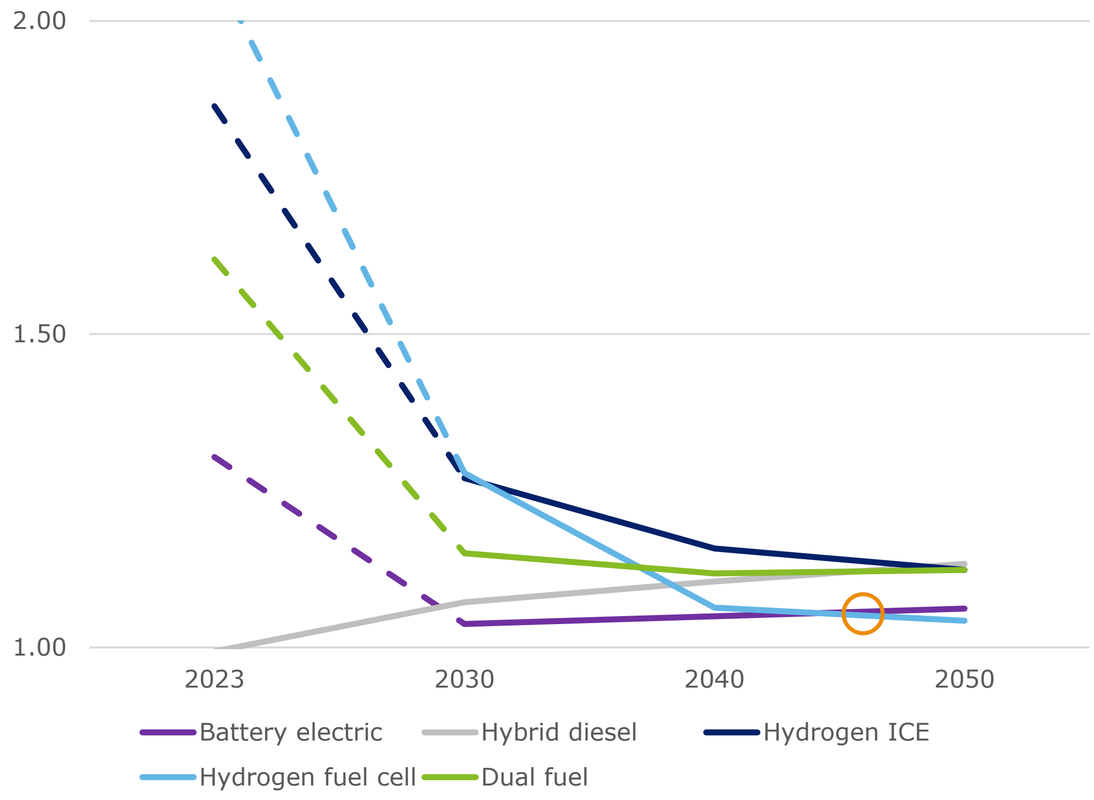
- **Battery electric** straddle carriers are projected to be the **most cost-efficient option**, even before 2030 (**1**), breaking even with **hybrid diesel**, the current incumbent solution. Significant technological improvements have been achieved in recent years. However, the solution is not yet fully developed: there are **still technical hurdles[1] to overcome, their availability is still uncertain, they have the largest impact on current operations and require a strong grid**.
- **Dual fuel** straddle carriers are projected to be the **next best alternative**, and particularly relevant in case hurdles for battery electric straddle carriers cannot be overcome. However, additional incentive will be required as they are projected to only become more interesting compared to hybrid diesel around 2040 (**2**). Dual fuel straddle carriers offer some advantages: current straddle carriers can be retrofitted, and they are not dependent on one energy source. This is specifically interesting during the **transition** where hydrogen supply might still be uncertain and can be introduced gradually.
- **Fuel cell** straddle carriers are projected to become more competitive compared to **ICE hydrogen** straddle carriers from 2030 onwards (**3**). Since both types are not yet commercially available, there is still a high overall uncertainty on the price of these straddle carriers. It should be kept in mind that there is currently no additional price included for the increased purity of hydrogen required for fuel cells. This could impact the outcome. Beyond 2040, and potentially earlier, cf. sensitivity analysis next slide, fuel cell straddle carriers are projected to become cost competitive with hybrid diesel straddle carriers (**2**).

**Notes**: (1) This includes stability issues, on fleet level charging infrastructure implications, etc.

# Sensitivity analysis – fuel cell efficiency

Projected total cost of ownership of straddle carriers, fuel cell efficiency of 70% from 2040

*2023 – 2050, EUR/year normalized for the straddle carrier types compared to the ICE diesel in 2023*



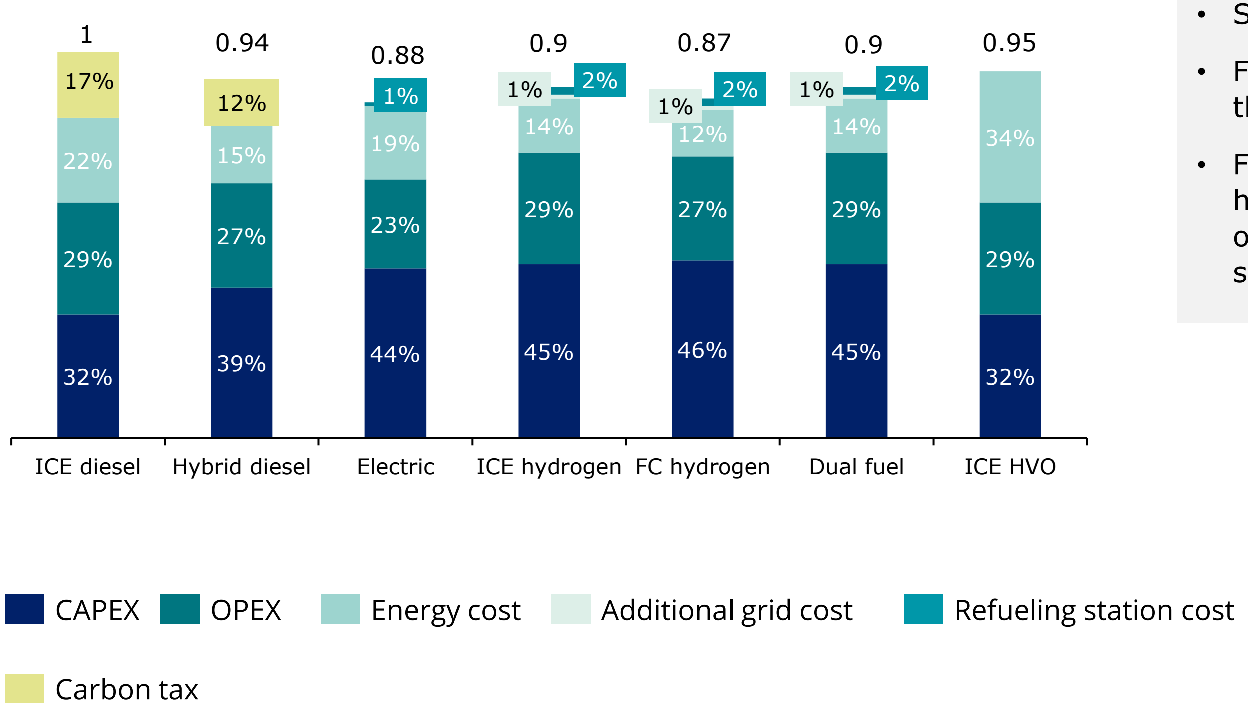

## Key takeaways

The general analysis assumes a fuel cell efficiency of 53%. However, various studies are being conducted on potential efficiency improvements of fuel cells. For instance, the Danish company Haldor Topsøe and the German company Bosch are working on a fuel cells with an efficiency of up to 90%[1,2]. If we therefore **assume an increased efficiency of around 70%** from 2040 onwards, it can be seen that **hydrogen fuel cells become cost competitive with battery electric straddle carriers**.

**Source**: 1) https://innovationorigins.com/en/denmark-is-building-a-fuel-cell-factory-that-offers-90-efficiency/. 2) https://energynews.biz/bosch-unveils-high-temperature-fuel-cells-with-90-efficiency/

# The CAPEX and OPEX are the biggest cost components for straddle carriers

Projected total cost of ownership comparison
*2050, normalized for the straddle carrier types compared to the ICE diesel in 2050*




## Key takeaways

- CAPEX and OPEX are the biggest cost components, followed by the cost for the energy (fuel cost)
- Straddle carriers using diesel as a fuel have a significant carbon tax by 2050
- For electric straddle carriers a grid reinforcement will be required, however this cost is minor compared to the total cost
- For straddle carriers using hydrogen an additional cost for the distribution of hydrogen via pipelines is included as well. This is dependent on the amount of hydrogen required and thus higher for internal combustion engine straddle carriers.

# Constraints for hydrogen port equipment

# Technical considerations

## General

The Antwerp-Bruges/Duisport case focusses on hydrogen powered port equipment. The value chain consist of hydrogen supply to site, hydrogen storage, fueling of straddle carriers, onboard storage of hydrogen and hydrogen prime mover.

## Current technology readiness

Due to the existing global market for merchant hydrogen, technologies for storage, transport and distribution of hydrogen are mature at small scale. However, a 100% hydrogen powered prime mover able to provide the operational performance for a straddle carrier is not yet commercially available.

## Technical considerations to hydrogen fuelled heavy duty vehicles

- Straddle carriers have specific performance characteristics determining the load curve of the prime mover which are mainly determined by hoisting, traversing and lowering motions of the straddle carrier. State of the art hydrogen-based solutions focus on dual fuel engines. Fuel cells or fuel cell battery hybrids fully powered by hydrogen have not yet been tested in relevant industrial environment. Therefore, the operational performance and stack-life time for variability in operation performance of straddle carriers have not been tested for (hybrid) fuel cell configurations.
- There is no definitive, universally accepted standard for hydrogen by pipeline. It is unknown whether supply by pipeline would meet the high purity standards of PEM fuel cells. Alternatively merchant supply by truck or barge is required.
- In case of merchant supply, hydrogen needs to be stored onsite. The storage conditions (compressed or liquefied) should align with vehicle fuel tank storage.

**Sources**:

# Safety considerations

## Description of situation

The potential implementation of straddle carriers powered by hydrogen.

## Safety considerations

- The fuel system of a hydrogen-fueled straddle carrier must be designed and installed to ensure the safe storage, transport, and use of hydrogen fuel. This may include features such as high-pressure tanks, pressure relief valves, and sensors that detect leaks. There should go specific attention that hydrogen is isolated from oxidizers, hazardous materials and dangerous equipment. Mechanical integrity of the fuel tank, with focus on the effects due to crash impact and associated development of guidelines for first aid response.
- Hydrogen is highly flammable and can ignite easily. Therefore, the design of a hydrogen-fueled straddle carrier must include features to prevent, detect, and extinguish fires that may occur. This may include fire suppression systems, automatic shut-off valves, and redundant safety systems. Further adequate ventilation should be available from the top of the vehicle.
- Hydrogen fuel cells produce high-voltage electricity, which can pose a hazard to workers and equipment. The electrical components of a hydrogen-fueled straddle carrier must be designed and installed to prevent electrical shock and ensure safe operation
- Hydrogen-fueled straddle carriers are subject to regulations and standards that govern the safe design, manufacture, and operation of fuel cell vehicles. Regulatory compliance is essential to ensure the safety of workers and the public.
- Thermal effects on durability, permeability and mechanical integrity of storage tanks.
- Leakage mechanisms of valves and other devices between the storage tank and fuel cell / combustion engine

## Recommendations

- Consider the size of the storage facilities for hydrogen. When above 5 tonnes one needs to adhere to the Seveso guidelines and below this limit one does not. When below the Seveso limit, it all depends on the knowledge and best practices available with the local authorities. As such it is advised to bring them into the conversation at the earliest possible opportunity. It is recommended to still consider SEVESO as a starting point, even below 5 tonnes of storage.

# Breakdown of actions and governance for hydrogen port equipment

# Timeline with key milestones to develop hydrogen fueled port equipment

## Hydrogen fueled port equipment

### Today

- Build strategy for green port equipment
- Bring together stakeholders
- Supplier discussions and developing of value proposition towards them

### 2024

- Execute feasibility studies for hydrogen fueled port equipment
- Investigate hydrogen requirements on-site

### 2025

- Select supplier partner
- Enable hydrogen use in the port area: hydrogen storage, refueling stations and distribution
- Set up pilot project

### 2027

- Assess pilot project
- Use of hydrogen fueled port equipment

# Governance and RACI-matrix for key stakeholders

| Task / Stakeholders | Users port equipment (e.g. terminal) | Port Authority | Green energy producers and distributors | Suppliers port equipment | Municipality | Ministers |
|---|---|---|---|---|---|---|
| Build strategy for green port equipment | A | I | I | C | I | I |
| Bring together stakeholders | A | I | C | C | C | C |
| Supplier discussions and developing of value proposition towards them | A | I | I | C | I | I |
| Execute feasibility studies for hydrogen fueled port equipment | A | I | I | C | I | I |
| Investigate hydrogen requirements on-site | A | I | C | I | I | I |
| Select supplier partner | A | I | I | C | I | I |
| Enable hydrogen use in the port area: hydrogen storage, refueling stations and distribution | A | C | C | I | I | I |
| Set up pilot project | A | I | I | C | I | I |
| Assess pilot project | A | I | I | C | I | I |
| Use of hydrogen fueled port equipment | A | I | I | C | I | I |

## Key takeaways

- **The users of the port equipment (e.g. port terminals) will play a key role** in the way towards climate neutral port equipment
- **Collaboration between various stakeholders is crucial** for the successful role-out of hydrogen fueled port equipment

| RACI | |
|---|---|
| **R - Responsible**<br>The organization who takes action to get the task done. They are responsible for part of the work that needs to be executed. | **A - Accountable**<br>The organization which owns the task or deliverable. They might not get the work done themselves, but they are responsible for making sure it is finalized. To avoid confusion and the diffusion of responsibility, it's best to have one accountable stakeholder per project task. |
| **C - Consulted**<br>The stakeholder who will help complete the task. They will have two-way communication with the people responsible for the task by providing input and feedback over the task completion. | **I - Informed**<br>The stakeholder that needs to be up to date on the task's progress. They will not have two-way communication, but it's essential to keep them informed since they will be affected by the final outcome of the task. |

# Anticipated benefits for hydrogen port equipment

# Anticipated environmental, societal and economic benefits

## Environmental benefits

- Avoid **$CO_2$ emissions**, thereby contributing to reaching the EU's climate objectives, cf. next slide
- Avoid **air pollution** (PM, $NO_x$, CO, $SO_x$)

## Societal benefits

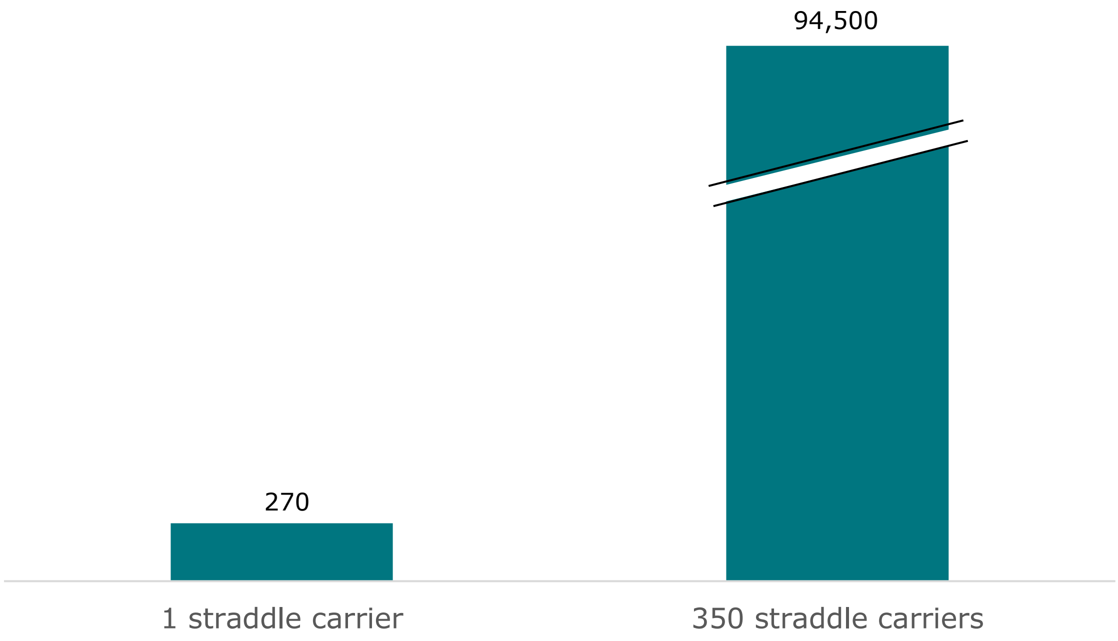
- Improve **citizens health** by reducing emissions and air pollution
- **Job creation** at the terminal will be minimal, however, there will be significant job creation in the whole supply chain of hydrogen
- A **new market** for hydrogen applications
- Put the Port of Antwerp-Bruges and Duisport on the map as a front-running **innovation hub** with national and international exposure
- **Build knowledge** on hydrogen production and usage in end-applications

## Economic benefits

- Avoid **$CO_2$ taxes**
- **Attract business** throughout the $H_2$ value stream in the port area

# Estimated cumulated greenhouse gas emission avoided through the use of hydrogen fueled straddle carriers

Projected cumulated avoided greenhouse gas emissions[1], *estimates (tonnes $CO_2$)*




## Assumptions

- A straddle carrier using diesel emits 54 kg $CO_2$/h
- With a lifetime of 60,000 h (+/- 12 years), using a straddle carrier fueled by hydrogen (fuel cell or internal combustion engine) avoids 3,240-ton $CO_2$ during its lifetime or 270-ton $CO_2$ per year[1]

## Key takeaways

- If all 350 straddle carriers at PSA are using clean hydrogen as a fuel, 94,500-ton $CO_2$ is projected to be avoided per year

Note: (1) This only includes emissions produced while using the straddle carriers. A full lifecycle analysis was not included, this might decrease the environmental benefits slightly due to the lower lifetime of fuel cells and/or internal combustion engines on hydrogen.

# Conclusions and recommendations

# Conclusions and recommendations for hydrogen port equipment

## Conclusions

1. The different technologies are still developing, which brings **a lot of uncertainties** towards the future
2. By performing a TCO analysis based on insights currently available, **battery electric straddle carriers are projected to be the most economically interesting**. However, there is **still a lot of uncertainty** in availability of batteries, reliability of these straddle carriers, the effect of the different charging rate, etc.
3. When looking into **hydrogen fuelled straddle carriers, fuel cells are projected to be the most economically interesting** on the long term. In 2050, they are projected to be 5% more expensive than full electric straddle carriers. Should the efficiency of fuel cells go up to 90% due to significant technological advancements, they can even become more cost efficient than the battery electric option. Next to that, fuel cell straddle carriers could play a role in areas where grid connection is unstable or not sufficiently powerful.
4. **Dual fuel straddle carriers could play a role in the transition** since current straddle carriers can be retrofitted, and they are not dependent on one energy source, which de-risks the investment.
5. Significant environmental, societal and economic benefits can be achieved by investing in carbon neutral port equipment

## Recommendations

1. Continue to invest in research and development
2. Maintain continued contact with different stakeholders so technological advancements can be benefitted from widely
3. Ensure the availability of hydrogen supply to diversify the decarbonization options of port equipment
4. Work towards shared infrastructure for other port equipment

# Case study 3

## The North Tyrrhenian Port Network Authority (Port of Livorno, Piombino and Portoferraio)

# Case study description

# Case study concerning hydrogen decarbonizing shipping in the North Tyrrhenian Port Network

## Location

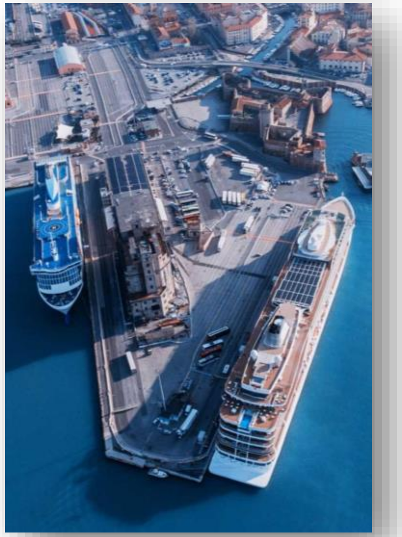
## Partners

- Port of Livorno

*Link with archetypes:* ***industrial***, ***logistics and transport***, ***bunkering*** *and* ***urban.***

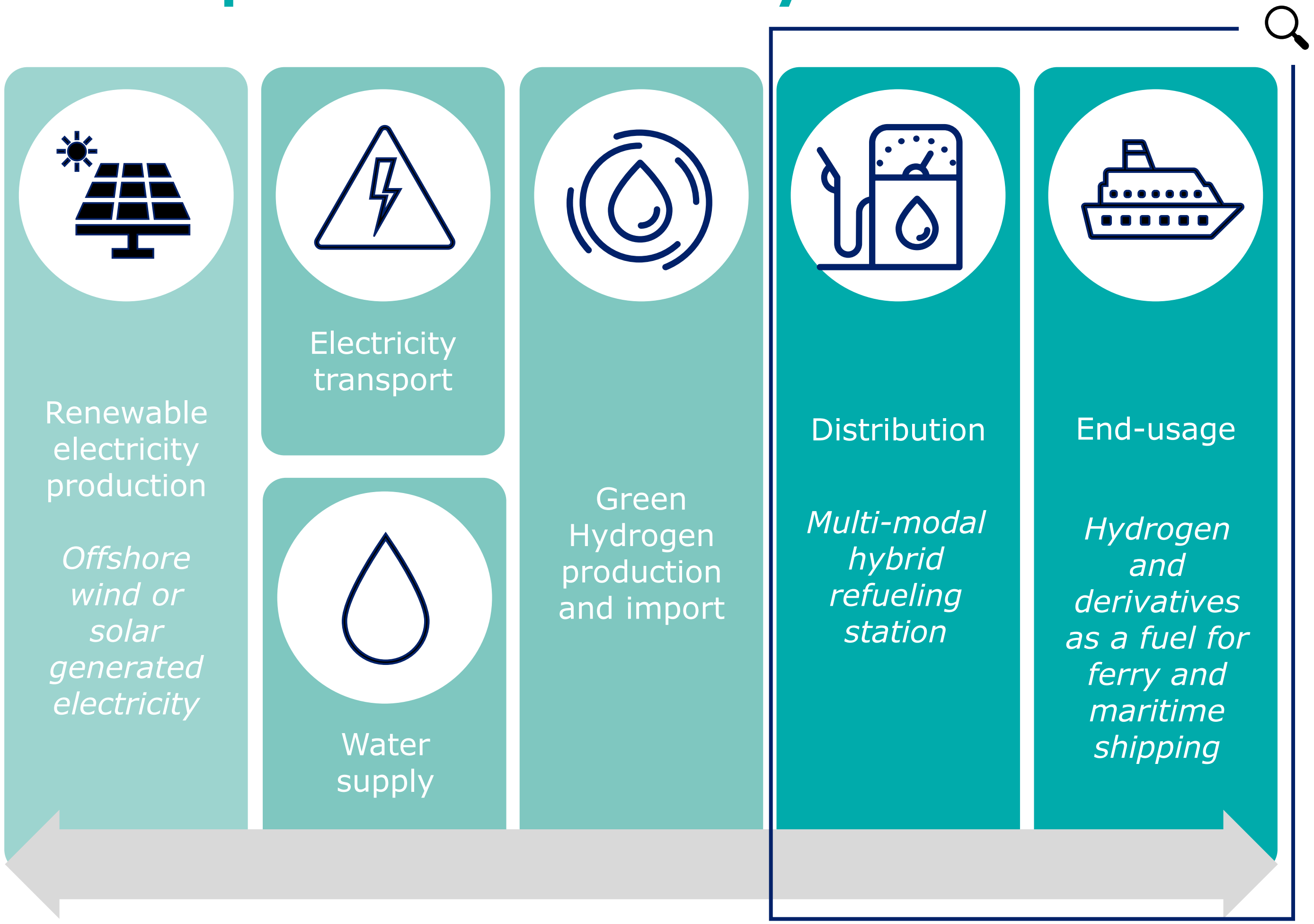
## Topic

**Hydrogen consumption**:



*This case study assesses the viability of decarbonizing shipping through a hydrogen powered ferry and ammonia fueled container ship.*

# The scope of this case study




## Snapshot 2030: hydrogen plan

**Electricity generation**
- In case all hydrogen is produced in Livorno, a capacity of 172.500 MW would be required
- Interporto Toscano Vespucci could partly supply this capacity through solar panels to be developed on premise

**Green H2 production/ import**
- 862,5 tonnes of $H_2$/year should be produced or imported

**Refueling station**
- 144 tonnes of $H_2$/year
- 4.226 tonnes of NH3

**Ferry**
- 23 tonnes of $H_2$/year

**Container ship**
- 16.906 tonnes of NH3

## Scope this case study

- This case study zooms-in on The **business case of hydrogen and ammonia as a fuel for maritime end-applications**; specifically looking at a ferry consuming 23 tonnes of hydrogen per year and a container ship consuming 16.906 tonnes of ammonia on a yearly basis
- This case study is modeled on a pilot-project considering a ferry with the capacity to transport **100 passengers** between Piombino and Portoferraio, a **56 km round trip**.
- The vessel used as example within this case study has a capacity of **1913 TEU**, sailing an average yearly distance of **160.000 kilometers**, transporting containers throughout the Mediterranean. The container ship is assumed to carry 4.226 Mt of ammonia
- Looking at the hydrogen plan in 2030, there will be **an excess supply of hydrogen** (at local level), to be used to satisfy hydrogen demand in the region. Ammonia refueling is dimensioned based on the container ship's storage tank
- Electricity generation and green hydrogen production or import are **out of scope** of this case study; although the import of green Hydrogen is a key strategic focus of the North Tyrrhenian region in order to become a European hydrogen hub

# This case study focuses on the hydrogen ecosystem in the North Tyrrhenian region, in which the port operates as facilitator and enabler

## North Tyrrenian Ports Network

- Ports network located on the western coast of Tuscany, which includes the port of Livorno, Piombino, Capraia, Portoferraio and Rio Marina
- The Interporto Toscano Vespucci serves as the logistics node of the port of Livorno through its storage capacity of 120.000 m² (within a total area of over 2.800.000 m²), making it a crucial lever in realizing the modal shift for the port area

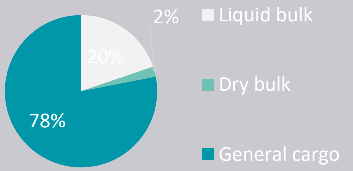
**Overall container traffic**
*2015-2022, historical data ('000 TEU)*


**Tonnes moved**
**39.118.620**

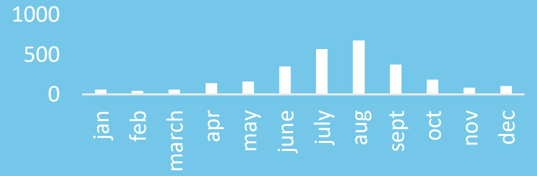
**Ferry passengers**
**9.471.354**

**Port calls**
**35.540**

**Breakdown of tonnes moved**
*2022, historical data (%)*

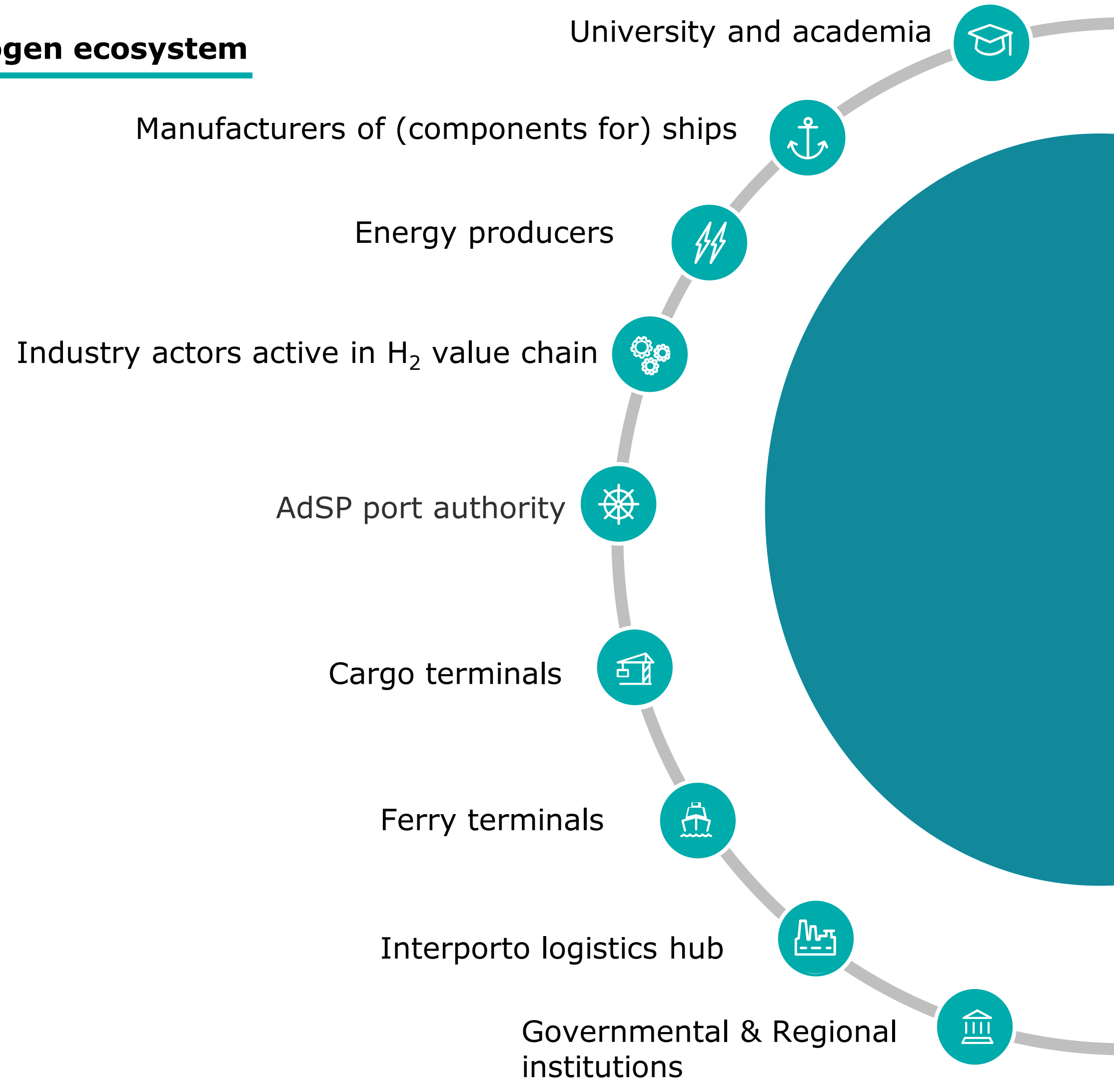



**Breakdown ferry passengers**
*2022, historical data ('000 passengers)*




**Cruise passengers**
**467.863**

## Hydrogen ecosystem



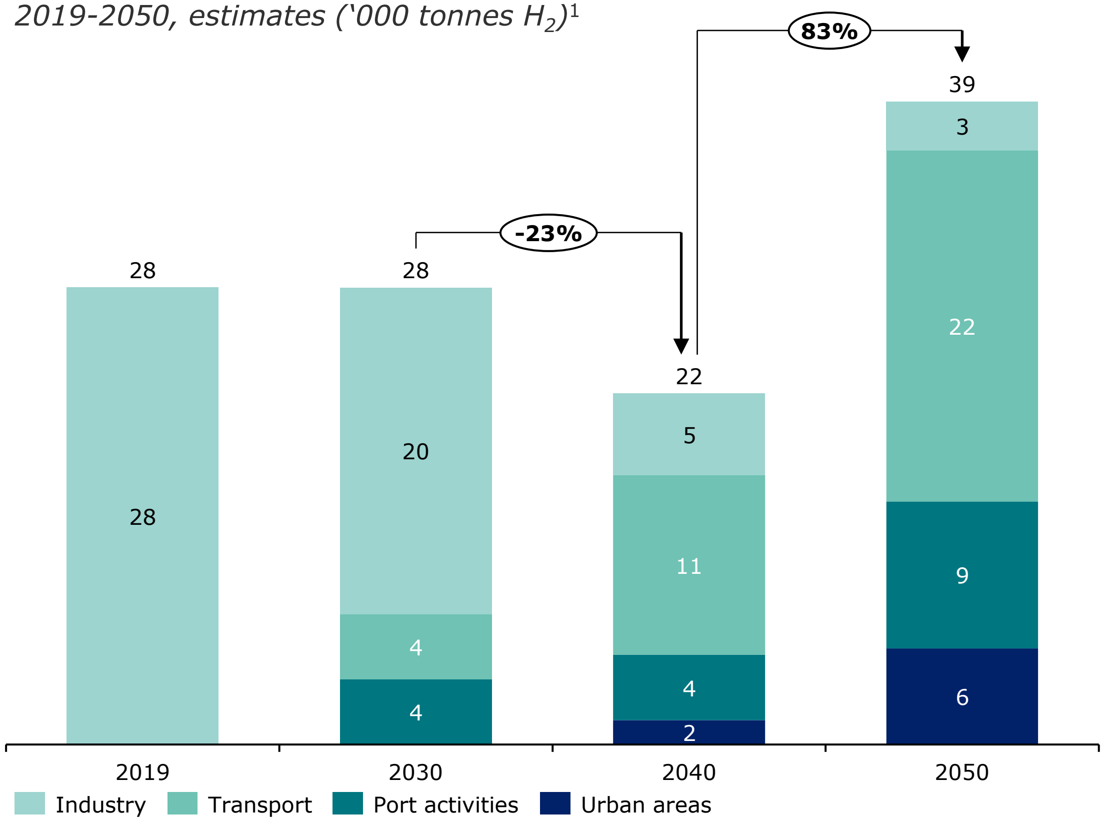



Source: AdSP port authority

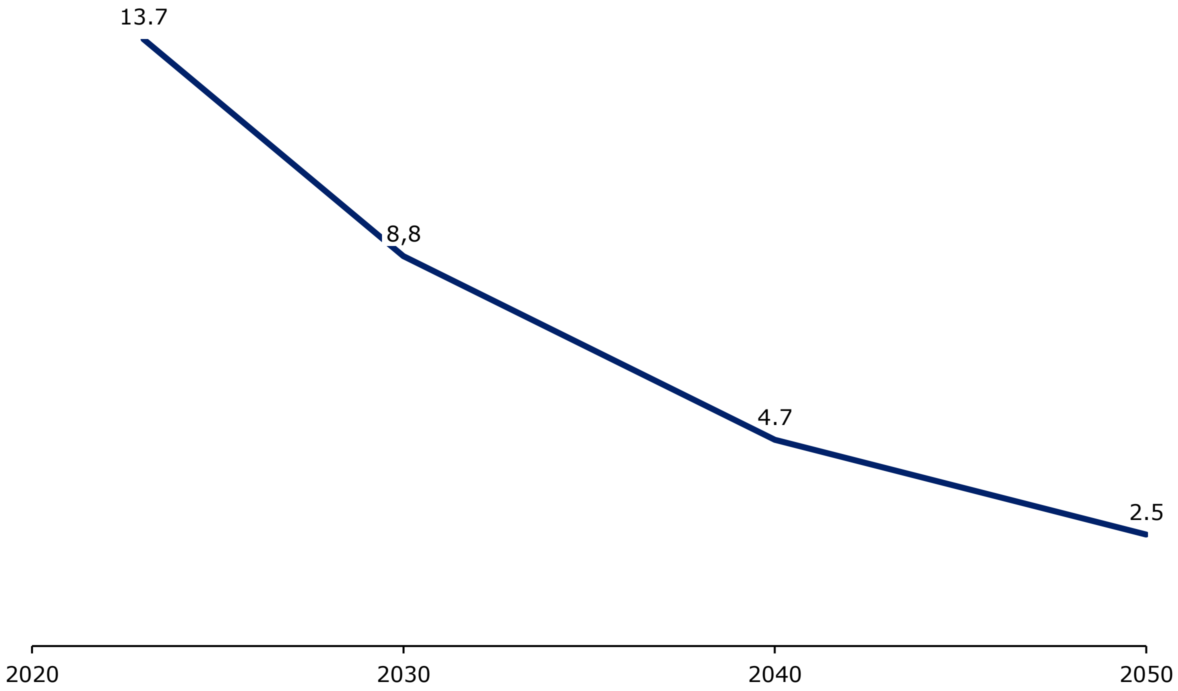
# Economic analysis

# Potential hydrogen demand and price in the North Tyrrhenian region

Hydrogen demand North Tyrrenian region
*2019-2050, estimates ('000 tonnes $H_2$)*[1]




Green hydrogen price North Tyrrhenian region
*2030-2050, estimate (EUR/kg)*[1]



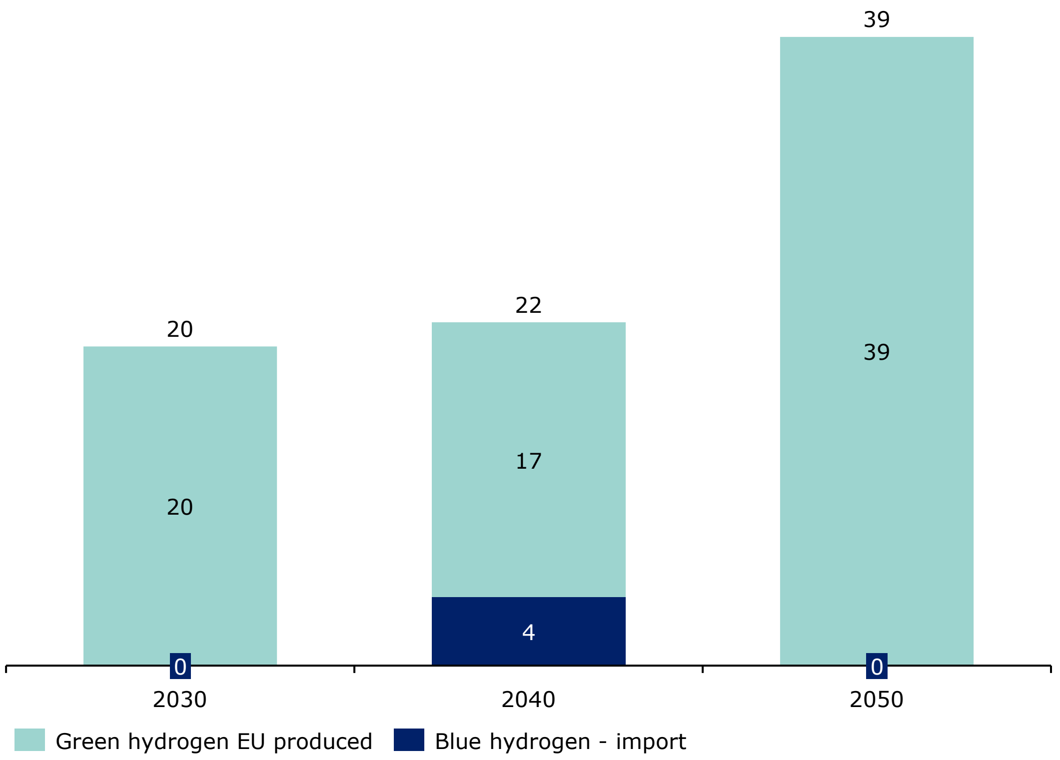

## Key takeaways

- **Hydrogen demand is expected to reach 39.000 tonnes in 2050**, an increase of 40% compared to 2019
- Current hydrogen demand is situated in **mineral oils for hydrogeneration of fossil fuels**. Demand for this specific end-use is expected to **progressively decrease until reaching zero in 2050**. Demand for hydrogeneration is expected to be **partially replaced by industrial heating** demand within the "industry" sector
- The **main hydrogen off-taking sector in the North Tyrenian region is estimated to be transport** with 56% of total demand in 2050
- The **green hydrogen price in the North Tyrrhenian region is currently around 14 EUR/kg**, and will steeply fall towards 2030, to reach a modelled price a bit below 9 EUR/kg in 2030. Towards 2050, the hydrogen price is expected to **further decrease towards 2,5 EUR/kg in 2050**

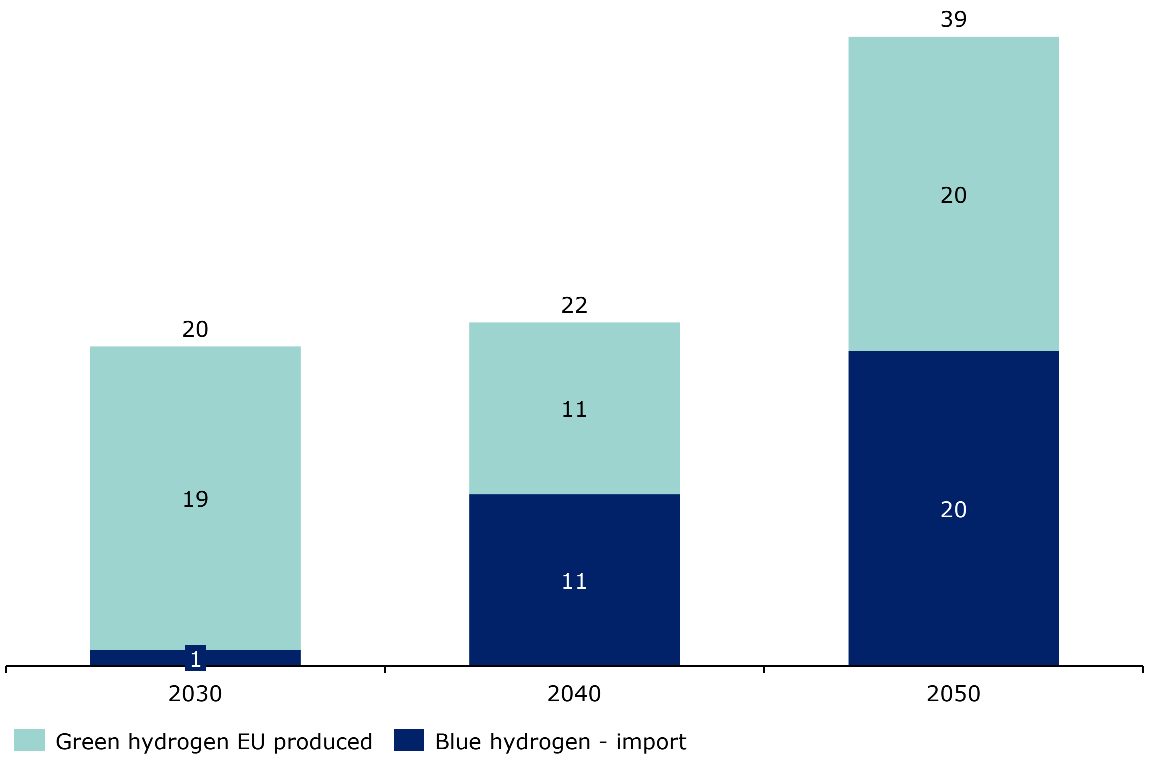
*[1]Study on Hydrogen in Ports and Industrial Coastal Areas (2023), report 1; Hydrogen observatory (2023) and expert interviews*

# Hydrogen supply in the North Tyrrhenian region

Hydrogen supply North Tyrrenian region – base case
*2030-2050, estimates ('000 tonnes $H_2$)*[1]




Hydrogen supply North Tyrrenian region – Increased import scenario
*2030-2050, estimates ('000 tonnes $H_2$)*[1]

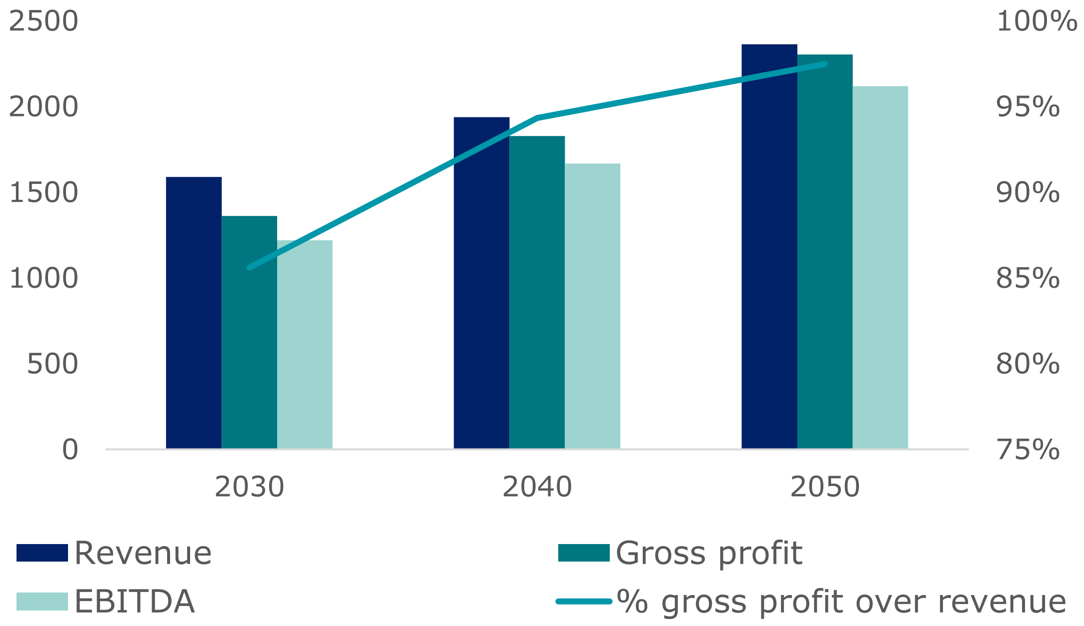



## Key takeaways

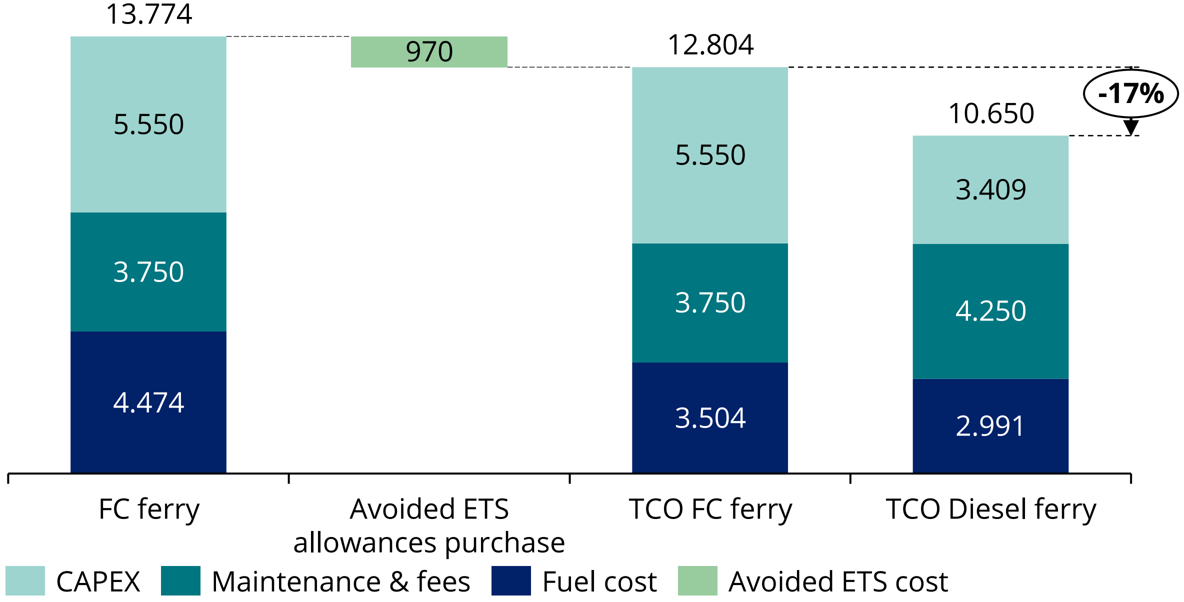
- Local production and import is modeled based on **three main categories**: (1) Attractiveness for wind & solar power generation, (2) Regional maturity of production technologies and (3) Local (renewable) energy consumption. Only hydrogen imported for consumption in the North Tyrrhenian region is included in these figures.
- Hydrogen to satisfy demand of end-applications in Livorno is expected to be **mainly produced in the EU in our base case**. Local production through PV's is estimated to play a major role, as well as imports from Greece. In 2040, around 4.000 tonnes of blue $H_2$ could be imported due to its cost competitiveness with local production
- In an **increased import scenario,** around 50% of hydrogen used would be imported.
- The port of Piombino is ideally positioned to serve as an **energy hub for hydrogen**, connecting imports from LATAM, North Africa and the Middle East to European industrial clusters such as Northern Italy and Bavaria

# Estimated income statement and TCO comparison for a green $H_2$ powered ferry

Income statement overview
*2025-2050, estimates ('000 EUR, %)*




Total cost of ownership comparison
*2025-2050, estimates ('000 EUR)* [1]




*[1]Diesel prices are calculated at 2023 values, and thus don't take into consideration price increases due to potential policy interventions. Avoided $CO_2$ cost is considered, reducing fuel cost of the hydrogen powered ferry*

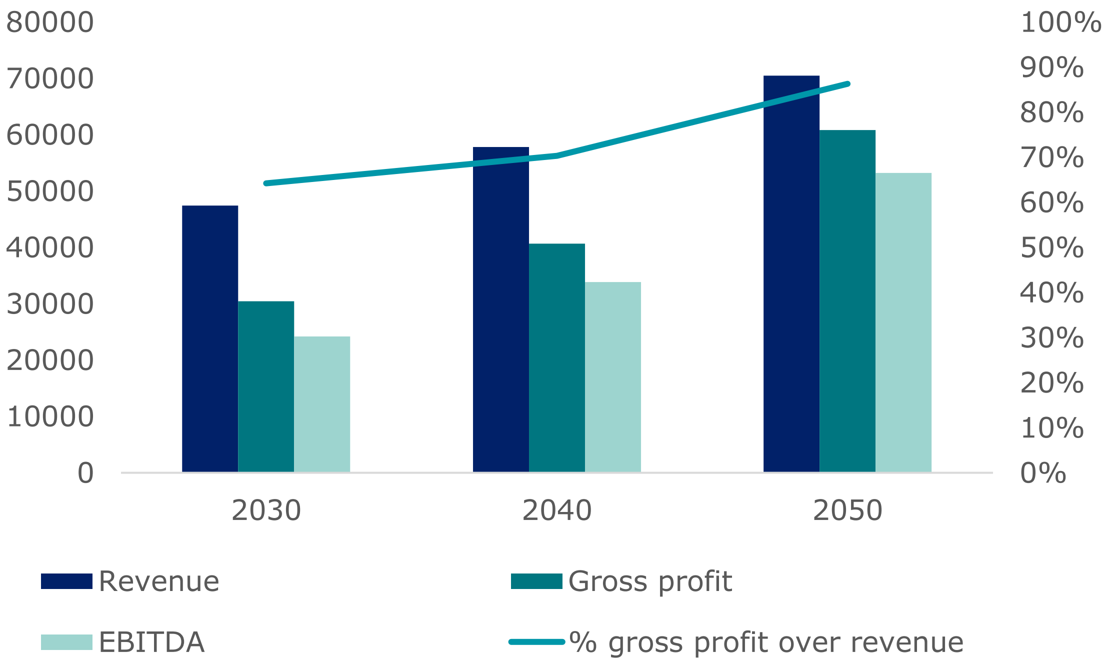
## Key takeaways

- The piloted hydrogen ferry is expected to sail between 2025-2050 with a capacity of 100 passengers at a real ticket price of €16/passenger. Revenues are expected to **steadily increase up to €2.4 million per year by 2050**, taking into account indexed values
- The **gross profit margin increases significantly, with 10% between 2030 and 2040**, due to a decreasing hydrogen price (from €8,8/kg in 2030 to €4,7/kg in 2040)
- Between 2025-2050, a hydrogen ferry in the North Tyrrenian region  is expected to have a **total cost of ownership 17% higher compared to a diesel ferry.**
- There is a **significant fuel cost gap due to inexpensive bunkering prices, and a strong investment gap** (of about 40%), which is only partly compensated for through lower maintenance costs and avoided carbon taxes.

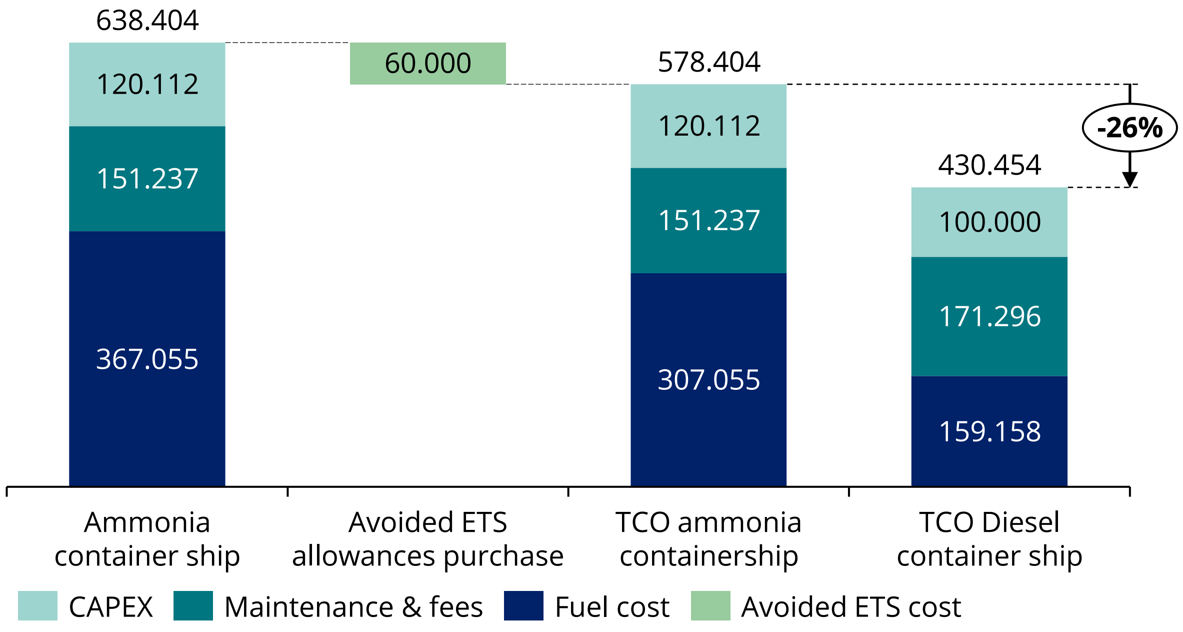
Economic analysis

# Estimated income statement and TCO comparison for a green $NH_3$ fueled containership

Income statement overview
*2025-2050, estimates ('000 EUR, %)*




Total cost of ownership comparison[1]
*2025-2050, estimates ('000 EUR)*



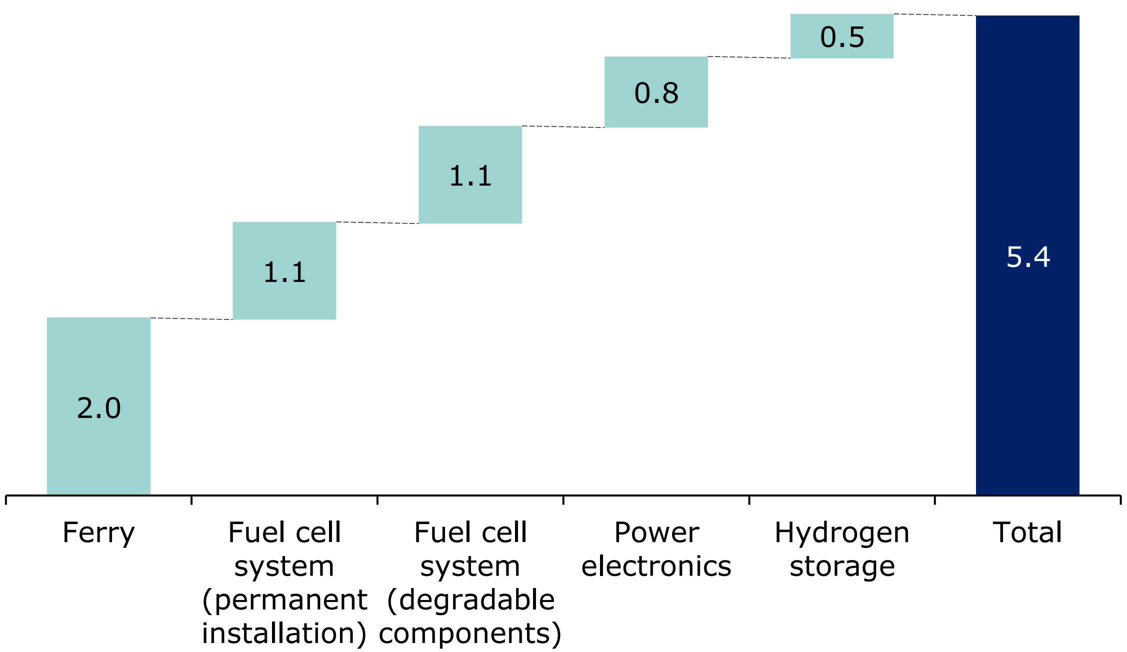

*[1]Diesel prices are calculated at 2023 values, and thus don't take into consideration price increases due to potential policy interventions. Avoided $CO_2$ cost is considered, reducing fuel cost of the ammonia powered container ship*

## Key takeaways

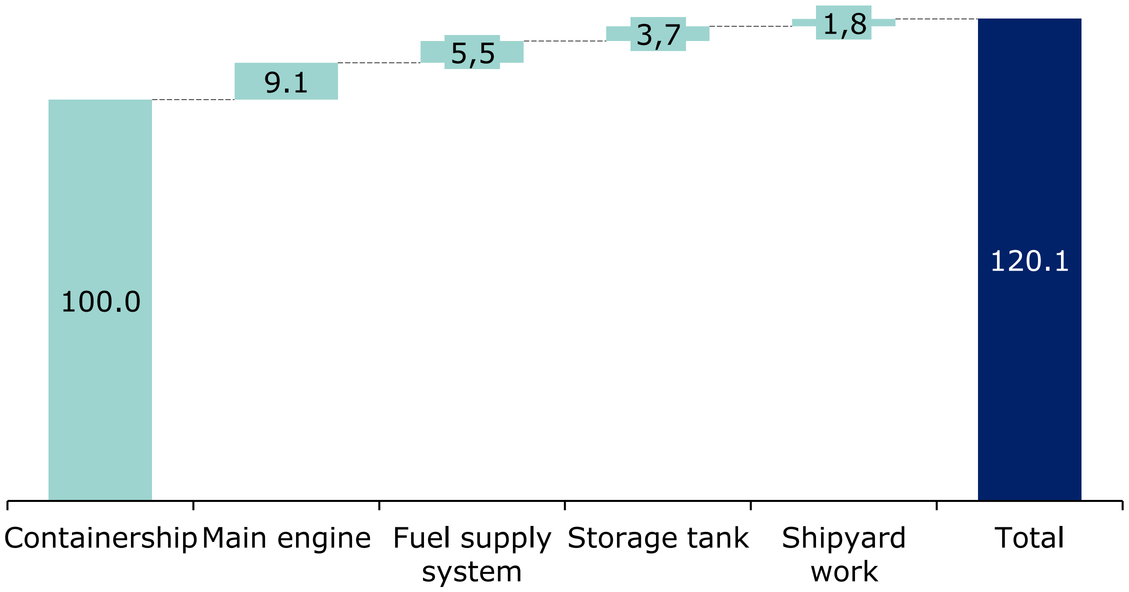
- The piloted container ship expected to sail between 2025-2050 with a capacity of 1913 TEU is estimated to bring in stable revenues, increasing at indexed values to **around 60 million EUR annually by 2050**
- The **gross profit margin** increases slowly up until 2040, to **accelerate towards 2050** due to decreasing green ammonia prices
- The TCO during the 2025-2050 period of an ammonia powered container ship is estimated to be **26% higher than the cost of ownership of a diesel ship**, driven by inexpensive bunkering prices
- Main drivers are the **additional fuel cost** of €5,5 million a year (almost double of bunkering cost) and the **additional CAPEX** for retrofitting the vessel, expected to be around €20 million

# Estimated investment requirements to develop hydrogen and ammonia powered maritime end-applications

CAPEX breakdown retrofitting $H_2$ powered ferry
*2023, estimates (million EUR)*[1]




CAPEX breakdown retrofitting $NH_3$ fueled containership
*2023, estimates (million EUR)*[2]




## Key takeaways

- The current CAPEX investment to retrofit a hydrogen powered ferry with a capacity of 100 passengers is estimated at **5,4 million EUR**, considering the construction of the fuel cell system, hydrogen storage and modifying power electronics.
- The estimated retrofit cost for an ammonia powered containership with capacity of TEU 1914 amounts to **20 million EUR**. This can be broken down to retrofitting the main engine, the fuel supply system, storage tank and the shipyard work.
- Both retrofitting a hydrogen powered ferry and a green ammonia fueled containership requires a **considerable investment, which increases the cost base** of operating these vessels. The **cost of doing nothing however also carries significant risk**, with regulatory pressure increasing (tighter regulations, maritime shipping added to EU ETS, etc.), meaning vessels need to be adapted.




**Source**: *(1) Aarskog et al (2020), (2) Griegstar (2023)*

# Key levers for a favorable IRR are pricing a green premium and public funding

Sensitivity analysis of IRR for $H_2$ powered ferry
*2025-2050, estimates (%)*

| | | Green premium in ticket price | | | | |
|---|---|---|---|---|---|---|
| | 9,74% | 0,00% | 5,00% | 10,00% | 15,00% | 20,00% |
| Capex subsidy | 0,00% | 9,74% | 10,92% | 12,10% | 13,29% | 14,49% |
| | 5,00% | 10,71% | 11,94% | 13,19% | 14,44% | 15,71% |
| | 10,00% | 11,77% | 13,08% | 14,39% | 15,73% | 17,09% |
| | 15,00% | 12,95% | 14,34% | 15,75% | 17,18% | 18,64% |
| | 20,00% | 14,28% | 15,77% | 17,29% | 18,84% | 20,42% |

Sensitivity analysis of IRR for NH3 powered containership
*2025-2050, estimates (%)*

| | | Green transportation premium | | | | |
|---|---|---|---|---|---|---|
| | 8,08% | 0,00% | 5,00% | 10,00% | 15,00% | 20,00% |
| Capex subsidy | 0,00% | 8,08% | 9,54% | 11,00% | 12,47% | 13,97% |
| | 10,00% | 9,71% | 11,31% | 12,92% | 14,55% | 16,22% |
| | 20,00% | 11,67% | 13,45% | 15,26% | 17,12% | 19,04% |
| | 30,00% | 14,10% | 16,14% | 18,25% | 20,44% | 22,72% |
| | 40,00% | 17,26% | 19,70% | 22,25% | 24,95% | 27,80% |

## Key takeaways

- **Due to the low technology maturity of hydrogen and its corresponding risk profile, targeting a 15% Internal Rate of Return (IRR) would be advisable**. If the aim for the project is not primarily a commercially viable project, but rather gathering knowledge and derisking future projects, lower IRR's could be justified
- Pricing a **green premium to customers for sustainable transportation can significantly increase the attractiveness of the business case**. To successfully implement this, the willingness to pay of customers for this green premium should be further investigated
- An alternative lever to improve the business case is to obtain CAPEX subsidies to **bridge the CAPEX gap between clean technologies and their alternatives**
- A third variable which can have a significant impact on the viability of the business case is the **spread in fuel cost between hydrogen or ammonia and diesel prices.** Policy interventions can bridge this TCO gap and thereby spur profitability of the business case, with Contracts for Difference being a potential option in this context

# Constraints

# Technical considerations

## General

The Livorno case focusses on marine fuels. The value chain consist of bunkering and use of hydrogen and hydrogen derived marine fuels.

## Current technology readiness

There are numbers of in-service ships utilizing hydrogen as a fuel. There are currently no in-service ships with ammonia as the primary fuel. Both engines and fuels cells for both fuels are under development.

## Technical considerations to hydrogen and hydrogen-derivatives as marine fuels

- Retrofitting existing vessels for ammonia would require the increase in the size of onboard fuel storage, the installation of a reliquefication unit, bunkering station, tank connection spaces with an ammonia release mitigation system, fuel preparation room, mechanical ventilation and double walled piping, and selective catalytic reduction unit to reduce NOx content in the flue gas.
- Retrofitting existing vessels for compressed hydrogen would require the installation of compressed hydrogen tank bundles, bunkering station, tank connection space with a vent mast system, pressure regulation unit, mechanical ventilation and double walled piping.
- Retrofitting existing vessels for compressed hydrogen would require the installation of cryogenic tanks, reliquefication units, vaporiser, bunkering station, tank connection space with a vent mast system, pressure regulation unit, mechanical ventilation and double walled piping.
- In case the prime mover is an ICE, selective catalytic reduction may be required to reduce the NOx content in the flue gas.
- In case the prime mover is a fuel cell, hybrid battery configuration may be required to deliver the required operational performance.

**Sources**:

# Safety considerations

## Description of situation

The handling and bunkering of all hydrogen-based maritime fuels in a port environment are associated with potential safety hazards (explosion, fire, toxicity) that can have an immediate impact on the physical safety of people, building structures and equipment in the direct proximity.

## Safety considerations

- Assessment of the cyclic thermal and pressure effects on durability and integrity of storage tanks and hoses during fueling.
- Design considerations and integrity of hoisted (swappable) fuel containers to survive unintentional drops from the swapping cranes in case of hydrogen.
- Ventilation considerations in terms of position of vent pipes relative to living quarters and height above deck; installation of gas detectors in fresh air ventilation to accommodation and working spaces.
- The location of the bunkering infrastructure in relation to the safety distance required; distances differ per phenomenon - toxicity (ammonia), overpressure (explosion) and heat radiation (explosion/fire)
- Determination of scale of the operations in light of the more stringent guidelines of SEVESO III (5 tonnes limit).
- The location of the storage tank on the ship with respect to the safety of the personnel aside from the location of the vents (boil-off) and ventilation in relation to both personnel and external safety.
- The development of low volume safety barriers around the onboard storage facilities from the rest of the equipment.
- With ammonia, the tuning of the engines (direct combustion) such that the emissions of ammonia to the environment, especially at cold start, are below the threshold values. In this respect the potential combustion byproduct N2O needs to be considered, which is a strong greenhouse gas.
- The mechanical integrity of storage tanks in relation to crash scenarios of the ships.
- The compatibility of the materials in contact with LH2 and (liquid) ammonia.

## Recommendations

- Consider the regulations for the navigation of the Rhine (RPR) from the CCNR (Central Commission for the Navigation of the Rhine) as they are being adapted to allow vessels to use hydrogen as fuel.
- Ensure unambiguous maintenance protocols for pipelines carrying the alternative fuels, especially those pipelines on the seabed.
- Ships have been retrofitted to burn ammonia instead of conventional fuels. Lessons learned from the respective shipowners may provide valuable information regarding potential emissions of ammonia through the process of bunkering and sailing.
- During the design of the ships, consider the potential impact of ammonia on the aquatic life, the environment and people for different spill scenarios. Also consider the difference between liquid and gaseous ammonia in this respect.

# Breakdown of actions and governance

# Timeline with key milestones to turn North Tyrrhenian area in a hydrogen hub and develop hydrogen end-use in the vicinity of the port

**Pilot projects on hydrogen in maritime end-applications**

**Today** — **2024** — **2025** — **2026** — **2027**

| | | | | |
|---|---|---|---|---|
| Monitor and cluster ongoing and expected hydrogen initiatives in vicinity of the port | Secure (public) funding | Initiate close contact with permitting authorities, to ensure smooth permitting processes | Develop hydrogen and derivatives distribution infrastructure | Upscale pilot projects on hydrogen end-usage |
| Develop hydrogen strategy for Livorno based on three strategic axis (develop hydrogen valley, become import hub and build infrastructure) | Build coalition of the willing among Italian ports to contribute to national hydrogen strategy with chapter on seaports | Develop renewable energy capacity (solar and wind) and connect to the grid | Assess the role pilot projects play in kick-starting the hydrogen valley of Livorno | Assess the need to further scale up hydrogen and derivatives imports |
| Bring together hydrogen ecosystem through various events | Liaise with governmental actors (such as ministry of economic development) for private actors | Upscale electricity distribution infrastructure | | Assess the need to further scale up distribution infrastructure |
| Execute technical and economical feasibility studies for hydrogen end-usage | Develop distributed knowledge center to compare clean technologies for end-applications | **Execute pilot project on $H_2$ or derivatives as maritime fuel** | | Assess need to further scale up hydrogen production |
| Define dedicated areas for renewable energy and hydrogen production | Develop matching tool to enable cross-value chain collaboration and facilitate sound investment planning | Execute pilot projects throughout hydrogen value chain | | |
| Development of concrete business cases for H2 or derivatives as maritime fuel, especially for ferry connections | Develop hydrogen and derivatives import infrastructure for green and blue $H_2$ | Develop local hydrogen production pilot plant | | |

# Governance and RACI-matrix for key stakeholders

| Task / Stakeholders | AdSP port authority | University & academia | Industry actors $H_2$ value chain | Ship manufacturers | Terminals & logistics | $H_2$ end-users | Energy producers & distributors | National institutions | Regional institutions |
|---|---|---|---|---|---|---|---|---|---|
| Monitor $H_2$ initiatives | A | C | C | C | C | C | C | C | C |
| Develop hydrogen strategy | A | C | C | C | C | C | C | C | A |
| Ecosystem building | A | C | C | C | C | C | C | C | C |
| Feasibility studies | A | R | R | R | I | A | I | I | I |
| Define dedicated RE & $H_2$ production areas | A | C | I | I | I | I | C | C | A |
| Business cases $H_2$ as maritime fuel | C | C | R | R | I | A | I | I | I |
| Secure public funding | R | I | I | C | I | A | I | C | R/A |
| Build coalition of the willing among ports | A | C | C | C | C | C | C | C | C |
| Liaise with governmental actors | A | I | C | C | C | C | I | C | C |
| Distributed knowledge center | A | C | C | C | I | C | I | I | I |
| Develop import infrastructure | R/A | I | R | I | I | C | A | C | A/C |
| Permitting contact | A | I | I | I | I | R | R | R | R |
| Develop renewable energy capacity | A | I | C | I | I | C | A | C | C |
| Upscale electricity distribution infrastructure | C | I | I | I | I | C | A | I | I |
| Pilot project on $H_2$ as maritime fuel | C | C | C | C | I | A | C | I | I |
| Pilot projects throughout $H_2$ value chain | C | C | C | C | I | A | C | I | I |
| Develop local $H_2$ production plant | R/A | I | R | I | C | C | A | C | A/C |
| Develop distribution infrastructure | R/A | I | R | I | C | C | A | C | C |
| Assess impact of pilot projects | A | C | C | C | C | R | R | C | C |
| Upscale pilot projects | C | I | R | R | I | A | C | I | I |
| Assess scale-up of $H_2$ production, import and distribution | C | C | C | I | C | C | A | C | C |

## Key takeaways

The AdSP port authority can move the needle in the hydrogen domain through 3 primary activities:

- Set out a common sense of direction through the **development of a common hydrogen strategy** with prioritized clusters based on the as-is economic fabric of the region
- Play a facilitating role in bringing together the relevant stakeholders through various shared forums to **enable knowledge sharing throughout the ecosystem**, and help ensure continuous contact and collaboration
- Act as **distributed knowledge center** through support of (feasibility) studies and pilot projects, and act ac **contact center** for government-related procedures (e.g. permitting)

## RACI

**R - Responsible**
The organization who takes action to get the task done. They are responsible for part of the work that needs to be executed.

**A - Accountable**
The organization which owns the task or deliverable. They might not get the work done themselves, but they are responsible for making sure it is finalized. To avoid confusion and the diffusion of responsibility, it's best to have one accountable stakeholder per project task.

**C - Consulted**
The stakeholder who will help complete the task. They will have two-way communication with the people responsible for the task by providing input and feedback over the task completion.

**I - Informed**
The stakeholder that needs to be up to date on the task's progress. They will not have two-way communication, but it's essential to keep them informed since they will be affected by the final outcome of the task.

# Anticipated benefits

# Anticipated environmental, societal and economic benefits in the North Tyrrenian region

## Environmental benefits

- Avoid **$CO_2$ emissions**, thereby contributing to reaching the EU's climate objectives
- Avoid **air pollution** (O3, $NO_2$, $SO_2$) also in the context of Emission Control Area (ECA) and in the prospective of MED-ECA.
- Improve living conditions of **marine life (PELAGOS project)** and water quality by reducing spillage of fuels
- Contribute to the **Mission Ocean and Waters Charter** by protecting marine ecosystems, preventing pollution of the ocean and developing a carbon neutral blue economy
- **Lead by example**, fostering other stakeholders to take climate action

## Societal benefits

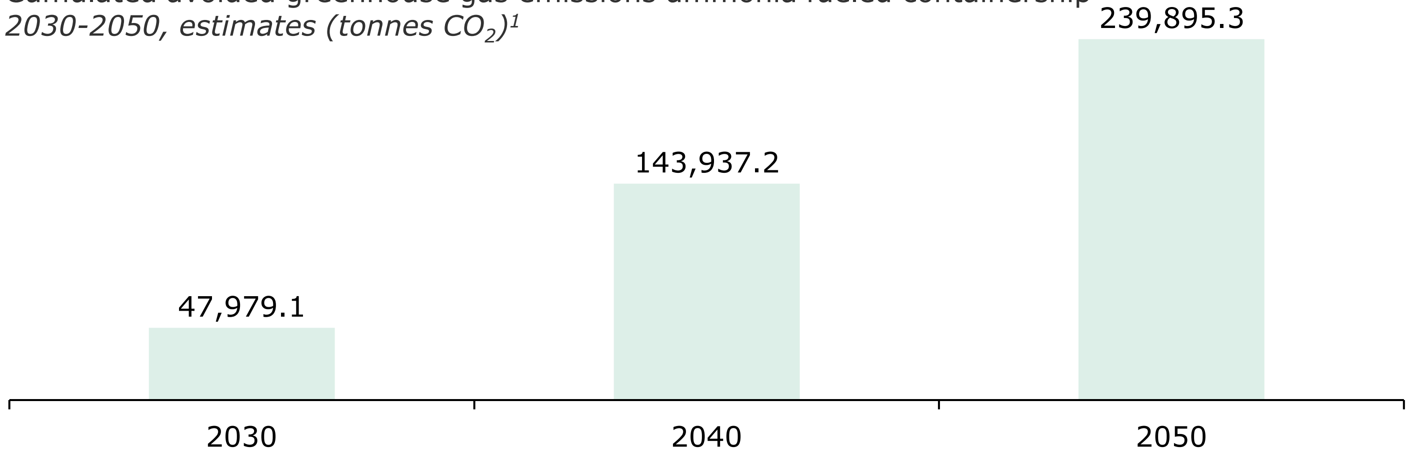
- Improve **citizens health** by reducing emissions and air pollution
- **Repurpose existing manufacturing assets** towards clean technologies
- Build on existing knowledge and capabilities to strengthen North Tyrrhenian region's position as **innovation hub** to export knowledge and technologies
- **Reskill current industrial workforce** to play a vital role in developing clean technologies
- Strengthen **hydrogen and logistics knowledge** at University of Pisa through pilot projects
- Develop the North Tyrrhenian region as a key **energy import hub** to play a facilitating role in supplying energy to the Italian and European hinterland

## Economic benefits

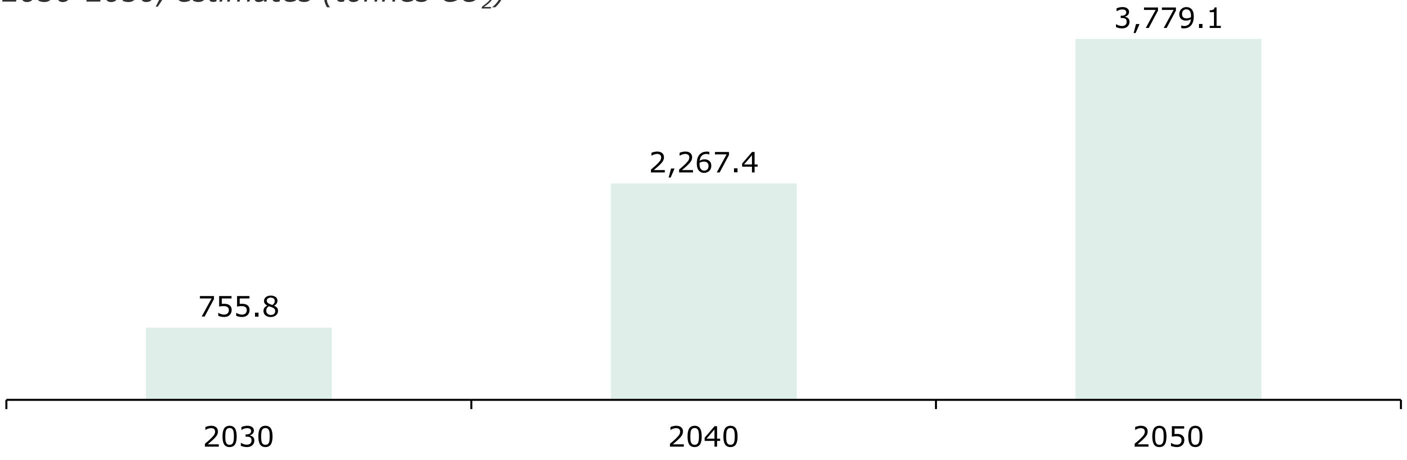
- Attract (foreign) **financial investments** in the local economy
- Reduce **environmental taxes**
- **Attract and retain talent** to realize the ambition of creating a hydrogen valley
- Build on already-existing capabilities to provide **clean technology solutions throughout the hydrogen value chain** (production, consumption and distribution)
- **Reinvent legacy industry** by developing a green industry cluster to sustain economic growth in the North Tyrrhenian region
- Build strong **trade relationships** with countries outside of the EU through hydrogen imports
- Create direct and indirect **jobs**

# Estimated cumulated greenhouse gas emission avoided through a hydrogen powered ferry and ammonia fueled container ship

Cumulated avoided greenhouse gas emissions ammonia fueled containership
*2030-2050, estimates (tonnes $CO_2$)*[1]




Cumulated avoided greenhouse gas emissions hydrogen powered ferry
*2030-2050, estimates (tonnes $CO_2$)*[2]




## Key takeaways

- Powering one containership with a capacity of 1913 TEU's with green ammonia would cumulatively **avoid almost 240.000 tonnes of $CO_2$ emissions by 2050**
- This leads to an **average emission reduction of 59 kg of $CO_2$ per km sailed**
- A green hydrogen powered ferry with a capacity of 100 passengers would cumulatively **avoid almost 4.000 tonnes of $CO_2$ emissions by 2050**
- Which details out to an **average emission reduction of 0,06 kg of $CO_2$ per passenger per km**

[1]*UK Department of Business, Energy and Industrial Strategy (2023)*

[2]*Grieg Star (2023)*

# Conclusions and recommendations

# Conclusions and recommendations for hydrogen production in Klaipeda

## Conclusions

1. Projections show the investments that need to be made to retrofit a ferry and containership towards clean fuel technologies are significant, **increasing the cost base of operating these vessels.**

2. The **cost of doing nothing** should also be considered, with rising regulatory pressures, reflected in the maritime shipping industry being gradually added to the EU Emission Trading System (gradually initiated in 2024, to completely fall under ETS as of 2026).

3. In order to mitigate this higher initial investment cost, a **green premium** can be charged to customers for providing zero-emission transport. Another option is mobilizing public funding to kick-start decarbonization efforts in a hard-to-abate sector through the development of pilot projects. Moreover, policy measures reducing the price gap between green- and fossil-fuels would also significantly improve the business case and bridge the TCO gap. Contracts for Difference could be a potential option

## Recommendations

### The North Tyrrhenian area as a hydrogen hub

1. **Refine and execute on hydrogen strategy** by mapping current hydrogen capabilities along the three strategic axes defined: developing a hydrogen valley, transitioning Piombino to a clean energy import hub for the European hinterland and developing zero emission logistics. Based on this assessment, a to-be should be distilled to serve as a direction of travel

2. Further develop **hydrogen ecosystem** - The North Tyrrhenian region can already rely on various startups, spin-offs, multinationals and academic research centers active throughout the hydrogen value chain. These different players should be brought together to facilitate exchange of knowledge and to foster collaboration and innovative tools to match, connect and optimize the various elements of the hydrogen-related value chain.

3. Position North Tyrrhenian as **hydrogen import hub** - One of the no-regret investments identified in this study is the development of infrastructure to enable maritime imports from the middle east to southern and central-Europe. The port authority should facilitate this by establishing relationships with H2 exporting ports as well as strengthen the network of H2 importing ports.

### Hydrogen end-applications

4. **Strengthen knowledge build-up** – the port authority can play a key-role in building up knowledge by supporting pilot projects and setting up (international) knowledge distribution platforms, to help companies make the right decisions when selecting clean technologies. In order to do so, the port authority can further build on existing initiatives, such as the ECA4MED Knowledge Center

5. **Act as liaison to get government support** – Guide companies through the administrative processes linked to applying for public funding and getting the right permits

# Case study 4

## Port of Rotterdam & Port of Pecém

# Case study description

# Case study concerning hydrogen import to the Port of Rotterdam produced in the Port of Pecém in Brazil

## Location

## Partners

- Port of Pecém
- Port of Rotterdam

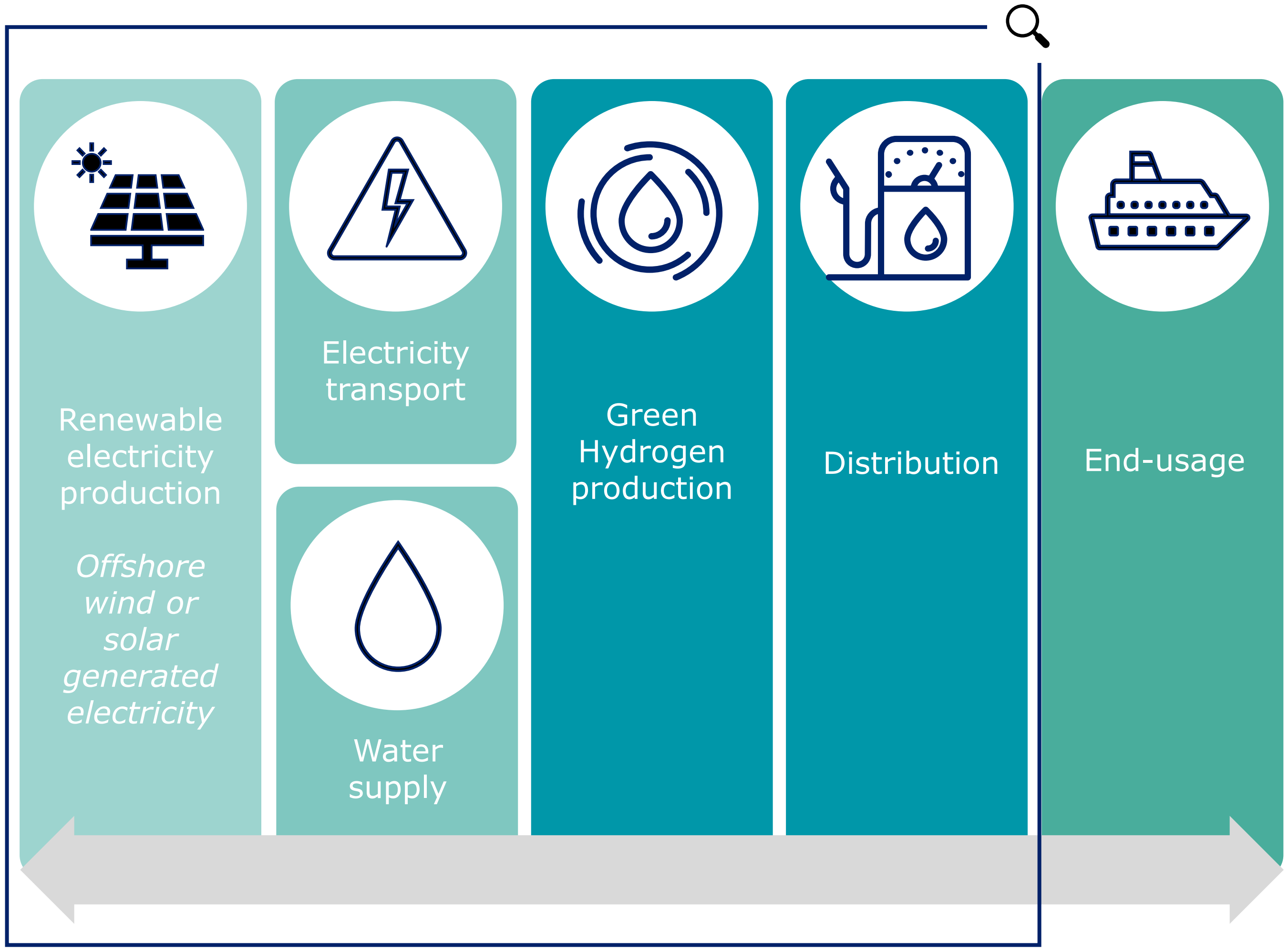
*Link with archetypes:* ***industrial****,* ***logistics and transport****,* ***bunkering*** *and* ***urban.***

## Topic

**Hydrogen import**:

*This case study examines the practical details of importing hydrogen produced in the Port of Pecém to the Port of Rotterdam.*

# The objectives and scope of this case study




## Objectives and scope

**Objectives:**

- The objective of this case study is to assess the practical implications, readiness, and next steps required to import hydrogen from the Port of Pecém in Brazil to the EU.

**Scope:**

- Recognizing the high potential of hydrogen in the transition to a climate-neutral energy system, the Port of Rotterdam is exploring both local production and import to meet the demand. The Port of Pecém is strategically located in Brazil, with abundant sun and wind energy, access to water, high standard universities, and a well-educated labor force.
- The case study covers the entire value chain from hydrogen production in Brazil to its consumption in the EU.
- While considering replicability to other ports, the study does not delve into detailed local legislation. Also, technical details on exact capacity requirements for an ammonia cracker are not included, but investments required for a certain capacity are taken into account.

# Partners of the case study – Port of Rotterdam

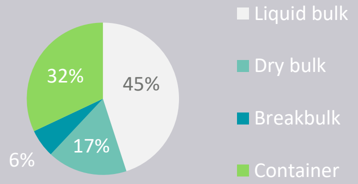
## Port of Rotterdam

- The Port of Rotterdam is **one of the largest ports in Europe**. Located in the city of Rotterdam in the Netherlands, the port handles a wide range of goods.
- The goal of the Port is to **import 20 Mt of hydrogen** by 2050, while also producing 2 Mt locally. This will help to meet the growing demand for clean energy and reduce reliance on fossil fuels. The port has several **innovative sustainability initiatives**:
    - The Port is developing a 2 GW conversion park, where the next project in line is **H2-Fifty**. This project aims to develop a 250 MW electrolyser by 2025.
    - To facilitate the transportation of the hydrogen, there will be an open access **backbone** through the port. This will help to ensure that the hydrogen can be transported safely and efficiently.
    - The creation of **RH2INE**, a climate-neutral transport corridor between Rotterdam and Genue. This will help to reduce emissions and pave the way for a more sustainable transportation industry.

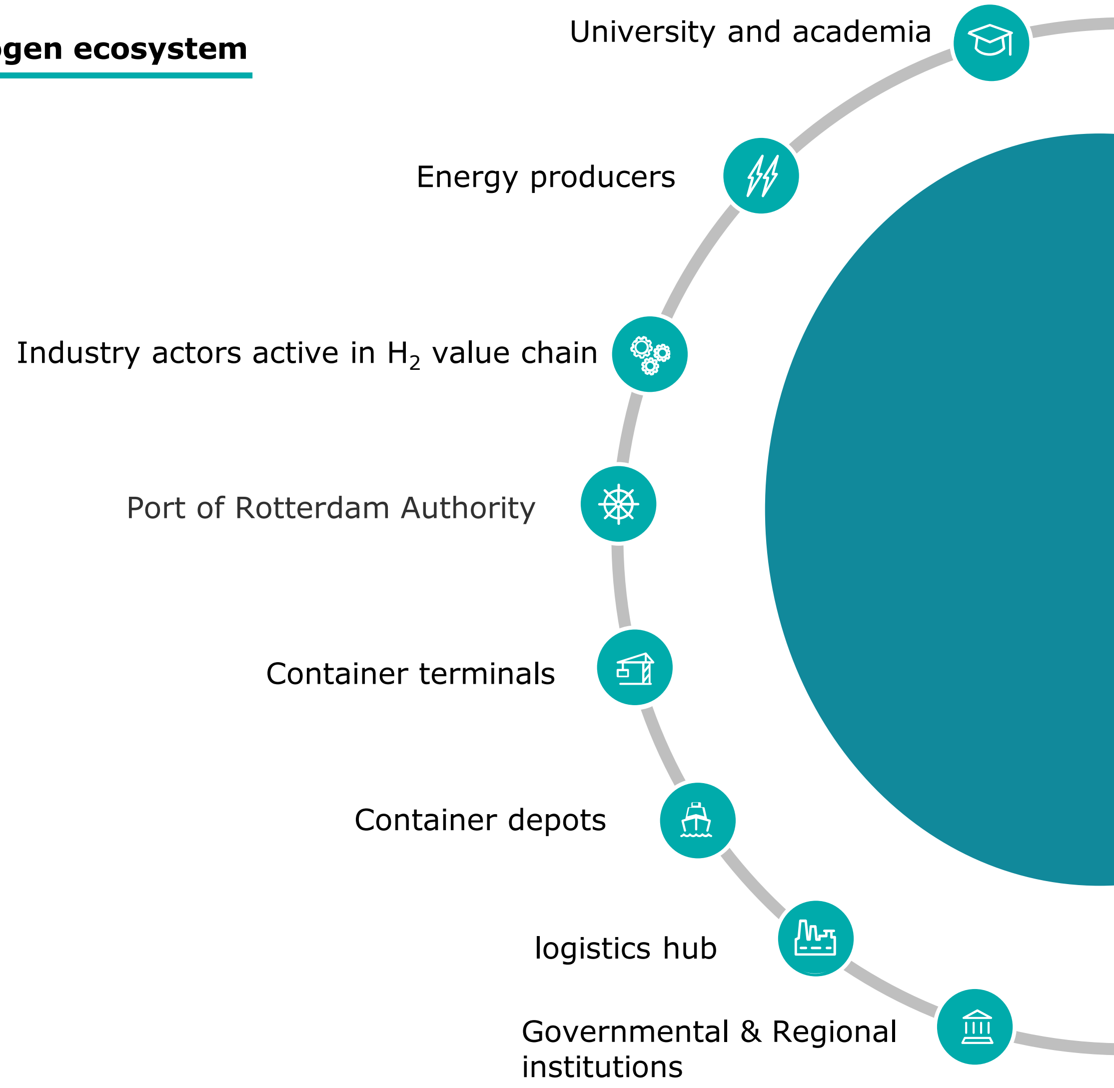
**Throughput**

**14 million TEU or 469.4 million tons**

**Breakdown of tonnes moved**
*2022, historical data (%)*




## Hydrogen ecosystem



# Partners of the case study – Port of Pecém

## Port of Pecém

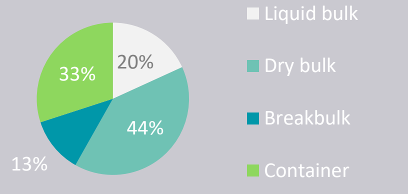
- The Port of Pecém is a **major seaport** located in the state of Ceará, Brazil. It is serving as a gateway for international trade in the Northeast region of Brazil as it is strategically located on the Atlantic coast.
- The Port of Pecém is **equipped with modern facilities and infrastructure** to handle a wide range of cargo, including containers, liquid bulk, dry bulk, and general cargo. In recent years, the port has undergone significant expansion and investment.
- The port actively **engages in all parts of the green hydrogen value chain**, including possible investments to facilitate production for export, while local offtake is a secondary long-term objective.
- The port has **19,000 ha industrial area for development** with 3 use cases: 1) export of green H2, 2) local consumption of green H2 for steel, cement fertilizer industry and future demand categories, and 3) service center for green H2 and renewable energy producers
- The port has a **potential of 880 GW onshore and 1,335 GW offshore wind energy**, plus solar production and the use of effluent water from the city

**Throughput**

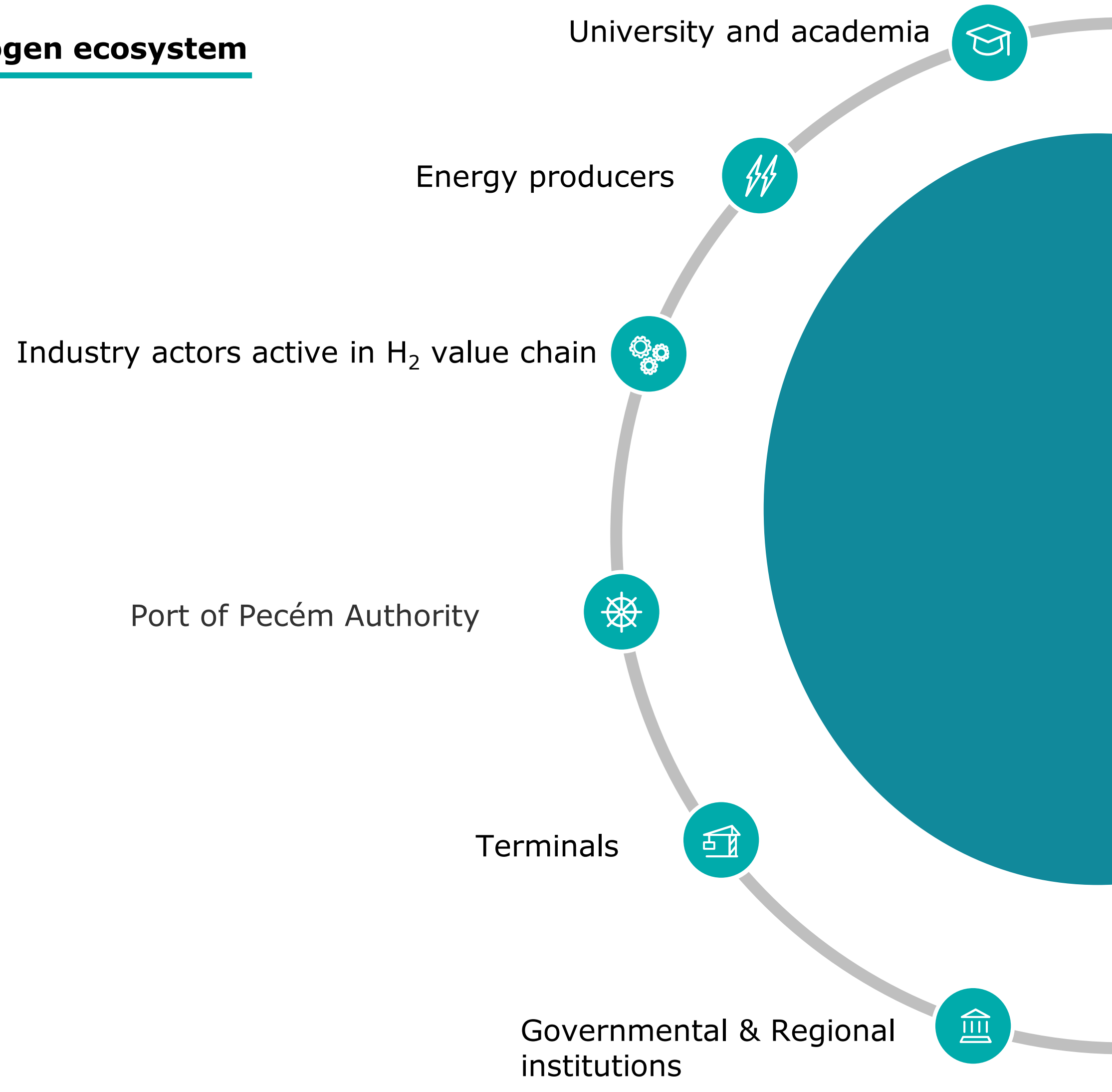
**417 thousand TEU**

**Breakdown of tonnes moved**

*2022, historical data (%)*

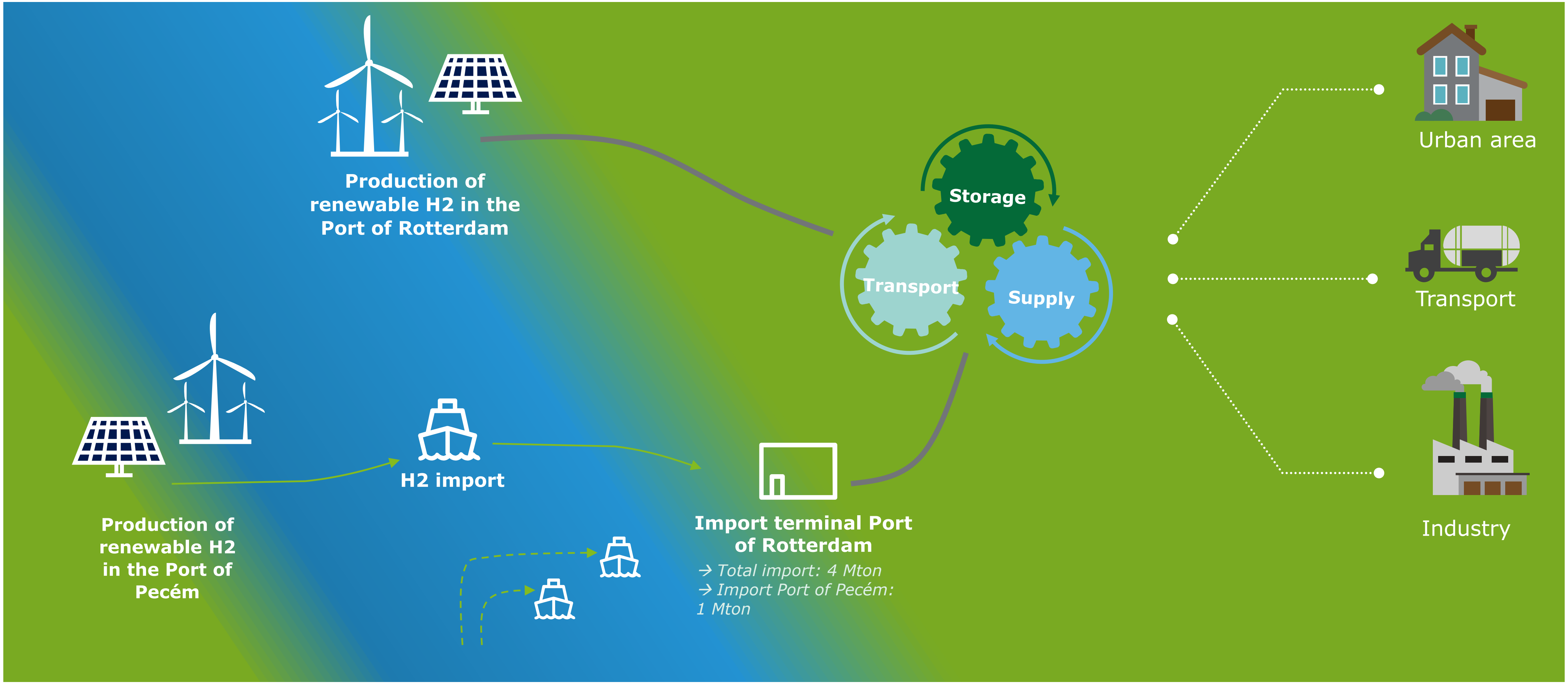



## Hydrogen ecosystem



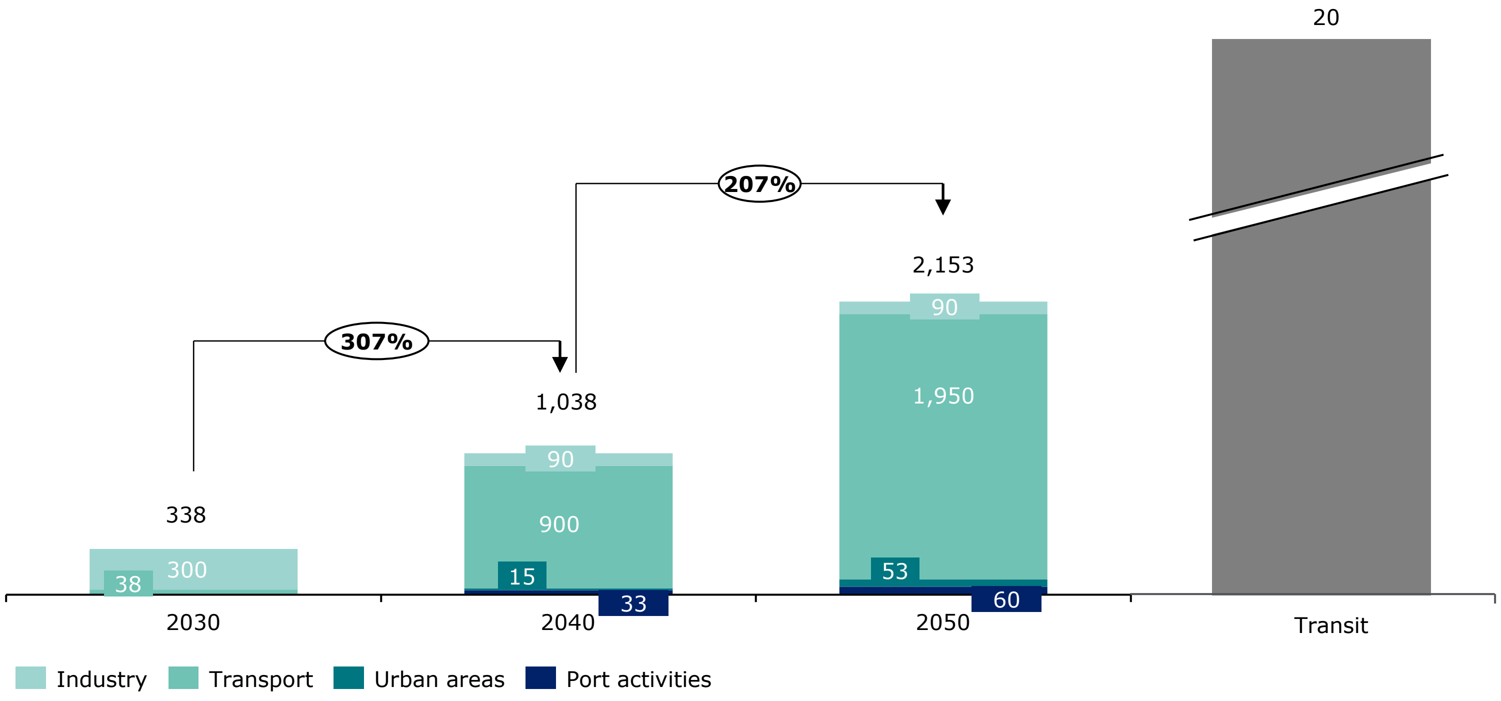
Case study description

# Case study value chain



# The Port of Rotterdam is projected to have a hydrogen demand of up to 2.2 Mt, and due to its transit role, it is expected to handle even higher volumes of hydrogen passing through the port

Hydrogen demand port of Rotterdam
*2030-2050, estimates ('000 tonnes $H_2$)*[1]




## Key takeaways

- By **2030**, the total hydrogen demand is projected to reach up to 0.3 Mt and by **2050 up to 2.2 Mt**. The largest demand is expected from international shipping (up to 1.9 Mt), with additional demand projected for industrial heating and port equipment and potentially for urban areas.
- **Ammonia** may be used as a form of hydrogen consumption for **international shipping**.
- Next to the projected volumes for hydrogen demand in the port of Rotterdam, the port has an important **transit role**. The Port of Rotterdam itself anticipates a green hydrogen throughput of **up to 20 Mt** by 2050[1,2].
- **REPowerEU** is expected to accelerate the scaling up of hydrogen demand

**Sources**: (1) https://www.enlit.world/hydrogen/port-of-rotterdam-ups-2030-hydrogen-supply-to-4-6mt/. (2) https://www.portofrotterdam.com/sites/default/files/2021-06/waterstofvisie-havenbedrijf-rotterdam-mei-2020.pdf

# The Port of Rotterdam envisions to import 4 Mton of H2 by 2030 coming from 4 to 5 projects around the world. The Port of Pecém predicts a production potential of 7.9 Mt ammonia from green hydrogen per year by 2030

Hydrogen plans by the ports:

- The **Port of Rotterdam** plans to import around 4 Mton of hydrogen by 2030. For this it is looking at 4 to 5 main projects around the world. Import from the Port of Pecém could be envisaged to represent up to 1 Mton by 2030.
- The **Port of Pecém** has 20 agreements in place for further development and studies, and 8 agreements in engineering & feasibility studies, MoU and/or reservation contracts to produce hydrogen

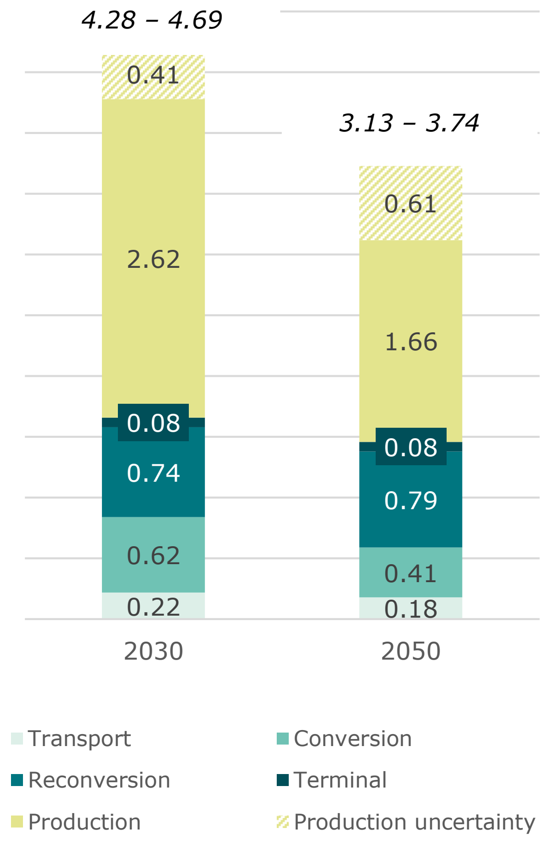
*Projected ammonia production from clean hydrogen (ton/year)*

| | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|
| | **100,000** | **400,000** | **2,650,000** | **4,500,000** | **5,800,000** | **6,200,000** | **7,900,000** |
| Export: | | | 97,000 | | 331,000 | 896,000 | 1,638,000 |

# Economic analysis

# The LCOH from the Port of Pecem to the port of Rotterdam is projected to be close to 3 EUR/kg by 2050 for the cheapest option

Levelized cost of hydrogen from Port of Pecém to Port of Rotterdam
*2030 – 2050, EUR/kg*




## Levelized cost of hydrogen (LCOH)[1]

**Production**:

- Brazil can become one of the most **competitive places** in the world **to produce green hydrogen** due to the country's **abundant renewable energy** sources. The country can be expected to be a significant player in the global H2 export market
- The PV capacity factor is assumed at 20%, the onshore wind capacity factor at 33%
- The production range of green hydrogen is projected to be **2.62 – 3.03 EUR/kgH2** in 2030 and **1.66 – 2.27 EUR/kgH2** in 2050, depending on the source used.

**Transport:**

- The distance between the Port of Pecém and the Port of Rotterdam is 4,100 nautical miles (7,600 km)
- Only ammonia shipping is considered in the LCOH calculation[2]
- The cost of local transport of hydrogen and electricity in Brazil is not considered to be able to compare the price to other regions.
- The transport costs is projected to be **0.22 EUR/kg$H_2$** in 2030 and **0.18 EUR/kg$H_2$** in 2050

**(Re)Conversion:**

- Since it is considered that the hydrogen is transported in the form of ammonia, a conversion and possibly reconversion step are required, depending on the end use.
- The conversion and reconversion costs are projected to be **1.36 EUR/kg$H_2$** in 2030 and **1.21 EUR/kg$H_2$** in 2050. If reconversion is not required, the cost is projected to be 0.62 EUR/kgH2 in 2030 and 0.41 EUR/kgH2 in 2050.

**Terminaling:**

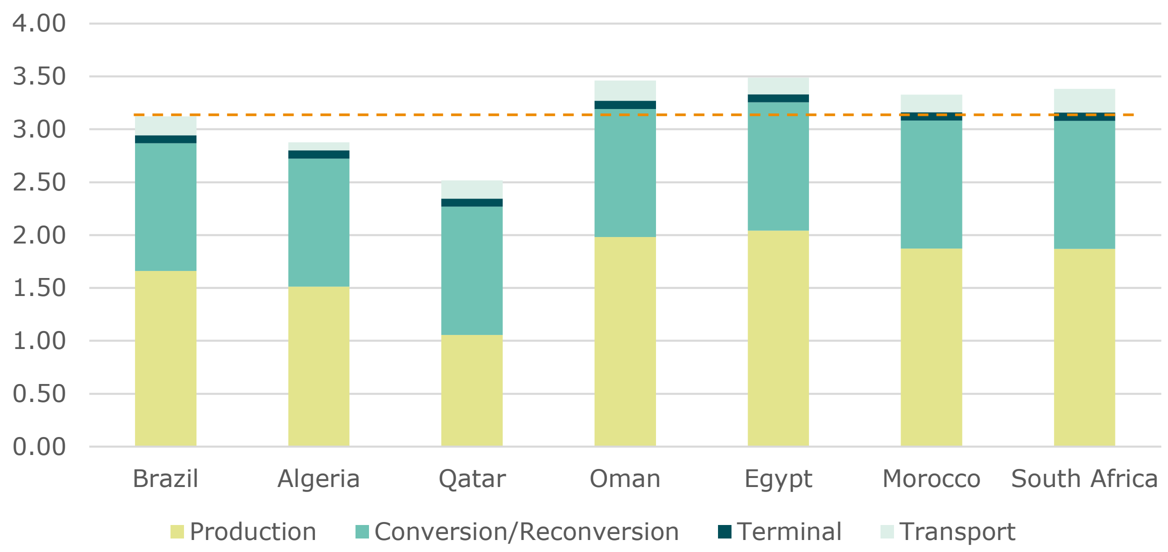
- Terminaling is required in the importing and exporting terminal
- The projected terminaling cost is **0.09 EUR/kgH2** in all years

Overall, the total levelized cost of hydrogen (LCOH) is projected to be **4.28 – 4.69 EUR/kgH2** in 2030 and **3.13 – 3.74 EUR/kgH2** in 2050.

**Note**: (1) All sources and assumptions can be found in the appendix. (2) Ammonia is selected as the preferred form of hydrogen transport due to its financial viability (compared to LH, in Report 1 of the study it was shown that transporting hydrogen overseas over long distances is more economical in the form of ammonia) and direct usability in certain applications, which helps to reduce investment risks.

# Imported hydrogen from the Port of Pecém is projected to be cost competitive to imports from other countries

Benchmark of the levelized cost of hydrogen from Port of Pecém to Port of Rotterdam
*2050, EUR/kg*

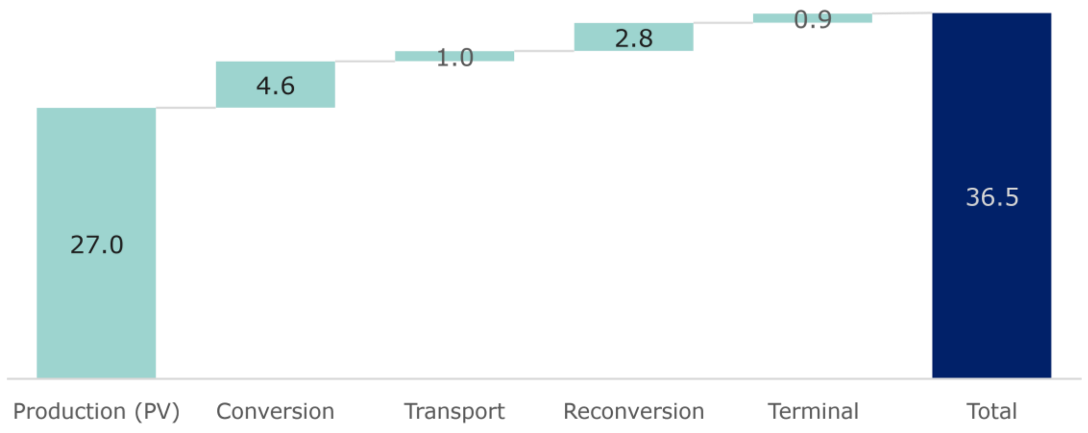



## Key takeaways

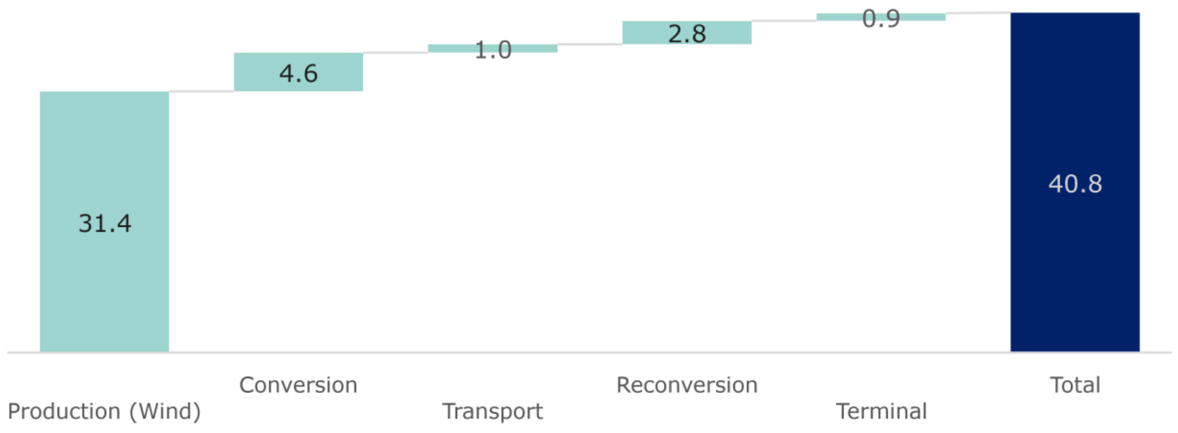
- Hydrogen imported from the Port of Pecém is cost competitive to green hydrogen import from other regions such as North Africa and the Middle East. Blue hydrogen import from Algeria and Qatar, however, still has a lower cost.
- The production cost and the conversion and reconversion cost are the biggest cost drivers of the LCOH. If the reconversion cost can thus be avoided by direct use of ammonia, the LCOH can be substantially lower.

# The production infrastructure requires the largest investment in the complete hydrogen import value chain

Investments required over the whole hydrogen value chain for the import of 1 Mton hydrogen from the Port of Pecém to the Port of Rotterdam produced from solar PV
*2030, '000 MEUR*




Investments required over the whole hydrogen value chain for the import of 1 Mton hydrogen from the Port of Pecém to the Port of Rotterdam produced from wind energy
*2030, '000 MEUR*

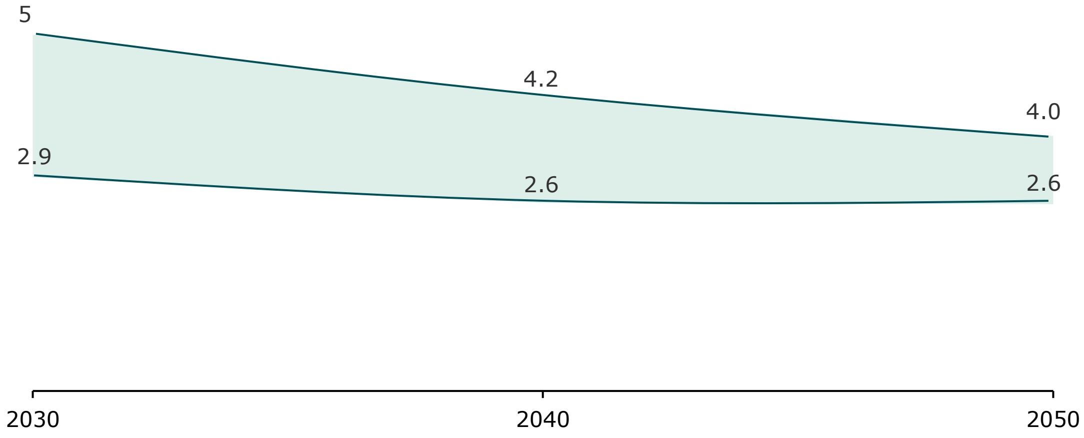



## Key takeaways

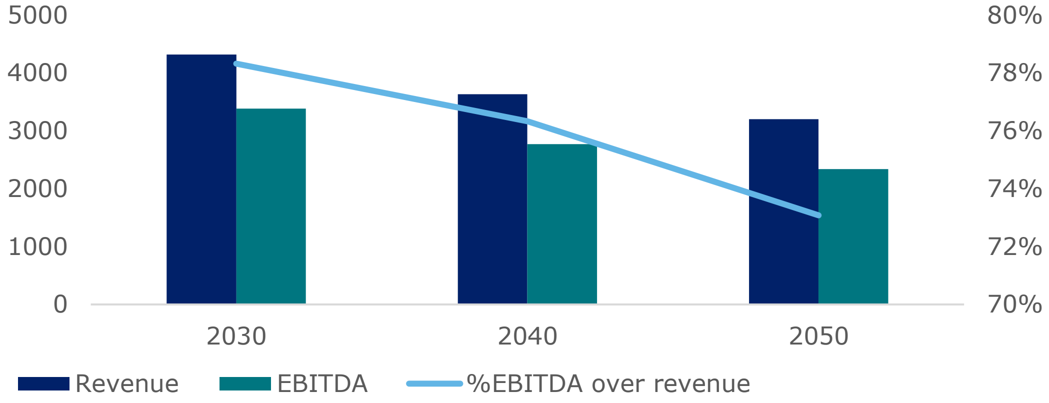
- For the investment case, it is assumed the whole hydrogen import value chain is operational for a volume of 1 Mton hydrogen by 2030. Upscaling is not assumed in the analysis.
- **Different infrastructure that is required** per step of the value chain:
    1. Production: electrolyser capacity and wind and/or sun energy
    2. Transport: ammonia ships
    3. (Re)Conversion: conversion and reconversion plants (NH3 synthesis and catalytic cracking)
    4. Terminaling: import and export terminals
- The **production step results in the largest CAPEX investment required**. Conversion and reconversion of hydrogen is also a big cost factor in the LCOH, however mostly due to its energy requirements.

# Income statement of the hydrogen import chain

Base case projected hydrogen cost port of Rotterdam area
*2023-2050, estimate (EUR/kg)*[1]




Income statement overview (solar PV)
*2030-2060, estimates ('000 EUR, %)*




## Key takeaways

- Mix between wind and solar energy is assumed to be 10% sourced by wind and 90% sourced by solar PV, based on the potential of these renewable energy sources in the North-East region of Brazil.
- The **price** at which the imported hydrogen from the Port of Pecém will be sold in the port of Rotterdam area is **assumed to be aligned with the LCOH** and the split between wind/solar energy. This equals to 4.32, 3.63 and 3.20 EUR/kg in 2030, 2040 and 2050, respectively.
- It is assumed that the **hydrogen price is fixed for 10-year periods**, i.e. between 2030 – 2040 and 2040 – 2050. This could be achieved via purchase agreements. This price is expected to decrease based on the market maturity. Revenues are therefore highest between 2030 and 2040 at 4.3 MEUR. Afterwards it declines based on decreasing hydrogen price and a fixed capacity of the value chain.
- **Attracting clients at an early stage will be key** to strengthen the commercial viability of the business case ( e.g., by purchase agreements)

*[1]Study on Hydrogen in Ports and Industrial Coastal Areas, Report 1 (2023). This is based on a combination of local production and import from various locations. The LCOH for hydrogen imported from the Port of Pecém falls within this range.*

# Key levers for a favorable IRR are public funding, off-taker agreements and the direct use of ammonia

Sensitivity analysis of IRR for $H_2$ import chain

*2030-2050, estimates (%)*

| Capex subsidy \ Subsidy H2 price | 0,00% | 5,00% | 10,00% | 15,00% | 20,00% |
|---|---|---|---|---|---|
| 6.10% | 0,00% | 5,00% | 10,00% | 15,00% | 20,00% |
| 0,00% | 6.10% | 6.70% | 7.30% | 7.90% | 8.50% |
| 5,00% | 6.70% | 7.30% | 7.90% | 8.50% | 9.10% |
| 10,00% | 7.30% | 7.90% | 8.50% | 9.10% | 9.80% |
| 15,00% | 7.90% | 8.50% | 9.10% | 9.80% | 10.60% |
| 20,00% | 8.50% | 9.10% | 9.80% | 10.60% | 11.40% |

## Key takeaways

- **Due to the low technology maturity of hydrogen and its corresponding risk profile, targeting a double-digit Internal Rate of Return (IRR) could be advisable**. If the aim for the project is not primarily a commercially viable project, but rather gathering knowledge and derisking future projects, lower IRRs could be justified. Further **having concrete off-taker agreements can also derisk the investment and allow for a lower IRR**.
- Pricing a **green subsidy for the H2 price can significantly increase the attractiveness of the business case**. To successfully implement this, the willingness to pay of customers for a green energy source should be further investigated
- An alternative lever to improve the business case is to obtain CAPEX subsidies for the various parts of the value chain to **bridge the CAPEX gap between clean technologies and their alternatives**
- A third variable which can have a significant impact on the viability of the business case is the **spread in energy cost between hydrogen or ammonia and natural gas prices for consumers.** An increasing carbon tax can bridge this gap and thereby spur profitability of the business case.
- Finally, if the **ammonia is directly used and the reconversion step is thus avoided**, the IRR becomes significantly better (2.5% in the base scenario)

# Constraints

# Technical considerations

## General

The port of Rotterdam/Pecem case focusses on the international transport of hydrogen through ammonia as a hydrogen carrier. The value chain consist of hydrogen production, hydrogen transport to ammonia synthesis plant, ammonia synthesis, transport of ammonia to export terminal and shipment to import destination, reconversion at import location to hydrogen through ammonia reforming.

## Current technology readiness

Due to the existing global market for ammonia, technologies for storage, transport and distribution of ammonia are mature. However, to recover hydrogen from the imported ammonia, the conversion of ammonia to hydrogen through reforming is required. **Ammonia reforming technology is the most immature technology in the ammonia value chain** with a TRL level of TRL6-7.

## Technical considerations ammonia reforming

- Heat is required for the endothermic reforming process. When heat is provided in allothermal configurations by ammonia combustion, NOx emissions should be accounted for. Alternatively other energy sources such as natural gas, electricity or hydrogen should be considered. In autothermal configurations additional purification may be required to meet NOx requirements in hydrogen standards. Nitrogen emissions (NOx, NH3) should be considered in tail-gas in PSA applications.
- There is not definitive, universally accepted standard for hydrogen. Hence, purification requirements are not definitive.
- The number of full load hours of renewable electricity limits the plant load factor, which can only be mitigated by electricity or hydrogen storage.
- Minimal load of the electrolyser technology and the flexibility of ammonia synthesis loop are important considerations for the load-following capability. The ammonia synthesis loop must be maintained in hot-standby to enable quick startup after a period of insufficient renewable electricity supply.
- Transportation pressure and operational pressure of electrolyser should be aligned to minimize hydrogen compression especially at low pressure.

# Safety considerations

### Description of situation

The development of an international hub for the import/export of liquid hydrogen and ammonia.

### Safety considerations

- Safety distances around the import terminal.
- External safety considerations for large scale storage of hydrogen carriers; position of venting lines during (especially) filling the storage facility.
- Considering the toxicity of ammonia and with that occupational safety, emission levels need to be minimized.
- Mechanical integrity and suitability of the materials in the various equipment used at different temperatures and pressures for liquefaction of ammonia and LH2.
- Ways to reduce the boil-off, as a small temperature increases causes a steep increase in pressure. Hence the flammable/toxic cloud formed in the atmosphere may pose a risk for both the facility and external safety (unless a re-liquefaction system is in place).
- The environmental impact of a spill of liquid ammonia in water, especially with respect to the aquatic life.
- Reliable detection techniques for ammonia and hydrogen.

### Recommendations

- The storage of large quantities of LH2 and/or ammonia in relation to the SEVESO III guidelines.
- Existing standards for the maximum permissible safety risk as determined for the environmental risk apply unaffectedly to hydrogen. Where such a standard is still lacking, the rule is that an activity must be at least as safe as the equivalent technology based on fossil energy sources.
- Consider potential noise/sound emissions from the new plants that may interfere with current and future activities in the harbor environment.
- The potential impact of ammonia on the aquatic life, the environment and people for different spill scenarios. Also consider the difference between liquid and gaseous ammonia in this respect.
- The location of both ammonia and hydrogen facilities, especially during loading/unloading, conversion and cracking (ammonia), is of paramount importance for the environment of the people nearby.
- The local authorities and other relevant stakeholders at an early stage to aid the permitting process, as there are still many unknows that may affect progress.

# Certification is required to provide transparency in the origin and sustainability of hydrogen, especially when imported

Certification is a crucial pre-condition to get the hydrogen economy underway. Certification can help provide **transparency in the origin and sustainability of hydrogen**. Green hydrogen imported from outside of Europe has to be certified as green in the region.

- The **European commission** proposed **detailed rules** to define what constitutes **renewable hydrogen in the EU**, via the **adoption of two Delegated Acts** under the Renewable Energy Directive (on 13/02/2023). They will ensure that all RFNBOs[2] are produced from renewable electricity. The acts were adopted in June 2023.
- The two Acts are inter-related and both necessary for the fuels to be counted towards Member States' renewable energy target.

**1st Delegated Act**

- Defines **conditions** where hydrogen and hydrogen-based fuels can be considered as an **RFNBO**
- Clarifies the principle of "**additionality**" for hydrogen: electrolysers will have to be connected to **new** renewable electricity production
    - Ensure that the generation of renewable hydrogen incentivizes an increase in the volume of renewable energy available to the grid
    - Sets out ways in which producers can demonstrate that the renewable electricity used for hydrogen production complies with additionality rules
    - Introduces criteria aimed to ensure that renewable hydrogen is only produced when and where sufficient renewable energy is available
- The rules will be **phased in gradually**. There will be a transition phase that will start operating before 1 January 2028.
- The requirements will apply to **domestic producers** as well as producers from **third countries** that want to export renewable hydrogen to the EU
- A **certification scheme relying on voluntary schemes** will ensure that producers, whether in the EU or in third countries, can demonstrate in a simple and easy way their compliance with the EU framework and trade renewable hydrogen within the Single Market

**2nd Delegated Act**

- Provides a methodology for **calculating life-cycle greenhouse gas emissions** for RFNBOs:
    - Takes into account GHG emissions across the **full lifecycle** of the fuels (including upstream emissions, emissions associated with taking electricity from the grid, from processing, and those associated with transporting these fuels to the end-consumer)

One of the most recognized certification schemes for green hydrogen is the **Renewable Hydrogen Certification Scheme (RHCS),** developed by the Renewable Energy Institute (REI) and the International Renewable Energy Agency (IRENA).

**Sources and notes**: (1) https://ec.europa.eu/commission/presscorner/detail/en/ip_23_594. (2) renewable fuels of non-biological origin

# Securing high-quality offtake agreements, to improve the business case, requires different steps

High-quality offtake agreements reduces the risks of investment and is thus important for the good continuation of the project. Different stages have to be followed to secure good offtakers.

**Collaboration development stages**

| Non-disclosure agreement ('NDA') | Non-binding Letter of Intent ('LoI') | Non-binding Expression of Interest ('EoI') | Conditional Head of Terms ('HoT') | Sales agreement |
|---|---|---|---|---|
| • Signed at **early stages** of engagement<br>• Aimed at **protecting commercial** and **technical** information | • Aimed at developing **joint view** on **green $H_2$** as a viable solution<br>• **Explore** opportunities for **joint advocacy** | • **Non-binding declaration** of interest to **collaborate**<br>• Indication on **key parameters** (e.g., volumes, timing, and economics) | • **Conditional declaration,** serves as basis for commercial negotiations<br>• **Establishment** of **key parameters** (e.g., volumes, timing, marketing model) | • Statement of **binding commercial terms** and **conditions** (e.g., pricing model, contract length, supply profile)<br>• **Conditional to FID** |

# Breakdown of actions and governance

# Timeline with key milestones to for hydrogen import to the Port of Rotterdam from the Port of Pecém

## Hydrogen import

### Today

- Bring together hydrogen ecosystem through various events
- Execute technical and economical feasibility studies for hydrogen end-usage
- Define dedicated areas for renewable energy and hydrogen production and import infrastructure
- Development of concrete business cases for $H_2$

### 2024

- Liaise with governmental actors on import guidelines (e.g. on certification and permitting)
- Set up partnerships for shared hydrogen import infrastructure
- Develop distributed knowledge center to compare clean technologies for end-applications

### 2025

- Develop renewable energy capacity (solar and wind) and connect to the grid
- Develop hydrogen and derivatives import infrastructure
- Execute pilot projects throughout hydrogen value chain (including derivatives vs. hydrogen) and set up off taker agreements

### 2026

- Assess off-takers pilot projects and agreements

### 2027

- Upscale pilot projects on hydrogen end-usage
- Assess the need to further scale up hydrogen and derivatives imports (including convertors)
- Assess the need to further scale up distribution and transport infrastructure
- Assess need to further scale up hydrogen production

# Governance and RACI-matrix for key stakeholders

| Task / Stakeholders | Port Authority Rotterdam | Port Authority Pecém | Companies part of port ecosystem | Green energy producers and distributors | Industry actors $H_2$ value chain | $H_2$ end-users | Governmental institutions |
|---|---|---|---|---|---|---|---|
| Bring together hydrogen ecosystem | A | A | C | C | C | C | C |
| Feasibility studies | A | A | C | C | C | C | C |
| Define areas for hydrogen production and import infrastructure | A | A | C | C | C | I | I |
| Develop business cases | A | A | C | C | C | C | I |
| Liaise with governmental actors | A | A | I | I | I | I | C |
| Set up partnerships for shared hydrogen import infrastructure | A | A | C | C | C | C | I |
| Develop distributed knowledge center | C | C | A | I | C | C | I |
| Develop renewable energy capacity | A | A | I | I | I | C | C |
| Develop hydrogen and derivatives import infrastructure | A | I | C | C | C | C | C |
| Pilot projects and off taker agreements | A | A | C | C | C | C | I |
| Assess off-takers pilot projects and agreements | A | A | C | C | C | C | I |
| Upscale pilot projects on hydrogen end-usage | C | C | C | C | C | A | I |
| Assess the need to further scale up hydrogen and derivatives imports | A | A | C | C | C | C | I |
| Assess the need to further scale up distribution and transport infrastructure | A | A | C | C | C | C | I |
| Assess need to further scale up hydrogen production | A | A | C | C | C | C | I |

## Key takeaways

- **The Port Authority of Rotterdam and Pecém will play a key role** in the import of renewable hydrogen
- **Collaboration between various stakeholders is crucial** for the successful role-out of hydrogen import value chain

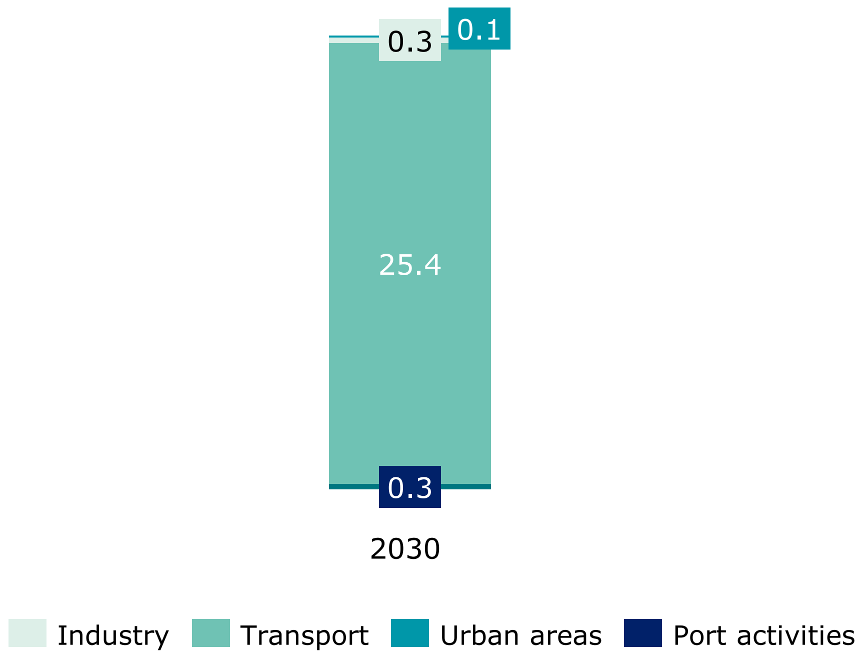
## RACI

| | |
|---|---|
| **R - Responsible**<br>The organization who takes action to get the task done. They are responsible for part of the work that needs to be executed. | **A - Accountable**<br>The organization which owns the task or deliverable. They might not get the work done themselves, but they are responsible for making sure it is finalized. To avoid confusion and the diffusion of responsibility, it's best to have one accountable stakeholder per project task. |
| **C - Consulted**<br>The stakeholder who will help complete the task. They will have two-way communication with the people responsible for the task by providing input and feedback over the task completion. | **I - Informed**<br>The stakeholder that needs to be up to date on the task's progress. They will not have two-way communication, but it's essential to keep them informed since they will be affected by the final outcome of the task. |

# Anticipated benefits

# Green hydrogen offers significant environmental benefits, including the potential to abate up to 26 Mton of CO2-eq., as well as other emissions

Expected hydrogen-related CO2-eq abatement per category in the Port of Rotterdam[1]
*2030, estimates (Million tonnes $CO_2$)*




## Environmental benefits

- The transition to green hydrogen offers significant environmental benefits, including the potential to abate **up to 26 Mton of CO2-equivalent emissions in 2030**, corresponding a hydrogen offtake of 1 Mt.
- In the Port of Rotterdam, the highest hydrogen-related CO2-eq. abatement is expected in the transport sector, particularly in international shipping. Similar as the highest projected hydrogen demand category.
- Additionally, the shift away from fossil fuel-based production and combustion processes will also result in avoided emissions of NOx, PM, CO, VOCs, SOx, and other harmful pollutants.

**Note**: (1) All sources and assumptions can be found in the appendix

# Anticipated societal and economic benefits

## Societal benefits

- Improve **citizens health** by reducing emissions and air pollution
- **Job creation** at the ports, and in the whole supply chain of hydrogen
- **Reskill current industrial workforce** to play a vital role in developing clean technologies
- Put the Port of Rotterdam and Pecém on the map as a front-running **innovation hub** with national and international exposure
- **Build knowledge** on hydrogen production and distribution

## Economic benefits

- **Attracting business** throughout the $H_2$ value stream
- Reduce **environmental taxes**
- **Attract and retain talent** to realize the ambition of creating a hydrogen valley
- Build on already-existing capabilities to provide **clean technology solutions throughout the hydrogen value chain** (production, consumption and distribution)
- Build strong **trade relationships** with countries outside of the EU through hydrogen imports

# Conclusions and recommendations

# Conclusions and recommendations for hydrogen import from outside the EU

## Conclusions

1. Overall, the total levelized cost of hydrogen (LCOH) from hydrogen produced in Pecém and imported to Rotterdam, is projected to be **4.28 – 4.69 EUR/kgH2** in 2030 and **3.13 – 3.74 EUR/kgH2** in 2050. This is cost competitive with other green hydrogen production locations as Egypt, Oman, etc.
2. By 2030, 1 Mton of hydrogen could be imported from Pecém. This would require an investment of 36.5 – 40.8 BEUR, depending on the source of renewable electricity.
3. When looking at the capital investments required in the whole value chain, the biggest investment will be required in the production step. However, the operating cost is the biggest in the conversion and reconversion step, due to the large amount of energy required.
4. In order to mitigate the investment risk, public funding can be mobilized to kick-start the decarbonization efforts via capex subsidies or **subsidies** on top of the hydrogen price. Further, policy measures can reduce the price gap between green- and fossil-fuels. Moreover, securing high-quality offtaker agreements can derisk the investment. Finally, avoiding a reconversion step of ammonia to hydrogen decreases the LCOH and the required investments. This would again improve the business case.
5. Restrictions on nitrogen emission may require specific adjustments or additions to the design of the purification and heat supply system.
6. Significant environmental, societal and economic benefit can be achieved by making sure hydrogen is available to replace fossil fuel alternatives

## Recommendations

1. Continue to invest in research and development to mature technologies and bring costs down
2. Maintain continued contact with different stakeholders so the hydrogen value chain is enabled and infrastructure is timely available
3. Set up contacts and contracts (including offtaker agreements) to ensure a positive business case for the investment in the hydrogen value chain infrastructure
4. In the chemical process industries extensive knowledge on the safe handling of the considered alternative fuels (hydrogen, ammonia, methanol, et cetera) is present, as these are used as chemical feedstock. Although the alternative fuels will be embedded in the public domain, which applies for chemical factories to a lesser extend, and hence the safety scenarios are different, the lessons learned in the industry present a valuable starting point.

# Appendix

# Data assumptions - Case study 1

Port of Klaipeda

# The main assumptions we took

| Topic | Assumption | Unit | Source |
|---|---|---|---|
| **General** | | | |
| CO2 Price | 92 | EUR/tonne | Amber (2023) |
| H2 production | 22,1 | *EUR/litre* | Global petroleum prices (2023) |
| $H_2$ price 2023 | 10 | *EUR/kg* | Klaipeda analysis (2022) |
| H2 price 2050 | 3,6 | *EUR/kg* | Study on H2 in ports (2023) |
| Capacity factor offshore wind | 39 | *%* | Statista (2023) |
| Electricity consumption | 50 | *KWh/kg production* | Klaipeda analysis (2022) |
| Water consumption | 17,4 | *l/kg produced* | Klaipeda analysis (2022) |
| Price electricity | 0,09 | *EUR/KWh* | Klaipeda analysis (2022) |
| Price water | 0,001 | *EUR/l* | Klaipeda analysis (2022) |
| Subsidy | 50 | *% of total CAPEX* | Klaipeda analysis (2022) |
| CAPEX hydrogen production | 7.821.500 | EUR | Nel Hydrogen (2023) |
| Maintenance and repairs | 78.100 | EUR | Klaipeda analysis (2022) |
| Salaries and wages | 22.212 | EUR | Klaipeda analysis (2022) |
| Stack lifetime | 80.000 | hours | IEA (2022) |
| Price of stack | 500.500 | EUR | Nel Hydrogen (2023) |
| CAPEX refueling station | 1.840.000 | EUR | Hydrogen fuel cell partnership (2022) |
| OPEX refueling station | 18.400 | EUR | Caponi et al (2021) |

# Data assumptions - Case study 2

Port of Antwerp-Bruges, Duisport &
WaterstofNet

# TCO assumptions: straddle carrier (1/3)

*Diesel ICE is seen as the base case. The CAPEX and OPEX of the other types of straddle carriers are given as a percentage compared to these.*

| | | Unit | 2023 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Diesel ICE | CAPEX | NORM | 1 | 1 | 1 | 1 |
| | OPEX per year[1] | NORM | 1 | 1 | 1 | 1 |
| | Lifetime | Hours | 60.000 (or 12 years) | 60.000 (or 12 years) | 60.000 (or 12 years) | 60.000 (or 12 years) |
| | Energy efficiency | % | 50% | 50% | 50% | 50% |
| | Refueling cost[2] | kEUR | 1.5-3 | 1.5-3 | 1.5-3 | 1.5-3 |
| Electric | CAPEX | NORM | +25% | +13% | +13% | +13% |
| | OPEX per year | NORM | -20% | -20% | -20% | -20% |
| | Lifetime | Hours | Battery lifetime: 30,000 | Battery lifetime: 30,000 | Battery lifetime: 30,000 | Battery lifetime: 30,000 |
| | Energy efficiency | % | 80% | 80% | 80% | 80% |
| | Refueling cost | kEUR | 2.5-4 | 2.5-4 | 2.5-4 | 2.5-4 |
| Hybrid diesel | CAPEX | NORM | +15% | +15% | +15% | +15% |
| | OPEX per year | NORM | -5% | -5% | -5% | -5% |
| | Lifetime | Hours | Battery lifetime: 30,000 | Battery lifetime: 30,000 | Battery lifetime: 30,000 | Battery lifetime: 30,000 |
| | Energy efficiency | % | 45% | 45% | 45% | 45% |
| | Refueling cost | kEUR | 1.5-3 | 1.5-3 | 1.5-3 | 1.5-3 |

Notes: (1) Does not include energy cost. (2) the cost for the infrastructure, not the energy cost

# TCO assumptions: straddle carrier (2/3)

| | | Unit | 2023 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Hydrogen ICE | CAPEX | NORM | +30% | +25% | +25% | +25% |
| | OPEX per year | NORM | 0% | 0% | 0% | 0% |
| | Lifetime | Hours | Engine lifetime: 20,000 | Engine lifetime: 20,000 | Engine lifetime: 30,000 | Engine lifetime: 30,000 |
| | Energy efficiency | % | 45% | 45% | 45% | 45% |
| | Refueling cost | kEUR | See next slides | | | |
| Hydrogen fuel cell | CAPEX | NORM | +40% | +26% | +20% | +20% |
| | OPEX per year | NORM | -5% | -5% | -5% | -5% |
| | Lifetime | Hours | Fuel cell: 10,000 | Fuel cell: 15,000 | Fuel cell: 20,000 | Fuel cell: 20,000 |
| | Energy efficiency | % | 53% | 53% | 53% | 53% |
| | Refueling cost per year | kEUR | See next slides | | | |
| Dual fuel | CAPEX | NORM | +30% | +25% | +25% | +25% |
| | OPEX per year | NORM | +5% | +5% | +5% | +5% |
| | Lifetime | Hours | Engine lifetime: 50,000 | Engine lifetime: 50,000 | Engine lifetime: 45,000 | Engine lifetime: 30,000 |
| | Energy efficiency | % | 45% | 45% | 45% | 45% |
| | Refueling cost | kEUR | See next slides | | | |

# TCO assumptions: straddle carrier (3/3)

Notes

1) Electric:
   - The battery costs between 150-250 EUR/kWh and the assumed battery is 650 kWh[4]
   - Currently, the technology is not mature enough to provide various electric straddle carriers.
   - Since there are various types of applications electrifying in the coming years at the terminal, the electricity grid will be reinforced. This cost is assumed in the analysis.
2) Hybrid:
   - A hybrid straddle carrier is similar to a diesel straddle carrier, but surplus energy is generated during braking/lowering load is stored in batteries. Since also electricity is used, a battery is required, and the engine is smaller.
3) Hydrogen ICE:
   - There is a low heating value of hydrogen of 33.33 kWh/kg, with an efficiency of 45%.
4) Hydrogen fuel cell:
   - The price of fuel cells and hydrogen tanks are expected to go down over time driven by the technology's increasing economies of scale. In the analysis a price decrease of 33% is assumed by 2030 and by 50% by 2040. Afterwards, the price is expected to be stabilized. However, various sources suggest an even steeper decline, i.e. already 50% decrease by 2030.[1,2,3]
   - The durability is expected to increase to up to around 20,000 hours by 2040.
5) Dual fuel:
   - For the dual fuel we assume a dual fuel motor is added to a hybrid straddle carrier. In the analysis, we assume an additional cost of +10% on top of the hybrid straddle carrier investment cost. In the beginning this will be a bit higher. The dual fuel motor is a standard motor with an additional injection piece for hydrogen.[4]
6) General:
   - The investments are annualized[5] to include in the TCO analysis with a discount rate of 8%
   - OPEX incudes the total operating cost over the lifetime of a straddle carrier, including labor, spare parts and tire costs. Energy cost is looked into separately
   - There are assumed to be 5000 hours/year
   - Energy consumption straddle carrier: 61.8-77.3 kWh/h

**Sources**: (1) https://theicct.org/wp-content/uploads/2022/09/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22.pdf. (2) https://www.horizoneducational.com/why-are-the-prices-of-fuel-cells-dropping/t1422?currency=usd#:~:text=In%20recent%20years%20the%20price,expected%20to%20be%20under%20%24%20100%2C000. (3) https://blog.ballard.com/fuel-cell-price drop. (4) Expert input. **Notes**: (5) Annualized investment [€/year] = (Capex [€]*Discount_Rate)/(1-(1+Discont_Rate)^(-LifeTime)).

# TCO assumptions: hydrogen refueling station (1/2)

| | Unit | 2023 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Lifetime | Years | 15[1] | 20[1] | 20 | 20 |
| Energy consumption | kWh/kg | 4[1,2] | 3[1,2] | 3 | 3 |
| Annual maintenance cost | EUR/kg | 0.5[1] | 0.3[1] | 0.3 | 0.3 |
| CAPEX | kEUR/kg/day | 1.7-2.5 [1] | 1.5 - 2[1] | 1.5 - 2[1] | 1.5 - 2[1] |
| CAPEX for 1 refueling station | kEUR | 680-1000 | 600 - 800 | 600 - 800 | 600 - 800 |
| OPEX (energy + maintenance cost) | EUR/year | 472 | 324 | 336 | 348 |

## Notes

- The different parameters are expected to stay constant from 2030 onwards.
- The refueling stations ate assumed to have a rather small capacity of 400 kg H2/day. Especially for hydrogen take-off this will be the case.
- The availability is assumed 98% and thus not a limitation
- The costs include on-site storage but exclude land cost.

Sources: (1) https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/fch-2-ju-mawp-key-performance-indicators-kpis_en in 2024.
(2) Station energy consumption per kg of hydrogen dispensed when station is loaded at 80% of its daily capacity - For HRS which stores H2 in gaseous form, at ambient temperature, and dispense H2 at 700 bar in GH2 from a source of >30 bar hydrogen.

# TCO assumptions: hydrogen refueling station (2/2)

| | Hydrogen consumption per hour | Hydrogen consumption per day | Allocation of investment cost to one straddle carrier | Total cost (investment & operating cost) |
|---|---|---|---|---|
| Fuel cell straddle carrier | 4.9 kg/h | 68.6 kg/day | 17.2% (since +/-5 straddle carriers can be charged at 1 station) | 6-8 kEUR/year |
| ICE hydrogen straddle carrier | 5.9 kg/h | 82.6 kg/day | 20.7% | 7-9 kEUR/year |
| Dual fuel straddle carrier | 4.8 kg/h | 67.2 kg/day | 16.8% | 5.5-7 kEUR/year |

Notes

- Running hours per day: 14
- Running hours per year: 5000
- It is assumed refueling stations will only be put in place when there are enough operating straddle carriers making use of hydrogen. Therefore, the capacity of the refueling stations is assumed to be used for 100%.

# TCO assumptions: energy carriers

| | Unit | 2023 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Electricity (average wholesale price) | EUR/kWh | 0.15-0.2 | 0.15-0.2 | 0.16-0.21 | 0.17-0.22 |
| Hydrogen | EUR/kg | 8-12 | 3-4 | 2-3 | 1.5-2.5 |
| Diesel | EUR/l | 0.75-0.9 | 0.75-0.9 | 0.75-0.9 | 0.75-0.9 |
| CO2 tax[1] | EUR/ton | 0 | 120-150 | 180-220 | 200-300 |

## Notes

1) The electricity price is expected to increase slightly until 2050.
2) The analysis only takes into account green hydrogen
3) Currently, no tax is paid for diesel. Since it is not yet decided/communicated when this might change, in this analysis no tax is included. If a tax would come in place, this will play in the advantage of carbon neutral options. Also for hydrogen, there is no tax assumed in the analysis.
4) A CO2 tax is projected from 2030.

Sources: (1) Based on IEA, Global Energy and Climate Model, December 2022. Net Zero Emissions by 2050 Scenario for advanced economies with net zero emissions pledges (p.20)

# Data assumptions - Case study 3

North Tyrrhenian port network

# The main assumptions we took – ferry (1/2)

| Topic | Assumption | Unit | Source |
|---|---|---|---|
| **General** | | | |
| $CO_2$ Price 2023 | 92 | EUR/tonne | Amber (2023) |
| $CO_2$ Price 2030 | 140 | EUR/tonne | IEA (2023) |
| $CO_2$ price 2040 | 205 | EUR/tonne | IEA (2023) |
| $CO_2$ price 2050 | 250 | EUR/tonne | IEA (2023) |
| Diesel price | 0,89 | *EUR/litre* | Global petroleum prices (2023) |
| $H_2$ price 2023 | 13,7 | *EUR/kg* | Expert interviews |
| H2 price 2050 | 2,52 | *EUR/kg* | Study on H2 in ports (2023) |
| Capacity factor solar | 25 | % | Statista (2023) |
| **H2 powered ferry** | | | |
| Ticket price | 16 | EUR/passenger | Direct ferries |
| Capacity | 100 | passengers | Institute for Energy Technology (2019) |
| CAPEX Ferry | 2.000.000 | EUR | Institute for Energy Technology (2019) |

# The main assumptions we took – ferry (2/2)

| Topic | Assumption | Unit | Source |
|---|---|---|---|
| **H2 powered ferry** | | | |
| CAPEX Fuel cell system (permanent installation) | 1.100.000 | EUR | Institute for Energy Technology (2019) |
| CAPEX Fuel cell system (degradable compoments) | 1.100.000 | EUR | Institute for Energy Technology (2019) |
| CAPEX Power electronics | 800.000 | EUR | Institute for Energy Technology (2019) |
| CAPEX Hydrogen storage | 500.000 | EUR | Institute for Energy Technology (2019) |
| Maintenance | 110.000 | EUR | Institute for Energy Technology (2019) |
| Fees | 40.000 | EUR | Institute for Energy Technology (2019) |
| Distance trip | 27,9 | Km | Expert interviews |
| $H_2$ consumption | 0,94 | Kg/km | Institute for Energy Technology (2019) |
| Hydrogen storage capacity | 453 | Kg | Institute for Energy Technology (2019) |
| $CO_2$ avoided per passenger | 0,0000602 | Tonne/km | Department for Energy (2021) |

# The main assumptions we took – Containership (1/2)

| Topic | Assumption | Unit | Source |
|---|---|---|---|
| **General** | | | |
| $CO_2$ Price 2023 | 92 | EUR/tonne | Amber (2023) |
| $CO_2$ Price 2030 | 140 | EUR/tonne | IEA (2023) |
| $CO_2$ price 2040 | 205 | EUR/tonne | IEA (2023) |
| $CO_2$ price 2050 | 250 | EUR/tonne | IEA (2023) |
| Diesel price | 0,89 | *EUR/litre* | Global petroleum prices (2023) |
| $H_2$ price 2023 | 13,7 | *EUR/kg* | Expert interviews |
| H2 price 2050 | 2,52 | *EUR/kg* | Study on H2 in ports (2023) |
| **Ammonia powered containership** | | | |
| Container transport price | 0,14 | EUR/km | Deloitte analysis (2023) |
| Capacity | 1913 | TEU | Grieg Star (2023) |
| CAPEX container ship | 100.000.000 | EUR | Grieg Star (2023) |
| CAPEX main engine | 9.100.000 | EUR | Grieg Star (2023) |
| CAPEX fuel supply system | 5.500.000 | EUR | Grieg Star (2023) |
| CAPEX storage tank | 3.700.000 | EUR | Grieg Star (2023) |
| Shipyard work | 1.800.000 | EUR | Grieg Star (2023) |

# The main assumptions we took – Containership (2/2)

| Topic | Assumption | Unit | Source |
|---|---|---|---|
| **Ammonia powered containership** | | | |
| Additional OPEX | 17,9 | EUR/container per day | Grieg Star (2023) |
| Yearly distance sailed | 160.013 | Km | Grieg Star (2023) |
| $CO_2$ per tonne per km | 3,48 | Gramme | Statista (2023) |
| $NH_3$ consumption per year per TEU | 8.833,36 | kg | Kyunghwa et all (2020) |
| cost $NH_3$ | 205 | EUR/MWh | IRENA (2022) |
| Container transport price | 0,14 | EUR/km | Deloitte analysis (2023) |
| Capacity | 1913 | TEU | Grieg Star (2023) |
| Additional CAPEX | 20.112.136 | EUR | Grieg Star (2023) |
| Additional OPEX | 17,9 | EUR/container per day | Grieg Star (2023) |
| Yearly distance sailed | 160.013 | Km | Grieg Star (2023) |

# Data assumptions - Case study 4

Port of Rotterdam & Port of Pecém

# LCOH production cost (1/3)

- 1 kg of hydrogen has an energy value of 33.3 kWh
- The efficiency of an electrolyser has an impact on the amount of electricity required to produce 1 kg of hydrogen
- The time an electrolyser operates has an impact on the kW required. In the analysis we assume the electrolyser operates 3000 hours per year

| | | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Electrolyser | Efficiency | % | 69 | 72 | 75 |
| | Electricity required to produce 1 kg of hydrogen | kWh | 48.3 | 46.3 | 44.4 |
| | Capacity electrolyser required to produce 1 kg of hydrogen | kW | 0.016 | 0.015 | 0.015 |

- The capacity load influences the electricity produced per kW:
  - Solar panels: 21%
  - Onshore wind: 33%

| | | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Solar panel | Efficiency | % | 90 | 90 | 90 |
| | Electricity produced per kW installed | kWh | 1655.6 | 1655.6 | 1655.6 |
| | Capacity required to produce 1 kg of hydrogen | kW | 0.029 | 0.028 | 0.027 |
| Onshore wind | Efficiency | % | 84 | 84 | 84 |
| | Electricity produced per kW installed | kWh | 2428.3 | 2428.3 | 2428.3 |
| | Capacity required to produce 1 kg of hydrogen | kW | 0.02 | 0.019 | 0.018 |

# LCOH production cost (2/3)

- Discount rate of 8%

| | | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Alkaline electrolysis | CAPEX | EUR15/kW | 385 | 320 | 254 |
| | OPEX | %CAPEX | 1.5 | 1.5 | 1.5 |
| | Lifetime | years | 20 | 20 | 20 |
| | Annualized CAPEX | EUR/kW | 39.21 | 32.59 | 25.87 |
| | Annualized OPEX | EUR/kW | 1.01 | 0.82 | 0.7 |
| Solar PV | CAPEX | EUR15/kW | 720 | 580 | 500 |
| | OPEX | %CAPEX | 1.7 | 1.7 | 1.7 |
| | Lifetime | year | 25 | 25 | 25 |
| | Annualized CAPEX | EUR/kW | 67.45 | 54.33 | 46.48 |
| | Annualized OPEX | EUR/kW | 1.15 | 0.92 | 0.80 |
| Onshore Wind | CAPEX | EUR15/kW | 1260 | 1220 | 1102 |
| | OPEX | %CAPEX | 3 | 3 | 3 |
| | Lifetime | year | 25 | 25 | 25 |
| | Annualized CAPEX | EUR/kW | 118.04 | 114.29 | 103.23 |
| | Annualized OPEX | EUR/kW | 2.02 | 1.63 | 1.41 |

# LCOH production cost (3/3)

| | | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Alkaline electrolysis | Annualized cost | EUR/kW | 40.22 | 33.41 | 26.57 |
| | Capacity required | kW/kg H2 | 0.016 | 0.015 | 0.015 |
| | Hydrogen cost | EUR/kg H2 | 0.65 | 0.52 | 0.39 |
| Solar PV | Annualized cost | EUR/kW | 68.60 | 55.26 | 47.64 |
| | Capacity required | kW/kg H2 | 0.029 | 0.028 | 0.027 |
| | Hydrogen cost | EUR/kg H2 | 1.99 | 1.55 | 1.29 |
| Onshore Wind | Annualized cost | EUR/kW | 120.06 | 115.92 | 104.64 |
| | Capacity required | kW/kg H2 | 0.02 | 0.019 | 0.018 |
| | Hydrogen cost | EUR/kg H2 | 2.40 | 2.20 | 1.88 |
| Total hydrogen cost Solar | | EUR/kg H2 | **2.64** | **2.06** | **1.68** |
| Total hydrogen cost wind | | EUR/kg H2 | **3.05** | **2.72** | **2.28** |

# Cost assumptions for hydrogen supply model – transport cost

| Fixed Cost | | Unit | 2030 | 2040 | 2050 | Source |
|---|---|---|---|---|---|---|
| Ammonia | Trucks | EUR/kgHydrogen | 0,038 | 0,034 | 0,029 | [1], [2] |
| | Ships | EUR/kgHydrogen | 0,083 | 0,074 | 0,065 | |
| Gaseous Hydrogen | Trucks | EUR/kgHydrogen | 0,25 | 0,24 | 0,23 | [1], [2] |
| | Pipeline | EUR/kgHydrogen | 0,005 | 0,005 | 0,005 | [1] |
| Liquified Hydrogen | Ships | EUR/kgHydrogen | 0,76 | 0,67 | 0,59 | |

| Variable cost | | Unit | 2030 | 2040 | 2050 | Source |
|---|---|---|---|---|---|---|
| Ammonia | Trucks | EUR/kgHydrogen/1000km | 0,567 | 0,504 | 0,4725 | [1], [2] |
| | Ships | EUR/kgHydrogen/1000km | 0,014 | 0,012 | 0,011 | |
| Gaseous Hydrogen | Trucks | EUR/kgHydrogen/1000km | 0,567 | 0,504 | 0,4725 | [1], [2] |
| | Pipeline | EUR/kgHydrogen/1000km | 0,11 | 0,11 | 0,11 | [1] |
| Liquified Hydrogen | Ships | EUR/kgHydrogen/1000km | 0,083 | 0,073 | 0,065 | |

| Fuel consumption | | Unit | Value | Source |
|---|---|---|---|---|
| Ammonia | Ships | kWh/kgHydrogen/1000km | 0,154 | [1] |
| Liquified Hydrogen | Ships | kWh/kgHydrogen/1000km | 0 | [1] - Ship carrying liquid hydrogen uses boil-off gas for propulsion |

**Sources**: (1) IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen. (2) Wijayanta, A. T., Oda, T., Purnomo, C. W., Kashiwagi, T., & Aziz, M. (2019). Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. International Journal of Hydrogen Energy, 44(29), 15026-15044.

# Cost assumptions for hydrogen supply model – (re)conversion cost

| Fixed Cost | | Unit | 2030 | 2040 | 2050 | Source |
|---|---|---|---|---|---|---|
| Conversion | NH3 synthesis | EUR/kgHydrogen | 0,38 | 0,34 | 0,3 | [1], [2], [3] |
| | Liquefaction | EUR/kgHydrogen | 0,57 | 0,51 | 0,45 | [1], [3] |
| Reconversion | Catalytic cracking | EUR/kgHydrogen | 0,23 | 0,21 | 0,19 | [1], [3] |

| Electricity consumption | | Unit | Value | Source |
|---|---|---|---|---|
| Conversion | NH3 synthesis | kWh/kgHydrogen | 3,76 | [2] |
| | Liquefaction | kWh/kgHydrogen | 6,1 | [1] |
| Reconversion | Catalytic cracking | kWh/kgHydrogen | 11,2 | [1] |

**Sources**: (1) IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen. (2) Hydrogen 4 EU study - https://www.hydrogen4eu.com/. (3) Blanco H., Nijs W., Ruf J., Faaij A., 2018b, Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization, Applied Energy 232, pp. 323-340

# Cost assumptions for hydrogen supply model – terminal cost

| Fixed cost | | Unit | 2030 | 2040 | 2050 | Source |
|---|---|---|---|---|---|---|
| Import terminal | Ammonia | EUR/kgHydrogen | 0,065 | 0,065 | 0,065 | [1], [2] |
| | Liquified Hydrogen | EUR/kgHydrogen | 0,52 | 0,38 | 0,24 | [1], [2] |
| Export terminal | Ammonia | EUR/kgHydrogen | 0,011 | 0,011 | 0,011 | [1], [2] |
| | Liquified Hydrogen | EUR/kgHydrogen | 0,079 | 0,064 | 0,05 | [1], [2] |

| Electricity consumption | | Unit | Value | Source |
|---|---|---|---|---|
| Import terminal | Ammonia | kWh/kgHydrogen | 0,02 | [1] |
| | Liquified Hydrogen | kWh/kgHydrogen | 0,20 | [1] |
| Export terminal | Ammonia | kWh/kgHydrogen | 0,01 | [1] |
| | Liquified Hydrogen | kWh/kgHydrogen | 0,61 | [1] |

**Sources**: (1) IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen. (2) Wijayanta, A. T., Oda, T., Purnomo, C. W., Kashiwagi, T., & Aziz, M. (2019). Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. International Journal of Hydrogen Energy, 44(29), 15026-15044.

# Cost assumptions for hydrogen supply model – commodities and electricity prices

**Average wholesale electricity price per region[1]**

| Category | Region | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Average Wholesale Electricity Price | Europe | ¢/kWh | 4,51 | 4,87 | 5,40 |
| Average Wholesale Electricity Price | Middle_east_and_north_africa | ¢/kWh | 3,99 | 5,68 | 5,65 |
| Average Wholesale Electricity Price | North_east_eurasia | ¢/kWh | 1,46 | 1,70 | 1,96 |
| Average Wholesale Electricity Price | Greater_china | ¢/kWh | 9,59 | 7,94 | 6,37 |
| Average Wholesale Electricity Price | Indien_subcontinent | ¢/kWh | 7,31 | 7,17 | 7,03 |
| Average Wholesale Electricity Price | South_east_asia | ¢/kWh | 7,17 | 7,69 | 7,40 |
| Average Wholesale Electricity Price | OECD_pacific | ¢/kWh | 6,42 | 4,06 | 2,99 |

**Transport fuel price[2]**

| Commodity | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Crude oil price | USD/Barrel | 55,67 | 53,00 | 50,333 |

**Sources**: (1) “Data from the DNV Energy Transition Outlook report is included in this work, © DNV AS. 2021. All rights reserved. eto.dnv.com” This work is partially based on data developed by DNV AS, ©DNV AS. 2021, but the resulting work has been prepared by Deloitte and does not necessarily reflect the views of DNV AS.”. (2) IEA (2021), World Energy Model, IEA, Paris https://www.iea.org/reports/world-energy-model - Sustainable Development Scenario

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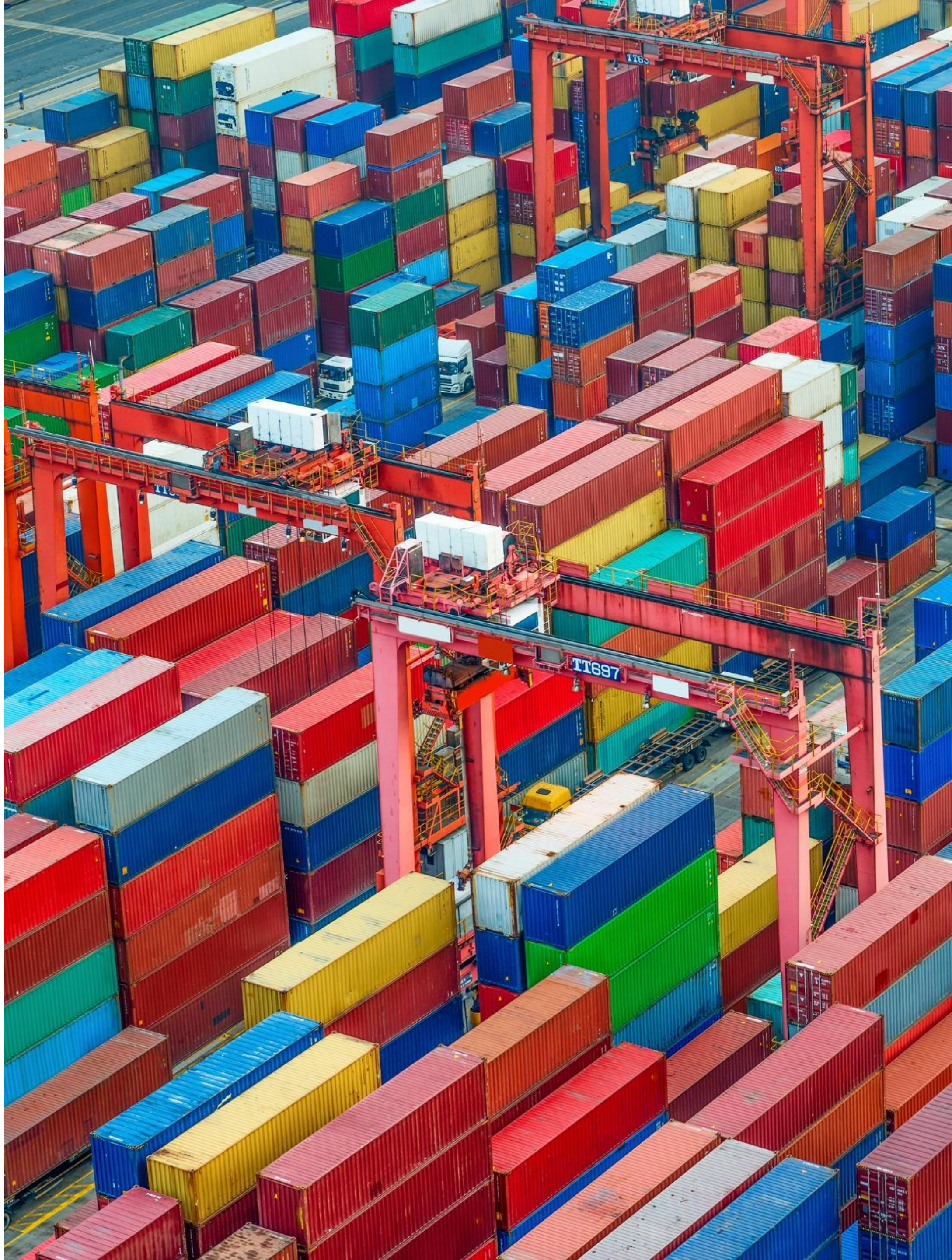


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