Hydrogen Council McKinsey & Company

Emerging trade corridors for hydrogen and its derivatives

Hydrogen Council - International Hydrogen Trade Forum joint initiative

May 13th 2024

Published in May 2024 by the Hydrogen Council. Copies of this document are available upon request or can be downloaded from our website: www.hydrogencouncil.com

The authors of the report confirm that:

1. There are no recommendations and / or any measures and / or trajectories within the report that could be interpreted as standards or as any other form of (suggested) coordination between the participants of the study referred to within the report that would infringe the EU competition law; and

2. It is not their intention that any such form of coordination will be adopted.

Whilst the contents of the report and its abstract implications for the industry generally can be discussed once they have been prepared, individual strategies remain proprietary, confidential, and the responsibility of each participant. Participants are reminded that, as part of the invariable practice of the Hydrogen Council and the EU competition law obligations to which membership activities are subject, such strategic and confidential information must not be shared or coordinated – including as part of this report.

Key takeaways (1/2)

Hydrogen and its derivatives are a critical enabler of the energy transition. Hydrogen can make a key contribution to global decarbonization targets, with 180 Mtpa total H_2e required by 2035 to stay on track to net zero. There is a continued momentum in the hydrogen industry with maturing projects that could make a significant contribution to decarbonization. However, final investment decisions are facing delays due to macroeconomic headwinds, including inflation and rising interest rates, as well as lack of certainty around the demand-side incentives and the enabling frameworks for hydrogen and its derivatives.

Cross-border trade of hydrogen and its derivatives could save USD 3.7 trillion in investment costs by 2050. Global trade routes could lower energy system costs by connecting high-demand areas with regions that can supply low-cost clean hydrogen and its derivatives. This would cut total system costs by 30%, or USD 3.7 tn compared to a scenario where all hydrogen is produced and consumed locally. Global trade can also increase the speed at which value chains grow by tapping into production areas that have limited scaling constraints and abundant access to clean energy and other input factors (e.g., iron ore, biogenic CO_2). Overall, USD 25 can be saved for every dollar invested in trade infrastructure.

Hydrogen trade flows could boost energy security, diversify supply, and enable an inclusive transition. The future hydrogen trade flows could connect all regions of the world with >30 active corridors required by 2035. The global hydrogen economy has the potential to create 20-25 mn jobs by 2050 in hydrogen production and transportation, of which 50% are expected to be created in the emerging markets and developing economies.

>180 Mtpa

total H_2e supply required by 2035 to stay on track with climate targets[1]

USD 25 saved

for every 1 USD invested in trade infrastructure

40 Mtpa

clean hydrogen transported over long distances by 2035, subject to demand drivers and infra readiness

20-25 mn

Jobs created globally in hydrogen production & transportation by 2050

1. Under the 1.9 degrees scenario; including renewable, low-carbon, and grey H_2 supply

Key takeaways (2/2)

Mind the gap: Government measures to incentivize and mandate hydrogen demand formation could fall short of their announced 2030 ambition. While key importing countries have put forward aspirational targets of ~25 Mtpa in hydrogen and derivative demand, only 3-7 Mtpa is supported by government demand-side mandates and support schemes. On the production side, there is a total 50 Mtpa announced reflecting up to 600 USD bn in required investments, of which 10 Mtpa are in FEED or beyond.

Clean hydrogen products are 2-4 times more expensive than their fossil fuel alternatives[1]. These high prices make it difficult for industrial consumers to commit to using hydrogen, as they risk losing their competitive edge in downstream markets. Mechanisms to support the cost-competitiveness of clean products (e.g., CfDs, tax credits, carbon penalties) coupled with safeguards against carbon leakage would help enable the large investments required in hydrogen technologies, underpinned by offtake commitments.

To kick-start the scaling of a global hydrogen ecosystem, this report identifies three key unlocks:

1. **Ensure more clarity, certainty, and support for demand drivers, with focus on accelerating the implementation of the announced demand-pull measures key to kick-start the market and secure the first 3-7 Mtpa of mandated demand volumes by 2030.**
2. **Retrofit, repurpose, and build infrastructure to enable interregional corridors and allow technologies to compete without 'picking winners' ensuring the most cost-effective and sustainable solutions thrive.**
3. **Establish aligned and consistent global market rules, industry standards and mutually recognized certification schemes could support the development of an international hydrogen market.**

600 USD bn

required to deploy clean hydrogen project pipeline announced to date

2-4x

more costly[1] to produce clean hydrogen vs. fossil alternatives

20 mtpa gap

between aspirational demand targets and announced incentives in 2030 (or 1,000 TWh)

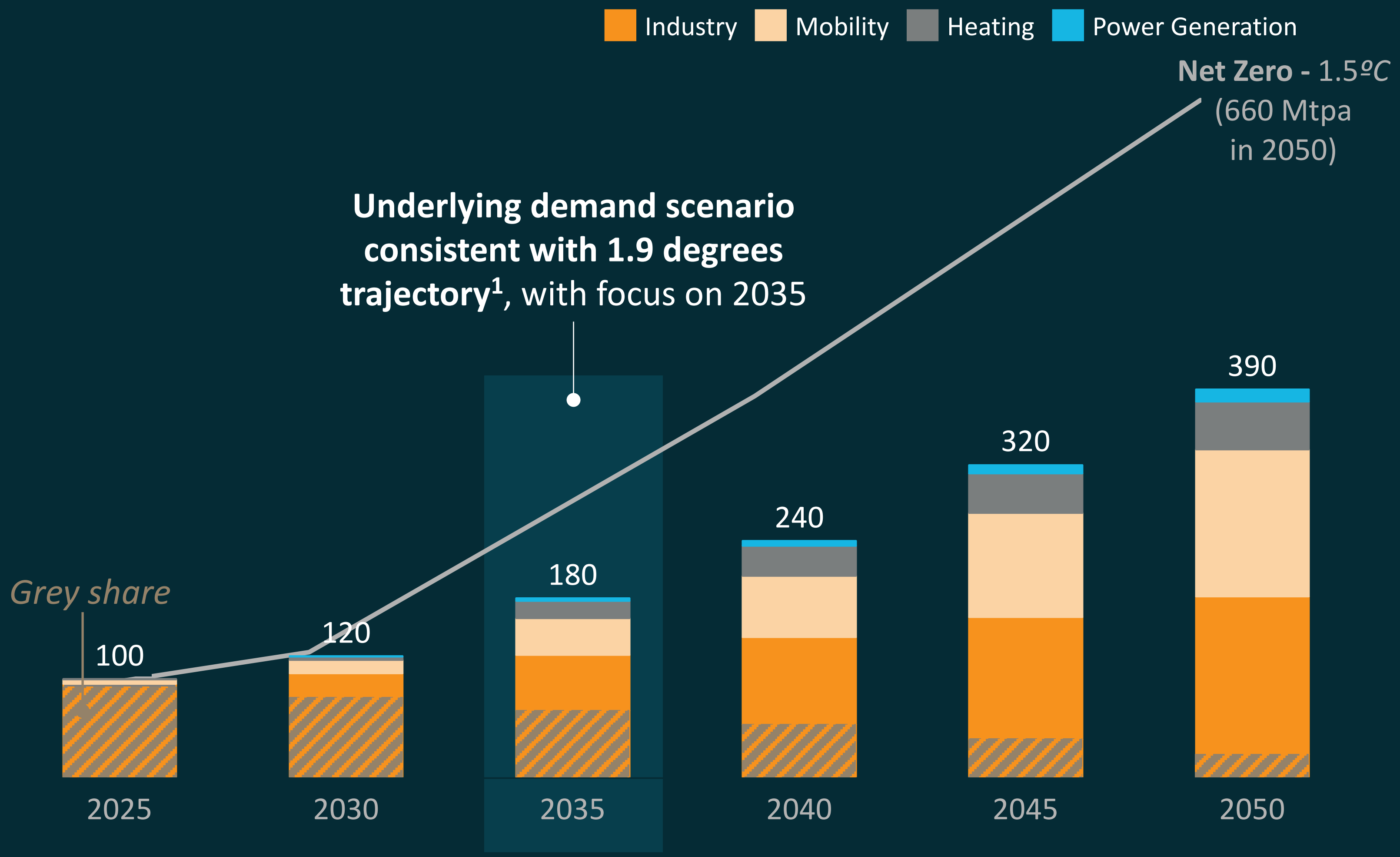
3-7 Mtpa

of demand could be unlocked by announced incentives by 2030 subject to their implementation

1. Excluding transportation costs – on "landed" basis, cost differential expected to be larger

>180 Mtpa hydrogen required by 2035 for the energy transition to stay on course

Required global demand for H_2 and derivatives, Mtpa grey and clean H_2 equivalent



180 Mtpa

of global demand for H_2 and derivatives required by 2035 to achieve longer term decarbonization ambitions in line with 1.9 degrees trajectory *(focus of this report)*

70%

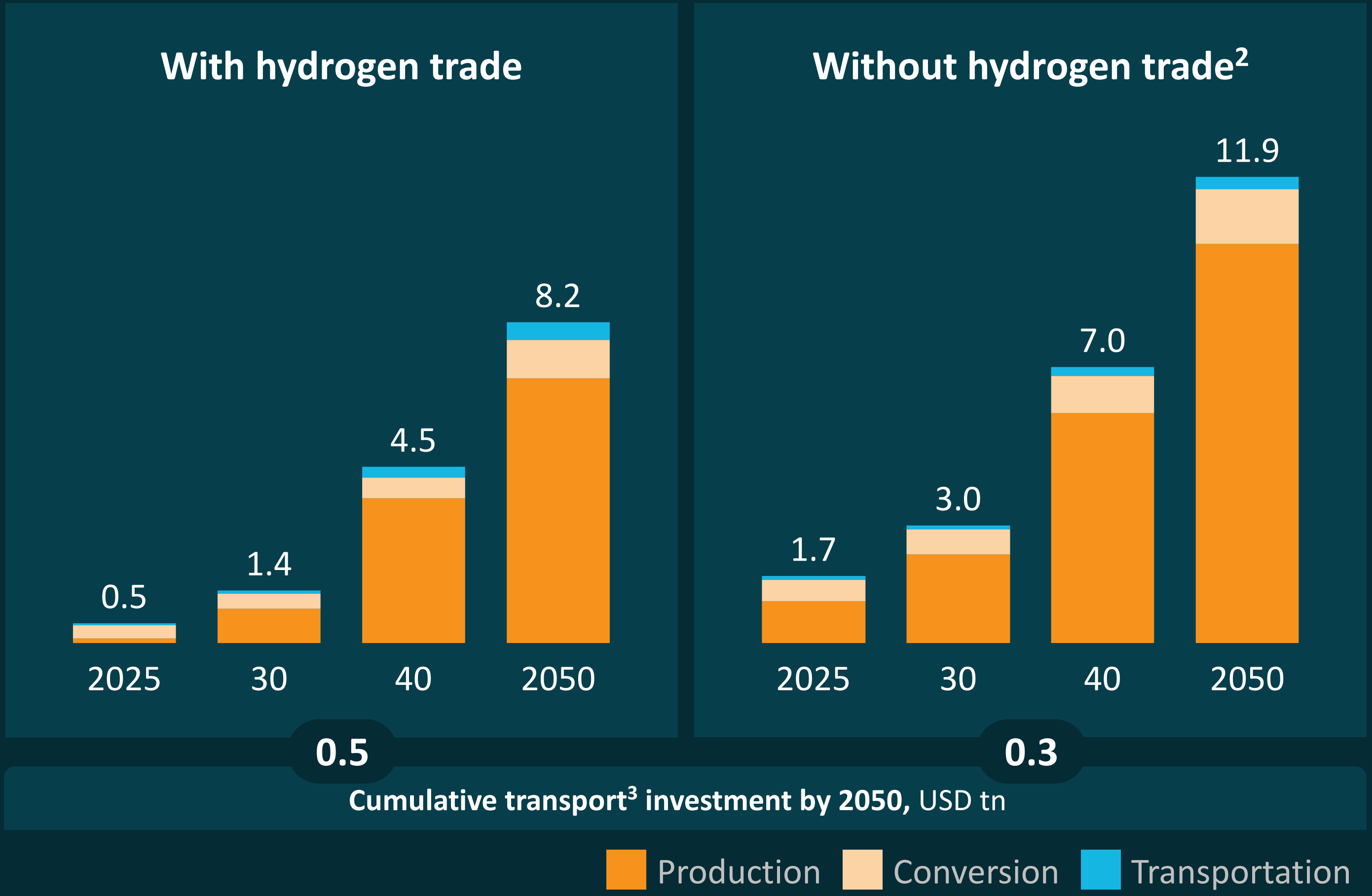
of H_2 demand required by industries which have no or limited alternative decarbonization options

1. The demand scenario predicts momentum towards further decarbonization across countries and sectors, driven by country-specific commitments to reach net-zero targets, but with significant hurdles to overcome (McKinsey Global Energy Perspective "Further Acceleration" scenario, 1.6 - 2.4 degrees)

Source: McKinsey Global Energy Perspective (2023)

USD 3.7 tn could be saved globally by 2050 through linking demand centers to regions with advantageous access to renewable and low-carbon energy resources

Cumulative capex investments[1] in H_2 and derivatives, USD tn



USD 3.7 tn

reduction in hydrogen-related investment[1] costs by 2050

USD 25 saved

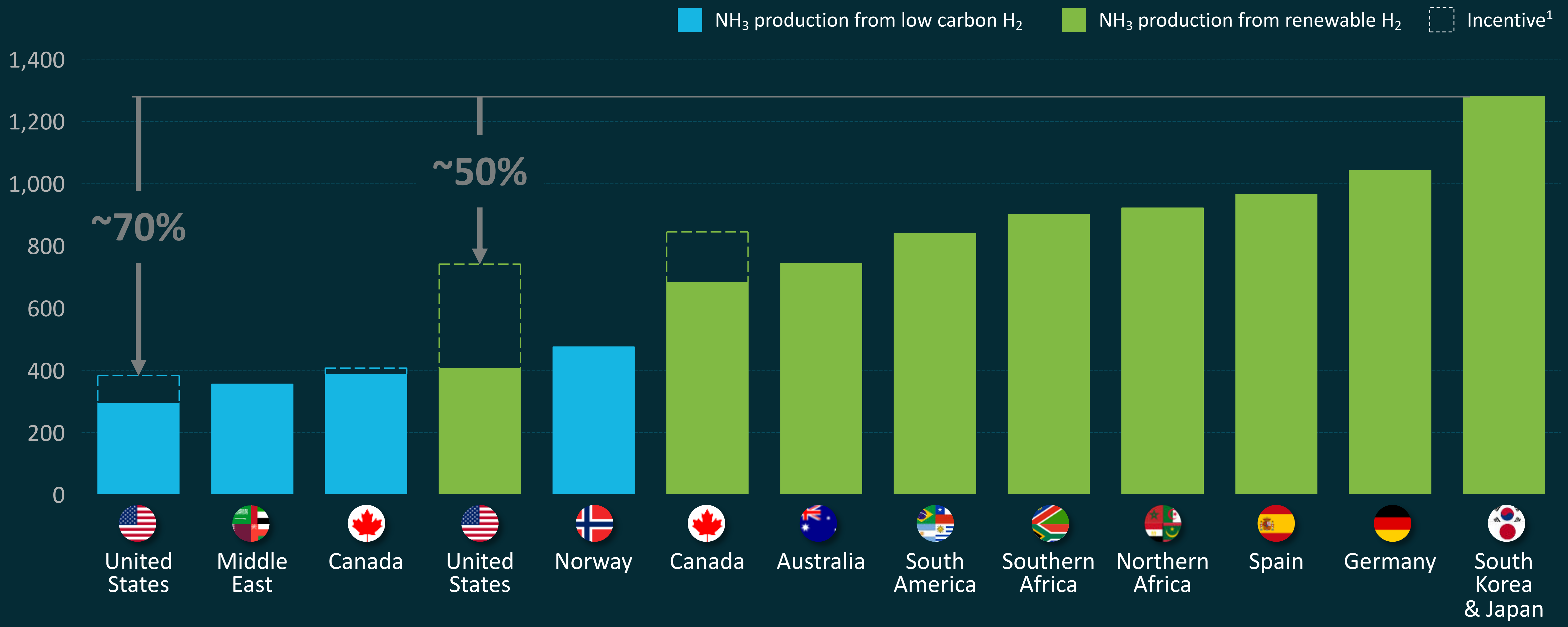
for every $1 invested in H_2 trade infrastructure through 2050

1. Capex incl. upstream renewables, low carbon plants, CCUS, electrolyser. Savings driven by exporters' lower cost renewables and low carbon endowment
2. Scenario where international trade is prohibited. Any region that would not be able to meet their demand due to production constraints have been given the option to build extra offshore wind at a cost equivalent to that of South Korea, among the higher unit costs.
3. For H_2 contains conversion, reconversion, domestic and international pipeline and shipping; for derivatives contains reconversion, domestic pipeline (i.e., H_2 to port for exports) and shipping

Source: Global Hydrogen Flows Model (December 2023)

Regions with abundant resource endowments can produce hydrogen and its derivatives at a lower cost

Global clean ammonia production cost curve – production by 2035 (2030 FID), USD/ton



1. Cost reduction due to national incentive schemes

Source: Global Hydrogen Flows Model (December 2023)

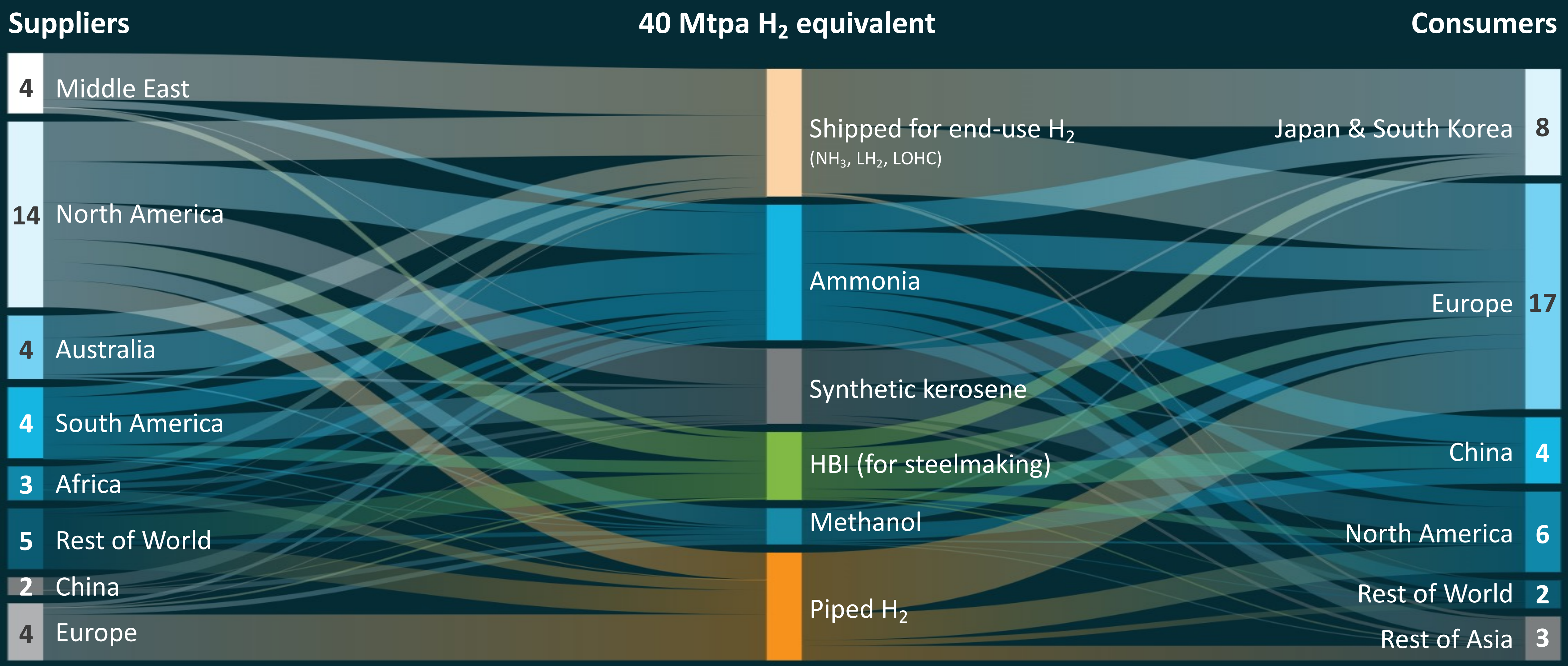
Hydrogen trade flows can connect all regions of the world by 2050

Europe, Japan, and South Korea are the main demand centers for interregional flows of hydrogen and derivatives

Source: Global Hydrogen Flows Model (December 2023)

By 2035, 40 Mtpa expected to be transported by ships or pipelines over long distance

Global clean hydrogen and derivatives long-distance trade flows, 2035

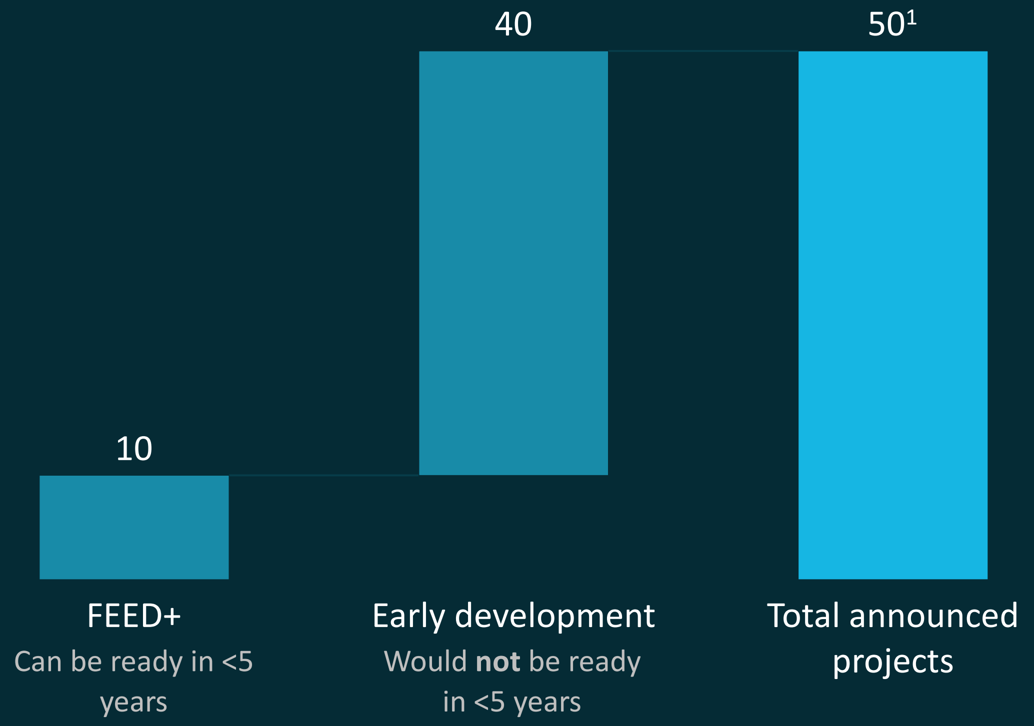


Source: Global Hydrogen Flows Model (December 2023)

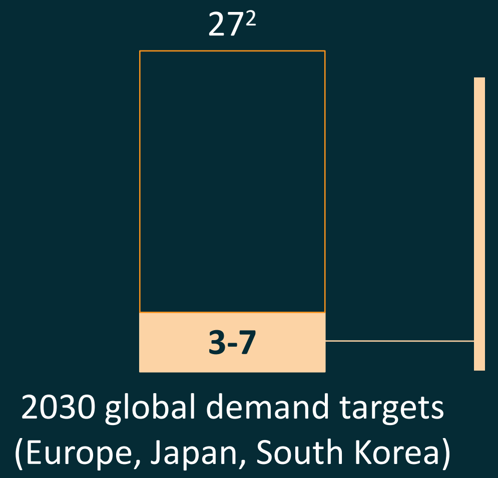
While projects on the supply side are maturing, implementation of mandated demand-side measures and incentives is critical to kick-start the market

Supply-side projects in advanced stages could cover the incentivized demand of 3-7 Mtpa in Europe, Japan and South Korea by 2030

Supply side: Global announced project pipeline



Demand side: Aspiration and support in core demand centers (Europe, South Korea, and Japan)



3-7 Mtpa incentivized and mandated demand

Estimates based on mandated demand in the EU[3] e.g., REDIII for industry subject to implementation at Member State level, and incentives for hydrogen and derivative imports in Japan and South Korea

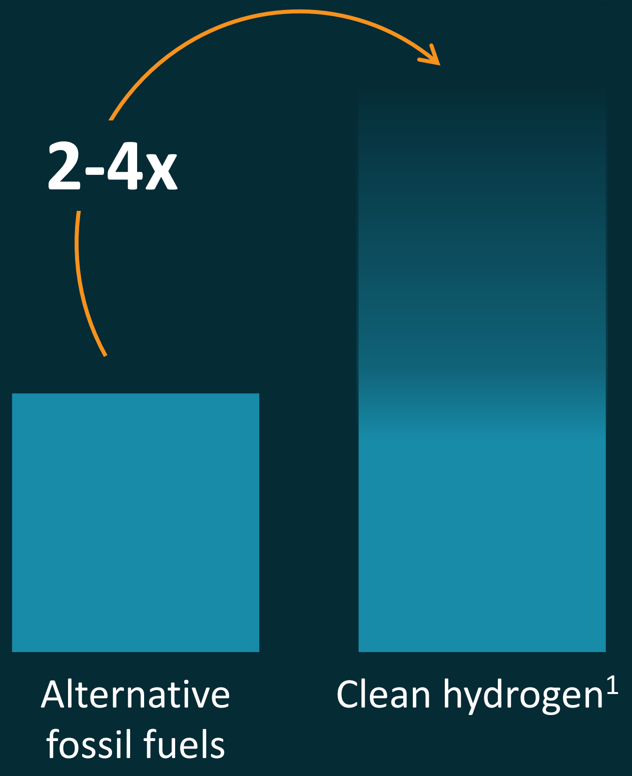
1. ~15 Mtpa produced in Europe, ~10 Mtpa produced in North America, ~7 produced in Latin America, ~6 Mtpa produced in Australia, ~2 Mtpa produced in Middle East and ~10 produced in Rest of World
2. 20 Mtpa target in EU, 3 Mtpa target in Japan and 3.9 Mtpa target in South Korea

Source: Project & Investment tracker as of Apr 2024

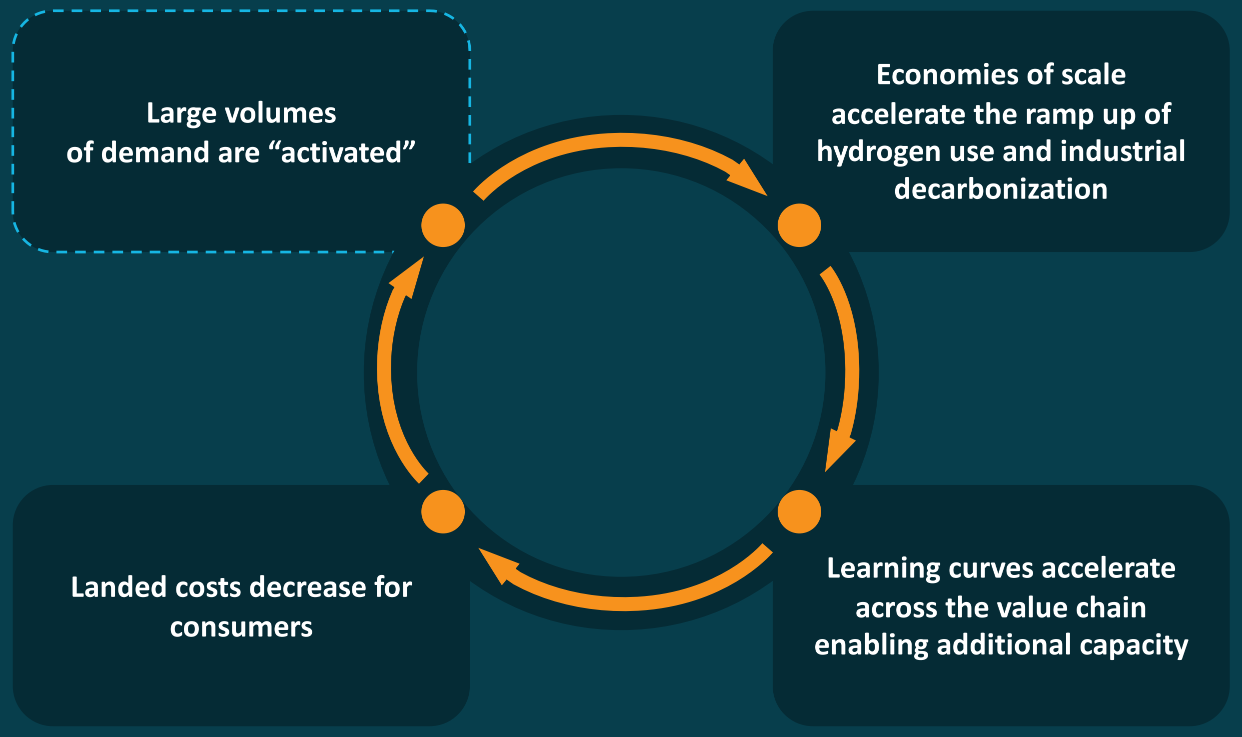
On a cost basis, clean hydrogen products are 2-4x more expensive than alternatives with higher carbon intensity

Differential between production costs for hydrogen and fossil alternatives, production by 2035 (2030 FID)

Cost differential between clean and grey remains high…



… however, scaling up the demand can accelerate the cost decrease



1. Without incentives – which can help bridge the gap

Source: Global Hydrogen Flows Model (December 2023)

There are 3 main unlocks that could enable and accelerate the hydrogen economy

Hydrogen "demand pull" is the key lever, supported by infrastructure development, global standards and mutually recognized certification schemes

	01	02	03
	Clarity, certainty and support for demand	**Infrastructure expansion, repurposing and buildout**	**Global standards and mutually recognized certification schemes**
WHY	A sufficiently **strong "demand-pull"** enables the business case and thus offtake commitments, drives investment decisions, and creates a "ripple effect" across the value chain **supporting project bankability**	**Strengthened infrastructure** (including repurposed or new pipelines, ships and ammonia crackers, storage) **and supporting technology scale-up** enables global supply and demand matching and **long-distance clean H_2 trade**	**Transparent frameworks** enable coherent global clean hydrogen and derivatives market by reducing transaction cost and market friction **facilitating deployment of large-scale clean hydrogen projects**
HOW	"Demand-pull" could be supported by creating **long-term incentives** for uptake of clean solutions and/or **leveling the playing field** between clean and higher carbon intensity solutions	**Expand global clean H_2 transport (pipeline and maritime) and storage capacity** by retrofitting, repurposing and expanding brownfield facilities as well as building infrastructure. **Develop transformation technology** and capacity for H_2 carrier	Development of the global industry standards for GHG emissions assessment of hydrogen on a life-cycle analysis basis, and for example, implementation of the COP28 Declaration of Intent on Mutual Recognition of Certification Schemes for Renewable and Low-Carbon

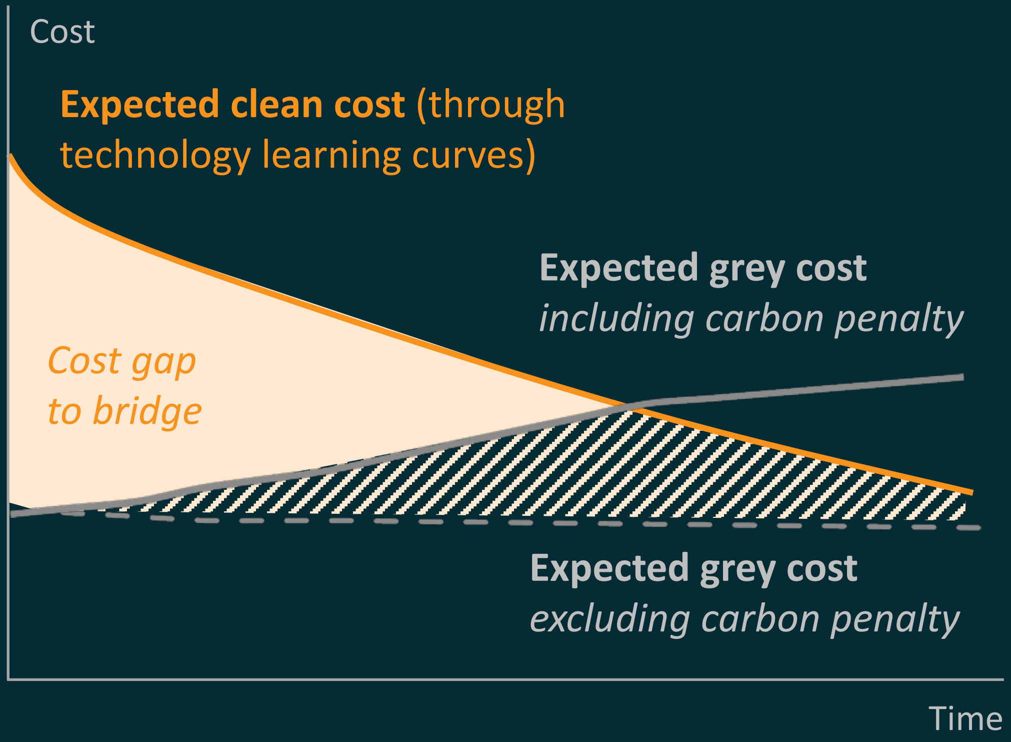
Clarity, certainty and support for demand

Certainty over the enabling frameworks and qualifications for hydrogen is key for getting projects over the line

Unlock

01

Illustrative product cost gap between clean hydrogen vs. grey alternatives



Examples of existing mechanisms to bridge the gap

Long-term offtake incentives

CfDs and auction-based supply contracts for the duration of 15-20 years (e.g., Japan's 15-year CfD)

Mandated industry targets (e.g., EU RED III[1])

Carbon pricing to level the playing field

Cap-and-trade systems, carbon taxes and carbon border measures (e.g., Europe ETS and CBAM)

1. Subject to transposition into national legislation by the EU Member State

Source: Global Hydrogen Flows Model (December 2023)

Appendices to the report

Appendix 1: Snapshots - Overview

Appendix 2: Snapshots – Supply hubs

Appendix 3: Snapshots – Demand hubs

This report provides an expanded analysis for selected import / export hubs

Other export hubs | Highlighted trade routes | Other trade routes | Existing shipping corridors

Export hubs

E1 North America
Expanding

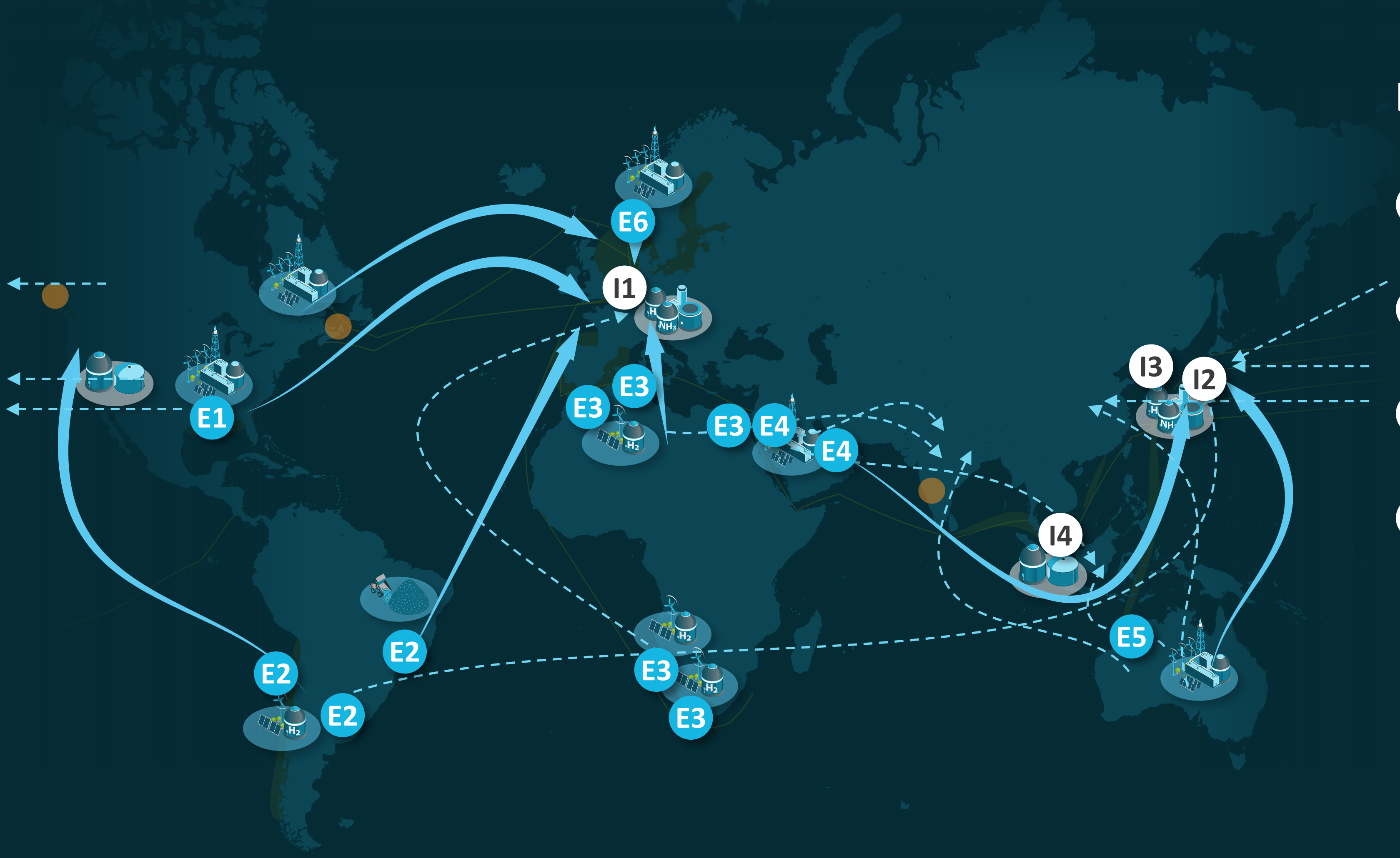
E2 South America
Building/Specializing

E3 Africa
Building

E4 Middle East
Building

E5 Australia
Expanding

E6 Norway
Expanding



Import hubs

I1 NW Europe
Multiple products

I2 Japan
Multiple products

I3 South Korea
Multiple products

I4 Singapore
Specialty product

Source: Global Hydrogen Flows Model (December 2023)

In the report, we assessed the characteristics of the export hubs, as well as the infrastructure required to unlock their potential

Export hubs in 2035

E1 US Gulf Coast (North America) Expanding

2.2 Mtpa of H_2e of exports in 2035, mainly shipped H_2 carriers and ammonia end-use to Northwestern Europe, Japan, and South Korea

In-land H_2 and CO_2 transportation is partially supported by **existing pipelines**

Export infrastructure for **ammonia and liquid H_2 needs expansion** from 0.5 to 2.4 Mtpa H_2e

E2 South America Building/Specializing

Chile targets to export 3.0 Mtpa of H_2e, mostly as ammonia and syn-kerosene, greenfield ammonia infrastructure required

Brazil, Argentina and Uruguay could become specialized exporters, aiming to export 1.1 Mtpa H_2e, mainly in the form of syn-kerosene and HBI for steelmaking

Existing infrastructure from iron ore and kerosene can be utilized, but buildout of CO_2 infrastructure needed

E3 Africa Building

Aims to export 2.4 Mtpa H_2e, with **0.9 Mtpa** expected via **H_2 pipelines to Europe**

Greenfield infrastructure and projects are still in **early stages**

E4 Middle East Building

4.4 Mtpa H_2e of exports in 2035, mainly shipped H_2 carriers and ammonia end-use to Japan, South Korea and Europe

Export terminals and **ports are being built close to production sites**

E5 Australia Expanding

Targets to export 4.4 Mtpa H_2e in 2035, most shipped H_2 carriers and ammonia end-use to Japan and South Korea

Expansion of liquid H_2 and ammonia export capacity from **0.2 Mtpa to 4.1 Mtpa H_2 needed to cater for increased export volumes**

E6 Norway Expanding

Aims to supply Europe with 2.4 Mtpa H_2 through new or repurposed pipelines connected to Northwestern Europe, and could become Europe**'s top H_2 supplier**

Source: Global Hydrogen Flows Model (December 2023)

We also assessed the characteristics of the import hubs, as well as the infrastructure needed to deliver on the transition

Import hubs in 2035

I1 NW Europe Multiple products

Strong growth in shipped **H_2 carriers and ammonia end-use** imports – **75%** covered by Norway, Middle East, and the North America

Large **investment in transformation technology** required. **24,800 km pipeline needs to be built** or repurposed to unlock the "European backbone" – the expected main delivery route of H_2 to end-users. For remaining products other transport means needs to be repurposed and expanded

I2 Japan Multiple products

Strong growth of shipped H_2 carriers and ammonia end-use import could be driven by the **power and transport sector**, primarily covered by the Middle East, Australia and North America

Investment **need for 2 Mtpa H_2e transformation technology**, and **3 Mtpa H_2e offloading** expansion. As industrial clusters are close to shore and ports, last-mile infrastructure need is minor

I3 South Korea Multiple products

Strong growth in shipped H_2 carriers and ammonia end-use import could be driven by the **power and transportation sector**, primarily covered by North America, Australia, Middle East, and Chile

Investment need for **2 Mtpa H_2e transformation technology**, 3 Mtpa H_2e offloading expansion, and 100 kt storage. For transportation to end-users there is potential to repurpose some of the **5,000 km existing gas pipelines** or expand truck network with 2,000+ vehicles

I4 Singapore Specialty product

Emerging as a **key port for green fuels** – already with significant investments in methanol bunkering and terminal capacity. Additional capacity for offloading and storing of 0.2 Mtpa H_2e needed before 2035

Limited domestic demand and production

Source: Global Hydrogen Flows Model (December 2023)

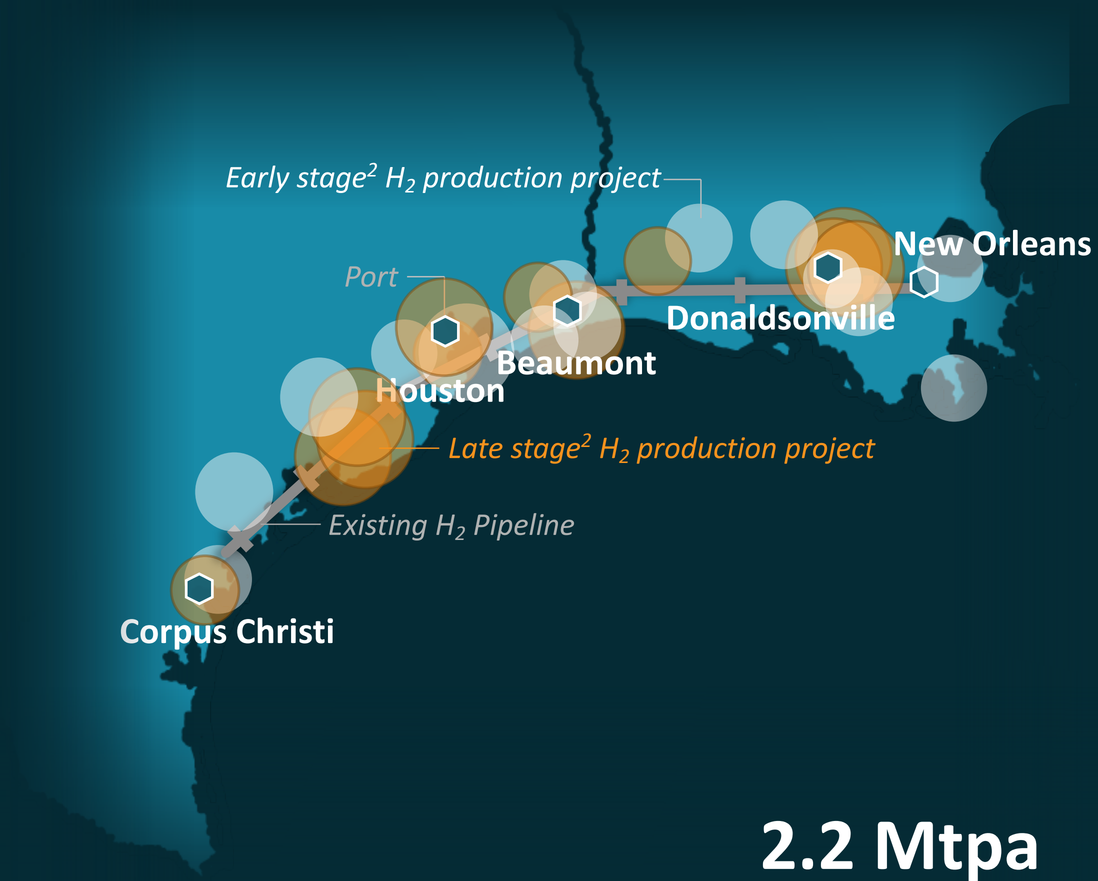
Appendix 1: Snapshots - Overview

Appendix 2: Snapshots – Supply hubs

Appendix 3: Snapshots – Demand hubs

US Gulf Coast: Supply of hydrogen for export

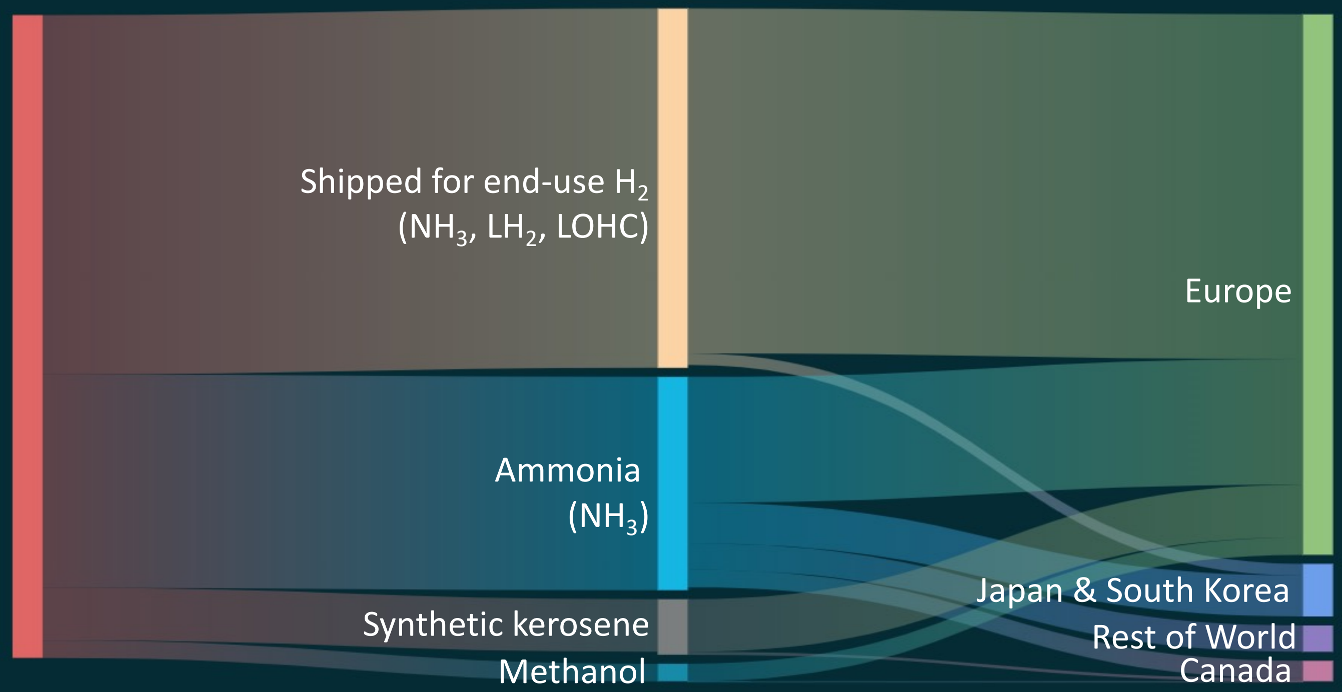
Production projects located close to ports, with 90% of exports targeting Europe or Asia



2.2 Mtpa

H_2e exports in 2035

Export flows of clean H_2 & derivatives in 2035[1]



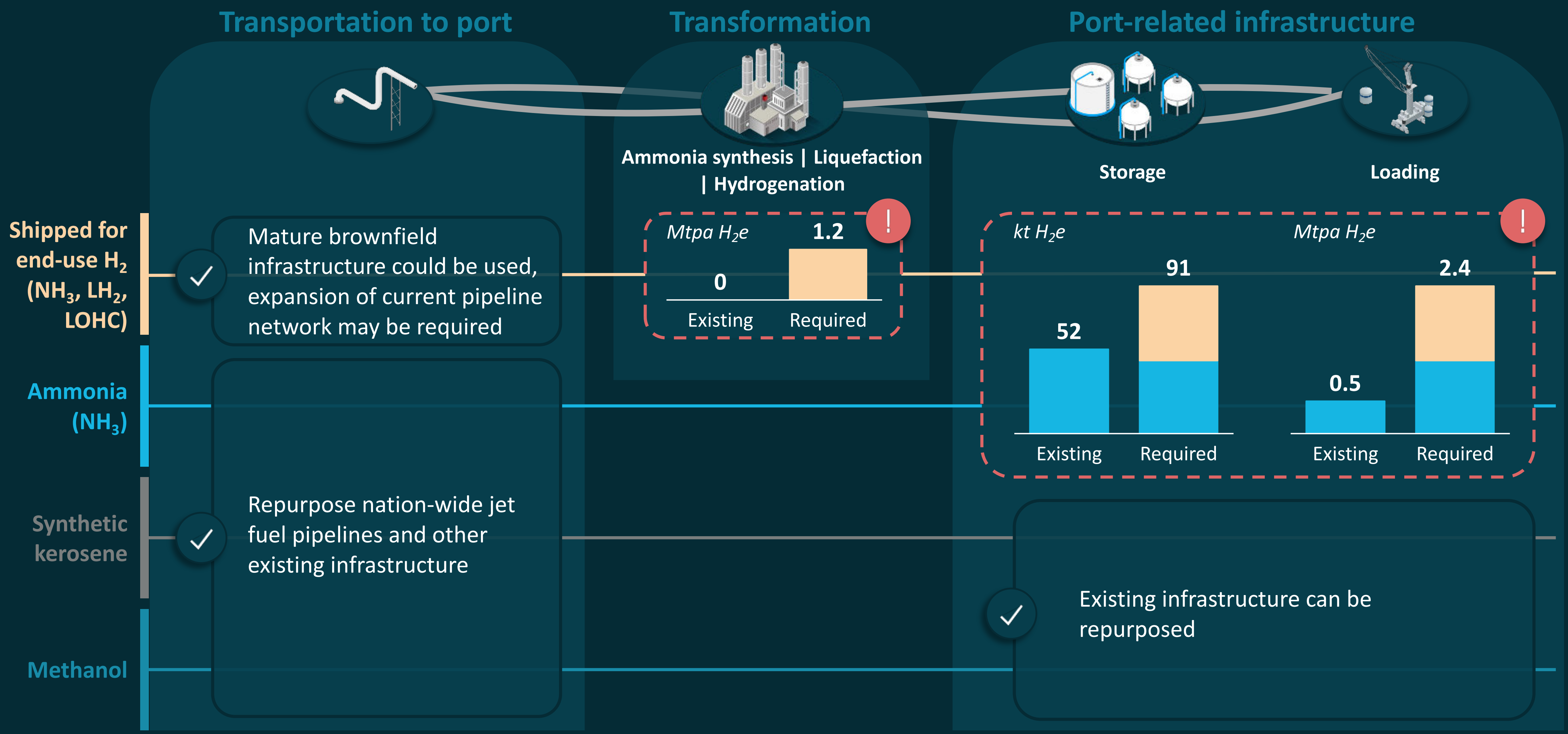
1.2 Mtpa	4.0 Mtpa	0.4 Mtpa	0.5 Mtpa
shipped H_2	ammonia	syn-kerosene	methanol

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees) ; including renewable and low-carbon H_2 supply
2. Early stage includes projects that are announced or in feasibility studies, late stage includes projects in FEED or beyond

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

US Gulf Coast: Infrastructure requirements by 2035

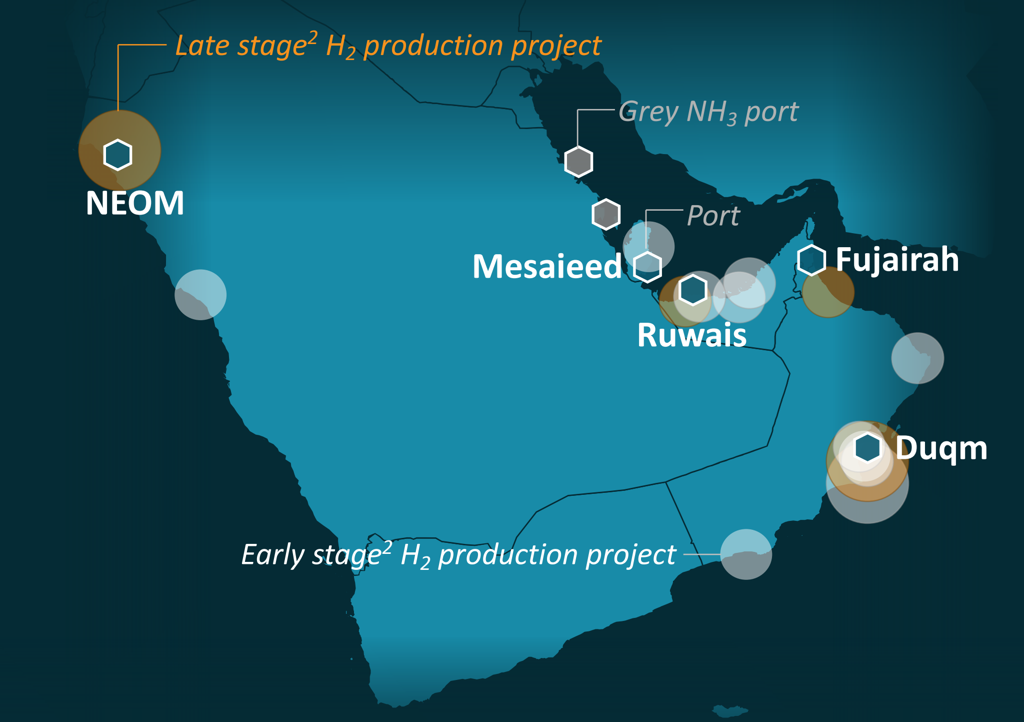
Mature brownfield infrastructure – 5x expansion needed to cater for greater export volumes of NH_3 and LH_2



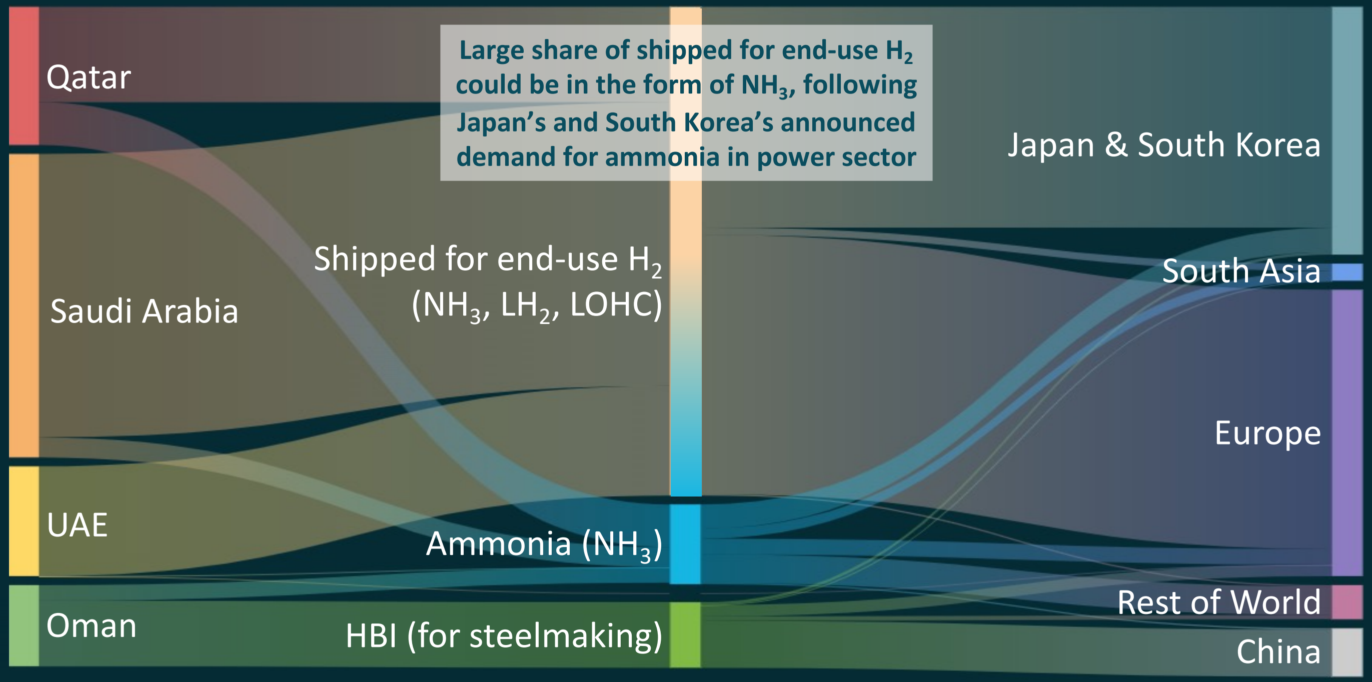
Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Middle East: Supply of hydrogen for export

>80% of exports targeting Europe, Japan, and South Korea with the largest projects located close to planned terminals



Export flows of clean H_2 & derivatives in 2035[1], Mtpa H_2e



4.4 Mtpa
H_2e exports in 2035

3.4 Mtpa shipped H_2

3.4 Mtpa ammonia

6.9 Mtpa HBI (for steel)

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply
2. Early stage includes projects that are announced or in feasibility studies, late stage includes projects in FEED or beyond

Source: Global Hydrogen Flows Model (December 2023), Project & Investment tracker as of Apr 2024

Middle East: Infrastructure requirements by 2035

>3.4 Mtpa H_2e of transformation capacity and 3.7 Mtpa newbuild NH_3 export capacity needs to be built

Transportation to port

Shipped for end-use H_2 (NH_3, LH_2, LOHC)

Ammonia (NH_3)

✓ Production to be built close to ports, including last mile delivery infrastructure (e.g., jetty for ammonia)

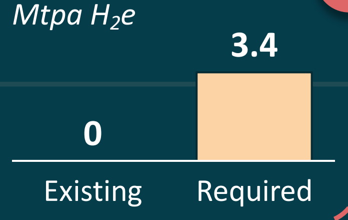
HBI

✓ Existing iron ore infrastructure can be repurposed

Transformation

Ammonia synthesis | Liquefaction | Hydrogenation

!

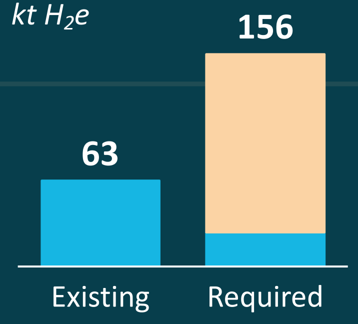


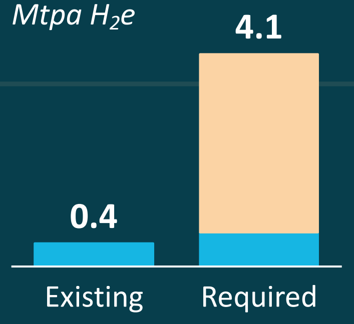
Port-related infrastructure

Storage

Loading

!





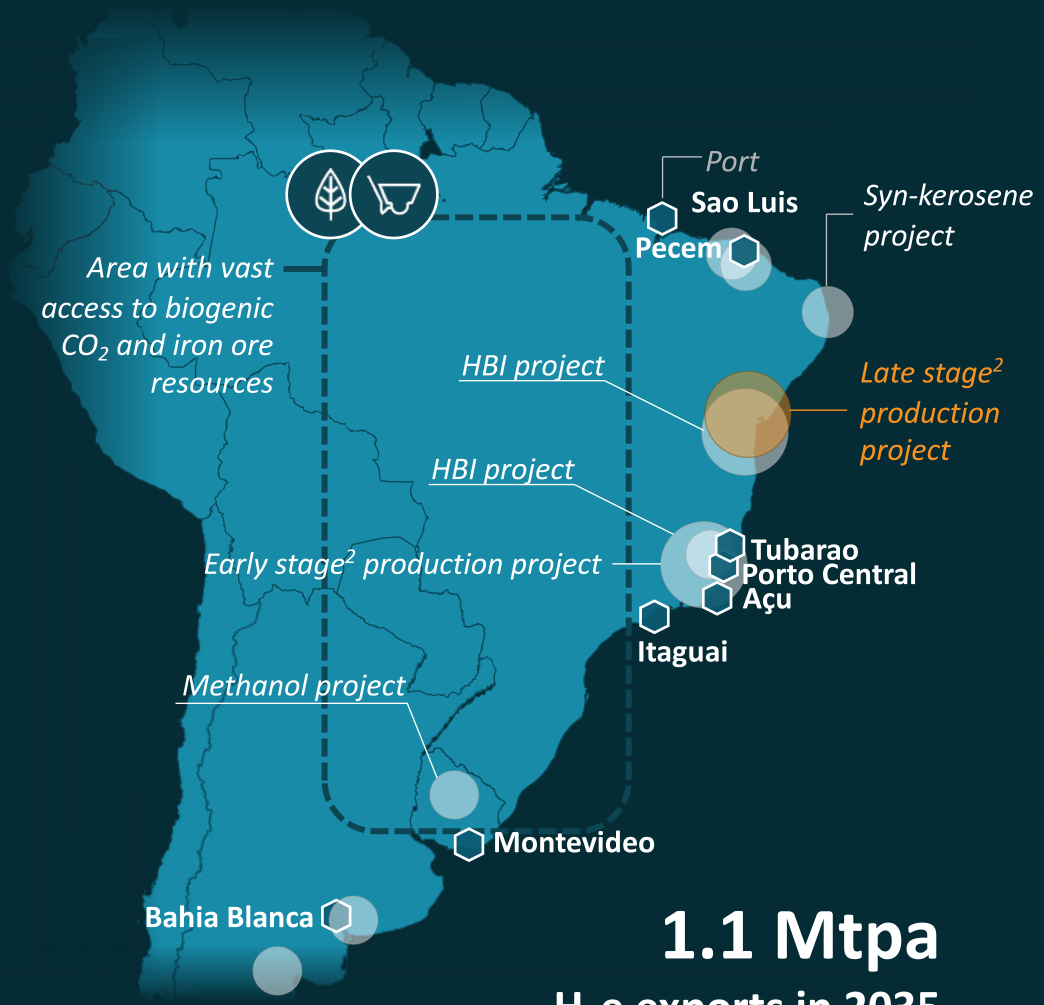
Capacity for clean products would likely be built greenfield, given location compared to current infrastructure

✓ Existing iron ore infrastructure can be repurposed

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Brazil, Argentina, Uruguay: Supply of hydrogen for export

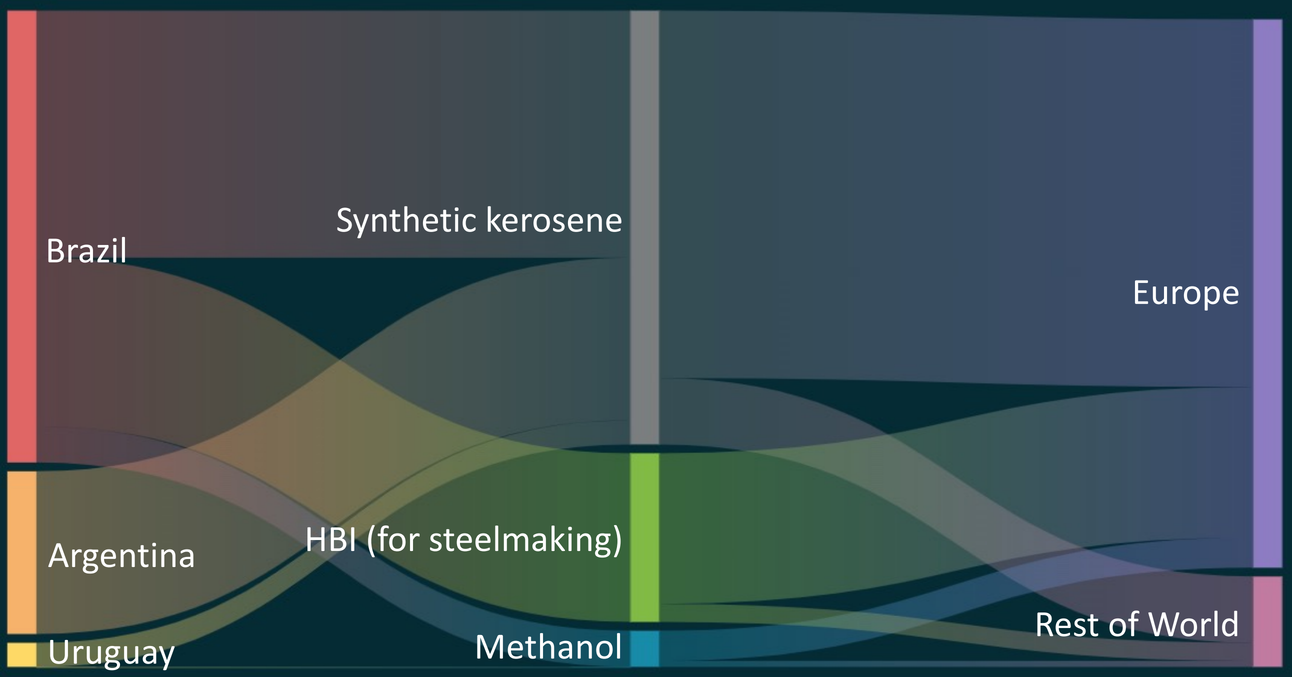
>80% specialized product exports targeting Europe, taking advantage of vast iron ore and biogenic CO_2 access



1.1 Mtpa

H_2e exports in 2035

Export flows of clean H_2 & derivatives in 2035[1], Mtpa H_2e



1.6 Mtpa syn-kerosene

5.2 Mtpa HBI (for steel)

0.5 Mtpa methanol

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply
2. Early stage includes projects that are announced or in feasibility studies, late stage includes projects in FEED or beyond

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Brazil, Argentina, Uruguay: Infrastructure requirements by 2035

Existing infrastructure from iron ore and kerosene can be utilized, but buildout of biogenic CO_2 infrastructure needed

	Transportation of input factors	Transportation to port	Port-related infrastructure
HBI (For steelmaking)		✓ Leverage existing iron ore infra, with 300+ Mtpa of train transport capacity and ~50 Mtpa of slurry pipeline	✓ >350 Mtpa of existing iron ore export capacity from 18 specialized ports that can be repurposed
Synthetic kerosene	! *CO_2 transport, Mtpa* — Existing: 0; Required: 4-6	✓ 700+ tank trucks or 20+ oil barges needed for such volumes – current infra can be used	✓ 80+ Mtpa of existing kerosene and oil products export infrastructure to use
Methanol	! *CO_2 transport, Mtpa* — Existing: 0; Required: 0.5-1	! 100+ methanol trucks or 5+ barges needed to transport product to port	✓ Existing chemical export infrastructure can be repurposed (>USD 15 bn of exports annually from region with well developed associated infrastructure)

Source: Global Hydrogen Flows Model (December 2023)

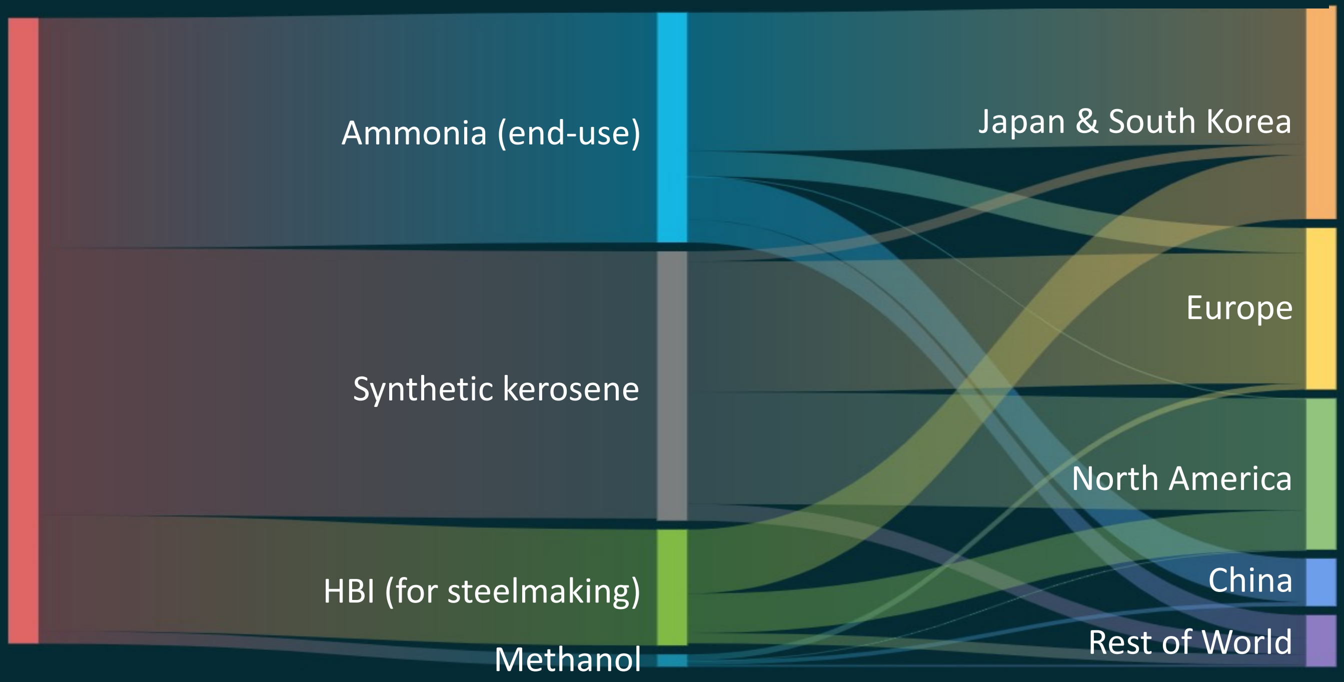
Chile: Supply of hydrogen for export

Specialized projects centered around existing commodity export hubs, while ammonia hubs in north and south are being built, with 60% of exports targeting Japan, South Korea and Europe

3.0 Mtpa

H_2e exports in 2035

Export flows of clean H_2 & derivatives in 2035[1], Mtpa H_2e



5.7 Mtpa ammonia

2.9 Mtpa syn-kerosene

10.3 Mtpa HBI (for steel)

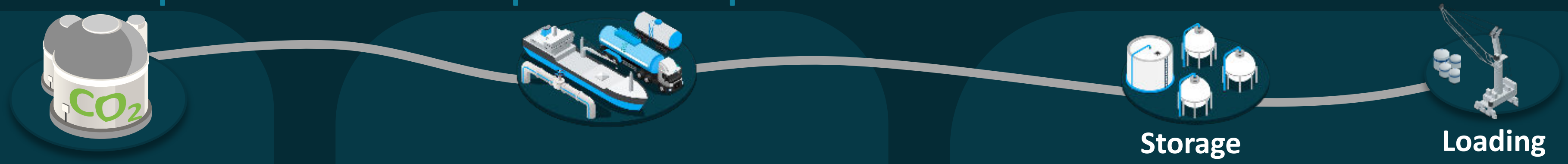
0.5 Mtpa methanol

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply
2. Early stage includes projects that are announced or in feasibility studies, late stage includes projects in FEED or beyond

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Chile: Infrastructure requirements by 2035

Buildout of ammonia terminals for 1 Mtpa of exports and 10 Mtpa of CO_2 transportation needed



Transportation of input factors

Ammonia (NH_3) / **Synthetic kerosene** / **Methanol** / **HBI (for steelmaking)**

CO_2 transport, Mtpa (!)

Existing	Required
0	10

Transportation to port

- Ammonia (NH_3): ✓ Production to be built close to ports
- Synthetic kerosene, Methanol, HBI (for steelmaking): ✓ Existing infrastructure can be repurposed

Port-related infrastructure

Storage / **Loading** (!)

kt H_2e

Existing	Required
0	38

Mtpa H_2e

Existing	Required
0	1.0

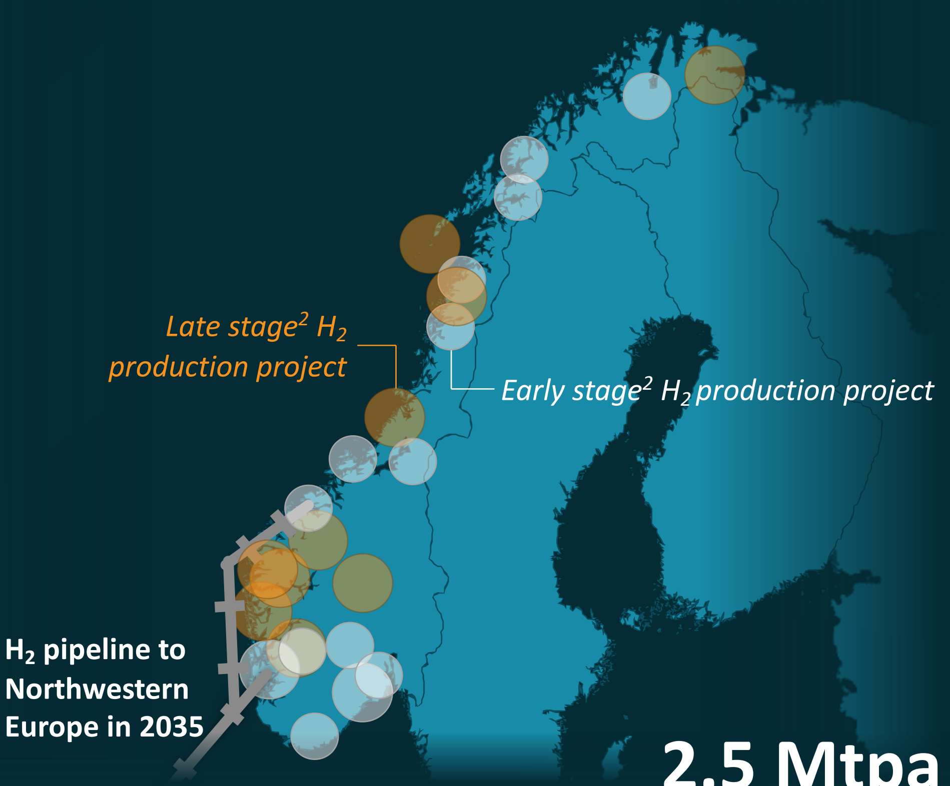
Greenfield archetype that needs to build out export infrastructure

✓ Reuse existing infrastructure, e.g., from oil products for syn-kerosene, iron ore for HBI and chemical products for methanol

Source: Global Hydrogen Flows Model (December 2023)

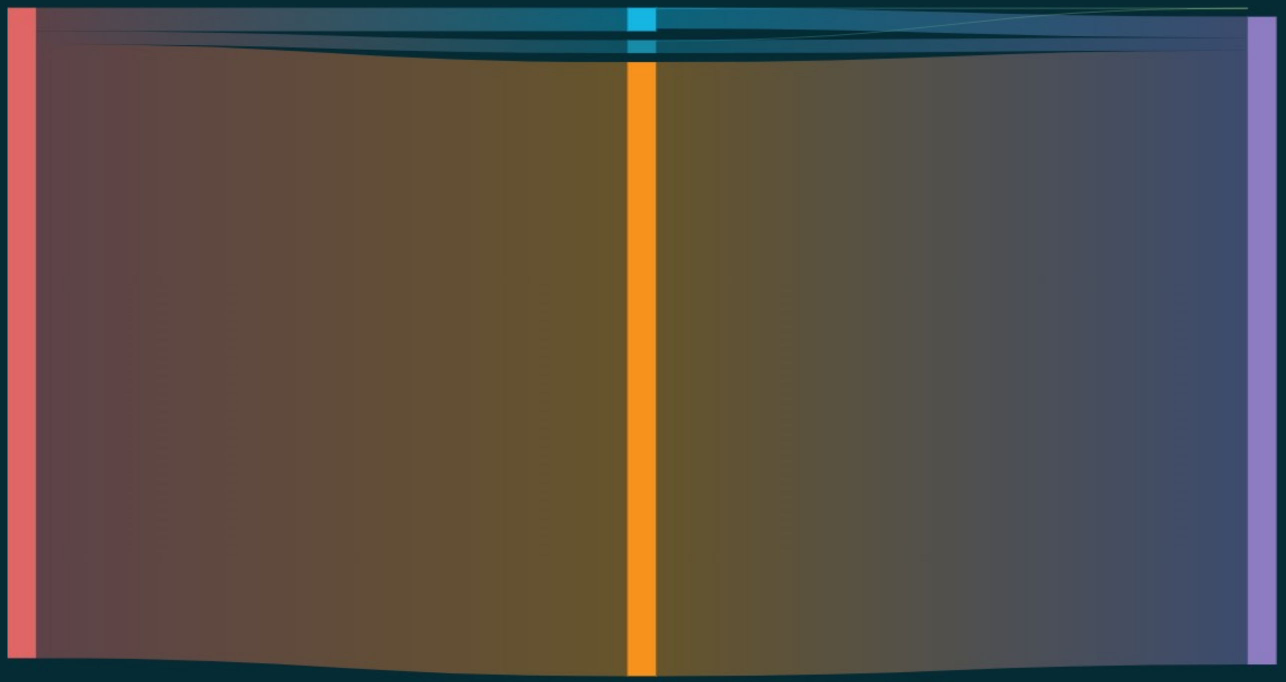
Norway: Supply of hydrogen for export

Norway could be one of Europe's top supplier of hydrogen with 2.4 Mtpa piped H_2 to Northwestern Europe



2.5 Mtpa
H_2e exports in 2035

Export flows of clean H_2 & derivatives in 2035[1], Mtpa H_2e



2.4 Mtpa	0.6 Mtpa	0.3 Mtpa
piped H_2	ammonia	methanol

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply
2. Early stage includes projects that are announced or in feasibility studies, late stage includes projects in FEED or beyond

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Norway: Infrastructure requirements by 2035

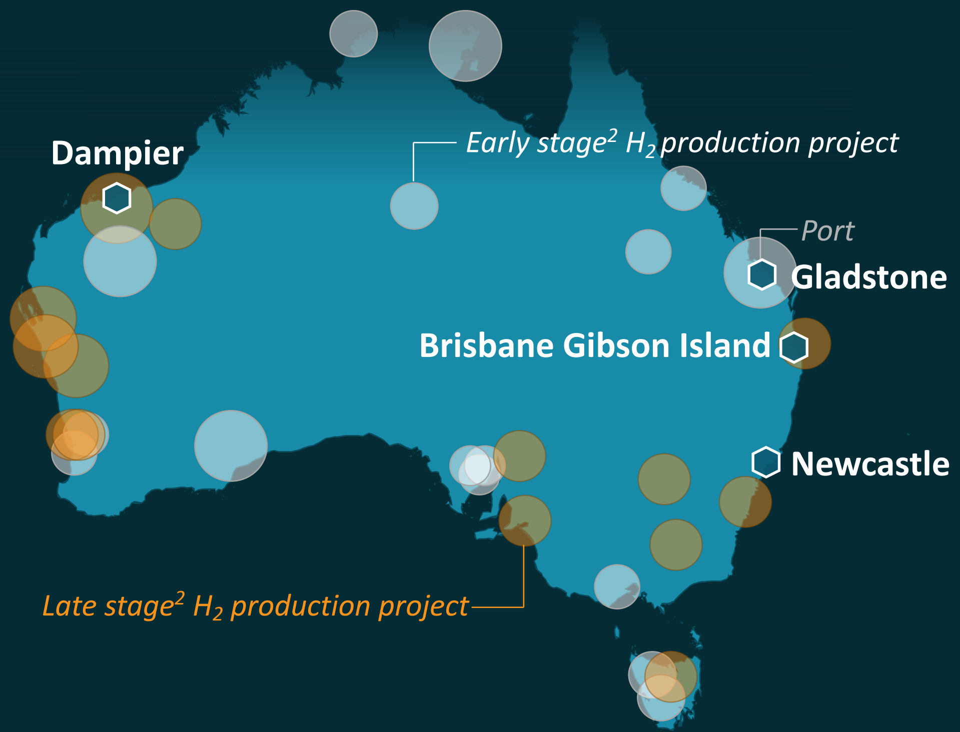
4 Mtpa H_2 pipeline capacity planned from Western Norway to Northwestern Europe

	Transportation to pipeline	Pipeline
Piped H_2	✓ Production expected to happen on-site at the starting points of the pipeline in Kårstø, Mongstad and Nyhamna	! **4 Mtpa** of H_2 pipeline capacity expected to be built from Nyhamna, Mongstad and Kårstø in Norway to Dornum or Wilhelmshaven in Germany In total 1,250+ km of pipeline needed, discussions in place regarding how much would be repurposed vs. newbuilt Pipeline would connect to the German H_2 network, including H_2ercules

Source: Press search

Australia: Supply of hydrogen for export

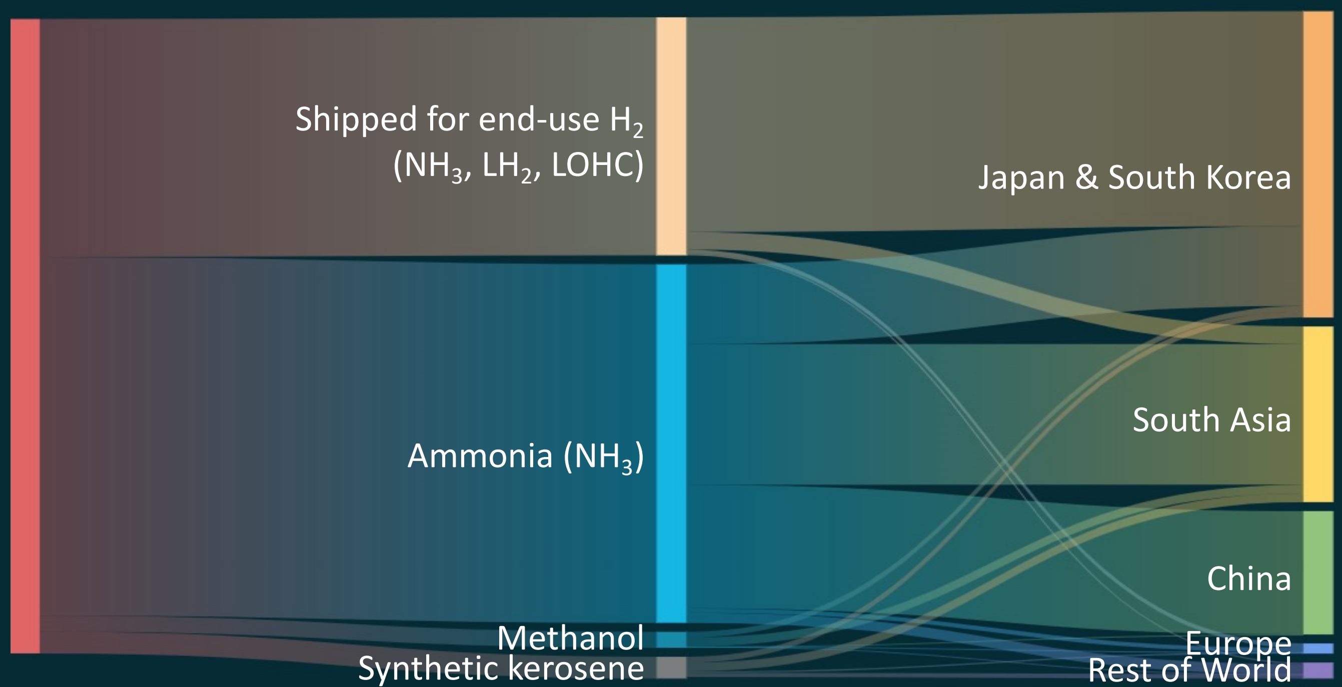
50% of exports target Japan and South Korea, and 60% could be for ammonia end-use



4.4 Mtpa

H_2e exports in 2035

Export flows of clean H_2 & derivatives in 2035[1], Mtpa H_2e



1.6 Mtpa shipped H_2	14.2 Mtpa ammonia	0.5 Mtpa methanol	0.2 Mtpa syn-kerosene

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply
2. Early stage includes projects that are announced or in feasibility studies, late stage includes projects in FEED or beyond

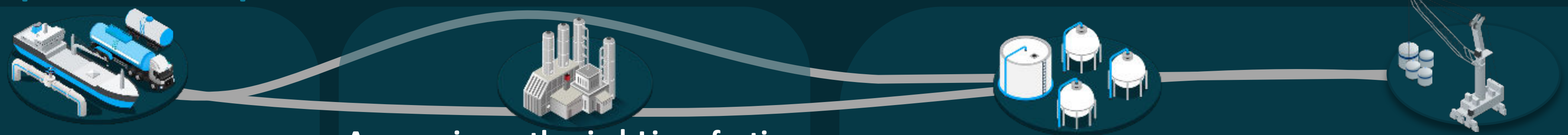
Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Hydrogen Council McKinsey & Company

Australia: Infrastructure requirements by 2035

Export infrastructure for ammonia and liquid H_2 needs a >20x capacity expansion

Transportation to port | Transformation | Port-related infrastructure



Shipped for end-use H_2 (NH_3, LH_2, LOHC)

- Transportation to port: ✓ Clean production projects likely to be co-located with export terminals, similar as for Australian ammonia production today
- Transformation – **Ammonia synthesis | Liquefaction | Hydrogenation** (!): *Mtpa H_2e* – Existing: 0; Required: 1.6
- Port-related infrastructure (!):
  - **Storage** – *kt H_2e* – Existing: 29; Required: 158
  - **Loading** – *Mtpa H_2e* – Existing: 0.2; Required: 4.1

Ammonia

Methanol

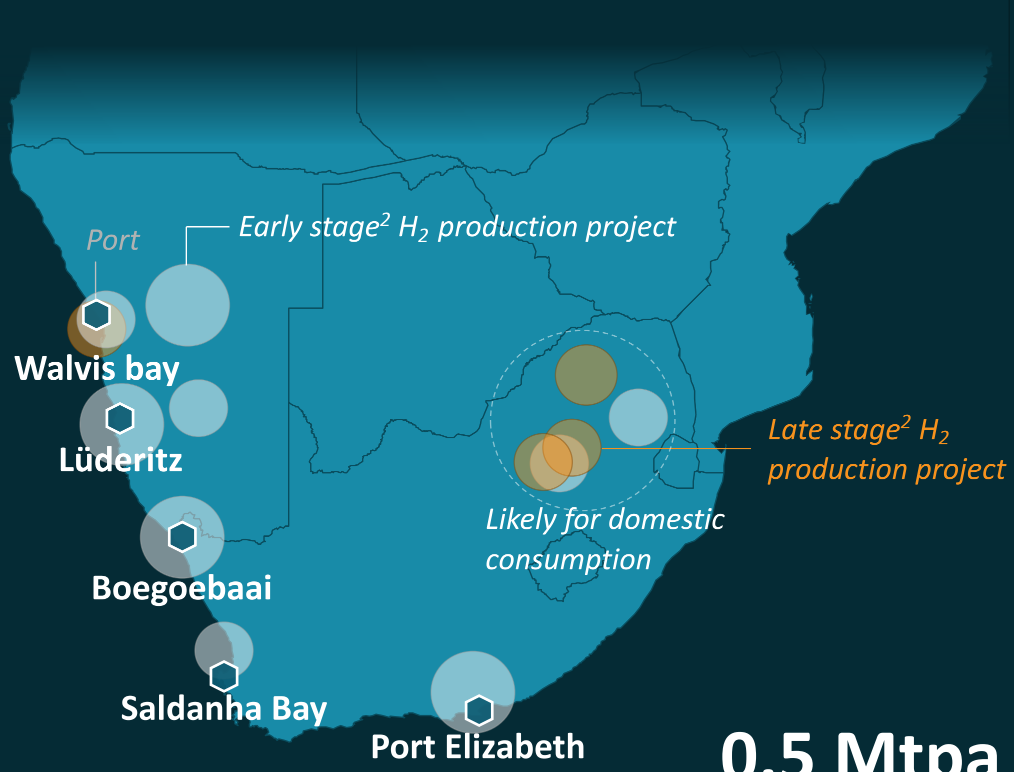
Synthetic kerosene

- Transportation to port: ✓ Limited volumes, for which existing infrastructure can be repurposed
- Port-related infrastructure: ✓ Limited volumes, for which existing infrastructure can be repurposed

Source: Global Hydrogen Flows Model (December 2023)

Southern Africa: Supply of hydrogen for export

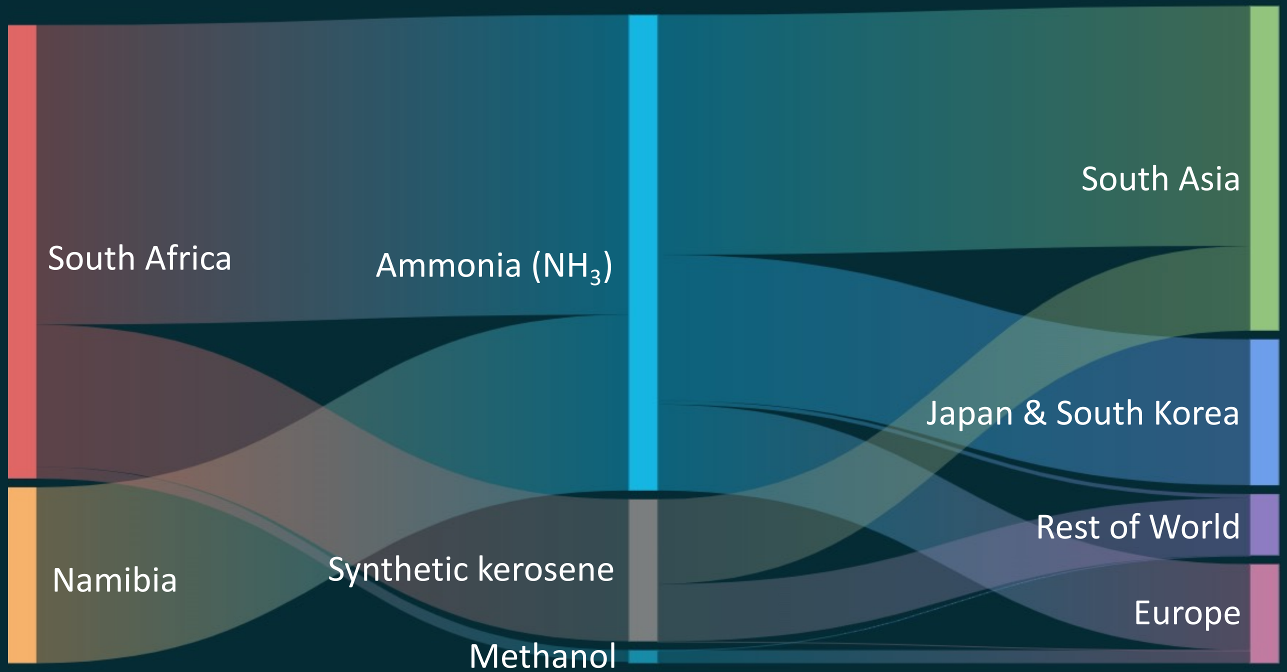
40% exports target Japan, South Korea and Europe, with largest projects co-located with planned export terminal



0.5 Mtpa

H_2e exports in 2035

Export flows of clean H_2 & derivatives in 2035[1], Mtpa H_2e



2.3 Mtpa ammonia

0.2 Mtpa syn-kerosene

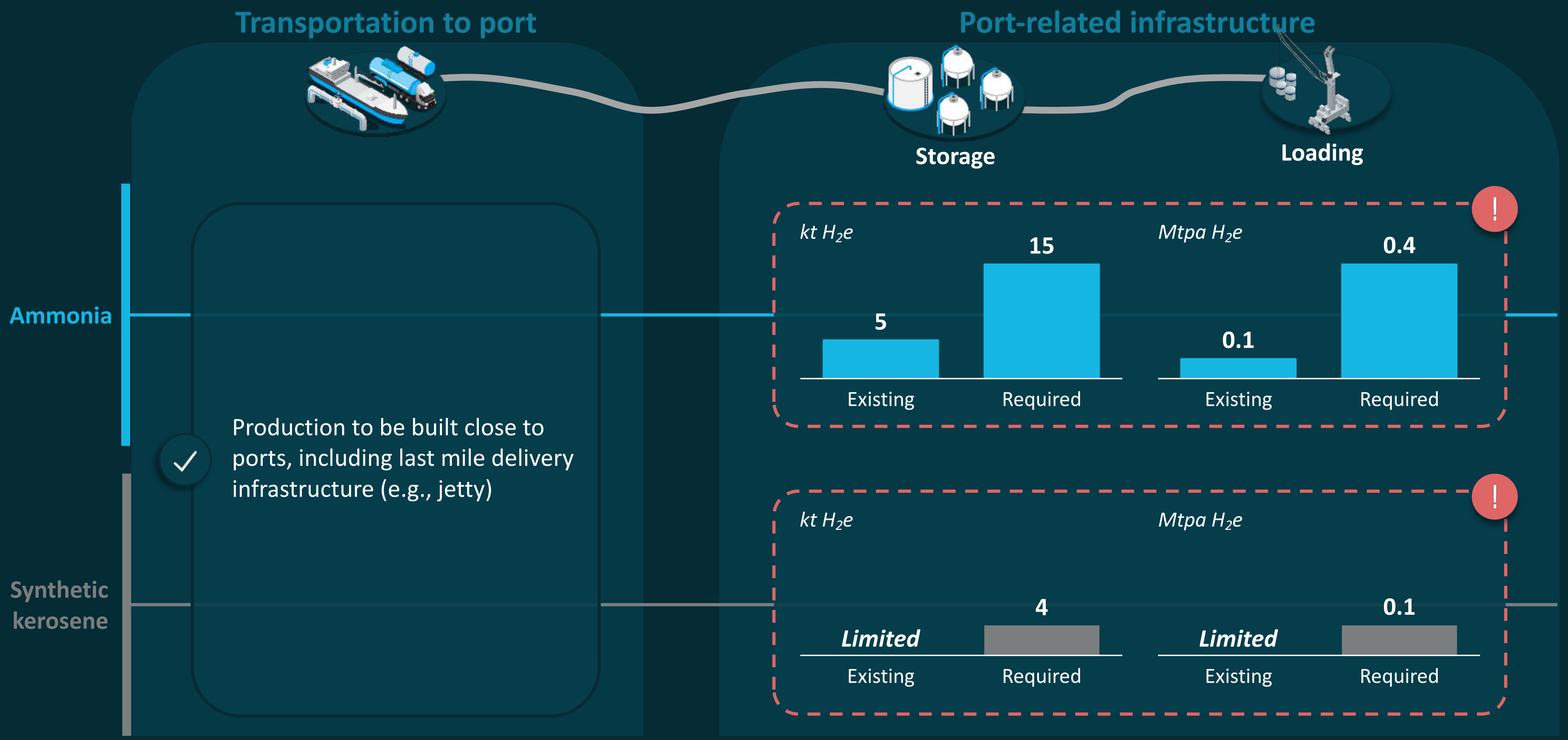
<0.1 Mtpa methanol

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees) ; including renewable and low-carbon H_2 supply
2. Early stage includes projects that are announced or in feasibility studies, late stage includes projects in FEED or beyond

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Southern Africa: Infrastructure requirements by 2035

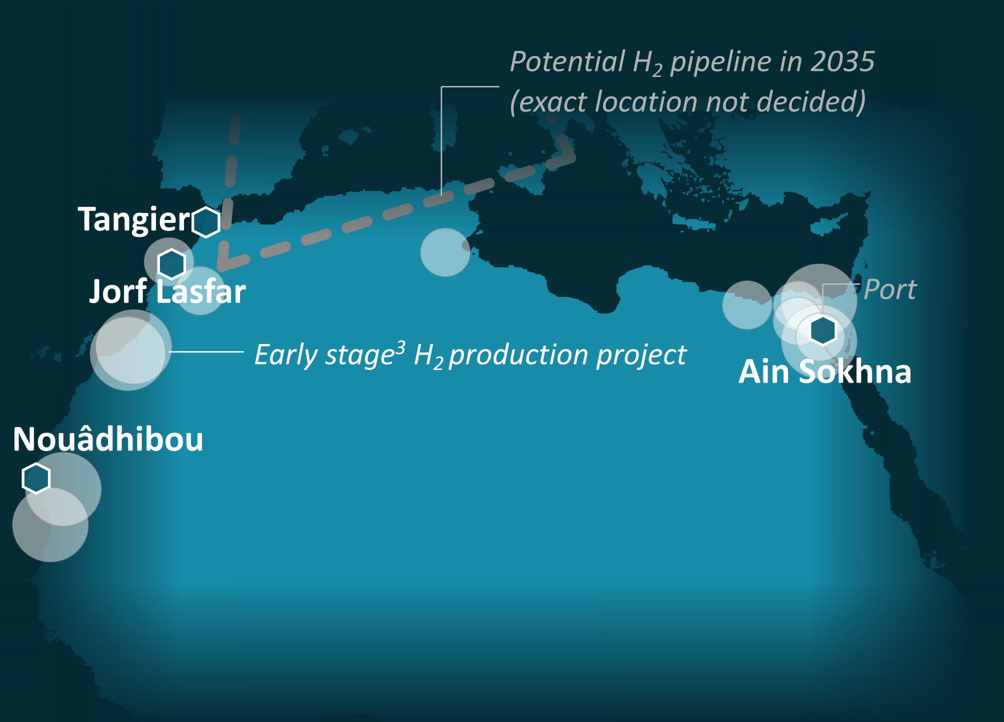
4x expansion of ammonia terminal capacity needed to accommodate the growth in export volumes



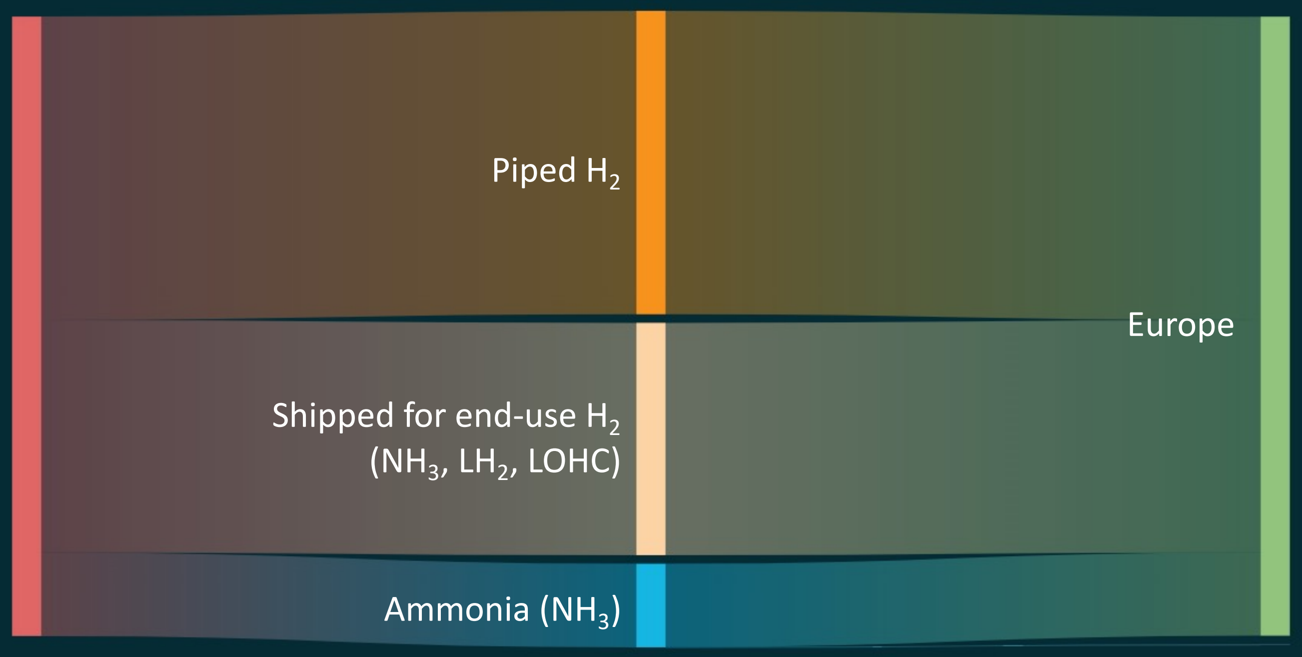
Source: Global Hydrogen Flows Model (December 2023)

Northern Africa: Supply of hydrogen for export

Almost all exports target Europe, of which 40% expected through pipelines – plans and projects still in early stages



Export flows of clean H_2 & derivatives in 2035[1,2], Mtpa H_2e



1.9 Mtpa
H_2e exports in 2035

0.8 Mtpa piped H_2	**0.6 Mtpa** shipped H_2	**0.7 Mtpa** syn-kerosene	**1.1 Mtpa** ammonia

1. Under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply | 2. Includes exports from Algeria, Egypt, Libya, Morocco, Mauritania
3. Early stage includes projects that are announced or in feasibility studies; includes also projects with capacity possibly online post-2030

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Northern Africa: Infrastructure requirements by 2035

Existing gas pipelines can be repurposed, and >2x expansion needed of ammonia and liquid H_2 export capacity

Transportation to export infrastructure

Piped H_2 / **Shipped for end-use H_2 (NH_3, LH_2, LOHC)**: ✓ Existing natural gas pipelines could be repurposed to connect production sites to export infrastructure

Ammonia: ✓ Existing infrastructure can be repurposed

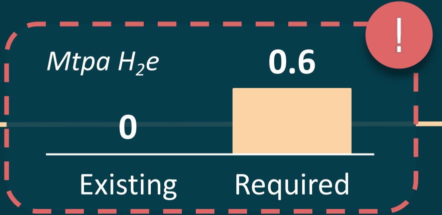
Synthetic kerosene: ✓ Refineries (where kerosene is produced) are located close to ports

Methanol: ✓ Existing infrastructure can be repurposed

Transformation

Ammonia synthesis | Liquefaction | Hydrogenation

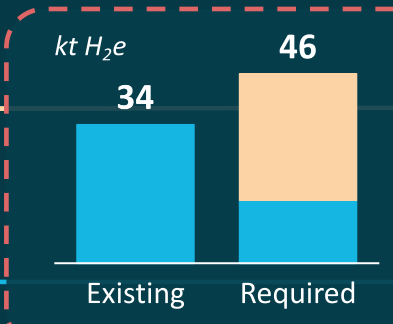
Shipped for end-use H_2:



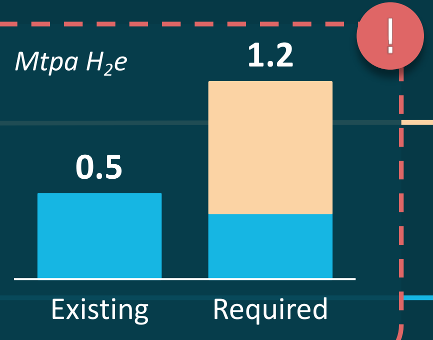
Port-related infrastructure

Storage

Shipped for end-use H_2 and Ammonia:



Loading



Synthetic kerosene and Methanol: ✓ Existing infrastructure can be repurposed

Source: Global Hydrogen Flows Model (December 2023)

Appendix 1: Snapshots - Overview

Appendix 2: Snapshots – Supply hubs

Appendix 3: Snapshots – Demand hubs

Northwestern Europe: Hydrogen demand and supply

Strong growth in hydrogen and ammonia imports – 75% could be covered by Norway, Middle East and North America

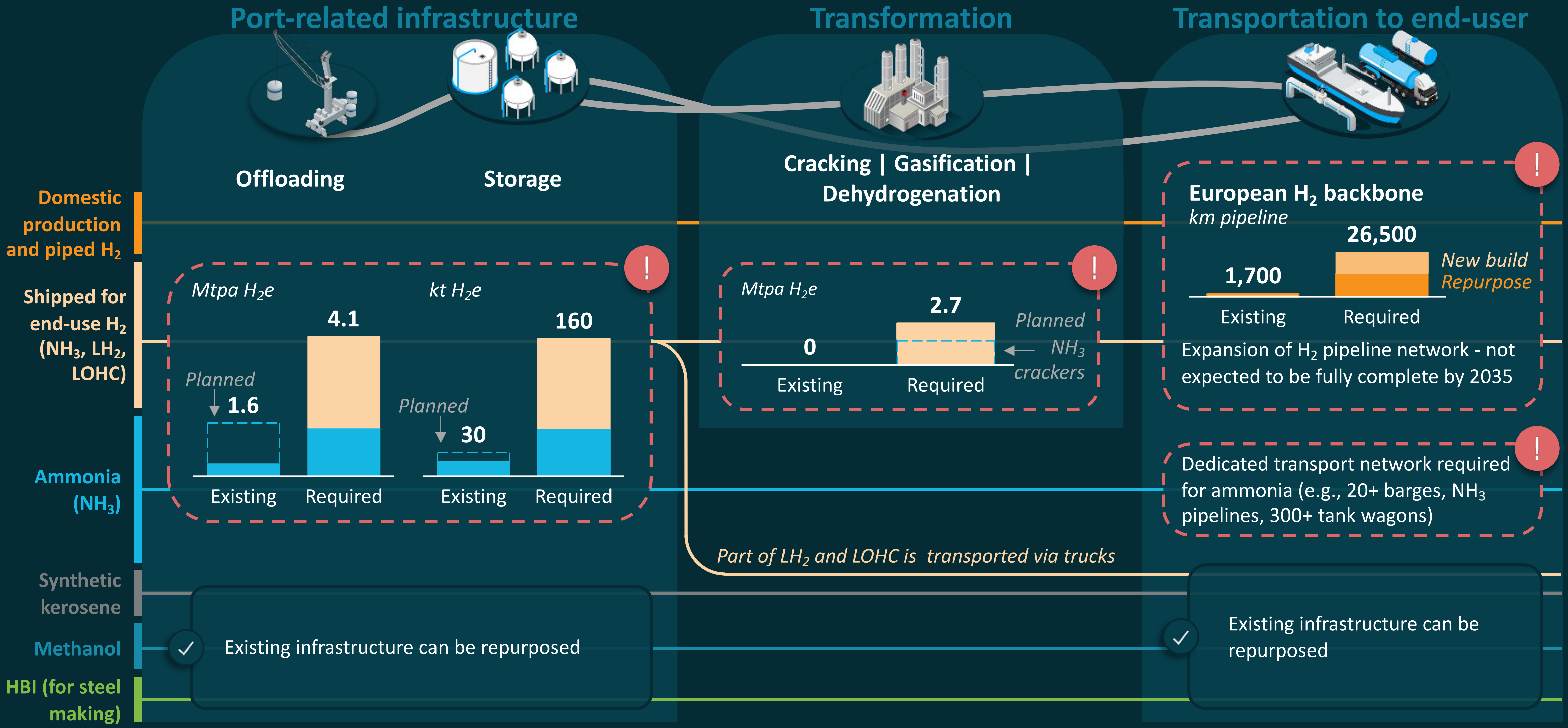
2035 mix Product	Required H_2 demand[1], Mtpa clean H_2e (Local production / Import)		Landed cost in Europe[2], USD/unit — Cost of imports, by year of production: 2030	2035	Unit
Domestic production and piped H_2	7.0		4 – 10	3 – 7	/kg H_2
Shipped for end-use H_2 (NH_3, LH_2, LOHC)	2.7		5 – 10	4 – 8	/kg H_2
Ammonia (NH_3)	1.6	9.2 Mtpa NH_3	550 – 1,450	450 – 1,000	/ton NH_3
Synthetic kerosene	1.2	2.6 Mtpa kerosene	1,900 – 3,300	1,200 – 2,350	/ton kerosene
Methanol	0.7	3.9 Mtpa methanol	1,000 – 1,550	700 – 1,250	/ton methanol
HBI for steelmaking	0.7	13 Mtpa HBI	300 – 650	300 – 500	/ton HBI

1. Meets target under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply
2. Landed cost of clean H_2 at port, excluding taxes, duties, and distribution and including national incentive programs

Source: Global Hydrogen Flows Model (December 2023)

Northwestern Europe: Infrastructure requirements by 2035

Need for transformation technologies, development of the European H_2 backbone and tailored transportation solutions to end-users



Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Japan: Hydrogen demand and supply

Power and mobility sectors could drive significant demand growth – 85% could come from North America, Australia and Chile

2035 mix Product	Required H_2 demand[1], Mtpa clean H_2e Local production / Import	Landed cost in Japan[2], USD/unit Cost of imports, by year of production
Shipped for end-use H_2 (NH_3, LH_2, LOHC)[3]	2.2[4]	2030: 5 – 12 2035: 4 – 8 /kg H_2
Ammonia (NH_3)	1.0 5.7 Mtpa NH_3	2030: 500 – 1,450 2035: 500 – 1,000 /ton NH_3
HBI for steelmaking	0.8 13 Mtpa HBI	2030: 400 – 800 2035: 350 – 700 /ton HBI steel
Synthetic kerosene	0.1 0.3 Mtpa kerosene	2030: 2,750 – 4,100 2035: 1,200 – 2,800 /ton kerosene

1. Meets target under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply | 2. Landed cost of clean H_2 at port, excluding taxes, duties, and distribution and including national incentive programs | 3. Potentially e-methane. Several Japanese gas utilities are exploring e-methane as an energy carrier | 4. 1.1 Mtpa H_2 produced locally

Source: Global Hydrogen Flows Model (December 2023)

Japan: Infrastructure requirements by 2035

150x increase in offloading and 17x in storage capacity, limited need for last-mile transportation as end-users are near the ports

Port-related infrastructure

Offloading — *Mtpa H_2e*: Existing 0.02; Required 3.03

Storage — *kt H_2e*: Existing 7; Required 120

Existing infrastructure can be repurposed

Transformation

Cracking | Gasification | Dehydrogenation — *Mtpa H_2e*: Existing 0; Required 2.0

Part of LH_2 and LOHC is transported via trucks

Transportation to end-user

Limited need for transportation from port as end-users are typically located near ports. Minor upgrades of pipes, trucks and rail might be required

Shipped for end-use H_2 (NH_3, LH_2, LOHC)

Ammonia (NH_3)

Methanol

HBI (for steel making)

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

South Korea: Hydrogen demand and supply

Power and mobility sectors could drive significant hydrogen demand – 70% could come from the Middle East, Australia and North America

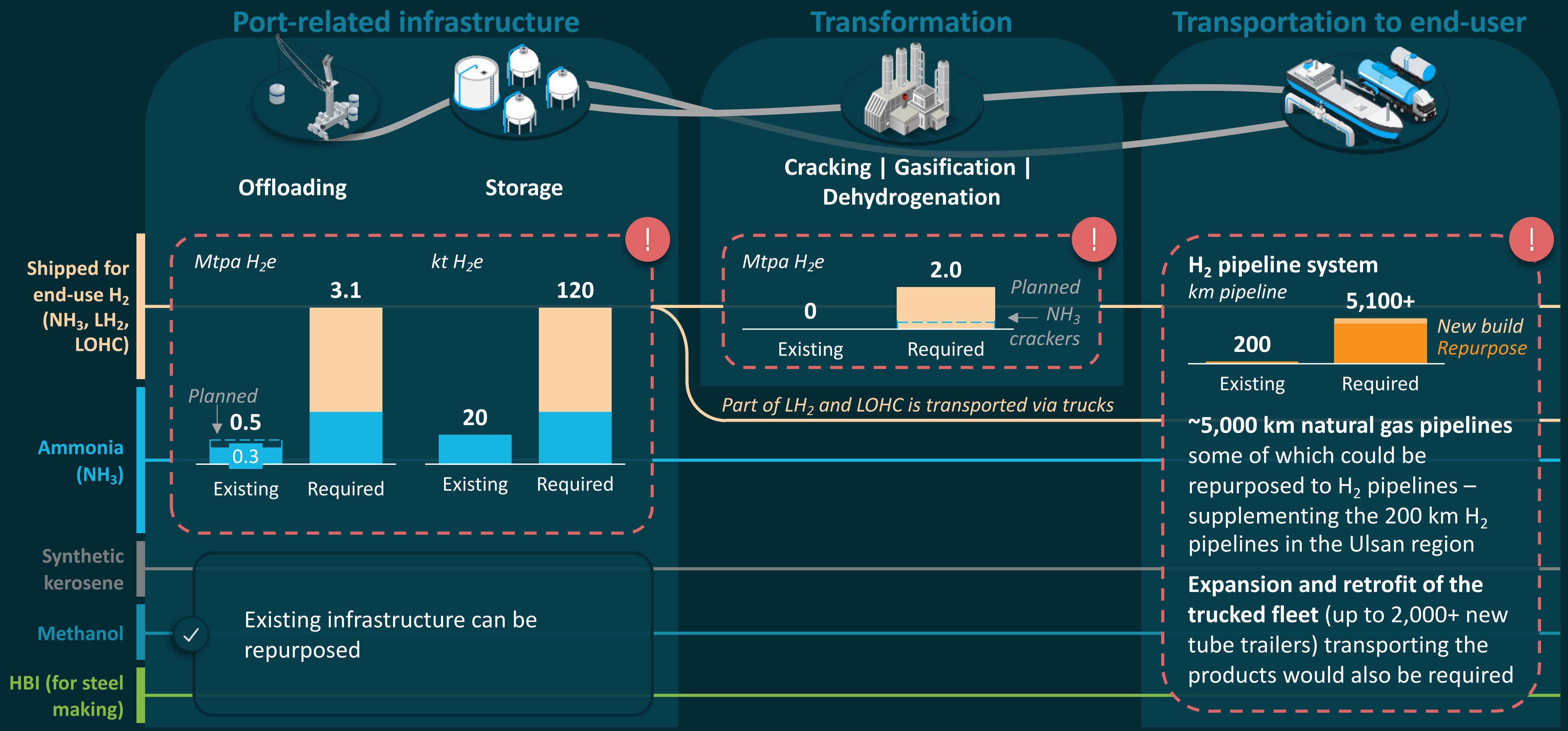
2035 mix Product	Required H_2 demand[1], Mtpa clean H_2e Local production	Import	Landed cost in South Korea[2], USD/unit Cost of imports, by year of production: 2030	2035	Unit
Shipped for end-use H_2 (NH_3, LH_2, LOHC)	2.0[3]		5–13	4–9	/kg H_2
Ammonia (NH_3)	1.0	5.7 Mtpa NH_3	500–1,450	500–1,000	/ton NH_3
HBI for steel making	0.5	9.4 Mtpa HBI	400–800	350–650	/ton HBI steel
Methanol	0.2	0.9 Mtpa methanol	1,400–1,750	800–1,400	/ton methanol
Synthetic kerosene	0.1	0.2 Mtpa kerosene	2,750–4,100	2,050–2,800	/ton kerosene

1. Meets target under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable and low-carbon H_2 supply | 2. Landed cost of clean H_2 at port, excluding taxes, duties, and distribution and including national incentive programs | 3. 0.6 Mtpa H2 produced locally

Source: Global Hydrogen Flows Model (December 2023)

South Korea: Infrastructure requirements by 2035

6-10x increase in offloading and storage capacity, potential to build out pipeline network or trailer fleet



Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Singapore: Hydrogen demand and supply

An emerging bunkering hub for renewable fuels of which 60% could be imported from Australia and the Middle East

0.5 Mtpa H_2e imported

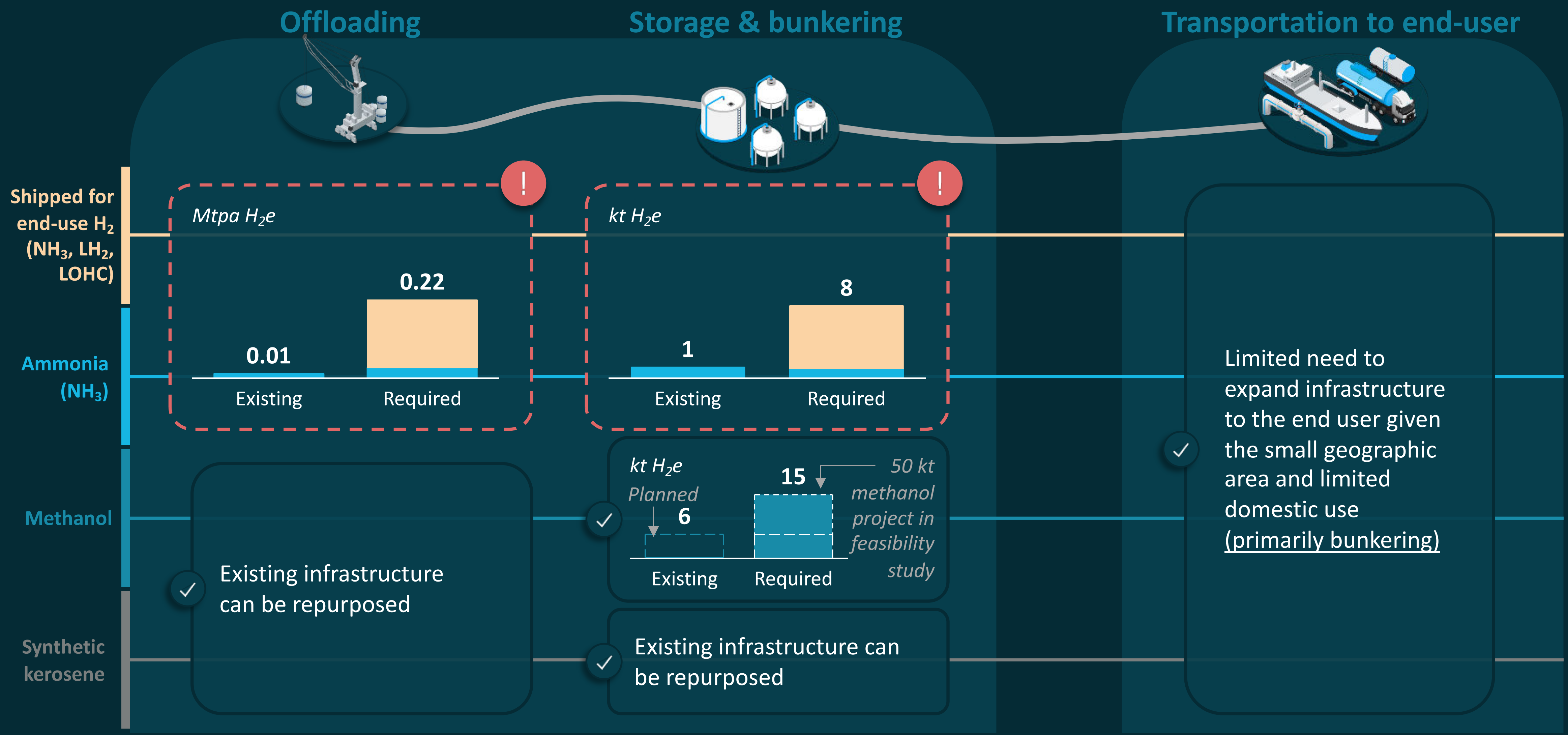
2035 mix Product	**Required H_2 demand[1],** Mtpa clean H_2e — Local production / Import		**Landed cost in Singapore[2],** USD/unit — Cost of imports, by year of production		
	Local production	Total	2030	2035	Unit
Shipped for end-use H_2 (NH_3, LH_2, LOHC)		0.2[3]	5–12	4–9	/kg H_2
Methanol	0.1	0.3 Mtpa methanol	1,300–1,900	1,050–1,350	/ton methanol
Ammonia (NH_3)	0.1	0.5 Mtpa NH_3	500–1,450	450–1,000	/ton NH_3
Synthetic kerosene	0.1	0.2 Mtpa kerosene	2,750–4,100	2,050–2,800	/ton kerosene

1. Meets target under the "Further Acceleration" scenario (1.6 - 2.4 degrees); including renewable, low-carbon, and grey H_2 supply | 2. Landed cost of clean H_2 at port, excluding taxes, duties, and distribution and including national incentive programs | 3. 0.2 Mtpa H_2 produced locally in addition

Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Singapore: Infrastructure requirements by 2035

>20x increase in offloading capacity, and 2.5-8x increase in bunkering capacity



Source: Global Hydrogen Flows Model (December 2023); Project & Investment tracker as of Apr 2024

Hydrogen Council

McKinsey & Company