Study on hydrogen in ports and industrial coastal areas

Report 1

March 2023

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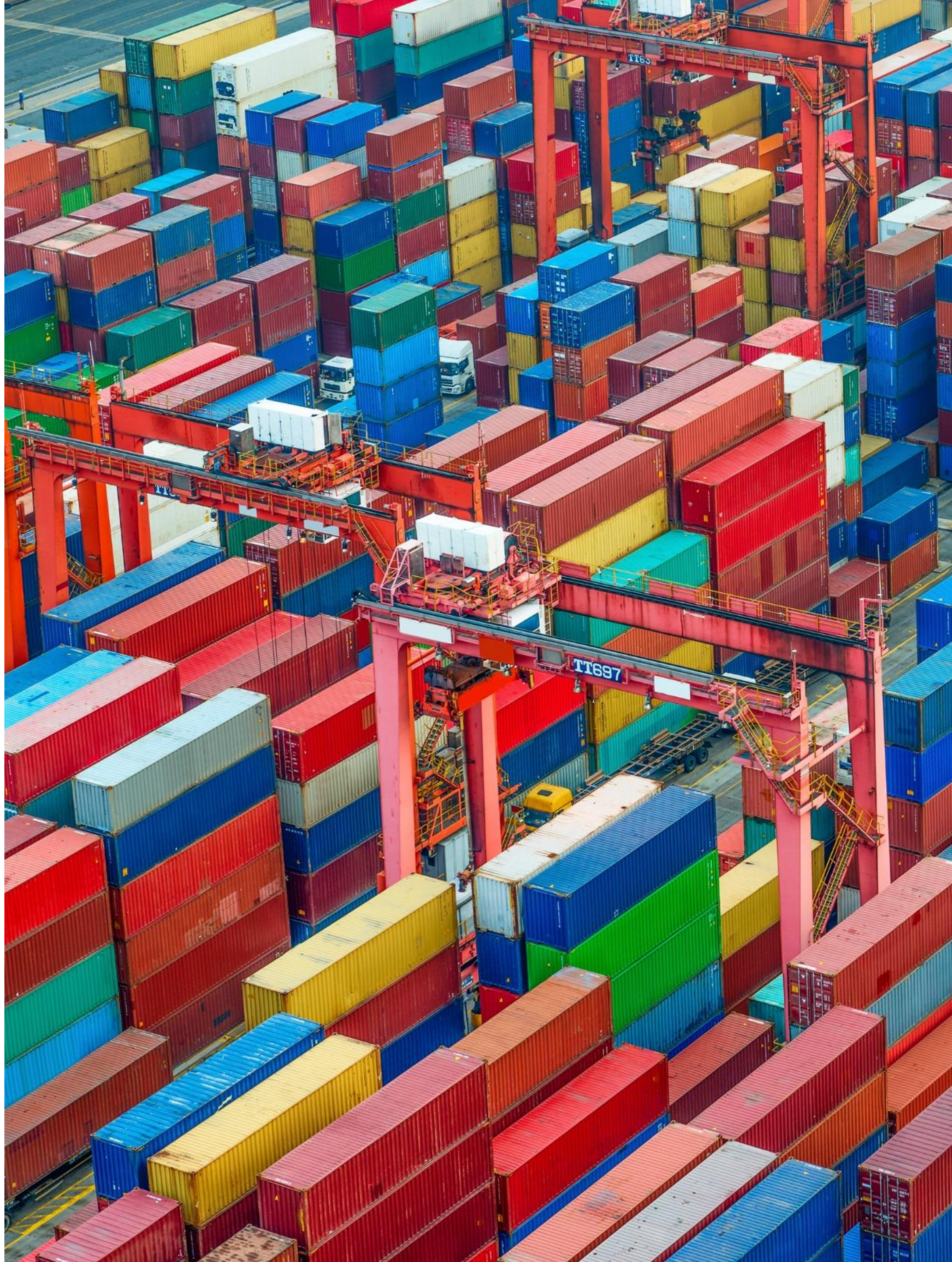

Content

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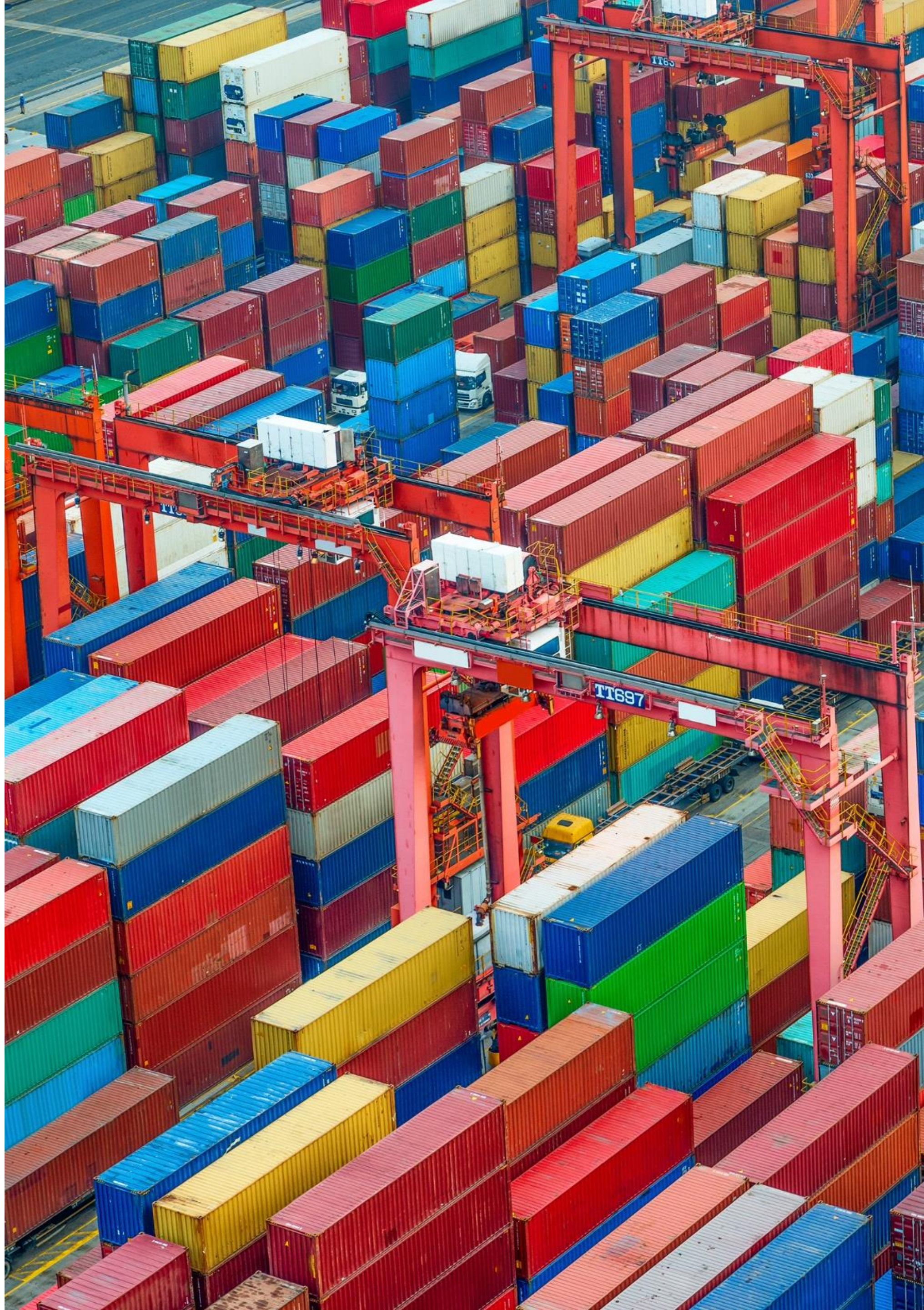

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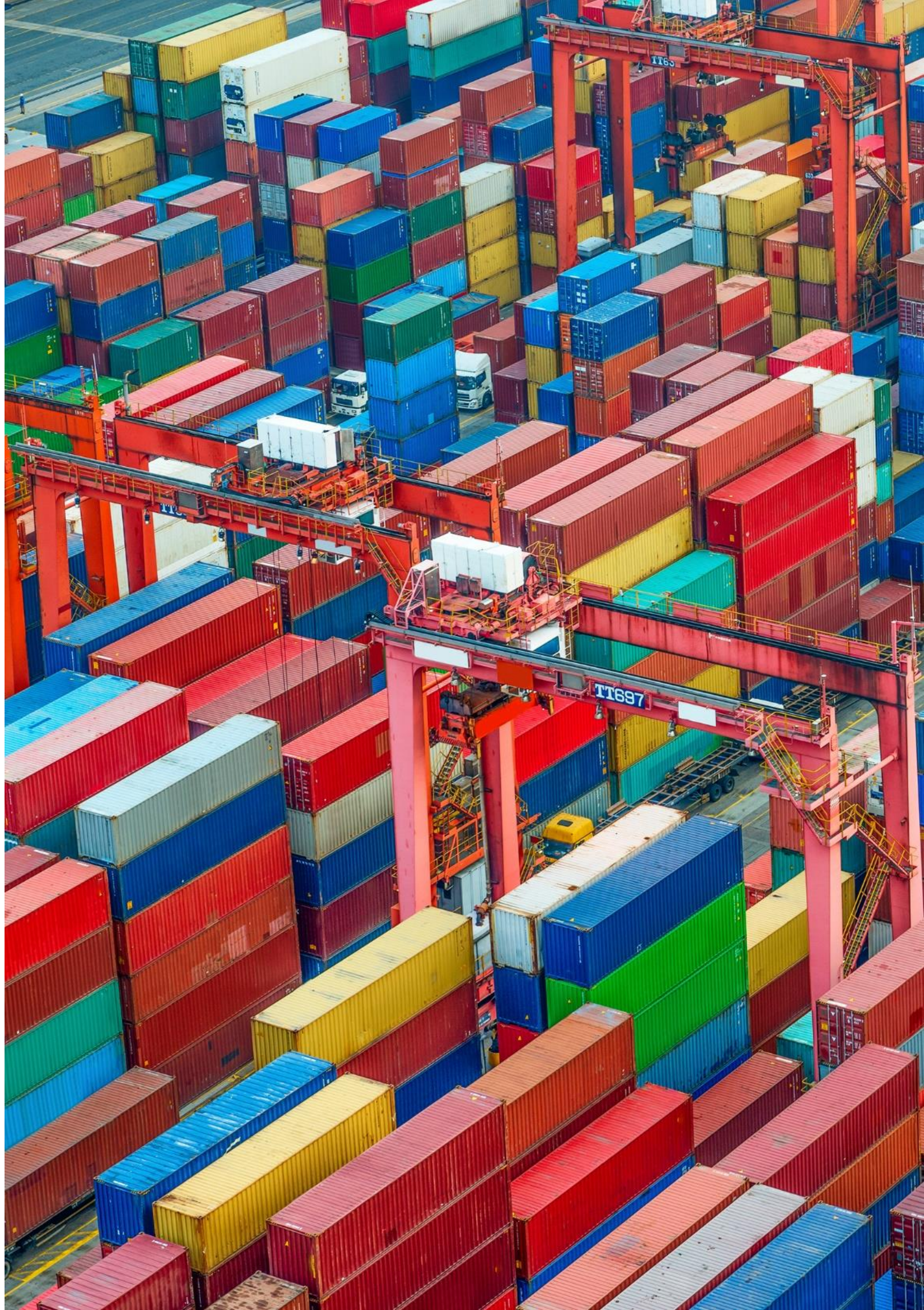

Context and objectives

Leadership perspective on study objectives

"The planned study will be a comprehensive assessment of the hydrogen demand in ports and industrial coastal areas, enabling the creation of a 'European Hydrogen Ports Roadmap'. It will also feature clear economic forecasts based on a variety of business models for the transition to renewable hydrogen in ports, while presenting new case studies and project concepts."

*"The objective is to provide new directions for research and innovation, guidance for regulation, codes and standards, and proposals on policy and regulation. The forthcoming study will also help **create impetus for stakeholders to come together and take a long-term perspective on the hydrogen transition in ports**. Finally, the study will be a centralized resource: It will form a Europe-wide hydrogen ports 'backbone' when combined with roadmaps and other materials created by individual ports."*

Bart Biebuyck, Executive Director of the Clean Hydrogen Partnership

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

Commissioned by

Clean Hydrogen Partnership

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Performed by

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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

Report 1

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

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.

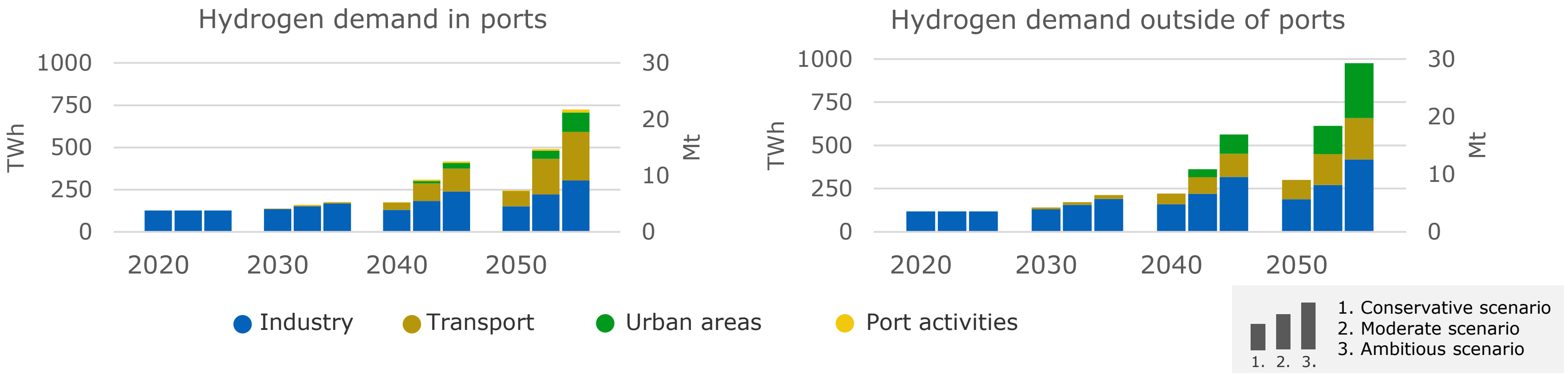
Executive summary

Task 1: Hydrogen demand and market potential in Europe

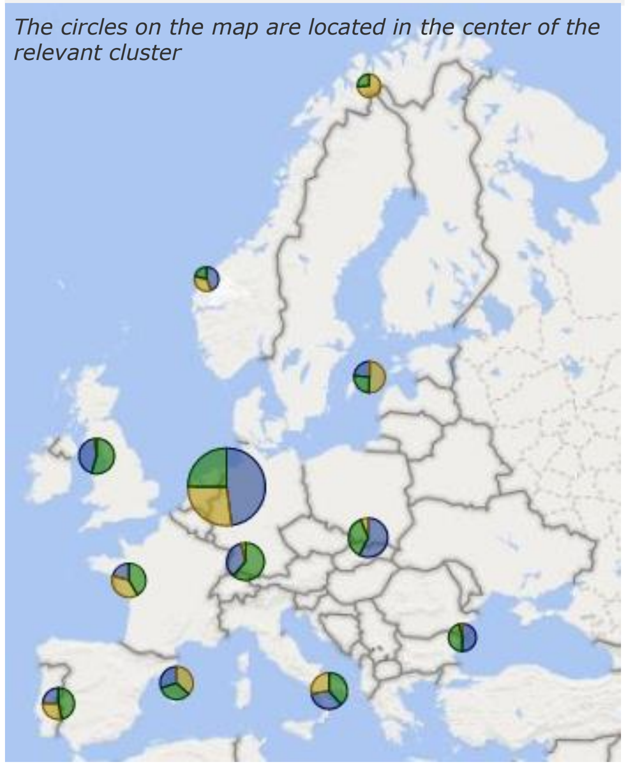
Sectoral scope of the hydrogen demand assessment

- Hydrogenation of mineral oil in refineries
- Production of ammonia for fertilizers
- Production of methanol for current uses
- Production of primary steel
- Production of High Value Chemicals
- Generation of heat for industrial processes
- Domestic shipping
- International shipping
- Heavy-duty vehicles
- Heating of residential buildings
- Heating of service buildings
- Cold ironing
- Cargo handling
- Port vessel fleet

High-level results across all demand segments*



Estimated hydrogen demand per cluster and per demand segments (Ambitious scenario in 2050)



Overview of the main findings

- Overall, hydrogen demand for new uses is expected to first take off in the **late 2020s** for **industrial applications** (mainly for primary steelmaking and high temperature process heat). From **2030 onwards**, in parallel with a strong increase in hydrogen demand in all industries, hydrogen demand is expected to accelerate in the **transport sector**, as shipping and heavy-road transport activities move towards decarbonization. Hydrogen demand for low-heat temperature applications in **urban areas** is uncertain and might start in the late 2030s to potentially increase from **2040 onwards**. Altogether, the incremental demand for hydrogen, both inside and outside the vicinity of ports, is foreseen to expand steadily in the 2030s, reaching up to **1764 TWh (53 Mt) in 2050**.
- Hydrogen demand in the vicinity of ports is expected **to be very substantial**, mainly **driven by industrial demand** and further **supplemented by hydrogen demand in the shipping sector** from the 2030s. When only considering hydrogen demand related to industrial and transport activity, the projected **hydrogen demand in port areas is about 50% of the overall hydrogen demand**.

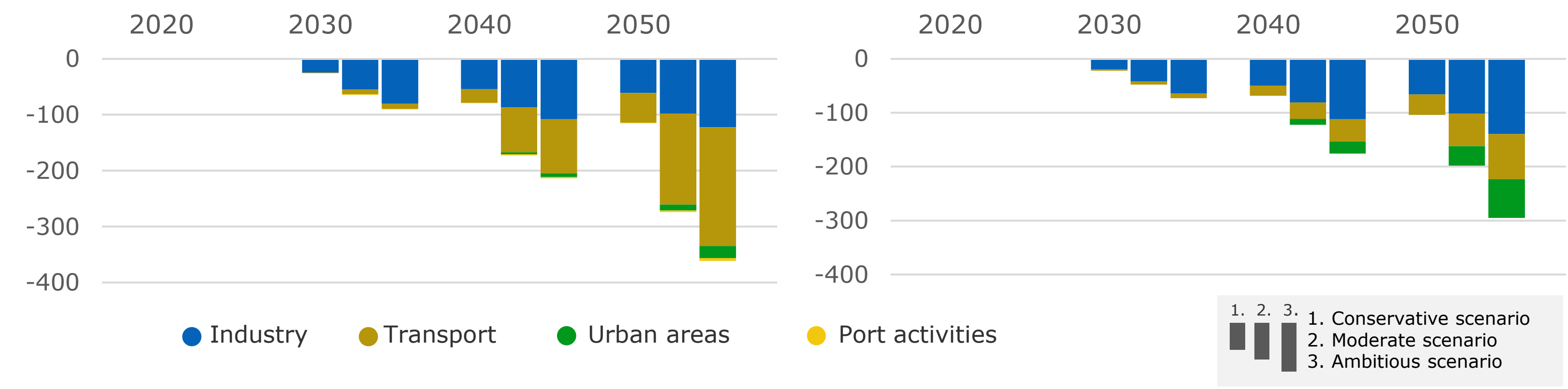
* Scenarios have been established in a pre-Russo-Ukrainian war context and do not account for the (partial) replacement of Russian fossil fuels by hydrogen, as envisaged by REPowerEU plan (cf. separate scenario).

Task 1: Environmental benefits

High-level results across all demand segments

Expected hydrogen-related CO_2–eq abatement in ports (Mt)

Expected hydrogen-related CO_2–eq abatement outside of ports (Mt)



Estimated hydrogen-related CO_2–eq abatement per cluster and per demand segments (Ambitious scenario in 2050)

Hydrogen-related CO_2-eq abatement: main conclusions

Expected hydrogen-related CO_2–eq abatement by 2050**

Category	Conservative scenario	Ambitious scenario
Industry	31%	64%
Transport	10%	34%
Urban areas	0%	20%
Port activities	4%	20%

Hydrogen uptake in all demand categories could abate up to 655 Mt of CO_2-eq emissions in 2050 (or 16% of all European* CO_2-eq emissions)**

Other environmental benefits

Expected hydrogen-related non-CO_2 emissions and pollutants abatement: Overall, existing literature points toward a largely shared consensus that significant reduction of toxic atmospheric emissions (i.e., CO, SOx, NOx, PM10, PM2.5, VOCs, N2O, SO2, black carbon, F-gases, methane), water pollutants (COD, ammonia, phenols, benzene, benzo(a)pyrene, vinyl chloride), as well as solid waste (slag, sludge, heavy metals) and noise emissions could be achieved by replacing current fossil fuels and grey hydrogen with green hydrogen in industries and various fuel combustion processes.

* Study defines Europe as EU27 + UK + Norway + Switzerland. ** (Relatively to) CO_2 emissions levels in 2019

Task 2: Hydrogen supply

Hydrogen supply sources in scope

- Local European production of green hydrogen from onshore and offshore windfarms
- Local European production of green hydrogen from solar PVs
- Imported green and blue hydrogen (incl. from Norway and UK)
- Local European production of blue hydrogen*

Two supply scenarios

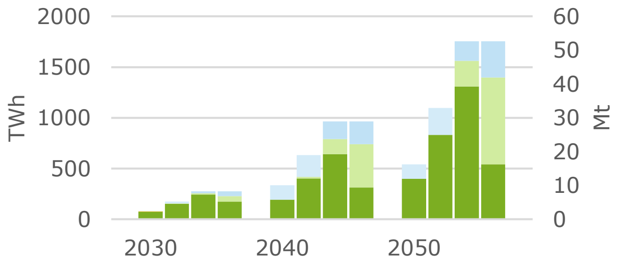
Economic model strives for overall cost minimization and is based on LCOH modelling taking into account all costs of the hydrogen supply chain.

Base supply scenario: set of three hydrogen supply scenarios matching respectively the forecasted hydrogen demand in the three demand scenarios.

Increased import supply scenario: additional hydrogen supply scenario matching only the hydrogen demand foreseen in the ambitious demand scenario and incorporating a predefined constraint in the rate of deployment (5%) of European renewable energy sources for hydrogen until 2050.

Overview of the main conclusions – hydrogen source of supply

Local European hydrogen production vs hydrogen import



- Green hydrogen - domestic
- Green hydrogen - import
- Blue hydrogen - import

1. Conservative scenario
2. Moderate scenario
3. Ambitious base scenario
4. Ambitious increased import scenario

Ports are expected to play a key role in facilitating the **hydrogen supply to the wider port community or even the hinterland in their role as energy hub**. We refer to the separately developed dashboards to understand hydrogen supply implications (and corresponding investments) on port level.

Base supply scenario:

> **Local European green hydrogen production:** It is projected that by 2050 around **75% of hydrogen demand could be met by European green hydrogen production** (400 TWh - 1,300 TWh). Solar PV is expected to be the most economically competitive renewable energy source to produce hydrogen (at a **levelized cost of hydrogen of around 2.2 EUR/kg**). The projected **local production is highly diversified between European countries** and is largest in **Spain, Denmark, Greece and Italy.**

> **Hydrogen imports:** Local European hydrogen production is expected to be supplemented by green and blue hydrogen imports, representing 25% of total hydrogen supply. North of Africa and the Middle East are expected to be the main suppliers of hydrogen to Europe by 2050 (at **LCOH of around 3.5 EUR/kg**).

Increased import supply scenario:

> **Local European green hydrogen production:** Setting a **constraint on the local deployment rate of renewables**, results in a shift to hydrogen being supplied by mainly green hydrogen imports. In this scenario, **only 30% of future hydrogen demand in Europe is expected to be supplied by local European production in 2050** (540 TWh).

> **Hydrogen imports:** Since the largest part of hydrogen will be supplied by import, Europe will need to significantly tap into more foreign sources, i.e., **increased import from North Africa and the Middle East** but also further distanced countries.

Estimated hydrogen supply per cluster and per type (Ambitious base scenario in 2050)

* Study assumes limited conversion of existing grey production to blue hydrogen and no additional blue hydrogen production following strong EU political impetus towards green hydrogen.

Task 2: Hydrogen supply

Overview on the required hydrogen-related infrastructures

Production — Transport — Import — Storage — Consumption

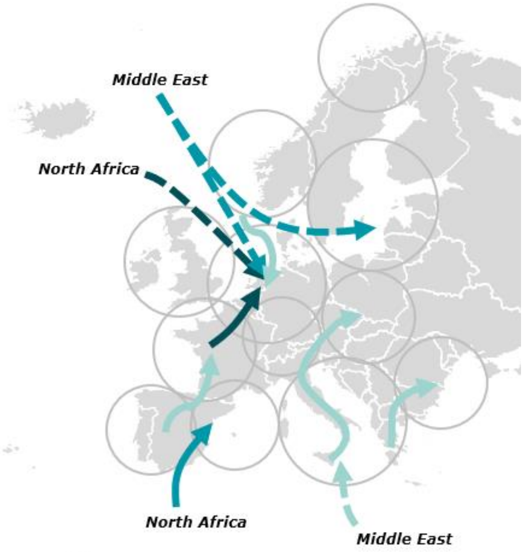
Overview of the main conclusions – transport, import, storage and consumption infrastructure

- **Production infrastructure:** Need for **160 – 720 GW of solar PV**, supplemented by **40 -125 GW of wind onshore** and **35 – 80 GW of wind offshore by 2050**, in the base supply scenario, depending on the demand scenario. In the increased import supply scenario, solar PV is almost 3x lower than in the base supply scenario, leading to a need for 240 GW of solar PV, supplemented by 85 GW of win onshore and 20 GW of wind offshore.
- **Transport infrastructure:** Most hydrogen **transport infrastructure** will be required **within local clusters** of countries, however there will be a need for some **transit corridors** in all scenarios (cf. right-hand side).
- **Import infrastructure:** Most hydrogen is **imported via ship** with **ammonia** as the most cost-effective carrier. In the base supply scenario only the clusters *Belgium, Netherlands, Denmark and North of Germany*; *Baltics, Finland and Sweden* and *Eastern Central Europe* via *Italy, Croatia and Greece* (supplying to *Eastern Central Europe)* will need to invest in import specific infrastructure such as **reconversion plants and import terminals**. In the increased import supply scenario this also includes the clusters *France (Atlantic coast)*.
- **Storage infrastructure:** In the ambitious demand scenario, existing subsurface gas storage locations would only be sufficient to meet 60% of the total storage needs. Storage needs will thus likely be met by both **repurposed and new assets**.
- **Consumption infrastructure:** Specific infrastructure is required for the transport sector and for port equipment such as **refueling stations and bunkering infrastructure**

No-regret investment roadmap

Boundary conditions can be translated in 'no-regret' investments:

- **In 2030**: Corridor from Spain to France (Atlantic coast), from Italy, Croatia and Greece to Eastern Central Europe and from Greece to Bulgaria and Central/South Romania. Import infrastructure is required in Italy, Croatia and Greece to accept hydrogen for the hinterland.
- **In 2040**: Import infrastructure in Belgium, Netherlands, Denmark and North of Germany, and in Baltics, Finland and Sweden. A corridor from North Africa to Western Mediterranean coast.
- **In 2050**: Corridor from France (Atlantic coast) to Belgium, Netherlands, Denmark and North of Germany.



- **Gradually until 2050**: renewable electricity production infrastructure, electrolysers, pipelines for industrial clusters, refueling stations.
- This study assumed that there will be pipelines and/or interconnections available to transport hydrogen within clusters in Europe and from the North Sea to the mainland of Belgium, Netherlands, Denmark and North of Germany.

Addendum: REPowerEU

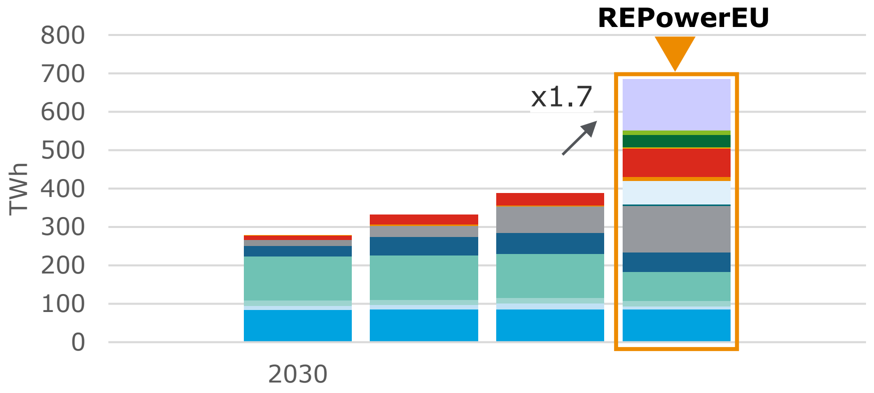
Due to changes in the context during the course of the study, it was decided to look into the implications of the REPowerEU plan in an addendum to the main report. The different goals stated in the REPowerEU plan were taken as a basis to construct an additional REPowerEU scenario.

Hydrogen demand

Assumptions

- Projected demand in 2030 is 20 Mt
- Additional sectors compared to the other scenarios: power sector and aviation

Projected hydrogen demand in Europe per year



The REPowerEU scenario, reflecting the short-term goal to (partially) replace Russian fossil fuels by hydrogen, shows an important **acceleration of the hydrogen uptake** compared to the other scenarios, established in a pre-Russo-Ukrainian war context.

Industries: Ammonia, HVC, Methanol, Mineral oil, Steel, Industrial heat

Transport: International shipping, Domestic shipping, Road freight

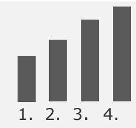
Port activities: Cargo handling, Port vessel fleet

Buildings: Residential buildings, Service buildings

Power generation

Aviation

Other



1. Conservative scenario
2. Moderate scenario
3. Ambitious scenario
4. REPowerEU scenario

Hydrogen supply

Assumptions

- All new hydrogen is assumed green
- Supply will be 50% local production and 50% imports in 2030
- 4 Mt will be imported in the form of ammonia (ships) and 6 Mt via pipelines

Supply:

- The projected **LCOH range** is between **3.1 – 5.4 EUR/kg**. Compared to the ambitious base and ambitious increased import scenario, the **average LCOH in REPowerEU** is about **10% higher** (4.1 EUR/kg) compared to the ambitious base and ambitious increased import scenario (3.7 EUR/kg).
- Green hydrogen imports are expected from **Algeria, Morocco, Egypt and Australia**

Infrastructure:

- **Production infrastructure:** Need **for 228 GW of domestic renewable electricity production capacity** corresponding to an investment of approximately 263 bEUR. Solar PV in combination with electrolysis is projected to be the most used technology. REPowerEU plan and its' short timeframe poses an important challenge to implement it and an **accelerated deployment of domestic renewables is key**.
- **Transport infrastructure:** Most hydrogen **transport infrastructure** will be required **within local clusters** of countries, however there will be a need for some **transit corridors**.
- **Import infrastructure:** Most imported hydrogen is **imported via pipelines** from **North Africa**. Further, for the clusters *Belgium, Netherlands, Denmark & North of Germany* and *Baltics, Finland and Sweden*, there is a projected hydrogen import via ship in the form of ammonia. These clusters will need to invest in import specific infrastructure such as **reconversion plants and import terminals**.
- **Storage infrastructure:** Storage needs will likely be met by both **repurposed and new assets**.
- **Consumption infrastructure:** Specific infrastructure is required for the transport sector and for port equipment such as **refueling stations and bunkering infrastructure**

Task 3: The potential roles of ports in the future hydrogen economy

Landlord

Providing land for hydrogen economy

Examples:* Port of Antwerp Bruges; North Sea Port; Port de Barcelona

Key investments for ports to consider

- **Provide land and/or make land available** to foster hydrogen activities across the value chain production facilities (MAKE), import terminals (BUY), pipelines, bunkering facilities, fuel stations etc. (BUY and MAKE)
- **Partner with companies** willing to place their facilities/assets/infrastructure on the available lands (BUY and MAKE)

Community builder and enabler

Bringing the right parties together locally and globally

Examples:* valenciaport (Autoridad Portuaria de Valencia); Port of Rotterdam; Port of Hamburg; constantza port; Port of Antwerp Bruges; North Sea Port

Key investments for ports to consider

- **Taking part in regional and global alliances and networks** (BUY and MAKE)
- For larger port with larger capacity, **forming a local platform** with actors to discuss hydrogen projects (BUY and MAKE) for the port itself
- **Developing solid relationships with the whole ecosystem** (industry actors, policy makers, government, investors, etc.) (BUY and MAKE)
- **Promoting hydrogen** as a sustainable energy carrier (BUY and MAKE)

Investor

Investing in infrastructure/equipment/etc. enabling the hydrogen economy

Examples:* Port of Antwerp Bruges; Port of Gothenburg

Key investments for ports to consider

- **Investing financial resources** to build production infrastructure (MAKE), import terminals (BUY), hydrogen pipelines (BUY and MAKE) and hydrogen fuel stations (BUY and MAKE)
- **Investing financial resources** in adjacent domains (e.g., windmills park) (MAKE and BUY)
- **Investing financial resources** in port infrastructure to welcome hydrogen infrastructure (MAKE and BUY)
- **Partnering with skilled actors** to set up the right infrastructures & activities (MAKE and BUY)
- **Financing** the transition as leverage for technological innovations & demo-facilities

The choice of positioning and associated investments is likely to be largely influenced by several factors, including: **the port archetype** (industrial, bunkering, logistics and transport, urban), **the size of the port** (smaller versus larger ports) and their **individual strategy**, often driven by their respective municipal and national strategy.

* These ports already take a specific role for hydrogen, examples are not exhaustive

Framework of the study

A rapidly evolving EU policy context creating momentum for the development of a European hydrogen economy in support of the EU's 2050 net zero target

2020 - EU Hydrogen Strategy[1]

Objective: to put forward a vision for the creation of a European hydrogen ecosystem from research and innovation to scale up production and infrastructure to an international dimension.

A roadmap for the EU toward 2050

> **2020-2024:** deployment of at least 6 GW of electrolyser capacity capable of **producing up to 1 Mt (or 33 TWh)** of renewable hydrogen. Focus is on decarbonizing current hydrogen production and facilitating the use of hydrogen in industrial processes and for heavy-duty long-distance transport.

> **2025-2030:** deployment of at least 40 GW of electrolyser capacity capable of **producing up to 10 Mt (or 333 TWh)** of renewable hydrogen. A network of hydrogen refueling stations and large-scale storage facilities will have to be established. A basic EU-wide hydrogen grid needs to be planned by repurposing parts of the existing gas grid. Deployment of **40 GW of electrolyser capacity** in countries **neighboring** the EU.

> **2030-2050:** Hydrogen technologies for the production and use of "clean" Hydrogen should **achieve maturity and reach all hard-to-decarbonize sectors** (such as aviation, maritime transport and industrial installations).

2021 – "Fit for 55" package[2]

Objective: to lay down the regulatory and policy framework for the timely development of hydrogen production, transport and end-use infrastructures until 2030.

> Revision of the **TEN-E Regulation**, defining the rules and vision for the development of trans-European hydrogen networks.

> Revision of the **Renewable Energy Directive** (RED III), requiring the **contribution of renewable hydrogen** (or other renewable fuels of non-biological origin - RFNBO) used for final energy and non-energy purposes to be **50% of the hydrogen used for final energy and non-energy purposes in industry** by 2030* and setting a new target for RFNBO of 2.6% by 2030 in the transport sector.

> Revision of the **Energy Taxation Directive**, granting the lowest minimum tax rate (EUR 0.15/GJ) to renewable hydrogen and e-fuels.

> Revision of the **Alternative Fuels Infrastructure Regulation**, setting several mandatory national targets for the deployment of hydrogen refueling stations in the EU, for road vehicles, vessels and stationary aircraft.

> **ReFuelEU Aviation Initiative**, setting minimum obligations for all fuel suppliers to increase the share of advanced biofuels and RFNBO in the fuel supplied to operators at EU airports.

> **FuelEU Maritime Initiative**, introducing increasingly stringent limits on carbon intensity of the energy used by vessels from 2025, which should oblige them to use alternative fuels such as hydrogen and hydrogen derivatives.

> Revision of the **EU ETS Directive**, including the production of hydrogen with electrolysers under the EU ETS, making renewable hydrogen facilities eligible for free allowances.

> **Revision of the Regulation and Directive on gas markets and hydrogen**, creating an EU legislative framework for hydrogen networks.

2022 – REPowerEU Plan[3]

Objective: to launch the Hydrogen Accelerator with a new target of 10 Mt of domestic renewable hydrogen production and 10 Mt of renewable hydrogen imports by 2030 (including 4 Mt in the form of ammonia).

To achieve this objective:

> **Alignment of the sub-targets for RFNBO** under RED III for industry (75%) and transport (5%).

> Accelerated efforts to **deploy hydrogen** production, transport, storage and import **infrastructures**.

> Support the development of **hydrogen import corridors** via the Mediterranean, the North Sea and Ukraine (as soon as conditions allow).

> Regular **report on hydrogen uptake**, and the use of renewable hydrogen in hard-to-abate appliances in industry and transport (from 2025).

> Launch of a large project to develop skills for the hydrogen economy to **address skills shortages**.

> Large **mobilization of EU funds** via Horizon Europe, CEF, Cohesion fund, RRF, Innovation Fund and the Clean Hydrogen Partnership, as well as roll out an EU-wide scheme for Carbon Contracts for Difference.

> Launch of **two delegated regulations**, setting out the requirements for RFNBOs to be counted as fully renewable and establishing a methodology to assess GHG emission savings from RFNBOs.

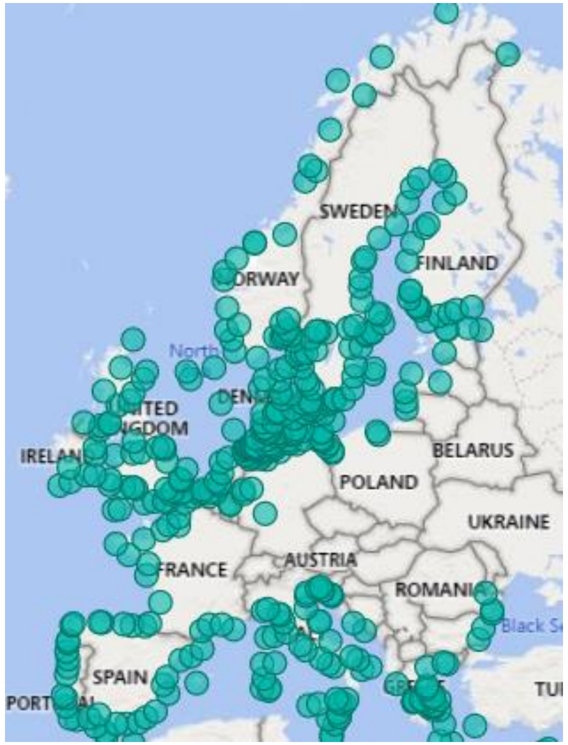
> Launch of the **EU External Energy Strategy** to build long-term partnerships with hydrogen suppliers.

Note: *excluding hydrogen used in refineries in the hydrogenation of mineral oil process. **Sources**: (1) COM(2020) 301 final; (2) European Commission, 2021; (3) European Commission, 2022

The link between future hydrogen demand and supply with European ports: overview of the general approach

Geographical coverage

Overview of ports in scope



Geographical coverage include ports in Europe, defined as **EU27 + UK + Norway**

Hydrogen demand

- Transport
- Port activities
- Urban areas
- Industries

Hydrogen supply

- Green Hydrogen from onshore and offshore windfarms
- Green Hydrogen hydrogen from solar PVs
- Blue Hydrogen from existing grey Hydrogen production sites
- Imported green and blue Hydrogen

Out of scope: pink hydrogen

During the course of the study the **REPowerEU** plan has been published and included in the scope of the study (cf. addendum)

Hydrogen business models

Comprehensive overview of relevant business models

Development of case studies

Selection of specific ... development ... studies

Sections covered in next reports

... recommendations

Analysis of technological, safety and non-technological barriers and definition of policy recommendations

Broad stakeholder's representativity*

- Port authorities
- Terminal operators
- Shipyard representative
- Ship owner and operators
- City/municipal authorities
- Heavy industries
- Gas infrastructure operator
- Heavy-duty transport
- Hydrogen and renewable energy producers
- European Commission

*Not exhaustive

A dual focus approach: perspectives of hydrogen demand and supply both within and outside the vicinity of European ports

Hydrogen demand in ports

Ports within scope

- Seaports located in Europe
- Seaports surpassing at least one of the following two thresholds: 1 Mt/year of traffic or 100,000 passengers per year.
- Inland ports selected based on stakeholder input[1] (mainly along the Seine, Rhine and Danube).

Conclusion: scope of this study includes at total of 420 seaports and 7 inland ports.

- We note that not all ports in scope are expected to play a (significant) role in the hydrogen economy. Amongst others, the availability of space can be an important barrier affecting local production, storage and bunkering activities.

Example of hydrogen demand in ports (sea and inland)

- For this study, the hydrogen demand of an entity (e.g., a primary steel producer) is considered to be directly attributable to a port if the entity is located within a **21 km radius** from the center of the port. All hydrogen demand is projected for specific locations, aggregated and mapped in PowerBI dashboards allowing individual ports to explore which hydrogen demand nodes close to the port would be considered in the port area and justifying certain investments by port stakeholders for local hydrogen end-use.

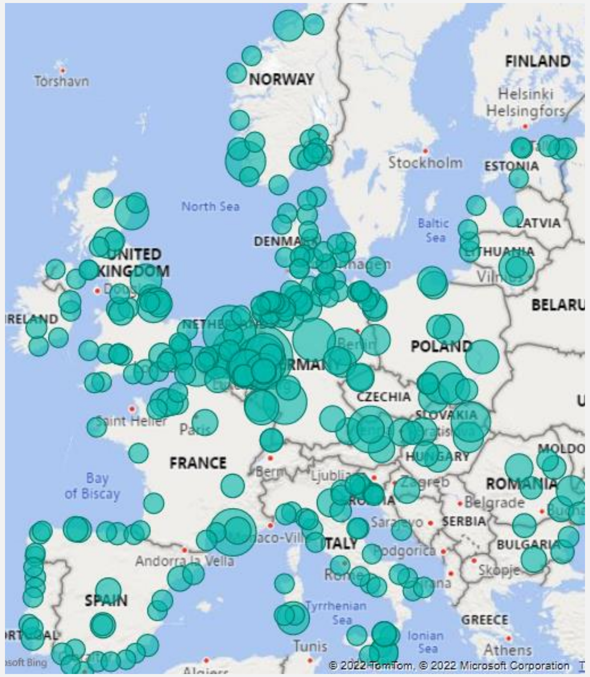
Hydrogen demand outside of ports

Areas outside of ports

- Since inland hydrogen demand can be expected to be supplied by hydrogen transiting through ports (i.e., future hydrogen imports), hydrogen demand from entities located outside the vicinity of ports is captured and accounted for in this study.

Key consideration: For this study, all hydrogen demand that is not attributable to ports (i.e., further than 21 km from a port), is considered as hydrogen demand outside of ports.

Example of hydrogen demand in industries outside of ports



Note: 1. HAROPA (Havre, Rouen, Paris), Duisburg, Galati, Budapest and Vienna.

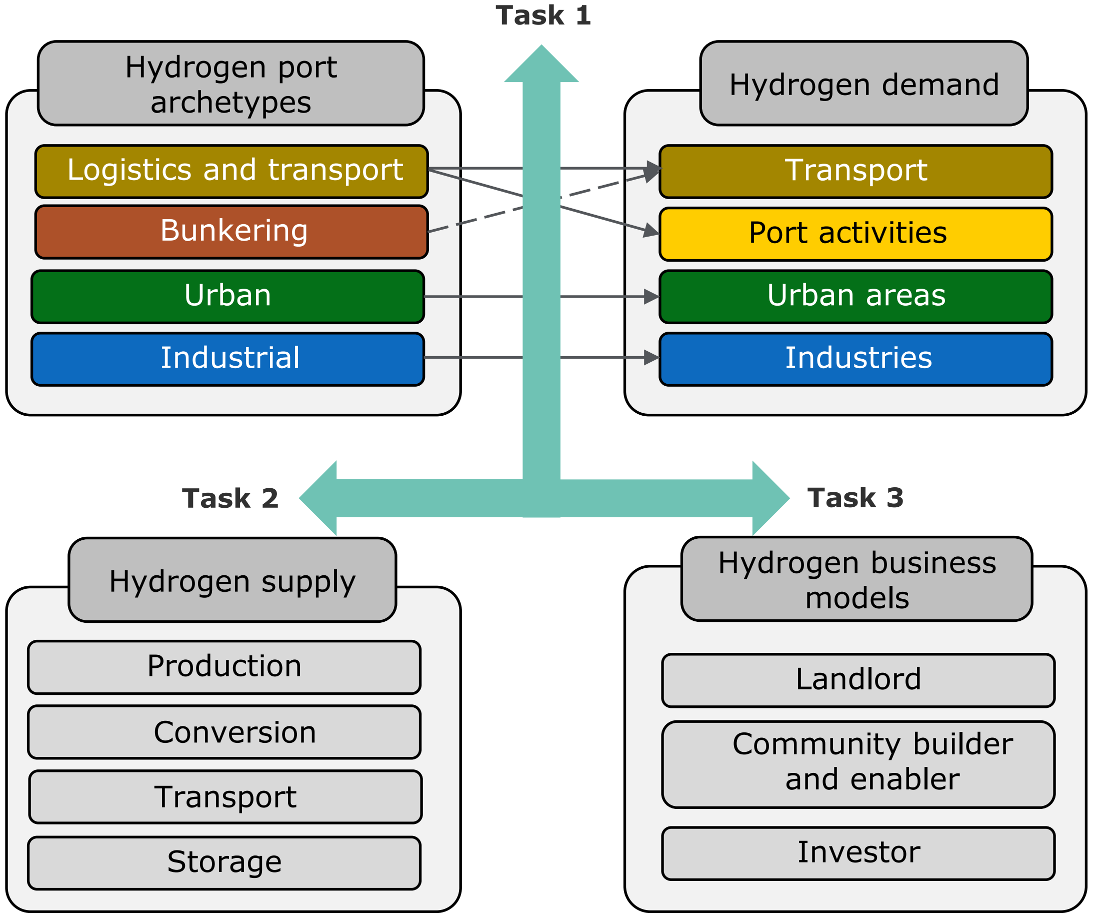
Hydrogen port archetyping as a mean to structure the discussion on hydrogen demand, hydrogen supply and the development of viable business models

Hydrogen port archetyping …

- Hydrogen port archetyping is a mean to structure the discussion on hydrogen demand, supply and market potential and the development of viable business models.
- Each port is linked to **one or more hydrogen port archetypes** on the basis of its main hydrogen activity drivers.
- A total of **4 hydrogen port archetypes** have been defined according to axes relevant for this study: Logistics and transport, Urban, Industrial and Bunkering.
- For each archetype, **Tier 1, Tier 2, and Tier 3 ports were identified based on the volume of dominant activity in their archetype**. With Tier 1 ports, regular feedback interactions were maintained during the course of the study.
- Ports can refer to these archetypes to **shape an appropriate business model aligned to their own specific context**. However, ports are not confined to a single archetype and can also examine business models applicable to other archetypes.

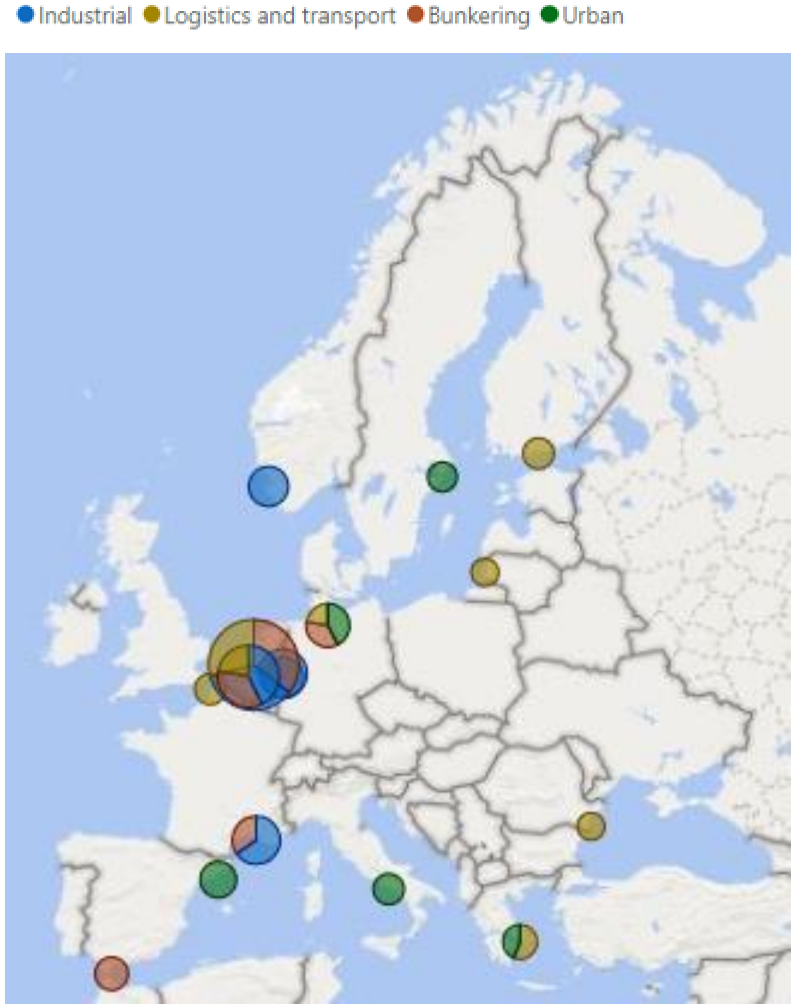
Logistics and transport	Large amount of liquid bulk, dry bulk, containers, cargo and passengers in the port
Urban	Large urban areas in proximity to the port
Industrial	High industrial activity in proximity to the port
Bunkering	Large amount of bunkering fuels in the port

… as a mean to link hydrogen demand, supply and business models



A total of 16 'Tier 1' ports geographically spread within Europe have been selected for regular feedback interactions in the course of the study

Geographical location



Port	Industrial archetype	Logistics and transport archetype	Bunkering archetype	Urban archetype
Rotterdam	●	●	●	
Antwerpen	●	●	●	
Calais		●		
Helsinki		●		
Piraeus		●		●
Algeciras			●	
Marseille	●		●	
Duisburg	●			
Düsseldorf	●			
Stavanger	●			
Barcelona				●
Hamburg		●	●	●
Napoli				●
Stockholm				●
Constanta		●		
Klaipėda		●		

Note: For the 4 port-related activities, a dark color (i.e., dark blue) refers to a high level of port involvement in the corresponding activity while a light color (i.e., light blue) refers to a relatively lower level of port involvement in the corresponding activity.

Industries, heavy-duty road freight, shipping to and from Europe, heating of urban areas and port activities are expected to drive hydrogen demand

Within the scope of the study

European industries

Existing uses of hydrogen

- Hydrogenation of mineral oil in refineries
- Production of ammonia for fertilizers
- Production of methanol for current uses

New uses of hydrogen

- Production of primary steel
- Production of high value chemicals
- Generation of heat for industrial processes

General assumption: Even tough it is acknowledged that European industries are facing is a risk of relocation (especially for ammonia and methanol plants), this study assumes that current European production capacities in all industrial sectors within scope will remain competitive with imports due to a favorable regulatory and technico-economic environment.

Road freight

- Heavy-duty road freight

Shipping to and from European ports

- Domestic shipping
- International shipping

Urban areas

- Heating of residential buildings
- Heating of service buildings

Port activities

- Cargo handling
- Port vessel fleet

Conclusion: The aim of this study is to investigate the future demand for hydrogen that has the most significant implication for activities in the vicinity of ports and industrial coastal areas. Given that estimates in the areas covered by this study already foresee a substantial hydrogen demand in Europe, especially from 2040 onwards, including additional potential hydrogen applications in scope would not have a tangible effect on the choices and actions that ports can undertake up to 2030.

Outside the scope of this study

Aviation sector (synthetic kerosene and hydrogen powered aircraft)

Power sector (use of hydrogen in gas-fired turbines for electricity generation)

Rail sector (hydrogen-powered trains)

Hydrogenation of biofuels (road transport) **and biokerosene** (aviation)

Cold ironing (use of hydrogen fuel cell to power ships at berth)

Hydrogen as a "by-product" (hydrogen produced in the following industrial/chemical processes: Coke oven gas, Ethylene, Chlor-alkali, Styrene, Sodium chlorate).

Rationale for excluding these sectors from the scope

1. The agreed upon term of this study does not foresee aviation and power sectors as being within the scope. We recognize that this exclusion choice leads to an underestimation of total potential hydrogen demand, especially in the 2040s and through 2050.
2. Hydrogen demand estimated to be relatively unsignificant to overall projected hydrogen demand in the EU up to 2050:
   - Hydrogenation of biokerosene (8 TWh or 0.24 Mt/year by 2030, 35 TWh or 1.06 Mt/year by 2040 and 44 TWh or 1.32 Mt/year by 2050[1]).
   - Hydrogen-powered rail transport (6.5 TWh/0.19 Mt/year in 2050 of hydrogen).
   - Hydrogen as a by-product (41 TWh or 1.23 Mt in 2020 with perspectives of significant decrease as industrial and chemical processes decarbonize[3]).
3. There are significant uncertainties with regards to the potential of road transport liquid biofuels in the long-term (up to 2050)[4].

Sources: (1) Guidehouse, 2021; (2) Based on own calculations if all existing trains not electrified yet switch to hydrogen-powered engines; Fuel Cells and Hydrogen Observatory, 2022 (3) Fuel Cells and Hydrogen Observatory, 2022; (4) Guidehouse, 2021

Using a scenario-based approach to encompass the range of potential hydrogen demand and supply development pathways in Europe

Future hydrogen demand in Europe

Existing hydrogen demand vs. new hydrogen demand

- In 2020, hydrogen demand in Europe was 288 TWh (8.64 Mt), with **refineries, ammonia, and methanol plants accounting for 84%** (7.29 Mt) **of total hydrogen demand**.
- From the 2020s until 2050, **new sectors and activities** are expected to use large amount of hydrogen, both for final energy purposes (fuel) and non-energy purposes (feedstock), to decarbonize and contribute to EU's 2050 net zero target.

Hydrogen demand: a scenario-based approach

Conservative scenario: Low and **slow uptake** of hydrogen by new hydrogen end-users. The role of hydrogen is often only marginal in sectoral decarbonization strategies, and its adoption is **mainly limited to existing users and other heavy industries**.

Moderate scenario: Moderate and **progressive uptake** of hydrogen by new hydrogen end-users. Hydrogen is seen as only **one of many options** (e.g., CCS, electrification, biomethane, etc.) in sectorial decarbonization strategies.

Ambitious scenario

- **Widespread** and **rapid uptake** of hydrogen for final energy (fuel) and non-energy (feedstock) purposes **in all sectors and activities** (covered by this study) not currently consuming hydrogen (new hydrogen end-users).
- For existing hydrogen users (refineries[1], ammonia and methanol plants) the contribution of green hydrogen used for final energy and non-energy purposes is assumed to reach the **50% of total hydrogen demand by 2030 target** proposed by the European Commission in the framework of the **revision of the Renewable Energy Directive** (RED III), followed by gradual increase to 100% by 2040 or 2050.

Scenarios have been established in a pre-Russo-Ukrainian war context.

Future hydrogen supply in Europe

Hydrogen supply: a dual scenario approach

Base supply scenario: **Three hydrogen supply scenarios matching** respectively the forecasted hydrogen demand in the **three demand scenarios**.

Increased import supply scenario: **Additional hydrogen supply scenario matching** only the hydrogen demand foreseen in the **ambitious demand scenario** and incorporating a **predefined constraint** in the annual rate of deployment (5%) of European renewable energy sources until 2050.

Hydrogen production in European territory

- Today, hydrogen is almost always produced at the consumption site (mainly in refineries, ammonia & methanol plants), so called captive market. The remaining hydrogen production is produced at central hydrogen plants and then distributed.
- Starting in the 2020s, it is assumed that **all the additional hydrogen production capacity in Europe will be supplied by central renewable hydrogen plants** which operate in a **cross-border hydrogen market** subject to economic forces.
- Over the same period, this study assumes that a **limited number of existing grey hydrogen facilities** within refineries and ammonia plants **will switch to blue hydrogen** by adding a CCS unit to their already installed methane reformers.

Hydrogen import to Europe

- Starting in 2030 and scaling-up until 2050, it is assumed that **some European countries will import hydrogen**, both from **within** and **outside Europe** (mainly from North Africa and the Middle East, but also from more distant horizons such as Chile or Australia).
- All supply scenarios assume that **hydrogen imported to Europe** between 2030 and 2050 2050 will be **both green and blue**.
- This study assumes that import of hydrogen will be ensured either **through shipping in the form of ammonia** or through **pipeline** in its gaseous form.

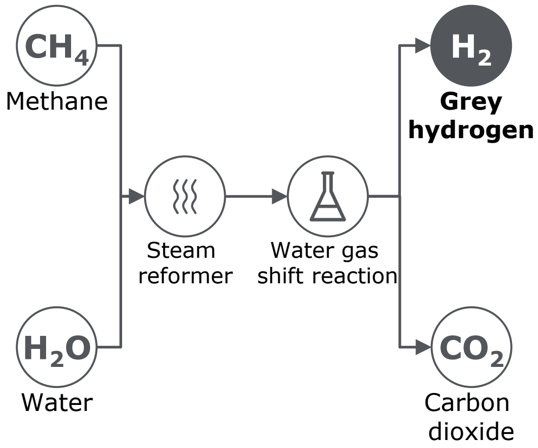
REPowerEU scenario: **Accelerated uptake of hydrogen**, reflecting short-term goal to (partially) replace Russian fossil fuels by hydrogen (cf. addendum)

Note (1) Even though hydrogen used as intermediate products for the production of conventional transport fuels is excluded from the RED III target (i.e., the contribution of green hydrogen used for final energy and non-energy purposes shall be 50 % of the hydrogen used for final energy and non-energy purposes in industry by 2030), this study assumes that, in the hydrogenation of mineral oil process, refineries will align their target for green hydrogen consumption share with the target laid down in RED III.

The future of hydrogen as energy: the hydrogen color spectrum

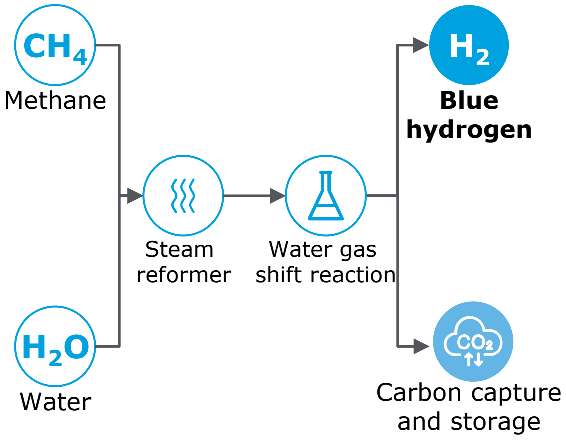
There are two dominant types of hydrogen for decarbonization: **"green" hydrogen** (also called **renewable hydrogen**), which is produced by electrolysis of water with electricity from renewable energy sources, and **"blue" hydrogen** (also called **low-carbon hydrogen**), which is produced in methane reforming plants equipped with CO_2 capture units and subsequent CO_2 storage[1].

Grey hydrogen



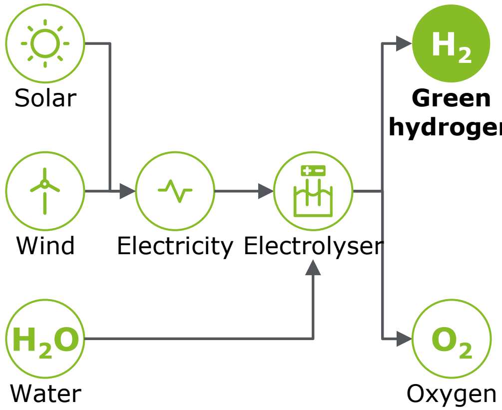
- Current hydrogen production in Europe is almost exclusively **grey hydrogen** from natural gas.
- The production of grey hydrogen is **highly carbon intensive**.

Blue hydrogen



- Blue hydrogen has the **same production method** as grey hydrogen but uses **carbon capture and storage (sequestration).**
- It has **controllable production capacity** hence does not require storage.
- Blue hydrogen is expected to contribute to **pave the way toward a green hydrogen economy**.
- Depends on the supply of natural gas to EU from a limited of countries with natural gas reserves.

Green hydrogen



- Green hydrogen is the only **100% renewable hydrogen** production method.
- It requires **storage** to balance out **fluctuating production** from intermittent renewables with constant demand.
- Electrolysis **technologies vary**; mature **alkaline** technology is best for **stable electricity** supply, newly developed **PEM** technology for **intermittent** supply.
- Unlocking green hydrogen allows to **diversify EU supply of energy** and decrease energy dependency via local EU production and countries with abundant sun and wind.

Note: (1) Even though not in the scope of this study, other hydrogen produced processes such as "pink hydrogen' (nuclear-based) and "turquoise" (methane pyrolysis) could also play a role depending on policy, technological and economical evolutions.

Due to strong political impetus at the EU level, the theoretical long-term potential of European blue hydrogen production is assumed to not be harnessed

Potential of mass blue hydrogen production …

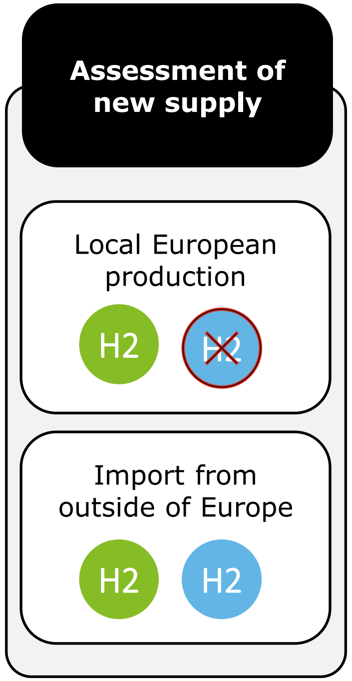
Large-scale European blue hydrogen production has the theoretical potential to decarbonize current hydrogen uses as well as new industrial and non-industrial hydrogen applications, while paving the way for a European green hydrogen economy.

- Producing very large quantities of green hydrogen within the EU is subject to public acceptance of an accelerated expansion of renewable installed capacity which goes much beyond planned expansions formulated in the current National Energy and Climate Plans (NECPs).
- **Assuming natural gas is available in sufficient quantities,** the technical potential for blue hydrogen production is theoretically limited only by CO_2 storage, the potential of which far exceeds the total projected hydrogen demand, even if it were fully met by blue hydrogen[1].
- Assuming natural gas supply in Europe is **available at a relatively low-cost** (compared to alternative low-carbon energy options), and that **technically efficient carbon capture and storage systems are cost-competitive**, blue hydrogen could support emissions reductions and accelerate the pace of the transition to low carbon/renewable hydrogen, particularly in the market ramp-up phase (2020s and 2030s), when the potential for green hydrogen supply from dedicated renewables alone may be insufficient to meet local and regional demand.
- Beyond 2035, the deployment of new blue hydrogen projects is likely to face **increasing competition from green hydrogen** (domestic and imported) as the latter becomes more widely available at lower cost. However, existing (by then) blue hydrogen projects, which have a 25-year lifespan, could still have a role to play as a marginal supply option and could contribute to system integration and balancing of variable green hydrogen through steady baseload hydrogen production.

… is assumed to not be harnessed

Due to significant political, regulatory, economic and technological barriers, this study assumes that the large-scale potential of European blue hydrogen production will not be harnessed.

- Starting with the EU Hydrogen Strategy (2020), emphasized in the "Fit for 55" policy proposal package (2021) and endorsed in the REPowerEU Communication (2022), **the EU has consistently outlined that institutional efforts** for the development of a hydrogen economy by 2030 and beyond **will be geared towards green hydrogen.**
- Therefore, given such **strong political impetus** at the EU level, which has been explicitly followed by most Member States, along with the **multiple political, regulatory, economic, and technological barriers** (i.e., regulatory and political acceptance constraints, high natural gas and carbon prices, uncertainties in the capture rate of CCS, little or no public subsidies, risks of methane leakage from natural gas during exploration and transportation, etc.) **to scaling up blue hydrogen production**, **this study makes the overarching assumption that no additional blue hydrogen production capacity** ('new supply') **will be built in Europe**.
- As such, in this study, **blue hydrogen deployment will be limited to a limited number of retrofitted existing grey hydrogen facilities** ('existing supply') **at refineries and ammonia plants**.



Note: an indicative estimate of the theoretical European blue hydrogen production in 2030, 2040 and 2050 for the three demand scenarios developed in this report is provided in Appendix 2.I. Model finds that blue hydrogen production in the EU (both from on-site and central hydrogen plants) could theoretically represent between 139 and 396 TWh/year in 2040 (4.17-11.88 Mt). Source: (1) Guidehouse, 2021.

The use of coastline and hinterland clusters as an interface for hydrogen demand and supply modelling in Europe

Coastline and hinterland clusters as interface between hydrogen demand and supply modelling

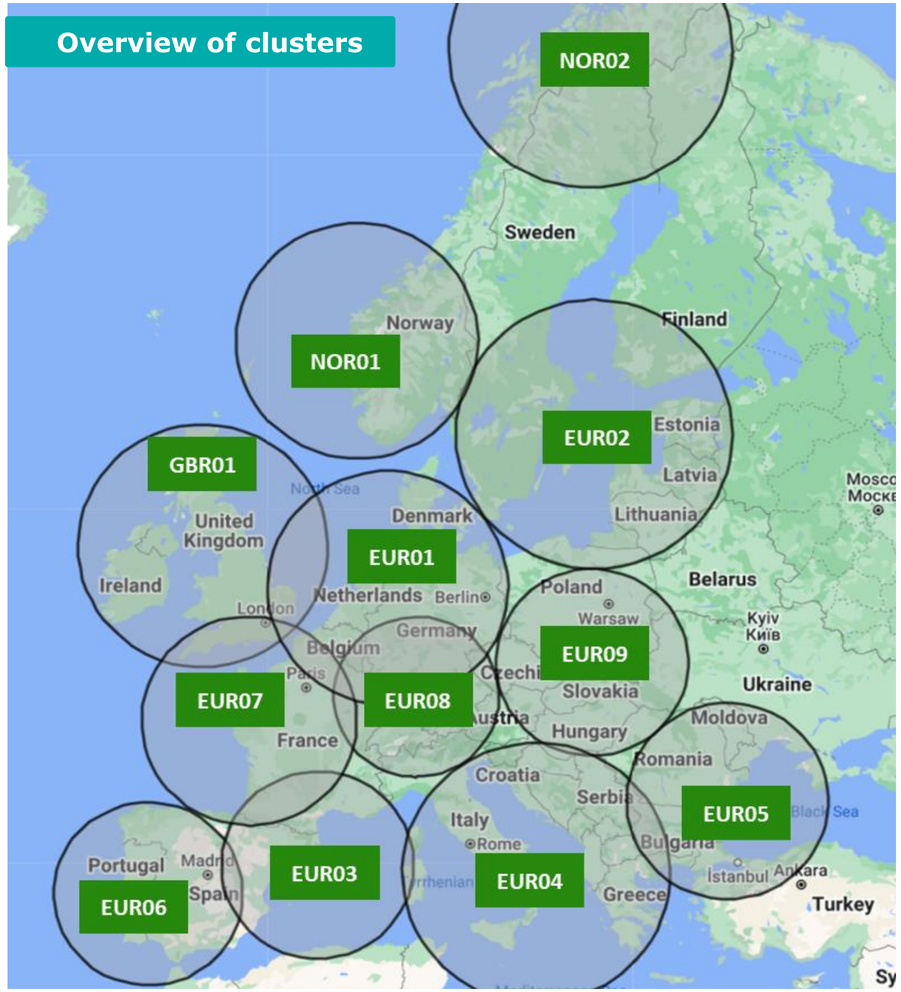
Explanation of the use of clusters:

The model assumes that the economic parameters of hydrogen supply in the geographical scope of this study is similar within a 700 km radius. Consequently, Europe has been segmented into **12 demand clusters**, each covering a specific geographical area of Europe. This cluster approach is designed to best reflect the economic, geographic (sea or pipeline link with importing countries) and climatic specificities of the various regions. The supply model matches hydrogen supply to the projected hydrogen demand, for each demand scenario, consolidated on cluster level.

Description of the demand clusters:

Among these clusters, "coastline" clusters are differentiated from "hinterland" clusters.

- The "**coastline" clusters** (EUR01 to EUR07) cover all the territories of the EU that are located within the vicinity of a coastal zone. In addition to housing a large portion of European industrial sites likely to use hydrogen in the short and medium term, these areas contain all European ports likely to play a role in the import and distribution of hydrogen from territories outside Europe.
- Meanwhile, the "**hinterland" clusters** (EUR08 and EUR09), essentially located in the center of Europe (western France, southern Germany, Switzerland, northern Italy, Poland, Slovakia, Hungary, Czechia, eastern Austria, northern Romania), cover European territories that are relatively far from a coastal zone. Although they have a significant hydrogen demand potential, these clusters will likely be at least partially dependent on port infrastructures located in the "coastline" clusters for hydrogen supply.
- Finally, the model integrates **three other clusters**, GBR01, NOR01 and NOR02, **located outside of European Union** (except for Ireland). Their geographical position, the strength of their historical political and economic links with European Union as well as their natural gas production and export make these regions preferential economic partners for importing hydrogen.



Note: For geographies that are covered by more than one demand cluster (e.g., central Germany or northern France), the model determines which hydrogen production cell can supply the most cost-effective hydrogen, and then allocates the corresponding demand of these geographies to the cluster that is in a position to supply hydrogen at the lowest cost.

Hydrogen demand modelling approach to estimate hydrogen demand in 2030, 2040, and 2050 by demand segment within and outside the vicinity of ports

Task 1 – Hydrogen demand

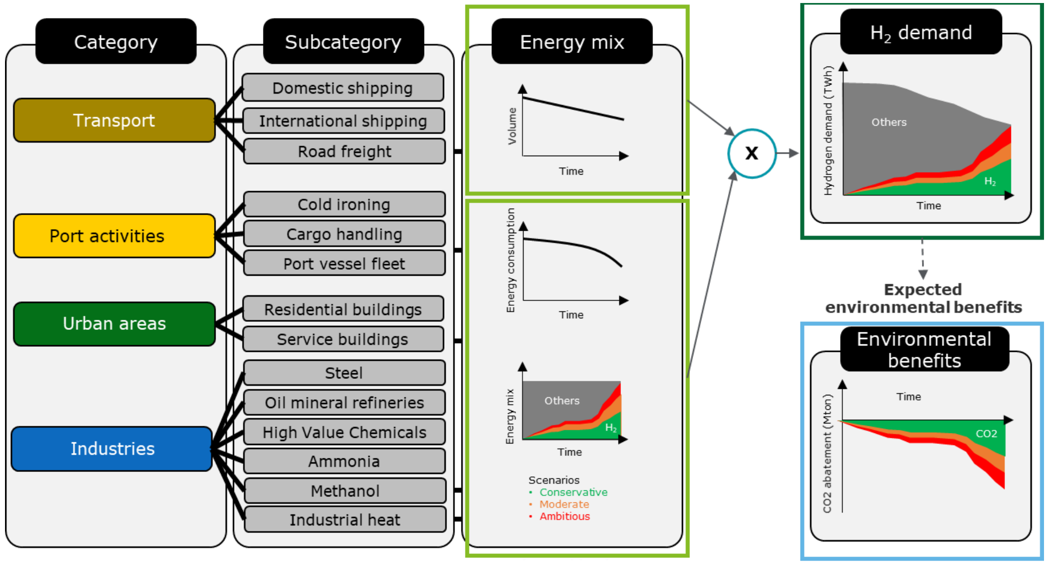
Modelling of hydrogen demand and market potential:

> Existing applications and potential applications of hydrogen demand are covered across 14 subcategories embedded within 4 categories (industries, transport, urban areas and port activities).

> For each subcategory, a stepwise rational approach allowing for sectorial specificities is developed to estimate the potential role of hydrogen in three scenarios (Ambitious, Moderate, Conservative).

> Results: estimate of future hydrogen demand in 2030, 2040, and 2050 by subcategory, both within and outside the vicinity of European ports.

Hydrogen demand modelling approach



Task 2 - Hydrogen supply

Modelling of hydrogen supply:

> HyPE[1] models locally produced (green) and imported (green and blue) hydrogen. The economic model strives for overall cost minimization and is based on the modeling of the Levelized Cost of Hydrogen (LCOH) taking into account all costs related to the hydrogen supply chain.

> HyPE models hydrogen flows in European port clusters and from port clusters to hinterland clusters.

> Results: hydrogen supply in 2030, 2040, and 2050 for ports and outside of ports.

Hydrogen supply modelling, hydrogen flows and demand-supply equilibrium

Hydrogen supply modelling approach to estimate where hydrogen supply will come from in 2030, 2040 and 2050 inside and outside of ports

Task 1 – Hydrogen demand

Modelling of hydrogen demand and market potential:

- Existing sources and potential new sources of hydrogen demand are covered across 14 subcategories embedded within 4 categories (industries, transport, urban areas and port activities).
- For each subcategory, a stepwise rational approach allowing for sectorial specificities is developed to estimate the potential role of hydrogen in three scenarios (Ambitious, Moderate, Conservative).
- Result: estimate of future hydrogen demand in 2030, 2040, and 2050 by subcategory, both within and outside the vicinity of European ports.

Hydrogen demand modelling approach

Task 2 - Hydrogen supply

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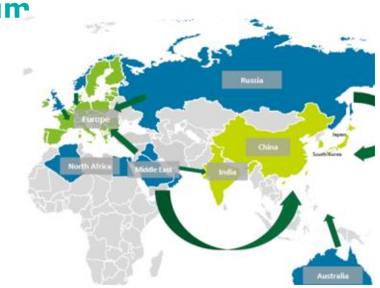
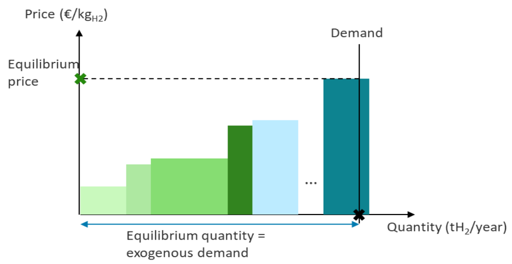
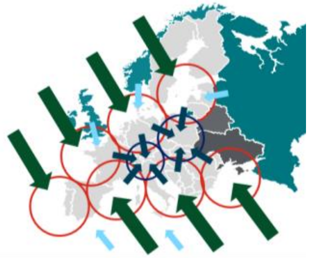
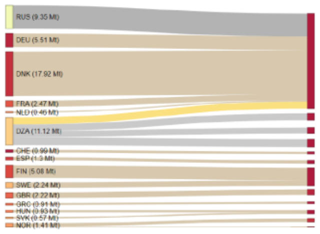
Hydrogen supply modelling, hydrogen flows and demand-supply equilibrium









Note: 1. Hydrogen Pathway Explorer (HyPE) is a model developed and maintained by Deloitte France.

Port-specific results on supply and demand projections for each of the 427 European ports are available in the associated Power BI dashboards[1]

Hydrogen demand data per port

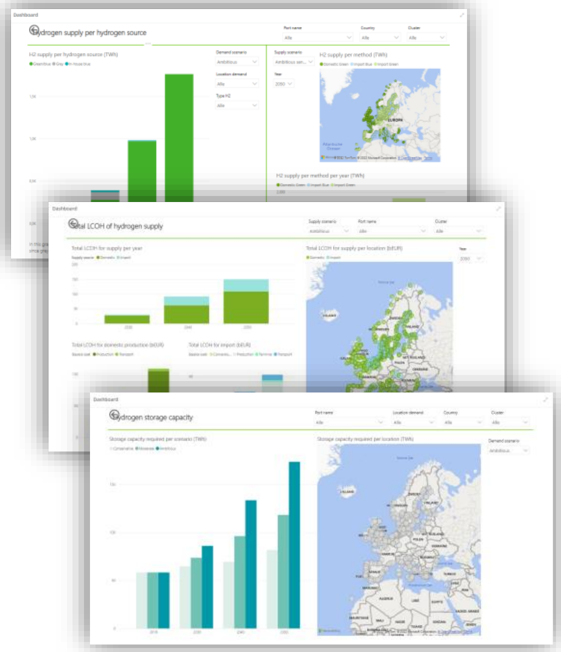
Port-specific projected hydrogen demand is available for each port:

- Projected hydrogen demand is calculated per port for each scenario and subcategory separately. All data can be freely consulted in the Power BI dashboards.
- The projected hydrogen demand is the result of the volumes in a port multiplied with the hydrogen demand per unit of volume. The units of volume can also be consulted per port in the dashboards.
- Projected hydrogen demand on cluster and EU level are obtained via aggregating projected hydrogen demand per port. Also, total hydrogen demand per country can be found in the dashboards.

Hydrogen supply data per port

Projected hydrogen supply is available per port:

- Contrary to the demand data which is calculated per port and then aggregated to obtain data per cluster and on European level, the supply data is not calculated per port but rather per cluster.
- To obtain the supply data per port, the total hydrogen supplies per cluster are divided over the different ports within a cluster, based on the relative share of the total expected demand per port within a cluster. All data can be freely consulted in the Power BI dashboards.



Note: (1) A more comprehensive explanation of available data in the PowerBI dashboards is provided in the section "Power BI dashboards" of the report

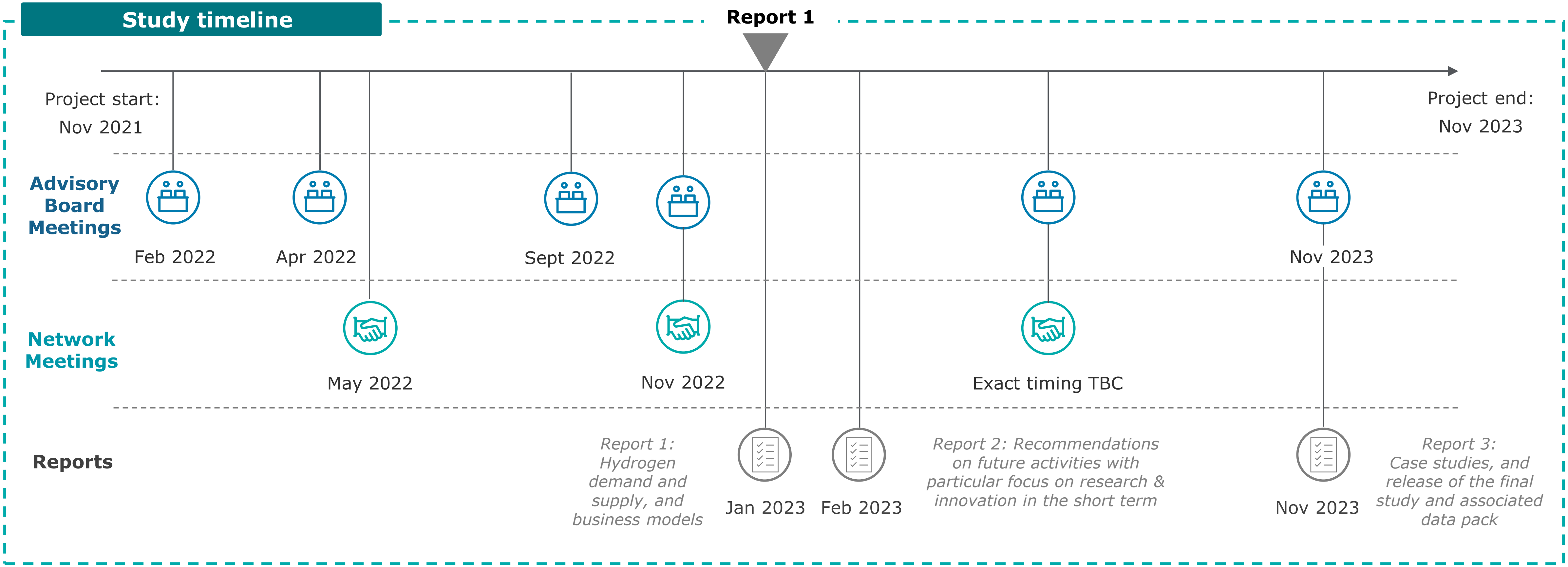
The Advisory Board provides guidance throughout the study and European Hydrogen Ports Network acts as a community building platform

Advisory Board

Main task of the Advisory Board is to provide **oversight and guidance** in the delivery of the study, particularly in **validation** of each Task. Advisory Board meetings are complemented by bilateral touchpoints to capture feedback

European Hydrogen Ports Network

Members are invited to take part in European Hydrogen Ports Network activities to **provide data and ideas** to the process, as well as to **exchange and connect** in order to boost hydrogen take-up in European ports.



Power BI dashboards

Accessing the port-specific results on hydrogen demand, supply and required infrastructures projections

Port-specific results on hydrogen demand, supply and required infrastructures projections are available in the dynamic dashboards accompanying this report

Accessing granular results on hydrogen demand, supply and required infrastructures

- In this report, the methods used to calculate the projected hydrogen demand, supply and required infrastructure is outlined, as well as the assumptions retained. However, **only the consolidated results for certain years are provided and discussed in this document**.

- For a **more granular view on detailed results** by cluster, by country, by port, as well as for each timeframe (2020, 2030, 2040 and 2050) and scenarios (Conservative, Moderate, Ambitious), **dynamic online dashboards are accompanying this report**. These dashboards allows the user to dynamically filter data across the various years, geographical locations (clusters), ports, scenarios, etc. The dashboards only show the results, all assumptions and methods used to obtain these results can be found in this report.

- The main purpose of the dashboards is to **provide a more detailed picture of the results of the study relevant for various interested parties**. For example, **port authorities can dive into hydrogen demand and supply projections and infrastructure requirements for their individual port ecosystems**, while **national decision-makers can zoom out to get a national or cluster-level view**.

- The dashboards are structured as follows:
  - The first section includes the results of the **hydrogen demand analysis** (incl. hydrogen related CO_2 abatement);
  - The second section includes the results of the **hydrogen supply analysis** (incl. analysis hydrogen infrastructure);
  - In the third section, a summary of all the results can be found on an individual port level. This section has the purpose to **make it immediately clear for ports how much the projected hydrogen demand is, how this demand will be supplied, the cost of the supply, and the required infrastructure and investments to enable the adoption of hydrogen**.

- The method to calculate the results on a port level:
  - **Hydrogen demand**: all volumes used to estimate the hydrogen demand are collected on a port level. The hydrogen demand is thus automatically assessed per port and then aggregated to obtain the overall results.
  - **Hydrogen supply**: the supply is looked into at a cluster level. To obtain the supply per port, and to make the results of the study actionable for the individual ports, the following assumption was made: the totals per clusters are split based on the share of hydrogen demand of a specific port compared to the overall demand in the cluster. However, in reality there might be a different ratio between the ports within one cluster.

- **Access to the dashboards** can be requested by sending an email to sdebrabander@deloitte.be

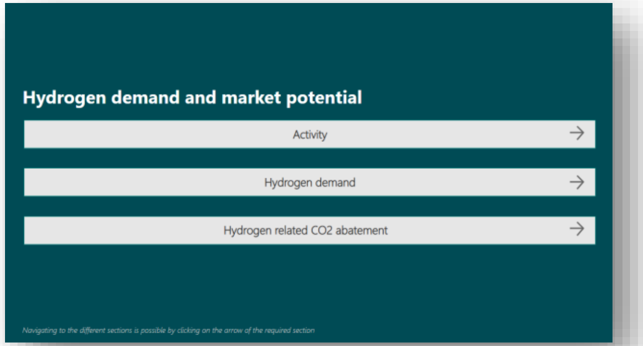
Projected hydrogen demand and related CO_2 abatement

Hydrogen demand and related CO_2 abatement

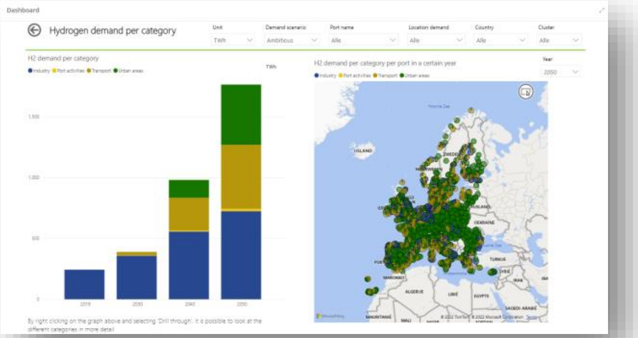
- Granular data on the following topics can be found in the 'hydrogen demand and market potential' dashboards:
  - **Activities conducted in the vicinity of ports**: i.e., the quantity of ammonia produced, the quantity of bunkering fuels sold, the total surface of residential buildings in proximity, etc. per year (2020, 2030, 2040 and 2050).
  - **The projected hydrogen demand** per year (2020, 2030, 2040 and 2050), scenario (Conservative, Moderate and Ambitious), demand category (e.g., industries) and demand subcategory (e.g., primary steel production).
  - **The corresponding hydrogen related CO_2 abatement** per year (2020, 2030, 2040 and 2050), scenario (Conservative, Moderate and Ambitious), demand category (e.g., industries) and demand subcategory (e.g., primary steel production).

Overview of the 'hydrogen demand' dashboards

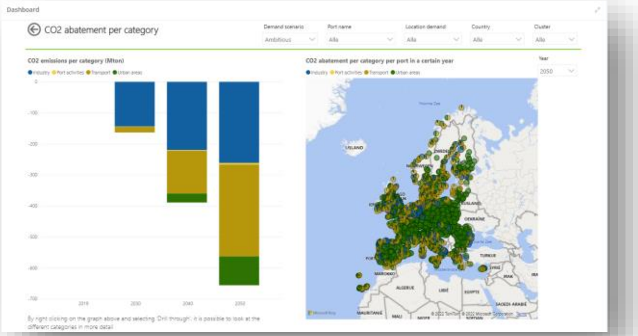
Access to the dashboard



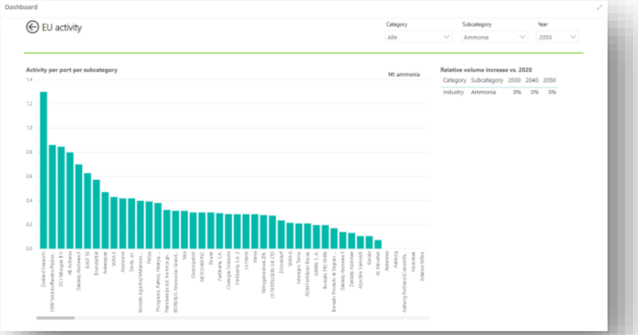
Hydrogen demand per category



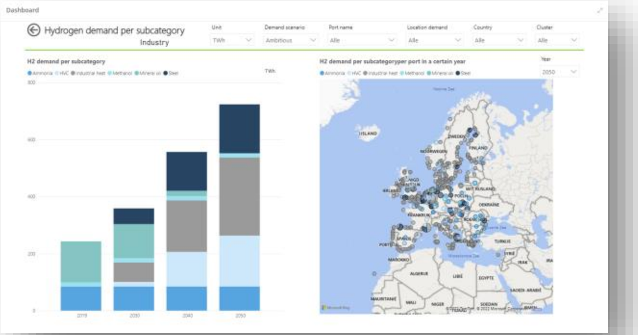
CO_2 abatement potential per category



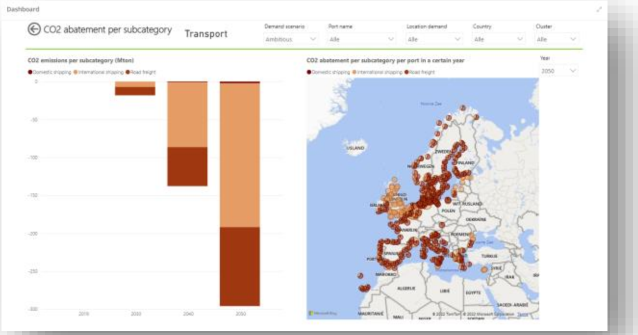
EU activity



Hydrogen demand per subcategory



CO_2 abatement potential per subcategory



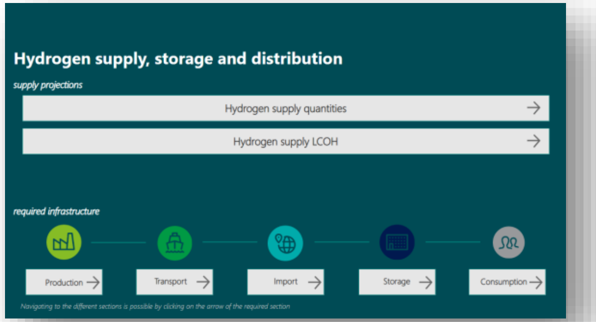
Projected hydrogen supply and required infrastructure

Hydrogen supply

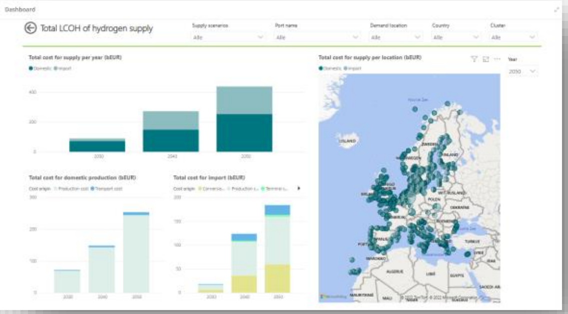
- Granular data on the following topics can be found in the 'hydrogen supply, storage and distribution' dashboards:
  - **Projected hydrogen supply quantities** per geographical source (import, domestic production) and production method (blue or green) per year (2020, 2030, 2040 and 2050), scenario (Conservative, Moderate and Ambitious), demand category and subcategory
  - **Projected LCOH for the supply of hydrogen** per year (2020, 2030, 2040 and 2050), scenario (Conservative, Moderate and Ambitious), demand category (e.g., industries) and demand subcategory (e.g., primary steel production).
  - **Required infrastructure capacities and associated investments** for production, transport, import, storage and consumption per year (2020, 2030, 2040 and 2050), scenario (Conservative, Moderate and Ambitious), demand category (e.g., industries) and demand subcategory (e.g., primary steel production).

Overview of the 'hydrogen supply, storage and distribution' dashboards

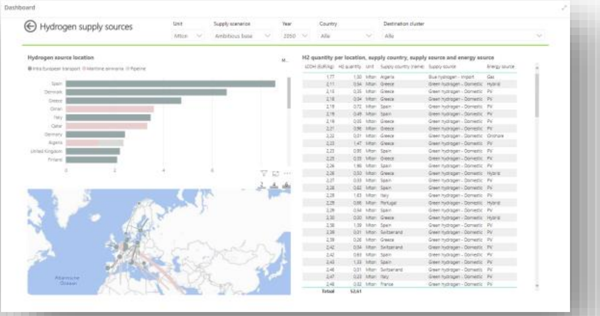
Access to the dashboard



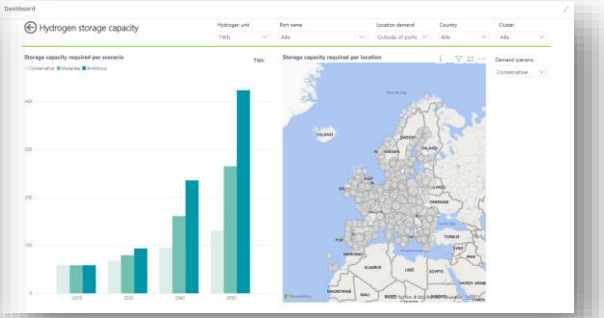
LCOH supply



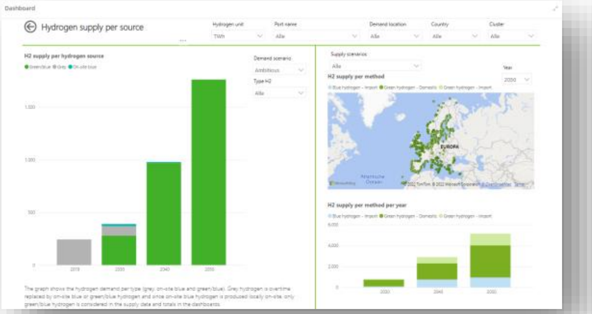
Supply sources



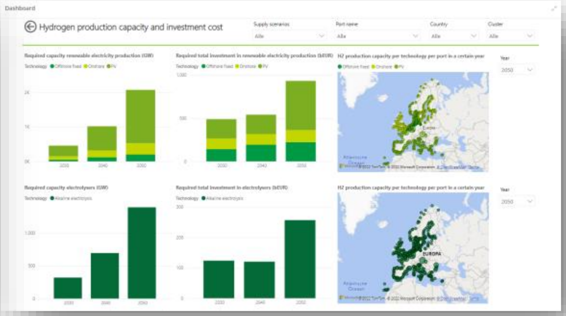
Storage capacity



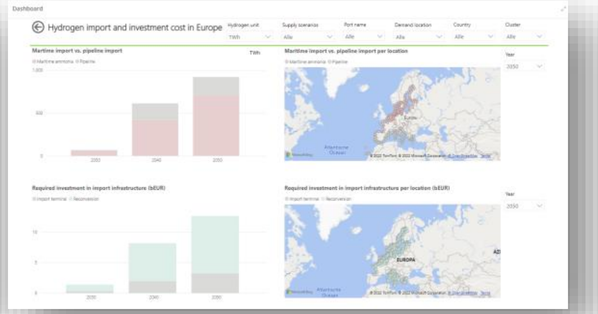
Type of supply



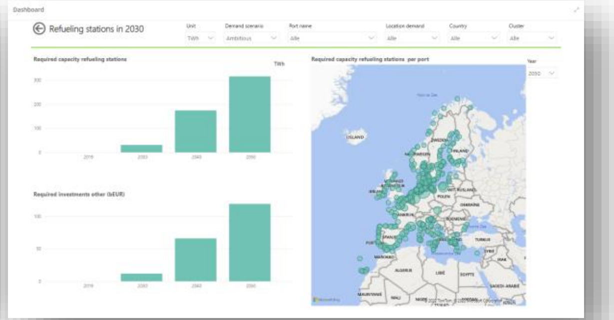
Production capacity, investments



Import capacity, investments



Refueling stations capacity



Projected hydrogen demand per port – Port of Antwerp-Bruges

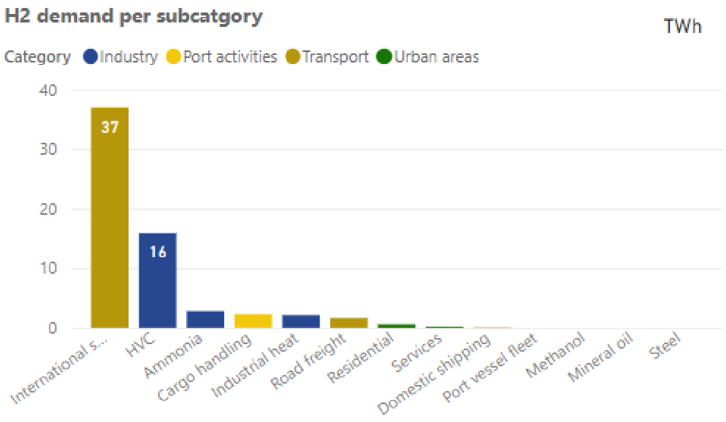
Dashboard

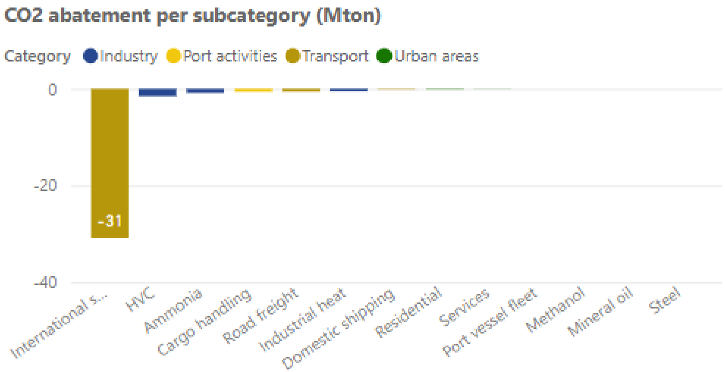
Hydrogen unit: TWh | Demand scenarios: Ambitious | Port [1]: Multiple selections | Year: 2050

Port: Antwerp-Bruges

Activity per port per subcategory

Category	Subcategory	Value	Unit
Industry	Ammonia	0.47	Mt ammonia
Industry	HVC	3.78	Mt product
Industry	Industrial heat	7.38	TWh natural gas
Industry	Methanol	0.00	Mt methanol
Industry	Mineral oil	0.00	Mt oil
Industry	Steel	0.00	Mt primary steel
Port activities	Cargo handling	19,610,666.67	TEU
Port activities	Port vessel fleet	24.35	million tonne-mile
Transport	Domestic shipping	6,333.37	million tonne-mile
Transport	International shipping	2,054,777.16	million tonne-mile
Transport	Road freight	13,574.08	million tonne-km
Urban areas	Residential	36,019,407.73	m2
Urban areas	Services	9,006,451.20	m2





Hydrogen demand

For the port: Antwerp-Bruges in 2050, in the Ambitious demand scenario:

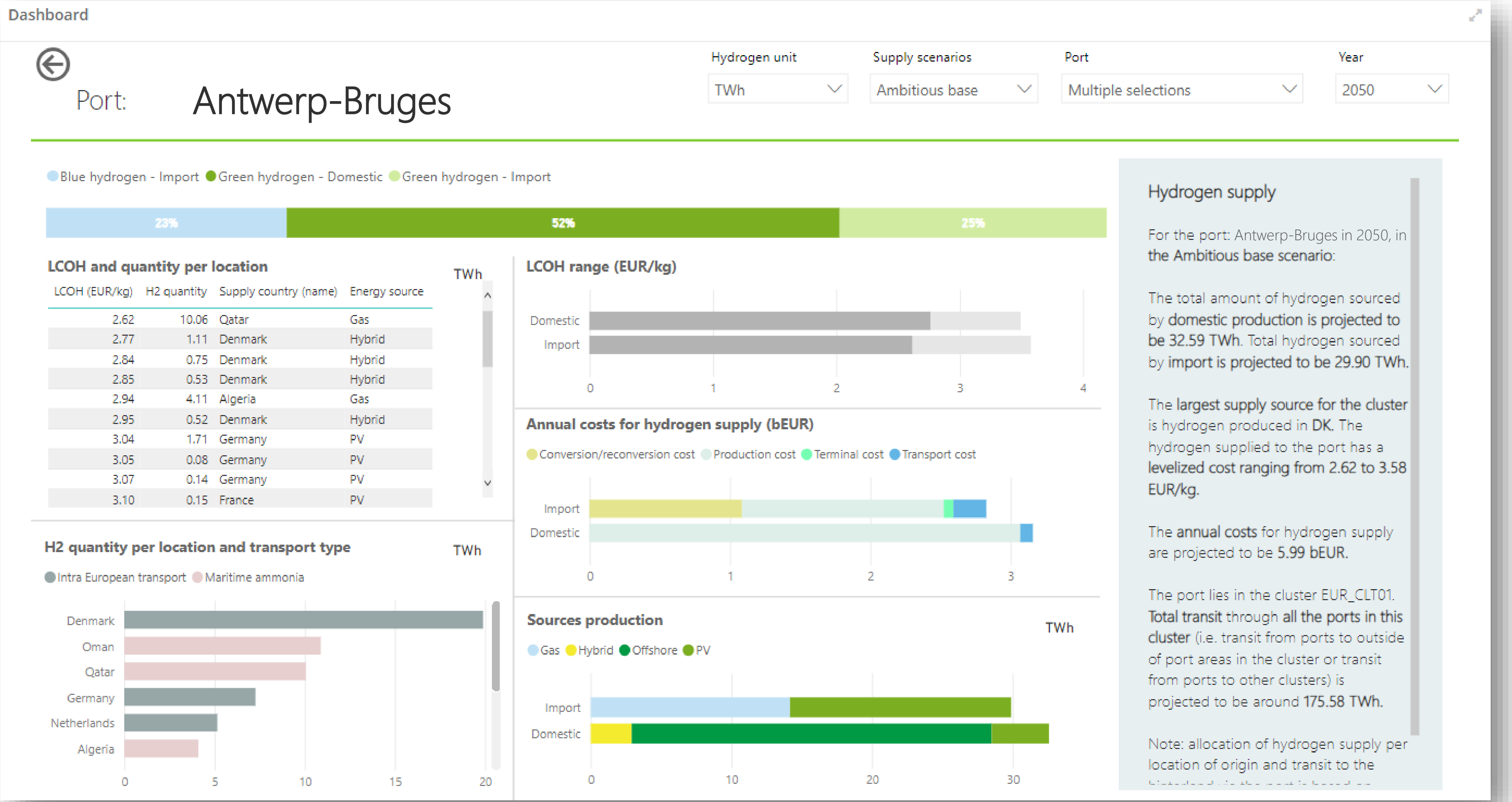
The total yearly hydrogen demand is projected to reach 62.49 TWh. Major drivers for the adoption of hydrogen are the decarbonisation of the category Transport which has the highest total yearly hydrogen demand at 38.71 TWh.

Hydrogen adoption in the port is projected to enable a yearly emissions reduction of 35.13 Mton in total. The highest CO2 emissions are abated in the category Transport with a total of 31.53 Mton. The subcategory with the most CO2 emissions abated yearly is International shipping with 30.83 Mton.

Note: (1) The ports listed are based on the databases consulted. In the analysis, collaborations or merges of different ports are not taken into account, since the demand data is based on the location of the port and assigning only one location to a collaboration or merger of different ports would lead to less accurate total demand data. However, it is possible to select more than one port in the dashboards. In the example shown, the port of Antwerp and the port of Zeebrugge are selected at the same time. This way, the total demand data can be consulted.

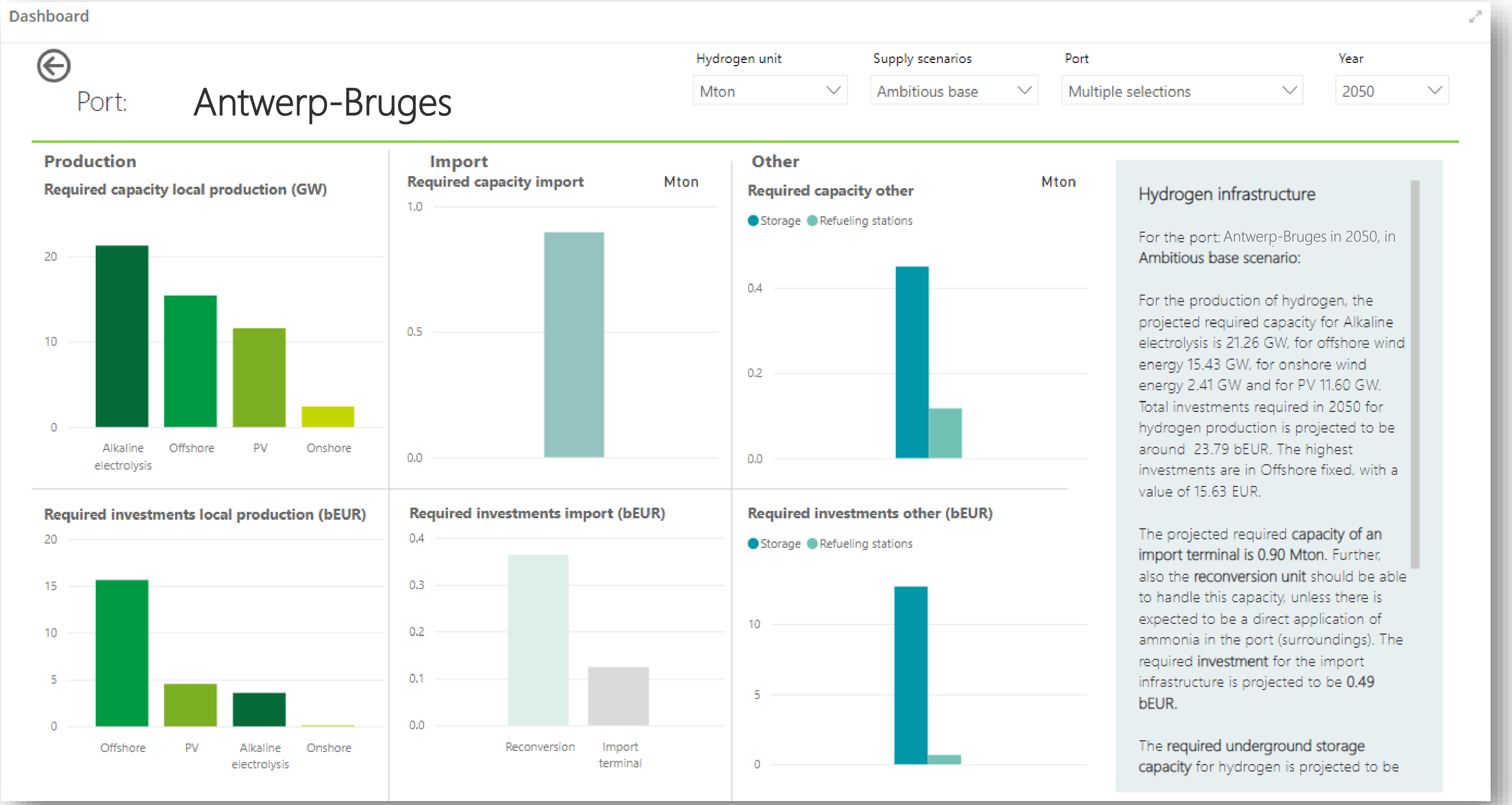
Projected hydrogen supply per port – Port of Antwerp-Bruges

Example



Example

Required hydrogen-related infrastructure per port – Port of Antwerp-Bruges



Task 1
Hydrogen demand and market potential

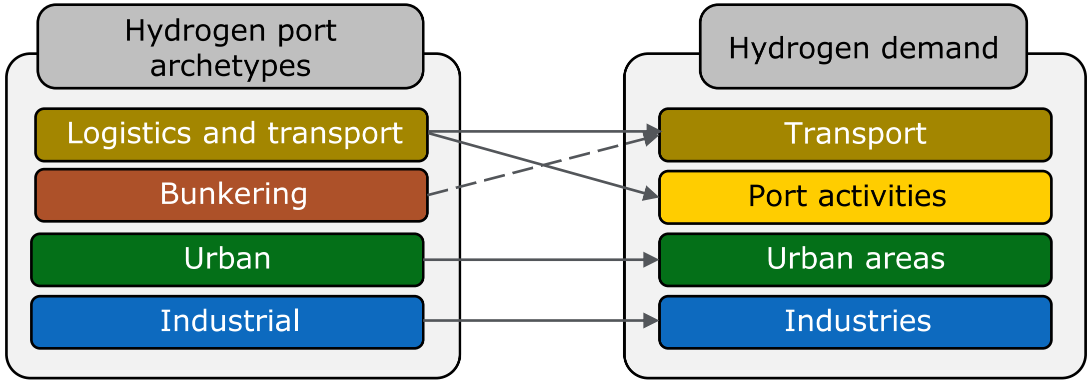
Port archetyping

Hydrogen port archetyping as a mean to structure the discussion on hydrogen demand, hydrogen supply and the development of viable business models

Port archetypes for this study

Hydrogen port archetype	Description	Main hydrogen activity driver(s)	Data sources
Logistics and transport	Large amount of liquid bulk, dry bulk, containers, cargo and passengers in the port	Sum of different types of cargo [Mt] and number of passengers to/from the port [#]	Deloitte port database (based on data ESTAT)
Urban	Large urban areas in proximity to the port	Population within a range of 21 km of the port [#]	Opendatasoft data hub
Industrial	High industrial activity in proximity to the port	Emissions of ETS installations within a range of 21 km of the port [CO_2-eq.]	EU ETS database
Bunkering	Large amount of bunkering fuels in the port	Volume of bunkering fuels [t]	Deloitte port database (based on data ESTAT)

- Hydrogen port archetyping is a mean to structure the discussion on hydrogen demand, supply and market potential and the development of viable business models.
- Each port is linked to **one or more hydrogen port archetypes** on the basis of its main hydrogen activity drivers.
- A total of **4 hydrogen port archetypes** have been defined according to axes relevant for this study: Logistics and transport, Urban, Industrial and Bunkering.
- For each archetype, Tier **1, Tier 2, and Tier 3 ports were identified based on the volume of dominant activity in their archetype**.
- **Ports are not confined to a single archetype** and can also examine business models applicable to other archetypes.



Normalization allows to assess relative importance of activity drivers for a port

Example of the Port of Antwerp

Input data

Port of Antwerp:

- **Logistics and transport activity**: 214,025 tonnes in 2019
- **Urban activity (nearby population)**: 678,436 people
- **Industrial activity**: 13,716,556 CO2 emissions in 2019
- **Bunkering activity**: 4,917,805 tonnes

Normalize over all ports

Normalized data

Port of Antwerp:

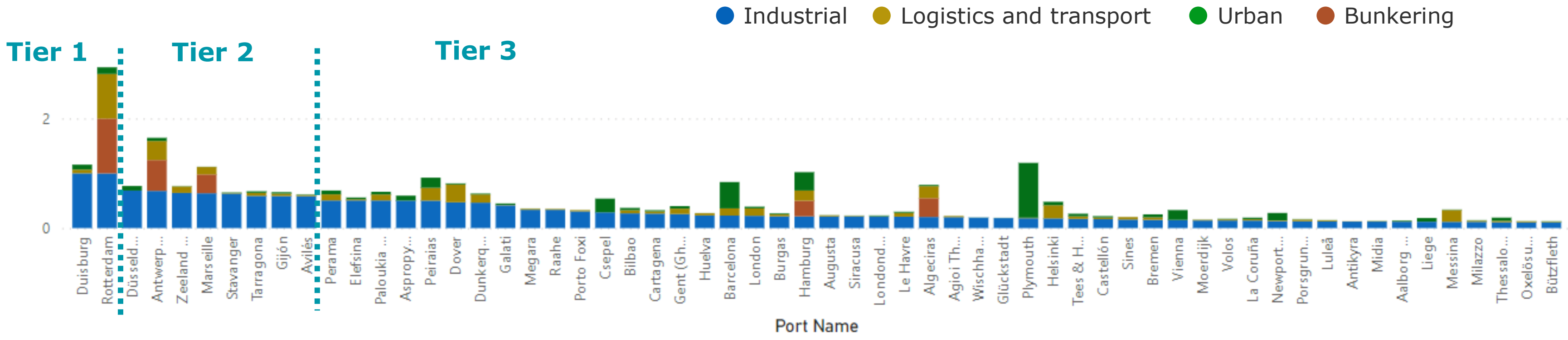
- **Logistics and transport activity**: 0.36
- **Urban activity (nearby population):** 0.12
- **Industrial activity**: 0.68
- **Bunkering activity** : 0.56

Normalization method

Within one Hydrogen activity driver, the port with the highest activity is equal to one and the lowest port activity is equal to zero. All other ports are scaled linearly within this range, per Hydrogen activity driver.

The industrial archetype

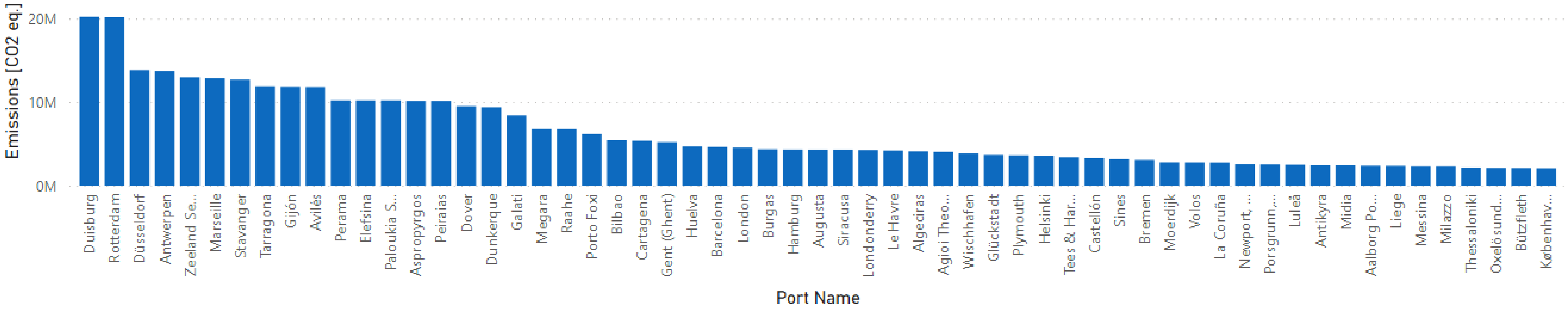
Activity distribution per port (normalized)



Key messages:

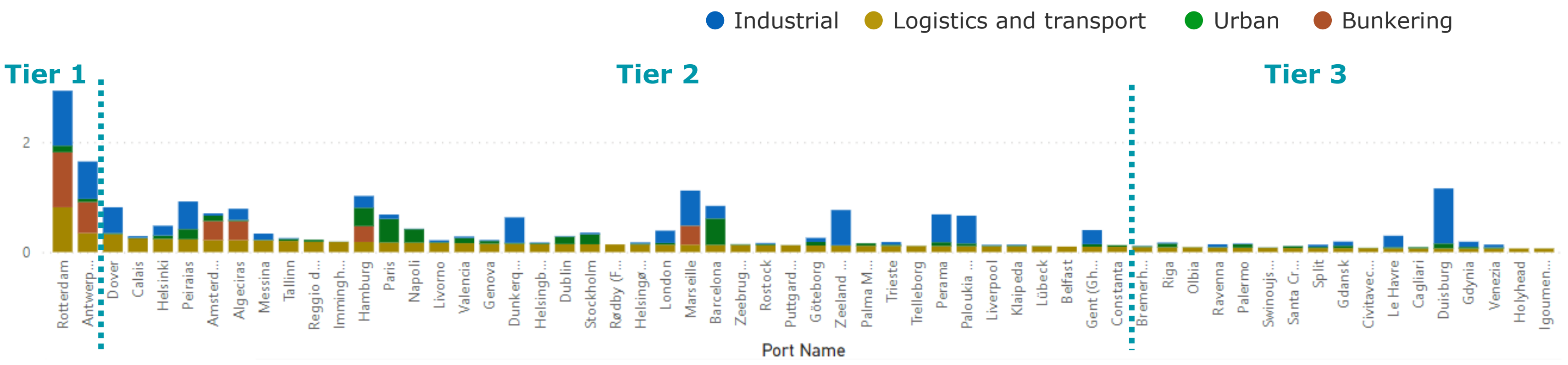
- The industrial archetype is highly relevant for the ports with a **high industrial activity**
- The industrial activity per port is based on the **amount of CO_2 emissions in proximity to the port from industrial installations**
- **Ports of Duisburg** and **Rotterdam** have the highest industrial activity in Europe

Industrial activity per port



The logistics and transport archetype

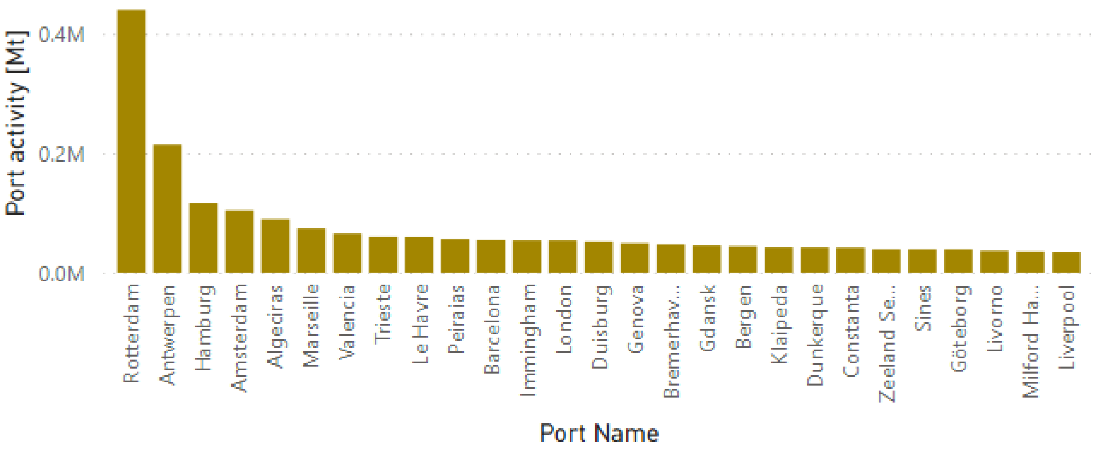
Activity distribution per port (normalized)



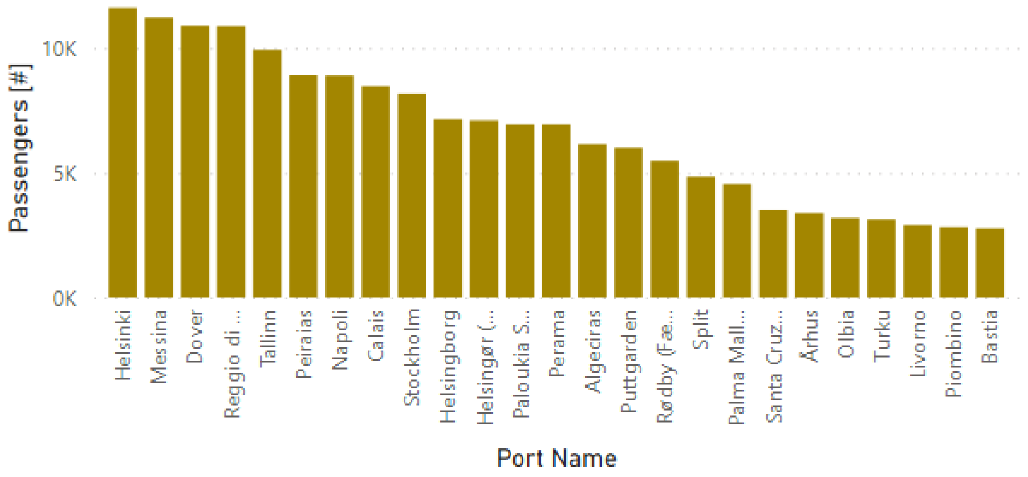
Key messages:

- The logistics and transport archetype is highly relevant for the ports with a **high port and passenger traffic.**
- The logistics and transport activity per port is based on the **volumes of port traffic and number of passengers.**
- **Rotterdam and Antwerp** have the highest total ports and passenger traffic.
- **Helsinki** has the highest passenger activity. **Rotterdam** has the highest cargo activity.

Logistics and transport activity (cargo) per port

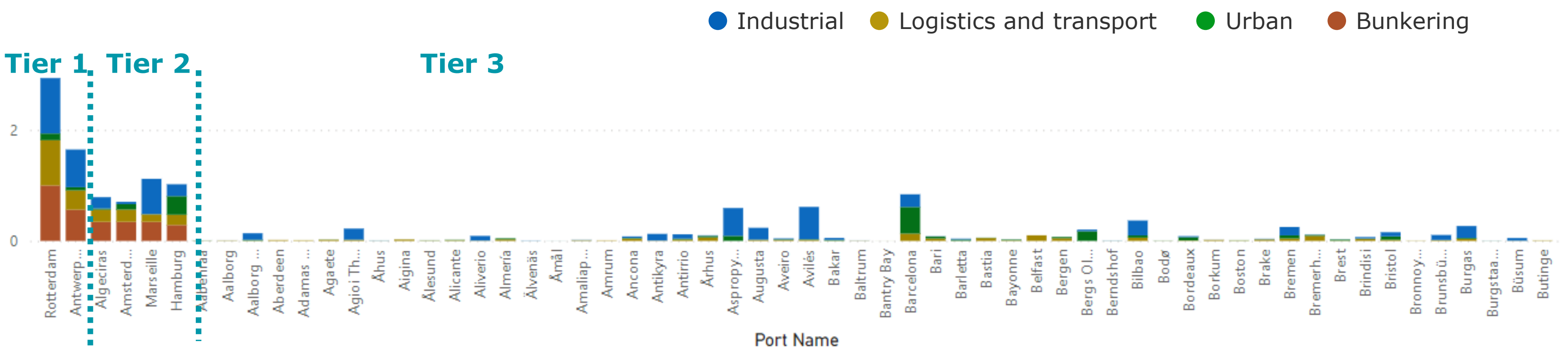


Logistics and transport activity (passengers) per port



The bunkering archetype

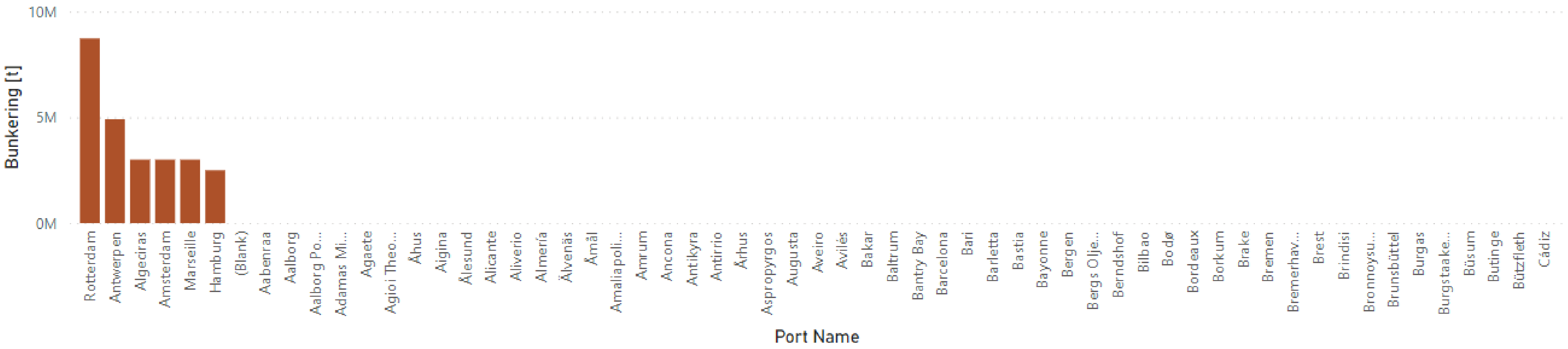
Activity distribution per port (normalized)



Key messages:

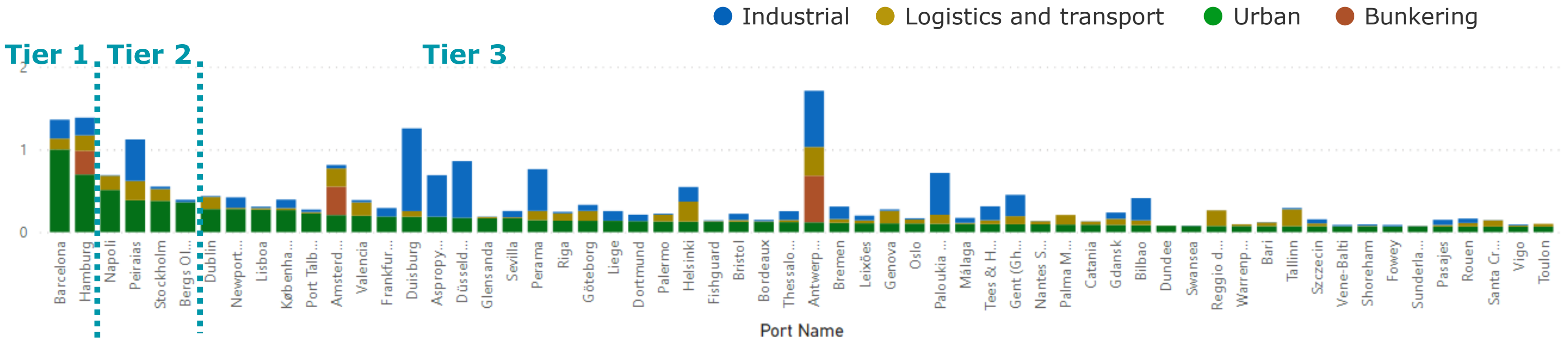
- The bunkering archetype is highly relevant for the ports with a **high bunkering activity**
- The bunkering activity per port is based on the **quantity of bunkering fuels sold in the port**
- **Rotterdam** followed by Antwerp has the highest bunkering activity

Bunkering activity per port

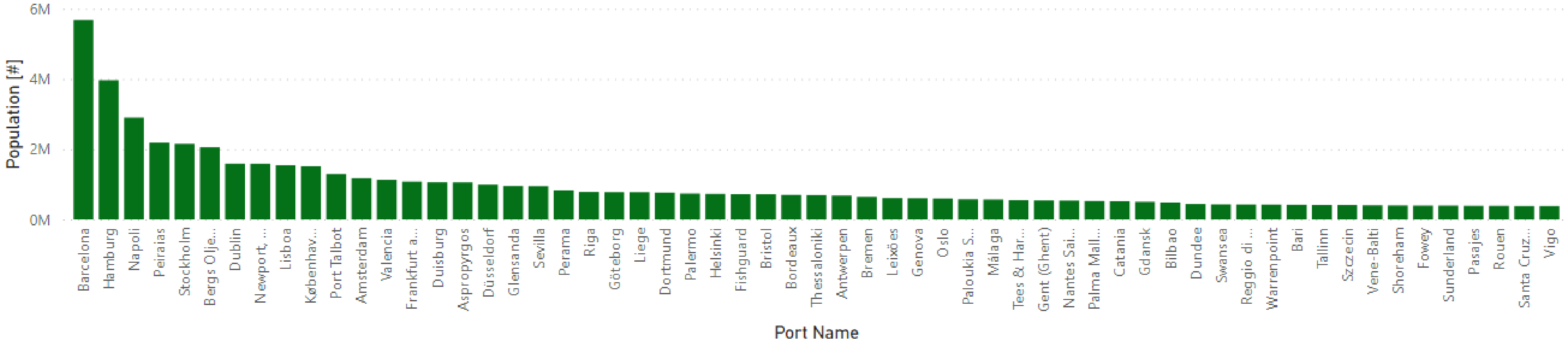


The urban archetype

Activity distribution per port (normalized)



Urban activity per port



Key messages:

- The urban archetype is highly relevant for the ports with a **high population nearby**
- The urban activity per port is based on the **amount of people living in cities in proximity to the port**
- **Ports of Barcelona** and **Hamburg** have the highest urban activity

Demand modelling approach

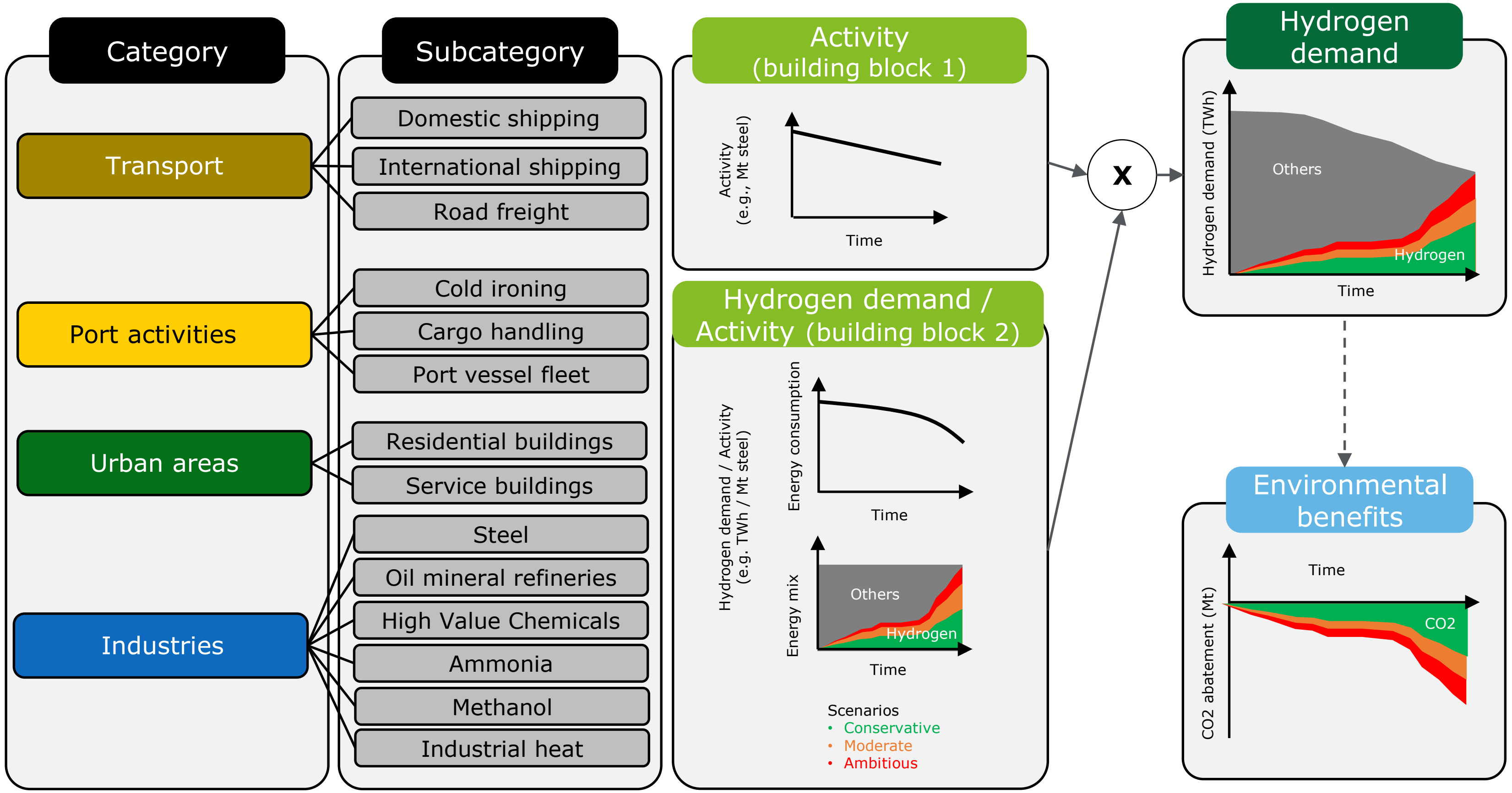
Overview of the hydrogen demand subcategories in scope

Category	Subcategory	Definition
Transport	International shipping	Volume of maritime bunker fuels sold in European ports.
	Domestic shipping	Volume of goods transhipped over a certain distance in inland waterways.
	Heavy-duty road freight	Volume of goods transhipped over a certain distance in heavy duty vehicles.
Port activities	Cargo handling	Total goods handled in European ports.
	Port vessel fleet	Number of vessels that have a function linked to port operations (i.e., dredging ships and tugboats).
Urban areas	Residential	Total surface of buildings used by inhabitants in cities.
	Services	Total surface of buildings used for all kind of services (offices, hospitals, shops, logistics, etc.) in cities.
Industries	Primary steel	Production of primary steel in Blast Furnace/Basic Oxygen Furnace steel plants.
	Hydrogenation of fossil fuels	Production of hydrogen to improve the quality of crude mineral oil-based products produced in refineries.
	HVCs	Production of olefins and aromatics for use as a building block in the organic chemical industry.
	Methanol (current uses)	Production of methanol in methanol plants for use as a building block in various chemical applications.
	Ammonia (for fertilizers)	Production of ammonia in ammonia plants for use as a building block in the fertilizer industry.
	Industrial heat	Production of fossil gas-based low, medium and high temperature heat for use in industrial processes.

A modular approach is used to project future hydrogen demand

Modular approach:

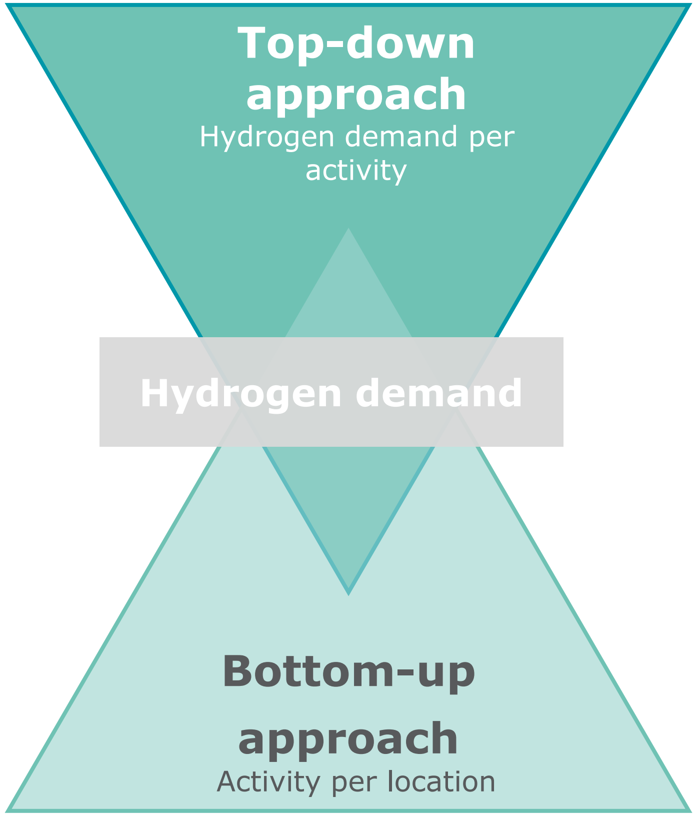
- A modular approach is used through different building blocks. By combining these building blocks, the future hydrogen demand and the corresponding CO_2 abatement can be projected.
- Building block 1 relates to current and **projected activity** (e.g., Mt steel, tonne-km road freight, etc.), for each port and all locations outside of ports.
- Building block 2 relates to the **hydrogen demand per unit of activity** defined for three scenarios. It depends on the energy efficiency of the required hydrogen technology and the share of hydrogen in the total fuel mix of a certain category.
- Building blocks 1 and 2 are determined for all 14 subcategories separately for every location (ports and outside of ports).
- **Hydrogen demand and environmental benefits are calculated** for each port and all locations outside of ports separately.



A customized approach to estimate the hydrogen demand per subcategory following a stepwise rationale

	Steps	Basis of work
Activity (building block 1)	i. Understanding of European **current market** (e.g., for industries: number of plants, location of plants, production capacity per plant, volume produced in 2019/2020 per plant, etc.) ii. Assumptions on the **evolution of activity** in 2030, 2040 and 2050 (e.g., evolution of steel production in the EU) as a % of the volume produced in 2019.	i. Bottom-up analysis combined with utilization of existing databases. ii. Desk research (emphasis on sectoral projected demand analysis)
x		
Hydrogen demand / Activity (building block 2)	i. Understanding of **current** energy use. ii. Understanding of main **pathways** to **decarbonize** the subcategory iii. Understanding of the **potential for using low-carbon hydrogen** (green and blue) as a pathway to decarbonization of the subcategory. iv. Formulation of an assumption on the **hydrogen required** to realize one unit of volume in the subcategory (e.g., hydrogen required per tonne-mile for shipping, or hydrogen required to produce one tonne of product for industries) v. Development of a **conservative, moderate, and ambitious scenario for low-carbon hydrogen demand per unit of volume** for 2030, 2040, and 2050. The main parameters used in the development of the scenarios are the share of total volume in 2030, 2040, and 2050 that uses low-carbon hydrogen	i. Desk research and Deloitte experts. ii. Desk research and Deloitte experts. iii. Desk research (emphasis on comparative studies) and Deloitte experts. iv. Desk research and Deloitte experts v. Own demand modelling based on desk research (emphasis on comparative studies) and Deloitte experts.
=		
Hydrogen demand	i. Calculation of total **hydrogen demand per ports, outside of ports and demand cluster**.	i. Own modelling
Environmental benefits	i. Calculation of the environmental benefits of hydrogen adoptions according to the different scenarios developed.	i. Own modelling and desk research

A combination of a top-down and bottom-up approach is applied to project the future hydrogen demand



Top-down approach

- Approach followed for building block 2 (hydrogen demand per activity);
- Scenarios are built based on general data and trends in EU;
- Hydrogen consumption efficiency is considered on EU level;
- Activity evolution trends are considered on EU level.

Bottom-up approach

- Approach followed for building block 1: activity
- All volumes are considered at the individual port level (e.g., for each port the bunkering volume, the number of domestic vessels, the amount of cargo activity, etc. are considered). Afterwards, all volumes are aggregated to obtain totals of hydrogen demand on EU level, per demand cluster, etc.
- In combination with the defined scenarios (Conservative, Moderate and Ambitious, increased efficiency and volume evolution trends, i.e., building block 2, the hydrogen demand is projected for each port individually based on their activity data

Example

Bottom-up approach example for one port

Activity per subcategory for Port of Antwerp-Bruges – 2050

Per port, all activity data per subcategory and per year is available. Example for 2050:

Industry

In proximity of the port (21 km):

Ammonia production:
0.47 Mt ammonia

HVC production:
5.89 Mt product

Mineral oil:
0 Mt refined mineral oil

Methanol production:
0 Mt methanol

Steel production:
0 Mt primary steel

Industrial heating:
7.35 TWh natural gas

Transport

Domestic shipping:
7,003 Mt-mile

International shipping:
2,065,477 Mt-mile

Road freight:
15,009 Mt-km

Port activities

Cargo handling:
19 million TEU

Port vessel fleet:
18.8 Mt-mile

Urban areas

Total surface of **residential buildings** in proximity of the port:
30.3 million m^2

Total surface of **service buildings** in proximity of the port:
7.6 million m^2

Top-down approach example for one subcategory

Hydrogen demand scenarios for the steel sector

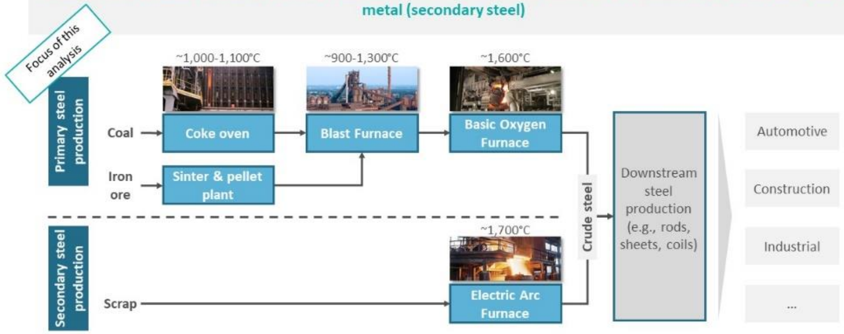
Example

Scope of the analysis: European steel market

Perspectives of hydrogen in the European steel sector

Steel production processes (simplified)

Crude steel is produced through a Blast & Basic Oxygen Furnace (primary steel) or an Electric Arc Furnace using scrap metal (secondary steel)



Source: Deloitte analyses

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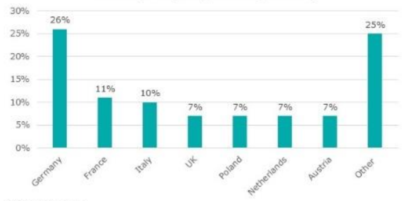
Perspectives of hydrogen in the European steel sector

Overview of the European steel production market (2019)

2019	Number of plants/sites	Capacity	Production	Production share
Primary production	26	~ 112 Mt	92.34 Mt	~59%
Secondary production	126	~90 Mt	65.12 Mt	~41%
Total	152	~ 202 Mt	157.47 Mt	100%

Share of primary steel production (EU27 + UK)



Location and relative size (in volume/year) of EU 27+UK primary steel plants

Sources: Eurofer, 2019 & Deloitte analysis

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Perspectives of hydrogen in primary steel making

Perspectives of hydrogen in the European steel sector

Overview of the main decarbonizations routes for primary steel production

Decreased demand for primary steel	Green H2 DRI-EAF	BF BOF CCS
The most effective and straightforward path to decarbonizing primary steel production is to reduce its demand. • **Option 1**: by decreasing overall steel demand • **Option 2**: by increasing the share of steel production through the secondary route (EAF). Decarbonizing secondary steel does not involve a complete transformation of the process, but simply a switch to renewable electricity. In addition, the limited amount of natural gas needed in the EAF could be replaced by low-carbon gaseous fuels (e.g., biomethane or synthetic methane), which could lead to additional hydrogen demand.	Decarbonizing primary steel can be done by completely transforming the production process, **moving away from the BF-BOF route**. Direct reduction of iron (DRI) with hydrogen is seen as the prime solution to decarbonize primary steel making. In hydrogen-based steel making, hydrogen is used to directly reduce iron in a direct reduction plant to produce sponge iron, which in turn can be melted in an EAF to produce steel. This production route requires 1.91 MWh (57.5 kg) of hydrogen per ton of crude steel (1).	Carbon Capture and Storage/Utilization (CCS/U) could also play a role in the decarbonization of primary steel production. Emissions from existing coke-based Blast & Basic Oxygen Furnace processes could be captured using (CCS/U).

Source: (1) IEA, 2019; FCH & Triconomix, 2020.

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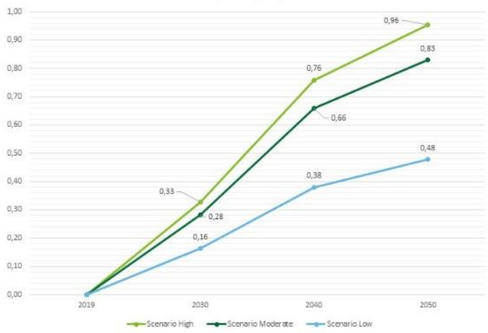
Perspectives of hydrogen in the European steel sector

Overview of the three scenarios

H2 demand per volume in the EU Steel sector (in TWh/Mt)



Key parameters of influence

While a **large amount of green hydrogen will most likely be needed** for future primary steel production, there is **uncertainty** about the volume of demand. The demand for green hydrogen in primary steel production will mainly depend on the following two parameters:

- Evolution of the **share of primary steel production** in the total steel production (assumed to be 50% in 2050 vs 58.3% in 2019).
- Whether primary steel producers will opt for the **BF-BOF CC(U)S** and/or **Green H2 DRI EAF** decarbonization route.

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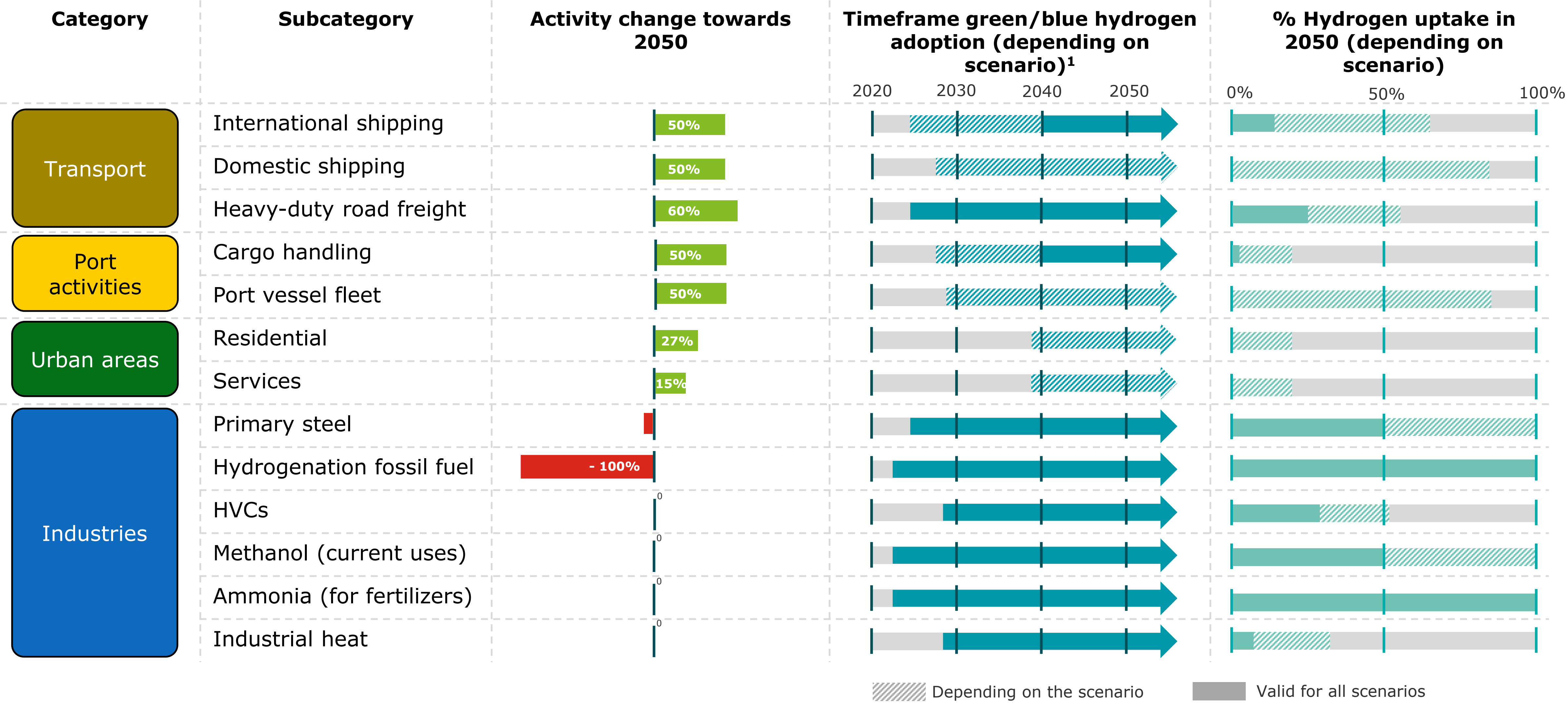
Development of demand scenarios

Activity and hydrogen demand per activity

Differentiated adoption of hydrogen as an energy carrier across demand subcategories



Note: (1) The estimate of the start of green/blue hydrogen adoption is only indicative and is based on the large-scale projects and initiatives announced by relevant stakeholders on European soil for each of the subcategories as of mid-2022.

Hydrogen demand for primary steel production should drastically increase by switching to the Hydrogen DRI-EAF production process

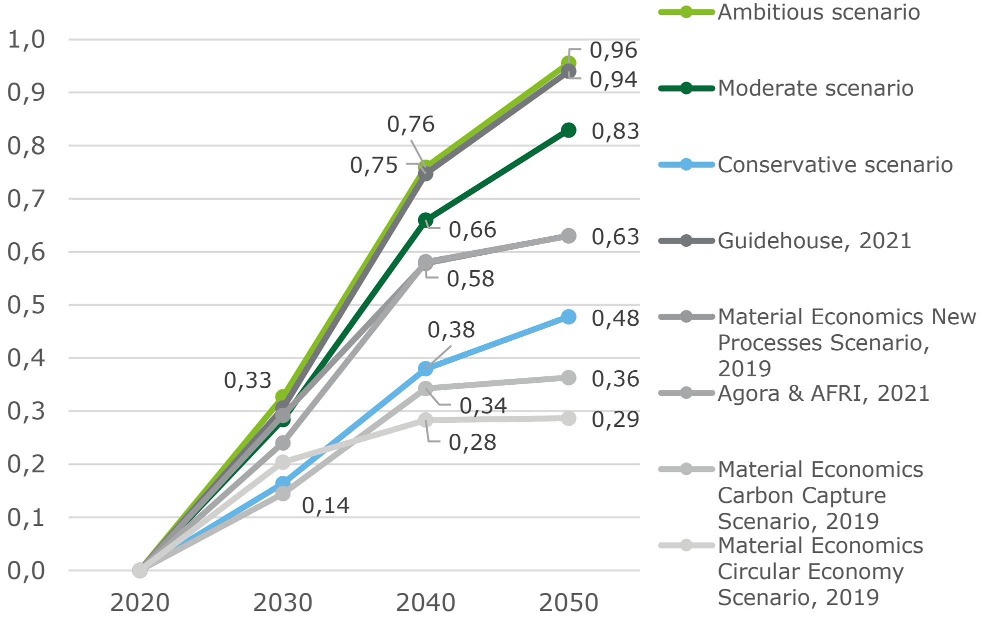
Activity

- In 2019, approximately 150 steel plants produced **a total of 157.5 Mt** of **primary** (92.34 Mt) and **secondary** (65.12 Mt) **steel** in Europe[1].
- Steel production is expected to increase at a **growth rate of 0.6% per year until 2040**, then **stabilizes until 2050[2]**. This growth rate translates into total steel demand equivalent to 168.2 Mt in 2030 (+7%) and 178.6 Mt in 2040 (+13%).
- The share of primary steel production in total steel production is expected to **gradually decrease**, **reaching 50%** in 2050[3].

Decarbonization routes

- The most effective and straightforward path to decarbonizing primary steel production is to **reduce its demand**, either **by decreasing overall steel demand** or by **increasing the share of steel production through the secondary route** (Electric Arc Furnace - EAF).
- Decarbonizing primary steel can also be done by completely transforming the production process, **moving away from the BF-BOF** route and **switching to the Hydrogen DRI-EAF** (Direct Reduction of Iron with EAF) route. This production route requires 1.91 MWh of hydrogen per tonne of crude steel[4].
- Alternatively, emissions from existing coke-based BF-BOF processes could be **captured using CCS/U** technologies.

Hydrogen demand per volume in the EU primary and secondary steel sector (in TWh/Mt)



Hydrogen demand scenarios

- **Ambitious scenario**: The hydrogen DRI process is the **only decarbonization pathway** chosen by steel producers for the decarbonization of primary steel production. The adoption rate **increases very rapidly** to 30% in 2030 and 75% in 2040. By 2050, **100%** of primary steel production uses the hydrogen DRI process.
- **Moderate scenario**: The hydrogen DRI process is the **preferred but not the only** decarbonization pathway chosen by steel producers for primary steel production. The adoption rate **increases rapidly** to 26% by 2030 and 65% by 2040. By 2050, **87%** of primary steel production uses the hydrogen DRI process. The remaining production uses BF-BOF CCS/U technologies.
- **Conservative scenario**: The hydrogen DRI process is **not preferred** by steel producers for decarbonization of primary steel production. The adoption rate **slowly increases** to 15% in 2030 and 38% in 2040. By 2050, **only 50%** of primary steel production uses hydrogen DRI-EAF. The other half of primary steel production uses BF-BOF CCS/U technologies.

While a **large amount of hydrogen** will most likely be needed for future primary steel production, there is **uncertainty about the volume of hydrogen demand**, which will mainly depend on the evolution of the share of primary steel production in total steel production and the decision of primary steel producers to opt for the BF-BOF CC(U)S and/or Hydrogen DRI EAF decarbonization route.

Note: Material Economics New Process (2019) and Agora & AFRI (2021) scenarios have similar hydrogen demand per volume estimates for 2040 and 2050.

Sources: (1) Eurofer, 2019. (2) Material Economics, 2019, Guidehouse, 2021; Agora & AFRI, 2021. (3) Guidehouse, 2021; Agora & AFRI, 2021. (4) IEA, 2019; FCH & Trinomix, 2020.

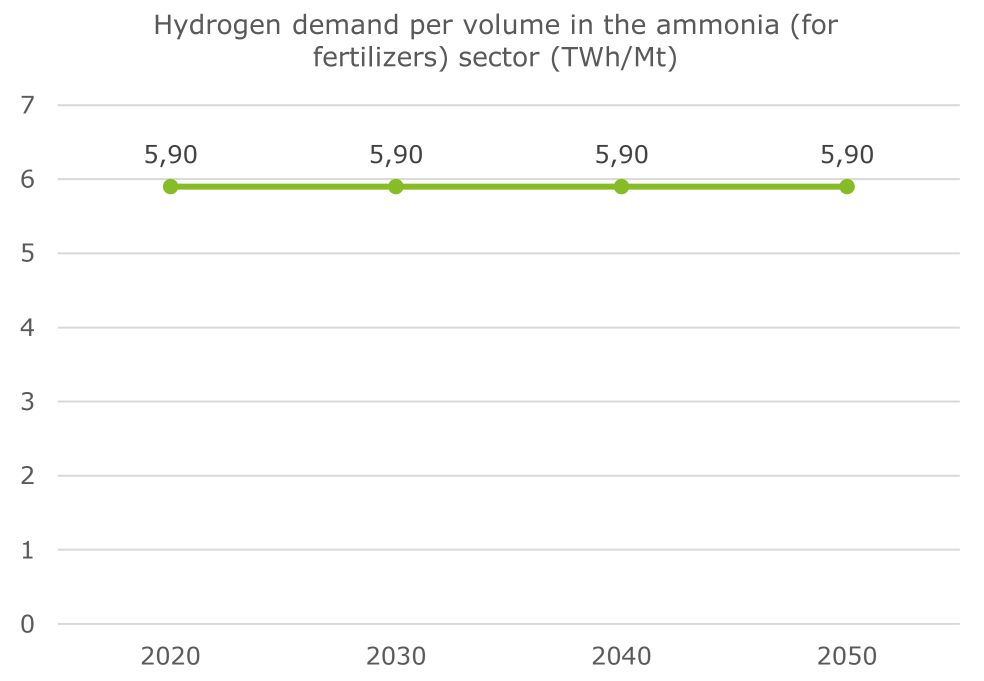
Hydrogen demand for ammonia (for fertilizers) production is expected to remain stable between 2020 and 2050

Activity

- In 2020, approximately 39 ammonia plants produced **a total of 14.37 Mt** of **ammonia** in Europe[1].
- Production of ammonia for fertilizers is projected to **remain constant** between 2020 and 2050 in Europe[2].
- In the current production process of ammonia, which combines Steam Methane Reforming (SMR) and the Haber-Bosch process, 5.90 MWh of hydrogen is required to produce one tonne of ammonia [3].

Decarbonization routes

- The hydrogen required in the ammonia production process can be produced via **electrolysis instead of by SMR**. While electrolysis of water consumes about 10.8 MWh of electricity per tonne of ammonia, this pathway reduces total direct emissions to zero if renewable electricity is used to power the electrolysis.
- Alternatively, **CCS can be applied to the SMR** unit to switch from grey to blue hydrogen production, reducing CO2 emissions associated with hydrogen production by up to 90%.
- Eventually, the natural gas feedstock used for the SMR can be replaced by biomethane, thereby achieving carbon neutrality. Biomethane is not considered in this study due to lack of interest from the sector [4].



Hydrogen demand

- Regardless of its production process, hydrogen is one of the main feedstocks used in the ammonia production process. In the coming decades, even though significant efforts are expected to be made to decarbonize the production of hydrogen currently used in European ammonia sector, **the same quantity of hydrogen will be used per tonne of ammonia produced**.
- Therefore, assuming that European ammonia production for fertilizers remains constant until 2050, **nearly 85 TWh (2.55 Mt) of hydrogen will be required annually** for ammonia production in the fertilizer industry.
- Following latest directions taken by European Union through the Proposal for a recast Renewable Energy Directive[5] and the REPowerEU Communication[6], this study assumes that **green hydrogen will be preferred by ammonia producers to decarbonize ammonia** (for fertilizers) **production**.

Note: While the EU and its Member States are committed to supporting the chemical industry's transition to net-zero production and still maintaining its competitiveness, ammonia is a commodity that is already highly sensitive to economic drivers, making its production particularly vulnerable to delocalization to regions outside of Europe with cheap access to natural gas or renewable energy. However, even though future ammonia plants for emerging uses of ammonia may not be built in the EU, **this analysis assumes that it will remain economically sound for European ammonia producers to maintain the operation of existing ammonia plants used for fertilizer production**.

Sources: (1) IFASTAT, 2019 & Deloitte analysis. (2, 3, 4) Guidehouse, 2021. (5) COM(2021) 557 final: in 2030, 50% of the hydrogen used in in industries shall be renewable-based hydrogen (renewable fuels of non-biological origin). (6) COM(2022) 230 final: The Commission calls on European Parliament and the Council to increase the minimum share of hydrogen from renewable sources in total industrial hydrogen consumption from 50% to 75% by 2030.

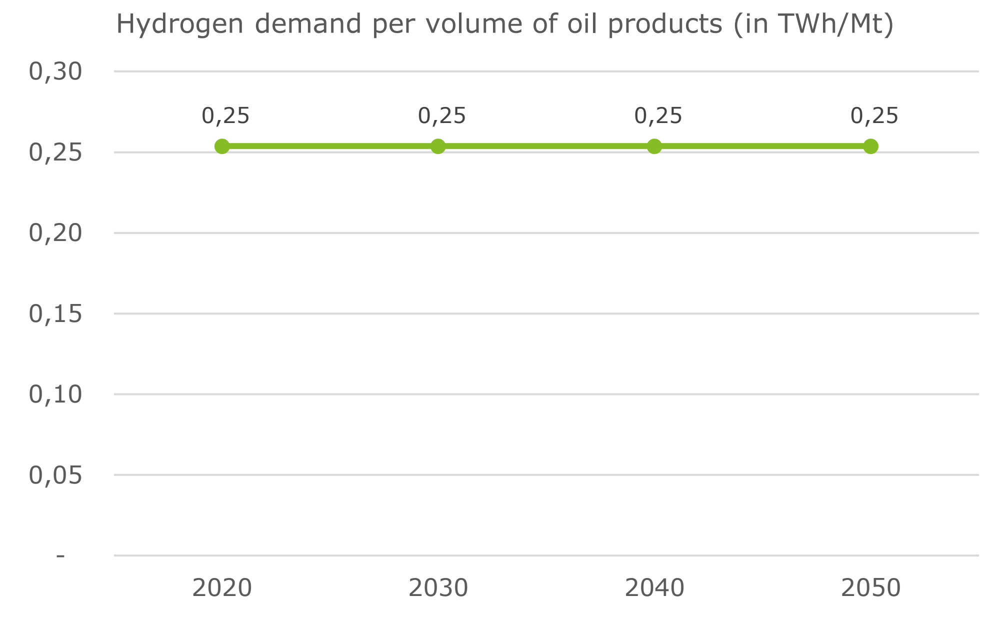
Hydrogen demand for hydrogenation of mineral oil in refineries is expected progressively decrease until reaching net-zero in 2050

Activity

- In 2020, approximately 94 oil refineries produced **a total of 567 Mt of refined oil products** in Europe[1]. The hydrogenation step required in the refining process to upgrade and improve the quality of oil products required the production of 144 TWh (4.32 Mt) of grey hydrogen[2].
- The demand for hydrogen for hydrogenation of fossil fuels is **expected to decrease by 20% in 2030** (115 TWh or 3.45 Mt), **90% in 2040** (15 TWh) et **100% in 2050**, due to the assumption that there will be a transition towards non-oil-based fuels[3,4].

Decarbonization routes

- The hydrogen required in the hydrogenation step of the mineral oil refining process can be produced **via electrolysis instead of by SMR**. This pathway reduces total direct emissions to zero if renewable electricity is used to power the electrolysis.
- Alternatively, **CCS can be applied to the SMR unit** to switch from grey to blue hydrogen production, reducing CO2 emissions associated with hydrogen production by up to 90%.



Hydrogen demand scenarios

- Regardless of its production process, hydrogen is one of the main feedstocks used in the hydrogenation of fossil fuel process in refineries. In the coming decades, even though the demand of hydrogen in refineries for hydrogenation of fossil fuels is expected to plummet and that significant efforts are expected to be made to decarbonize the production of hydrogen currently used in European refineries, **the same quantity of hydrogen will be used per Mt of refined oil products.**
- Since it is foreseen that mineral oil demand will progressively decrease until reaching zero in 2050, the total amount of hydrogen demand for hydrogenation of fossil fuels will also reach zero. In this downsizing market, following latest directions taken by European Union through the Proposal for a recast Renewable Energy Directive[5] and the REPowerEU Communication[6], this study assumes that **green hydrogen will be preferred by refineries to decarbonize the hydrogenation of fossil fuels step in the mineral oil refining process.**

Notes:
1. Biofuels from biomass also needs to be upgraded using hydrogen, especially in the case of biokerosene (aviation) due to the high energy density required for aviation fuels. Guidehouse (2021) estimates hydrogen demand in the EU+UK for biokerosene upgrading at 8 TWh by 2030, 35 TWh by 2040 and 44 TWh by 2050[7]. In this study, **future hydrogen demand for hydrogenation of biofuels (road transport) and biokerosene (aviation) is not assessed**.
2. Fuel production is assumed to remain at the same refining location as today in Europe.

Sources: (1) Concawe, 2019; FuelsEurope, 2022. (2) FCHO, 2022. (3) Agora & AFRI, 2021. (4) Guidehouse (2021). (5) Even though hydrogen used as intermediate products for the production of conventional transport fuels is excluded from the RED III target (i.e., the contribution of RFNBO used for final energy and non-energy purposes shall be 50 % of the hydrogen used for final energy and non-energy purposes in industry by 2030), this study assumes that, in the hydrogenation of mineral oil process, refineries will align their target for green hydrogen consumption share with the target formulated in RED III. (6) COM(2022) 230 final: The Commission calls on European Parliament and the Council to increase the minimum share of hydrogen from renewable sources in total industrial hydrogen consumption from 50% to 75% by 2030. (7) Guidehouse, 2021.

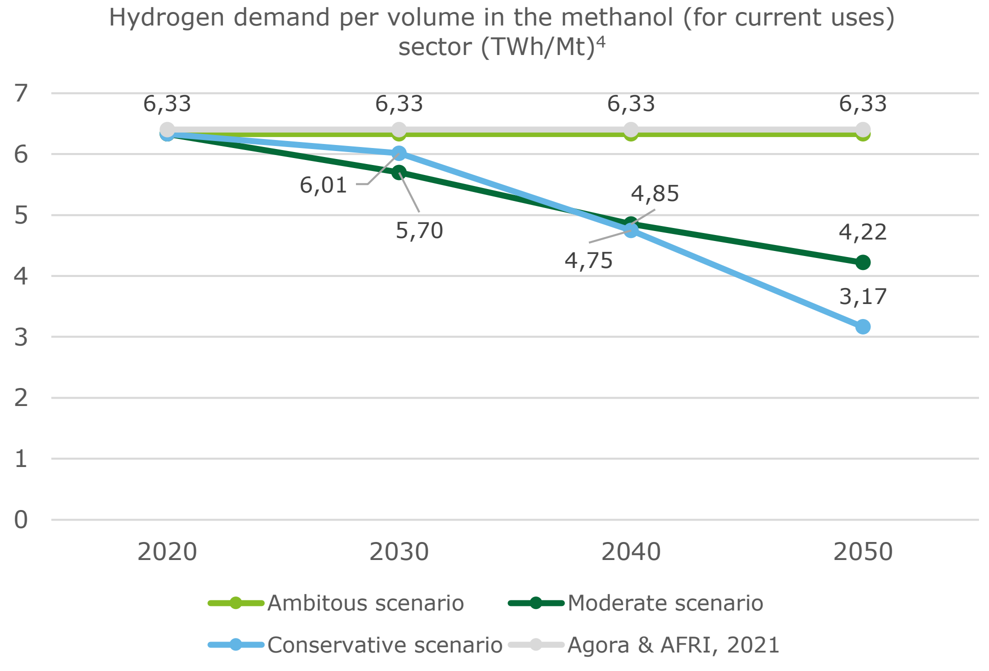
Hydrogen demand for methanol (current uses) production is expected at best to remain stable between 2020 and 2050

Activity

- In 2020, approximately 9 ammonia plants produced **a total of 2.3 Mt of methanol** in Europe[1]. Methanol production in Europe is highly concentrated in Germany, the Netherlands and Norway.
- Production of methanol for current uses is projected to **remain constant** between 2020 and 2050 in Europe[2].
- In the current production process of methanol, which combines Steam Methane Reforming (SMR) methanol synthesis, 6.33 MWh of hydrogen is required to produce one tonne of methanol[3].

Decarbonization routes

- While SMR is the dominant technology for hydrogen production in the methanol industry, methanol synthesis does not only require hydrogen as an input, **but also CO2**.
- One decarbonization route is to produce **bio-methanol from sustainable biomass** (e.g., forestry and agricultural waste, biogas, municipal solid waste, black liquor from the pulp and paper industry).
- The other decarbonization route is to produce **green e-methanol by using CO2 captured from renewable sources** (bioenergy with carbon capture and storage [BECCS] and direct air capture [DAC]) **and green hydrogen**.



Hydrogen demand scenarios

- **Ambitious scenario**: The green e-methanol route is the **only decarbonization pathway** chosen by producers for decarbonizing methanol production. Over time, the grey hydrogen that is currently used as an input in the methanol production process is gradually being substituted by green hydrogen. By 2050, **100%** of European methanol production uses green hydrogen in the production process.
- **Moderate scenario**: Although the green e-methanol pathway is the **preferred decarbonization pathway**, **bio-methanol** from sustainable biomass is **also expected to play a role** in decarbonizing the methanol industry. By 2050, **2/3** of European methanol production will use hydrogen in the production process.
- **Conservative scenario**: The pathway of **e-methanol is being considered as much as bio-methanol** by methanol producers to decarbonize methanol production. By 2050, **50%** of European methanol production uses hydrogen in the production process.

Notes:

1. In 2030, hydrogen demand per volume of methanol produced in the Moderate scenario is lower than in the Conservative scenario due to the **faster uptake of bio-methanol replacing grey hydrogen-based methanol**, thus leading to a larger overall decrease in hydrogen demand than in the Conservative scenario.
2. With less than 10 methanol plants in Europe, European methanol production market is **highly concentrated**. Therefore, the decarbonization pathways chosen by each player will have a **strong impact** on the demand for (green) hydrogen in the methanol sector. However, due to the limited amount of methanol produced, even a full switch to **bio-methanol** in Europe will have **only a marginal impact on the overall European demand for hydrogen.**

Sources: (1) Deloitte analysis. (2) Agora, 2021. (3) IRENA, 2021. (4): Agora & AFRI (2021) assumes that 6.40 MWh of hydrogen is used for each tonne of ammonia produced (compared to 6.33 MWh/t in Deloitte's scenarios), explaining the incremental variation with Deloitte's Ambitious scenario.

Hydrogen demand for High Value Chemicals (HVCs) production could potentially drastically increase from 2030 onwards

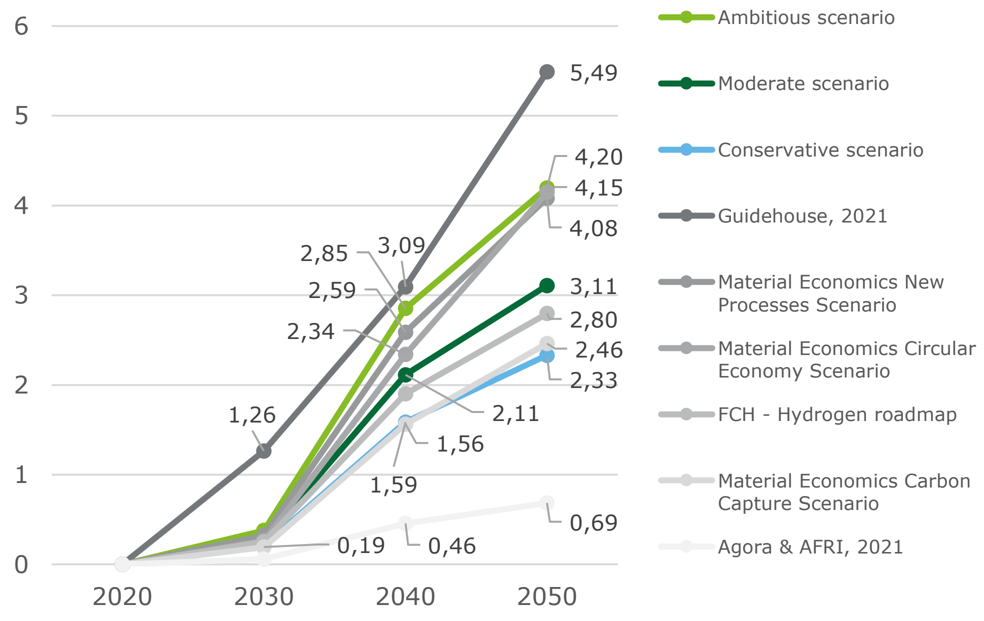
Activity

- In 2019, approximately 48 steam crackers[1] produced ~21.9 Mt of ethylene[2] which in turn was used to produce ~42.9 Mt of HVCs in Europe[3].
- Production of HVCs is projected to **remain constant** between 2020 and 2050 at 42.9 Mt per year in the EU+UK[4]. The future increase in plastic demand (main end-use of HVCs) is assumed to be compensated by increase of mechanical recycling.

Decarbonization routes

- Olefins and aromatics are primarily made by 'cracking' of naphtha and ethane, which are respectively obtained by refining crude oil and from natural gas. To decarbonize HVCs production, companies can choose **defossilization** and/or **emission reduction routes**, as organic chemicals inherently contain carbon.
- **Emission reduction solutions** include **E-cracking** and **steam cracking with CCS technologies**.
- **Defossilization solutions** include the **Methanol to Olefins (MtO)** and the **switch to low-carbon feedstocks** (bio-based methanol and plastic waste) routes.

Hydrogen demand per volume in the EU HVCs sector (in TWh/Mt of HVC)[5]



Hydrogen demand scenarios

- **Ambitious scenario**: The **defossilization solutions** (the MtO and switch to low-carbon feedstocks routes) are the preferred decarbonization pathways, accounting for **90%** (45% each) of total HVC production in Europe in 2050. **Emission reduction solutions** (E-cracking) account for the remaining **10%**.
- **Moderate scenario**: The two **defossilization solutions** (the MtO and switch to low-carbon feedstocks routes) account for 66% (33% each) of total HVC production in Europe in 2050. **Emission reduction solutions** (E-cracking and cracking with CCS) account for the remaining **33%** (~17% each).
- **Conservative scenario**: The two **defossilization solutions** (the MtO and switch to low-carbon feedstocks routes) are being considered as much as the two **emission reduction solutions** (E-cracking and cracking with CCS) by HVCs producers. **Each of the four solutions account for 25%** of the total HVC production in Europe in 2050.

Decarbonization pathways in the HVC sector are **highly uncertain**, and **no clear direction** has been chosen by European chemical industry. Given that a **wide range of decarbonization options appear feasible**, some of which require hydrogen and some of which do not, the extent to which hydrogen will play a significant role in decarbonizing HVC production **remains largely speculative**.

Note: The Guidehouse (2021) scenario foresees a much larger role for hydrogen-based decarbonization pathways (67% of HVC commodities produced with hydrogen-based processes in 2050 for Guidehouse, compared to our Ambitious scenarios (52.5%) explaining the discrepancies in estimates between these two "ambitious" scenarios.

Sources: (1) Petrochemicals Europe, 2019 & Deloitte analysis. (2) Deloitte analysis based the overage ratio nameplate capacity/production between 1999 and 2019 for steam crackers located in the EU 15 + Norway. (3) Deloitte analysis based on ratio production of ethylene/production of HVCs used in Guidehouse, 2021. (4) Guidehouse, 2021. (5) For the FCH - Hydrogen Roadmap scenario, in view of the lack of publicly available data, the assumptions for HVC volumes and hydrogen uptake rates were considered similar to those in the Deloitte's scenarios (to allow for comparison).

Hydrogen could potentially play a significant role in the decarbonization of medium- and high- temperature industrial heat, ramping up in the 2030s

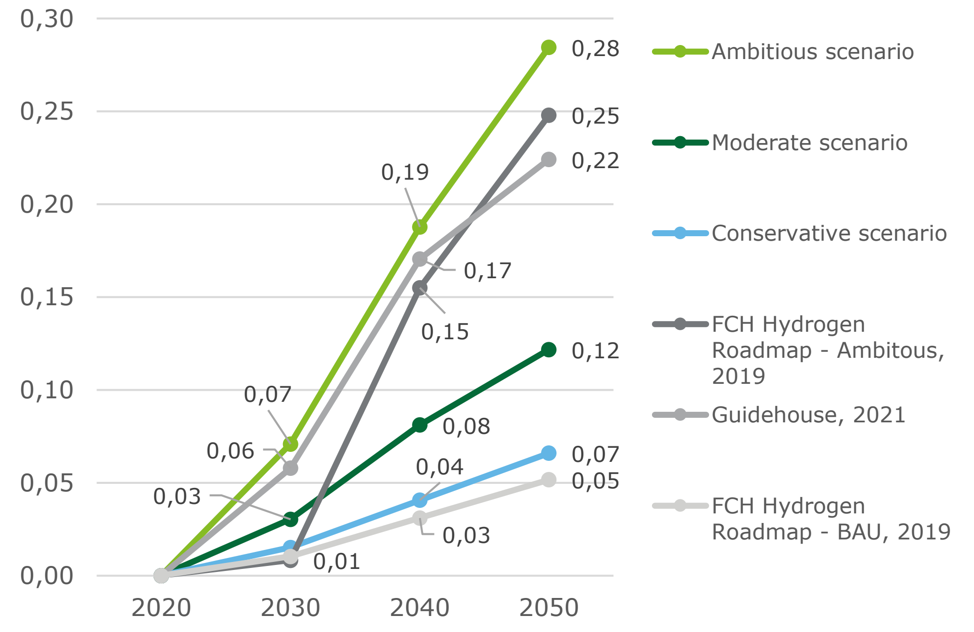
Activity

- In 2019, approximately **971 TWh were produced by natural gas for industrial heat** in the EU+UK, including 389 TWh for low-temperature industrial heat (<100°C), 234 TWh for medium-temperature industrial heat (100 to 500°C), and 348 TWh for high-temperature industrial heat (>500°C)[1].
- Production of industrial heat is projected to **remain constant** between 2020 and 2050 at 971 Mt per year in the EU+UK[2].

Decarbonization routes

- **For low-temperature heat**, **heat pumps** and **direct electrification** are the preferred option because of its increased efficiency compared to gas-based options.
- For many **medium- to high temperature processes**, **hydrogen can be a suitable decarbonization pathway** due to the difficulties associated with direct electrification. The energy demand when using hydrogen instead of natural gas is at 85% of energy natural gas uses for medium- and high temperature heat[3].
- Remaining fossil fuel uses could be replaced with **electricity** or other **renewable and low-carbon gas** such as biomethane.

Hydrogen demand per volume of natural gas used for industrial process heat (in TWh/TWh)[4]



Hydrogen demand scenarios

- **Ambitious scenario**: Hydrogen is **playing a significant role** in the decarbonization of medium- and high-industrial heat. In the medium-temperature heat sector, 5% of current natural gas demand is replaced by hydrogen in 2030, 25% by 2040 and 50% by 2050. In the high heat sector, 20% of current natural gas demand is replaced by hydrogen in 2030, 45% by 2040 and 60% by 2050. Overall, **33% of total industrial heat (low, medium and high temperature) is fueled with hydrogen in 2050**.
- **Moderate scenario**: Hydrogen **is not playing a significant role** in the decarbonization of medium- and high-industrial heat until at least 2040. In the medium-temperature heat sector, 0% of current natural gas demand is replaced by hydrogen in 2030, 10% by 2040 and 15% by 2050. In the high heat sector, 10% of current natural gas demand is replaced by hydrogen in 2030, 20% by 2040 and 30% by 2050. **Overall, 14% of total industrial heat (low, medium and high temperature) is fueled with hydrogen in 2050.**
- **Conservative scenario**: Hydrogen is **playing only a marginal role** in the decarbonization of medium- and high-industrial heat. In the medium-temperature heat sector, 0% of current natural gas demand is replaced by hydrogen in 2030, 5% by 2040 and 10% by 2050. In the high heat sector, 5% of current natural gas demand is replaced by hydrogen in 2030, 10% by 2040 and 15% by 2050. **Overall, 8% of total industrial heat (low, medium and high temperature) is fueled with hydrogen in 2050**.

There is a great uncertainty on the ability of hydrogen to play a role in the decarbonization of industrial heat. Although demand for hydrogen in the industrial heat sector is **expected to expand by 2050**, the extent to which hydrogen will play a significant role in decarbonizing industrial heat production **remains largely speculative**.

<ins>**Sources**</ins>: (1) Agora & AFRI, 2021. (2) Guidehouse, 2021. (3) DNV GL, 2018. (4) FCH – Hydrogen Roadmap Europe, 2019: in view of the lack of publicly available data, the assumptions for natural gas demand for industrial heat volumes were considered similar to those in the Deloitte's scenarios (to allow for comparison).

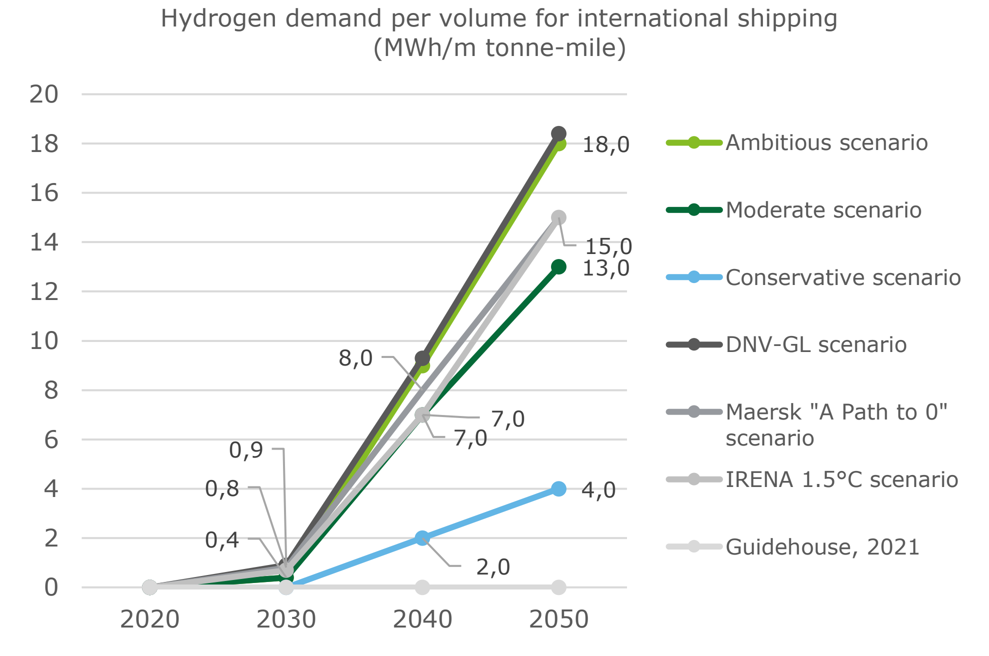
Hydrogen and derivatives are expected to take an important role for the decarbonization of international shipping, ramping up after 2040

Activity

- International shipping fuel volumes per port are based on the bunkering sales in a specific port[1].
- Economic development will probably continue to foster global trade as well as shipping activity. **International shipping volumes** are expected to **grow 19% by 2030**, after which it will slow down in line with macro-economic developments (**2040: 35%**, **2050: 50%)**[2,4]. This is also impacted by the trade and manufacturing sector.
- Per Mt-mile, in 2020, 47-, 28- or 28-MWh hydrogen would be required if ammonia, e-methanol or hydrogen would be used as a fuel, respectively[3].

Decarbonization routes

- Total energy demand is expected to decrease due to **improvements in energy efficiency** of new fleet by 1.5%/year (following historical improvements)[3].
- **Main possible decarbonizations routes** for international shipping are: 1) **electrification**, 2) **hydrogen** and **derivatives** (methanol and ammonia) and 3) **biofuels**.
- Hydrogen adoption time and volumes will depend on government intervention, hydrogen price and availability, and market/technological developments.



Hydrogen demand scenarios

- **Ambitious scenario**: By 2030, hydrogen adoption will still be challenging and thus limited to 2% of total ships. By 2050, renewable ammonia will form the backbone of decarbonizing international shipping (55% of vessels). Further, also e-methanol (10%) will be adopted leading to **a total of 65% of tonne-miles for ships fueled by hydrogen derivatives**.
- **Moderate scenario**: Equal to the ambitious scenario, by 2030 hydrogen adoption will still be challenging leading to 2% of total ships. By 2050, renewable ammonia will still form the backbone of decarbonizing international shipping, however less than in the ambitious scenario (40% of vessels). Further, also e-methanol (5%) and hydrogen (5%) will be adopted, leading to **a total of 50% of tonne-miles for ships fueled by hydrogen or derivatives**. The total percentage is lower than in the ambitious scenario leading to a lower hydrogen demand, but also the lower energy intensity of hydrogen in e-methanol and hydrogen than in ammonia leads to a lower hydrogen demand.
- **Conservative scenario**: In 2050 international shipping will still be using fossil fuels and LNG for a large part of the demand. Further, after 2030 there will be a slight uptake of renewable ammonia leading to 10% of ships using it by 2050. Similarly, e-methanol will provide fuel to 5% of ships. **In total 15% of tonne-miles for ships will be fueled by hydrogen derivatives**. In 2030 hydrogen adoption will still be 0.

While hydrogen derivatives (ammonia and methanol) appear as one of the preferred decarbonization route for international shipping, there is still large **uncertainty about the share of international ships that will be fueled by hydrogen derivatives.**

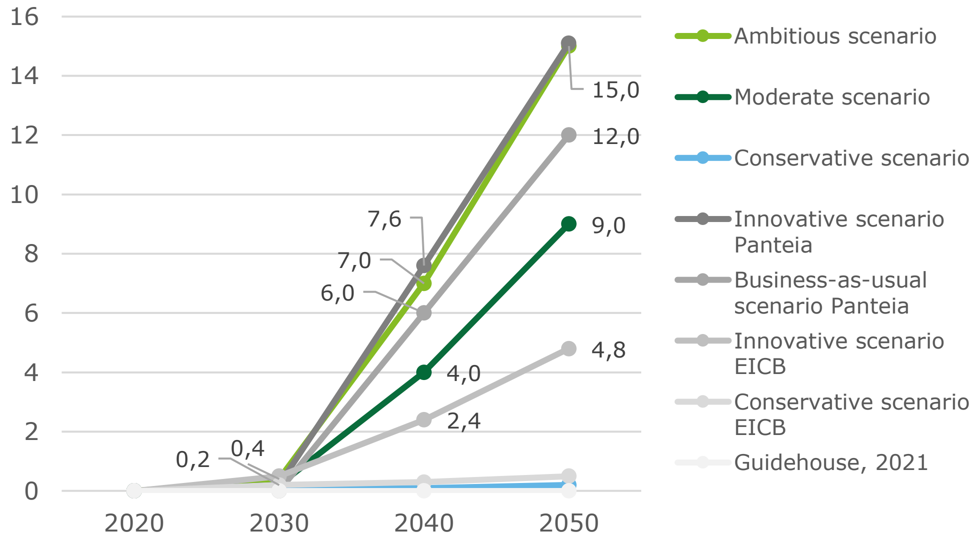
Sources and notes: (1). It is assumed that the ports Antwerp, Rotterdam, Hamburg, Marseille, Algeciras, Amsterdam and Götenburg account for 90% of bunkering volumes. The other 10% are distributed over the other ports based on their total volumes handled. (2). Based on European Commission, *Impact assessment – part 2/2,* 2020. From 2030 onwards, it is assumed that volumes will grow by 1.5%/year; (3). Irena, *A pathway to decarbonize the shipping sector by 2050*, 2021 and Deloitte internal sources; (4). Irena, *A pathway to decarbonize the shipping sector by 2050*, 2021: "*The International Maritime Organization (IMO) indicates that by 2050 maritime trade could increase between 40 and 115% in comparison to 2020 levels*"

The adoption of hydrogen and derivatives for domestic shipping is expected to remain limited until 2030 before potentially starting to ramp up in the 2030s

Activity

- Domestic shipping volumes per port are based on modal split per country[1] and assigned to a specific port based on the volumes handled per port within a country.
- Domestic shipping volumes are expected to grow 19% by 2030, after which it will slow down in line with macro-economic developments (2040: 35%, 2050: 50%)[2,4].
- Per Mt-mile, in 2020, 47-, 28- or 28-MWh hydrogen would be required if ammonia, e-methanol or hydrogen would be used as a fuel, respectively[3].

Hydrogen demand per volume for domestic shipping (MWh/m tonne-mile)



Decarbonization routes

- Total energy demand is expected to decrease due to **improvements in energy efficiency** of new fleet by 1.5%/year (following historical improvements)[3].
- **Main decarbonizations routes** for domestic shipping are: 1) **electrification**, 2) **hydrogen and derivatives** (methanol and ammonia) and 3) **biofuels**.
- Hydrogen adoption time and volumes will depend on government intervention[5], hydrogen price and availability, and market/technological developments.

Hydrogen demand scenarios

- **Ambitious scenario**: By 2030, hydrogen adoption will still be challenging and thus limited to 2% of total ships. By 2050, it is assumed that hydrogen will be available at a low cost and that government will intervene to make the adoption of hydrogen more favorable. Further it is assumed that the amount of battery fueled ships will be limited. **This leads to 85% of tonne-miles for vessels for domestic shipping fueled by hydrogen (derivatives).**
- **Moderate scenario**: Equal to the medium scenario, by 2030 hydrogen adoption will be challenging, adoption will even be slightly lower: 1% of total ships. By 2050, it is also assumed that hydrogen will be available at a low cost and that government will intervene to accelerate the hydrogen uptake in ships and limited diesel consumption. **This leads to 50% of tonne-miles for vessels for domestic shipping fueled by hydrogen (derivatives).**
- **Conservative scenario**: Domestic shipping will be powered completely by electricity or biofuels, not by hydrogen. **Therefore, 0% of energy demand for domestic shipping will be hydrogen (derivatives)**.

Hydrogen (derivatives) appears as one of the leading decarbonization routes for domestic shipping. Compared to international shipping, there is possibly a larger role for the adoption of hydrogen directly, since the low volumetric density of hydrogen might be less troubling than for larger distances. Further, there might also be a role for electrification due to the shorter distances, which is less likely for international shipping. In general, however, there is still large **uncertainty about the fuels that will be used for domestic ships.**

Sources: (1) EUROSTAT database. (2) Based on European Commission, *Impact assessment – part 2/2,* 2020. From 2030 onwards, it is assumed that volumes will grow by 1.5%/year. (3) Irena, *A pathway to decarbonize the shipping sector by 2050*, 2021 and Deloitte internal sources. (4) Irena, *A pathway to decarbonize the shipping sector by 2050*, 2021: "*The International Maritime Organization (IMO) indicates that by 2050 maritime trade could increase between 40 and 115% in comparison to 2020 levels*". (5) Panteia, *Op weg naar een klimaatneutrale binnenvaart per 2050*, 2019

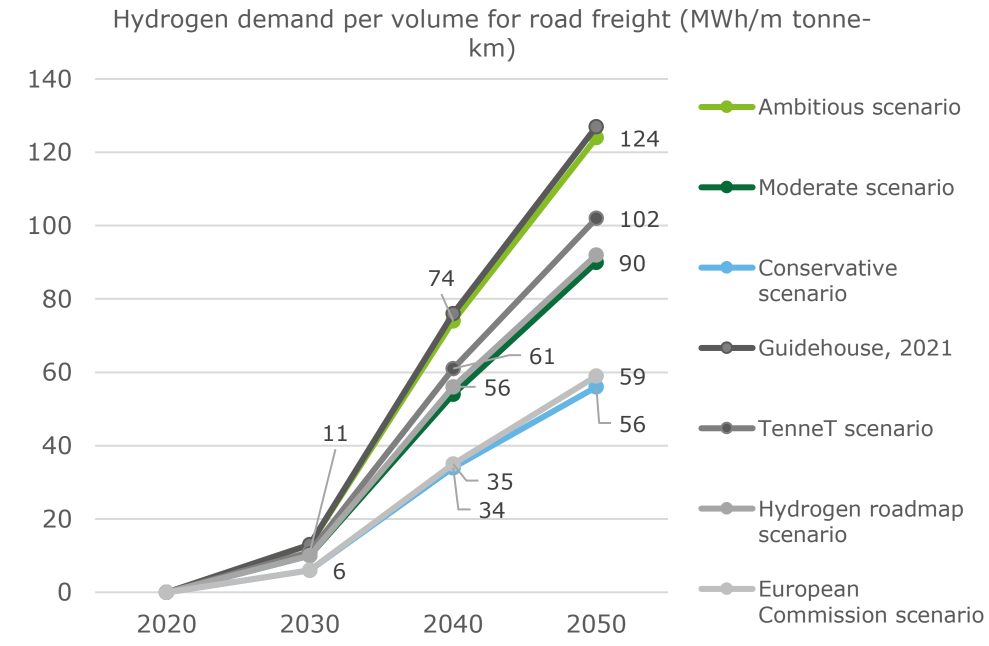
Hydrogen demand in heavy road freight is expected to ramp up after 2030 and play a major role in decarbonization of heavy-duty vehicles

Activity

- Road freight volumes per port are based on modal split per country[1] and assigned to a specific port based on the volume handled per port within a country. Further 20% of total road freight in a country is assigned to the ports[2].
- Road freight volumes are **expected to grow 34% by 2030**, after which it will **slow down** in line with macro-economic developments (**2040: 45%, 2050: 60%)**[3].
- Per tonne-km, in 2020, 0.29 MWh hydrogen would be required if hydrogen would be used as a fuel[4].

Decarbonization routes

- Total energy demand is expected to decrease due to **improvements in energy efficiency** by 0.8%/year[4].
- **Main decarbonizations routes** for road freight are: 1) battery electric trucks, 2) fuel cell trucks and 3) biomethane (bio-CNG/bio-LNG) trucks.
- Hydrogen adoption time and volumes will depend on hydrogen price and availability, availability refueling stations and market/technological developments.



Hydrogen demand scenarios

- **Ambitious scenario: **By 2050, **55% of heavy-duty vehicles is assumed to be powered by fuel cells**. The uptake will start slowly in 2030 (5%) and increase exponentially afterwards (30% by 2040).
- **Moderate scenario**: By 2050, **40% of heavy-duty vehicles is assumed to be powered by fuel cells**. Equal to the ambitious scenario, the uptake will start slowly in 2030 (4%) and increase exponentially afterwards (22% by 2040).
- **Conservative scenario**: By 2050, **only 25% of heavy-duty vehicles is assumed to be powered by fuel cells**. Equal to the ambitious and moderate scenario. The uptake will start slowly in 2030 (2%) and increase exponentially afterwards (14% by 2040).

Even though fuel cell trucks appear as one of the leading decarbonization route for road freight, there is still large **uncertainty about the share of road freight that will powered by fuel cell technologies** since also other options, such as electric and biofuels might play a role**.**

Sources: (1) EUROSTAT database. (2) Based on TNO, *hydrogen in port of Rotterdam.* (3) Based on European Commission, *Impact assessment – part 2/2,* 2020. (4) Deloitte internal sources. (5) Irena, *A pathway to decarbonize the shipping sector by 2050*, 2021 and Deloitte internal sources

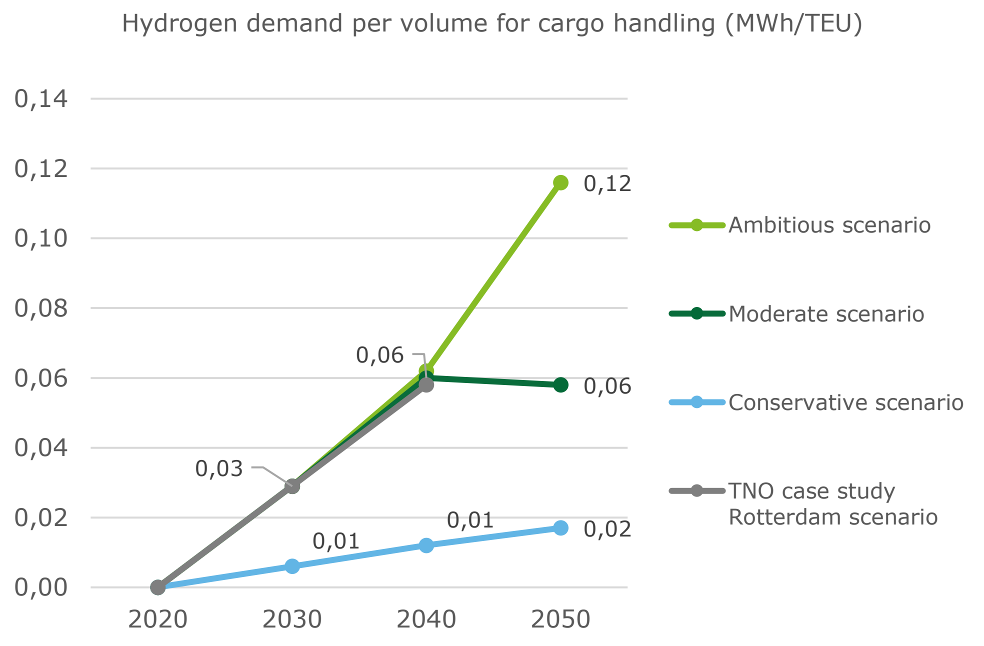
The potential adoption of hydrogen in cargo handling depends largely on the specific situation

Activity

- Cargo handling volumes per port are based on the number of containers (in TEU) handled in a port[1], the amount of port equipment required is assumed to be dependent on number of containers (e.g., depending on the number of containers handled in a port, more reach stackers will be required)[2].
- Since cargo handling will increase if more containers are handled within a port, cargo handling is assumed to have a similar growth to shipping volumes (19% by 2030, 35% by 2040 and 50% by 2050)
- Per TEU, 0.58 MWh hydrogen would be required if cargo handling was fueled with hydrogen[3]. This is based on a mix of hydrogen required per port equipment (RTG crane, forklift, straddle carrier, container handler, reach stacker and yard tractor) and port equipment required per TEU.

Decarbonization routes

- **Main decarbonizations routes** for cargo handling are: 1) **electrification** and 2) **hydrogen fuel cells**.
- Hydrogen adoption time and volumes will depend on hydrogen price and availability, and market/technological developments.



Hydrogen demand scenarios

- **Ambitious scenario**: By 2030, it is assumed that fuel cell integration in cargo handling is around 5%. By 2040, this is doubled to 10% and **by 2050 this is doubled again to 20%.**
- **Moderate scenario**: By 2030, it is assumed that fuel cell integration in cargo handling is around 5%. **By 2040, this is doubled to 10% after which the adoption is assumed to stabilize** since the other cargo handling equipment will mostly be fueled by electricity.
- **Conservative scenario**: It is assumed that the large majority of cargo handling equipment will be fueled by electricity in the future. **Adoption of hydrogen is thus limited**. By 2030 integration of fuel cell electric vehicles is only 1% of cargo handling. This increases slightly towards 3% by 2050.

There is a great uncertainty on the ability of hydrogen to play a role in the decarbonization of cargo handling activities. Although demand for hydrogen for cargo handling activities is **expected to expand by 2050**, the extent to which hydrogen will play a significant role in decarbonizing cargo handling activities **remains largely speculative and will depend on the specific situation of a port**.

Sources and notes: (1) EUROSTAT and calculation from tonne to TEU based on values in report ESPO (see here). (2) This might lead to an underestimation of the hydrogen demand for cargo handling in non container focused ports. 1 TEU is assumed to be around 9 tonnes, therefore hydrogen demand for other ports could be calculated as 0.06 MWh hydrogen required per tonne of volume handled in a port if all equipment would be fueled by hydrogen. The scenarios can then be adopted. (3) per million containers, 47.4 t Hydrogen/day if all port terminal equipement is fueled by Hydrogen. This equals to 576,258.2 MWh Hydrogen/year (Pacific Northwest et al., *Hydrogen Fuel Cell Applications in Ports: Feasibility Study at Multiple U.S. Ports*, 2019 & TNO, *hydrogen in port of Rotterdam)*

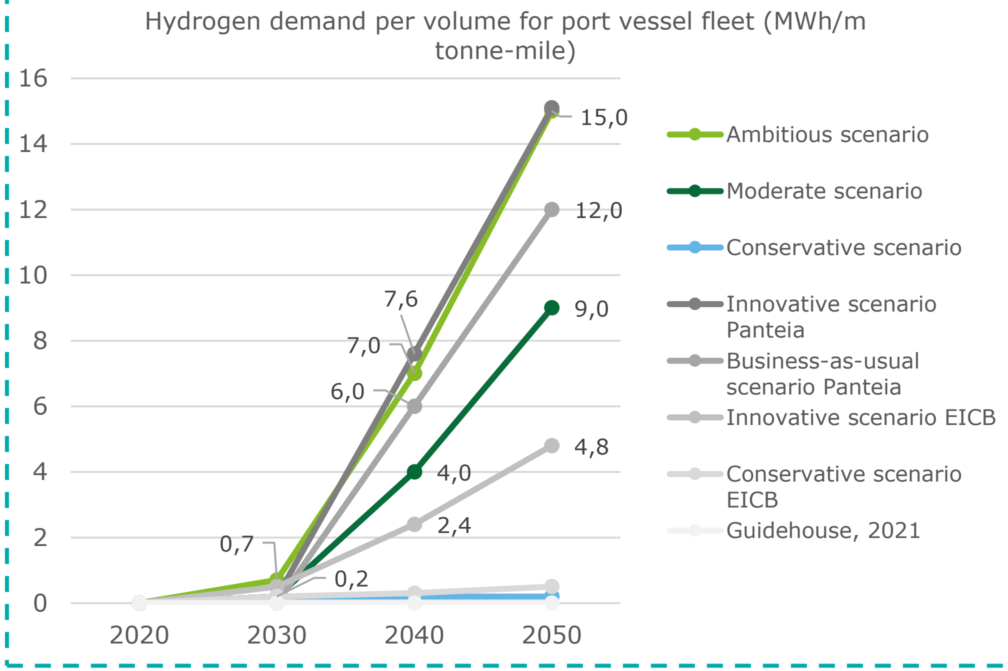
Hydrogen and derivatives could potentially play a role in decarbonizing port vessel fleet from 2030 onward

Activity

- Port vessel fleet volumes per port are based on number of vessels per port[1]. This is a mix of vessels that maintain port functionality, such as dredging ships and tugboats. The number of vessels is transformed in tonne-miles which is the unit of the volumes in this case.
- Since there will be more port vessels required when shipping increases, **port vessel fleet is assumed to have a similar growth to shipping volumes** (19% by 2030, 35% by 2040 and 50% by 2050)
- Per Mt-mile, in 2020, 47, 28 or 28 MWh hydrogen would be required if ammonia, e-methanol or hydrogen would be used as a fuel, respectively[2].

Decarbonization routes

- Total energy demand is expected to decrease due to **improvements in energy efficiency** of new fleet by 1.5%/year (following historical improvements)[2].
- **Main decarbonizations routes** for port vessel fleet are: 1) **electrification**, 2) **hydrogen and derivatives** (methanol and ammonia) and 3) **biofuels**.
- Hydrogen adoption time and volumes will depend on government intervention, hydrogen price and availability, and market/technological developments.



Hydrogen demand scenarios

Same assumptions are taken as for domestic shipping, since similar conditions are valid and thus a similar uptake of hydrogen is expected.

Sources: (1) Number of ships taken from individual reports of ports (Antwerpen and Hamburg) and compared with number of containers in the port to obtain an average number of ships per TEU. It is assumed that around 306 kg Hydrogen is consumed per ship (Pacific Northwest et al., *Hydrogen Fuel Cell Applications in Ports: Feasibility Study at Multiple U.S. Ports*, 2019). Volume in Mt-mile is obtained by dividing amount of hydrogen by hydrogen per tonne-mile. (2) Irena, *A pathway to decarbonise the shipping sector by 2050*, 2021 and Deloitte internal sources

Hydrogen could potentially play a significant role in the decarbonization of residential buildings, ramping up in the 2030s

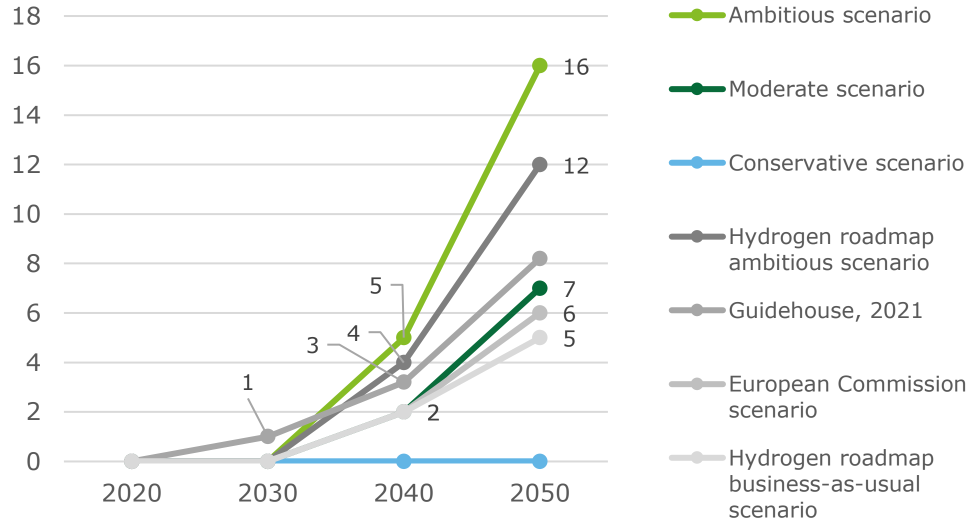
Activity

- Residential buildings' volumes per port are based on the number of inhabitants in cities in proximity of 12 km of the port and the amount of m² per capita[1].
- Residential buildings' volumes are expected to **grow proportional to the population growth**. On top of that, there is a 1% annual growth rate of floor space per inhabitant and a demolition rate of 0.1% per year[2]. **In total this leads to a volume increase of 9% by 2030, 18% by 2040 and 27% by 2050**.
- Average energy consumption in 2020: 104 kWh/m² [3].

Decarbonization routes

- Total energy demand is expected to decrease due to **renovation of houses.** In the analysis, a business-as-usual renovation rate is assumed, which will reduce the total energy demand by 25% per m² by 2050.
- **Main decarbonizations routes** for heating in residential building heating are: 1) **electrification**, 2) **hydrogen** and 3) **other climate neutral gases such as biomethane.**
- Hydrogen adoption time and volumes will depend on hydrogen price and availability, price and availability of other sustainable gases and renovation rate.

Hydrogen demand per volume for heating residential buildings (kWh/m²)



Notes: IEA scenario is similar to Deloitte's Conservative scenario

Hydrogen demand scenarios

- **Ambitious scenario**: By 2030, there will be no hydrogen adoption in buildings yet. By 2050, 50% of the heating demand will be provided by electricity through heat pumps. Further, enough biomethane will be available to provide 60% of the remaining heating demand that has to be provided by sustainable gases. Finally, **20% of heating demand for buildings will be provided by hydrogen**.
- **Moderate scenario**: By 2030, there will be no hydrogen adoption in buildings yet. By 2050, 50% of the heating demand will be provided by electricity through heat pumps. Further, in contrary to the ambitious scenario, enough biomethane will be available to provide 80% of the remaining heating demand that has to be provided by sustainable gases, leading to **10% of heating demand for buildings provided by hydrogen**.
- **Conservative scenario**: Hydrogen will not become cost competitive or will not be prioritized for the building sector, leading to **0% of buildings heated by hydrogen**.

The extent to which hydrogen will play a significant role in decarbonizing residential building heat **remains largely speculative** and will depend on other factors, such as the amount of other climate neutral gases available at a location, the degree of renovation that can be reached and technological advancements.

Sources: (1) Number of m² per capita per country: https://entranze.enerdata.net/. (2) Guidehouse, *European hydrogen backbone – Analysing future demand, supply, and transport of hydrogen*, 2021; (3) Average energy consumption of buildings in Europe is 180 kWh/m2 for residential buildings. Of this, space heating accounts for the largest share (68%) (https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-use-buildings_en). To take into account the difference in energy efficiency for hydrogen boiler in comparison to current heating technologies a factor of 85% is applied

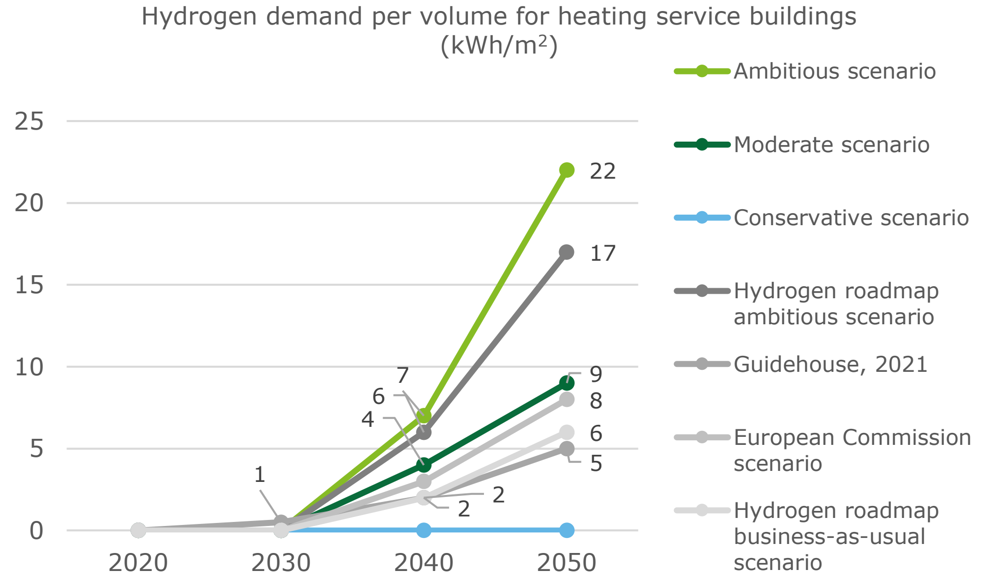
Hydrogen could potentially play a significant role in the decarbonization of service buildings, ramping up in the 2030s

Activity

- Service buildings[1] volumes per port are based on the number of inhabitants in cities in proximity of 12 km of the port and the amount of m^2 per capita[2].
- Service buildings' volumes are expected to **grow proportional to the population growth**. On top of that, there is a 1% annual growth rate of floor space per inhabitant and a demolition rate of 0.5% per year[3]. **In total this leads to a volume increase of 5% by 2030, 10% by 2040 and 15% by 2050**.
- Average energy consumption in 2020 : 145 kWh/m^2 [4].

Decarbonization routes

- Total energy demand is expected to decrease due to **renovation of houses.** In the analysis, a business-as-usual renovation rate is assumed, which will reduce the total energy demand by 25% per m^2 by 2050.
- **Main decarbonizations routes** for service building heating are: 1) **electrification**, 2) **hydrogen** and 3) **other climate neutral gases such as biomethane.**
- Hydrogen adoption time and volumes will depend on hydrogen price and availability, price and availability of other sustainable gases and renovation rate



Notes: IEA scenario is similar to Deloitte's Conservative scenario.

Hydrogen demand scenarios

- **Ambitious scenario**: By 2030, there will be no hydrogen adoption in buildings yet. By 2050, 50% of the heating demand will be provided by electricity through heat pumps. Further, enough biomethane will be available to provide 60% of the remaining heating demand that has to be provided by sustainable gases. Finally, **20% of heating demand for buildings will be provided by hydrogen**.

- **Moderate scenario**: By 2030, there will be no hydrogen adoption in buildings yet. By 2050, 50% of the heating demand will be provided by electricity through heat pumps. Further, in contrary to the ambitious scenario, enough biomethane will be available to provide 80% of the remaining heating demand that has to be provided by sustainable gases, leading to **10% of heating demand for buildings provided by hydrogen**.

- **Conservative scenario**: Hydrogen will not become cost competitive or will not be prioritized for the building sector, leading to **0% of buildings heated by hydrogen**.

The extent to which hydrogen will play a significant role in decarbonizing service building heat **remains largely speculative** and will depend on other factors, such as the amount of other climate neutral gases available at a location, the degree of renovation that can be reached and technological advancements.

Sources: (1) Buildings for all kind of services, including offices, hospitals, shops, logistics, etc. (2). number of m^2 per capita per country: https://entranze.enerdata.net/. (3). Guidehouse, *European hydrogen backbone – Analysing future demand, supply, and transport of hydrogen*, 2021. (4) Average energy consumption of buildings in Europe is 250 kWh/m2 for service buildings. Of this, space heating accounts for the largest share (68%) (https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-use-buildings_en). To take into account the difference in energy efficiency for hydrogen boiler in comparison to current heating technologies a factor of 85% is applied

Demand projection

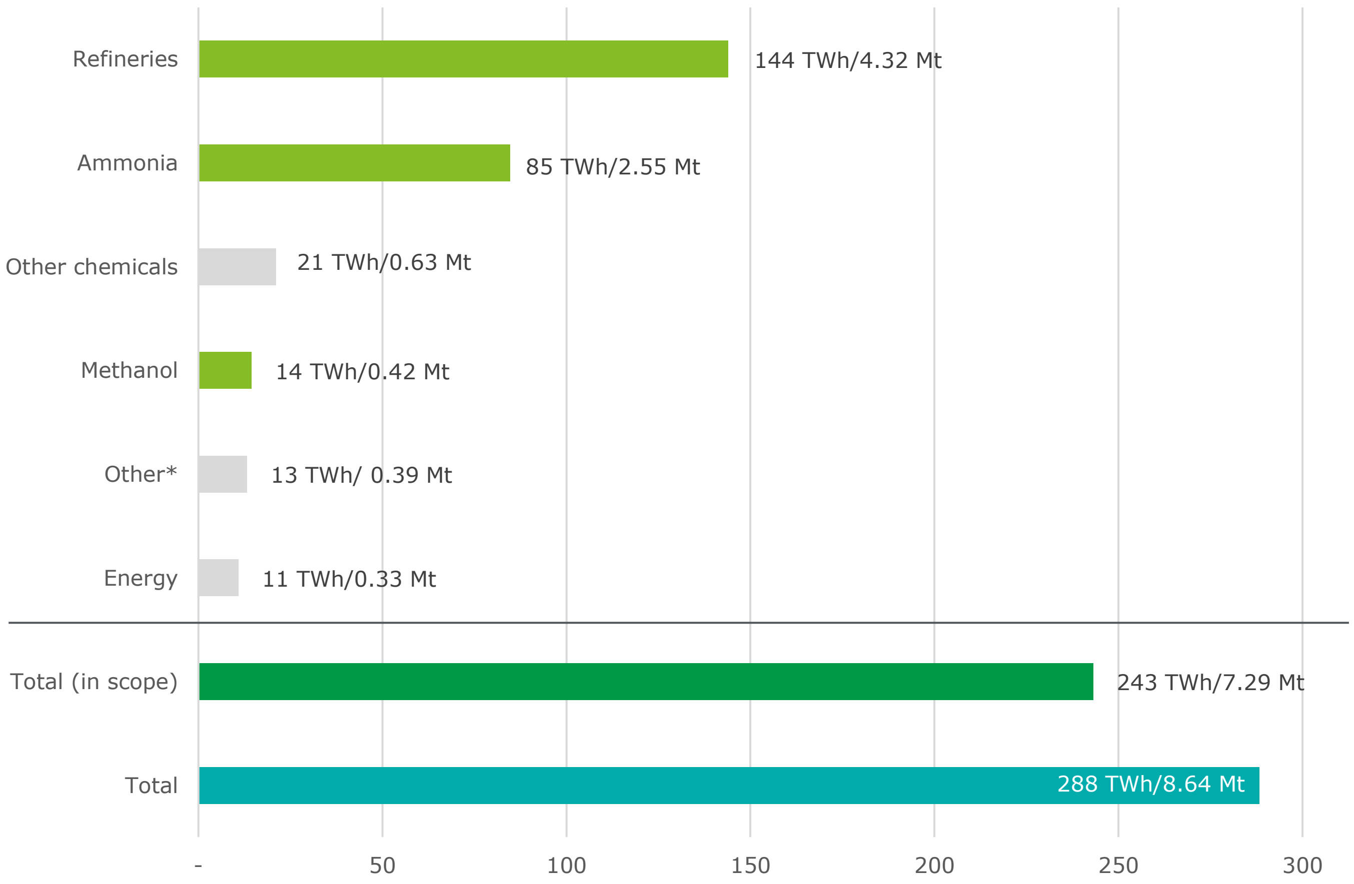
In 2020, hydrogen demand in Europe was 288 TWh with refineries, ammonia, and methanol plants accounting for 84% of total hydrogen demand

Hydrogen demand by sector in 2020 (in TWh/year)

- In March 2022, the Fuel Cells and Hydrogen Observatory (FCHO) estimated hydrogen demand in 2020 in the Europe* to be **288 TWh (8.65 Mt)**[1].
- Accounting for almost 75% of total demand, the main consumers of hydrogen were:
  - Germany (20%)
  - the Netherlands (15%)
  - Poland (9%)
  - Spain (7%)
  - Italy (7%)
  - France (6%)
  - Belgium (5%)
  - and the UK (5%).
- The **industrial sector** is currently the main user of hydrogen, with the oil hydrogenation process in **refineries** (144 TWh or 4.4 Mt), **ammonia** (85 TWh or 2.5 Mt) and **methanol** (14 TWh or 0.4 Mt) production **accounting for about 84%** of total hydrogen demand.
- According to the FCHO, the "other chemicals", "other" and energy sectors together represent a grey hydrogen demand equivalent to 45 TWh (1.3 Mt), or 16% of the hydrogen demand in Europe. These segments[2] of the current hydrogen demand **are out of scope of this study**.

Note: the "Other" category covers the demand from small to medium scale hydrogen users, including the food industry, glass manufacturing, automotive, generator cooling in the power sector, metal welding and cutting, electronics, research labs and other small-scale applications.

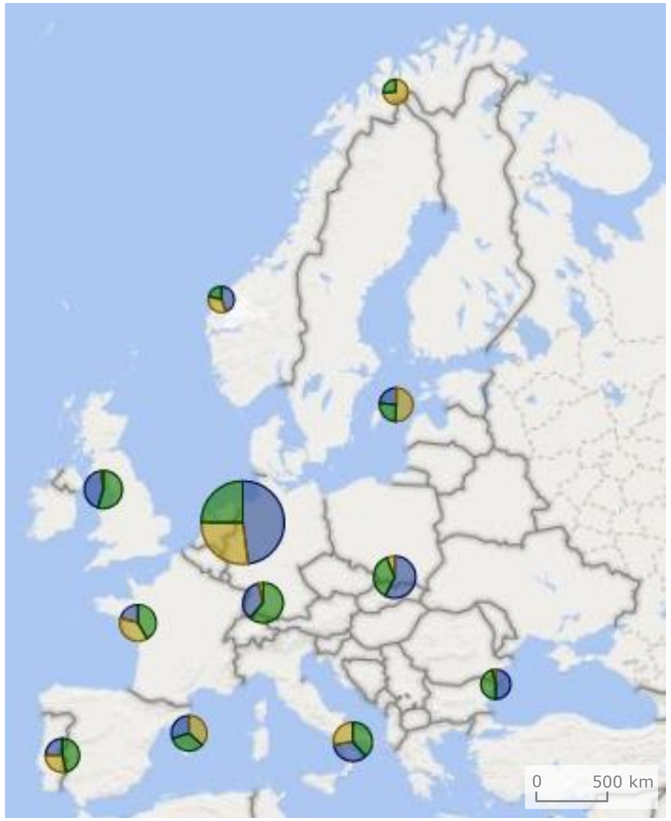
Estimated hydrogen demand by sector in 2020 in Europe (in TWh and Mt/year)*



Sources: (*) Europe is defined as the EU27+UK+Norway+Switzerland. (1) FCH JU, 2019. (3) FCHO, 2022. (2) Covering mainly small to medium scale hydrogen users, such as some chemical plants as well as the food industry, glass manufacturing, automotive, generator cooling in the power sector, metal welding and cutting, electronics, research labs etc.

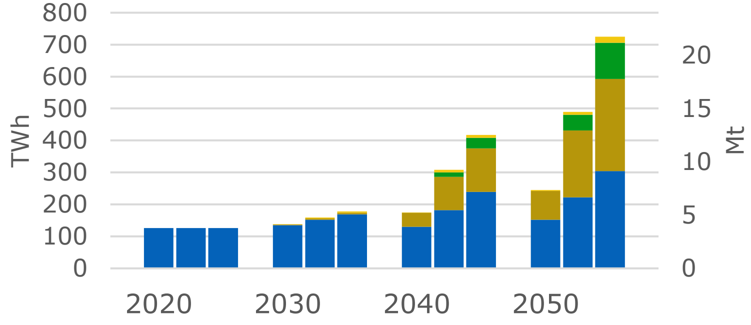
Overview of hydrogen demand projections until 2050 in Europe across all demand subcategories

Hydrogen demand per demand cluster per category – ambitious scenario in 2050

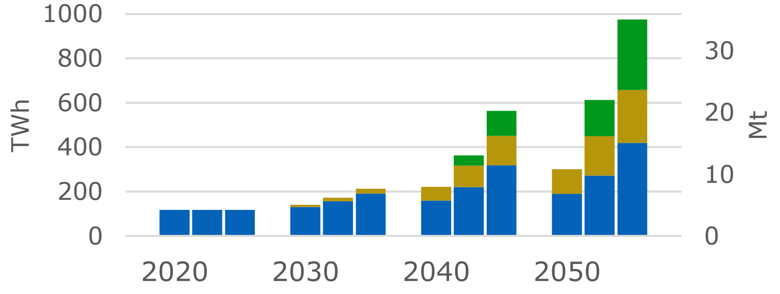


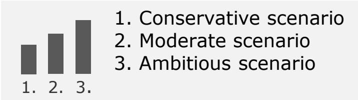
The circles on the map are located in the center of the relevant cluster

Hydrogen demand per category in ports



Hydrogen demand per category outside of ports





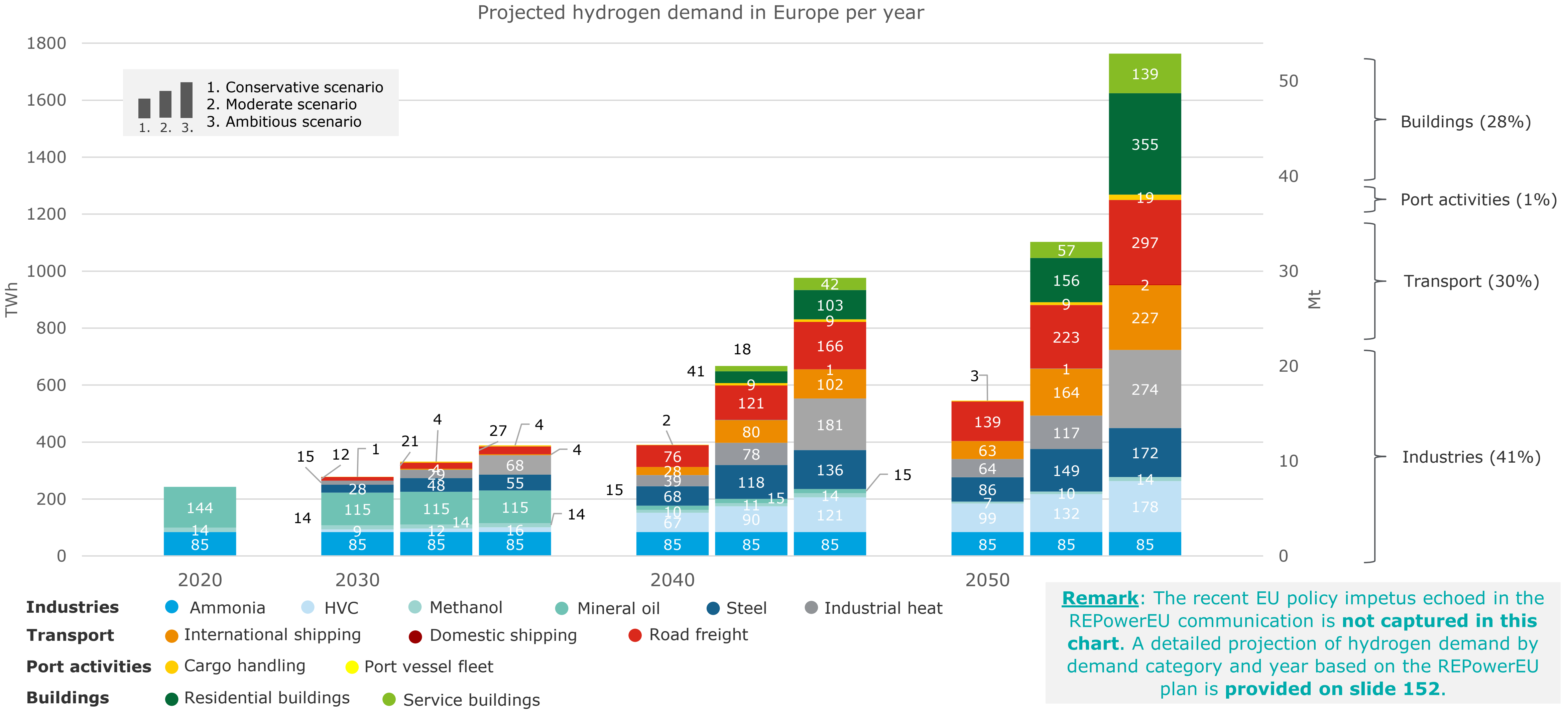
Key messages:

- Total hydrogen demand projections at the EU level and per cluster are obtained by **summing the hydrogen demand per individual port and areas outside of the ports.**
- Green/blue hydrogen demand will likely only **start to take off from 2030** onwards. Industries will likely be the first to deploy low-carbon hydrogen, followed by the transport sector and port activities. Finally, buildings in urban areas may adopt hydrogen from 2040 onwards.
- In 2030, total hydrogen demand is projected to be between 283 TWh and 389 TWh (8.49 to 11.70 Mt).
- In 2050, total hydrogen demand is projected to be between 545 TWh and 1764 TWh (16.35 to 52.92 Mt).
- By 2050, **industry will likely be the largest demand sector** for low-carbon Hydrogen, followed by transport, urban areas and finally port activities.

Note: all values in the graphs are given in TWh (left y-axis) and Mt (right y-axis)

● Industry ● Transport ● Urban areas ● Port activities

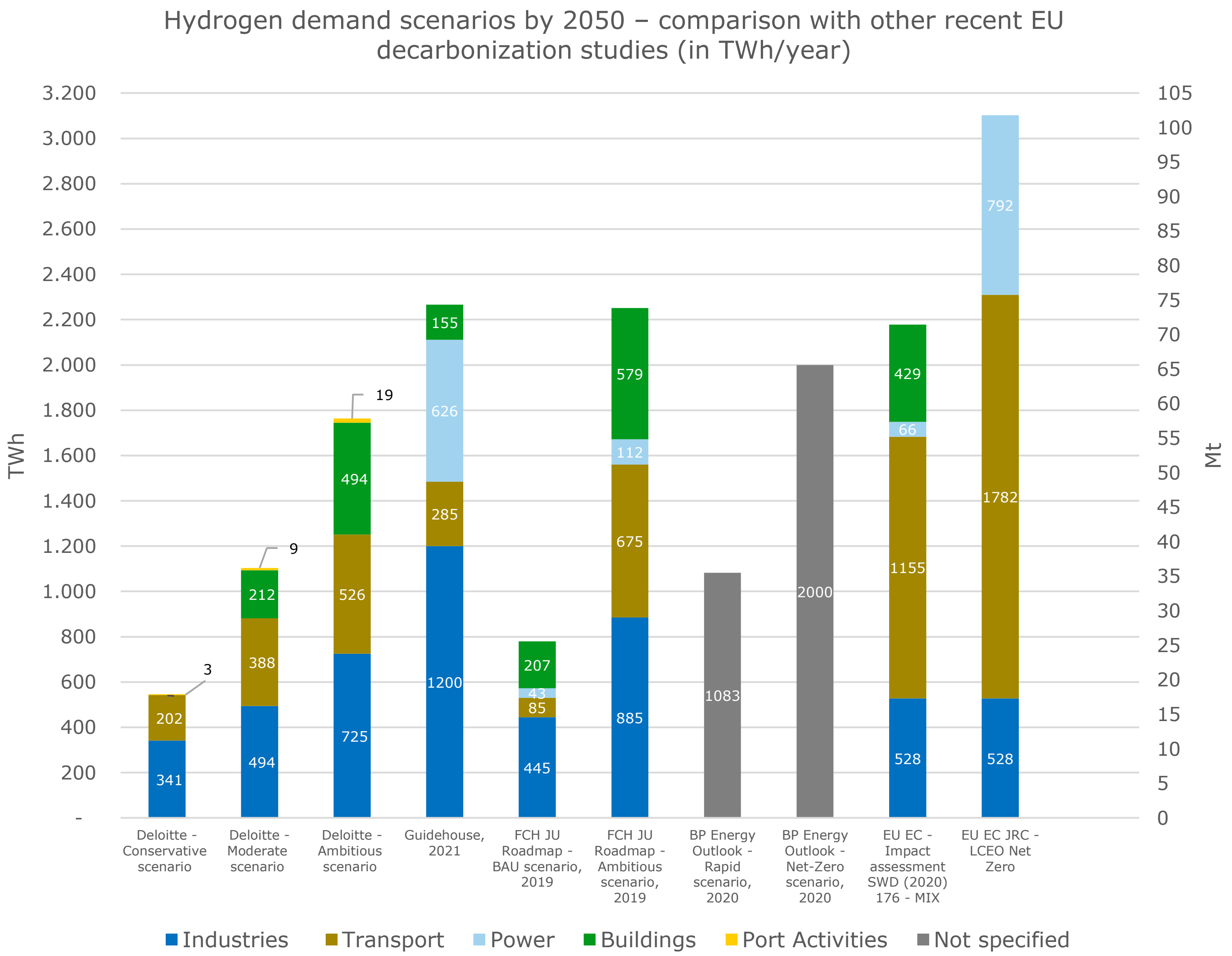
Hydrogen demand in Europe per demand subcategory and scenario for 2020, 2030, 2040 and 2050



Remark: The recent EU policy impetus echoed in the REPowerEU communication is **not captured in this chart**. A detailed projection of hydrogen demand by demand category and year based on the REPowerEU plan is **provided on slide 152**.

Note: The large differences in estimates of future hydrogen demand reflect the great degree of uncertainty that currently exists in the adoption of hydrogen as a replacement for fossil fuels in some sectors, notably the 'Buildings' sectors (heating of residential and service buildings). For all the other sectors in scope of this study (industries, transport and port activities), all three scenarios foresee a role for hydrogen, at least to some extent.

Comparison of the hydrogen demand estimates by 2050 in our scenarios with comparable estimates found is recent EU studies



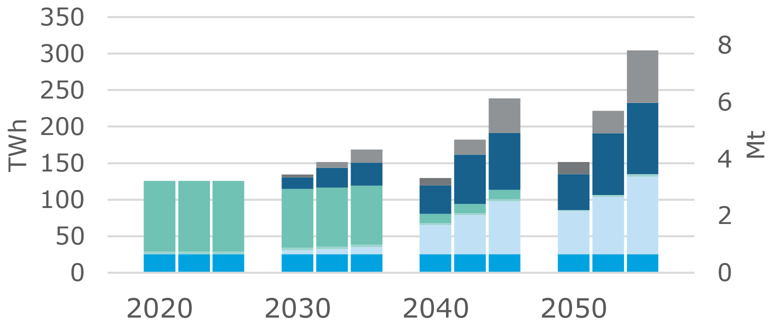
Comparative scenarios

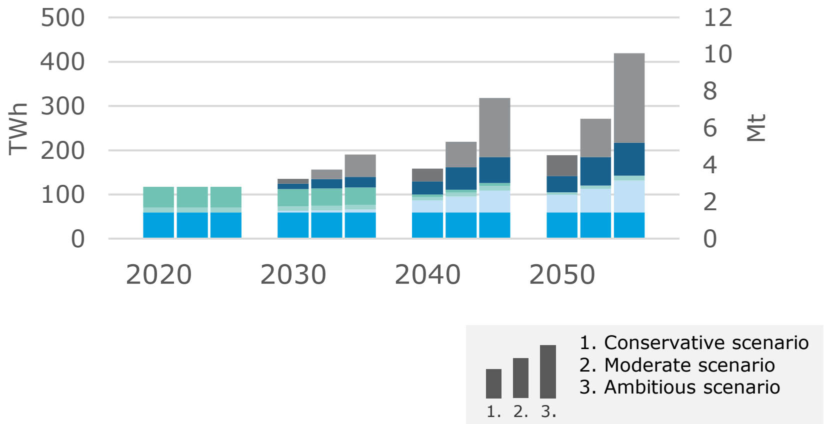
- Guidehouse, 2021: Hydrogen demand for synthetic fuels is categorized under "Industries" rather than under transport, as is done in the other scenarios. No hydrogen demand for shipping is assumed.
- FCH JU Roadmap – Business-as-usual (BAU) scenario: Current policies continue, but no step-up of activities takes place. The EU fails to reach the 2-degree target in 2050. Transport is broader than the scope of our analysis.
- FCH JU Roadmap - Ambitious scenario: Shows the full potential of hydrogen with a coordinated effort of industry, investors and policymakers. Transport is broader than the scope of our analysis.
- BP Energy Outlook - Rapid scenario, 2020: Series of policy measures, led by a significant increase in carbon prices and supported by more-targeted sector specific measures, which cause carbon emissions from energy use to fall by around 70% by 2050.
- BP Energy Outlook - Net-Zero scenario, 2020: The policy measures embodied in Rapid are both added to and reinforced by significant shifts in societal behavior and preferences, which leads to carbon emissions from energy use fall by over 95% by 2050.
- EU EC - Impact assessment SWD (2020) 176 – MIX: Hydrogen demand estimates are from the aggregation and consolidation effort performed in Guidehouse (2021)'s analysis (page 52).
- EU EC JRC - LCEO Net Zero: Hydrogen demand estimates are from the aggregation and consolidation effort performed in Guidehouse (2021)'s analysis (page 52).

In industries, hydrogen demand in Europe could reach up to 360 TWh (10.80 Mt), 560 TWh (16.80 Mt) and 725 TWh (21.75 Mt) per year in 2030, 2040 and 2050

Hydrogen demand per demand cluster per category – ambitious scenario in 2050

The circles on the map are located in the center of the relevant cluster





Ammonia HVC Methanol Mineral oil Steel Industrial heat

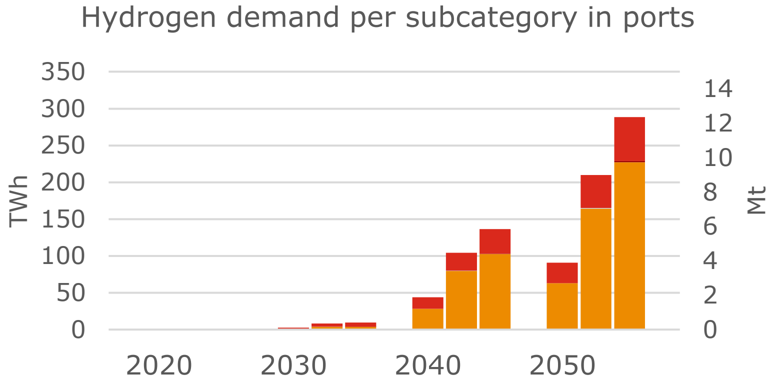
Key messages:

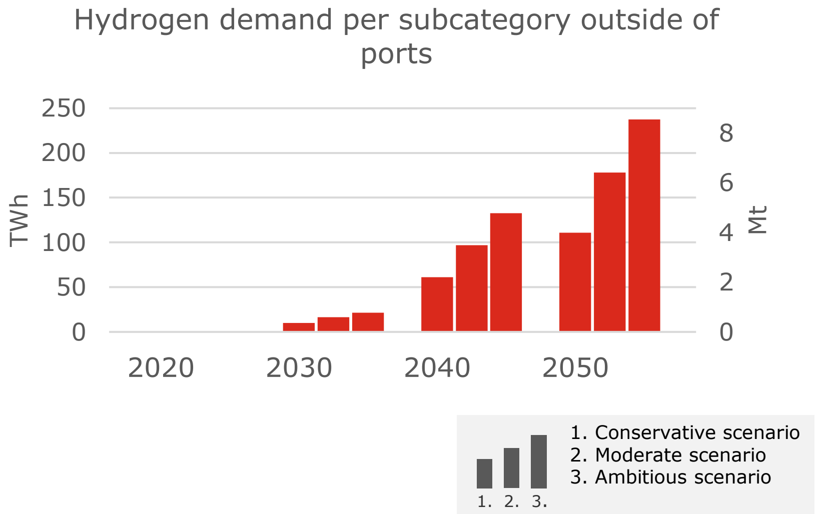
- Hydrogen demand in industries that do currently use hydrogen (i.e., primary teel, industrial heat and HVC) will likely **only start to take off from 2030** onwards.
- In 2030, total hydrogen demand is projected to be between 270 TWh (8.10 Mt)and 360 TWh (10.80 Mt). In 2050, total hydrogen demand is projected to be between 341 (10.23 Mt) TWh and 725 TWh (21.75 Mt), compared to 243 TWh (7.29 Mt) in 2020.
- **By 2050, industrial heat is expected to become the main application for the use of hydrogen in the industrial sector (274 TWh/year), followed by HVCs (178 TWh/year) and primary steel manufacturing (174 TWh/year).**
- Current hydrogen consumers are expected to either maintain the same demand for hydrogen over the decades (ammonia for fertilizer production, methanol for current uses) or not be hydrogen consumers in 2050 (the mineral oil refining process).
- By 2050, a significant proportion of the total hydrogen demand in industries is expected to emerge in the vicinity of ports.

In the transport sector, hydrogen demand will only start ramping up after 2030 in Europe and could reach up to 530 TWh (15.90 Mt) in 2050

Hydrogen demand per demand cluster per category – ambitious scenario in 2050

The circles on the map are located in the center of the relevant cluster





International shipping   Domestic shipping   Road freight

Key messages:

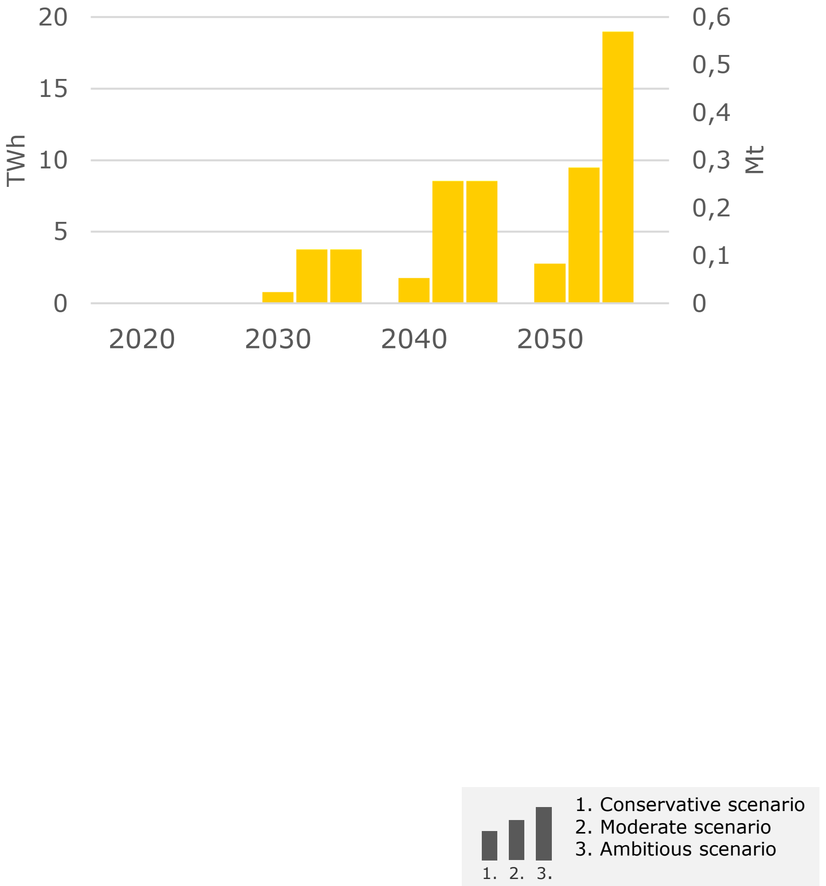
- Hydrogen demand in heavy duty road freight will likely **only start to take off from 2030** onwards, **and from 2040 for maritime transport.**
- In 2030, total hydrogen demand is projected be between 12 TWh (0.36 Mt) and 31 TWh (0.93 Mt). In 2050, total hydrogen demand is projected be between 200 TWh (6.0 Mt) and 530 TWh (15.90 Mt).
- **In the vicinity of ports and by 2050, international shipping is expected to become the main application for the use hydrogen in the industrial sector (227 TWh/year), followed by road transport (59 TWh/year).**
- Due to lower volumes and lower expected uptake of hydrogen, **the use of hydrogen in domestic shipping is expected to remain rather limited**, with a maximum of 2 TWh/year in 2050. Therefore, visibility on graphs is limited.
- Outside of the vicinity of ports, a significant amount of hydrogen is expected to be used in heavy duty road freight (up to 238 TWh per year in 2050, equivalent to 7.14 Mt).

Cargo handling accounts for the largest hydrogen demand in port activities, reaching up to 19 TWh in 2050

Hydrogen demand per demand cluster per category – ambitious scenario in 2050

The circles on the map are located in the center of the relevant cluster

Hydrogen demand per subcategory in ports



Cargo handling
Port vessel fleet

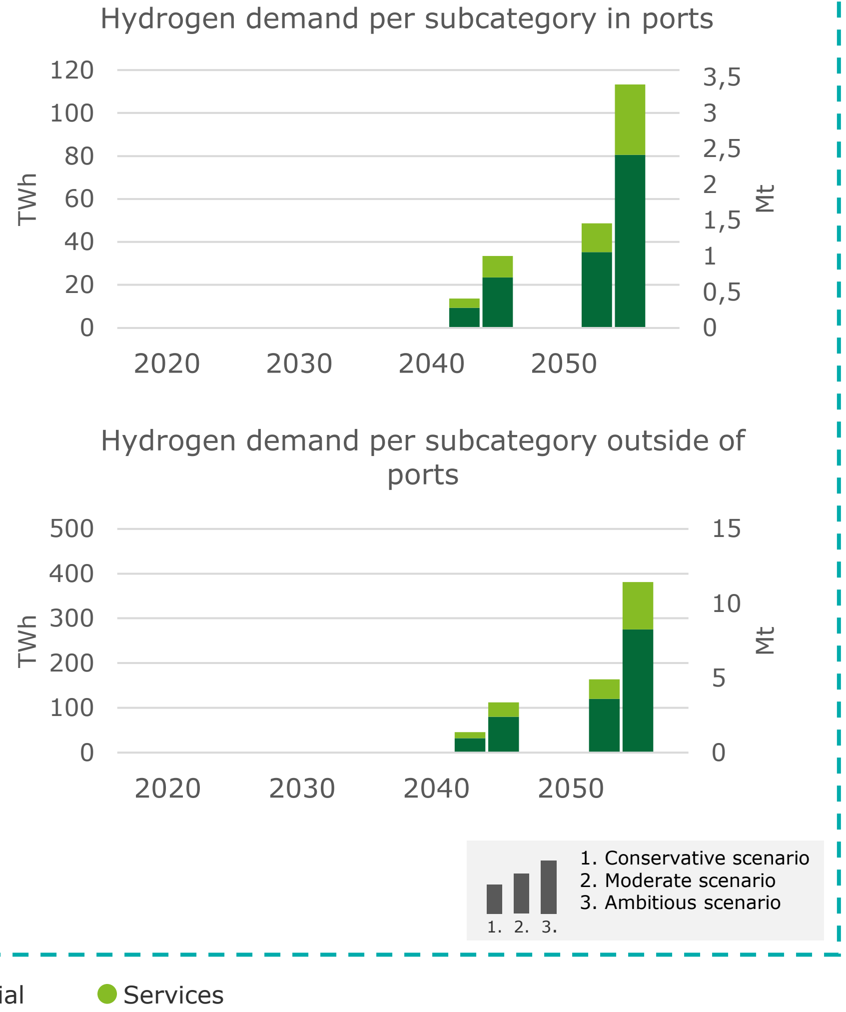
Key messages:

- Hydrogen demand for application in port activities (cargo handling and port vessel fleet) will likely **only start to take off from 2030** onwards.
- In 2030, total hydrogen demand is projected be between 0.8 TWh (0.02 Mt) and 4 TWh (0.12 Mt). In 2050, total hydrogen demand is projected be between 2.8 TWh (0.08 Mt) and 19 TWh (0.57 Mt).
- **By 2050, cargo handling is expected to become the main application for the use hydrogen for port activities (19 TWh/year).** Hydrogen demand for port vessel fleet is expected to remain rather limited.
- By definition, all hydrogen demand for port activities is assigned to a port. Therefore, no hydrogen demand outside of ports is identified.

Hydrogen demand in urban areas is highly uncertain, but could reach up to 490 TWh in 2050

Hydrogen demand per demand cluster per category – ambitious scenario in 2050

The circles on the map are located in the center of the relevant cluster

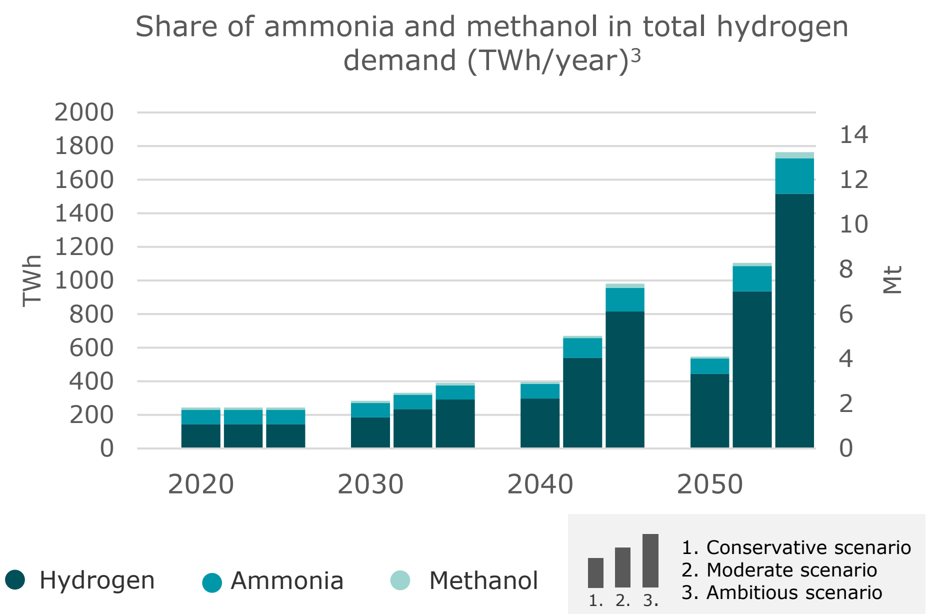


Key messages:

- Should hydrogen demand materialize in the building sector for heat production, it is expected to only **take off from 2040 onwards**.
- In 2040, total hydrogen demand is projected be between 0 TWh and 145 TWh (4.35 Mt). In 2050, total hydrogen demand is projected be between 0 TWh and 494 TWh (14.82 Mt).
- **Residential buildings is expected to account for the largest part (about 72%)** of hydrogen demand in the building sector due to a larger number of residential buildings than service buildings.

The share of ammonia and methanol in the total projected hydrogen demand by 2050 is 15 to 20%

Energy carrier	Current demand sectors	Projected future demand sectors[1;2]
Ammonia	• Production of fertilizers	• Production of fertilizers • Bunkering fuel international shipping
Methanol	• Chemical industry for the manufacture of countless every produces such as plastics, paints, cosmetics, carpeting, etc.	• Chemical industry for the manufacture of countless every produces such as plastics, paints, cosmetics, carpeting, etc. • Bunkering fuel international shipping



Key messages:

- Today, ammonia and methanol account for about 40% of the total hydrogen demand in Europe (only considering sectors in scope – see slide 71).
- In the coming years and decade, while the demand for ammonia and methanol for current applications is expected at best to remain stable, the international shipping sector is expected to become a significant consumer of green ammonia and methanol, since the sector is likely to depend on these molecules for its low-carbon transition.
- Therefore, taking into account the future expected demand of ammonia and methanol in international shipping, it should be considered that a share of the projected hydrogen demand in 2030/2040/2050 is likely to be used in the form of ammonia or methanol, and not in the form of hydrogen.
- Overall, by **2050**, it is expected that **between 15% and 20% of the total demand for hydrogen in Europe will be consumed in the form of ammonia and methanol**.
- Ammonia and methanol may also be preferred energy carriers for the import of green hydrogen to Europe. This is particularly relevant for those use cases where no reconversion to hydrogen is required, and the corresponding cost can be avoided. More information can be found in the section discussing hydrogen supply modelling results

<u>**Note**</u>: (1) The future demand for methanol in the HVC sector (Methanol-to-Olefins) is not included in the ammonia/methanol share shown here, as the volume of methanol for this particular end-use has not been quantified in this study (only the amount of hydrogen required per tonne of HVC produced via each of the Methanol-to-Olefins pathways); (2) Other sectors that are not in the scope of this study could use ammonia/methanol now or in the future (e.g., aviation); (3) Ammonia and methanol demand is considered, not the production location of the methanol and ammonia.

Environmental benefits

An approach consisting in accounting for direct CO_2 equivalent (abbreviated as CO_2-eq) is adopted in this study to estimate the CO_2-eq abatement resulting from the replacement of current fossil fuels and gases by green hydrogen

Hydrogen-related CO_2-eq abatement

The direct CO_2-eq emission abatement resulting from the replacement of current fossil fuels and gasses by green hydrogen in combustion processes is derived from the following calculation: CO_2-eq emission abatement (Mt CO_2-eq /year) = Direct CO_2-eq emission abatement[1] per unit of volume produced in 2020 * Number of units produced per year (2030, 2040 or 2050) using green hydrogen, green hydrogen-based processes or green hydrogen derivatives).

Overarching assumptions used for estimating the potential CO_2 abatement that could result from the replacement of current fuels by hydrogen

Since the carbon footprint associated with the use of hydrogen and fossil fuels in various production/combustion processes can vary depending on a number of factors[2], **an approach that considers only the CO_2-eq emissions emitted during fuel combustion (direct emissions) was chosen for this study**, therefore allowing for relevant comparison between direct emissions resulting from the use of fossil fuels and hydrogen in the end-use applications in scope. This approach to estimating the reduction in CO_2 emissions associated with the use of hydrogen leads to **following assumptions being made**:

> Given that all CO_2-eq emissions associated with the production and use of green hydrogen are related to the upstream and downstream value chain, and not it's production and use of the hydrogen itself, **the production and use of green hydrogen is assumed to not emit any CO_2**.

> Given that CO_2-eq emissions associated with the production and use of blue hydrogen are related to the production phase (depending on the carbon capture rate) as well as the upstream and downstream value chain, and not the consumption of the hydrogen itself, **the use of imported blue hydrogen is assumed to not emit any CO_2**.

> **With regards the conversion of grey hydrogen to on-site blue hydrogen** (which is estimated to account for a maximum of 10% of the hydrogen used for ammonia (for fertilizers) production and fossil fuel hydrogenation in refineries in 2030 and 2040, and 0% in 2050), **no CO_2-eq reduction potential was retained in this study**. This choice is justified by the following considerations:

1. There is a high uncertainty regarding the rate of CO_2 capture in future carbon capture units;
2. The CO_2 captured can be re-used (CCU) and emitted in another process instead of being stored in the ground, therefore not leading to absolute CO2 emission savings, and
3. The overall limited impact of CO_2-eq emission abatement due to the conversion from grey to blue hydrogen due to the small foreseen uptake of blue hydrogen production on the EU soil.

> Therefore, for those **industrial sectors where hydrogen demand is expected to be supplied by both on-site blue hydrogen and green hydrogen,** only the CO_2-eq reduction associated with the **replacement of fossil fuel-based processes with green hydrogen-based processes is accounted for**.

Note: (1) Encompasses only the CO_2 emissions resulting from the phases of the production processes that will cease with the switch to hydrogen-based processes; (2) e.g., fossil fuel extraction method, fuel transportation method and distance, material sourcing for wind and solar electricity infrastructures, electricity sources and other raw materials used alongside hydrogen or fossil fuels in industrial processes, methane leaks in the fossil gas or hydrogen value chain, manufacturing of electrolysers, etc.).

Data and assumptions used to estimate the direct reduction of CO_2-eq emissions from the use of hydrogen in Europe

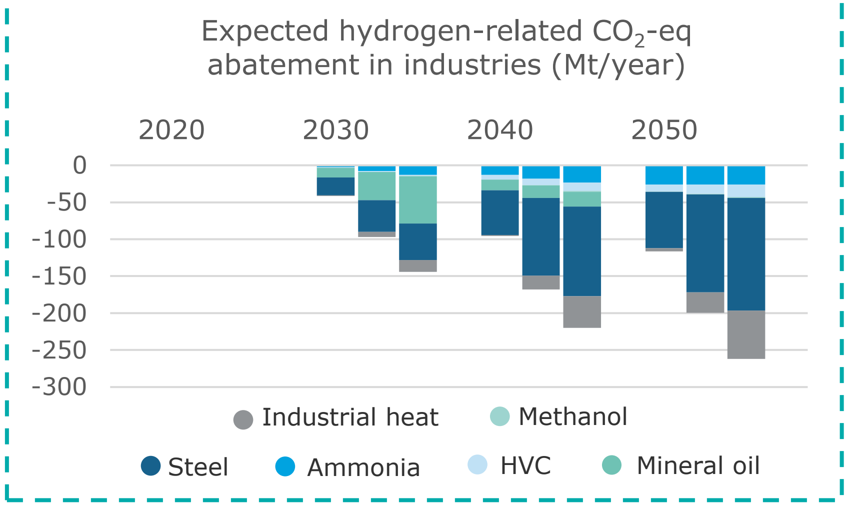
The use of hydrogen (derivatives) has to potential to reduce GHG emissions in EU ports. **In this analysis, only the direct CO_2-eq emission abatement due to hydrogen (derivatives) adoption is investigated**. Hydrogen-related indirect emission abatement and abatement resulting from the transition of fossil fuels to other energy vectors such as biofuels or increased energy efficiency are not considered.

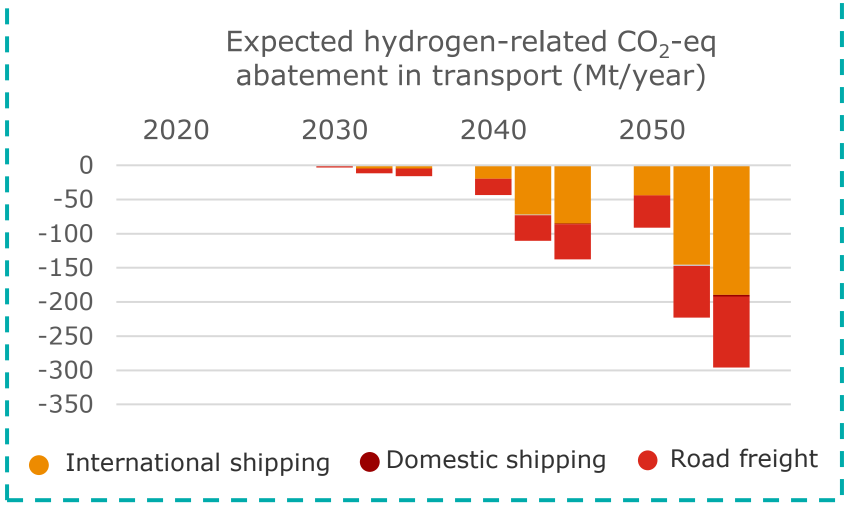
The table below contains the data used and specific assumptions chosen to calculate the hydrogen-related CO_2-eq abatement.

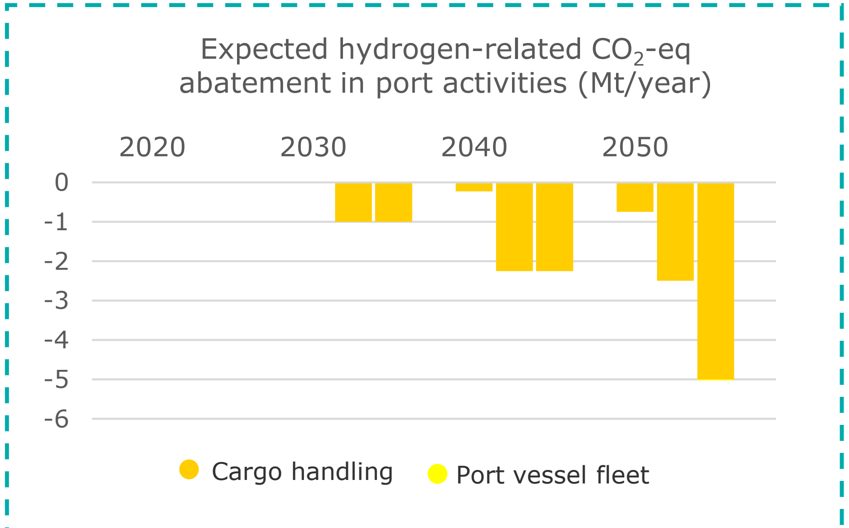
Category	Subcategory	Unit (per year)	CO_2-eq emissions (in t) per unit of volume*	Assumptions
Industry	Steel	tonne of primary steel	1.70	Based on Material Economics (2019) estimate*
	Ammonia	tonne of ammonia	1.80	Based on Material Economics (2019) estimate**
	Mineral oil	MWh of grey hydrogen	0.27	Based on European Commission (2020) estimate
	Industrial heat	MWh of fossil gas	0.20	Based on FCH & Triconomix (2020) estimate
	Methanol	tonne of methanol	0.50	Based on IRENA (2021) estimate
	HVC	tonne of HVCs	0.76	Based on Dechema (2017) estimate
Transport	International shipping	Mt-mile	23.10	• Energy per volume: 41.7 MWh/m tonne-mile*** • CO2 emissions per energy volume: 0.55-tonne CO_2/MWh[1]
	Domestic shipping	Mt-mile	23.10	• Energy per volume: 41.67 MWh/m tonne-mile • CO2 emissions per energy volume: 0.55-tonne CO_2/MWh
	Road freight	Mt-km	237.60	• CO2 emissions per energy volume: 0.26-tonne CO_2/MWh
Urban areas	Residential	m^2	0.015	• CO2 emissions per energy volume: 0.12 kg CO_2/kWh****
	Service	m^2	0.021	• CO2 emissions per energy volume: 0.12 kg CO_2/kWh
Port activities	Port vessel fleet	Mt-mile	23.10	• Energy per volume: 41.7 MWh/m tonne-mile • CO2 emissions per energy volume: 0.55-tonne CO2/MWh
	Cargo handling	TEU	0.15	• CO2 emissions per energy volume: 0.26-tonne CO_2/MWh

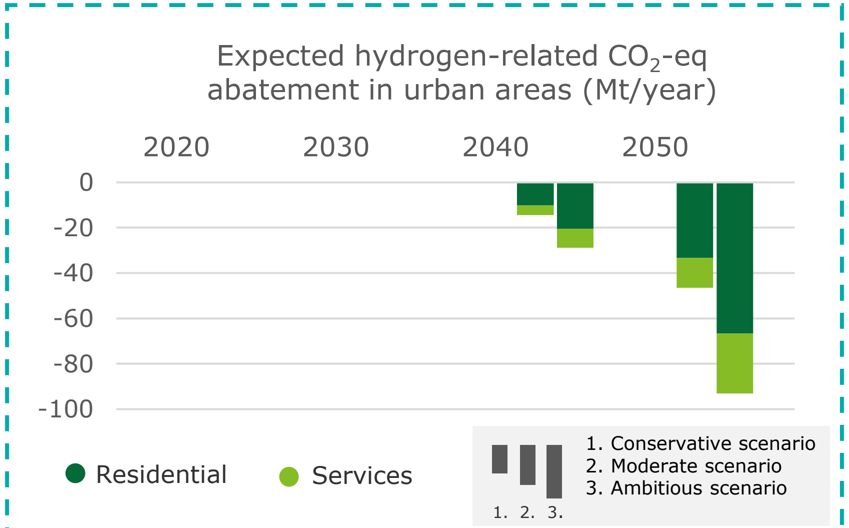
Notes:*Estimates of CO_2-eq emissions (in t) per unit of volume for primary steel only account for process emissions related to coke preparation (0.3t CO_2/t steel), iron-making in blast furnace (1.3t CO_2/t steel) and steel-making in basic oxygen furnace (~0.1t CO_2/t steel). ** Estimates of CO_2-eq emissions (in t) per unit of volume for ammonia only account for process emissions related to grey hydrogen production via steam methane reforming (1.8t CO_2/t steel). *** Average of different fuels used today. **** calculated based on current energy mix in heating of houses in Europe (5% electricity, 10% derived heat, 38% gas, 4% solid fuels, 14% oil/petroleum and 28% renewables and wastes). **Sources**: (1) JRC, 2014. (2) JRC, 2013.

Of all demand categories in scope, green hydrogen could significantly contribute to CO_2-eq emission abatement in industrial and transport sectors









Key messages:

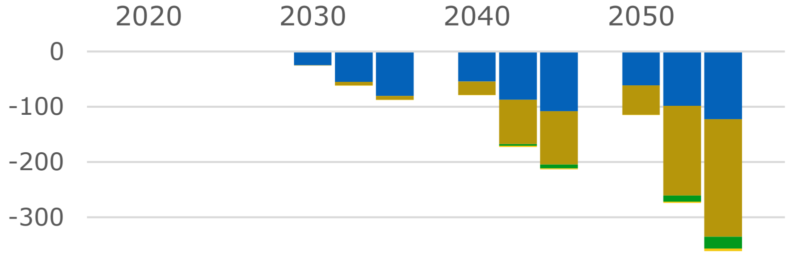
- **Industries**. Mainly driven by potential CO_2 emissions abatement in primary steel and industrial heat (respectively up to 150 and 65 Mt/year in 2050 compared to 2020), total CO_2-eq abatement resulting from the replacement of current fossil fuels by green hydrogen in industries could range between 116 Mt/year (conservative scenario) and 261 Mt/year (ambitious scenario), accounting for respectively 31% and 64% of all industrial CO_2-eq emissions in 2020.
- **Transports.** Total CO_2-eq abatement resulting from the replacement of current fossil fuels by green hydrogen in international shipping and heavy-duty road freight could range between 91 Mt/year (conservative scenario) and 296 Mt/year (ambitious scenario), accounting for respectively 10% and 34% of all CO_2-eq emissions from these activities in 2020.
- **Urban areas**. Green hydrogen penetration in building heating could abate up to 93 Mt/year in 2050, representing 20% of all residential and services building-related CO_2-eq emissions in 2020.
- **Port activities**. Green hydrogen use in port activities could abate up to 5 Mt/year in 2050, representing 20% of all port-activities related CO_2-eq emissions in 2020.

Hydrogen uptake in all demand categories could abate up to 655 Mt of CO_2-eq emissions in 2050 (or 16% of all European CO_2-eq emissions in 2019[1])

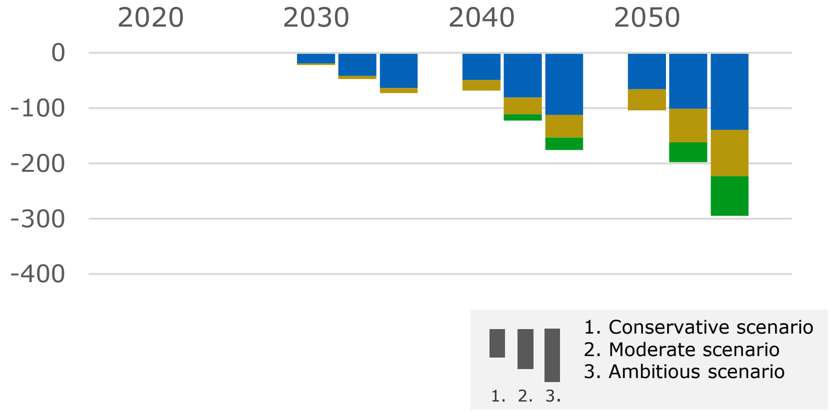
Expected hydrogen-related CO_2-eq abatement per demand cluster per category – Ambitious scenario in 2050

The circles on the map are located in the center of the relevant cluster

Expected hydrogen-related CO_2-eq abatement per subcategory in ports (Mt)



Expected hydrogen-related CO_2-eq abatement per subcategory outside of ports (Mt)



Key messages:

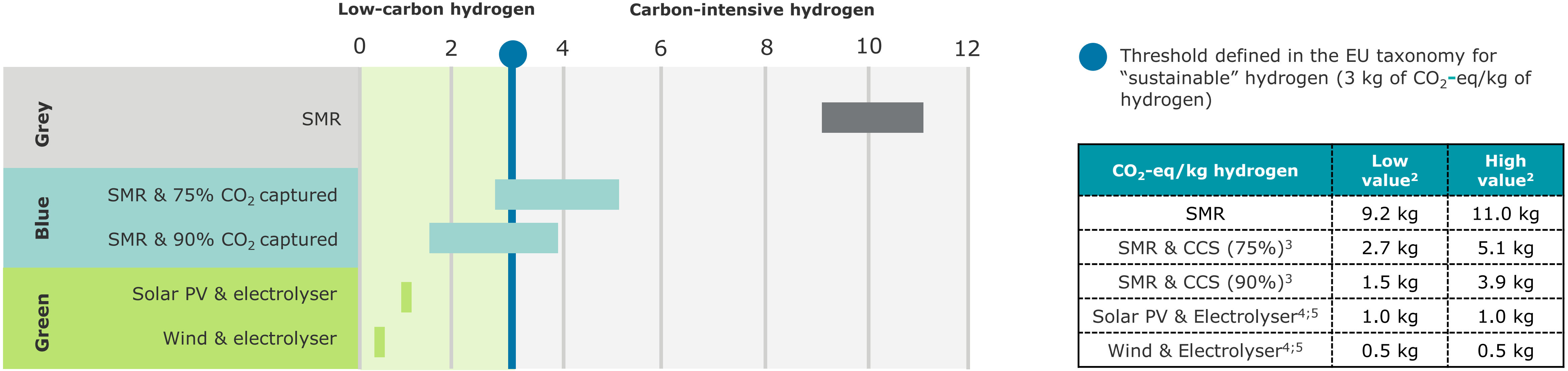
- Overall, mainly driven by potential CO_2-eq emissions abatement in industrial and transport sectors, total CO_2-eq **abatement resulting from the replacement of current fossil fuels by green hydrogen in demand categories in scope could reach up to 655 Mt** (ambitious scenario) in 2050 compared to CO_2-eq emissions in 2020, accounting for a **37% abatement of CO_2-eq emissions in these sectors**.
- In the conservative scenario, the replacement of current fossil fuels by green hydrogen abates only 12% of the CO_2-eq emitted by demand categories in scope in 2020.
- Largely driven by CO_2 emissions abatement in industries and international shipping, the potential for **CO_2 abatement resulting from the replacement of current fossil fuels by green hydrogen in demand categories located in the vicinity of European ports could account for up to 55% (361 Mt/year) of all potential CO_2-eq abatement in Europe** for demand categories in scope (ambitious scenario).

Industry Transport Urban areas Port activities

Source: (1) GHG emissions in the EU27 + UK + Norway + Switzerland in 2019 were 4,068 Mt (European Environment Agency, 2022).

Using a life-cycle assessment approach, the production of 1 kg of green and blue hydrogen in the EU is respectively associated with 0.5 - 1 kg and 1.5 - 5.1 kg of CO_2-eq emissions (compared to 9.2 – 11 kg for grey hydrogen)

Life-cycle assessment of hydrogen production (in kg CO_2-eq/kg hydrogen)[1]



CO_2-eq/kg hydrogen	Low value[2]	High value[2]
SMR	9.2 kg	11.0 kg
SMR & CCS (75%)[3]	2.7 kg	5.1 kg
SMR & CCS (90%)[3]	1.5 kg	3.9 kg
Solar PV & Electrolyser[4;5]	1.0 kg	1.0 kg
Wind & Electrolyser[4;5]	0.5 kg	0.5 kg

Notes:

1. In the context of this study, blue hydrogen refers only to hydrogen produced from SMR (or ATR) with a carbon capture rate of 90%.
2. For SMR-based technologies, low values refer to hydrogen based on natural gas from Norway (1,700 km pipe), high values refer to hydrogen based on natural gas from Russia (5,000 km pipe). Carbon footprint of hydrogen based on natural gas from LNG route would be higher than the Russian route.
3. A 90% (or 75%) carbon capture rate does not reduce GHG emissions by 90% (or 75%), as additional energy is needed to power the capture and sequestration process, and GHG emissions occur over the natural gas supply chain.
4. The difference between the carbon footprint of green hydrogen produced from wind and solar technologies is mainly the result of the higher embedded emissions for solar PV, due to the global grid mix taken into account for the manufacture of PV panels and the greater amount of raw materials required to produce a given amount of electricity from solar PV compared to wind power (resulting in a higher carbon emission intensity for electricity generated from solar PV than for wind energy.
5. For wind and solar technologies, applying recycling rates of 80% and more for different metals at end of life versus using virgin materials would reduce GHG emissions by 0.1 to 0.3 kg CO_2-eq/kg hydrogen.

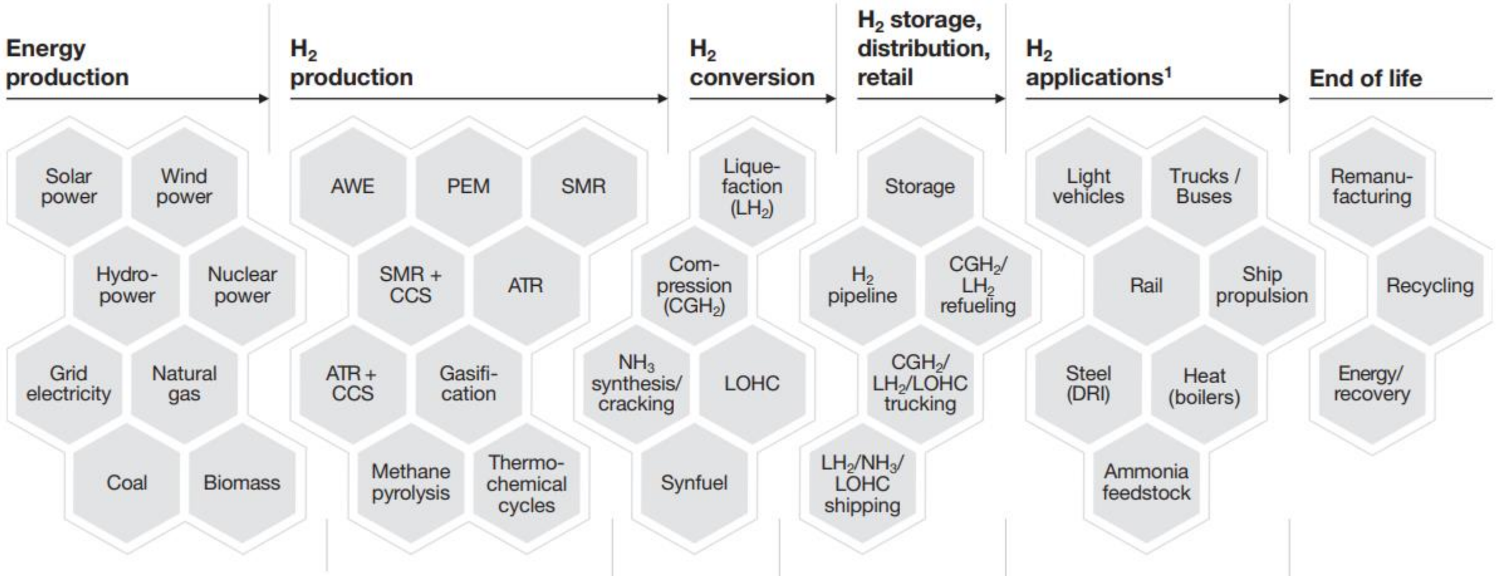
Source: (1) Hydrogen Council, 2021.

Therefore, by not accounting for indirect carbon emissions resulting from the development of an international hydrogen market and associated large-scale infrastructures, estimated CO_2-eq reduction potentials are overestimated

> Based on the assumptions chosen, **the CO_2-eq reduction potentials estimated in this study should be interpreted as overestimated** since only the direct reduction of CO_2-eq emissions resulting from the combustion of green hydrogen instead of fossil fuels and gases is taken into account.

> With the development of a European hydrogen economy and associated large-scale hydrogen-related infrastructures, the **carbon emissions associated with the upstream and downstream value chain of green and blue hydrogen**, both for import and local production, will also **need to be considered and minimized** in the development of green and blue hydrogen projects*.

Hydrogen production pathways and associated steps in upstream and downstream the value chain with embedded CO_2 emissions[1]



In all cases, it must be considered that, due to the potentially high carbon intensity of the fossil gas value chain in many non-EU countries (extraction method, efficiency of operations, method and distance of fossil gas transport, methane leakages, etc.), uncertainties regarding the carbon capture rate of carbon capture technologies as well as the development of required infrastructure (construction and operation of carbon capture facilities, CO_2 pipeline, underground CO_2 storage), it is highly likely that **imported blue hydrogen from non-EU countries will consistently exhibit a significantly higher GHG emission intensity than locally produced or imported green hydrogen**.

Note: *Based on a life-cycle assessment approach, the previous slide displays the values of CO_2-eq emissions resulting for the production of 1kg of hydrogen using different production pathways.

Source: (1) Hydrogen Council, 2021.

In addition to potentially contributing to a significant share of the total GHG emission reduction required for the net-zero target to be reached in 2050, switching to green hydrogen-based industrial processes and fuels leads to additional environmental benefits

Green hydrogen-related non-CO_2 environmental benefits

For all categories of green hydrogen demand in this study, the non-CO_2 environmental benefits of replacing current fossil fuels and grey hydrogen with green hydrogen in combustion processes have been qualitatively assessed based on the existing literature available.

Conclusion: Overall, existing literature points toward a **largely shared consensus that significant reduction of toxic atmospheric emissions** (i.e., CO, SOx, NOx, PM10, PM2.5, VOCs, N_2O, SO_2, black carbon, F-gases, methane), **water pollutants** (COD, ammonia, phenols, benzene, benzo(a)pyrene, vinyl chloride), as well as **solid waste** (slag, sludge, heavy metals) and **noise emissions could be achieved** by replacing current fossil fuels and grey hydrogen with green hydrogen in industries and various fuel combustion processes.

Approach to the analysis: Since the environmental externalities (other than CO_2 emissions) resulting from the use of hydrogen and fossil fuels in various combustion processes can vary depending on a number of factors (e.g., fossil fuel extraction method, fuel transportation method and distance, material sourcing for wind and solar electricity infrastructure, electricity sources and other raw materials used alongside hydrogen or fossil fuels in industrial processes, methane leaks in the fossil gas or hydrogen value chain, etc.), **only the reduction of direct emissions of air pollutants at the combustion/production (industrial process) phase are being discussed in this study*.**

- CO = Carbon Monoxide (greenhouse gas); SOx = Sulphur Dioxide (contributes to land and water acidification); NOx = Nitrogen Oxides (responsible for respiratory diseases, contributes to acidification as well as to the formation of smog); PM = Particulate Matter (responsible for respiratory and heart diseases and contributes to the formation of smog), VOC = Volatile Organic Compounds (contributes to for the formation of smog and can cause serious health problems); COD = Chemical Oxygen Demand (harmful to aquatic life).

Notes on indirect non-CO_2 emissions resulting from the production and transport of hydrogen:

- Although hydrogen is neither intentionally emitted to the atmosphere when used nor a direct greenhouse gas, **hydrogen losses** (e.g., hydrogen leakage in the supply chain) to the atmosphere impacts the lifetime of other GHG, namely methane, ozone, and water vapor, indirectly contributing to the **increase of the Earth's temperature in the near-term**[1].
- For blue hydrogen, evidence suggests that the introduction of **CCS into an SMR plant is likely to increase all non-CO_2 emissions**, due to increased energy requirements and the construction of equipment for CO_2 capture, compression and injection. Depending on the CCS technology adopted, emissions related to the higher energy input requirement could potentially be mitigated using renewable electricity or on-site waste heat for the carbon capture process, but additional emissions from the infrastructure requirements of CCS may be hard to reduce[2].

Note: *For each of the demand categories, only the most significant environmental externalities (air pollutants) other than CO_2 emissions are discussed. **Sources**: (1) JRC, 2022. (2) BEIS, 2018

The transition from current fossil fuel-based production/combustion processes to green hydrogen (derivatives) is expected to significantly reduce emissions of key air pollutants (NOx, Sox, PM, CO and VOC)

Demand subcategories	Environmental benefits of the transition from current fossil fuel-based production/combustion processes to green hydrogen	Sources
Primary steel	Compared to a conventional BF-BOF primary steel plant, switching to the green hydrogen DRI-EAF process significantly reduces toxic air emissions (CO, SOx, NOx, PM10, PM2.5 and dust), water pollutants (COD, ammonia, phenols), as well as solid waste (slag, sludge, heavy metals). In addition, the hydrogen DRI-EAF process requires less energy and water resources per tonne of primary steel produced.	Renzulli, P.A et al., 2016; Strezov et al., 2013; European Commission, 2021
Ammonia; Methanol; Hydrogenation of mineral oil	Compared to the conventional Steam Methane Reforming (SMR) hydrogen production process, the switch to electrolysis hydrogen production powered by wind or solar energy sources significantly reduces the toxic air emissions (CO, SOx, NOx, PM10, PM2.5, VOCs) that are emitted at the combustion of natural gas phase in the SMR process.	BEIS, 2018; Sun et al., 2019; Sharma et al., 2021; Acar and Dincer, 2013
High Value Chemicals (HVCs)	The production of ethylene from naphtha with natural gas as the energy source in the steam cracking process produces significant atmospheric emissions of SOx, NOx, metals (copper, selenium and zinc), non-metals (arsenic), organic chemicals (such as polychlorinated biphenyls), VOCs (such as benzene and toluene), PM10, PM2.5 and CO, as well as harmful water pollutants (benzene, benzo(a)pyrene, vinyl chloride). Switching to defossilization solutions (the MtO pathway and the low carbon feedstock pathway) using green hydrogen can significantly contribute to reducing emissions of these substances.	Ghanta et al., 2014; Environmental law Institute, 2018; Variny et al., 2021; IEA, 2019
Natural gas-based industrial heat	The combustion of natural gas in industrial heat processes produces significant levels of NOx and CO, negligible levels of mercury and PM and virtually no SOx emissions. The shift to electrolysis hydrogen production fueled by wind or solar energy sources for industrial heat would eliminate CO, PM and SOx emissions. Further research is needed to estimate the extent to which NOx emissions could evolve as a result of a switch to green hydrogen-based industrial heat.	Gould and McGlade, 2017; Union of Concerned Scientists, 2014; EMEP/EEA, 2019
Shipping and port vessel fleet	Compared to a conventional shipping fuels such as fuel oils, switching to hydrogen (derivatives) significantly reduces toxic air emissions such as CO, N_2O, NOx, SOx and PM. Further research is needed to estimate the extent to which NOx emissions could evolve as a result of a switch to green ammonia as a fuel in the shipping sector.	ICCT, 2017, IPCC, 2018; Ash and Scarbrough, 2019; EMEP/EEA, 2019
Road freight	Compared to conventional fuels such as diesel, switching to hydrogen (fuel cells) almost eliminate all non-CO2 pollutants such as NOx, VOCs, SO_2, CO, PM and F-gases.	EMEP/EEA, 2019 ;Lewis, 2021
Cargo handling	Compared to conventional cargo handling equipment, fuel cells-powered equipment can decrease noise emissions and NOx, but also other air pollutants (VOCs, SO_2, CO, PM)	FCH, 2017
Residential and Service building	Compared to natural gas boilers, switching to hydrogen would eliminate CO, PM and SOx emissions. Further research is needed to estimate the extent to which NOx emissions could evolve as a result of a switch to green hydrogen-based heating in the residential and service building sectors.	FCH, 2020; Lewis, 2021; Cellek and Pınarbaşı (2018)

Emission factors of the transition to green hydrogen for the leading air pollutants (NOx, Sox, PM, CO and VOC)

Green hydrogen application	Unit	NOx		SOx		PM (10 & 2.5)		CO		VOC		Remark
		BAU	Green Hydrogen	BAU	Green Hydrogen	BAU	Green Hydrogen	BAU	Green Hydrogen	BAU	Green Hydrogen	
Primary steel	kg/tonne	1	0.24	1	0.0007	0.16	0.35	56	9.8	/	/	1
Ammonia; Methanol; Oil hydrogenation	mg/kWh H_2	240.6	56.2	194.9	40.4	106	5.1	1301	0.80	30.5	/	2
High Value Chemicals (HVCs)	g/kg	0.45		0.03		0.1		0.3		2.4		3
Heating (industries and buildings)	g/kWh	0.32	**Unclear[1]**	0.001	/	0.003	/	0.14	~0.0	/	/	4
Heavy duty road freight (fuel cells)	g/kg fuel	33.37	/	/	/	0.94	/	7.58	~0.0	/	/	5
Shipping and port vessel fleet	kg/tonne fuel	69.1	**Unclear[2,3]**	19.2	/	5.2	Drop[3]	3.67	/	1.67	/	6

Relative change between a Business-As-Usual (BAU) situation and green hydrogen adoption in air pollutants emissions

- Decrease by a factor of at least 5
- Decrease by a factor of 2 to 5
- Decrease by a factor of 0 to 2
- Increase
- / No emissions
- Data not available

Remarks

1. Comparison between the BF/BOF (BAU) and (Hydrogen) DRI-EAF production route of primary steel. Source: Strezov et al., 2013 (see Table 1 – page 16).
2. Comparison between direct air emissions from SMR process in centralized gaseous hydrogen production facilities from Miller (2017) (BAU) and direct air emissions from the electrolysis process (Spath and Mann, 2004). Source: BEIS, 2018 (see Table 5 – page 13 and Table 7 page 16).
3. Source for BAU: Young at al, 2022 (see Table 3 page 6 and Fig 3 page 8- Olefins production). Given the plurality of hydrogen-based decarbonization pathways for HVC manufacturing, the air pollutant emission factors associated with the adoption of green hydrogen-based processes in HVC manufacturing are not documented in this study. However, significant improvements in emissions of all air pollutants are expected as a result of the shift to hydrogen-based processes in the manufacture of HVCs.
4. Comparison between fossil gas-based industrial heat (BAU) and green hydrogen-based industrial heat. Source for BAU: EMEP/EEA, 2019 (see Table 3-4 page 17). Source for green hydrogen: Lewis (2021); Cellek and Pınarbaşı (2018).
5. Comparison between diesel (BAU) and fuel-cells green hydrogen used to power heavy-duty trucks. Source for BAU: EMEP/EEA, 2019 (see Table 3-5 and 3-6 pages 19 & 20). Source for green hydrogen (fuel cells): Lewis, 2021.
6. Comparison between bunker fuel oil (BAU) and (green) ammonia used as a fuel in international and national navigation. Source for BAU: EMEP/EEA, 2019 (see Table 0-1 page 16). Source for (green ammonia): Ash and Scarbrough, 2019.

Notes: (1) Potentially lower NOx than natural gas according to Lewis (2021) and up to six times greater according to Cellek and Pınarbaşı (2018); (2) Likely to outperform heavy fuel oil equivalents, with major sulphur co-benefits (Lewis, 2021), but strong uncertainties remain (Ash and Scarbrough 2019); (3) Combustion of ammonia in engines should lead to a substantial drop of emissions of particulate matters (Ash and Scarbrough 2019).

Task 2

Hydrogen supply, storage and distribution

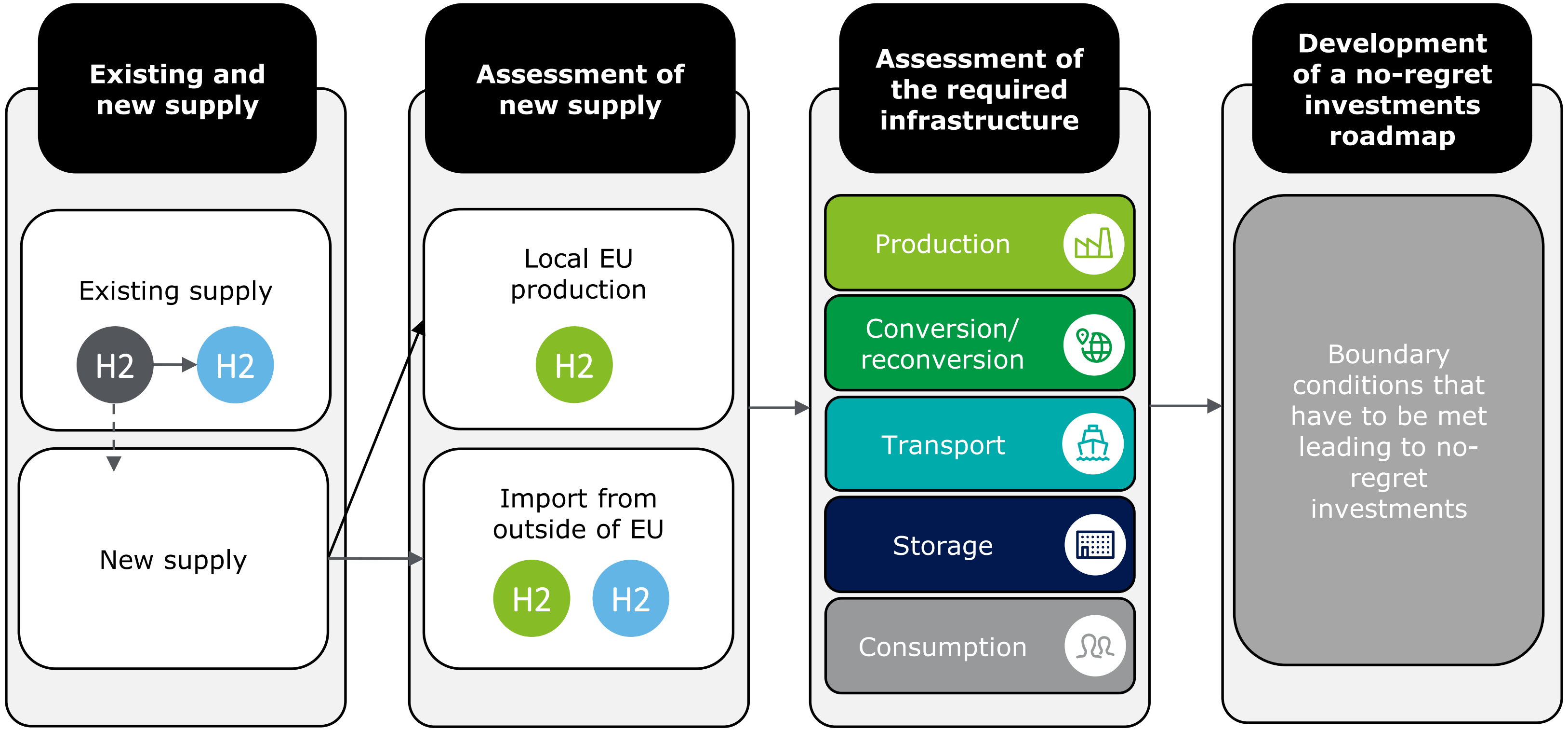
Supply modelling approach

Study distinguishes between existing and new supply, and uses a hydrogen supply model to assess new supply and corresponding infrastructure needs

Approach:

- In the first step, a distinction is made between existing and new supply based on desk research and interviews. **Existing supply** is defined as the hydrogen which is currently being supplied to refineries and ammonia plants. Today, this grey hydrogen is mostly produced on-site. Grey hydrogen production will either be equipped with CCS technology, referred to as "on-site blue hydrogen (retrofit)" or be replaced by other forms of green/blue hydrogen supply.
- In the second step, the **new supply** of green and other blue hydrogen is assessed by the supply model. For this, **local EU production** of green hydrogen[1] and **import** of green/blue hydrogen outside of the EU is considered, as detailed further on.
- In the third step, the **required infrastructure** is assessed for the different steps of the value chain
- Finally, a **no-regret investments roadmap** is constructed based on the assessment of the required infrastructure and the outcome of the supply model.

Stepwise approach:



Basis of work:

Desk research, interviews	Hydrogen supply model, desk research, interviews

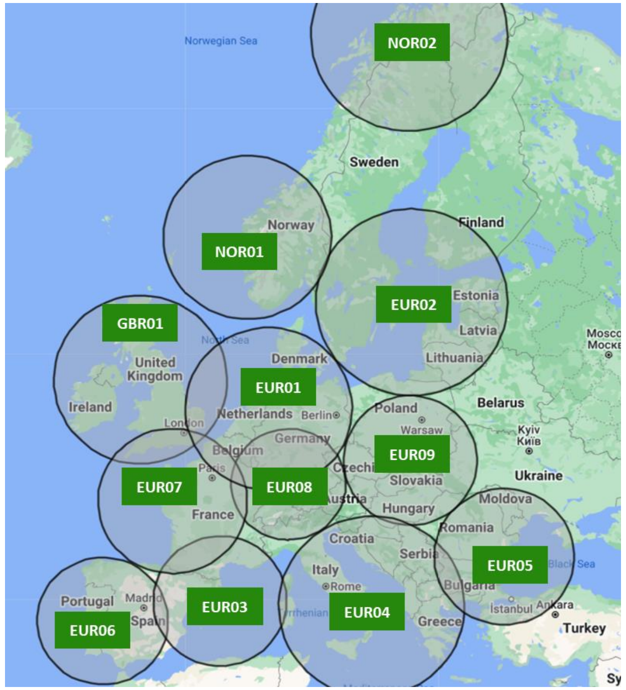
Note: (1) An alternative view is presented in the appendix where blue hydrogen could also play a role in local EU production, on top of replacing existing grey hydrogen

The hydrogen supply model strives for overall cost minimization considering different possible supply options per cluster, not based on policy initiatives

The hydrogen supply is modelled with the Hydrogen Pathway Explorer (HyPe) model[1], which compares different possible supply options per cluster and strives for overall cost minimization based on Levelized Cost of Hydrogen (LCOH) modelling considering all costs of the hydrogen supply chain

Geographical clusters[2] are used to model the hydrogen supply:

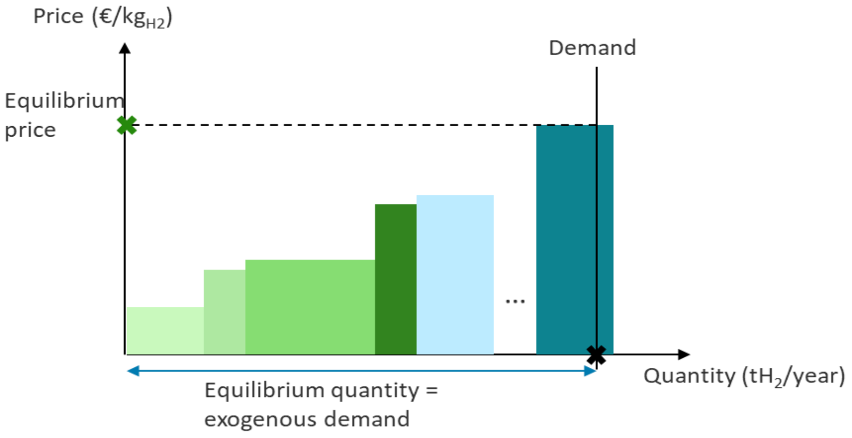
- **Economic parameters** of hydrogen supply are assumed **similar within one cluster** (e.g., transport cost)[3]
- The supply model matches projected hydrogen demand with supply within a cluster



12 clusters defined:	
EUR1	Belgium, Netherlands, Denmark and North of Germany
EUR2	Baltics, Finland and Sweden
EUR3	Western Mediterranean coast (Spain and France)
EUR4	Italy, Croatia and Greece
EUR5	Bulgaria and Central/South Romania
EUR6	Spain and Portugal
EUR7	France (Atlantic coast)
EUR8	Western Central Europe
EUR9	Eastern Central Europe
NOR1	Southern Norway
NOR2	Northern Norway
GBR1	UK and Ireland

Per cluster and at overall system level, an **equilibrium** is sought between hydrogen demand and supply:

- The model focusses on finding the **economic optimum**, i.e., it strives for overall cost minimization based on LCOH per supply option for the whole time period.
- **Policy initiatives** and EU member state strategies on electrolyser deployment or bilateral agreements with importing countries are **not taken into account**.



Notes: (1) Developed and maintained by Deloitte France. It has a modular and flexible architecture that allows to easily adapt the temporal and geographical scope, as well as the input assumptions to address questions around the international hydrogen trade. (2) Clusters have been chosen based on best overall representation of Europe. Locations/ports who fall outside of clusters on the map are assigned to the closest cluster. Locations/ports who lay within two or more clusters are assigned to the cluster of which the center is located the closest. (3) All assumptions taken in the model can be found in the appendix

The hydrogen supply model has a modular and flexible architecture to easily respond to the rapidly changing environment

Scope:

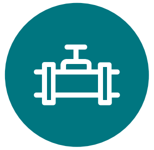
- **Time scope**: 2030 – 2050 with a 5-year time step
- **Considered countries[1]**: EU27, Norway (NO), United Kingdom (GB), Australia (AU), Algeria (DZ), Morocco (MA), Egypt (EG), Qatar (QA), Iraq (IQ), Saudi Arabia (SA), Oman (OM), United Arab Emirates (AE), China (CN), India (IN), South Korea (KP) and Japan (JP)
- **Supply side**: all low-carbon and renewable hydrogen production technologies (e.g., blue, turquoise and green hydrogen).
- **Transport options**:

Liquid Hydrogen

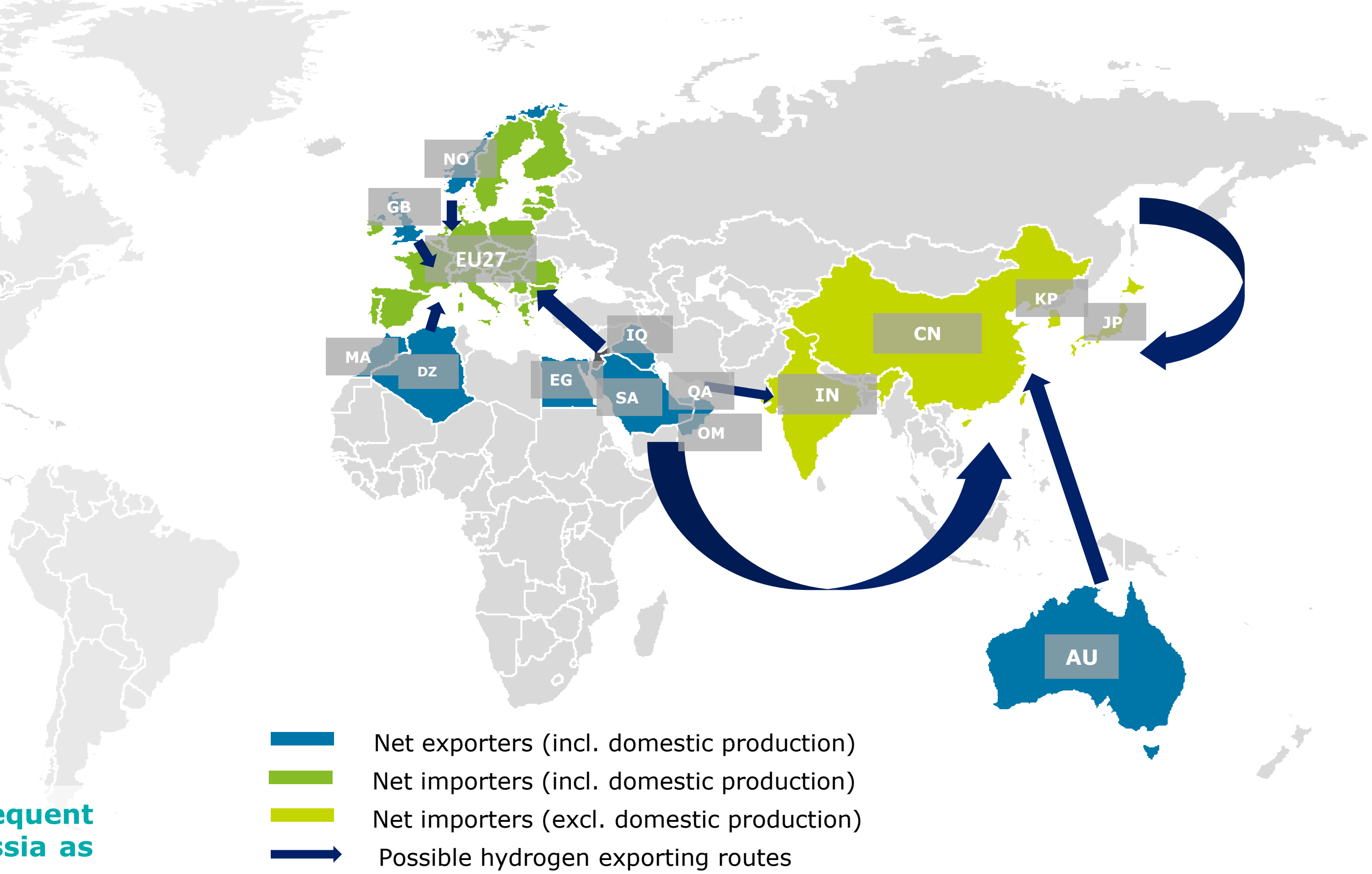
Liquid NH_3

Gaseous Hydrogen

Liquid NH_3



Gaseous Hydrogen



In view of Russia's invasion of Ukraine and the subsequent political response of the EU, the model excludes Russia as a potential exporter of hydrogen to the EU.

Note: (1) The supply model takes into account an extensive, yet limited, list of possible importing countries. There are other countries in the world with favorable sun and wind conditions, such as Chili and Namibia. The relevance of these countries is discussed in a qualitative manner in the description of the results of the supply modelling. Russia is not considered for imports to Europe

The hydrogen supply model makes use of different inputs and workflows and uses a dynamic optimization to find an economic optimum

Resource assessment

- Renewable energy technical potential in the region/countries under the scope
- Assessment of oil & gas industry trends defining gas availability and price for hydrogen production

Cost structure

- Production cost of hydrogen technologies
- hydrogen importing countries’ willingness to pay
- Domestic and international transport cost with a full set of hydrogen transport options
- Conversion, reconversion and terminal cost are also included

Hydrogen demand

- Domestic demand of exporting countries estimated using a top-down approach given the country-specific climate ambitions (as for the last NDC) as well as other exogeneous assumptions.

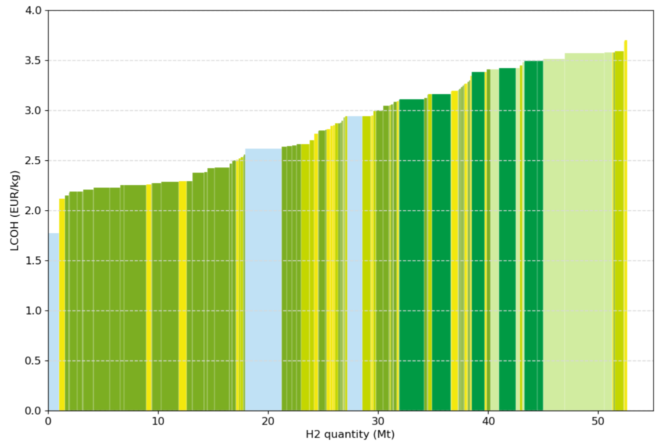
A cost optimization model

Least-cost hydrogen production and transport options with 5-year timestep, considering the whole delivery chain

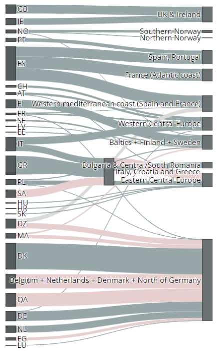
GAMS IBM CPLEX

Model outcome examples

- Merit-order curve



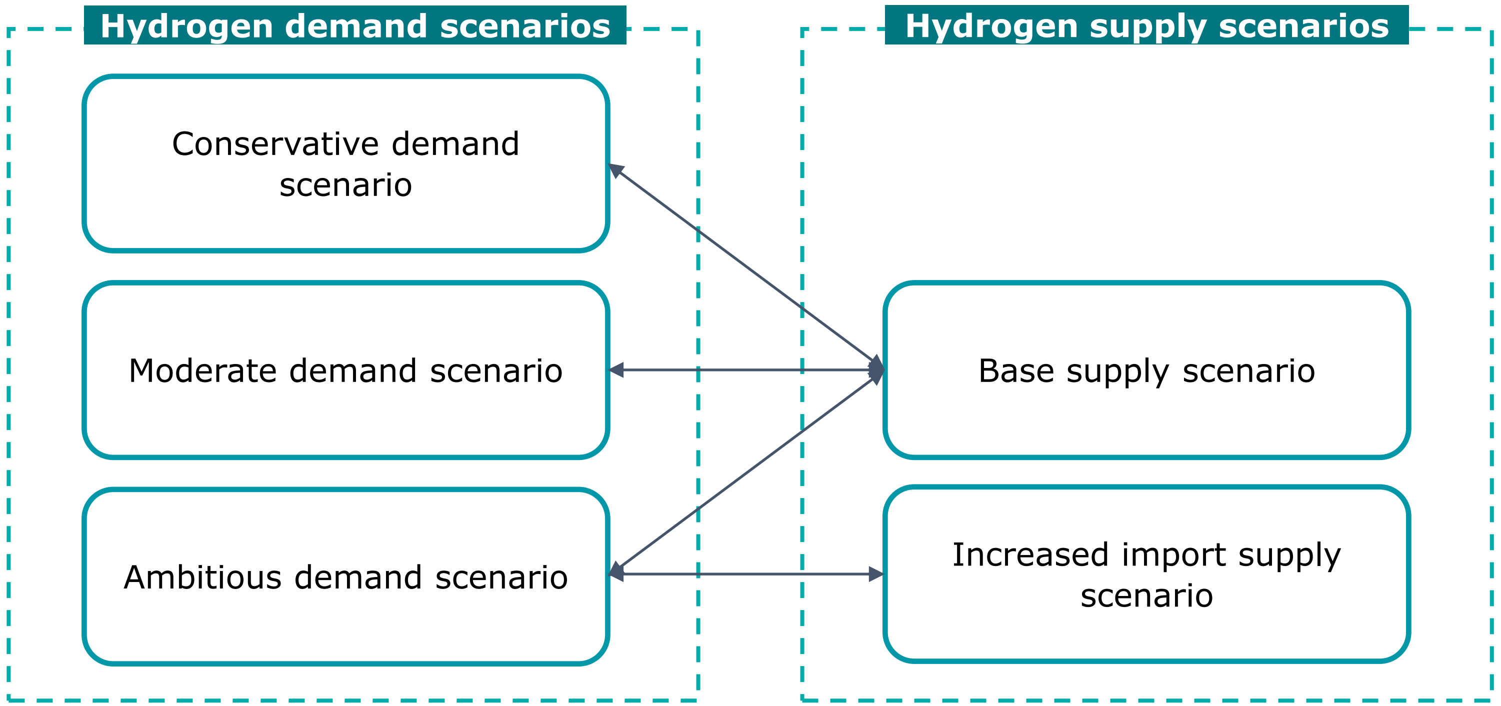
- Hydrogen flow network



Disclaimer: Results (choice of technologies, importing/exporting routes, etc.) come from a cost-optimization model that doesn’t consider political nor non-economical behaviors.

Hydrogen supply is calculated for all demand scenarios and on top, for the ambitious scenario, an alternative increased import supply scenario is set up

- The hydrogen supply model calculates the economic optimum for **all three hydrogen demand scenarios**, i.e., the conservative, moderate and ambitious scenarios. From a supply perspective this outcome is considered as the **base supply scenario**.
- In consultation with the Advisory Board members, the **timely and substantial deployment of local EU renewables for hydrogen production**, on top of what is required for direct electrification purposes, is identified as one of the **largest uncertainties**[1]. Hence an alternative scenario, referred to as **increased import supply scenario**, is set up to reflect the impact / sensitivity of this constraint on the potential hydrogen supply. In this scenario, the deployment of renewables in the EU is more moderate. Given the recent evolutions (e.g., REPowerEU initiative) the ambitious scenario is considered as the hydrogen demand scenario which should be strived towards, thus the increased import scenario is run for the ambitious scenario.



Note: (1) Limiting factors can be permitting, not-in-my-backyard, etc.

Model assumptions

Several assumptions are taken regarding the renewable hydrogen potential from PV and wind with electrolysers

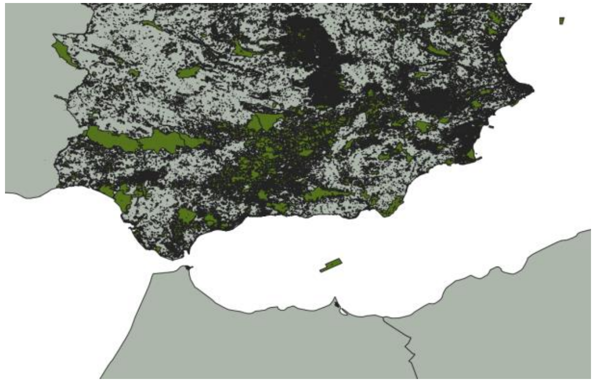
Renewable potential depends on local factors

Methodology[1,2]

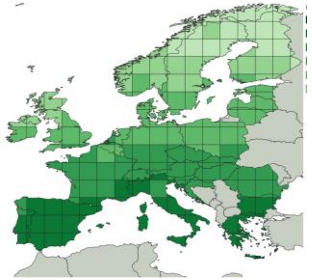
- The entire geographical scope has been divided in cells of 2.5° where wind speeds and solar irradiation data were collected (using 2016 as the historical year).
- For each country, the available land-use has been estimated, excluding notably residential and industrial areas, national park or bodies of water.
- The technical renewable energy potential is used to estimate the renewable hydrogen production potential. For hydrogen exporting countries, we only considered cells within 1,000 km maximal distance to prospected hydrogen international exit point (terminal or pipeline) due to national transport costs and energy losses.
- For European local hydrogen production, we considered that hydrogen is transported via pipelines between clusters, assuming the realization of a European hydrogen backbone[3].
- Electricity from renewable resources evolution in Europe (excl. hydrogen production) is subtracted from technical renewable energy potential[4] (based on TYNDP analysis).
- For the base scenario, the local EU deployment rate of renewables is set at 10%/year, which is not prohibitive for the deployment of renewables for hydrogen production (within limits of the technical potential). For the increased import scenario, this deployment rate is reduced to 5%/year to reflect potential difficulties in a timely and substantial rollout.
- Results were cross validated for European countries[5] and international potential estimates[6].

Assumptions

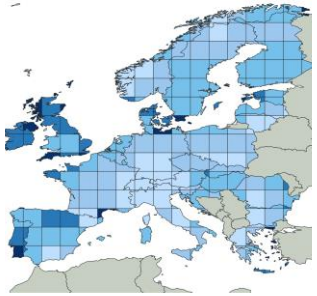
- Calculations are made on hub height (130m) using real power curve data of turbine models.
- Both PV tilt angle and electrolyser capacity are optimized in each location.
- We assumed 85 MW/km^2 power density for PV with 3% of land available (ENSPRESSO).
- We assumed 10 MW/km^2 power density for Onshore wind with 5% of land availability.
- We took ENSPRESSO's estimation for Offshore wind (fixed and floating) technical potential of low-restriction scenario.



Land use in Spain
Source: Geofabrik and OSM



PV LCOH 2050
Source: Deloitte – hydrogen for Europe study



Onshore wind LCOH 2050
Source: Deloitte – hydrogen for Europe study

Sources: (1) Ruiz et al. (2019). (2) Milbrandt and Mann (2007). (3) Guidehouse, *European hydrogen backbone – Analysing future demand, supply, and transport of hydrogen*, 2021. (4) Based on TYNDP analysis. (5) EC JRC, 2019. (6) NREL, 2019

The production potential for low-carbon hydrogen from methane does not depend on the topology but on the availability and price of natural gas

Production potential of low-carbon hydrogen

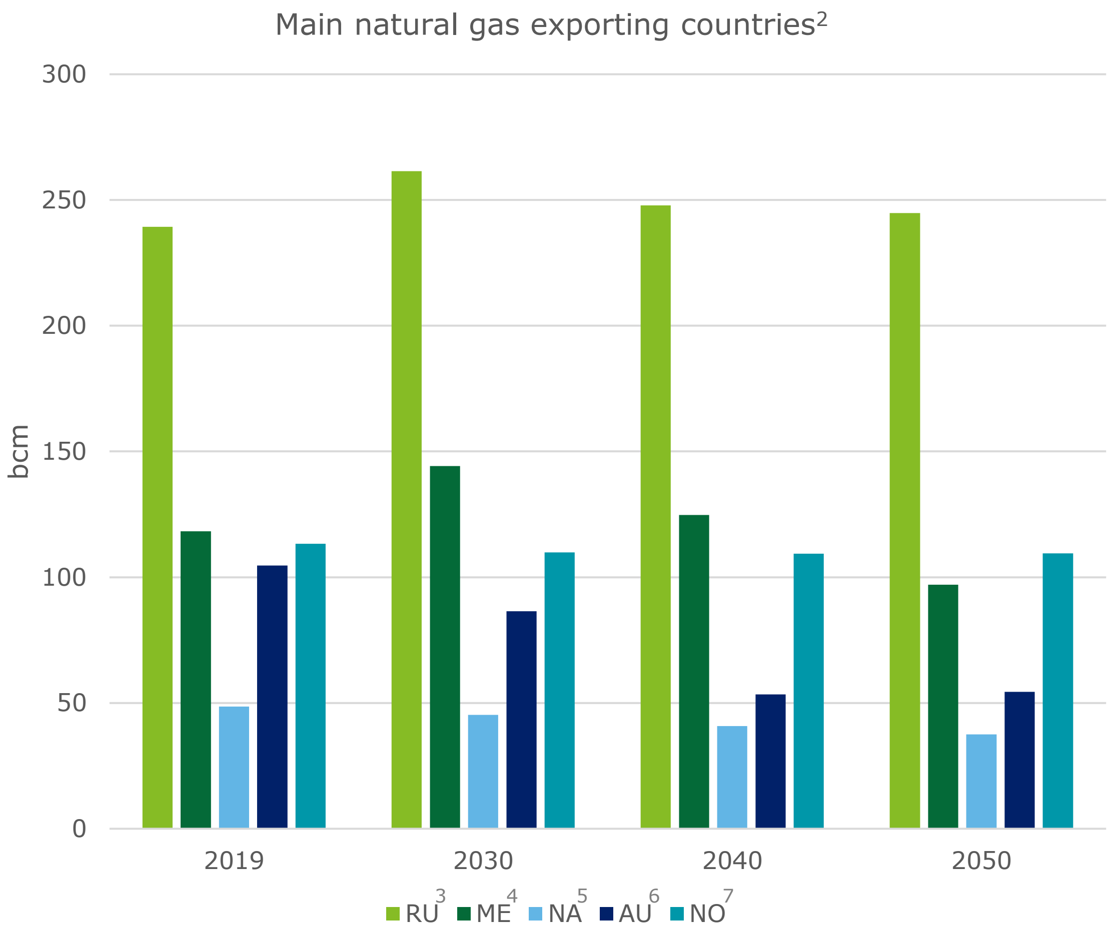
Only natural gas (NG) exporting countries are considered as possible exporters of abated NG-based low-carbon hydrogen. Given that NG infrastructure is well developed in these countries, blue hydrogen production facilities are assumed to be installed near the hydrogen exporting terminal location to avoid additional transport costs.

Technologies Considered

- Reforming technologies with CCS: Steam methane reforming (SMR), Autothermal reforming (ATR) and Gas heating reforming (GHR). Estimates of CO_2 storage potential are included.
- Methane pyrolysis (co-product revenues from carbon black are included).

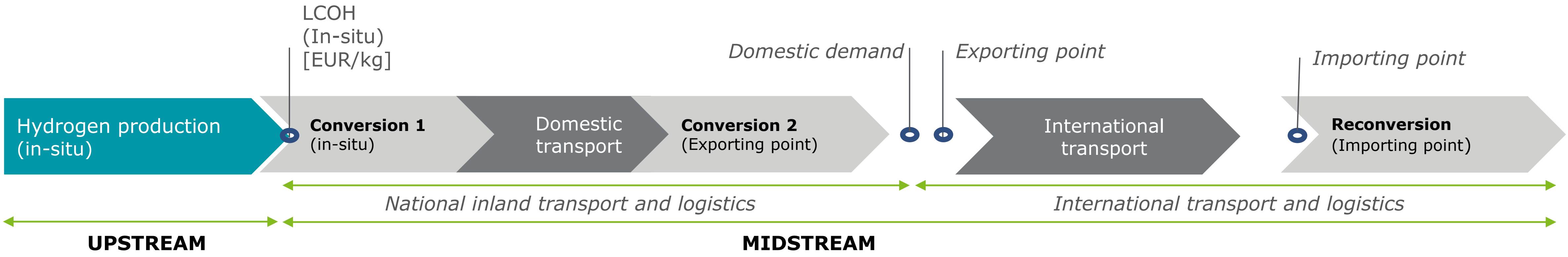
Assumptions

- Gas production growth has been estimated based on historical data and proven reserves.
- Domestic gas consumption, export and import have been estimated using forecast studies from the IEA, BP and GECF outlooks.
- When calculating blue hydrogen LCOH, a cost add-up on a CO_2 price trajectory has been assumed: linear trajectory from 50\$/tCO_2 up to 250\$/tCO_2 in 2050[1].
- The model optimizes natural gas usage for blue hydrogen production.



Sources and notes: (1) Based on IEA, 2021. (2) Deloitte EA analysis. (3) Russia. (4) Middle East. (5) North Africa. (6) Australia. (7) Norway

LCOH cost structure: the hydrogen supply model finds the least-cost pathway by optimizing the whole hydrogen value chain



Transport

Transport cost includes:
- Fixed cost in EUR/kg hydrogen
- Variable cost in EUR/kg hydrogen/1000km
- Fuel cost for seaborne transport

In case of European domestic supply, a grid cost is considered instead of truck transport

Conversion

Conversion and reconversion cost includes:
- Fixed cost in EUR/kg hydrogen
- Electricity cost specific to the country where conversion and/or reconversion take place

These costs occur for Ammonia and liquified hydrogen transport

Production

hydrogen production cost includes:
- CAPEX, fixed and variable OPEX of each technology
- Efficiency gains and cost reduction over years

For blue and turquoise hydrogen, commodities prices, CO_2 transport, and storage cost and non-abated CO_2 price are considered

Terminal

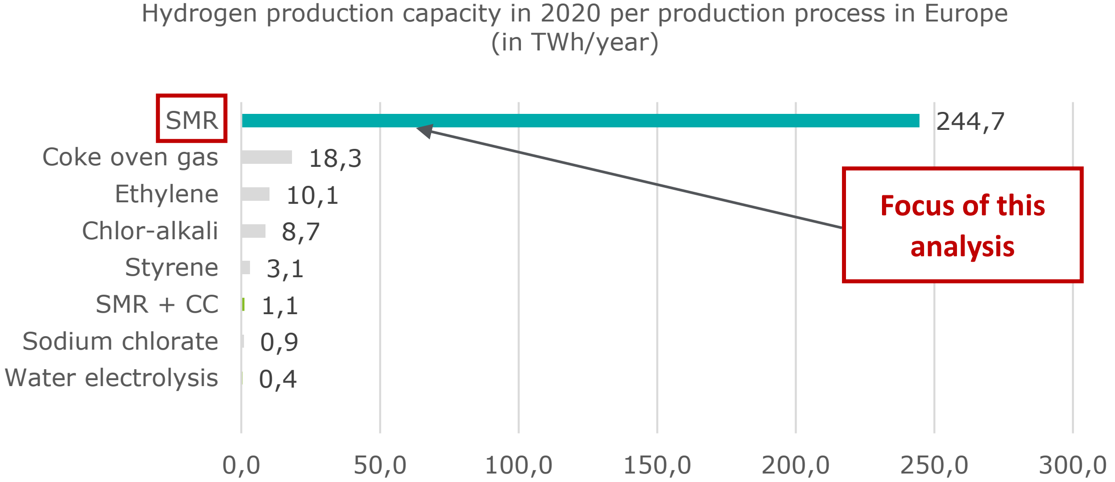
Import and export terminal costs depend on the form in which hydrogen is stored (ammonia, gaseous or liquified hydrogen) and includes:
- Storage cost in EUR/kg hydrogen
- Electricity cost specific to the country in which hydrogen will be stored whether for export or import

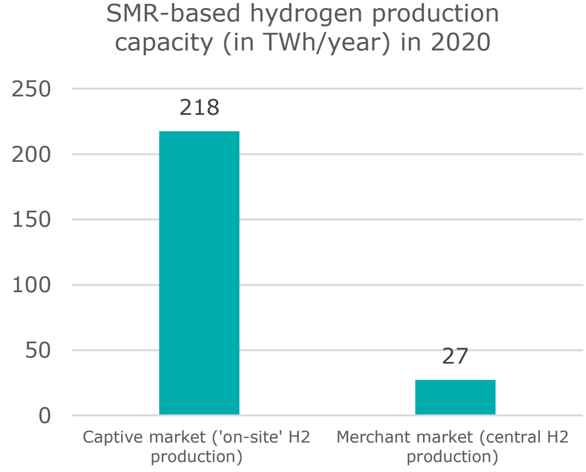
Sources: IEA, JRC, Deloitte EA, WBG, TYNDP and others

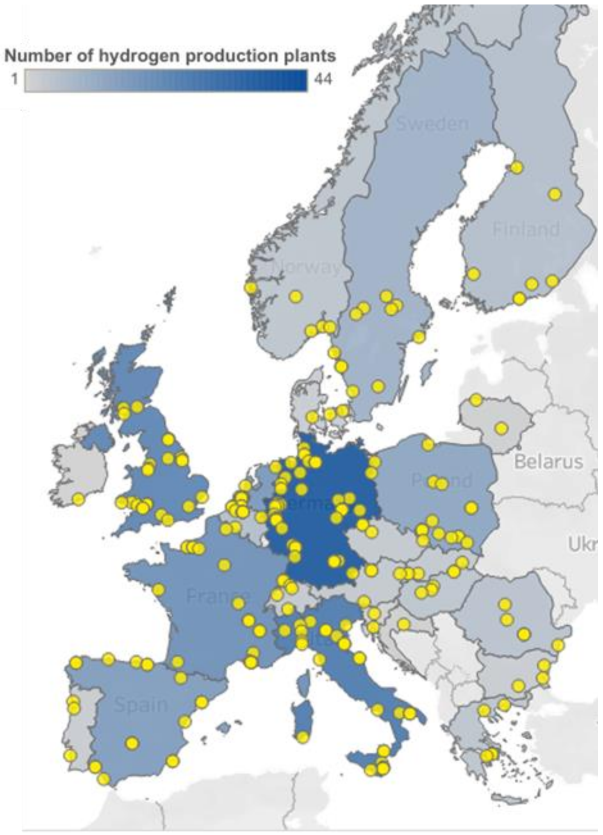
Assumption on split between existing and new supply

Assessment of the current hydrogen supply capacity in Europe – focus on hydrogen produced in Steam Methane Reforming (SMR) plants

In 2020, **251 SMR plants** with a **total grey hydrogen production capacity of 245 TWh (7.35 Mt)** were scattered across Europe[1]. In parallel, about **41 TWh of hydrogen** (14% of total EU production) **were produced as by-products** of various industrial and chemical processes[2]. Blue (1.1 TWh) and green (0.4 TWh) hydrogen accounted for only 0.5% of total hydrogen production in Europe.

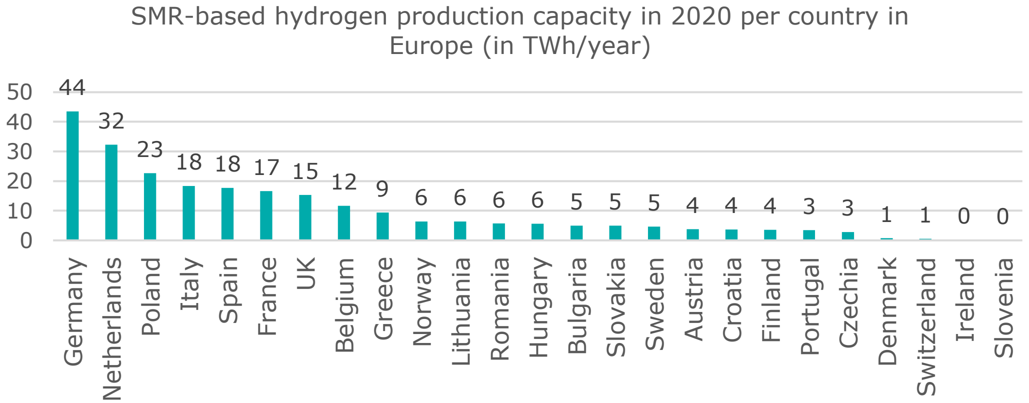






European SMR plants in 2020

- In 2020, **more than 99%** of the 245 TWh of hydrogen production capacity (excl. hydrogen produced as a by-product) in Europe **was grey hydrogen**.
- Within this production, **most hydrogen production capacity (89%) is on-site** (mainly in refineries, ammonia & methanol plants), so called **captive market**, with the remaining capacity (11%) from central hydrogen production.
- Overall, only **6 countries, namely** Germany (18%, the Netherlands (13%), Poland (9%), Italy (7%), Spain (7%) and France (7%) **account for 2/3rd of European SMR-based hydrogen production capacity**.



Sources and notes: (1) Fuel Cells and Hydrogen Observatory, 2022; (2) Hydrogen is produced as a "by-product" in the following industrial/chemical processes: Coke oven gas, Ethylene, Chlor-alkali (in 58% of the production), Styrene and Sodium chlorate. By-product hydrogen is out of the scope of this study.

Production of blue hydrogen in Europe faces strong political, regulatory, economic and technological barriers, limiting its development outlook

Due to the below mentioned policy, regulatory, economic and technological barriers, **the study assumes a limited role of European blue hydrogen production**.

- In the proposal for a recast **Renewable Energy Directive** (RED III), blue hydrogen is not recognized as contributing to the goal of 50% low carbon/renewable hydrogen in total hydrogen used for energy and non-energy end uses in industry by 2030.
- The **REPowerEU communication** sets ambitious roadmaps for reducing natural gas consumption in the EU. This major policy shift leads to disregarding the rollout of blue hydrogen production in Europe and upholds a bold political will to focus exclusively on the scale-up of green hydrogen production and imports.
- Carbon capture and storage (CCS) technologies today faces strong **regulatory and political acceptance constraints** in most of the EU Member States, limiting the rollout of public subsidies schemes in support of blue hydrogen production.
- In an economic environment characterized by **high natural gas** and **carbon prices** on European market, and with **little or no public subsidies** for the development of blue hydrogen production projects in most European countries, it can be expected that blue hydrogen will encounter stiff competition from alternative decarbonization solutions (i.e., electrification, biomethane), from large-scale European green hydrogen projects and from hydrogen imports, therefore limiting large-scale deployment perspectives.
- Due to high **uncertainties in the capture rate of CCS** technologies for hydrogen production and the risks of **methane leakage** from natural gas during exploration and transportation, blue hydrogen can only play a transitional role in contributing to the EU's 2050 net-zero goal, **challenging the long-term** (up to 25 years) **economic viability** of blue hydrogen projects.

EU announces 'full switch' of existing grey hydrogen production to green H2, backed by carbon contracts

Long-awaited REPowerEU plan unveiled with host of renewable H2 measures to help wean Europe off Russian gas

18 May 2022 11:56 GMT UPDATED 18 May 2022 13:28 GMT

By Leigh Collins

Home / News / Energy & Environment / Energy / German government disavows blue hydrogen

German government disavows blue hydrogen

By Nikolaus J. Kurmayer | EURACTIV.com 17 janv. 2022 (updated: 18 janv. 2022)

Blue hydrogen for Europe died on Feb 24, where to for green?

Cheap, secure, and renewable – Europe bets on green hydrogen to fix energy woes

Share

March 21, 2022

As the cost of blue and gray hydrogen surge in line with rising fossil fuel prices, the feasibility of green hydrogen as an affordable and secure source of renewable energy in Europe is growing, Rystad Energy research predicts.

Sustainable Energy & Fuels

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Cite this: *Sustainable Energy Fuels*, 2022, 6, 66

On the climate impacts of blue hydrogen production

Christian Bauer,[a] Karin Treyer,[a] Cristina Antonini,[b] Joule Bergerson,[c] Matteo Gazzani,[d] Emre Gencer,[e] Jon Gibbins,[f] Marco Mazzotti,[b] Sean T. McCoy,[c] Russell McKenna,[g] Robert Pietzcker,[h] Arvind P. Ravikumar,[i] Matteo C. Romano,[j] Falko Ueckerdt,[h] Jaap Vente[k] and Mijndert van der Spek*[l]

Natural gas based hydrogen production with carbon capture and storage is referred to as *blue hydrogen*. If substantial amounts of CO_2 from natural gas reforming are captured and permanently stored, such hydrogen could be a low-carbon energy carrier. However, recent research raises questions about the effective climate impacts of blue hydrogen from a life cycle perspective. Our analysis sheds light on the relevant issues and provides a balanced perspective on the impacts on climate change associated with blue hydrogen. We show that such impacts may indeed vary over large ranges and depend on only a few key parameters: the methane emission rate of the natural gas supply chain, the CO_2 removal rate at the hydrogen production plant, and the global warming metric applied. State-of-the-art reforming with high CO_2 capture rates combined with natural gas supply featuring low methane emissions does indeed allow for substantial reduction of greenhouse gas emissions compared to both conventional natural gas reforming and direct combustion of natural gas. Under such conditions, blue hydrogen *is* compatible with low-carbon economies and exhibits climate change impacts at the upper end of the range of those caused by hydrogen production from renewable-based electricity. However, neither current blue nor green hydrogen production pathways render fully "net-zero" hydrogen without additional CO_2 removal.

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rsc.li/sustainable-energy

'EU support for blue hydrogen would make it harder for Europe to wean itself off Russian gas'

Human rights group issues scathing assessment of plans to include H2 from fossil gas in the bloc's Renewable Energy Directive

6 May 2022 10:33 GMT UPDATED 6 May 2022 10:37 GMT

By Rachel Parkes

ELSEVIER

Energy Policy

Volume 167, August 2022, 113072

Is blue hydrogen a bridging technology? - The limits of a CO_2 price and the role of state-induced price components for green hydrogen production in Germany

Jan Frederick George[a,b], Viktor Paul Müller[a], Jenny Winkler[a], Mario Ragwitz[b,c]

Distinction between grey, on-site blue (retrofit), green and other blue hydrogen supply – Focus on existing supply

Existing supply

Grey hydrogen (H2)

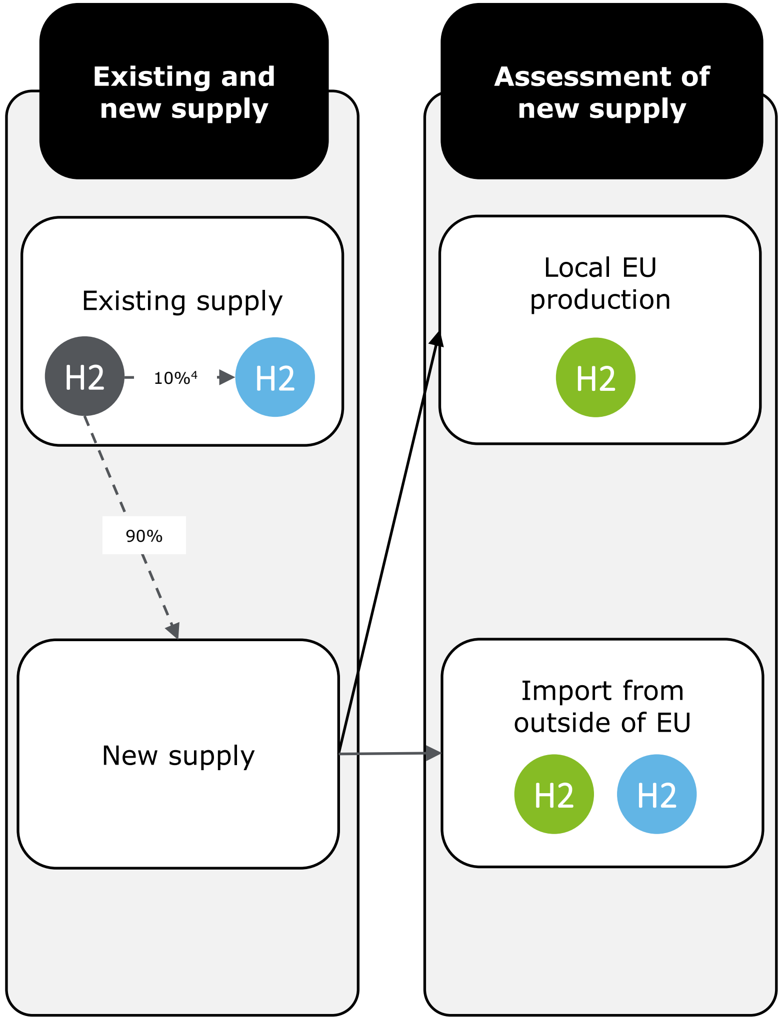
- In 2020, Europe produced about 245 TWh of grey hydrogen (by steam methane reforming - SMR), mainly for use as **feedstock** in three main production processes: **fossil fuel hydrogenation** in refineries, **ammonia** production and **methanol** production[1].
- Currently, within this production, **most hydrogen (89%) is produced on-site**, so called **captive market**, with the remaining production (11%) from central hydrogen production[1].
- In the future, the study assumes that the production of grey hydrogen in Europe will
  1. Remain bound to **the same industrial demand** as today;
  2. Be maintained at the **same production sites** as today; and
  3. Decrease over the next few decades and **reach zero in 2050**, in line with the long-term goal of a climate neutral European energy system.

In the **supply model of this study**, it is therefore necessary to **subtract** the future demand of grey hydrogen to prevent it from being counted as a demand that can be met by a future cross-border hydrogen market.

On-site blue hydrogen (retrofit) (H2)

- This study assumes that by 2050, **petroleum-based fuel refining** as well as **ammonia** (for fertilizers) **plants will remain at the same location as today.**
- Since blue hydrogen production only requires adding a CCS unit to existing SMR facilities – which are currently located at the refinery, ammonia and methanol plant site[2] - it is reasonable to assume that at least a part of the future supply of blue hydrogen will be produced **at the existing hydrogen production units**. The terminology **'on-site blue hydrogen'** is used in this study to describe this type of hydrogen.
- While blue hydrogen production is still in its nascent phase (0.3 TWh of blue hydrogen produced in EU+UK in 2020[1]), the study assumes that in 2030 and 2040, **10% of the current grey hydrogen** used as feedstock for **fossil fuel hydrogenation** in refineries[3] and **ammonia** production will be converted to **on-site blue hydrogen**. By 2050, **on-site blue hydrogen production is assumed to drop to zero**, in line with the goal of a climate neutral European energy system.

In the **supply model of this study**, it is therefore necessary to **subtract** the future demand of on-site blue hydrogen to prevent it from being counted as a demand that can be met by a future cross-border hydrogen market.



Note: (1) Fuel Cells and Hydrogen Observatory, 2022; (2) Blue hydrogen is not an option for methanol production since methanol synthesis does not only require hydrogen as an input, but also CO_2; (3) Except for the hydrogenation of fossil fuels in refineries in the Ambitious scenario, which assumes that green hydrogen constitutes the totality (100%) of hydrogen production by 2040; (4) Only in 2030 and 2040, since by 2050, on-site blue hydrogen production is assumed to drop to zero, in line with the goal of a climate neutral European energy system

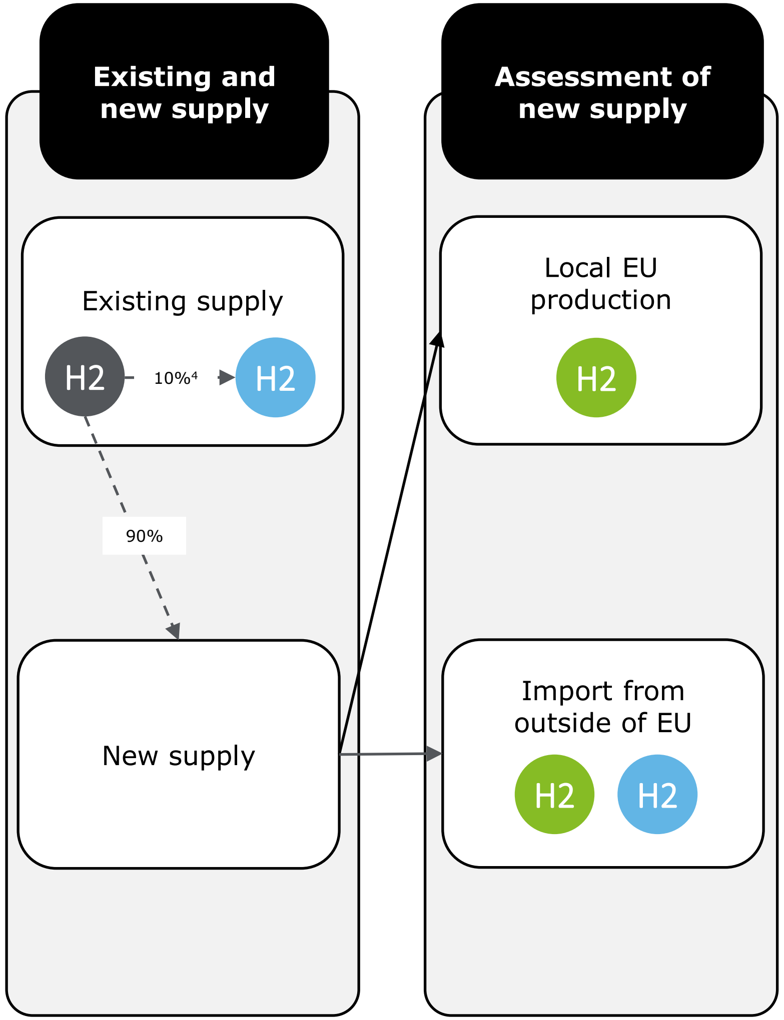
Distinction between grey, on-site blue (retrofit), green and other blue hydrogen supply – Focus on new supply

New supply

Green and other blue hydrogen H2 H2

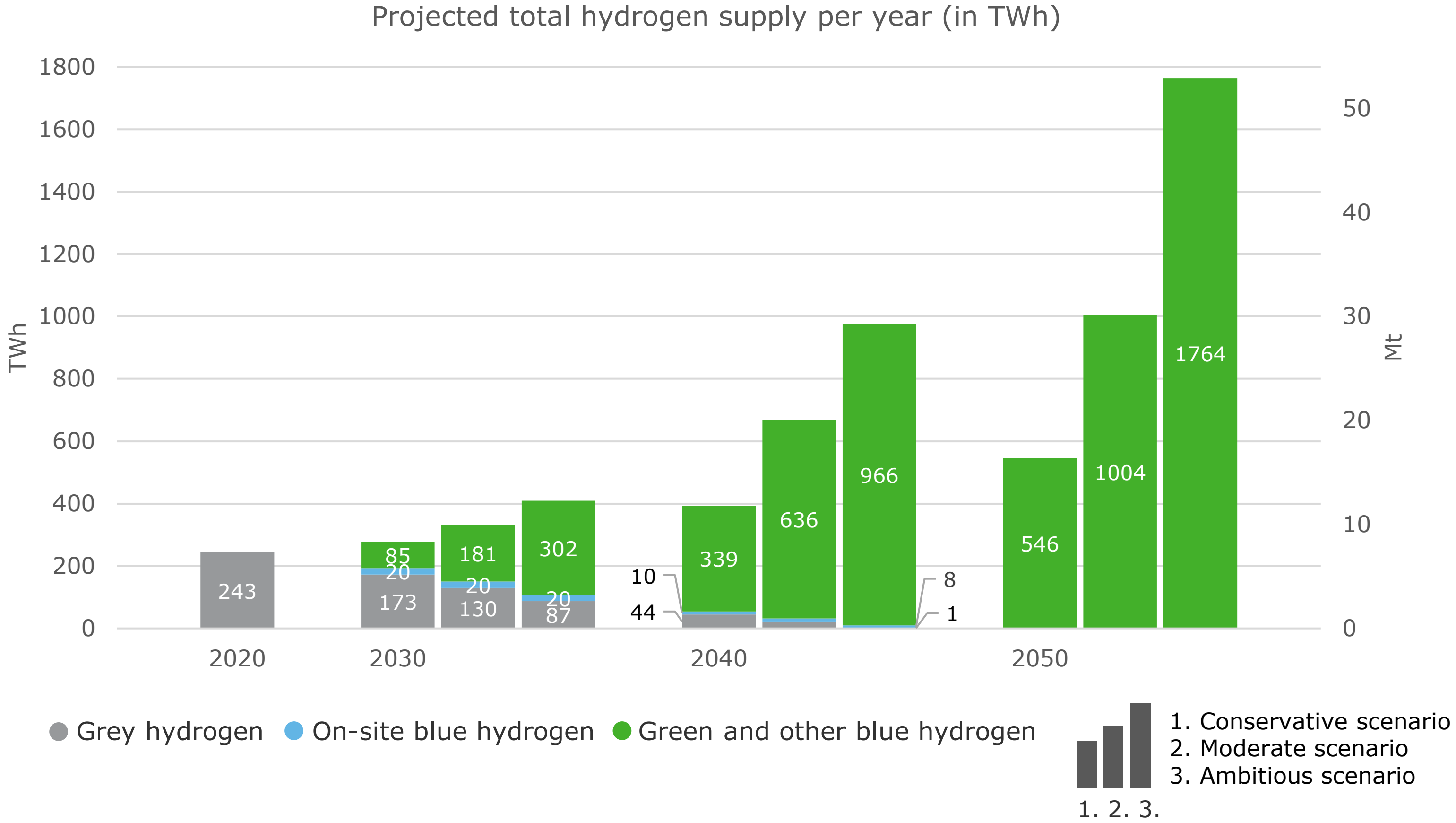
- Today, similar to blue hydrogen, green hydrogen projects are still in the demonstration phase (0.4 TWh of green hydrogen produced in EU+UK in 2020[1])
- The study assumes that, by 2040, **a large share** (i.e., ranging from 50% in the Conservative scenario to 100% in the Ambitious scenario) **of the current grey hydrogen** used as feedstock for **fossil fuel hydrogenation** in refineries[2] and **ammonia** production will be **substituted by green/blue hydrogen produced outside of existing on-site SMR facilities** and therefore subject to cross-border economic market forces. In all scenarios, this share is assumed to **reach 100% in 2050 at the latest** (complete phase out of European on-site blue hydrogen production is assumed).
- Over the same period, the study assumes that **100% of hydrogen feedstock and energy heat for new industrial applications** (primary steelmaking, industrial process heat and HVCs production) will be **supplied by green and/or blue hydrogen produced outside of current industrial plants**, either within or outside (imports) the EU+UK.
- Eventually, over the same period, the study assumes that **100% of hydrogen for new non-industrial applications** (i.e., transport, urban areas, port activities) will be supplied by green and other blue hydrogen produced either within or outside (imports) of the EU+UK.

Overall, the "Green and other blue hydrogen" supply category combines both green hydrogen production in Europe and green and blue hydrogen imported from outside Europe.



Note: (1) Fuel Cells and Hydrogen Observatory, 2022; (2) Except for the hydrogenation of fossil fuels in refineries in the Ambitious scenario, which assumes that green hydrogen constitutes the totality (100%) of hydrogen production by 2040.

Synthesis of the assessment of the overall grey, on-site blue and green and other blue hydrogen supply required per year from 2020 to 2050



This study assumes that, aside from refineries and ammonia production plants that will in part meet their decarbonized hydrogen needs by on-site blue hydrogen production, the **future demand for hydrogen in industries, transport, urban areas and port activities** from European countries will be met by **hydrogen subject to cross-border economic market forces.**

Synthesis of the scenarios:

- In this context, the results of our analysis show that, over time, the quantity of green and blue (excl. on-site) hydrogen that will need to be produced in or supplied to European countries are the following:
  - Between **85 and 302 TWh** (or 2.55 to 9.06 Mt) per year in 2030;
  - Between **339 and 966 TWh** (or 10.17 to 29 Mt) per year in 2040;
  - Between **546 and 1764 TWh** (or 16.38 to 52.92 Mt) per year in 2050.

Since only the "Green and other blue" category of hydrogen will be subject to cross-border economic market forces, the supply model in this study will therefore only consider future supply estimates that fall within the "Green and other blue" hydrogen category.

New supply projection

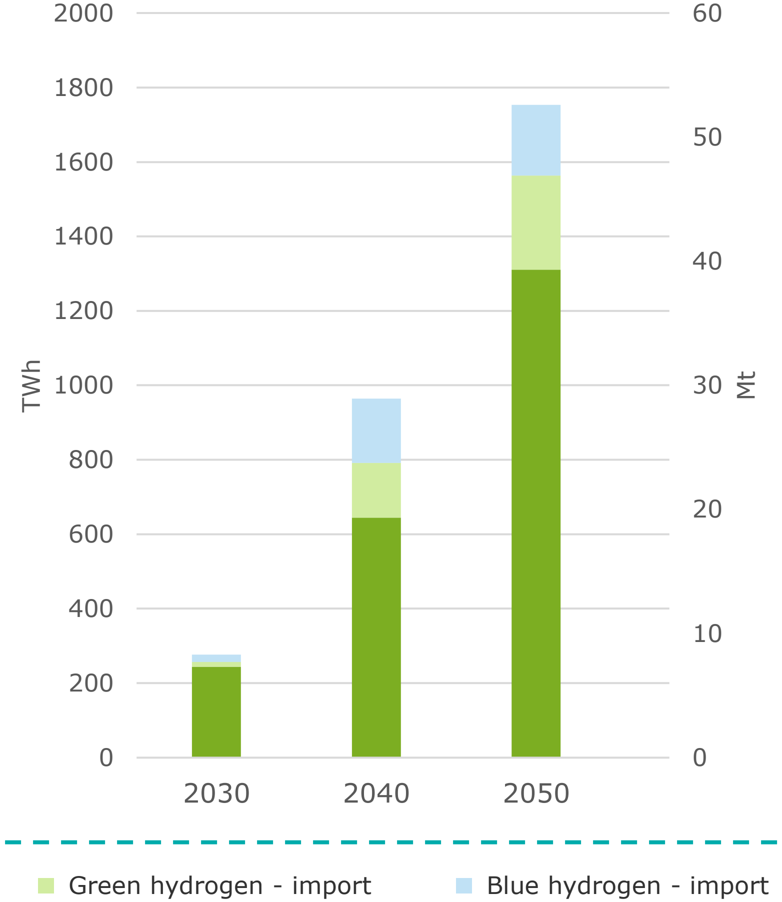
Comparison of base supply scenario with increased import supply scenario

The ambitious base scenario[1] evolves to a 75% - 25% split of local production vs. import of hydrogen by 2050, with important variation between clusters…

Local hydrogen production vs. import per cluster per type – base scenario in 2050

The circles on the map are located in the center of the relevant cluster

Local hydrogen production vs. hydrogen import



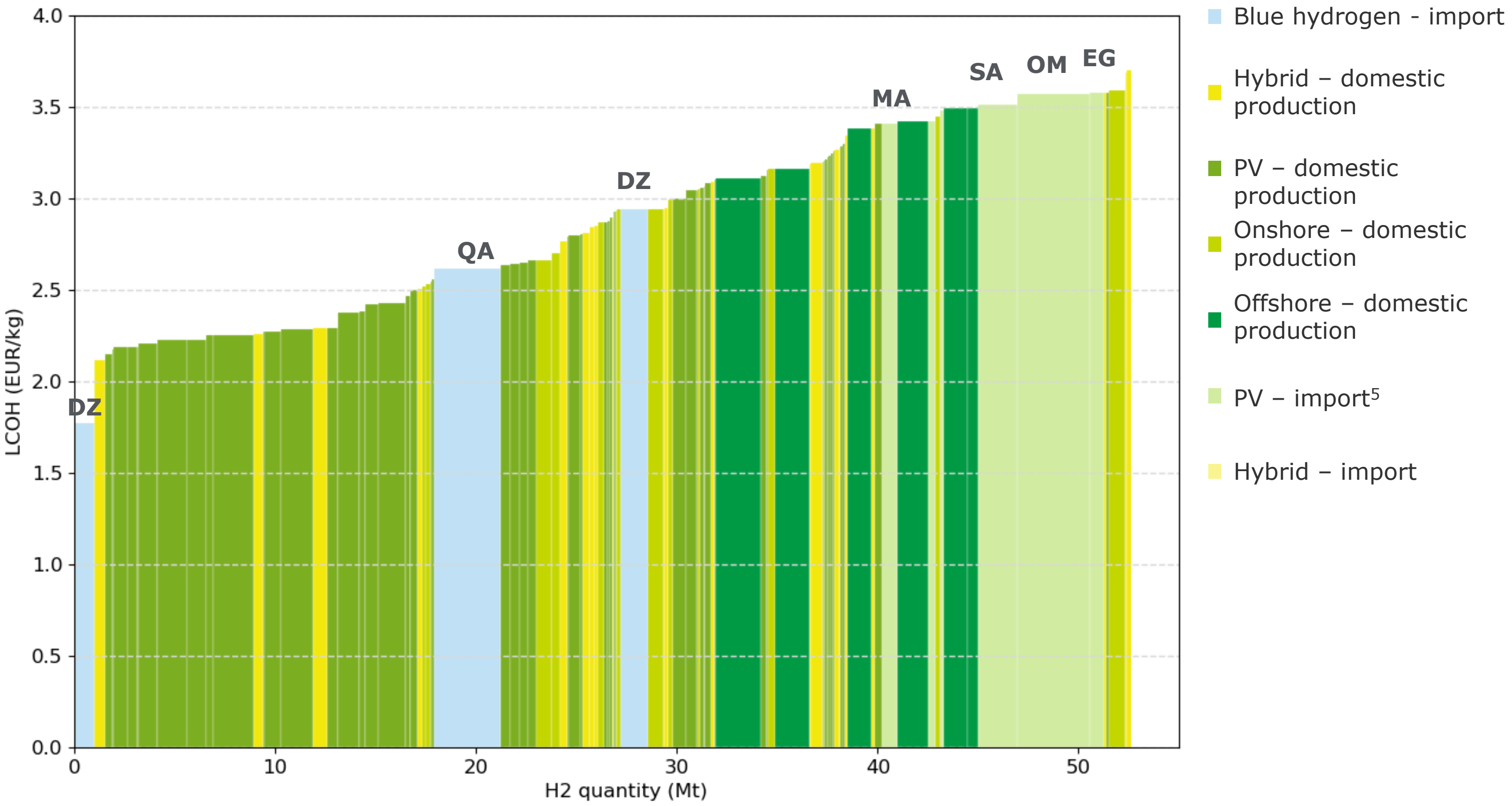
Key messages:

- In the ambitious **base scenario**, most of the hydrogen is projected to be supplied by local European production. Split **local production vs. import** is expected to be **75% - 25%** by 2050, while in 2030, imports are expected to be less than 10%.
- By 2050 the **majority of imported hydrogen is green** (60%) however the balance green vs. blue only sways to green after 2040.
- Most clusters rely almost completely on local European production for their hydrogen supply however, this is not the case for all clusters. The **largest demand cluster** *Belgium, Netherlands, Denmark and North of Germany* **relies for over 40% of its supply on import**, whereas the clusters *Western Mediterranean coast* and *Eastern Central Europe* rely for over 50% of their supply on import.

Note: (1) The ambitious scenario is the default demand scenario for which supply is matched, unless stated otherwise. (2) Turquoise hydrogen via pyrolysis was also considered an option in the model, however, LCOH was higher than for GHR and thus not an outcome of the model.

… for which the cheaper local production and blue imports are complemented with more expensive local production and green imports

Merit order curve hydrogen supply – base scenario in 2050



Key messages:

- **The LCOH range is 1.7 – 3.7 EUR/kg**
- **Local PV and hybrid systems** are the most cost-effective hydrogen sources and have the possibility to provide **at least 15 Mt of hydrogen** at a **cost lower than 2.5 EUR/kg**
- Further, local hydrogen supply is based on other onshore wind, PV and hybrid systems at a cost between 2,1 and 3,3 EUR/kg and **offshore wind** at a cost between **3 and 3.5 EUR/kg**
- **Blue hydrogen imports** are expected from Algeria and Qatar at a **cost below 3 EUR/kg**
- **Green hydrogen imports** are expected from Morocco, Oman, Saudi Arabia and Egypt at around **3.5 EUR/kg**. The hydrogen supply model assumes consumption of hydrogen, however in many cases the carrier used for transport, such as **ammonia**, can be used directly **without conversion to hydrogen**. Avoiding this conversion step makes the **import case significantly more competitive** (cost reduction of 0.4[2] to 0.8[3] EUR/kg) for sectors where direct offtake of these carriers is expected (e.g., shipping). We refer to ongoing initiatives such as HyPort Dugm or HyEx where ammonia will be imported from Oman and Chili, respectively.
- Finally, we note that the range of LCOH is relatively narrow and change in cost assumptions can cause reshuffling of the merit order curve.

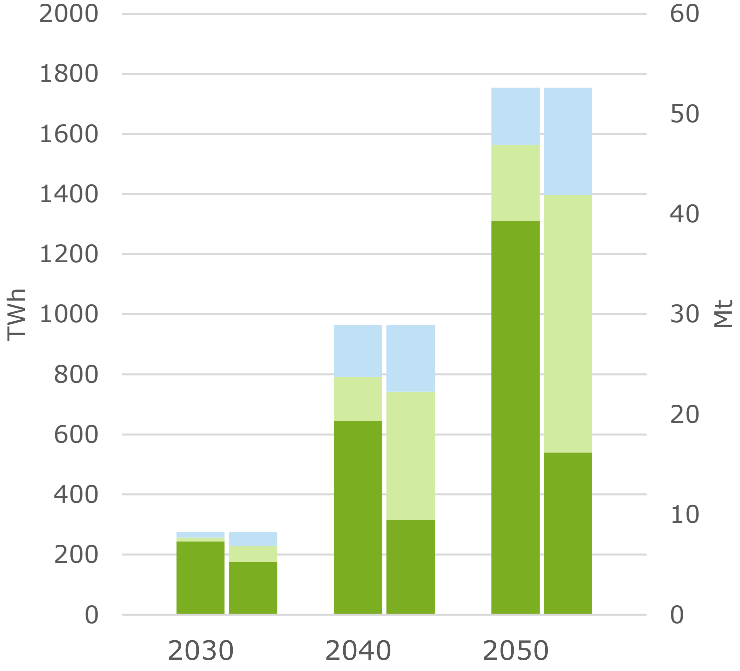
Note: (1) Hybrid systems: wind onshore + PV. (2) Hydrogen import coalition. (3) Own cost assumption, cf. appendix. (4) Merit order curve for the year 2030 can be found in Appendix II. (5) The results from the model show a large role for PV-based hydrogen import, linked to the high solar resource potential in regions such as North Africa and Middle East. However, it can be expected that some countries will also tap into their wind energy potential to complement their hydrogen production. Examples include Morocco or Chile, cf. IRENA, Global Atlas for renewable energy

In the increased import supply scenario, with constrained EU renewables deployment, there is a significant shift to 70% hydrogen imports …

Hydrogen local hydrogen production vs import per cluster per source – increased import supply scenario in 2050

The circles on the map are located in the center of the relevant cluster

Local European hydrogen production vs hydrogen import



The left bar in each year is the base scenario, while the right bar is the increased import scenario

Key messages:

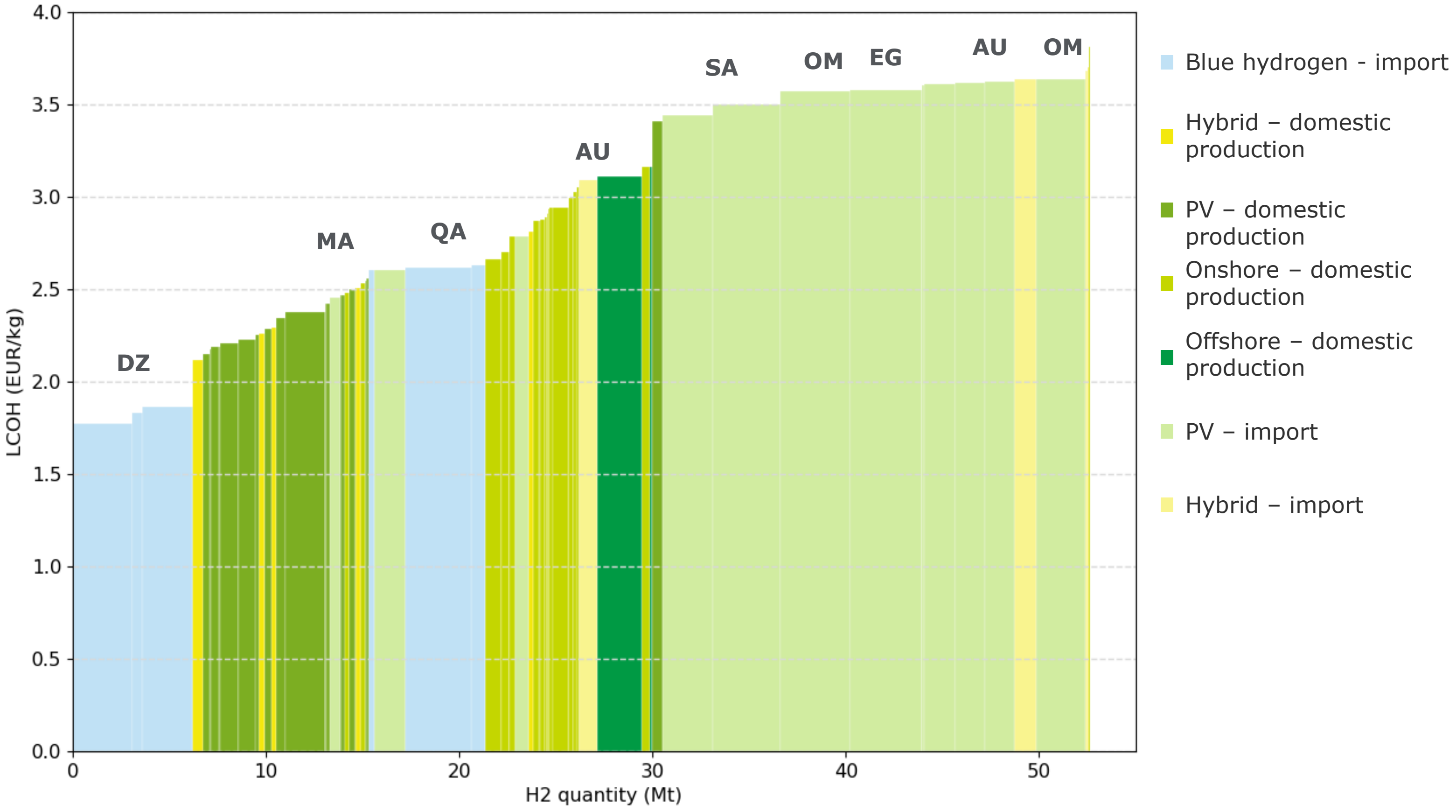
- In the **increased import supply scenario**, where local European renewables are expected to be deployed slower than in the base supply scenario, there is a significant shift from local European hydrogen production to more import. The split between **local production vs. import** is expected to be **30% - 70%** by 2050, in 2030, imports are expected to be already more than 35%.
- By 2050 the **imported hydrogen is predominantly green** (70%), this is already the case in 2030.
- A significant variety exists amongst clusters in split local production vs. import as well as the type of hydrogen imported.
- The **largest demand cluster** *Belgium, Netherlands, Denmark and North of Germany* **relies for about 80% of its supply on import**. Correspondingly, these countries are signing MoUs for hydrogen import[1].

Green hydrogen - domestic   Green hydrogen - import   Blue hydrogen - import

Note: (1) E.g., Belgium (or Belgian ports) are signing memorandums of understanding (MoUs) with Oman, Namibia and Chili; The Netherlands (or ports in the Netherlands) with the United Arab Emirates (Africa-focused); Germany with Australia

… for which Europe will need to significantly tap into more other foreign sources, mainly imports from North Africa and the Middle East

Merit order curve hydrogen supply – increased import scenario in 2050

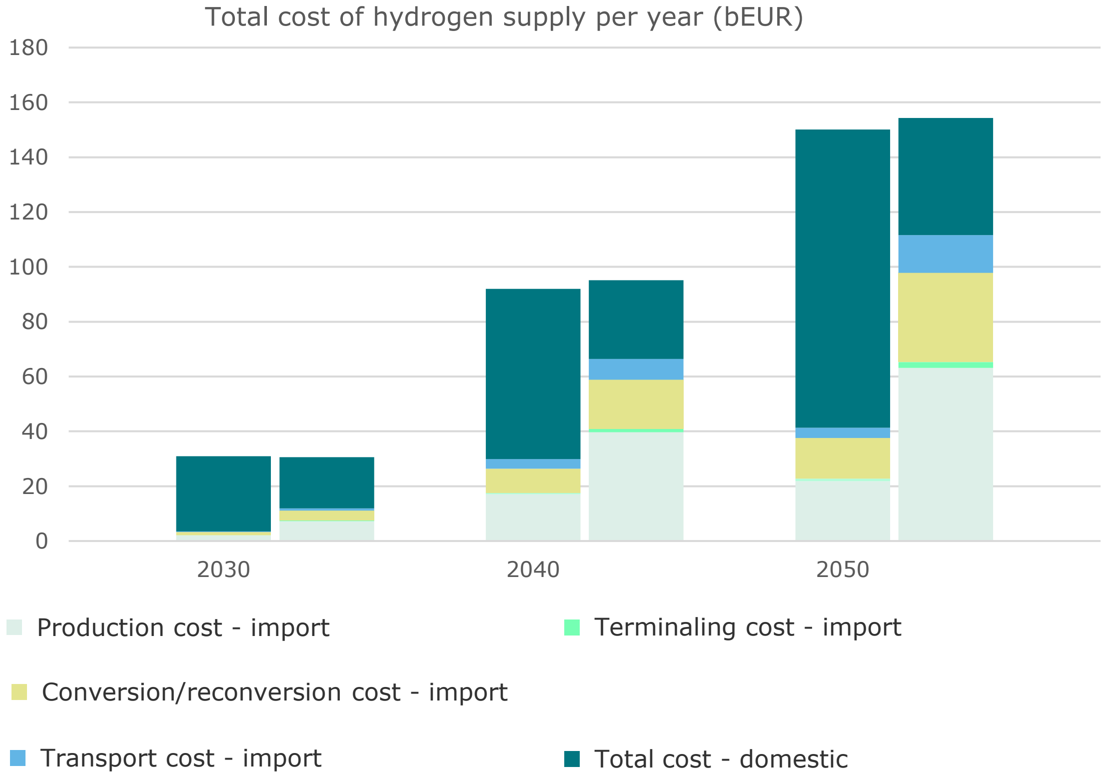


Key messages:

- **The LCOH range is 1.7 – 3.8 EUR/kg**
- Local hydrogen supply is coming from wind onshore, PV, hybrid and wind offshore systems. **Around 10 Mt** of green hydrogen is produced **locally at a cost lower than 2.5 EUR/kg**
- **Larger share of blue hydrogen** is imported from Algeria and Qatar at a cost below and around 2.5 EUR/kg.
- **More green hydrogen** is **imported from North Africa** (Morocco, Egypt), **Middle East** (Oman, Saudi Arabia) and even **Australia**. The **maximum LCOH of around 3.5 EUR/kg is similar to the base supply scenario but the ramp-up is much steeper** with plateaus of green imports.
- Note that other regions with favourable conditions for wind and sun such as Chili, Namibia and South Africa may supply to the global hydrogen market and become competitive, especially at increasing demand levels and depending on capacity factor, transport distance, local infrastructure, etc. At the projected hydrogen demand, the willingness-to-pay for hydrogen imported from outside of Europe is up to ~3.5 EUR/kg.
- The same remark with regards to the direct offtake of ammonia or methanol is valid here, favouring the import case for those use cases. This accounts for 15% of the demand, or 8 Mt.

Note: (1) Hybrid systems: wind onshore + solar PV. (2) Since an economic optimum is sought for the complete time period 2030 to 2050, the LCOH of imports per location cannot be directly compared between the scenarios in a certain year, rather all years should be taken into account when comparing the cost and quantity per location. (3) Merit order curve for the year 2030 can be found in Appendix II.

When more hydrogen is imported, overall costs only increase slightly, however other parameters such as energy dependency should be considered



The left bar in each year is the base scenario, while the right bar is the increased import scenario

Key messages:

- The **total costs of hydrogen supply per year do not differ significantly between both import scenarios**
- Having **more import means Europe's energy dependency increases**. In the increased import supply scenario, it will be important to **diversify import sources** to secure reliable supply of energy at competitive prices
- In the base supply scenario, domestic production is responsible for most of the supply cost
- In the increased import supply scenario, the largest contributor to the supply cost is the cost of import. Of the **import costs,** the **largest share** goes to **production cost** (57%), **followed by conversion/reconversion cost** (29%), **transport cost** (12%) and finally **terminal cost** (2%). When hydrogen is imported via ship, ammonia is preferred over liquefied hydrogen as a carrier. Not having to reconvert the ammonia to hydrogen could save costs and make import economically more attractive as explained earlier.
- This analysis shows total costs. The section on required infrastructure further on in this report discusses infrastructure investments related to local production and import such as renewables capacity, electrolysers, transport, reconversion and terminalling infrastructure, etc.

Note: (1) All cost assumptions can be found in Appendix II. (2) Carbon Border Adjustment Mechanism will also be applicable in the future for imported hydrogen. This will add to the supply cost, depending on the carbon footprint of the imported hydrogen.

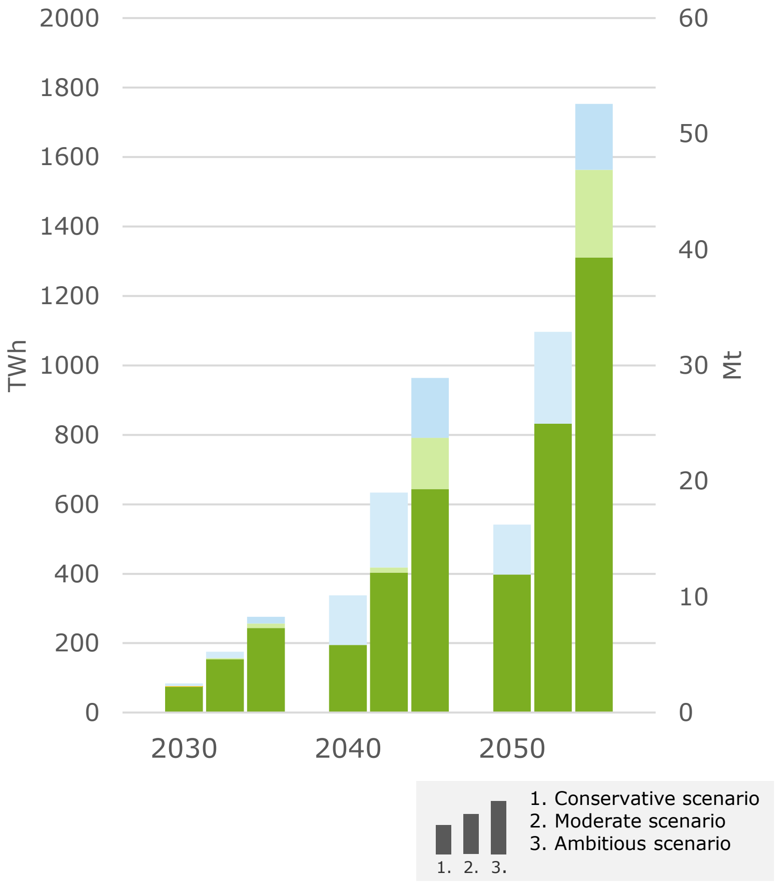
Comparison of all demand scenarios for the base supply scenario

When hydrogen demand is lower, in the conservative and moderate scenario, there is a shift from green to blue hydrogen import …

Hydrogen local hydrogen production vs import per cluster per source – moderate scenario in 2050

The circles on the map are located in the center of the relevant cluster

Local European hydrogen production vs hydrogen import



Key messages:

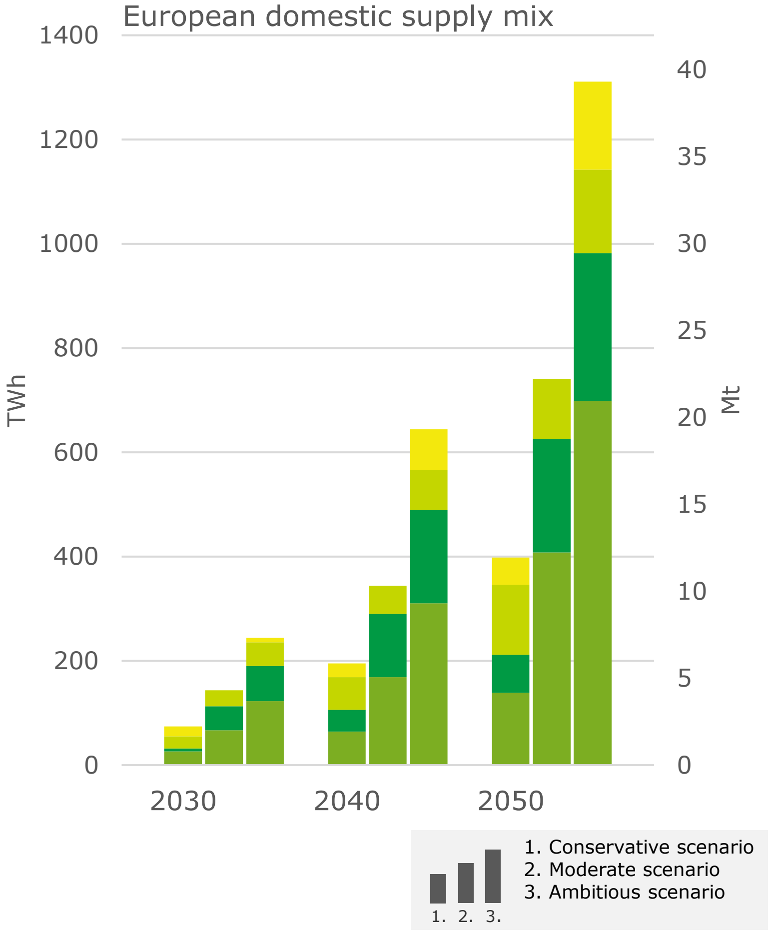
- The split local production vs. import remains about 75% - 25%, also for the moderate and conservative scenario.
- Both the **conservative** and **moderate scenario almost only show blue imports** and do no longer feature green imports.
- The projected share of local production versus import differs strongly between clusters and scenarios:
    - In the moderate scenario, only the cluster *Eastern Central Europe* has more than 50% import.
    - In the conservative scenario, the cluster *Italy, Croatia and Greece* and *Western Mediterranean coast (Spain and France)* have more than 50% import.

Green hydrogen - domestic
Green hydrogen - import
Blue hydrogen - import

… while also in these scenarios, PV based hydrogen accounts for largest share in European domestic supply mix, with important variation between clusters

Hydrogen local hydrogen production supply mix – ambitious scenario in 2050

The circles on the map are located in the center of the relevant cluster



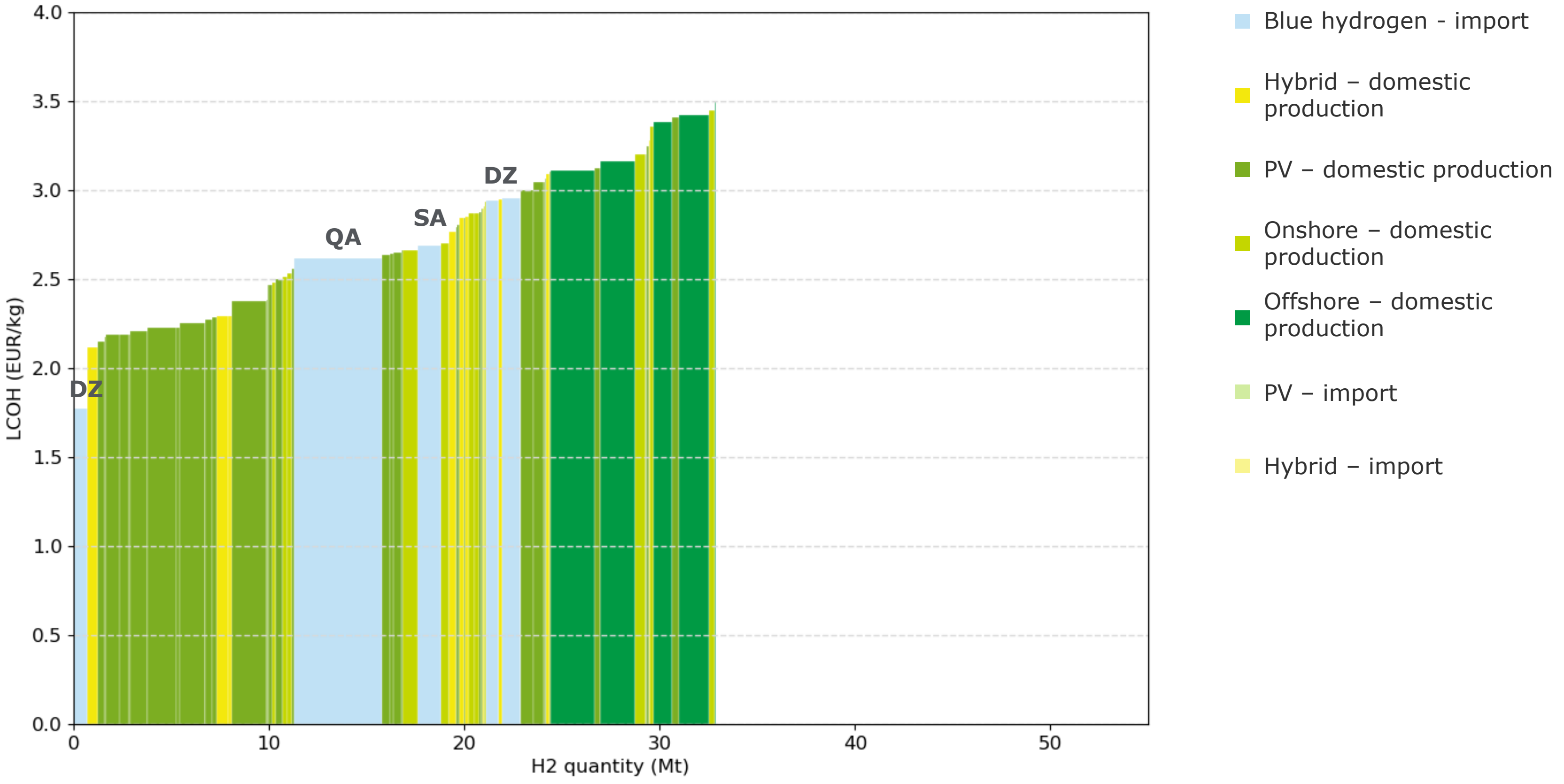
PV - domestic   Offshore wind - domestic   Onshore wind - domestic   Hybrid - domestic

Key messages:

- In 2050, it is projected that hydrogen produced from PV accounts for the largest share in European domestic hydrogen supply mix:
  - **140 – 700 TWh** from **PV**,
  - **200 – 440 TWh** from **wind**,
  - **50 – 170 TWh** from **hybrid** systems
- The **domestic supply mix varies strongly between the different clusters**. In the southern clusters, there is more solar PV, while in the northern clusters there is more wind energy available
- Only in the cluster *Belgium, Netherlands, Denmark and North of Germany*, there is offshore wind energy used to produce hydrogen. This energy is transported to Germany, Denmark and the Netherlands

When hydrogen demand is about 34 Mt, around 10 Mt of green hydrogen could be produced locally at a cost lower than 2.5 EUR/kg

Merit order curve hydrogen supply – moderate scenario in 2050



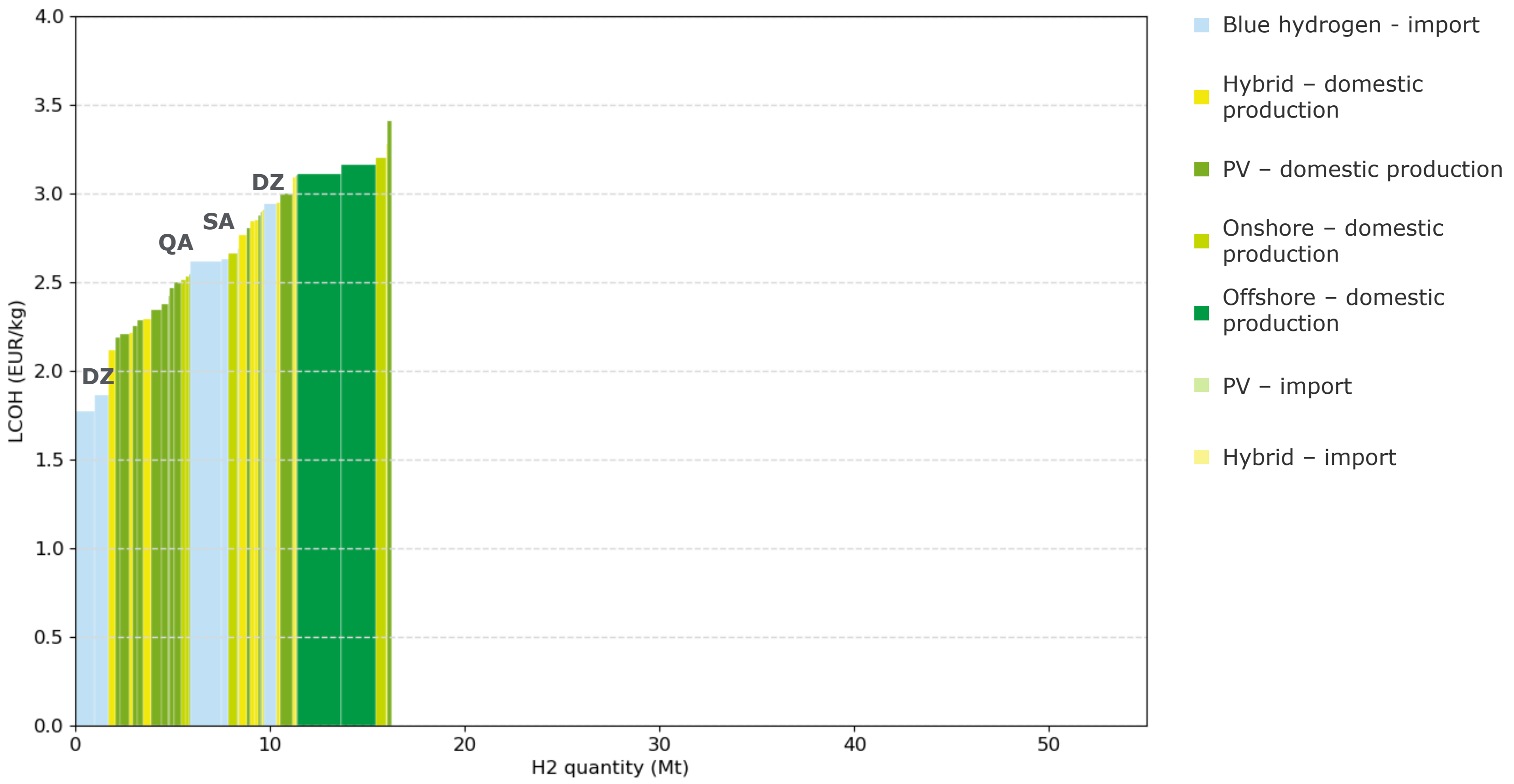
Key messages:

- The LCOH range is 1.8 – 3.5 EUR/kg
- Blue hydrogen is imported from Algeria, Saudi Arabia and Qatar. There is no green hydrogen import.
- Local hydrogen supply is mainly coming from PV and offshore systems, but also from wind onshore and systems
- Around 10 Mt of green hydrogen is produced locally at a cost lower than 2.5 EUR/kg

Note: (1) Hybrid systems: Wind onshore + Solar PV. (2) Merit order curve for the year 2030 and 2040 can be found in Appendix II

When hydrogen demand is about 17 Mt, around 5 Mt of green hydrogen could be produced locally at a cost lower than 2.5 EUR/kg

Merit order curve hydrogen supply – conservative scenario in 2050



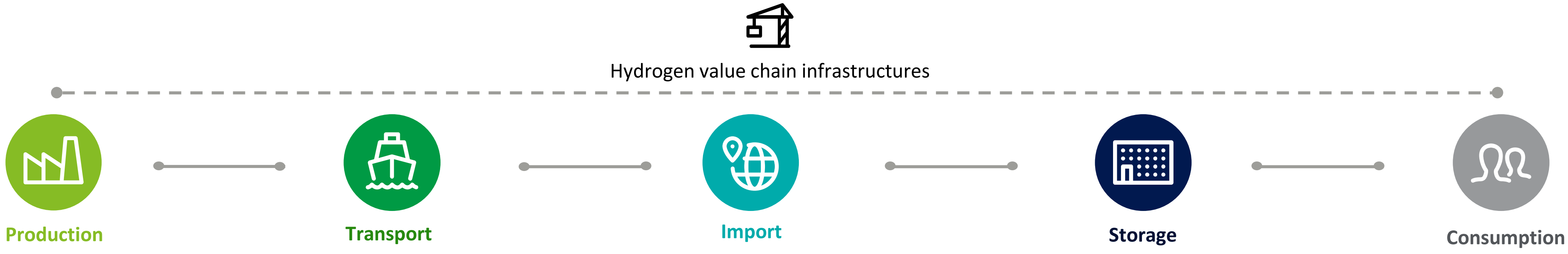
Key messages:

- The LCOH range is 1.8 – 3.4 EUR/kg
- Blue hydrogen is imported from Algeria, Saudi Arabia and Qatar. There is no green hydrogen import.
- Local hydrogen supply is mainly coming from PV and offshore systems, but also from wind onshore and systems
- Around 5 Mt of green hydrogen is produced locally at a cost lower than 2.5 EUR/kg

Note: (1) Hybrid systems: Wind onshore + Solar PV. (2) Depending on the hydrogen demand per cluster, some clusters with more interesting resources , i.e. with a lower LCOH, will produce less since there might not be enough demand to satisfy. This causes some differences between the various scenario's and the LCOH per source. In the PowerBI dashboards, more detailed info concerning the source and LCOH per cluster can be found. (3) Merit order curve for the year 2030 and 2040 can be found in Appendix II

Required hydrogen value chain infrastructure

The provision of hydrogen supply infrastructures is a prerequisite for hydrogen demand to take off



Production

- **Renewable hydrogen**:
  - electrolysers
  - Renewable electricity production
- **Low carbon hydrogen:**
  - SMR / ATR / GTR infrastructure
  - CCS/CCU infrastructure
  - Pyrolysis infrastructure

Transport

- **Pipelines (export/import/local):**
  - New dedicated hydrogen network
  - Existing gas network that has the potential to be retrofitted

Import

- **(Re)conversion infrastructure**
- **Import terminal**

Storage

- **Flexibility in system**: Flexibility provided by hydrogen pipelines, pressurized tanks, atmospheric tanks, liquefied tanks, compressed cylinders and storage at import terminals
- **Underground storage**: salt caverns, depleted fields and aquifers

Consumption

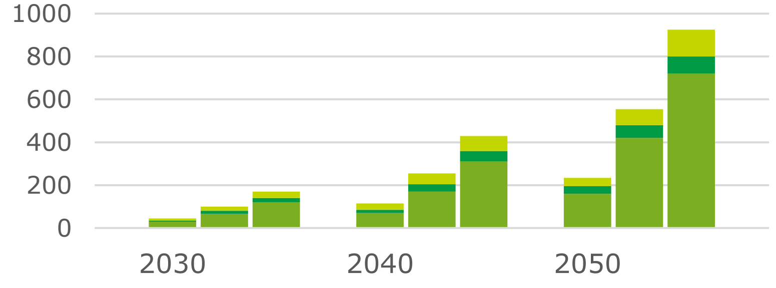
- **Industry:** industrial processes adopted to use hydrogen
- **Transport:** bunkering facilities, refueling stations and adapted ships/trucks
- **Port activities:** refueling stations and adapted machinery
- **Urban areas:** hydrogen heating technologies such as hydrogen boilers or fuel cells

Note: (1) A prerequisite for the development of hydrogen supply infrastructure at port areas is that there is space available. This was not assessed for the different ports in scope of the study.

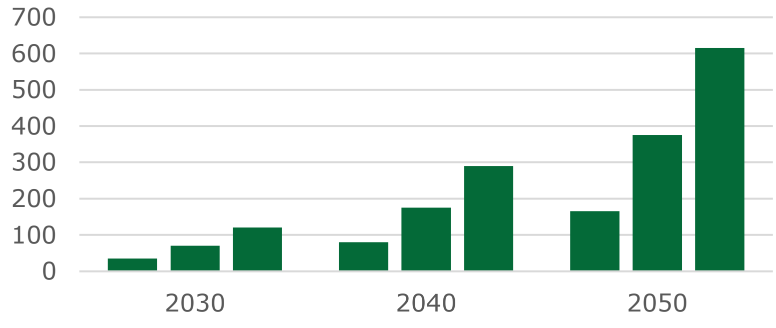
Solar PV in combination with electrolysis is projected to be requiring the highest capacity and investments

Required local production capacity

Required capacity renewable electricity production technology (GW)

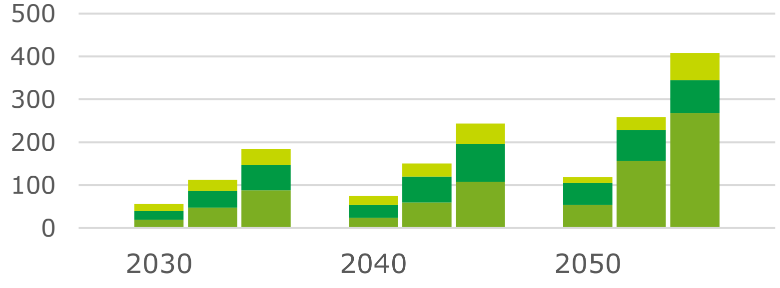


Required capacity electrolysers (GW)

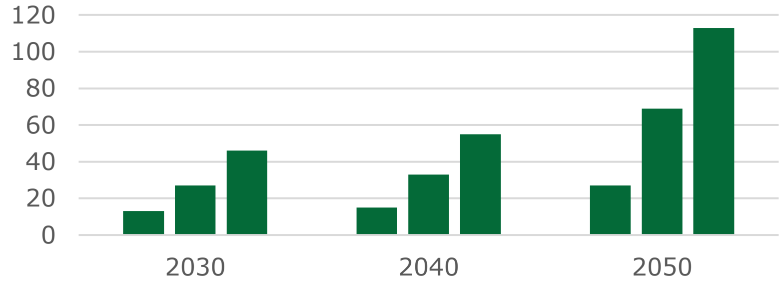


Required investments in local production capacity

Required total investment in renewable electricity production technology (bEUR)



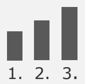
Required total investment in electrolysers (bEUR)



PV solar   Offshore wind   Onshore wind

Key messages:

- Total **capacities required** in 2050 for the different technologies are:
  - For PV: 160 – 720 GW
  - For offshore wind: 35 – 80 GW
  - For onshore wind: 40 – 125 GW
  - For electrolysers: 165 – 615 GW
- **Solar PV in combination with electrolysis** is projected to be the **most used technology** to locally produce hydrogen
- Compared to the required capacities, wind energy takes a larger share in the required investments. This is due to the **higher CAPEX price of wind installations**
- The investments are the total investments required in a certain year to provide the necessary capacities taking into account the lifetime of the technology and thus also reinvesting in technology if the lifetime has passed. *Changing value of money is not taken into account.*



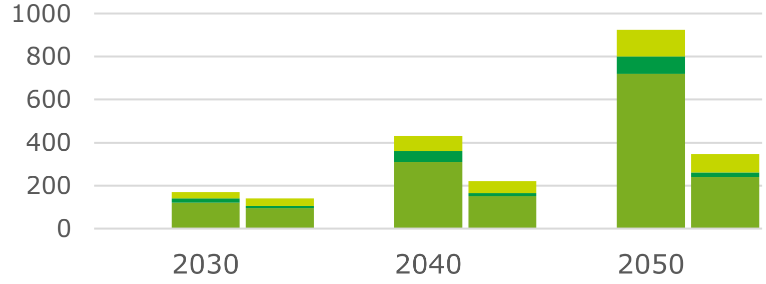
1. Conservative scenario
2. Moderate scenario
3. Ambitious scenario

Note: (1) All assumptions can be found in Appendix II. (2) In the model, RES installations are considered to be only dedicated for hydrogen production. Therefore, the sizing of electrolysers consists of an optimization problem to find the least-cost combination of components. In HyPE model, the capacity ratio is determined by minimizing LCOH in each location based on RES capacity factors, technologies' efficiencies and cost data. In such a set-up, the model calculates electrolysers' capacity to optimally produce hydrogen from renewable resources by mitigating intermittency problem.

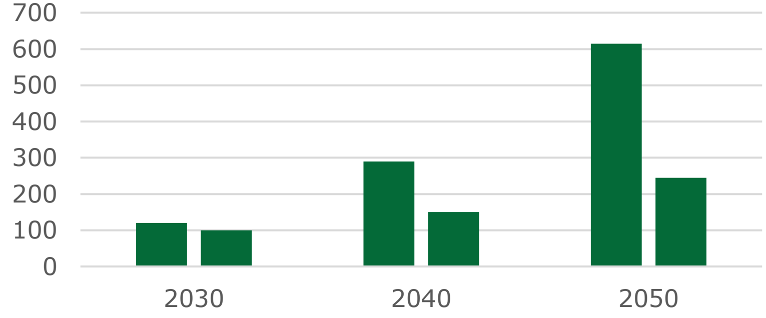
Required capacities and investments for local production technologies are almost 3x lower in the increased import supply scenario

Required local production capacity

Required capacity renewable electricity production technology (GW)

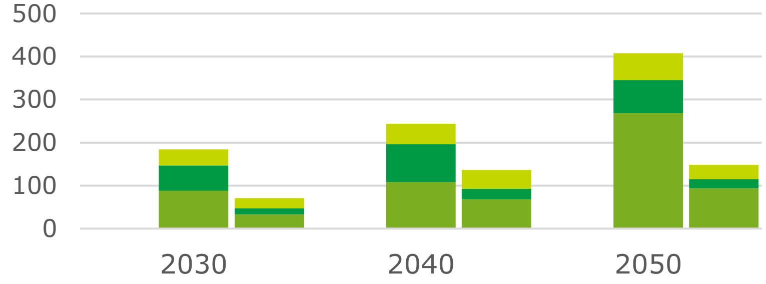


Required capacity electrolysers (GW)

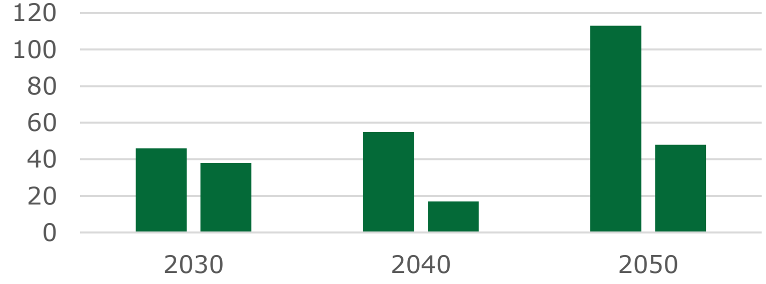


Required investments in local production capacity

Required total investment in renewable electricity production technology (bEUR)



Required total investment in electrolysers (bEUR)



Key messages:

- Since there is less local hydrogen production in the increased import scenario (only 40% of the total local hydrogen demand in the base scenario), there will be less local hydrogen production capacity required and related investments will be lower. In total, the **capacity required** for renewable electricity production is **almost 3x lower in the increased import supply scenario compared to the base supply scenario in 2050**. This is slightly lower than 40% due to the difference in cost of the various renewable electricity production methods. Also, the required electrolysis capacity is lower in the increased import scenario (~60% lower).
- Linked to required capacities, the required investments in local production technology for hydrogen are much lower in the increased import supply scenario

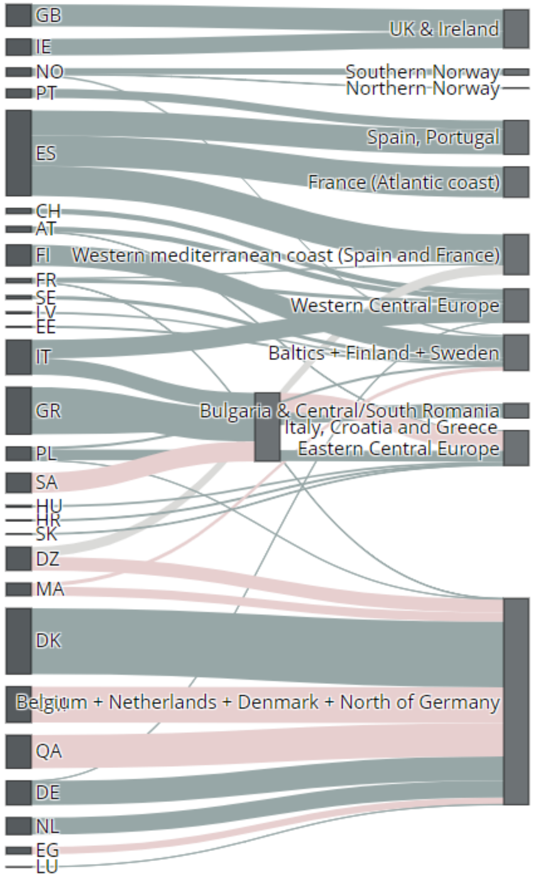
The left bar in each year is the base scenario, while the right bar is the increased import scenario

PV solar   Offshore wind   Onshore wind

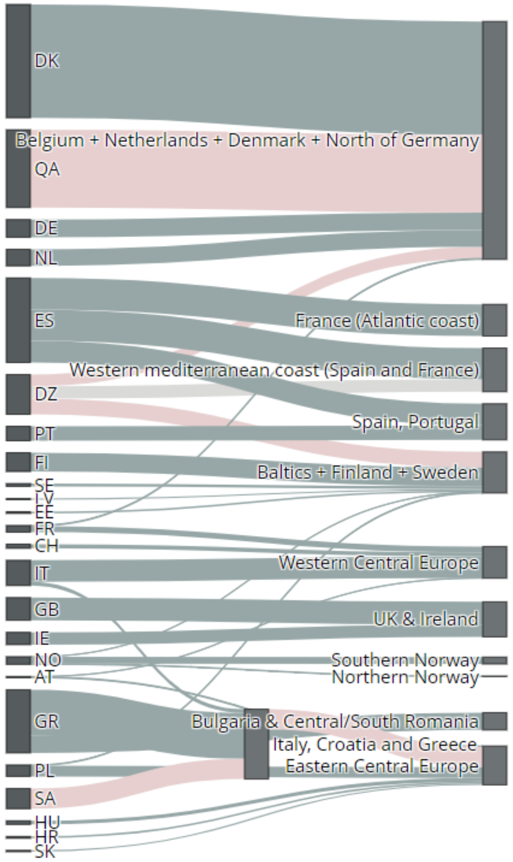
Note: (1) All assumptions can be found in Appendix II. (2) In the model, RES installations are considered to be only dedicated for hydrogen production. Therefore, the sizing of electrolysers consists of an optimization problem to find the least-cost combination of components. In HyPE model, the capacity ratio is determined by minimizing LCOH in each location based on RES capacity factors, technologies' efficiencies and cost data. In such a set-up, the model calculates electrolysers' capacity to optimally produce hydrogen from renewable resources by mitigating intermittency problem.

Most hydrogen transport infrastructure will be required within clusters, however there will be a need for some corridors between clusters

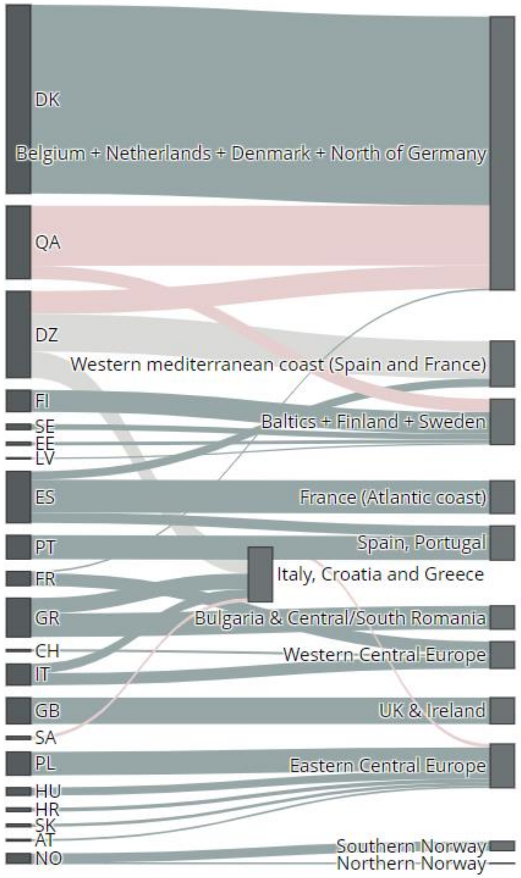
Ambitious scenario in 2050



Moderate scenario in 2050



Conservative scenario in 2050



Maritime import   Pipeline import   Intra European transport[2]

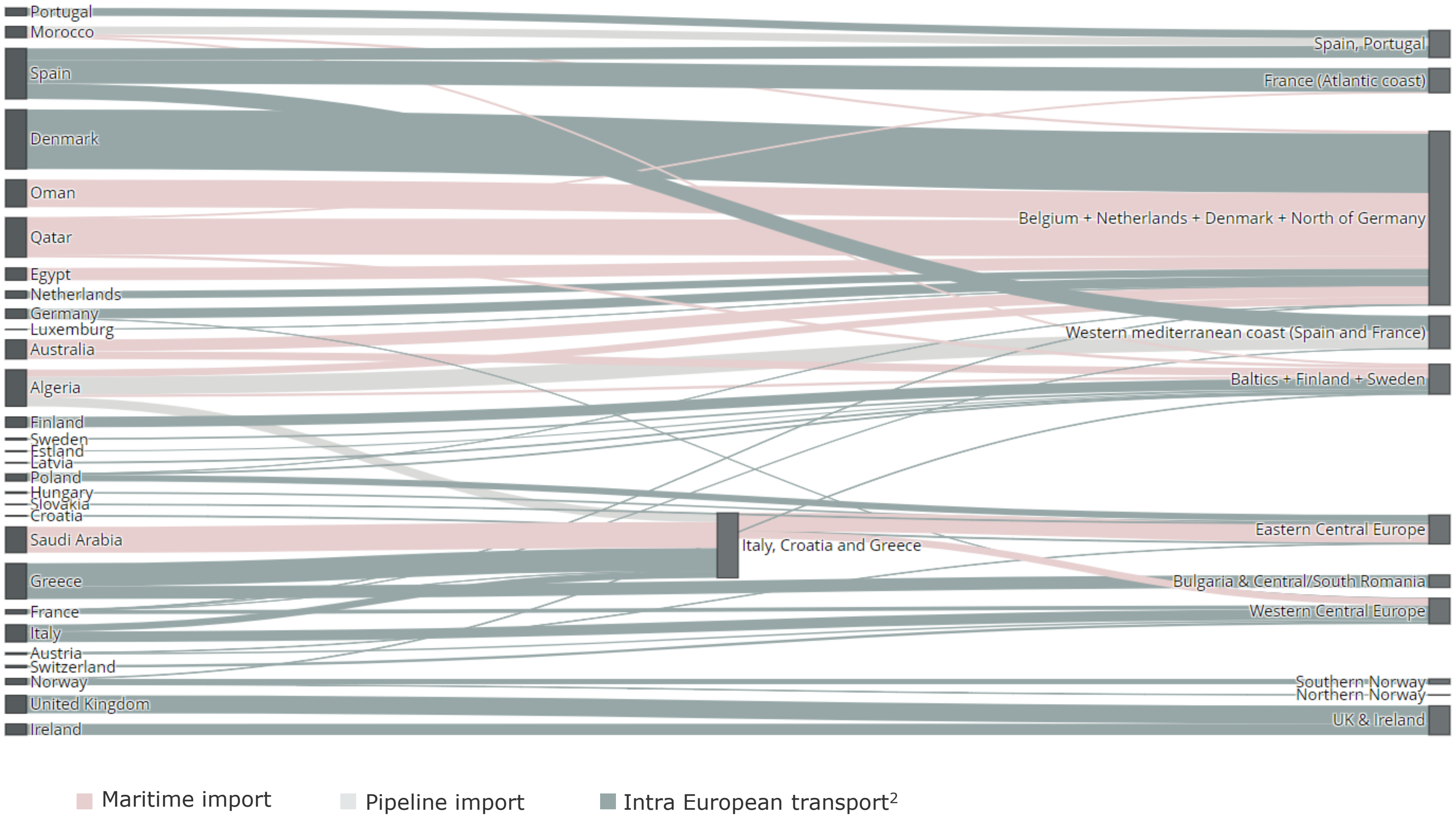
Key messages:

- Most hydrogen transport infrastructure will be required within clusters, however there will be a need for some corridors
- If hydrogen is transported via pipeline, which is an option for intra European transport or import, new, dedicated hydrogen pipelines could be constructed or existing natural gas pipelines could be repurposed
- The sources of supply for the individual clusters are similar in all three scenarios.
- The largest amount of import will, in all scenarios, be required in the cluster *Belgium, Netherlands, Denmark and North of Germany*
- The figures concerning the three scenarios can be found in more detail in the next slides

__Notes__: (1) Country codes can be found in glossary at the end of the report. (2) Intra European transport includes hydrogen pipelines between the clusters and renewable electricity transport via the grid within a cluster. (3) for data concerning the other years, we refer to the Power BI dashboards. Further, in the dashboards a map visualization of the data can be found. This gives a good overview of the sources per cluster.

Hydrogen supply locations per clusters in the ambitious demand scenario in 2050

Ambitious scenario in 2050



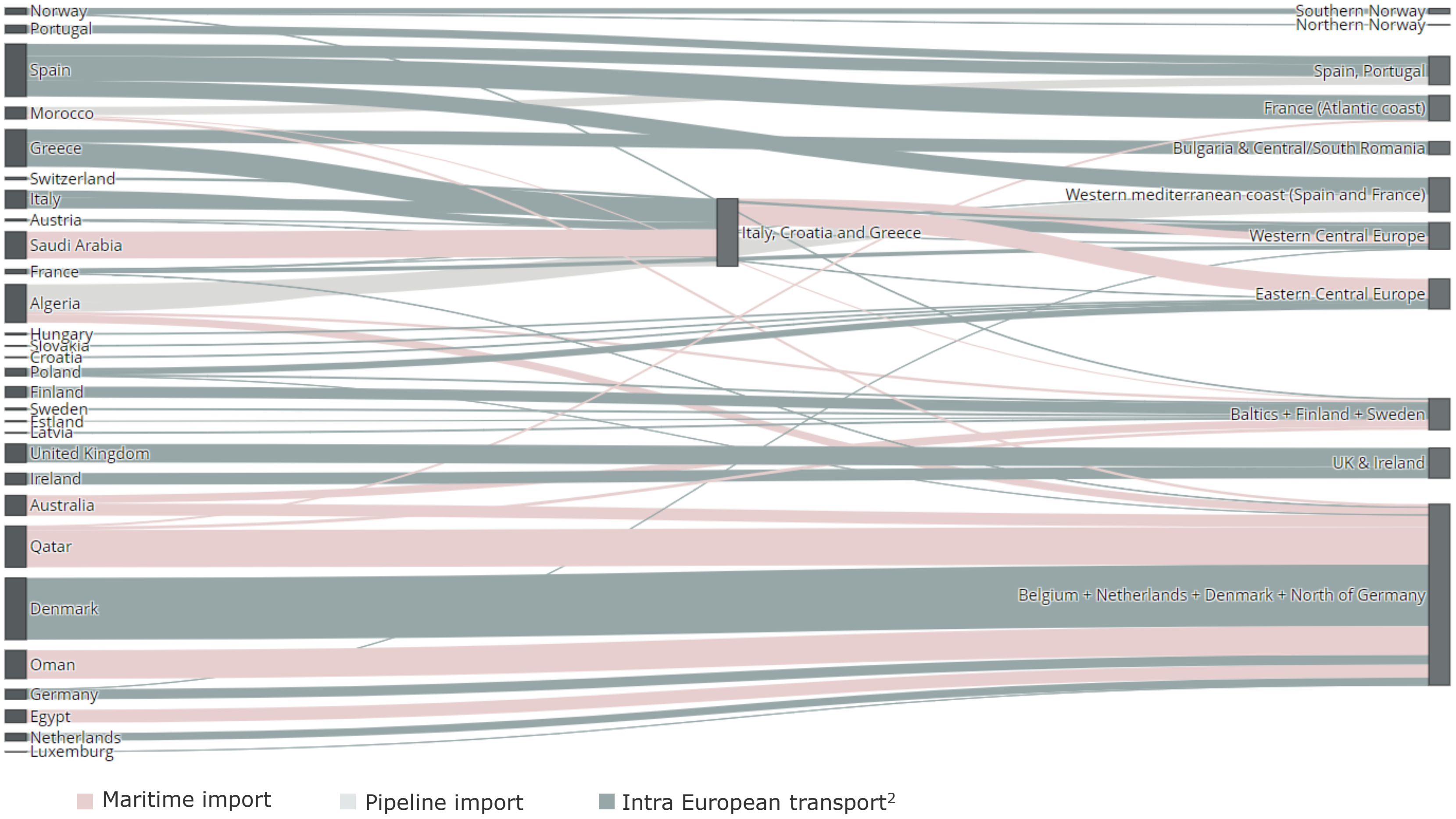
Key messages:

- To the clusters *UK and Ireland; Spain and Portugal; France (Atlantic coast); Bulgaria and Central/South Romania; Southern and Northern Norway* hydrogen is projected to be only supplied from sources inside of Europe. All other clusters will require hydrogen import from outside of Europe.
- Hydrogen is projected to be imported via pipeline from North Africa to the clusters *Western mediterranean coast (Spain and France)* and *Italy, Croatia and Greece.*
- To the cluster *Belgium, Netherlands, Denmark and North of Germany; Baltics, Finland and Sweden; Western Central Europe and Eastern Central Europe* it is projected that part of the hydrogen required will be supplied via maritime import. However, for the *Western and Eastern Central Europe* clusters this will not be directly supplied to the cluster, rather the cluster *Italy, Croatia and Greece* will serve as a transit cluster.

Notes: (1) Country codes can be found in glossary at the end of the report. (2) Intra European transport includes hydrogen pipelines between the clusters and renewable electricity transport via the grid within a cluster

Hydrogen supply locations per clusters in the moderate demand scenario in 2050

Moderate scenario in 2050



Key messages:

- To the clusters *UK and Ireland; France (Atlantic coast); Bulgaria and Central/South Romania; Southern and Northern Norway* hydrogen is projected to be only supplied from sources inside of Europe. All other clusters will require hydrogen import from outside of Europe.
- Hydrogen is projected to be imported via pipeline from North Africa to the clusters *Western mediterranean coast (Spain and France), Spain and Portugal* and *Italy, Croatia and Greece.*
- To the cluster *Belgium, Netherlands, Denmark and North of Germany; Baltics, Finland and Sweden; Western Central Europe and Eastern Central Europe* it is projected that part of the hydrogen required will be supplied via maritime import. However, for the *Western and Eastern Central Europe* clusters this will not be directly supplied to the cluster, rather the cluster *Italy, Croatia and Greece* will serve as a transit cluster.

Notes: (1) Country codes can be found in glossary at the end of the report. (2) Intra European transport includes hydrogen pipelines between the clusters and renewable electricity transport via the grid within a cluster

Hydrogen supply locations per clusters in the conservative demand scenario in 2050

Conservative scenario in 2050

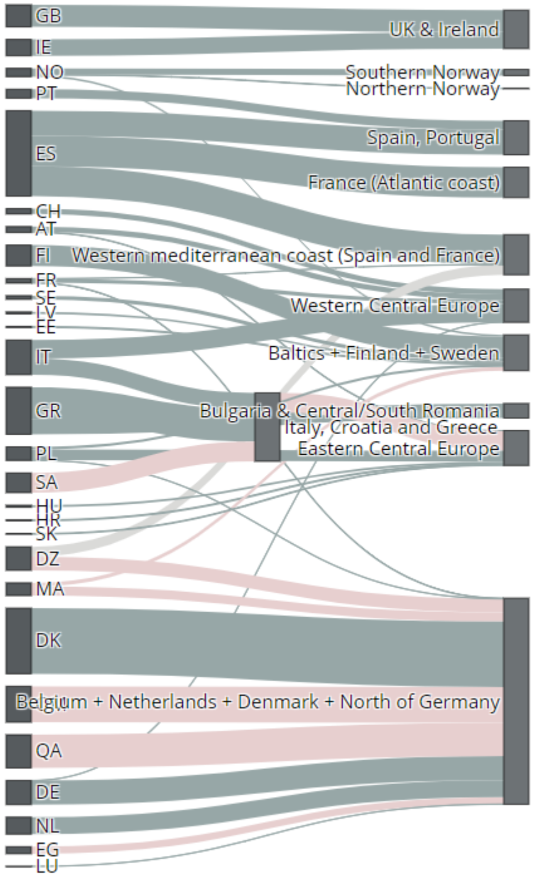
Key messages:

- To the clusters *UK and Ireland; France (Atlantic coast); Bulgaria and Central/South Romania; Southern and Northern Norway* hydrogen is projected to be only supplied from sources inside of Europe. All other clusters will require hydrogen import from outside of Europe.
- Hydrogen is projected to be imported via pipeline from North Africa to the clusters *Western mediterranean coast (Spain and France); Spain and Portugal* and *Italy, Croatia and Greece.*
- To the cluster *Belgium, Netherlands, Denmark and North of Germany; Baltics, Finland and Sweden; Western Central Europe and Eastern Central Europe* it is projected that part of the hydrogen required will be supplied via maritime import. However, for the *Western and Eastern Central Europe* clusters this will not be directly supplied to the cluster, rather the cluster *Italy, Croatia and Greece* will serve as a transit cluster.

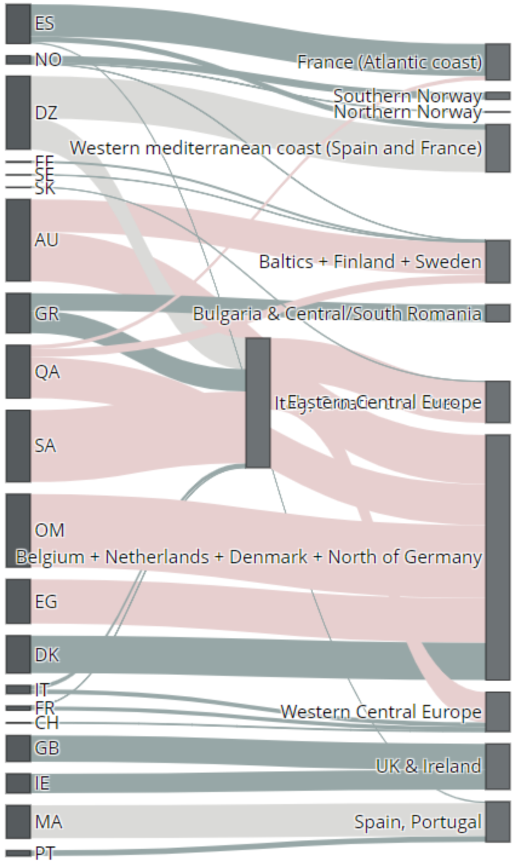
Notes: (1) Country codes can be found in glossary at the end of the report. (2) Intra European transport includes hydrogen pipelines between the clusters and renewable electricity transport via the grid within a cluster

In the increased import scenario, required transport infrastructure will be more focused on import than on distributing locally produced hydrogen

Base supply scenario in 2050



Increased import supply scenario in 2050



Maritime import Pipeline import Intra European transport

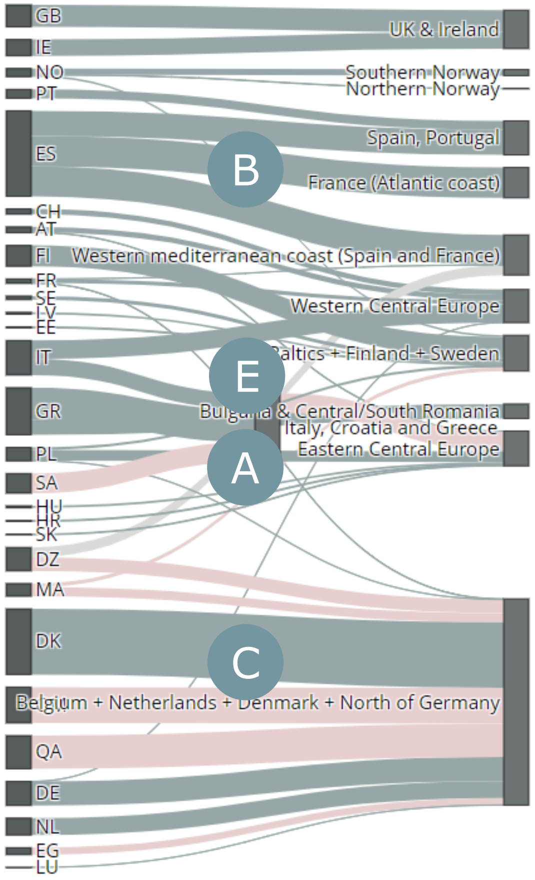
Key messages:

- It is projected that locally produced hydrogen will mostly be supplied to countries within the same cluster. In this case there will be **hydrogen transport infrastructure required within a cluster**. For the cluster *Belgium, Netherlands, Denmark and North of Germany*, there will be infrastructure required to transport **offshore energy from the North Sea to the mainland**.
- There are some exceptions where countries will export to other European countries not located within their cluster. If this is the case, a pipeline connection between the clusters should be in place. In our analysis, it is projected that **Spain will supply hydrogen to France**. The **hinterland clusters** (*Eastern central Europe* and *Western central Europe*) are projected to be supplied **via the cluster *Italy, Croatia and Greece*** with hydrogen coming from Saudi-Arabia, next to hydrogen being produced directly in the cluster.
- In the base supply scenario, **imports from Algeria** are the only projected imports from outside of Europe via pipeline. The other countries will export to Europe via ship.
- In the **increased import supply scenario**, next to pipeline import from Algeria, hydrogen is also projected to be imported via pipeline from **Morocco** to Spain and Portugal. Also, there will be less hydrogen produced from offshore wind, thus the corridor required between the mainland and the North Sea will be more limited, there is only a connection projected via Denmark.

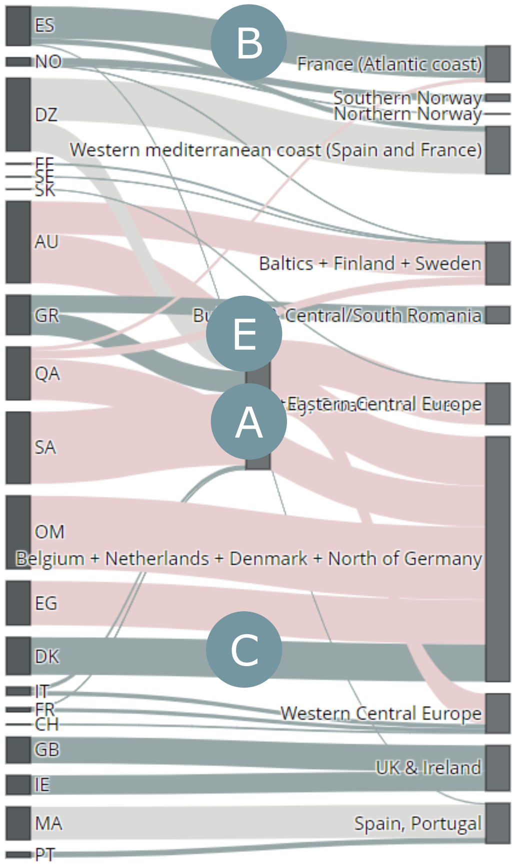
Notes: (1) Country codes can be found in glossary at the end of the report. (2) for data concerning the other years, we refer to the Power BI dashboards.

The projected need for specific corridors largely aligns with the communicated corridors in European Hydrogen Backbone vision

Base supply scenario in 2050



Increased import supply scenario in 2050



Maritime import | Pipeline import | Intra European transport

Comparison to identified corridors in European Hydrogen Backbone vision[1]

- To deliver the hydrogen demand and supply targets set by the REPowerEU plan, five large-scale pipeline corridors are envisaged by European Hydrogen Backbone initiative:
  - Corridor A: North Africa and Southern Europe (from Algeria through Italy to Central Europe)
  - Corridor B: Southwest Europe and North Europe
  - Corridor C: North Sea
  - Corridor D: Nordic and Baltic regions
  - Corridor E: East and South-East Europe

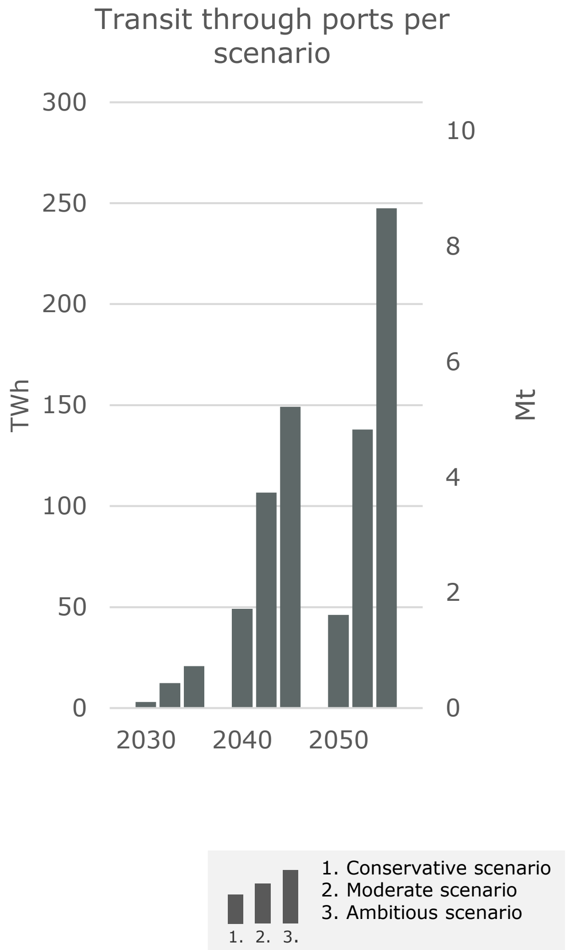
- From our economical analysis, it can be concluded that there is indeed a **projected need for corridor A, B, C and E.** It should be noted that our analysis is an economic optimization and does not take into account other factors such as policy initiatives and the adoption of additional supply routes to ensure security of supply.

Sources and notes: (1) Guidehouse, *Five hydrogen supply corridors for Europe in 2030*, 2022. (2) Country codes can be found in glossary at the end of the report

Most hydrogen supplied to the ports via ships will be transported to other ports or demand locations outside of the port areas

Transit in the ambitious base scenario in 2050

The circles on the map are located in the center of the relevant cluster



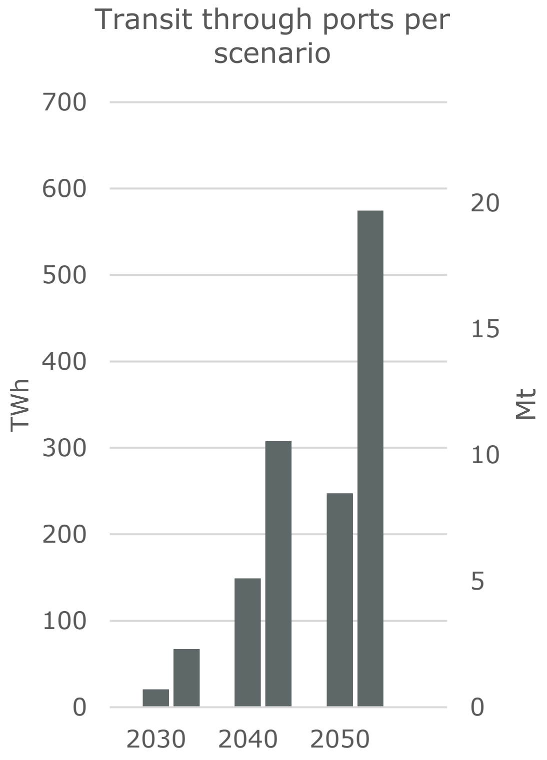
Key messages:

- Hydrogen is mostly imported to ports via ship. Part of the supply is for the ports themselves, however, **most hydrogen demand comes from outside of port areas** as was seen in the discussion concerning demand. Therefore, a large part of the hydrogen that is supplied to a port via ship will not be consumed in the port area but transit to the demand location. Further, the **hinterland clusters cannot be supplied via ship**, therefore, the imported hydrogen will have to pass through other ports.
- Transit is only assumed if hydrogen is imported via ship. If hydrogen is imported via pipeline, it is assumed that the hydrogen does not have to transit through the port area.
- There are **two types of transit assumed** in the model:
  - Transit within clusters: hydrogen imported via ship goes via the ports to the demand location outside of port areas
  - Transit between clusters: hydrogen is imported via ship via one cluster and transported to another cluster (this counts for the hinterland clusters)
- **The majority of transit happens within a cluster**. Only the cluster of ***Italy, Croatia and Greece*** **will transit hydrogen to other clusters** as can be seen from the previous slides.

In the increased import supply scenario, the amount of hydrogen that transits through ports is 1.5x higher in 2050 than in the base supply scenario

Transit in the ambitious increased import scenario in 2050

The circles on the map are located in the center of the relevant cluster



The left bar in each year is the base ambitious scenario, while the right bar is the increased import scenario.

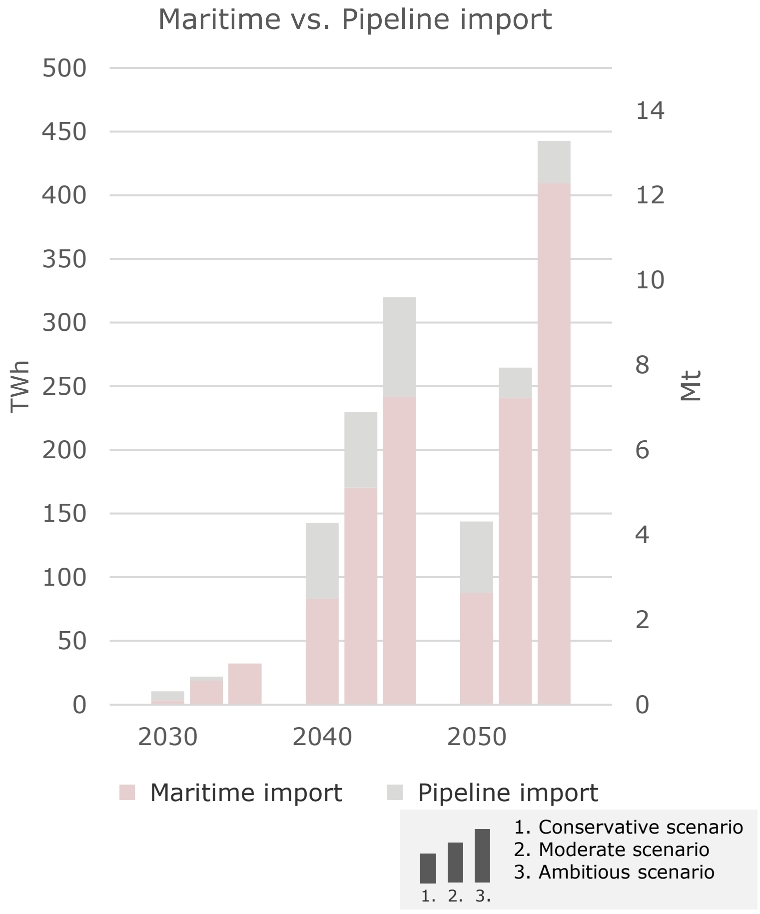
Key messages:

- Compared to the base ambitious scenario, the increase import supply scenario has a higher transit volume.
- Still **only the cluster of *Italy, Croatia and Greece* will transit hydrogen to other clusters.**

In all scenarios, of the imported hydrogen, the largest part is imported via ship with ammonia as the most cost-effective carrier

Maritime vs. pipeline import – ambitious base scenario in 2050

The circles on the map are located in the center of the relevant cluster



Key messages:

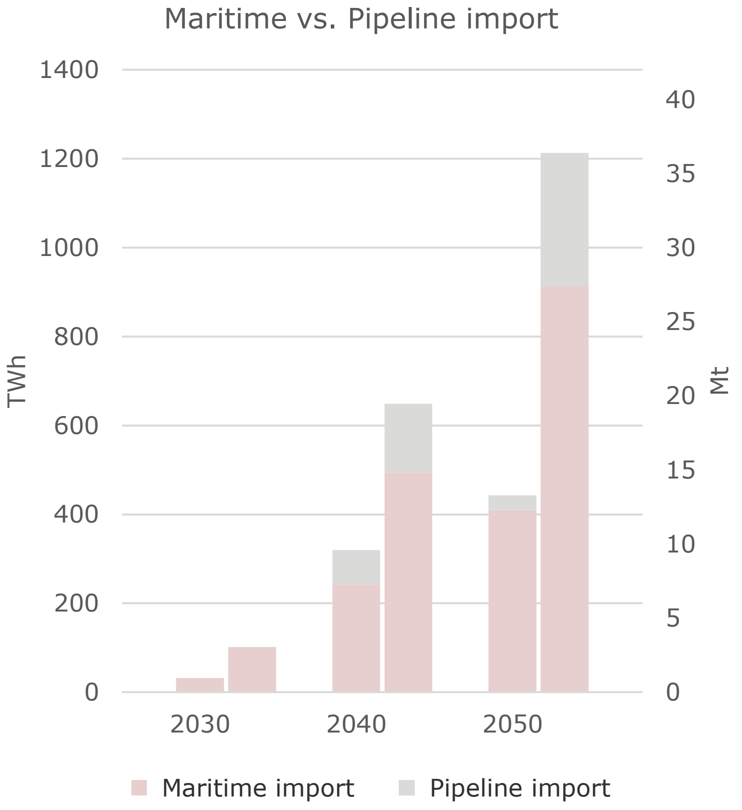
- In 2050, it is projected that **most of the hydrogen import will happen via ship** (60 – 93%). The remainder is imported via pipeline.
- When importing via ship, **ammonia** is projected to be the **most cost-effective** option[1]. The **cost of reconverting these molecules was weight against the lower transport costs** that importing via ship has compared to importing via pipeline.
- It is projected that between 2040 and 2050 **import via pipelines will decrease** with 5 – 60%, while **import via ship will increase** with 6 - 70%
- The maps show import via ship to the cluster *Eastern Central Europe.* The hydrogen is imported via the cluster *Italy, Croatia and Greece,* after which it is transported via pipeline to the hinterland cluster.

Note: (1) Only liquid hydrogen and ammonia were considered in the model, however, studies have shown similar conclusions.

Import is 2.7x higher in the increased import supply scenario compared to the base supply scenario and is still mostly via ship (75%)

Maritime vs. pipeline import – ambitious increased import scenario in 2050

The circles on the map are located in the center of the relevant cluster



The left bar in each year is the base ambitious scenario, while the right bar is the increased import scenario.

Key messages:

- In general, there is **more import in the increased import supply scenario** (~2.5x more in 2050)
- As in the base supply scenario, in 2050 in the increased import supply scenario, it is projected that **most of the hydrogen import will happen via ship** (75%). The remainder is imported via pipeline.
- In the **base supply scenario**, it is projected that between 2040 and 2050 **import via pipelines will decrease**, while **import via ship will increase.** In the **increased import supply scenario**, it is project that **import via pipeline as well as via ship will increase** by 65% and 85%, respectively.
- As discussed before, the maps show import via ship to the cluster *Eastern Central Europe* and now also to *Western Central Europe.* This again is hydrogen imported via the cluster *Italy, Croatia and Greece,* after which it is transported via pipeline to the hinterland clusters.

Ports that are importing hydrogen (derivatives) will have to invest in specific import infrastructure as import terminals and reconversion infrastructure

Import terminal

- At import terminals, storage of hydrogen or derivatives is required.
- In this analysis, an assumption is taken that a LH2 terminal storage has a **utilization rate of 50% and a storage/send-out capacity ratio of 2.5%.** Therefore, in order to calculate the required storage at an import terminal, the annual send-out capacity has to be multiplied by 1.25% (50% of 2.5%).[2] The **average storage size of a LH2 tank is 9 GWh[2]** with a CAPEX cost of 0.6[1] - 2.7[2] MEUR/GWh. **Ammonia can also be stored directly**. The average storage size of an ammonia refrigerated tank is 328 GWh with a CAPEX cost of 0.196 MEUR/GWh.[2] However, this is not further calculated in the analysis.
- Further, the send-out process of hydrogen from the storage tanks to the grid is very similar to LNG and will require process equipment such as pumps, BOG[3] compressors and evaporators.[4]

Reconversion infrastructure

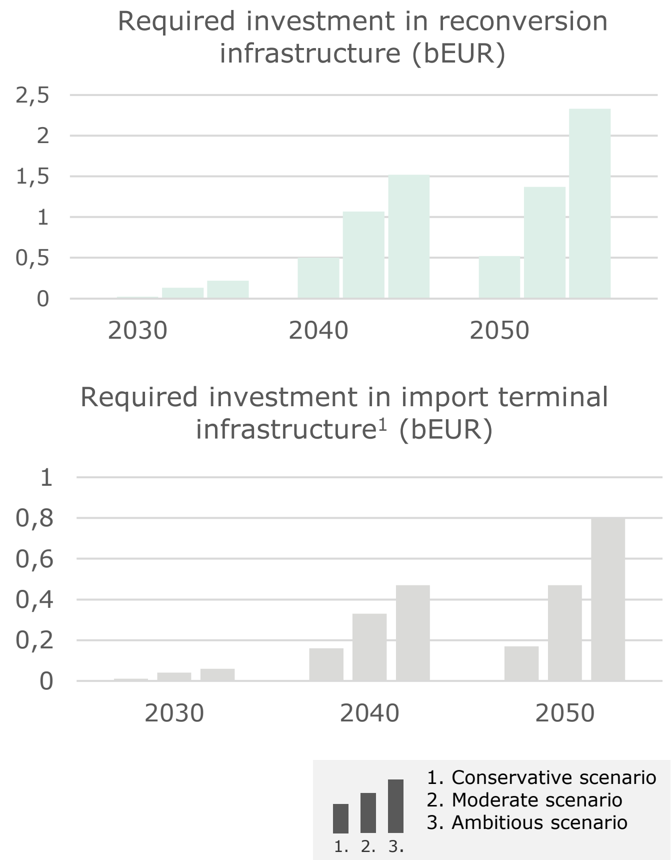
- In the model, only ammonia is imported via ships, and thus only ammonia will need to be reconverted to hydrogen. To retrieve hydrogen from ammonia, infrastructure needs to be in place to crack the ammonia.
- The **infrastructure is assumed to require an annualized investment of 0.23 EUR/kgH2 in 2030, decreasing to 0.19 EUR/kg H2 in 2050[1]**. Further, the **processes of cracking ammonia requires electricity** (assumed to be 11.2 kWh/kg H2).[1]
- The **amount of reconversion plants required will depend on the size of the plant**. E.g., if a reconversion plant has a capacity of 0.32 Mt/year, the total ammonia imported per port has to be compared to this number to estimate the required plants.
- We note that reconversion infrastructure is not required in case of direct offtake of ammonia, which will most often happen. Hence, most of this investment may be avoided in practice.

Sources: (1) Assumptions on all costs can be found in the Appendix II. (2) Energy Transition Expertise Center (EnTEC), *The role of renewable Hydrogen import & storage to scale up the EU deployment of renewable Hydrogen,* 2022. (3) Boil Off Gas. (4) Converting the LNG-Peakshaver to be fit for processing LH2: An LH2 import terminal, 2021

It is expected that only three clusters will need to invest in import specific infrastructure such as reconversion plants and import terminals

Required investment in import infrastructure – ambitious base scenario in 2050

The circles on the map are located in the center of the relevant cluster



Key messages:

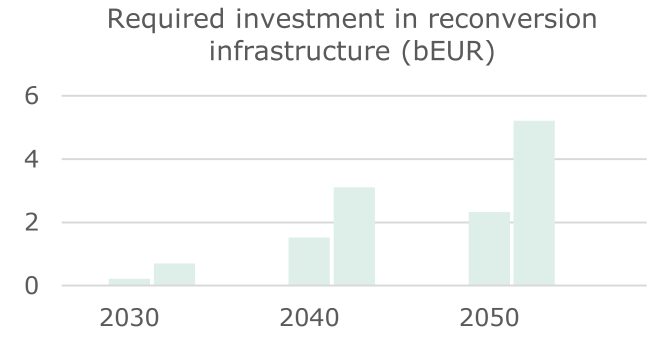
- The graphs show the required investments in a certain year in import infrastructure in Europe. The total cost for investing was annualized[2]. Only import infrastructure for hydrogen (or derivatives) imported via ship is assumed to require import infrastructure in the model (import terminal and reconversion plant). Hydrogen imported via pipeline will also require storage, however, this is considered part of the next section 'Storage' since it is not (always) required at the port area.
- There are **only three clusters that will import hydrogen (derivatives) via ship and thus require import infrastructure as discussed**: *Belgium, Netherlands, Denmark and North of Germany*; *Baltics, Finland and Sweden* and *Italy, Croatia and Greece* to provide hydrogen to *Eastern Central Europe* amongst others. This does not automatically mean that all ports in the cluster will have to invest.
- The **dominating factor** in the total investment cost for importing via ship is **reconversion infrastructure**. The CAPEX cost however is still only a small part of the total cost of reconversion, since the largest cost is the energy required in the process[3].
- Capacities of the infrastructure for reconversion, as well as for terminals, should be large enough to handle the amount of hydrogen supplied via ship. All numbers per scenario can be found in the previous slides, in 2050 this is equal to 88 – 410 TWh (2.6 – 12 Mt) in 2050. This annual send-out capacity leads to a required storage at import terminals of 1.1 – 5.1 TWh (equal to 122 – 567 LH2 storage tanks assuming a capacity of 9 GWh). **The number of reconversion plants required depends on the size of the plant** (assuming a capacity of 0.32 Mt/year, 38 plants would be required)[4]
- Note that **reconversion might not always be necessary** as mentioned before due to direct applications, leading to lower costs.

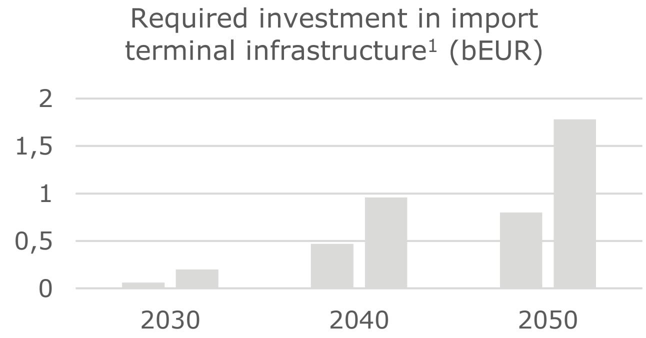
__Note__: (1) A temporary storage is included in the import terminal, before reconversion. Seasonal and long-term storage will be in salt caverns and are looked into in the next topic. (2) The model does not make an investment decision and it thus not bound to the infrastructure lifetime, only the CAPEX cost at a certain year is given. (3) Assumptions on all costs can be found in the Appendix II. (4) Not taking into account location for demonstration purposes.

Investment in import infrastructure is 2.2x higher in the increased import scenario compared to the base scenario

Required investment in import infrastructure – ambitious increased import scenario in 2050

The circles on the map are located in the center of the relevant cluster





The left bar in each year is the base ambitious scenario, while the right bar is the increased import ambitious scenario.

Key messages:

- The graphs show the required investments in a certain year in import infrastructure in Europe.
- Compared to the base scenario, an **additional cluster imports hydrogen via ship and thus require import infrastructure** in the increased import supply scenario in 2050: *France (Atlantic coast).* Also the *Western Central Europe* cluster will require import via ship imported via the cluster *Italy, Croatia and Greece.* Since there is more import in the increased import scenario compared to the base scenario, the required capacities for import infrastructure are higher and thus also the related costs.
- Capacities of the infrastructure for reconversion, as well as for terminals, should be sized to handle the amount of hydrogen supplied via ship, which can be found in the previous slides
- The projected hydrogen imported via ship in the increased import scenario is 913 TWh (27 Mt) in 2050. This leads to a required capacity of storage at import terminals of 11 TWh (equal to 1222 LH2 storage tanks with a capacity of 9 GW). **The number of reconversion plants required depends on the size of the plant** (with a capacity of 0.32 Mt/year, 86 plants would be required)[2]

Note: (1) A temporary storage is included in the import terminal, before reconversion. Seasonal and long-term storage will be in salt caverns and are looked into in the next topic. (2) Not taking into account location for demonstration purposes.

Storage is required to ensure the resilience of the energy system and will be provided by different types

Storage is required to ensure the resilience of the energy system as a whole, by balancing supply and demand on all timescales. Next to having variability in demand, supply variability will increase due to intermittency of renewable energy production. The specific hydrogen storage requirements will be determined by developments in hydrogen supply, demand, interrelations with other sectors and the use of other flexibility tools such as batteries.

Types of hydrogen storage

There are **different types of storage[1, 2]:**

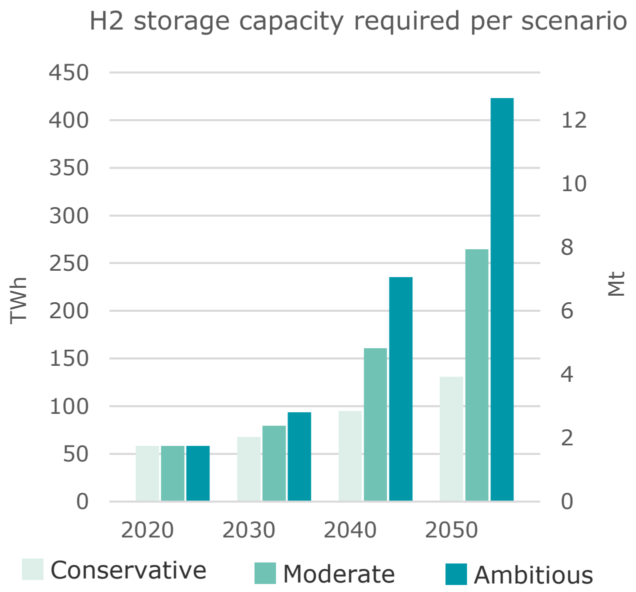
- **flexibility provided by the system for short-term storage[3]** (pipelines, pressurized tanks, atmospheric tanks, liquefied tanks, compressed cylinders and storage at import terminals). These could be used for short-term balancing of power supply intermittency. For longer-term balancing, underground storage sites will likely have to be used due to the combined need for power rating and discharge time and the lower costs of underground storage. Further, there is also a constraint in space available at ports. Most of the ports will need space for reconversion plants. At the moment, there is a hydrogen storage capacity of approximately 23 TWh of hydrogen in LNG import terminals. Repurposing these facilities however is not straightforward. Capacity of LNG tanks typically range from 50,000 – 250,000 m^3. Further storage at import terminals is discussed previously. There will be a need for surface storage for smooth operation, but the majority will likely be stored in subsurface storage sites.
- **underground storage [1, 3]** : Underground storage sites, which today store natural gas, could be repurposed to store hydrogen or new sites can be developed. The choice depends on factors as availability, suitability of the specific storage site, … Further, some portion of the current gas storage capacity will likely be required for storage of (synthetic and bio)methane and possible for CO2 storage. There are three types of underground storage options to be mainly considered: salt caverns, depleted fields and aquifers.

  1. **Salt caverns are a proven concept**, since they have been used for years to store hydrogen. An example of this is the Teesside chemical complex in the UK. Although salt caverns are proven to be technically feasible, they are limited by geographical availability across Europe since they are only present at some countries, mostly in the northwest of Europe and the UK. At the moment, there are 51 salt caverns in the EU, currently used to store natural gas, that could be repurposed for hydrogen. These current sites have the potential to store **50 TWh (1.50 Mt) of hydrogen**, if repurposed. The total technical potential of salt caverns in Europe is around 85,000 TWh (2,550 Mt) of hydrogen, which is much larger than required for hydrogen demand.
  2. **Depleted gas fields and aquifers still need pilot and demonstration projects to assess feasibility.** These projects are of high importance. An example of such project to keep track of is the HyStorIES project, which aims to go beyond salt caverns and explore alternative subsurface storage options. However, they are **very likely to be feasible since** natural gas reservoirs should be able to operate as hydrogen storage as well because they have demonstrated their ability to store gas for millions of years. Several storage operators are in various stages of examining this. Depleted natural gas reservoirs have been used for storage for decades and make up about 64% of the total natural gas storage capacity in the EU27 and the UK. Current sites have an estimated potential of **215 TWh (6.45 Mt) of hydrogen**, if repurposed. As for salt caverns, the potential of new sites is very large, and likely to be even larger than storage capacity in salt caverns, however not yet quantified. Depleted gasfields and aquifers are more geographically spread than salt caverns.

Sources: (1) Guidehouse, *Picturing the value of underground gas storage to European hydrogen system, 2021*. (2) Energy Transition Expertise Center (EnTEC), *The role of renewable Hydrogen import & storage to scale up the EU deployment of renewable Hydrogen,* 2022. (3) Above-ground storage solutions generally have a higher levelized cost than underground solutions for pure hydrogen.

In the ambitious demand scenario, repurposing all existing subsurface gas storage locations would only be sufficient to meet 60% of storage needs

Amount of hydrogen storage required



Key messages:

- Hydrogen has a **low volumetric density;** it thus takes up a lot of space. Compared to natural gas, there is around 4 times more volume required for an equivalent energy amount[1]. In this analysis, **storage capacity required is assumed to be 24% of the yearly hydrogen demand[1],** in line with current natural gas systems but different studies show variability.
- By 2030, 70 to 95 TWh (2.1 to 2.85 Mt) of storage capacity would be required for the projected hydrogen demand. This demand is mainly coming from industrial clusters, which will probably manage their supply mostly locally.
- By 2050, 130 to 425 TWh (3.90 to 12.75 Mt) of storage capacity would be required for the projected hydrogen demand. As mentioned, current underground storage of gas has been estimated to be able to store 265 TWh (7.95 Mt) of gaseous hydrogen. In **the ambitious scenario, existing storage locations would thus have to be expanded or additional sites will have to be developed**. Since the required storage capacity is based on the hydrogen demand, there is no difference in the ambitious increased import scenario.
- It should be considered that there will still be a need for storage of methane gases and thus not all current storage locations will be available for repurposing, and the repurposing of storage locations will take time, leading to the development of new storage locations that will likely be required before 2050 in the different demand scenarios. It is thus likely **storage needs will be met by both repurposed and new assets** (e.g. salt caverns not yet used for gas storage) **in the different years**.

Location of hydrogen storage[1]

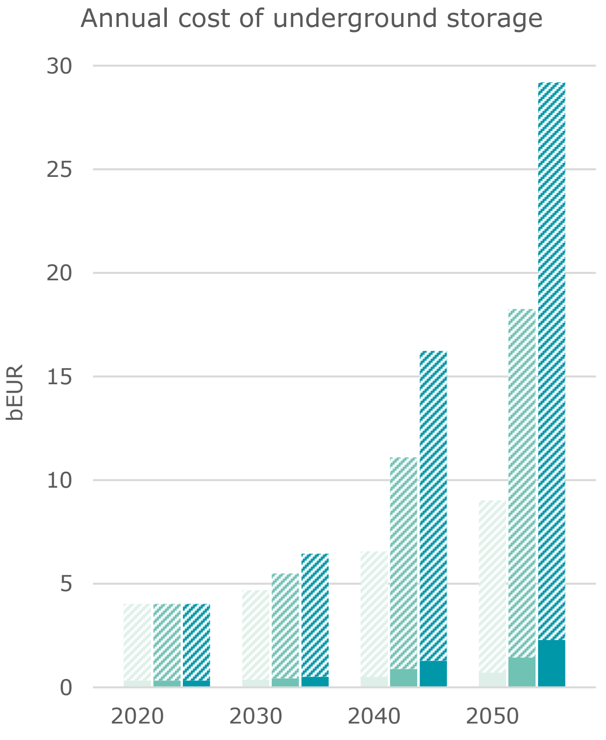
- Volatility will mainly come from supply, which is why it might be preferred to locate hydrogen storage close to supplied locations.
- The choice of type and exact location of storage sites, will depend on the geographical availability of underground storage sites. The need for storage and the **geographical availability of underground storage varies across the EU**, leading to different storage options potentially becoming competitive in different locations.
- Since each storage site will have to be analyzed individually to assess its compatible with hydrogen, which is highly dependent on its geological characteristics, it is not possible to make a general overview of preferred storage locations.

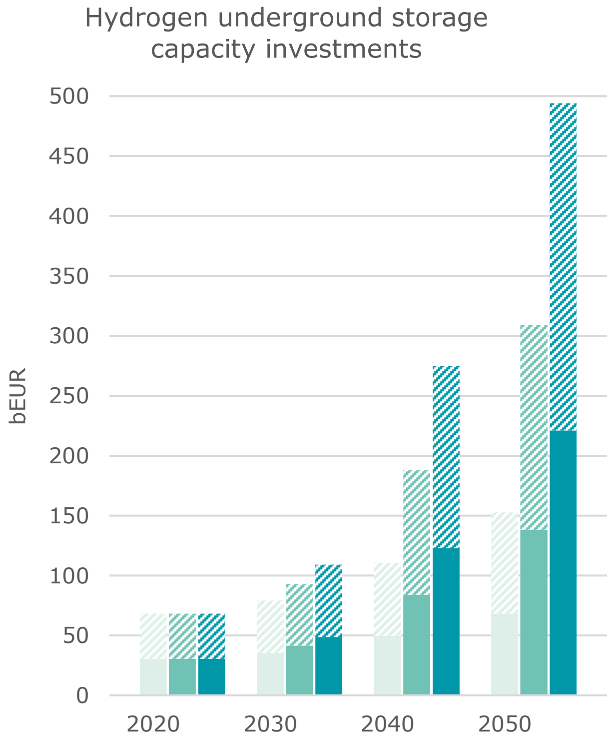
__Sources__: (1) Guidehouse, *Picturing the value of underground gas storage to European hydrogen system,* 2021; estimation based on current ratio between the cumulative natural gas demand and underground storage working gas capacity. However, this is still uncertain and different studies show high variability.

The cost of supply of hydrogen is highly dependent on the scenario, the type of storage used, the specifications of the storage site, etc.

Cost of hydrogen storage[1]

The costs of hydrogen storage sites highly depend on the size, operating conditions and number of injection and withdrawal cycles. Therefore, **it is difficult to generalize the costs.** However, to give an estimation of the cost of hydrogen storage, based on different sources and different type of storage, **cost ranges are defined**. These are highly uncertain and provided here only to give an order of magnitude, and will as mentioned largely depend on the size, location, … Further, it is assumed that repurposing existing storage sites will likely be around 20-30% more cost-effective than developing new ones.





Conservative Moderate Ambitious

Levelized cost of storage and investment cost (CAPEX) estimations for hydrogen underground storage[1]

Type of storage	Levelized cost of storage (EUR/kgH2)	CAPEX (EUR/kgH2)
Salt cavern	0.18 0.23 0.35 1.34	29 N/A 25.50 27.46
Depleted gas field	1.02	17.41
Aquifer	1.07	17.80
Hard rock cavern	2.3	38.91

- The estimated range of the levelized cost of underground storage is: 0.18 – 2.30 EUR/kg. This is used to calculate the annual cost of storage. The range of investments in underground storage is: 17.41 – 38.91 EUR/kg.
- In 2030, the cost of supply is between 0.4 and 4.7 bEUR in the conservative scenario and between 0.5 and 6.5 bEUR in the ambitious scenario. The required investments in storage by then are between 35 and 47 bEUR in the conservative scenario and between 49 and 106 bEUR in the ambitious scenario.
- In 2050, the cost of supply is between 0.7 and 9 bEUR in the conservative scenario and between 2.3 and 29.3 bEUR in the ambitious scenario. The required investments in storage by then are between 68 and 152 bEUR in the conservative scenario and between 221 and 494 bEUR in the ambitious scenario.

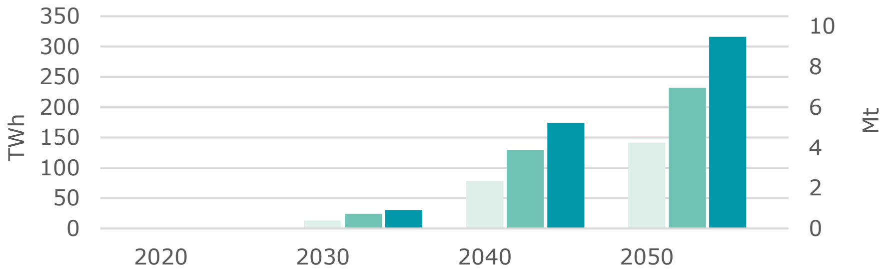
Sources: (1) Guidehouse, *Picturing the value of underground gas storage to European hydrogen system,* 2021

Specific infrastructure is required for the transport sector and port equipment, in particular refueling stations and bunkering

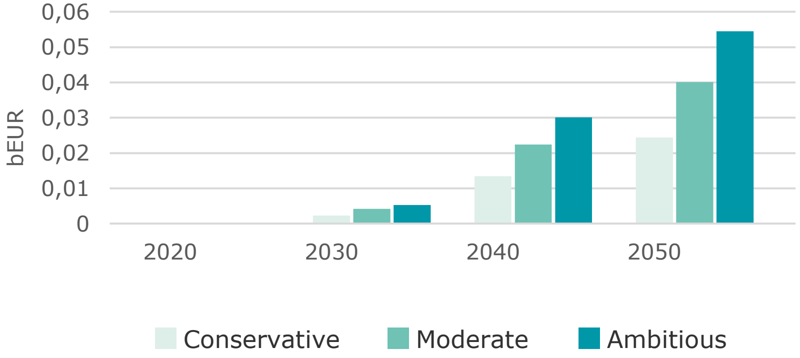
Four demand categories are identified for hydrogen in ports: **industries, transport activities, urban areas and port activities**. For industries and urban areas, the most important role for ports is to enable the transport of hydrogen to the place of demand. For transport and port activities, refueling stations and bunkering options should be in place, these are discussed in more detail.

Refueling stations

H2 refueling stations capacity required per scenario



H2 refueling stations required investments



- Capacity of hydrogen refueling stations has a large range[1]. In the model, a capacity of 2,000 kg/day is assumed[2]. Larger daily capacity stations are supplied by liquid hydrogen tankers, smaller daily capacity stations are supplied by gaseous tube trailers.
- Cost are approximately 1,200 – 3,000 EUR/kg/day, depending on the hydrogen delivery method[3,4]. In the analysis, a cost of **2,100 EUR/kg/day** is assumed to calculate the cost per hydrogen refueling station. Correspondingly, the **cost for one refueling station** with a capacity of 2,000 kg/day is about **4.2 MEUR**.
- Number of refueling stations required per port are calculated based on the hydrogen demand per scenario for **road freight and cargo handling**. The total hydrogen demand for these two subcategories equals the capacity that is required for refueling.[5]
- After 2030, it is possible that the capacity of the hydrogen refueling stations further increases[6]. This will depend on technological advancements, which is why the required capacity is expressed in TWh rather than number of refueling stations.
- Hydrogen refueling for port/inland vessels is currently at small/pilot scale[7]. This leads to uncertainty on the investment costs projections and has been excluded. With projected hydrogen demand being at least an order of magnitude smaller than for road freight and cargo handling the impact on overall investment should be limited.
- The **required capacity is projected to be 13 – 31 TWh** (0.4 – 0.9 Mt) **by 2030**, and **141 – 316 TWh** (4.2 – 9.5 Mt) **by 2050.**
- The **required investments in refueling stations capacity is projected to be 2.3 - 5.3 bEUR by 2030**, and **24 – 55 bEUR by 2050.**

Sources and notes: (1) For example, John Cockerill offers stations with 100 to 1,000 kg per day depending on the requirements of the vehicles (https://Hydrogen.johncockerill.com/en/products/hydrogen-refuelling-station/). (2) HyTrucks project. (3) https://www.hydrogen.energy.gov/pdfs/21002-hydrogen-fueling-station-cost.pdf. (4) IEA, The future of Hydrogen, 2019: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf. (5) For road freight, only the hydrogen demand in the port area is assumed for the required capacity in port refueling stations. It is not assumed that ports will be a fuelling node for other trucks and vehicles in the general area. (6) A larger capacity influences the safety circle since more storage will be required. This is especially relevant in urban areas. (7) E.g. CMB.TECH, Multimodal refueling station, Port of Antwerp-Bruges (8) mainly relevant for **Transport and logistics archetype**

Specific infrastructure is required for the transport sector and port equipment, in particular refueling stations and bunkering

Four demand categories are identified for hydrogen in ports: **industries, transport activities, urban areas and port activities**. For industries and urban areas, the most important role for ports is to enable the transport of hydrogen to the place of demand. For transport and port activities, refueling stations and bunkering options should be in place, these are discussed in more detail.

Bunkering

- There are three main bunkering options:
  - **Shore to ship**: bunkered directly from a storage tank or pipelines[1]
  - **Ship to ship**: refueling from cargo tanks of a refueling vessel
  - **Truck to ship**: truck is connected to the ship on the quayside
- Ship to ship and truck to ship enables bunkering during the unloading operation of the ship, so there is no need to move to another place for bunkering and no separate construction is required in the port. This also travel and waiting time for ships.
- The infrastructure required for ship to ship bunkering is berthing facilities, for truck to ship this is bunkering stations. Further, on-site storage tanks at ports accommodate stable weekly refueling demand, and refueling vessels are deployed for demand peaks.
- In the short-/midterm it could be useful to swap compressed hydrogen containers to initiate the use of hydrogen in inland shipping. In the long-term this will not be the most efficient method.
- Ports can become multi-fuel hubs as in shipping (international as well as domestic), the largest role for bunkering fuels is seen for ammonia and methanol. Since there is also a role for ammonia as import carrier, reconversion might not (always) be required.
- It is not expected that all ports in scope are assumed to engage into hydrogen or hydrogen-based fuels bunkering activities.

At the moment, the information available on capacities for the bunkering of hydrogen at the ports is still limited, which is why no concrete capacities are given in the analysis.

Sources and notes: (1) Also floating systems could be an option to bunker ammonia. This way, safety threats coming from ammonia can be minimized. (2) DNV, *RHydrogenINE Kickstart Study*, 2021. (3) **bunkering archetype.**

Development of a hydrogen ports no-regret investments roadmap

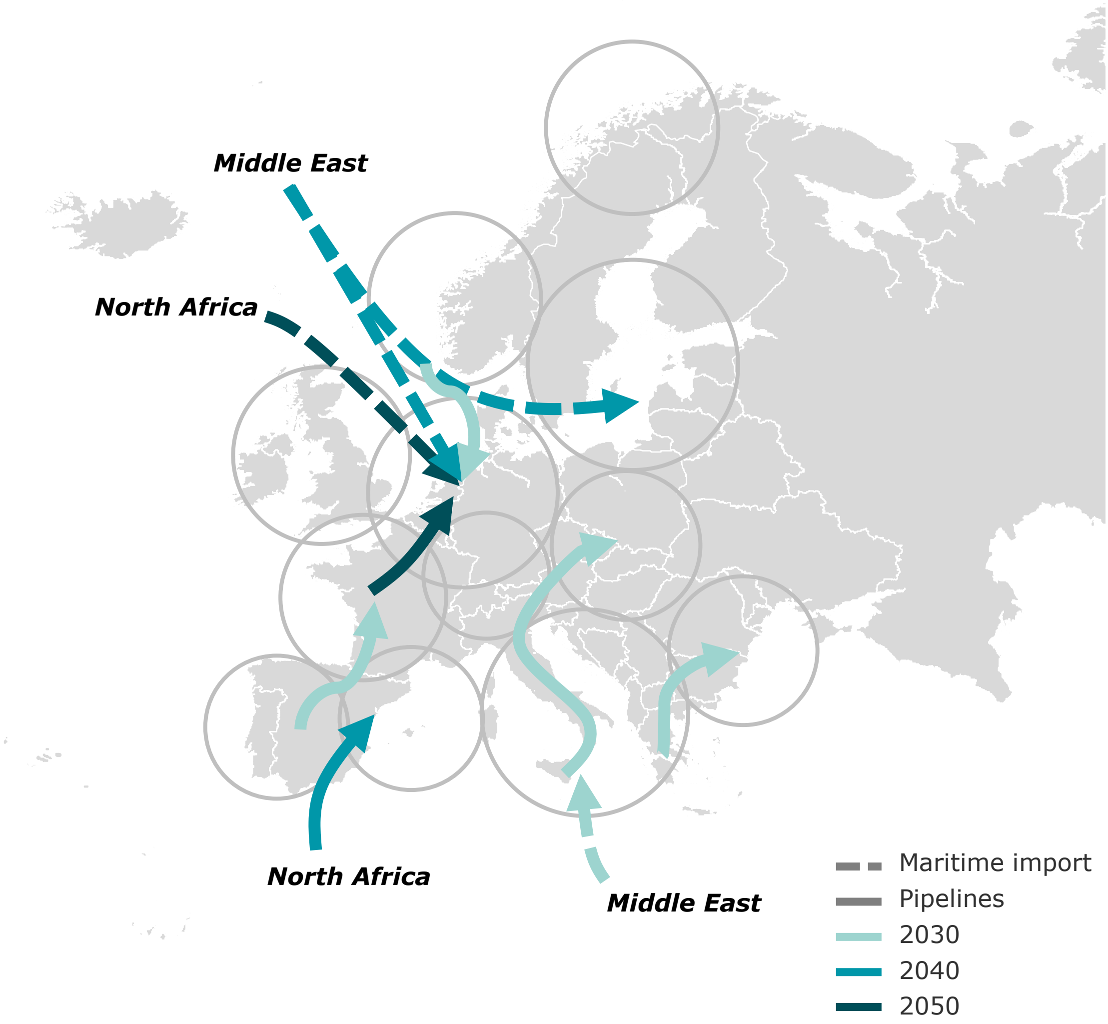
Boundary conditions can be translated in no-regret investments

Certain boundary conditions have to be met in order for hydrogen supply and demand as projected to be realized. These boundary conditions can be translated in no-regret investments.

Boundary conditions

- Hydrogen transportation networks available
- Enough renewable electricity (solar PV and wind) and electrolyser capacity installed
- Investments to reinforce net capacity
- Providing companies investment security (robust networks available)
- Development of international hydrogen market: affordability of hydrogen, security and reliability of supply
- Increasing the demand to upscale supply and achieve reduced costs
- Land for infrastructure: electrolysers, import terminals, fuel stations, etc.

By focusing on no-regret investment options, the risk of oversizing hydrogen infrastructure is minimized



No-regret transport investments over the different years:

- Investments are considered as 'no regret' if they are required in all three hydrogen demand scenarios for use until at least 2050.
- In 2030:
  - A pipeline from **Spain to the France Atlantic coast** cluster
  - A pipeline from the cluster ***Italy, Croatia and Greece*** to the ***Eastern Central Europe*** cluster;
  - **Maritime import infrastructure**, i.e., import terminals and reconversion infrastructure, from the Middle East to the cluster of ***Italy, Croatia and Greece;***
  - A pipeline from **Greece** to the cluster of ***Bulgaria and Central/South Romania;***
  - Offshore wind energy production from the **North Sea** to produce green hydrogen in ***Belgium, Denmark, North of Germany and the Netherlands.***
- In **2040**:
  - **Maritime import infrastructure** (import terminals and reconversion infrastructure) from the Middle East to the cluster ***Belgium, Denmark, North of Germany and the Netherlands;***
  - **Maritime import infrastructure** from the Middle East or North Africa to the cluster ***Sweden, Finland and Baltics;***
  - A pipeline from **North Africa to the cluster *Western Mediterranean coast*** *(Spain and France).*
- In **2050**:
  - **Upscale maritime import infrastructure** to import hydrogen from North Africa to the cluster ***Belgium, Denmark, North of Germany and the Netherlands;***
  - A pipeline from **France to the cluster *Belgium, Denmark, North of Germany and the Netherlands.***

Further, other investments in infrastructure will be no-regret, such as **renewable electricity production infrastructure** (PV, onshore and offshore wind) and **electrolyser capacity,** which should be installed at all clusters. Also, the **consumption of hydrogen requires infrastructure investments**. For transport and port activities this will be refueling stations, bunkering terminals, etc. For industries and urban areas, having pipelines in place to transport hydrogen to the location of demand and having adjusted equipment for the consumption of hydrogen will be required. Finally, land should be made available for the development of the different infrastructures along the hydrogen value chain.

Source and notes: (1) Guidehouse, *Five hydrogen supply corridors for Europe in 2030*, 2022. (2) It should again be noted that our analysis is an economic optimization and does not take into account other factors such as policy initiatives and the adoption of additional supply routes to ensure security of supply. The comparison with the identified corridors in the European Hydrogen Backbone vision can be found earlier in the analysis.

Addendum: REPowerEU

Context

The 2020 EU hydrogen strategy explores how producing and using renewable hydrogen can help decarbonize the EU economy in a cost-effective way

In July 2020, within the framework of the EU strategy for energy system integration, the Commission adopted a new dedicated hydrogen strategy. The strategy explores how producing and using renewable hydrogen can help decarbonize the EU economy in a cost-effective way.

A roadmap for the EU

1 **2020-2024:** at least 6 GW of electrolyser capacity capable of **producing up to 1 Mt (or 33 TWh)** of renewable Hydrogen. Focus is on decarbonizing current Hydrogen production and facilitating the use of Hydrogen in industrial processes and for heavy-duty long-distance transport.

2 **2025-2030:** at least 40 GW of electrolyser capacity capable of **producing up to 10 Mt (or 333 TWh)** of renewable Hydrogen. A network of Hydrogen refueling stations and larger-scale storage facilities will have to be established. A basic EU-wide Hydrogen grid needs to be planned by repurposing parts of the existing gas grid.

3 **2030-2050:** Hydrogen technologies for the production and use of "clean" Hydrogen should **achieve maturity and reach all hard-to-decarbonize sectors** (such as aviation, maritime transport and industrial installations). Up to a quarter of renewable electricity will be needed for renewable Hydrogen production by 2050.

i The priority for the EU is to develop **renewable Hydrogen**, produced using mainly wind and solar energy. However, in the short and medium term, other forms of **low-carbon Hydrogen (blue hydrogen) are needed** to rapidly reduce emissions from existing Hydrogen production and support the parallel and future uptake of renewable Hydrogen.

An investment agenda for the EU

For the production and distribution part of the hydrogen value chain, the Commission assesses the **investment requirement up to 2030** at:

- EUR 24–42 billion for electrolysers;
- EUR 220–340 billion to scale up 80-120 GW of solar and wind energy capacity for the electrolysers;
- EUR 11 billion to retrofit half of the plants producing "fossil-based" hydrogen with CCS technologies;
- EUR 65 billion for hydrogen transport, distribution and storage as well as Hydrogen refueling stations.

To **support these investments,** the Commission established (among other things):

- European **Clean Hydrogen Alliance**, which coordinates investment between public authorities and industry, determine viable investment projects and set up a clear "investment pipeline" with them;
- the **InvestEU programme** supports the scale-up of Hydrogen supply by incentivizing private investment;
- European **Regional Development Fund** and the **Cohesion Fund** contribute to support innovations in the field of renewable and low-carbon Hydrogen.

Boosting demand and expanding supply

Boosting the demand

- In **industries** with existing Hydrogen demand (refineries, ammonia, methanol) and in the steel sector.
- In **road transport** where electrification is more difficult (local city buses, commercial fleets and heavy-duty road vehicles, including coaches).
- In **trains** where the electrification route is difficult or not cost-effective.
- In inland waterways, short-sea **shipping**; longer-distance and deep-sea shipping with conversion of renewable hydrogen in synthetic fuels, methanol or ammonia.
- Hydrogen can support in the longer-term the **aviation** sector to decarbonize.

Expanding supply

- Installation of **40 GW of electrolyser capacity** is planned for countries **neighboring** the EU by 2030.
- EU trade policy should prevent the emergence of market and trade barriers at an early stage.

The 2021 Global Gateway initiative is launched to boost smart, clean and secure economic links with non-EU partners

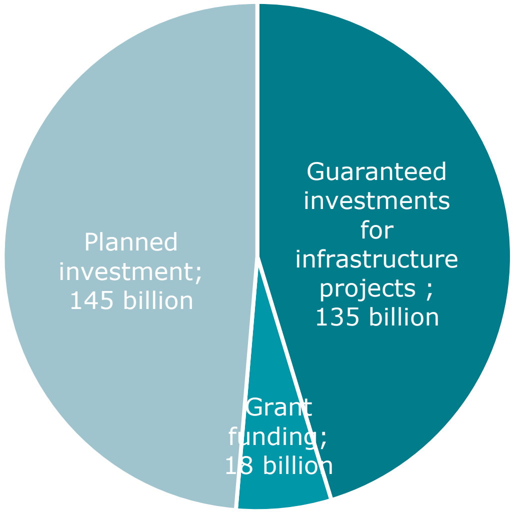
In December 2021, the EU launched the Global Gateway, the new European Strategy to boost smart, clean and secure economic links to underpin a lasting global recovery, considering our partners needs and EU's own interests.

Global Gateway aims to **mobilize up to EUR 300 billion in investments** between 2021 and 2027.

The key sector for investments priorities under Global Gateway:

- Investment in **digital** networks and infrastructures
- Investment in **energy** infrastructure and support in enacting regulation to foster the energy transition
- Investment in **transport** infrastructures and networks in all modes of transport as well as logistics, and border-crossing points.
- Investment in **pharmaceutical** supply chains security and the development of local manufacturing.
- Investment in quality **education**, including digital education and strengthen cooperation on **research and innovation**.

Breakdown of fundings in the Global Gateway Initiative



Implications of the investment package of Global Gateway Initiative for the hydrogen value chain:

- Increase the production of renewable energy and hydrogen **in EU neighboring countries**. One of the objectives is to reach at least **40 GW of electrolyser capacity** by 2030 on the African continent;
- Increase access to affordable, reliable and sustainable energy;
- Support regional hydrogen **market integration** and sector reforms to enable hydrogen to be **traded internationally** and within the EU without export restrictions;
- Help develop the renewable hydrogen sector by unlocking **business opportunities** in both the supply and demand side for energy intensive industries.

However, the EU should use the Global Gateway to implement the international aspects of European Green Deal – not merely to enhance Africa's exports of green energy (such as hydrogen) for European consumption.

The 2022 REPowerEU plan aims to make Europe independent from Russian fossil fuels and provides opportunities for accelerated decarbonization

In March 2022, in light of Russia's invasion of Ukraine, European Commission has proposed an outline of a plan to make Europe independent from Russian fossil fuels well before 2030, starting with gas.

The REPowerEU will increase the resilience of the EU's energy system by:

- **Diversifying gas supplies**, via higher LNG imports and pipeline imports from non-Russian suppliers, and higher levels of biomethane and hydrogen.
- **Reducing our dependence on fossil fuels** more rapidly in the buildings, industrial and power sectors by boosting energy efficiency gains, increasing the share of renewables and addressing infrastructure bottlenecks.

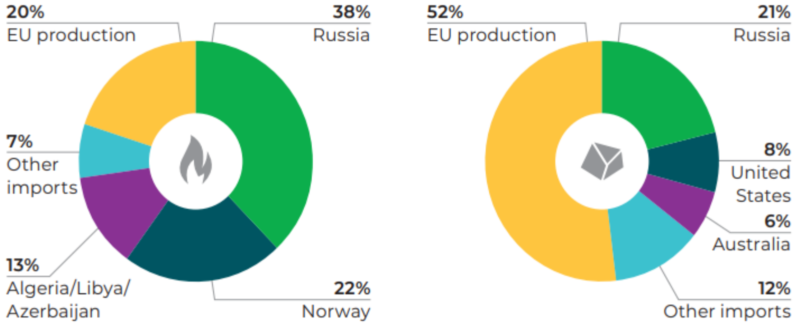
Implications of REPowerEU for European hydrogen value chain:

Objective: to supply the equivalent of 25-50 bcm per year of imported Russian gas by 2030 with additional 500 TWh - (333 TWh of imports and 167 TWh of European production) of renewable hydrogen on top of the 187 TWh foreseen under the Fit for 55.

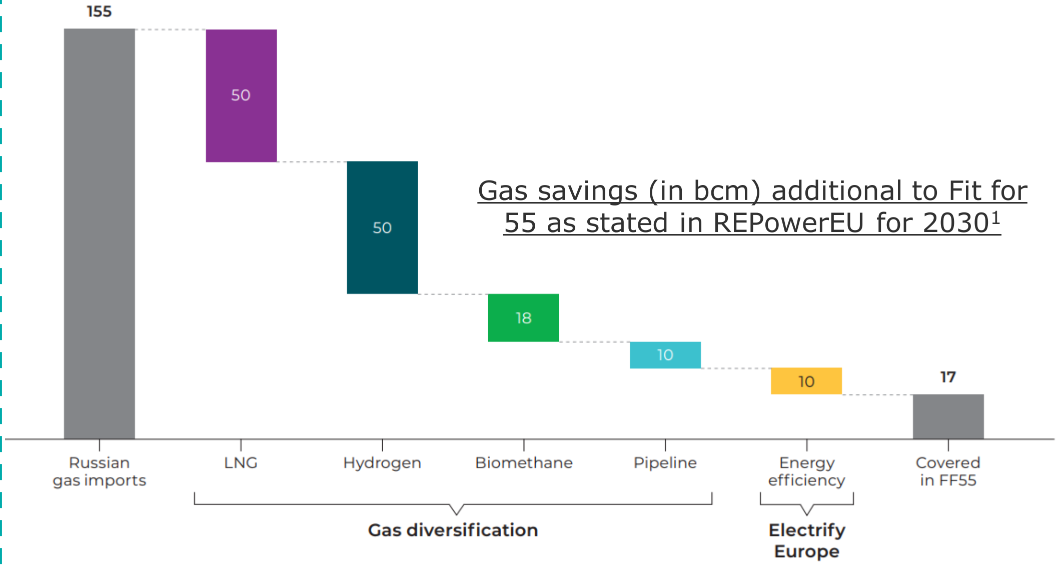
How: to achieve this objective, the Commission will:

- Further develop the regulatory framework to promote a European market for hydrogen.
- Support the development of an integrated gas and hydrogen infrastructure, hydrogen storage facilities and port infrastructure & ensure that new cross border infrastructure are hydrogen compatible.
- Assess State aid notification for hydrogen projects as a matter of priority.
- Support pilot projects on renewable hydrogen production and transport in the EU neighborhood.
- Establish Green Hydrogen Partnerships and a Global European Hydrogen Facility, boosting Member States' access to affordable renewable hydrogen.

Gas and coal imports as a % of total EU consumption in 2020[1]



Gas savings (in bcm) additional to Fit for 55 as stated in REPowerEU for 2030[1]



Sources: (1) Gas for Climate & Guidehouse, 2022

REPowerEU scenario

Main assumptions

A dedicated REPowerEU scenario has been developed based on assumptions defined in the REPowerEU plan

Following an evolving context during the course of the study, it was decided to look into the implications of the REPowerEU plan in this addendum to the main report. The different goals stated in the **REPowerEU plan** were taken as a **basis** to construct an additional REPowerEU scenario. Assumptions are thus based on the REPowerEU plan. This scenario reflects to **short-term goal to replace Russian fossil fuel imports (partially) by green hydrogen**, whereas the scenarios developed in the main report have been established in a pre-Russo-Ukrainian war context.

Assumptions taken in the REPowerEU scenario for hydrogen demand:

1. The **projected hydrogen demand in 2030** is about **20 Mt** (or 687 TWh).
2. **Two additional hydrogen demand sectors** were considered compared to the other scenarios in the study: the power sector and aviation.

Assumptions taken in the REPowerEU scenario for hydrogen supply:

1. **All new hydrogen supply** is assumed to be **green** (i.e., no blue hydrogen imports are considered).
2. The hydrogen demand in 2030 will by supplied for **50% by local production and for 50% by import**.
3. Out of the 10 Mt (333 TWh) of imports, **4 Mt will be imported in the form of ammonia** via tankers (ships) and **6 Mt will be imported via pipelines** in the form of gaseous hydrogen, for which supply capacity for transporting hydrogen into Europe is assumed to be established by 2030[2]

Note: (1) EPRS, The potential of hydrogen for decarbonizing EU industry, 2021. (2) For the pipeline import, it is assumed that current natural gas pipelines are repurposed by 2030. The other scenarios on the other hand assume inter-European hydrogen pipeline infrastructure would not be ready by 2030.

Hydrogen demand

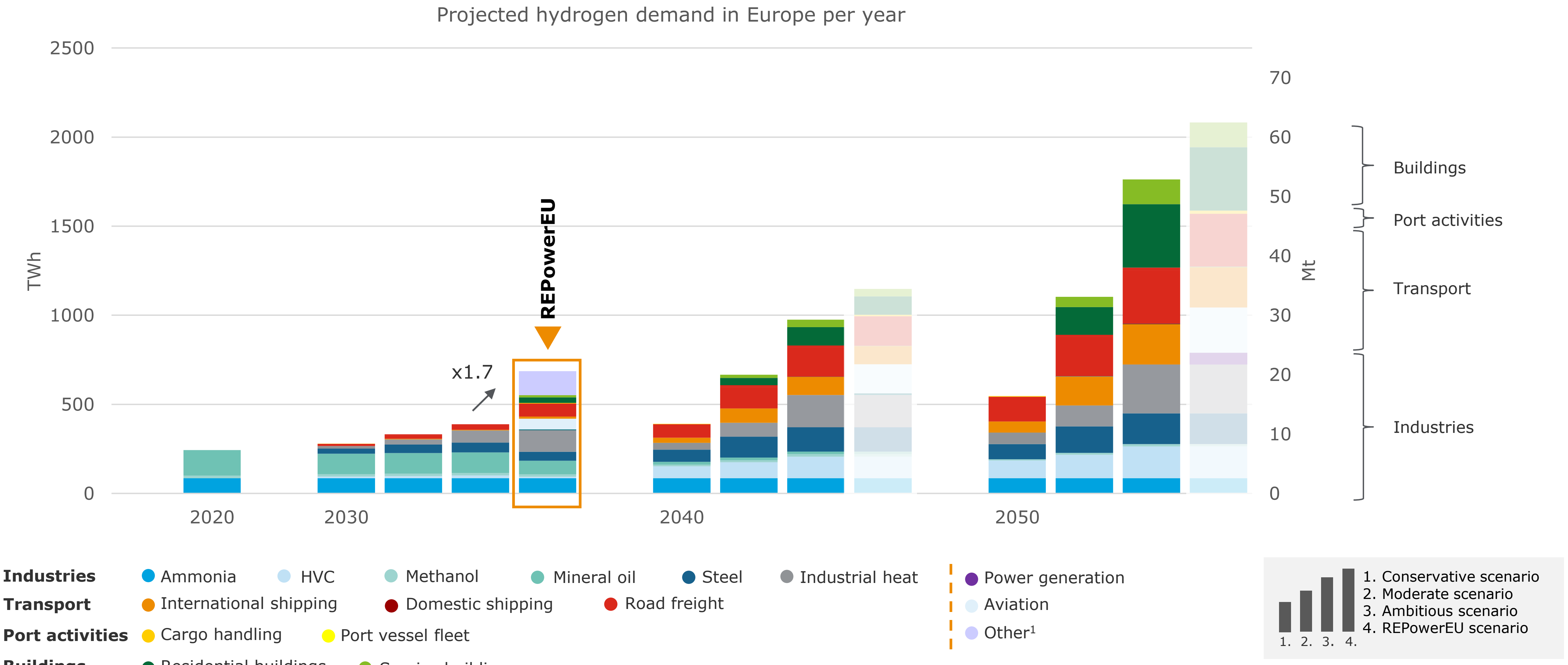
Comparison of the REPowerEU demand data[1] with the ambitious scenario

REPowerEU Communication	Demand estimates 2030 (TWh)
Refineries	77
Industrial heat	120
Transport	77
Petrochemicals (ammonia)	107
Blast furnaces	50
Synthetic fuels	60
Power generation	3
Blending	43
Ammonia/derivatives imports	133
Total	**687**

Deloitte study	Ambitious scenario 2030 (TWh)	New REPowerEU scenario 2030 (TWh)	Increase (in %)
Hydrogenation of fuels	115	77	-36%
Industrial heat	68	120	+76%
Heavy-duty road freight	27	73	+170%
Cargo handling	4	4	+0%
Ammonia (fertilizers)	85	85	+0%
HVCs	16	8	-50%
Methanol (for current uses)	14	14	+0%
Primary steel	55	50	-9%
Aviation	/	60	/
Power generation	/	3	/
Residential heating	0	30	/
Service heating	0	13	/
International shipping[2]	4	12	+300%
Domestic shipping	~0	1	/
Port vessel fleets	~0	~0	/
Other sectors (split between clusters)	/	133	/
	388	**687**	**+174%**

Source: (1) The sector split is based on REPowerEU's Staff Working Document (page 27). **Note:** (2) Hydrogen demand in international shipping is added on top of the communicated REPowerEU hydrogen demand of 20 Mt, due to studies (EPRS, The potential of hydrogen for decarbonizing EU industry, 2021) showing hydrogen is no-regret option for shipping in 2030.

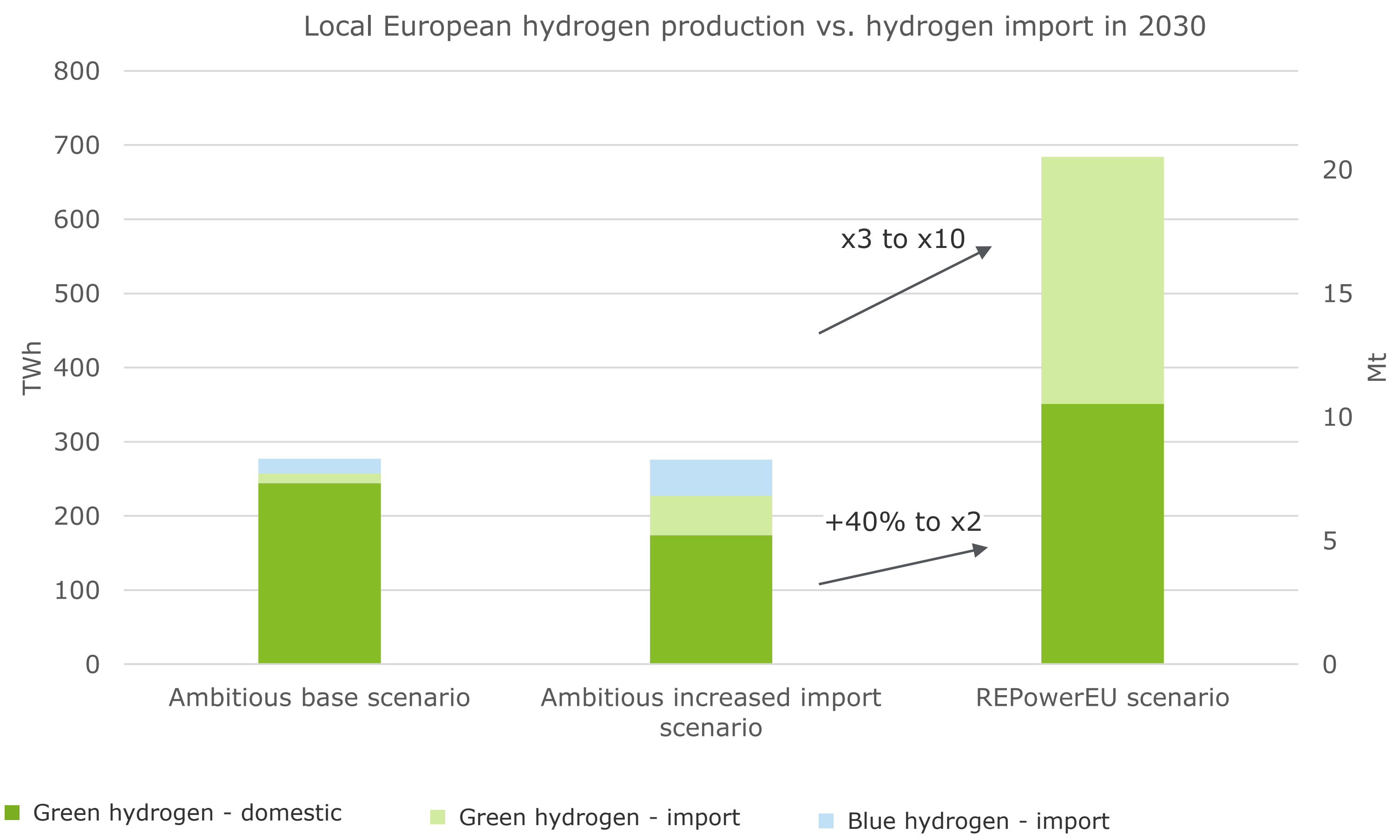
REPowerEU represents a significant acceleration in terms of hydrogen uptake in Europe compared to other scenarios



Note: The large differences in estimates of future hydrogen demand reflect the great degree of uncertainty that currently exists in the adoption of hydrogen as a replacement for fossil fuels in some sectors, notably the 'Buildings' sectors (heating of residential and service buildings). For all the other sectors in scope of this study (industries, transport and port activities), all three scenarios foresee a role for hydrogen, at least to some extent. (1) This category includes part of the ammonia/hydrogen derivatives imports defined in the REPowerEU communication

Hydrogen supply

REPowerEU scenario shows a very significant increase of imported green hydrogen, next to an important increase of locally produced green hydrogen

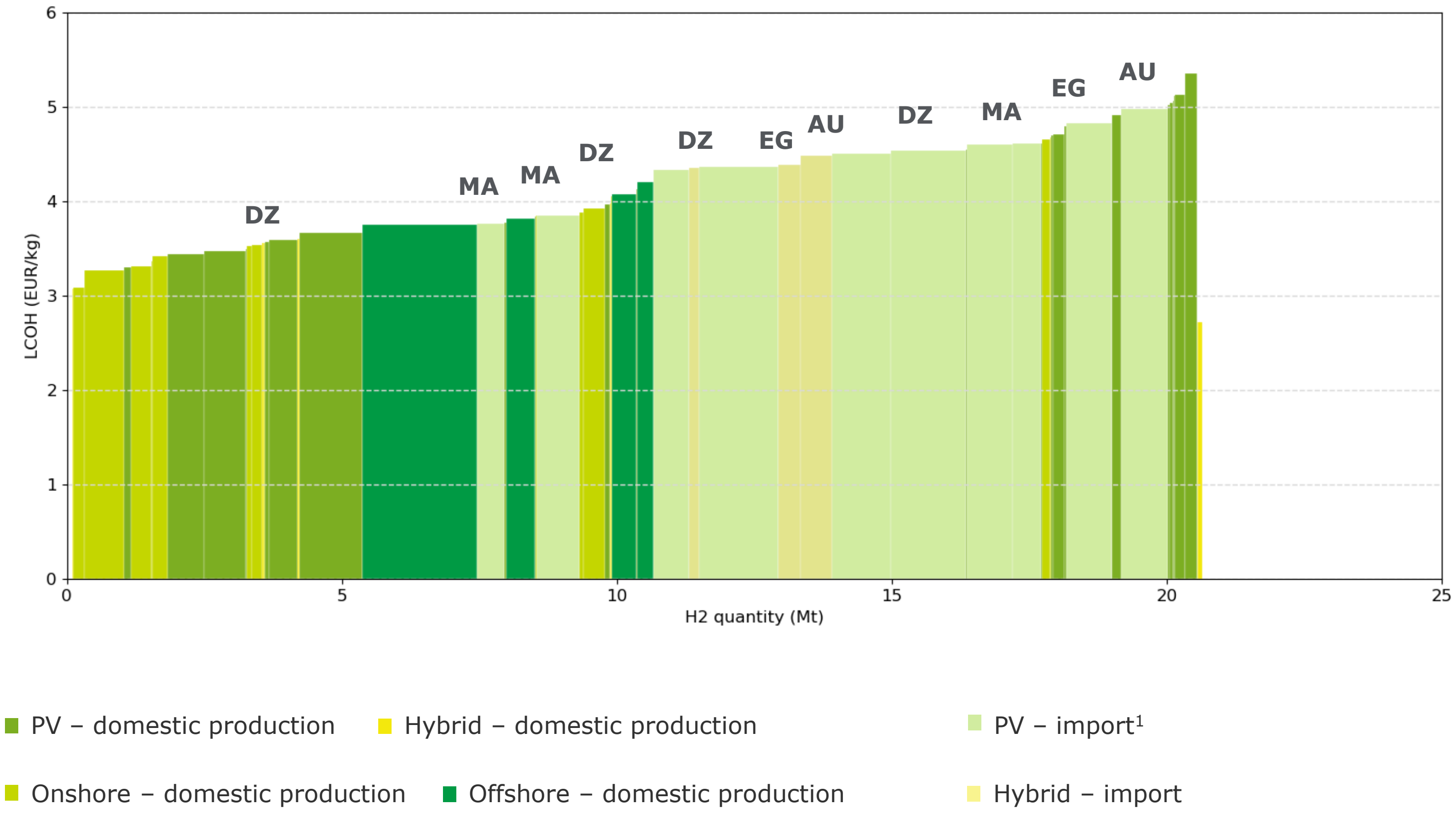


Key messages:

- The REPowerEU scenario assumes **50%** of the hydrogen demand will be **supplied by local production and 50% by import**
- The REPowerEU scenario foresees a **hydrogen import** in 2030 which is **x3 to x10 higher** compared to the respective ambitious scenarios. By definition the REPowerEU scenario only foresees **green hydrogen import**
- The REPowerEU scenario foresees a **local hydrogen production** in 2030 which is **40% to x2 higher** compared to the respective ambitious scenarios
- Note that this and subsequent graph(s) only show new supply, as defined in Task 2, and consequently do not show grey or on-site blue hydrogen supply, which is present in both ambitious scenarios

Local onshore, PV and hybrid produced hydrogen is the most cost-effective and complemented by more expensive local production and green imports

Merit order curve hydrogen supply – REPowerEU scenario in 2030

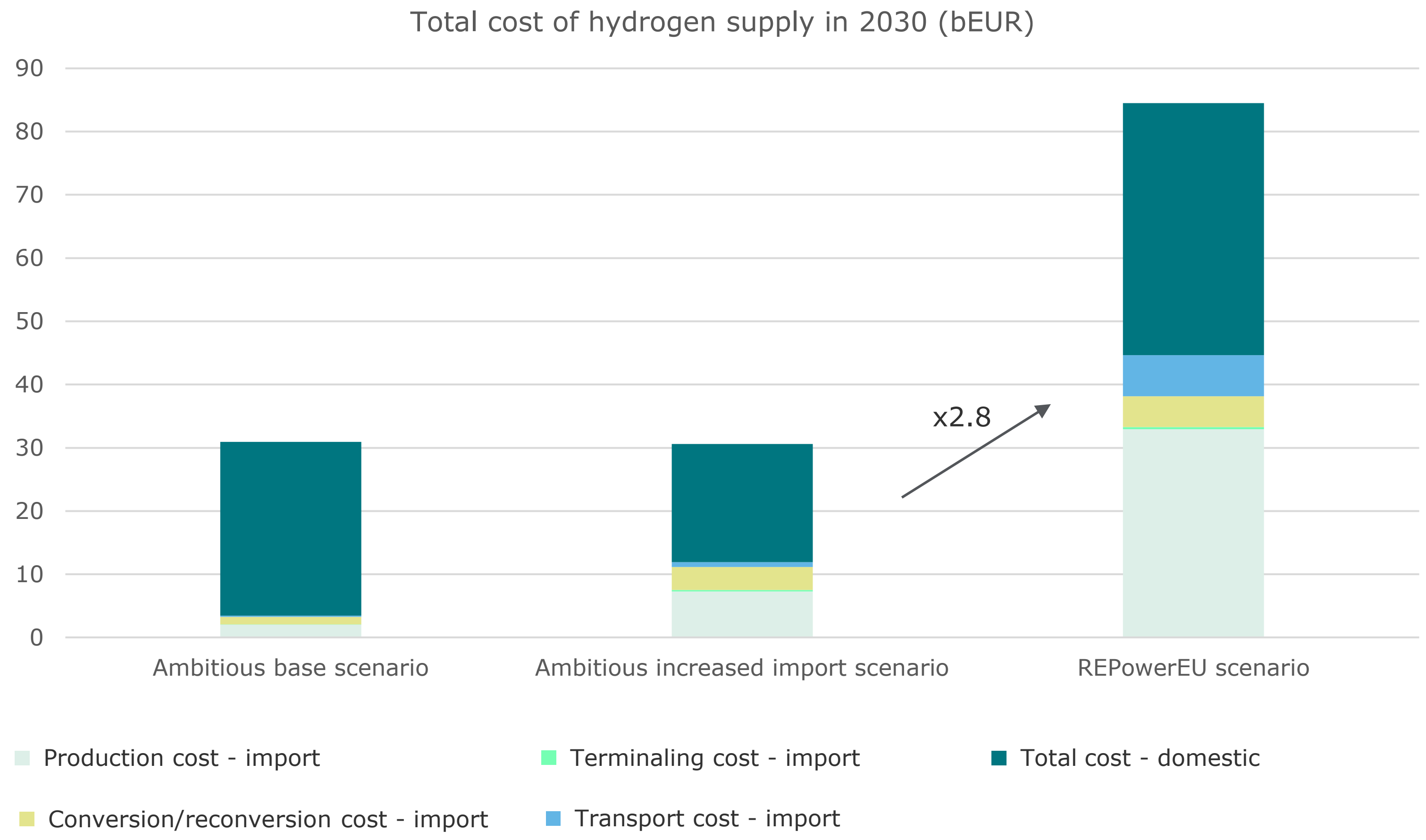


Key messages:

- In the REPowerEU scenario:
  - The projected **LCOH range** is between **3.1 – 5.4 EUR/kg**.
  - Local onshore, PV and hybrid systems are the most cost-effective hydrogen sources.
  - Green hydrogen imports are expected from **Algeria, Morocco, Egypt and Australia** at 3.8 – 5 EUR/kg.
  - The majority of hydrogen import is PV sourced.
- Compared to the ambitious base and ambitious increased import scenario:
  - The **average LCOH** is about **10% higher** in the REPowerEU scenario (4.1 EUR/kg) compared to the ambitious base and ambitious increased import scenario (3.7 EUR/kg).
- Half of the hydrogen is supplied from local production and half is imported, as assumed by REPowerEU.

Note: (1) The results from the model show a large role for PV-based hydrogen import, since in certain export countries there might be a large role for hydrogen production based on PV generated electricity, such as Oman. However, in reality it is likely, also wind energy could play a large role for imported hydrogen, e.g. in Morocco there is projected a role for wind farms as well as solar power plants for the production of hydrogen.

REPowerEU scenario projects the annual cost of hydrogen supply to be around 84.5 bEUR in 2030

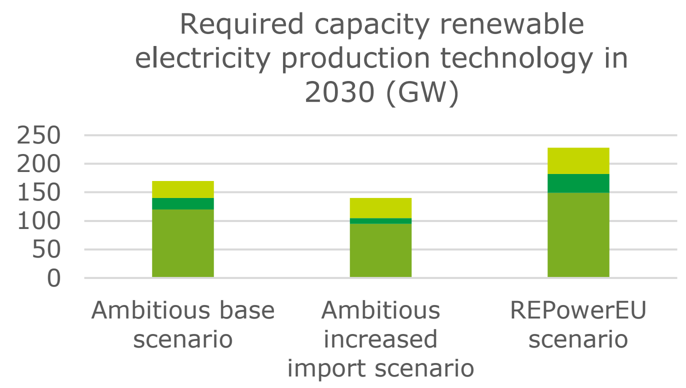


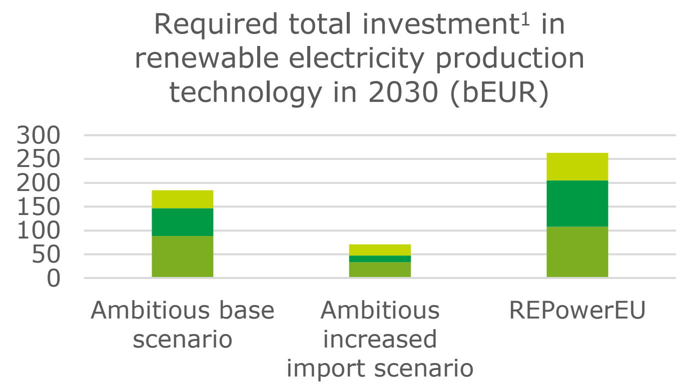
Key messages:

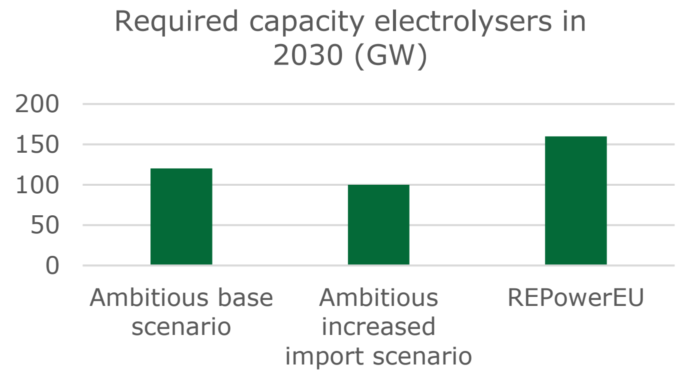
- REPowerEU scenario projects the **annual cost of hydrogen supply** to be around **84.5 bEUR per year**, of which the cost of locally produced hydrogen is 40 bEUR and imported hydrogen 44.5 bEUR, in 2030
- To satisfy the increased hydrogen demand the cost of hydrogen supply in the REPowerEU scenario is about **x2.8 higher** compared to the other ambitious scenarios (excluding the cost of grey and on-site blue hydrogen)
- The cost of hydrogen supply will be **partially compensated** by reduced fossil-fuel import. The compensation is highly dependent on the natural gas price. At a natural price of 65 EUR/MWh, the **natural gas savings by using hydrogen** in the REPower EU plan additional to Fit for 55 (50 bcm), **could save 32 bEUR per year**
- The annual cost does not include longer term hydrogen storage, which might be required.

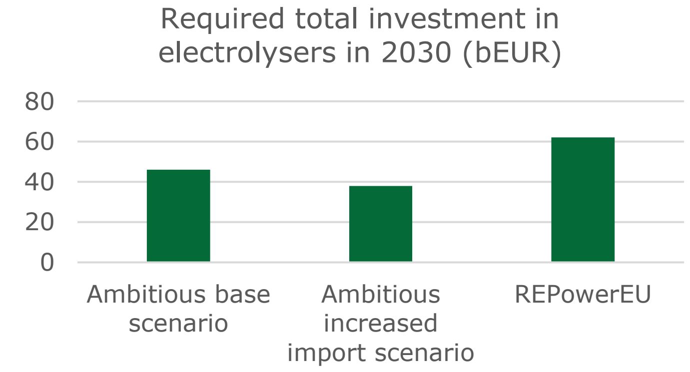
Required hydrogen value chain infrastructure

Solar PV in combination with electrolysis is projected to be requiring the highest capacity and investments









PV solar Offshore wind Onshore wind

Key messages:

- REPowerEU scenario requires **228 GW** of domestic **renewable electricity production capacity** corresponding to a total investment of approximately **263 bEUR**:
  - **Solar PV in combination with electrolysis is projected to be the most used technology** to locally produce hydrogen
  - Compared to the required capacities, **wind energy takes a larger share in the required investments**. This is due to the higher CAPEX price per GW of wind installations.
  - This represents a **significant addition to today's renewable capacity of 512 GW in EU**[2], especially given the increased need for renewable electricity for direct electrification which would bring the total renewable energy generation capacity envisaged by the **REPowerEU plan to 1,236 GW by 2030**.
- The total **investments required** by 2030 in hydrogen production technology are **x1.4 to x3 higher in the REPowerEU scenario** compared to the respective ambitious scenarios

Note: (1) The investments are the total investments required in a certain year to provide the necessary capacities taking into account the lifetime of the technology and thus also reinvesting in technology is the lifetime has passed. Changing value of money is not taken into account. **Sources:** (2) IRENA, *Renewable Capacity Statistics 2022*

Comparison of study results with REPowerEU plan for investments in renewable electricity and electrolysers

	EU Hydrogen Strategy	REPowerEU plan	Deloitte study results – REPowerEU scenario	Deloitte study results – other scenarios
Renewable electricity capacity by 2030	80 -120 GW	Not specified	228 GW	45 – 170 GW
Investments in renewable electricity by 2030	220 – 340 bEUR	200 – 300 bEUR	263 bEUR	51 – 169 bEUR
Electrolyser capacity by 2030	> 40 GW	120 GW	160 GW	35 – 120 GW
Investments in electrolysers by 2030	24 – 42 bEUR	50 – 75 bEUR	62 bEUR	13 – 47 bEUR
	EU communications		*Study results*	

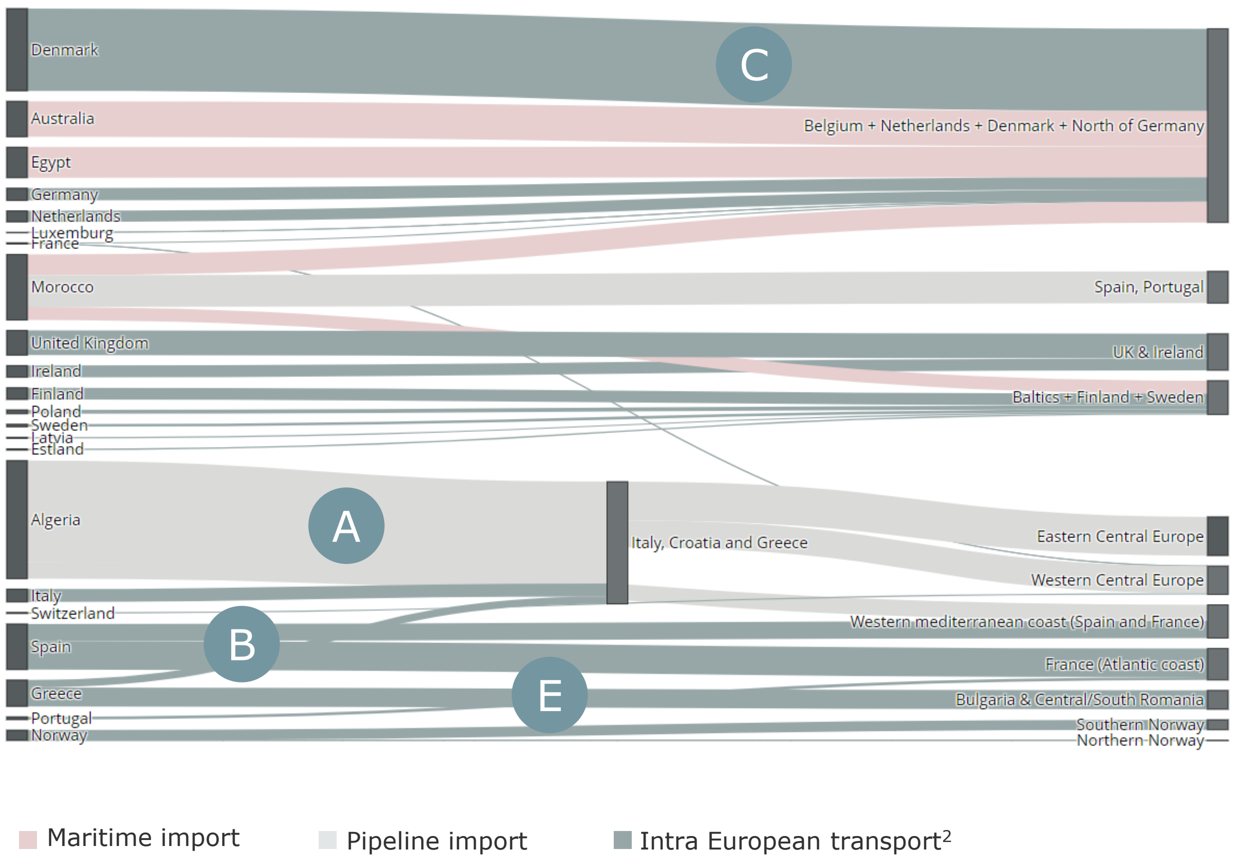
Key messages:

- The **projected investments in the REPowerEU scenario** in our study are **in line** with the projection made in the REPowerEU plan
- The **factor renewable energy capacity vs. electrolyser capacity is projected to be lower** in our study compared to e.g. NECP ratio. This can be explained because the HyPE model optimizes the overall installation electrolyser + renewable energy system in each location based on climate data, technology-related data and economic parameters. The model will always try to choose best locations with higher capacity factors to lower the cost and get higher hydrogen output.
- As indicated in the previous slide, the REPowerEU plan and its' short timeframe set to achieve independence from Russian fossil fuels poses an important challenge to implement it and an **accelerated deployment of domestic renewables is key**. It should be noted that focus on domestically produced green hydrogen creates a meaningful risk of cannibalizing scarce renewable electricity resources[1].

Note: Looking at the implications of the investment package of the **Global Gateway Initiative** for the hydrogen value chain, we can compare these with the study results: 1) In the study results, there are green hydrogen imports from Morocco and Egypt. This aligns with the objective to increase electrolyzer capacity in EU neighboring countries, such as countries in the African continent. 2) The results show that almost all hydrogen will be supplied at a maximum cost of 3.5 EUR/kg in 2050. 3) Hydrogen to be traded internationally and within the EU without export restrictions is a prerequisite for the outcome of the model. 4) Industries are the largest contributors to hydrogen demand in the results. **Source:** (1) Florence School of Regulation, *A first look at REPowerEU: The European Commission's plan for energy independence from Russia*, 2022

There is a diversified mix of supply sources and different corridors, increasing the supply resilience

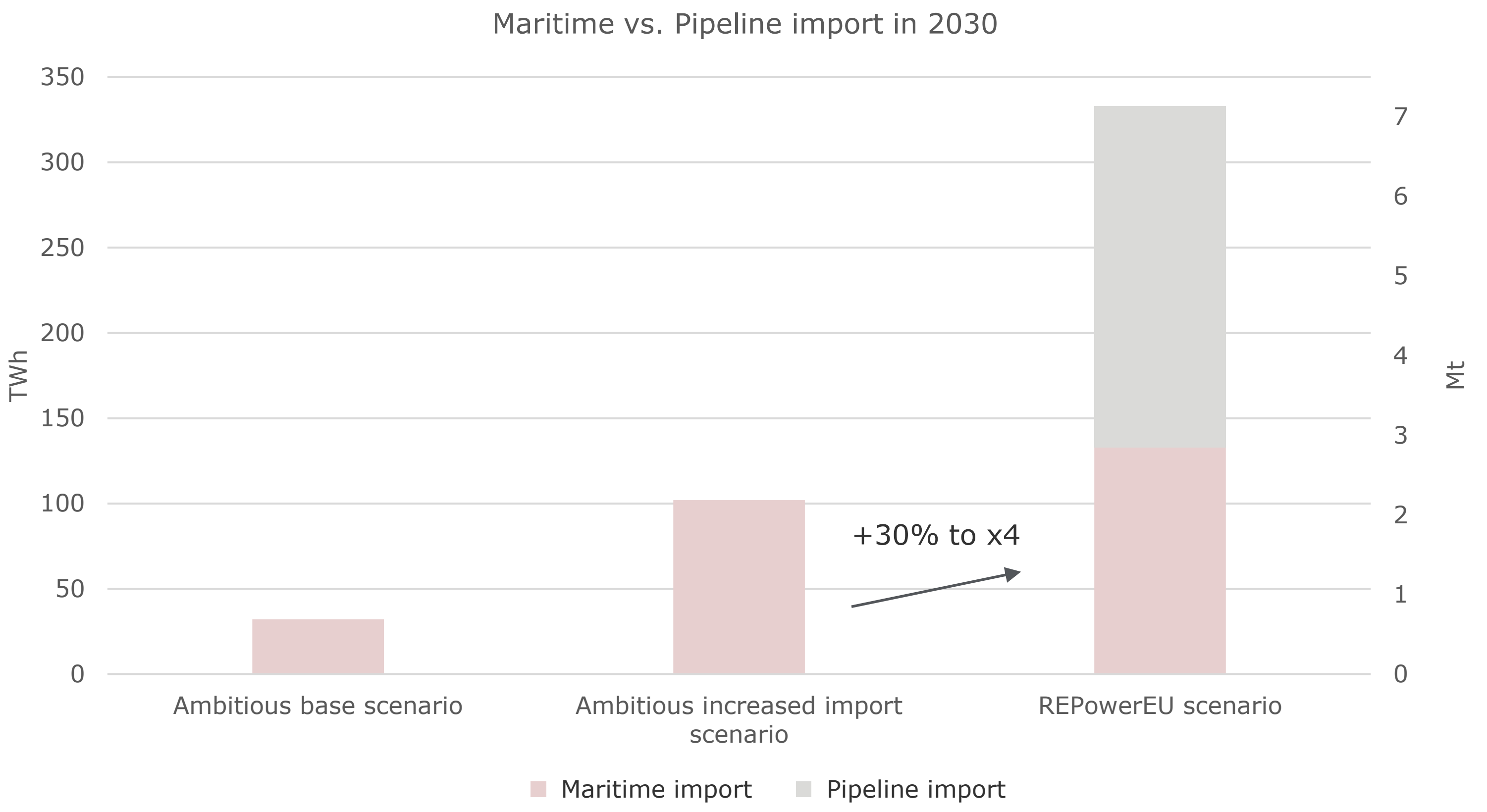
REPowerEU scenario in 2030



Key messages:

- There is a **diversified mix of supply sources, in line with the European resilience strategies** with a notable dependency on **hydrogen from Algeria, and significant domestic production reliance on Denmark and Spain.**
- The clusters *UK and Ireland; France (Atlantic coast); Bulgaria and Central/South Romania; Southern and Northern Norway* hydrogen are projected to be only supplied from **sources inside of Europe, notably Spain, UK and Greece**. All other clusters will require hydrogen import from outside of Europe.
- Hydrogen is projected to be imported via **pipeline from North Africa carrying hydrogen from Algeria and Morocco** to the clusters *Western mediterranean coast (Spain and France); Spain and Portugal* and *Italy, Croatia and Greece*, via which hydrogen will be transitted to the clusters *Western and Eastern Central Europe*
- The cluster *Belgium, Netherlands, Denmark and North of Germany; Baltics, Finland and Sweden* it is projected that next to **domestic production from Denmark**, Germany and the Netherlands, hydrogen will be supplied via **maritime import**.
- To deliver the hydrogen demand and supply targets set by the REPowerEU plan, five large-scale pipeline corridors are envisaged by European Hydrogen Backbone initiative, as introduced in Task 2. From our economical analysis, it can be concluded that there is indeed a projected need for corridor A (North Africa and Southern Europe (from Algeria through Italy to Central Europe)), B (Southwest Europe and North Europe), C (North Sea) and E (East and South-East Europe).

In the REPowerEU scenario, of the imported hydrogen, the largest part is imported via repurposed pipelines

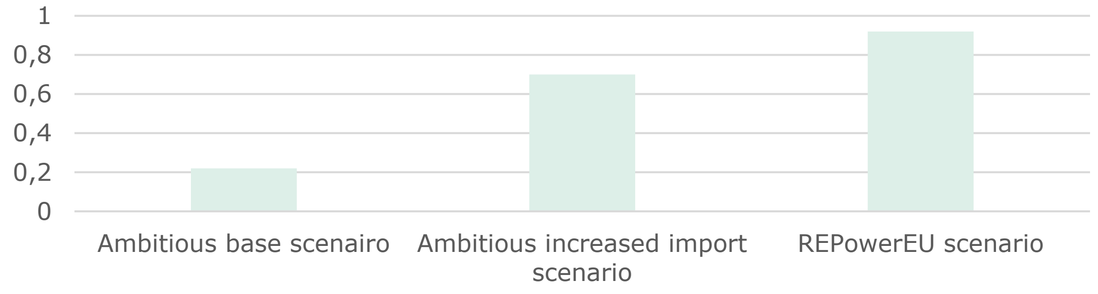


Key messages:

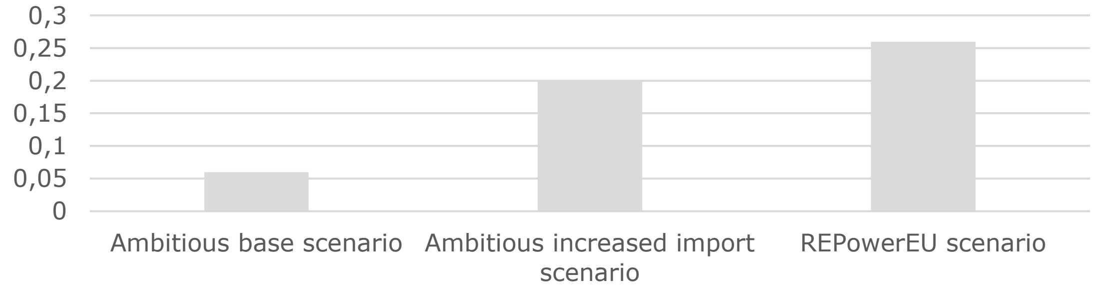
- In 2030 in the REPowerEU scenario, it is assumed that **60% of the imported hydrogen will be imported via pipelines** in the form of gaseous hydrogen. The other **40% will be imported via ship** in the form of ammonia, an increase of +30% to x4 compared to the ambitious scenarios
- For the pipeline import, it is assumed that **current natural gas pipelines are repurposed by 2030**. The earlier LCOH analysis shows that these pipeline imports are cost-effective compared to maritime imports, especially for H2 end-uses requiring ammonia cracking in the case of maritime import. The **other ambitious scenarios** do not exhibit pipeline imports by 2030 because these scenarios assume inter-European hydrogen **pipeline infrastructure would not be ready by 2030.**

Investment in import infrastructure follows the increase of maritime import

Required investment in reconversion infrastructure in 2030 (bEUR)



Required investment in import terminal infrastructure in 2030[1] (bEUR)

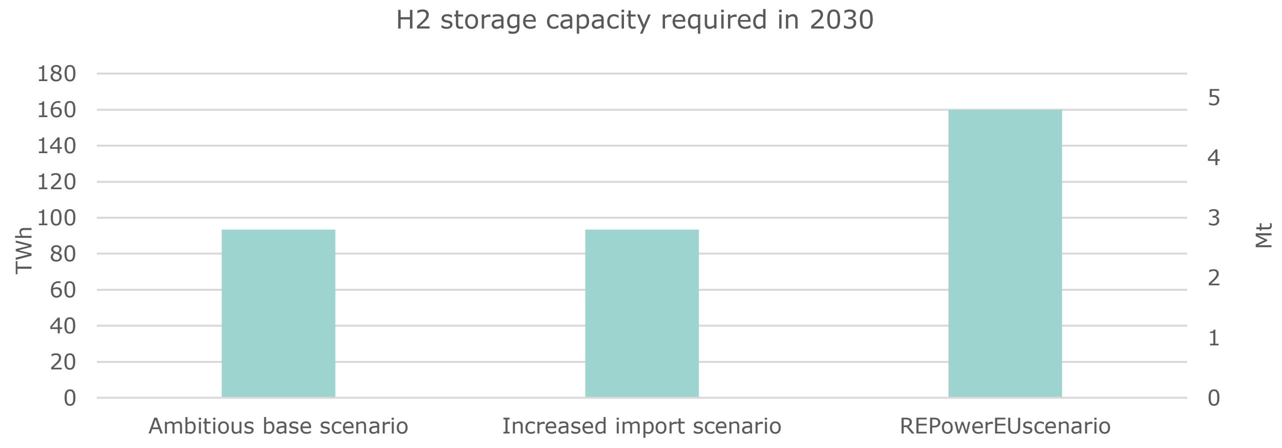


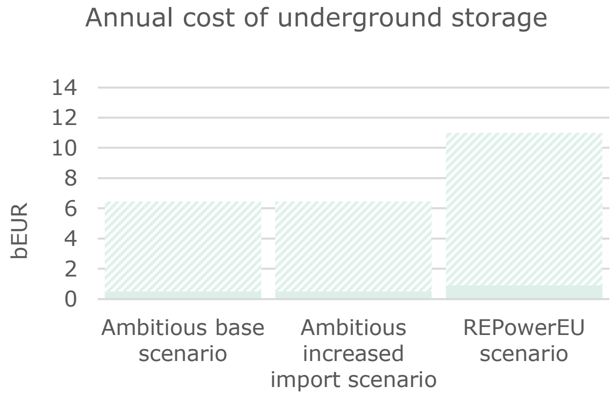
Key messages:

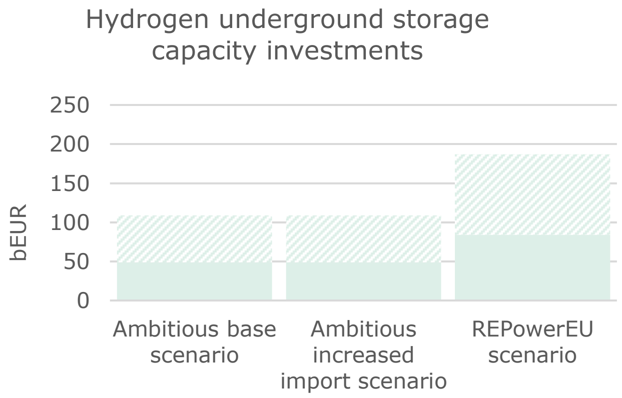
- The graphs show the required **investments in a certain year in import infrastructure in Europe**. The total cost for investing was annualized[2]. Only import infrastructure for hydrogen (or derivatives) imported via ship is assumed to require import infrastructure in the model (import terminal and reconversion plant). Hydrogen imported via pipeline will also require storage, however, this is considered part of the next slide since it is not (always) required at the port area itself
- The **dominating factor in the total investment cost for importing via ship is reconversion infrastructure**. Note that reconversion might not always be necessary due to direct applications, leading to lower costs
- Capacities of the infrastructure for reconversion, as well as for terminals, should be large enough to handle the amount of hydrogen supplied via ship. All numbers per scenario can be found in the previous slide, in the REPowerEU scenario in 2030 this is equal to 133 TWh (4 Mt). This annual send-out capacity leads to a required storage at import terminals of 1.7 TWh (equal to ~190 LH2 storage tanks assuming a capacity of 9 GWh)[4]. The number of reconversion plants required depends on the size of the plant (assuming a capacity of 0.32 Mt/year, ~13 plants would be required)[3,4]

Note: (1) A temporary storage is included in the import terminal, before reconversion. (2) The model does not make an investment decision and it thus not bound to the infrastructure lifetime, only the CAPEX cost at a certain year is given. (3) Not taking into account plants for demonstration purposes. (4) All assumption can be found in the main deck (slide 131)

In the REPowerEU scenario cost for storage is around twice as high as in the ambitious base and increased import scenario





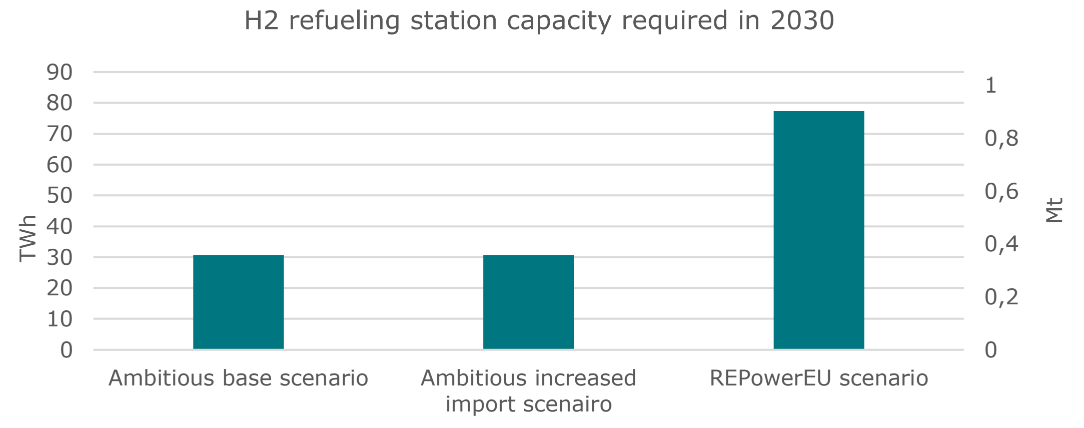


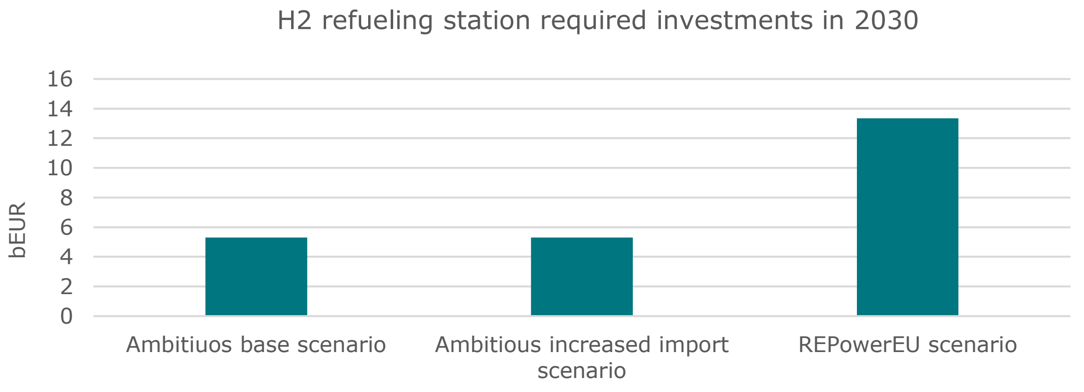
Key messages:

- In 2030, **160 TWh (4.8 Mt) of storage capacity** would be required for the projected hydrogen demand in the REPowerEU scenario.[1]
- Current underground storage of gas has been estimated to be able to store 265 TWh (7.95 Mt) of gaseous hydrogen. It should be considered that there will still be a need for storage of methane gases and thus not all current storage locations will be available for repurposing, and the repurposing of storage locations will take time, leading to the development of new storage locations that will likely be required before 2050. It is thus likely future storage needs will be met by both repurposed and new assets (e.g. salt caverns not yet used for gas storage)[2].
- To give an estimation of the cost of hydrogen storage, based on different sources and different type of storage, cost ranges are defined. The estimated range of the levelized cost of underground storage is: 0.18 – 2.30 EUR/kg[1]. This leads to a **projected cost of supply between 0.9 – 11 bEUR** in the REPowerEU scenario in 2030.
- The range of investments in underground storage is estimated at: 17.41 – 38.91 EUR/kg[1]. This leads to projected **required investments in storage between 84 and 187 bEUR** in the REPowerEU scenario by 2030.
- For hydrogen storage, attention should be paid to the safety aspect. This is however out of scope of this report.

Sources: (1) Guidehouse, *Picturing the value of underground gas storage to European hydrogen system,* 2021; estimation based on current ratio between the cumulative natural gas demand and underground storage working gas capacity. However, this is still uncertain and different studies show high variability. (2) the total potential capacity of salt caverns alone is estimated at around 85,000 TWh, as mentioned in the main deck (slide 134)

The unfolding of the REPowerEU scenario will substantially accelerate the speed of hydrogen adoption in the transport sector, resulting in increased requirements for refueling station capacity and associated investments (2.5 times higher than in the ambitious scenarios).





Key messages:

- The REPowerEU scenario assumes a substantial increase in hydrogen demand linked to heavy-duty freight (cf. slide 151) leading to and increased need for hydrogen refuelling stations.
- In the model, a capacity of 2,000 kg/day is assumed, at a cost of 2,100 EUR/kg/day. The cost for one refueling station with a capacity of 2,000 kg/day is thus 4.2 MEUR.
- Hydrogen refueling stations capacity required per port are calculated based on the hydrogen demand per scenario for road freight and cargo handling.
- The **required hydrogen refueling station capacity in the REPowerEU scenario is projected to be 77 TWh (2.3 Mt)** in 2030.
- The **required investments in refueling station capacity in the REPowerEU scenario is projected to be 13 bEUR** by 2030.

Note: (1) mainly relevant for **Transport and logistics archetype**

Task 3

Hydrogen business models for ports

Roles of ports

Overview

Landlord

Providing land for hydrogen economy

Examples

Port of Antwerp providing land for fuel station for shipping — Port of Antwerp Bruges

North Sea Port providing space for the construction of electrolysis unit by VoltHydrogen Terneuzen on the port site — North Sea Port

Port of Barcelona in the Hydrogenising Barcelona initiative — Port de Barcelona

Community builder and enabler

Bringing the right parties together locally and globally

Examples

Transhydrogen Alliance — Port of Rotterdam

Hydrogen Import Coalition — Port of Antwerp Bruges

Joining forces to develop a hydrogen network in the port area — North Sea Port

Hamburg Green Hydrogen Hub — Port of Hamburg

Bringing together different parties to enable HydrogenPorts project — valenciaport, Autoridad Portuaria de Valencia

Part of Pioneers project — constantza port

Investor

Investing in infrastructure/equipment/etc. enabling the hydrogen economy

Examples

Hydrogen gas pump for heavy goods vehicles by 2023-24 — PORT OF GOTHENBURG

Port of Antwerp initiated the construction of the first tugboat on hydrogen — Port of Antwerp Bruges

Landlord

*Ports that would endorse a landlord role in the hydrogen economy will essentially **provide the required lands for companies to install their hydrogen infrastructures & solutions**. Mostly this happens through concessions in which the ports have the capacity to conclude contracts, enforce standards, and make rules and regulations applicable within the port area. The role is more "passive", but it needs to be well thought through in terms of ecosystem to make sure all the new actors can co-exist with current port activities and actors. Often they take up the responsibility to make sure all boundary conditions to enable a hydrogen economy are met (e.g. how hydrogen import can happen safely)*

Key port activities across the hydrogen value chain

Production

Ports providing land for companies to build **hydrogen production facilities or import terminals**

Examples:

- *Port of Rotterdam: Hydrogen-Fifty project*
- *Port of Bremen: Skribble electrolysis test field*

Conversion, transport & storage

Ports providing land for **hydrogen pipelines** to connect producers, distributors and customers, or in their role as energy & transit hub

Ports providing land to install **bunkering facilities** for hydrogen

Example:

- *Port of Gothenburg and Statkraft entered an agreement to investigate the potential for interim storage*

Consumption

Port providing land for **hydrogen fuel stations** for road freight, locomotives, cargo handling & other port equipment, and shipping.

Examples:

- *Port of Antwerp: fuel station capable of supplying green hydrogen directly to ships*
- *Port of Duisburg: host Europe's first carbon neutral container terminal powered by hydrogen*

Port providing land for **industrial hydrogen consumers**

Investments ports should consider

- ***Provide land and/or make land available** to foster hydrogen activities across the value chain (production facilities (MAKE), import terminals (BUY), pipelines, bunkering facilities, fuel stations etc.)*
- ***Partner with companies** willing to place their facilities/assets/infrastructure on the available lands*

Added value for ports

- ***Enable ports in their transition to net-zero** (e.g. hydrogen fuel stations for port equipment)*
- ***Attract companies** to the port to tap into the opportunities created by the available land to support hydrogen activities*
- ***Increase port traffic & attract new companies** since port enables the supply and availability of hydrogen*

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

Community builder and enabler

*Ports that would endorse a community builder and enabler role in the hydrogen economy will essentially **provide a platform for the actors involved in the hydrogen value chain to discuss, collaborate and innovate**. The community builder and enabler role implies a variety of involvement degree from a port, it can go from taking part in region or global network (for smaller ports for example) or bringing actors together to set up new projects on premises (for larger ports for example). They look beyond the port perimeter to engage in strategic partnerships. In some cases this includes connecting with the government, bringing insights to regulatory bodies and help shaping regulations or delivering consultancy to other ports.*

Key port activities across the hydrogen value chain

Production	Conversion, transport & storage	Consumption

Ports bringing actors together by organising events with European industry, policy makers, government representative, research community and other ports to exchange knowledge (Clean hydrogen alliance, global Ports Hydrogen Coalition), but as well developers, builders, users and investors capable of carrying concrete projects. Ports can also open up and serve as testing grounds to develop new technologies related to the hydrogen economy.

Examples:

- *Port of Valencia: creation of an advisory board to work on the construction of the hydrogen value chain for port*
- *Port of Antwerp-Bruges: be an "incubator" for potential demonstrators*

Ports being part of global network to import or produce hydrogen and actively develop trade of hydrogen as global trade routes around hydrogen are emerging, and international cooperation with other regions is crucial.

Examples: Port of Rotterdam - Signed a Memorandum of Understanding with the Government in Western Australia agreeing to collaborate on the development of the hydrogen supply chain

Ports promoting hydrogen as an important and sustainable energy carrier

Investments ports should consider

- ***Taking part in regional and global alliances and networks*** *(BUY and MAKE)*
- *For larger port with larger capacity,* ***forming a local platform*** *with actors to discuss hydrogen projects (BUY and MAKE) for the port itself*
- ***Developing solid relationships with the whole ecosystem*** *(industry actors, policy makers, government, investors, etc.) (BUY and MAKE)*
- ***Promoting hydrogen*** *as a sustainable energy carrier (BUY and MAKE)*

Added value for ports

- ***Steer investment and projects*** *in the right direction by bringing ports knowledge to the table*
- ***Have a say in important decisions*** *taken by actors of the hydrogen economy*
- ***Increase port traffic & attract new companies***
- ***Enable ports in their transition to net-zero***

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

Investor

*Ports that would **invest in projects & infrastructure** to enable the hydrogen economy across the value chain with the aim to accelerate the transition & play a very active role in projects.*

Key port activities across the hydrogen value chain

Production	Conversion, transport & storage	Consumption
Ports invest in **infrastructures** for hydrogen. The type of infrastructure is depending on the buy/make decision (production vs import terminals)	Ports invest in **hydrogen pipelines** to connect producers, distributors and customers, or in their role as energy & transit hub *Example: Port of Rotterdam coinvesting in hydrogen pipelines from the port to refinery in Pernis together together with GasUnie*	Port investing in **hydrogen fuel stations** for road freight, locomotives, cargo handling & other port equipment, and shipping *Example: Port of Gothenburg plans to install a hydrogen gas pump for heavy goods vehicles by 2023-24*

Investments ports should consider

- ***Investing financial resources** to build production infrastructure (MAKE), import terminals (BUY), hydrogen pipelines (BUY and MAKE) and hydrogen fuel stations (BUY and MAKE)*
- ***Investing financial resources** in adjacent domains (e.g., windmills park)*
- ***Investing financial resources** in port infrastructure to welcome hydrogen infrastructure*
- ***Partnering with skilled actors** to set up the right infrastructures & activities (MAKE and BUY)*
- ***Financing** the transition as leverage for technological innovations & demo-facilities*

Added value for ports

- ***Enable and accelerate the development of hydrogen projects** on their facilities (with the benefits to increase traffic by attracting companies interested in hydrogen)*
- ***Enable ports in their transition to net-zero***
- ***Secure their viability on the long term** by making sure their business model is resilient with the energy transition*
- ***Kick-start the hydrogen economy** and paving the way for private companies*
- *Ports mentioned that **getting a return on investment** was **not a primary reason** to invest in hydrogen projects*

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

Overview of port investments

Key investments ports should consider if they want to act as …

Landlord

- ***Provide land and/or make land available*** *to foster hydrogen activities across the value chain production facilities (MAKE), import terminals (BUY), pipelines, bunkering facilities, fuel stations etc. (BUY and MAKE)*
- ***Partner with companies*** *willing to place their facilities/assets/infrastructure on the available lands (BUY and MAKE)*

Community builder and enabler

- ***Taking part in regional and global alliances and networks*** *(BUY and MAKE)*
- *For larger port with larger capacity,* ***forming a local platform*** *with actors to discuss hydrogen projects (BUY and MAKE) for the port itself*
- ***Developing solid relationships with the whole ecosystem*** *(industry actors, policy makers, government, investors, etc.) (BUY and MAKE)*
- ***Promoting hydrogen*** *as a sustainable energy carrier (BUY and MAKE)*

Investor

- ***Investing financial resources*** *to build production infrastructure (MAKE), import terminals (BUY), hydrogen pipelines (BUY and MAKE) and hydrogen fuel stations (BUY and MAKE)*
- ***Investing financial resources*** *in adjacent domains (e.g., windmills park) (MAKE and BUY)*
- ***Investing financial resources*** *in port infrastructure to welcome hydrogen infrastructure (MAKE and BUY)*
- ***Partnering with skilled actors*** *to set up the right infrastructures & activities (MAKE and BUY)*
- ***Financing*** *the transition as leverage for technological innovations & demo-facilities*

Investment will depend on several factors

Archetypes

- *Each archetype can play a role in the hydrogen economy*
- *However the port archetype matters for some specific roles:*
  - *›* ***Industrial ports*** *can better provide land for industrial hydrogen consumers*
  - *›* ***Bunkering port*** *are better position to provide land for bunkering facilities*
  - *›* *It makes the most sense for* ***Bunkering & Logistics and transport ports*** *to provide land for hydrogen fuel stations or to invest in them*
  - *›* ***Urban ports*** *will probably not invest in hydrogen pipelines compared to other archetypes.*

Size

The size of the port is also a factor to take into account:

- ***Smaller ports*** *will play a less active role in the hydrogen economy. They will less likely invest in any type of project nor provide land for large infrastructure. They can take part in alliances and network to be aware of what is coming in terms of hydrogen developments but are less likely to host their own.*
- ***Bigger ports*** *will play a more active role in the hydrogen economy. They have more lands available to enable the hydrogen economy to grow. They also have more power in decision regarding hydrogen. They even have a key role when it comes to connecting the dots around the world with other ports. Their ecosystem allows them to play an active role globally in alliances and network but also to gather the right actors locally.*

Strategies

Each port will eventually ***choose what role they want to endorse*** *more, or less, taking into account other elements in their strategy and their forecasts.*

However, the majority of ports we interviewed are publicly owned. This means their hydrogen strategy is strongly ***related to municipal and national strategy****.*

Therefore, although ports may have their own views on what role to take in the hydrogen economy, some of their decisions are influenced by the national strategy.

That's the case for the BUY or MAKE decision. This decision will impact the investment ports should make in short and long term. But it is not a decision made only by a port itself. It usually will be part of a bigger strategy involving other actors of the ecosystem.

Glossary

Glossary of key terms in this study

Term	Full description
Inland port	Port not located on a sea or ocean coastline
'Europe' or 'European countries'	Include the 27 Member States of European Union (EU27), United Kingdom, Norway and Switzerland
Grey hydrogen	Fossil-based hydrogen produced through the reforming of natural gas
Blue hydrogen	Fossil-based hydrogen produced through the reforming of natural gas in plants equipped with CO_2 capture units and subsequent CO_2 storage. Effectiveness of carbon capture units is estimated to reach a maximum of 90%.
Green hydrogen	Hydrogen produced via electrolysis, using renewable (mainly wind and PV) based electricity
Turquoise hydrogen	Hydrogen produced via pyrolysis, using hydrocarbon feedstock, such as methane (CH_4) in natural gas
Renewable hydrogen derivatives	Comprises all products and fuels produced with renewable hydrogen. In the frame of this study, they include e-ammonia, e-methanol, e-liquids (also called liquid derivatives), e-gases
On-site hydrogen	Hydrogen that is produced in the same location (often an industrial facility) where it is consumed (for example, hydrogen currently produced for ammonia production). On-site hydrogen production belongs to the so called "captive" hydrogen market.
Green and other blue hydrogen	Combines both green hydrogen production in Europe and green and blue hydrogen imported from outside Europe
Merchant hydrogen	Hydrogen that is not produced in the location where it is consumed, but from central hydrogen production plants spread both within and outside of the EU.
Ambitious scenario	Widespread and rapid uptake of hydrogen for final energy (fuel) and non-energy (feedstock) purposes in all sectors and activities (covered by this study) not currently consuming hydrogen (new hydrogen end-users).
Moderate scenario	Moderate and progressive uptake of hydrogen by new hydrogen end-users. Hydrogen is seen as only one of many options (e.g., CCS, electrification, biomethane, etc.) in sectorial decarbonization strategies.
Conservative scenario	Low and slow uptake of hydrogen by new hydrogen end-users. The role of hydrogen is often only marginal in sectoral decarbonization strategies, and its adoption is mainly limited to existing users and other heavy industries.
Base supply scenario	Development of three hydrogen supply scenarios matching respectively the forecasted hydrogen demand in the three demand scenarios and incorporating a predefined constraint in the annual rate of deployment (10%) of European renewable energy sources until 2050
Increased import supply scenario	Development of an additional hydrogen supply scenario matching only the hydrogen demand foreseen in the ambitious demand scenario and incorporating a predefined constraint in the annual rate of deployment (5%) of European renewable energy sources until 2050
Coastline clusters	Cover all the territories of the EU that are located within the vicinity of a coastal zone. These areas contain all European ports likely to play a role in the import and distribution of hydrogen from territories outside Europe.
Hinterland clusters	Cover European territories that are relatively far from a coastal zone.

List of abbreviations

Acronym	Full description
ATR	Autothermal reforming
BECCS	Bioenergy with Carbon Capture and Storage
BF-BOF	Blast Furnace-Basic Oxygen Furnace
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CH4	Methane
CO	Carbon Monoxide
COD	Chemical Oxygen Demand
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DAC	Direct Air Capture
DRI-EAF	Direct Reduced Iron - Electric Arc Furnace
EU	European Union
ETS	Emission Trading System
FCHO	Fuel Cells and Hydrogen Observatory
GHR	Gas heating reforming
H_2	Hydrogen
HVC	High Value Chemicals
HyPE model	Hydrogen Pathway Explorer model

Acronym	Full description
IEA	International Energy Agency
LCOH	Levelized Cost of Hydrogen
LCOS	Levelized Cost of Underground Storage
LH2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MeOH	Methanol
MoU	Memorandum of Understanding
MtO	Methanol to Olefins
MS	Member State
NECP	National Energy and Climate Plan
NG	Natural Gas
NH3	Ammonia
NOx	Nitrogen Oxides
OPEX	Operating Expenses
PEM	Proton Exchange Membrane
PM	Particulate Matter
Solar PV	Solar Photovoltaic
RED	Renewable Energy Directive
RES	Renewable Energy Sources

Acronym	Full description
RFNBO	Renewable Fuels of Non-Biological Origin
SOEC	Solid Oxide Electrolyser Cell
SOx	Sulphur Dioxide
SMR	Steam methane reforming
VOC	Volatile Organic Compounds
WACC	Weighted Average Cost of Capital

List of units and conversation tables

Acronym	Full description
bcm	billion cubic meters
bEUR	Billion of euros
EUR	Euro
g	gram
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt-hour
kWh	Kilowatt-hour
Kg	Kilogram
MEUR	Million of euros
mg	Milligram
Mt	Megaton
MWh	Megawatt-hour
PJ	Petajoule
t	tonne
TEU	Twenty Foot Equivalent Unit
TWh	Terawatt-hour

Conversion tables			
Hydrogen units			
Mt	TWh	Bcm	PJ
1	33.33	3.41	119.99

Energy units			
TWh	GWh	MWh	kWh
1	1,000	1,000,000	1,000,000,000

Weight units			
Mt	t	kg	g
1	1,000,000	1,000,000,000	1,000,000,000,000

Country codes used in the report

Country code	Country
GB	United Kingdom
IE	Ireland
NO	Norway
PT	Portugal
ES	Spain
CH	Switzerland
AT	Austria
FI	Finland
FR	France
SE	Sweden
LV	Latvia
EE	Estonia
IT	Italy
GR	Greece
AU	Australia
CN	China
JP	Japan
IQ	Iraq

Country code	Country
PL	Poland
SA	Saudi Arabia
HU	Hungary
HR	Croatia
SK	Slovakia
DZ	Algeria
MA	Morocco
DK	Denmark
QA	Qatar
DE	Germany
NL	Netherlands
EG	Egypt
LU	Luxemburg
OM	Oman
IN	India
KP	South Korea
AE	United Arab Emirates

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APPENDIX I – Task 1

I.1. Hydrogen demand subcategories deep dives (industries and transport)

I.2. Assessment of the ‘multimodality' functions of ports

I.1. Hydrogen demand subcategories deep dives (industries and transport)

Hydrogen demand for one unit of volume per hydrogen demand subcategory

Category	Subcategory	Unit	Hydrogen demand for 1 unit of volume
Transport	International shipping	million tonne-mile	44 MWh hydrogen (47 MWh if ammonia, 28 MWh if e-methanol)[1]
Transport	Domestic shipping	million tonne-mile	44 MWh hydrogen (47 MWh if ammonia, 28 MWh if e-methanol)[1]
Transport	Road freight	million tonne-km	0.29 MWh[2]
Port activities	Cargo handling	TEU	0.58 MWh[3]
Port activities	Port vessel fleet	million tonne-mile	44 MWh (47 MWh if ammonia, 28 MWh if e-methanol)[1]
Urban areas	Residential	m^2	104 kWh[4]
Urban areas	Services	m^2	145 kWh[5]
Industry	Steel	Mt primary steel	1.91 TWh[6]
Industry	Mineral oil	Mt refined oil	0.25 TWh[7]
Industry	HVC	Mt HVC	See note*
Industry	Methanol	Mt methanol	6.33 TWh[8]
Industry	Ammonia	Mt ammonia	5.90 MWh[9]
Industry	Industrial heat	TWh natural gas**	0.85 TWh[10] (see note**)

Notes

The hydrogen demand per volume can change over the different years due to increasing energy efficiency.

* Hydrogen demand for 1 Mt of bio-based HVCs via route Anaerobic Digestion (Green H2 + Biomass) route is assumed to be 9.99 TWh (source: Material Economics, 2019); Hydrogen demand for 1 Mt of bio-based HVCs via synthetic methanol (green e-methanol) route is assumed to be 6.33 TWh (source: IRENA, 2021); Hydrogen demand for 1 Mt of chemically recycled HVCs via route Gasification route (Waste to Methanol) is assumed to be 6.66 TWh (source: Material Economics, 2019).

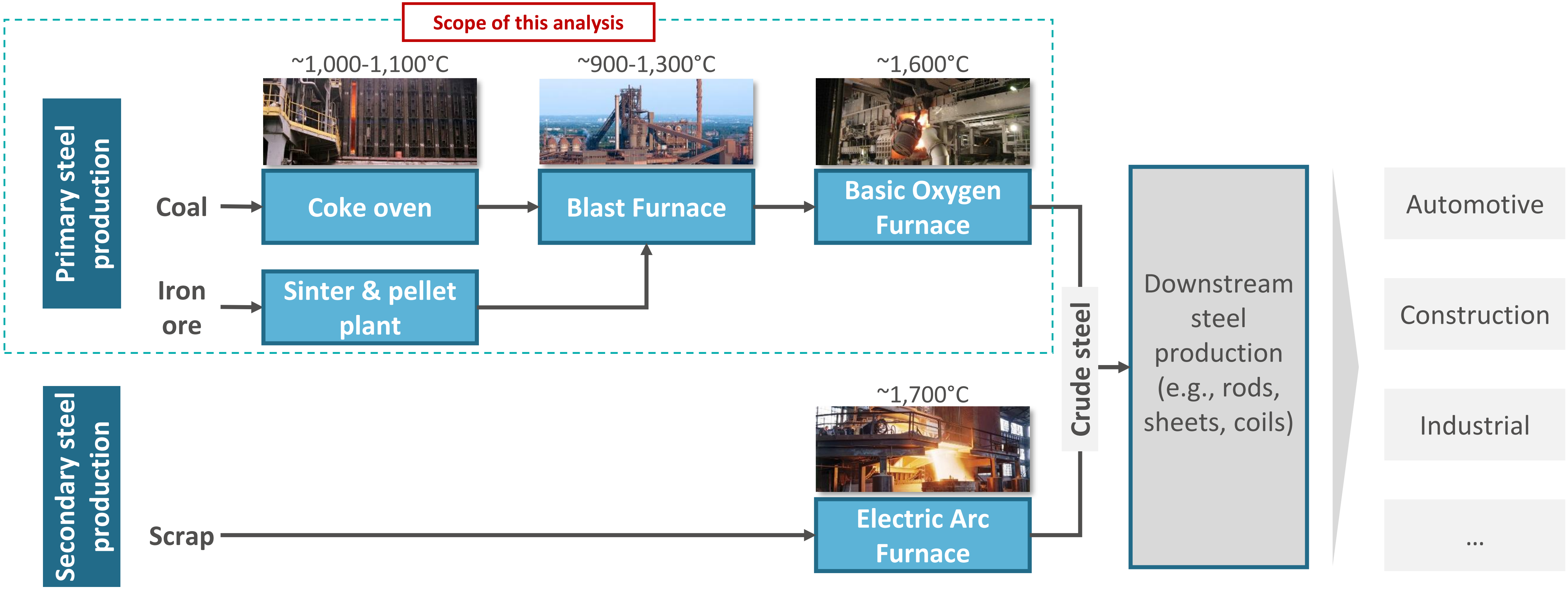
** Refers to hydrogen demand per TWh of natural gas (conversion natural gas / hydrogen) for medium and high-temperature industrial process heat.

Sources: (1) Irena, *A pathway to decarbonize the shipping sector by 2050*, 2021 and Deloitte internal sources; (2) Deloitte internal sources; (3) per million containers, 47.4 t Hydrogen/day if all port terminal equipement is fueled by Hydrogen. This equals to 576,258.2 MWh Hydrogen/year (Pacific Northwest et al., *Hydrogen Fuel Cell Applications in Ports: Feasibility Study at Multiple U.S. Ports*, 2019 & TNO, *hydrogen in port of Rotterdam)*; (4) Average energy consumption of buildings in Europe is 180 kWh/m2 for residential buildings. Of this, space heating accounts for the largest share (68%) (https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-use-buildings_en). To take into account the difference in energy efficiency for hydrogen boiler in comparison to current heating technologies a factor of 85% is applied; (5) Average energy consumption of buildings in Europe is 250 kWh/m2 for service buildings. Of this, space heating accounts for the largest share (68%) (https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-use-buildings_en). To take into account the difference in energy efficiency for hydrogen boiler in comparison to current heating technologies a factor of 85% is applied; (6) IEA, 2019; FCH & Triconomix, 2020; (7) Deloitte's own assumption based on the total demand for refined oil products in the EU27+UK (FuelEurope, 2022) divided by the total hydrogen demand for hydrogenation of fossil fuels (FCHO 2022); (8) IRENA, 2021; (9) Guidehouse, 2021, Rivaloro et. al, 2019, Dolci, 2018; (10) DNV GL, 2018 (used by Guidehouse, 2021)

Steel

Steel production processes (simplified)

For primary steelmaking in Europe, the predominant production method is Blast Furnace/Basic Oxygen Furnace (BF/BOF), using iron ore as feedstock next to coke and coal, which are also the main energy carriers. In secondary steelmaking the main route is Scrap-Electric Arc Furnace, which uses scrap (recycled steel) as feedstock and electricity as main energy carrier, while also needing a limited amount of natural gas or coal for its carbon content.

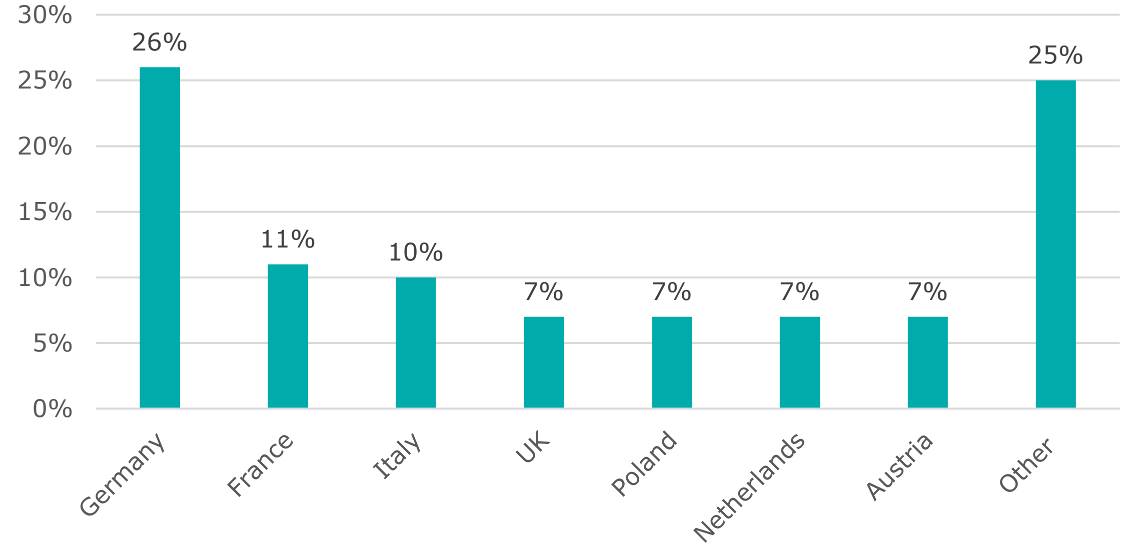


Source: Deloitte analyses

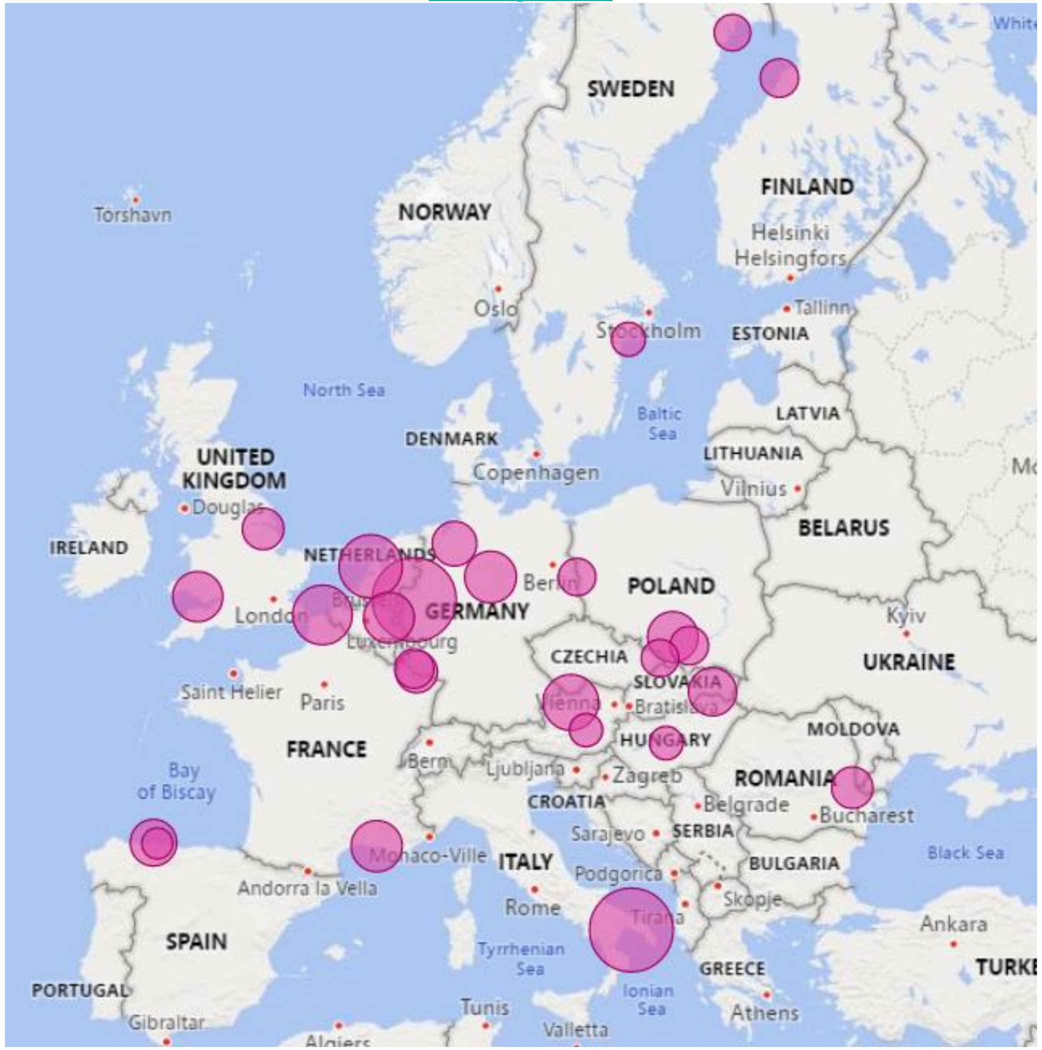
Overview of European steel production market (2019)

2019	Number of plants/sites	Capacity	Production	Production share
Primary production	26	~ 112 Mt	92.34 Mt	~59%
Secondary production	126	~ 90 Mt	65.12 Mt	~41%
Total	152	~ 202 Mt	157.47 Mt	100%

Share of primary steel production (EU27 + UK)



Location and relative size (in volume/year) of EU 27+UK primary steel plants



Sources: Eurofer, 2019 & Deloitte analysis

Overview of the main decarbonizations routes for primary steel production

Decreased demand for primary steel

The most effective and straightforward path to decarbonizing primary steel production is to reduce its demand.

- **Option 1**: by decreasing overall steel demand
- **Option 2**: by increasing the share of steel production through the secondary route (EAF).

Decarbonizing secondary steel does not involve a complete transformation of the process, but simply a switch to renewable electricity. In addition, the limited amount of natural gas needed in the EAF could be replaced by low-carbon gaseous fuels (e.g., biomethane, synthetic methane, hydrogen), which could lead to additional hydrogen demand.

Green Hydrogen DRI-EAF

Decarbonizing primary steel can be done by completely transforming the production process, **moving away from the BF-BOF route**.

Direct reduction of iron (DRI) with hydrogen is seen as the prime solution to decarbonize primary steel making. In hydrogen-based steel making, hydrogen is used to directly reduce iron in a direct reduction plant to produce sponge iron, which in turn can be melted in an EAF to produce steel.

This production route requires 1.91 MWh (57.5 kg) of hydrogen per tonne of crude steel[1]

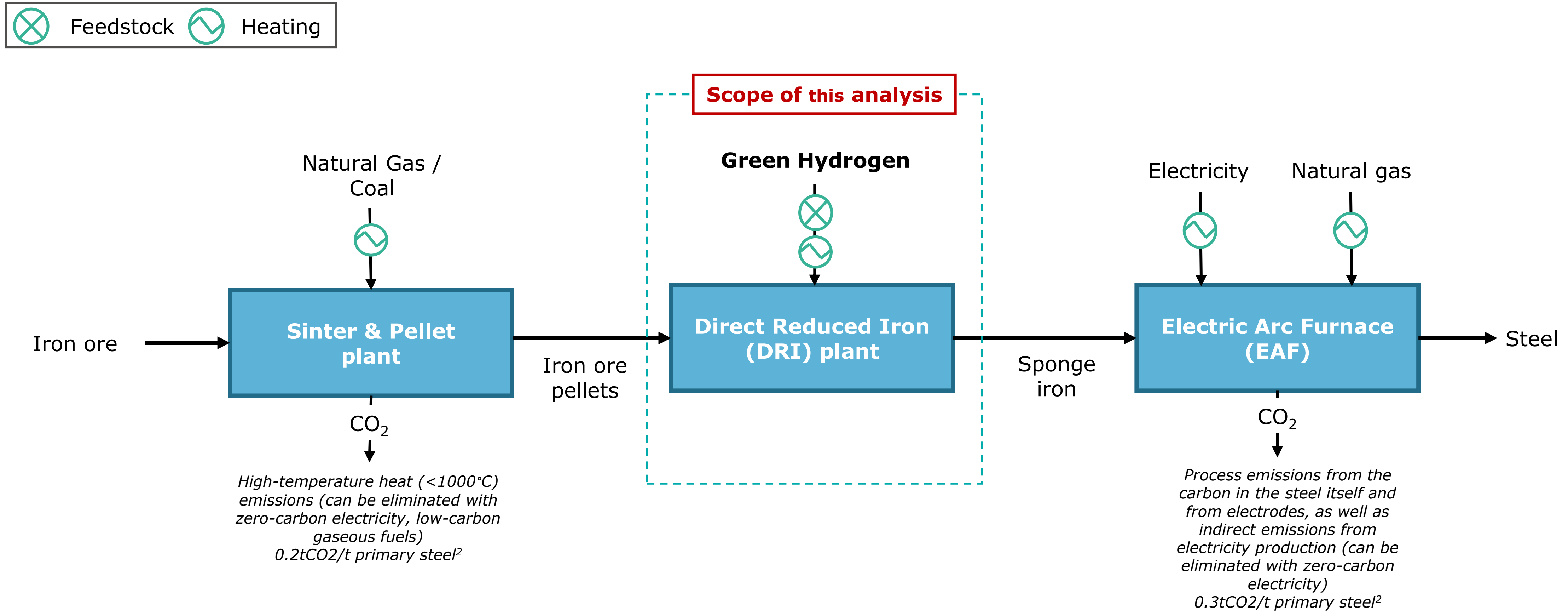
BF BOF CCS

Carbon Capture and Storage/Utilization (CCS/U) could also play a role in the decarbonization of primary steel production. Emissions from existing coke-based Blast & Basic Oxygen Furnace processes could be captured using (CCS/U).

Source: Deloitte analysis. (1) IEA, 2019; FCH & Triconomix, 2020.

Direct Reduced Iron and Electric Arc Furnace (DRI-EAF process)

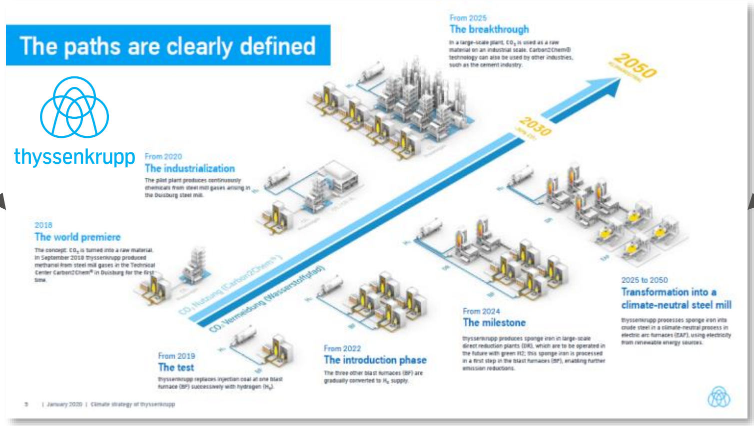
Direct Reduced Iron and Electric Arc Furnace (DRI-EAF process) can replace the BF-BOF, substituting coal with Hydrogen and electricity[1]



Sources: (1) Deloitte analyses. (2) Material Economics, 2019

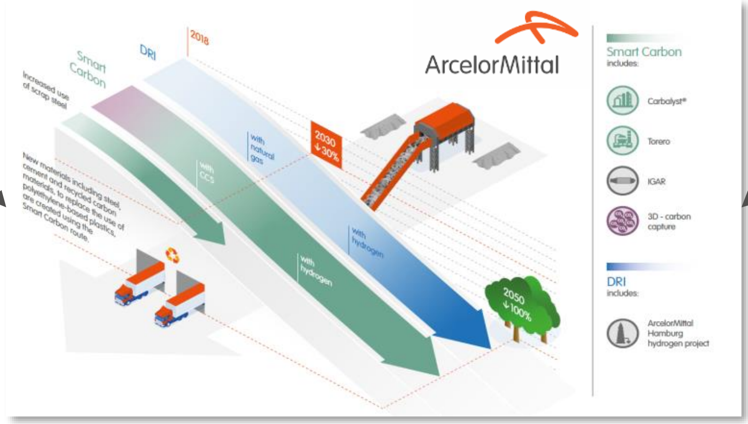
Examples of ongoing decarbonization roadmaps

BF CCS path	
2018	Combine BF with CCUS **pilot**
2020	Combine BF with CCUS **scale-up**
2050	Combine BF with CCUS at **scale**



DRI path	
2019	**Pilot** Hydrogen injection in BF
2022	**Scale-up** Hydrogen injection in BF
2024	**Transition** part of BF to DRI plant with NG
2050	**Full transition** of BF to DRI with hydrogen

BF CCS path	
2020	Substitute coal in BF with **alternatives**
2020	Combine BF with **CCUS**
2030 +	Combine BF with CCUS and **hydrogen**

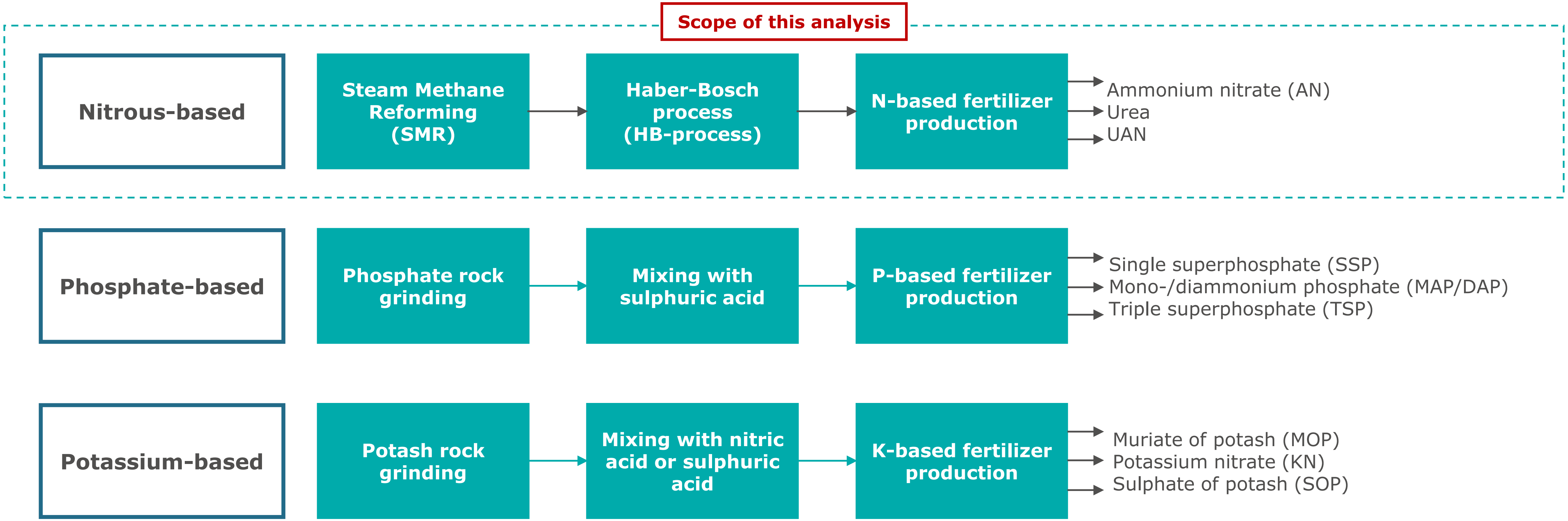


DRI path	
2020	*N/A*
2030	**Start DRI** with Natural Gas
2030 +	Replace Natural Gas in **DRI with hydrogen**

Ammonia for fertilizers

Fertilizer production processes (simplified)

The three main plant nutrients are nitrogen, phosphorus and potassium. Ammonia is a foundational chemical of the fertilizer industry, used both as a fertilizer itself and as a building block for other fertilizer chemicals, such as ammonium nitrate and urea. Roughly 90% of global ammonia production is for the fertilizer industry.

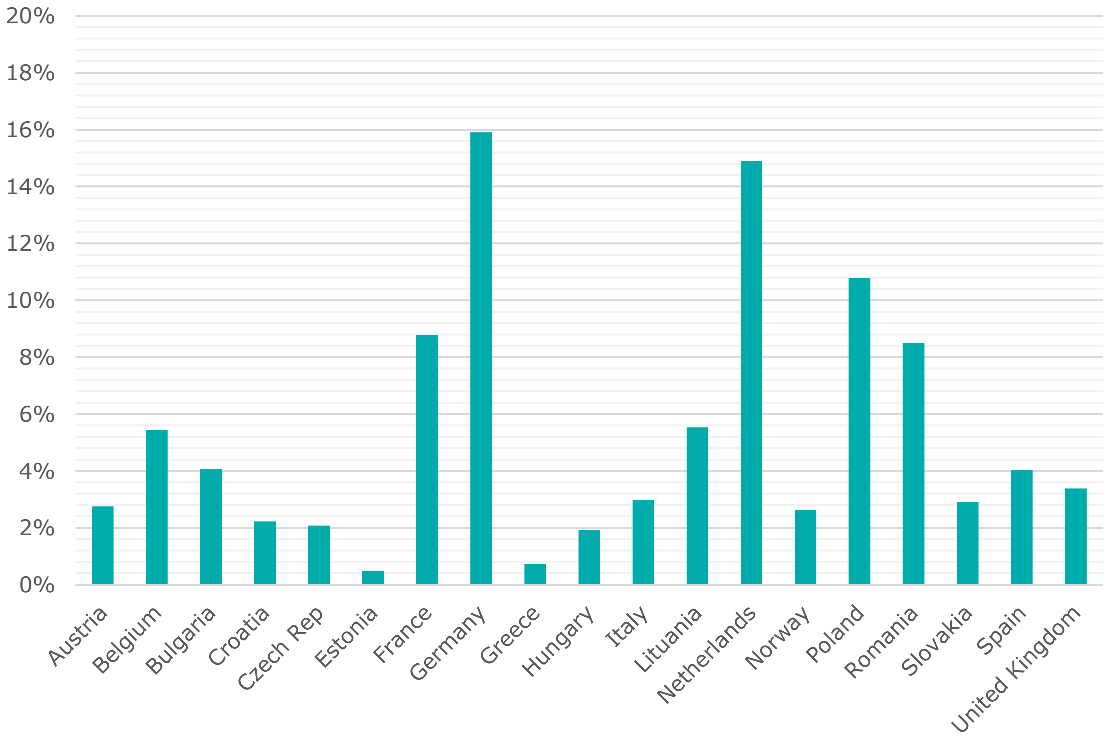


Source: Deloitte analyses

Overview of European ammonia (fertilizers) production market (2019)

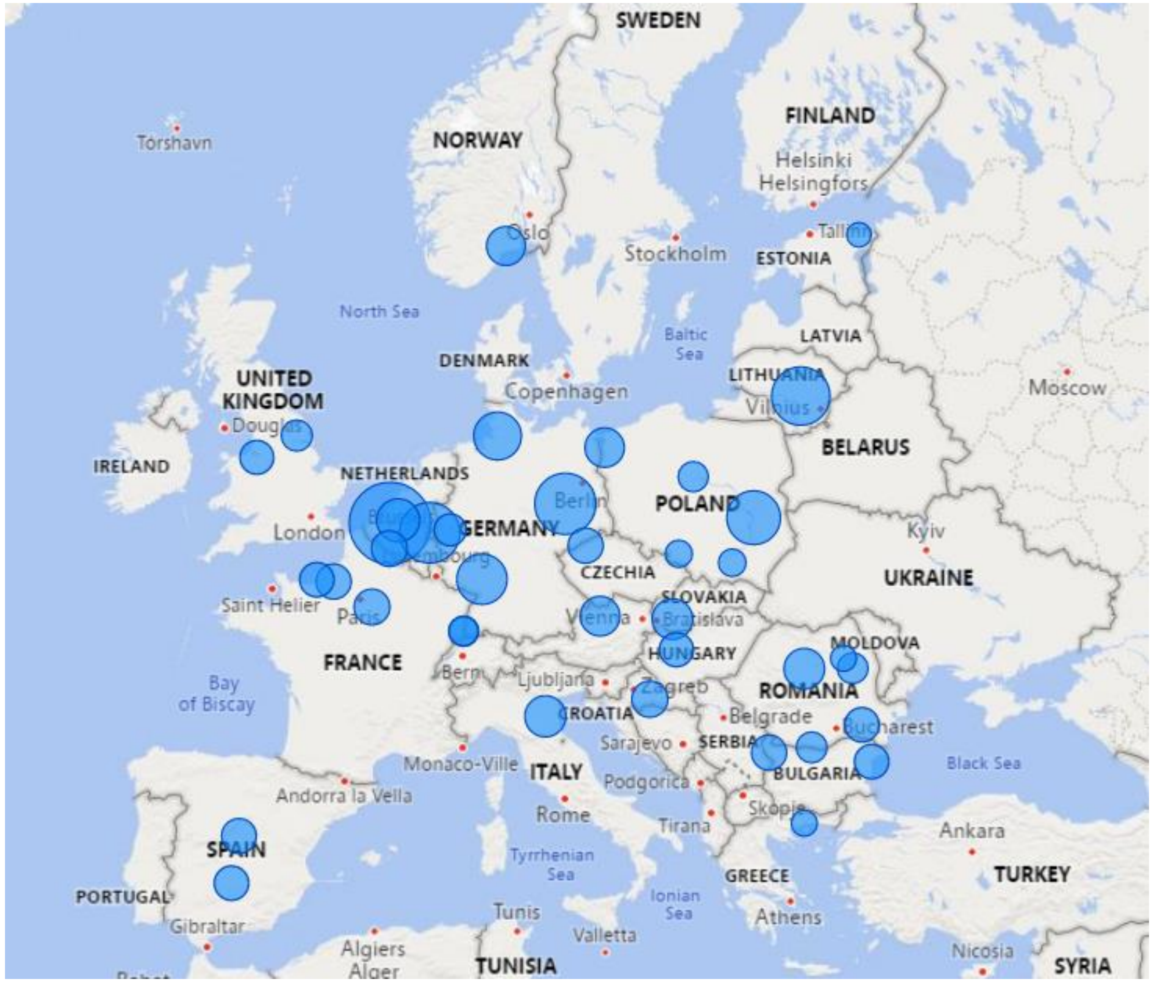
2019	Number of plants/sites	Capacity	Production
Total	~ 39	~ 20 Mt	16,5 Mt

Share of ammonia production (EU27 + UK)



Sources: IFASTAT, 2019 & Deloitte analysis

Location and relative size (in volume/year) of EU 27+UK ammonia plants



Overview of the main decarbonizations routes for ammonia production

Green Hydrogen

Green hydrogen can be produced via electrolysis to replace the SMR. Electrolysis of water consumes about 10.8 MWh of electricity per tonne of ammonia, and if renewable electricity is used to power all equipment, this pathway reduces total emissions to zero.

SMR + CCS

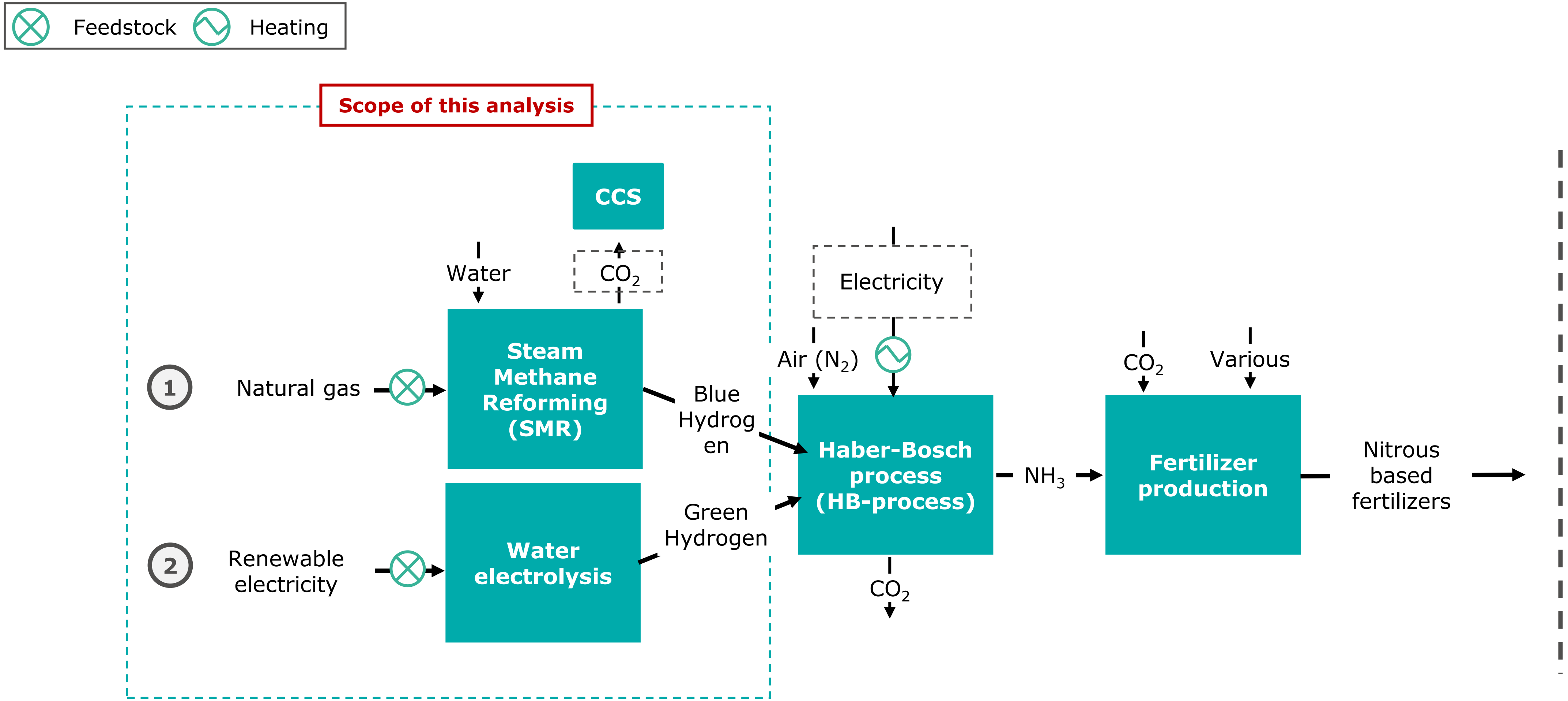
CCS can be applied to SMR to switch from fossil to blue hydrogen production in order to reduce emissions from ammonia production by up to 95%. While the first 60-65% is relatively inexpensive to capture (since it relates to pure CO_2 from the SMR process) the additional 30-35% is less economical. Carbon capture leads to additional electricity consumption because the captured CO_2 needs to be compressed, transported, and stored.

Biogas/Biomethane

Without any changes to the process itself, the natural gas feed used for SMR can be replaced by biomethane, resulting in carbon neutrality. Biomethane is not considered in this study. Indeed, as stated in the Guidehouse's study (2021): "national and European chemical associations have identified blue hydrogen production via SMR with CCS or water electrolysis as the primary decarbonization options".

Source: Guidehouse, 2021; Deloitte analyses

Low-carbon Hydrogen for ammonia production



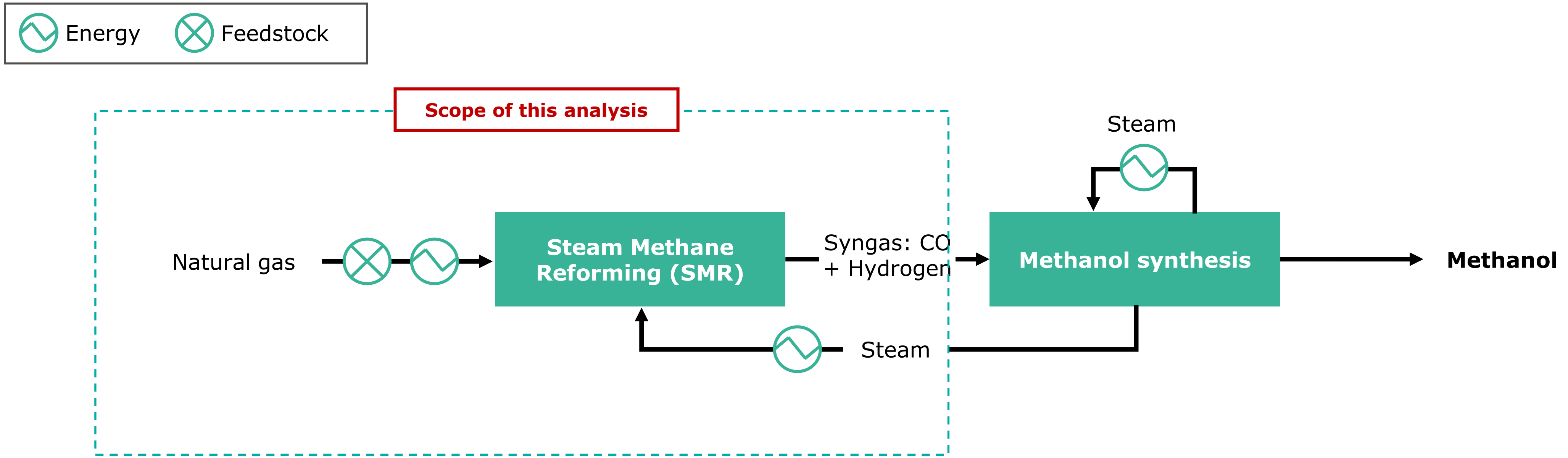
Source: Deloitte analyses

Methanol

Methanol production processes (simplified)

Liquid methanol is made from synthesis gas, a mix of hydrogen, carbon dioxide and carbon monoxide. As for ammonia industries and refineries, SMR is the dominant technology for hydrogen production in the methanol industry. However, an important difference is that methanol synthesis does not only require hydrogen as an input, but also CO2.

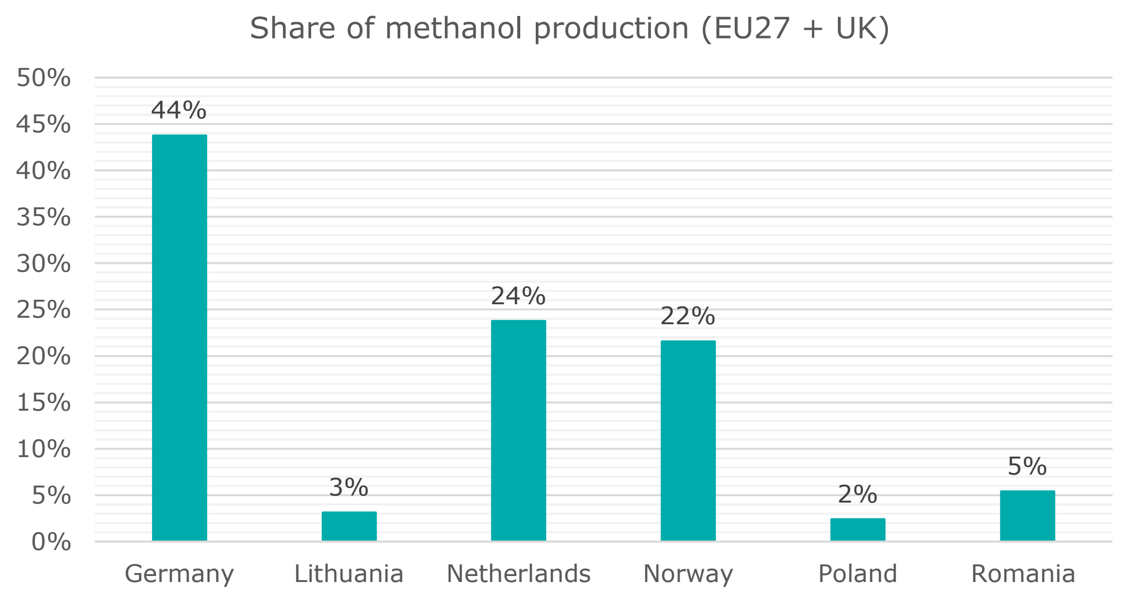
Methanol production process



Overview of the methanol production market (2019)

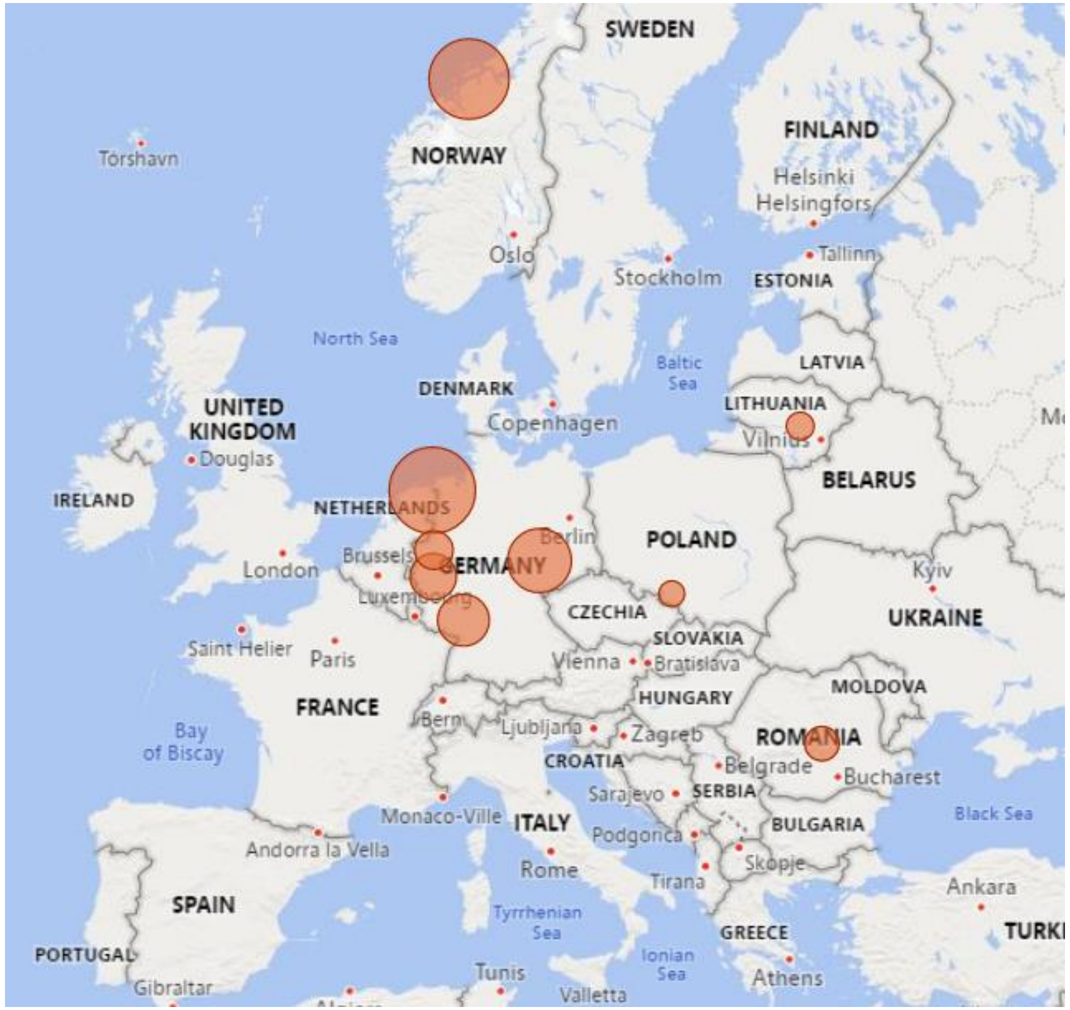
2019	Number of plants/sites	Capacity	Production
Total	~ 9	~ 4 Mt	2,8 Mt

Methanol production in Europe is highly concentrated, with Germany, the Netherlands and Norway being the main producers, and a few additional smaller plants located in Lithuania, Poland and Romania.



Sources: Deloitte analysis

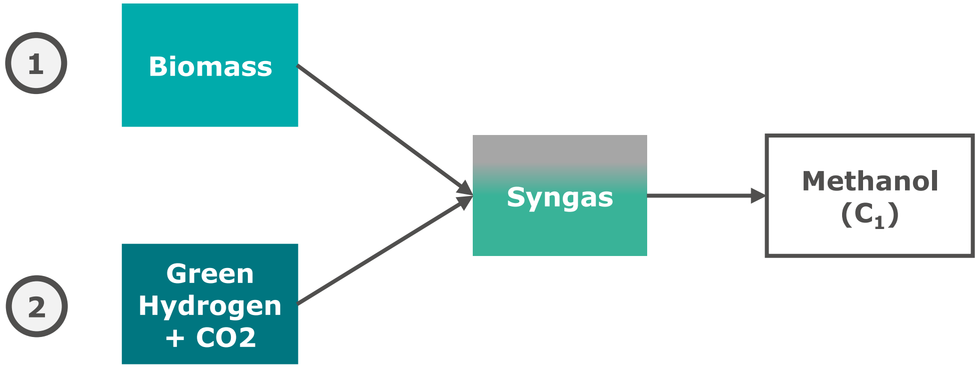
Location and relative size (in volume/year) of EU 27+UK methanol plants



Overview of the main decarbonizations routes for methanol production

A switch to renewable hydrogen always needs to be complemented with a 'climate-neutral' source of CO2, such as biogenic CO2 or CO2 captured from the atmosphere. A switch to renewable hydrogen-based processes will hence be more costly in the methanol industry than in the ammonia industry or in refineries (that strongly depend on SMR-based hydrogen).

Bio-methanol	Green e-methanol
Bio-methanol is produced from biomass. Key potential sustainable biomass feedstocks include forestry and agricultural waste, biogas from landfill, sewage, municipal solid waste and black liquor from the pulp and paper industry	Green e-methanol is obtained by using CO2 captured from renewable sources (bioenergy with carbon capture and storage [BECCS] and direct air capture [DAC]) and green hydrogen.

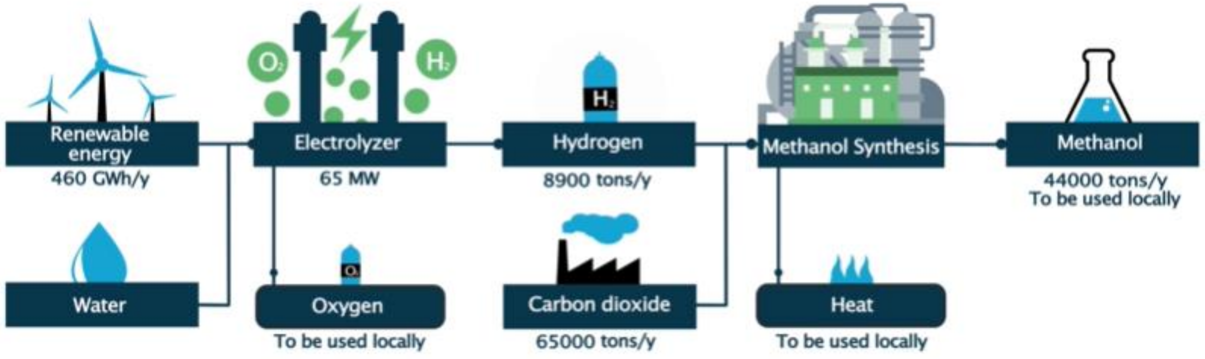


Sources: IRENA, 2021; Methanol Institute 2018; Deloitte analysis

Examples of ongoing decarbonization roadmaps

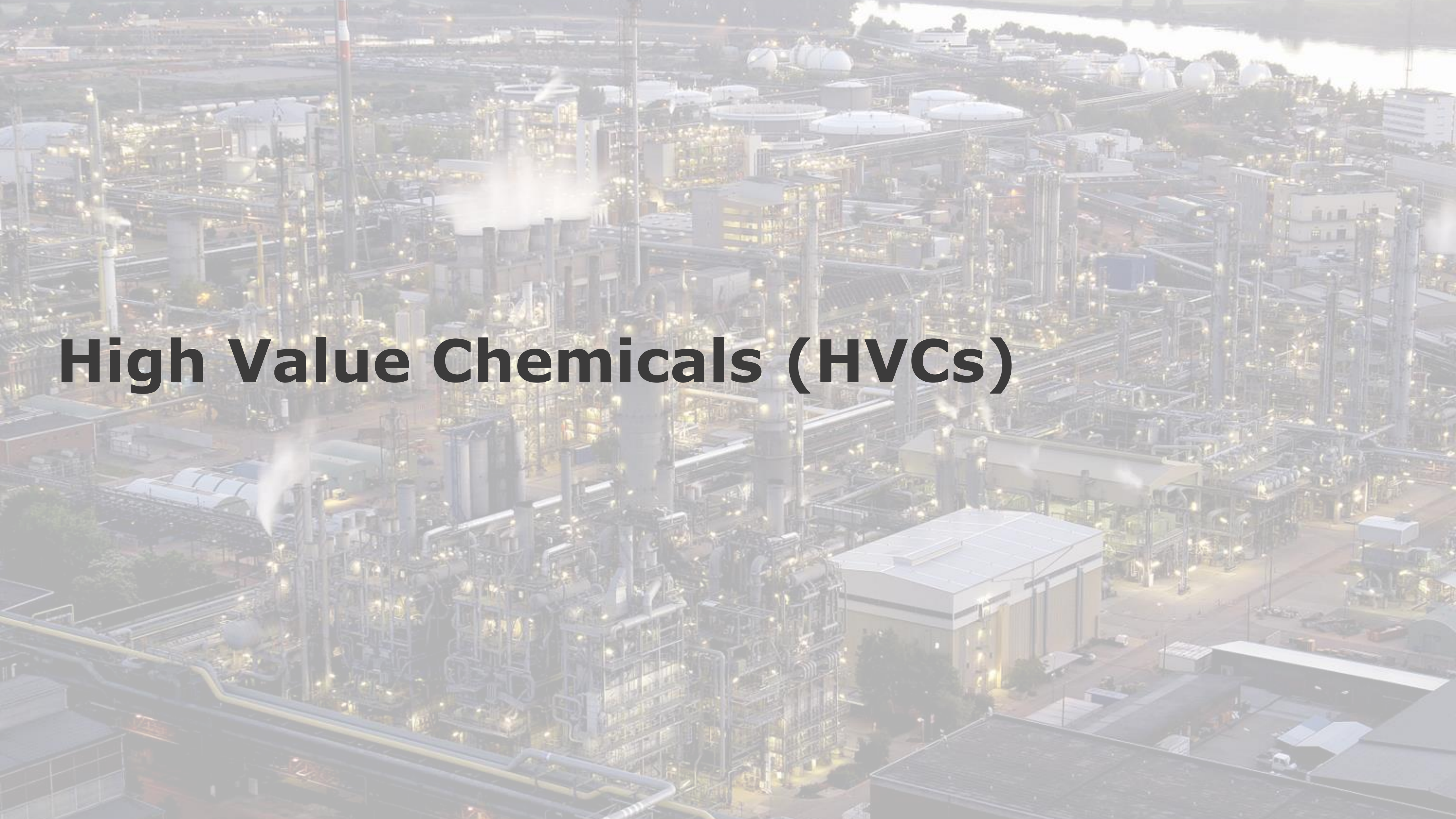
Projects like 'North-C Methanol' are focusing on renewable hydrogen-to-methanol

- Timeline, electrolyser capacity / hydrogen use:
  - 2024: 65 MW / 9 ktonne
  - 2028: 300 MW / 40 ktonne
  - **2030: 600 MW / 80 ktonne**
- Applications:
  - (Agro-/bio-) **chemicals**[1] > e.g., Cargill
  - **Fuels** for marine vessels and railroads
- **Valorization of CO_2 emissions** from companies such as ArcelorMittal and Alco Biofuel



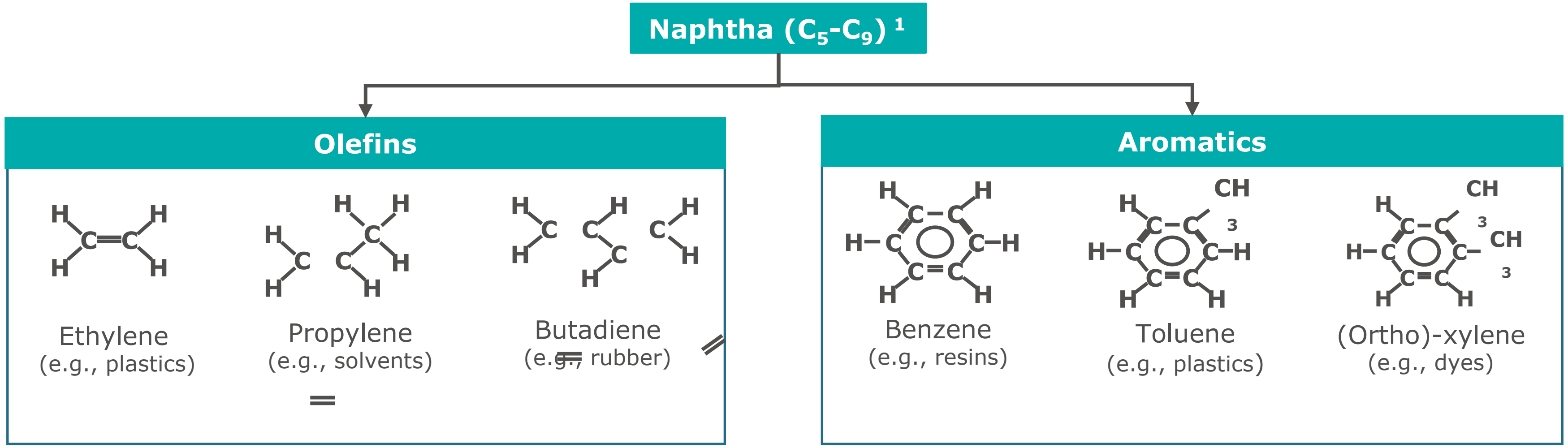
North CCU Hub partners

High Value Chemicals (HVCs)

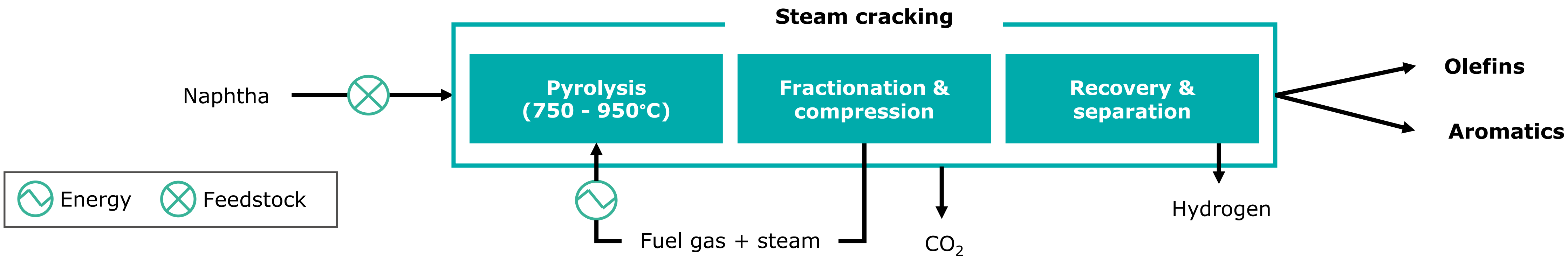


HCVs production processes (simplified)

Olefins and aromatics form the basis of the organic chemical industry. They are primarily made by 'cracking' of naphtha and ethane, which are respectively obtained by refining crude oil and from natural gas.



Olefins & aromatics production[2]

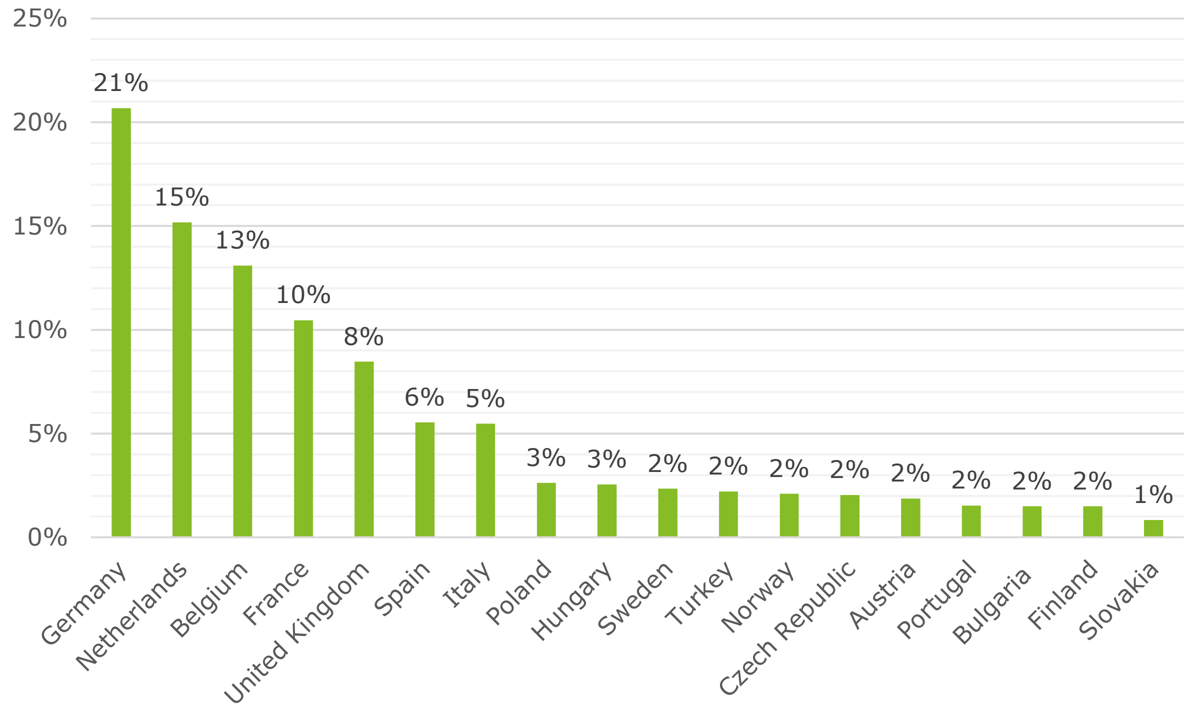


Notes: 1) These chemical building blocks have many applications (examples are illustrative and in no way comprehensive) 2) not all olefins and aromatics are produced through steam cracking, but it is by far the most important production method

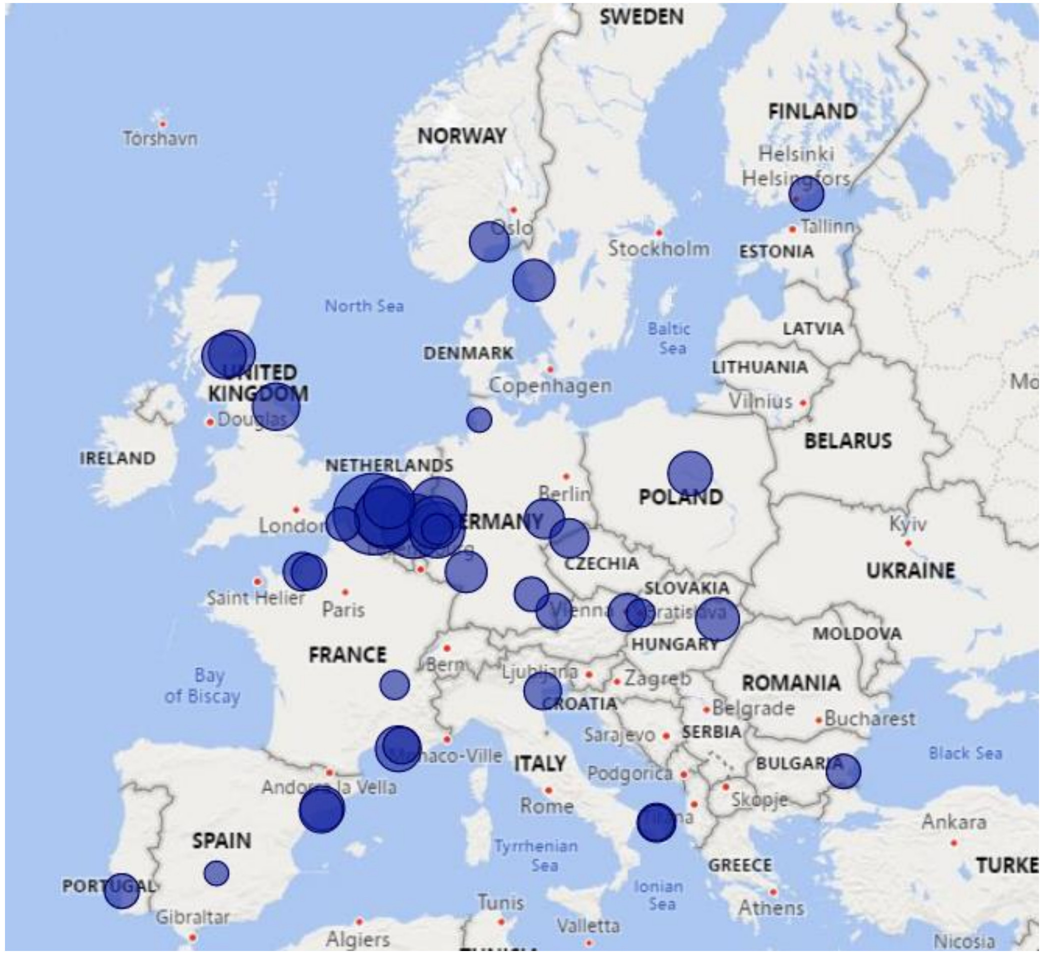
Overview of European HVCs production market (2019)

2019	Number of steam crackers[1]	Capacity Mt ethylene/year[1]	Production of ethylene/year[2]	Production HVCs/year[3]
Total	~ 48	~ 25.4 Mt	~ 21.9 Mt	~ 42.9 Mt

Share of HVCs production (EU27 + UK and Turkey)



Location and relative size (in volume/year) of EU 27+UK steam crackers



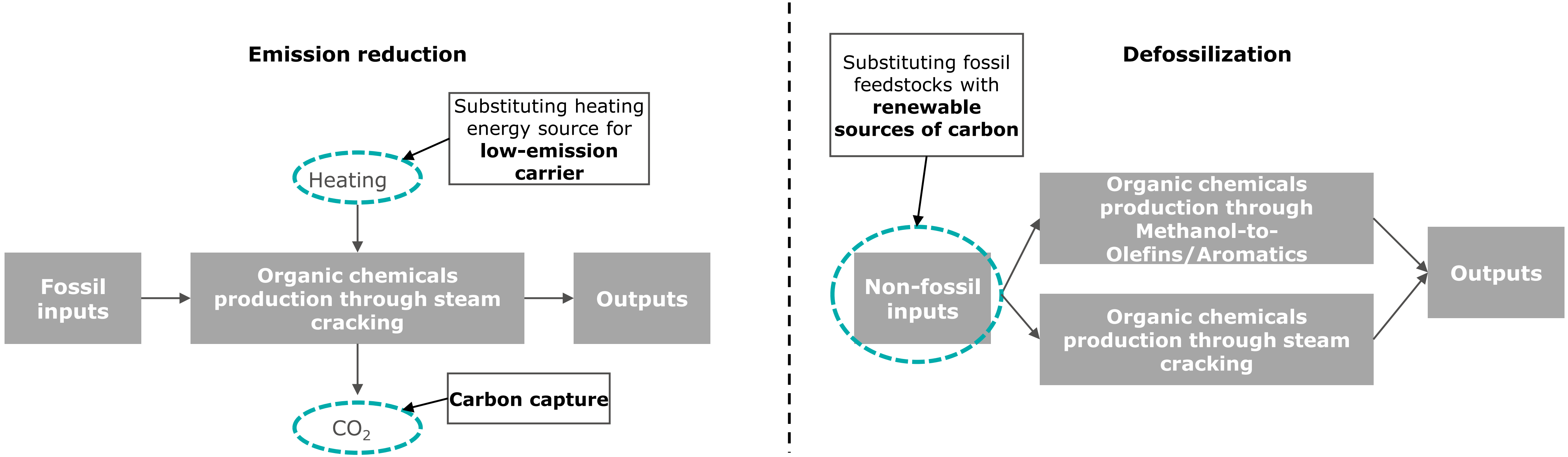
Sources: (1) Petrochemicals Europe, 2019 & Deloitte analysis (the production capacity of the INEOS Antwerp steam cracker currently under construction has been accounted for); (2) Deloitte analysis based the overage ratio nameplate capacity/production between 1999 and 2019 for steam crackers located in the EU 15 + Norway; (3) Deloitte analysis based on ratio production of ethylene/production of HVCs used in Guidehouse, 2021.

Overview of the main decarbonizations routes for HVCs production

Companies can go for defossilization in addition to emission reduction, as organic chemicals inherently contain carbon

Defossilization versus emission reduction

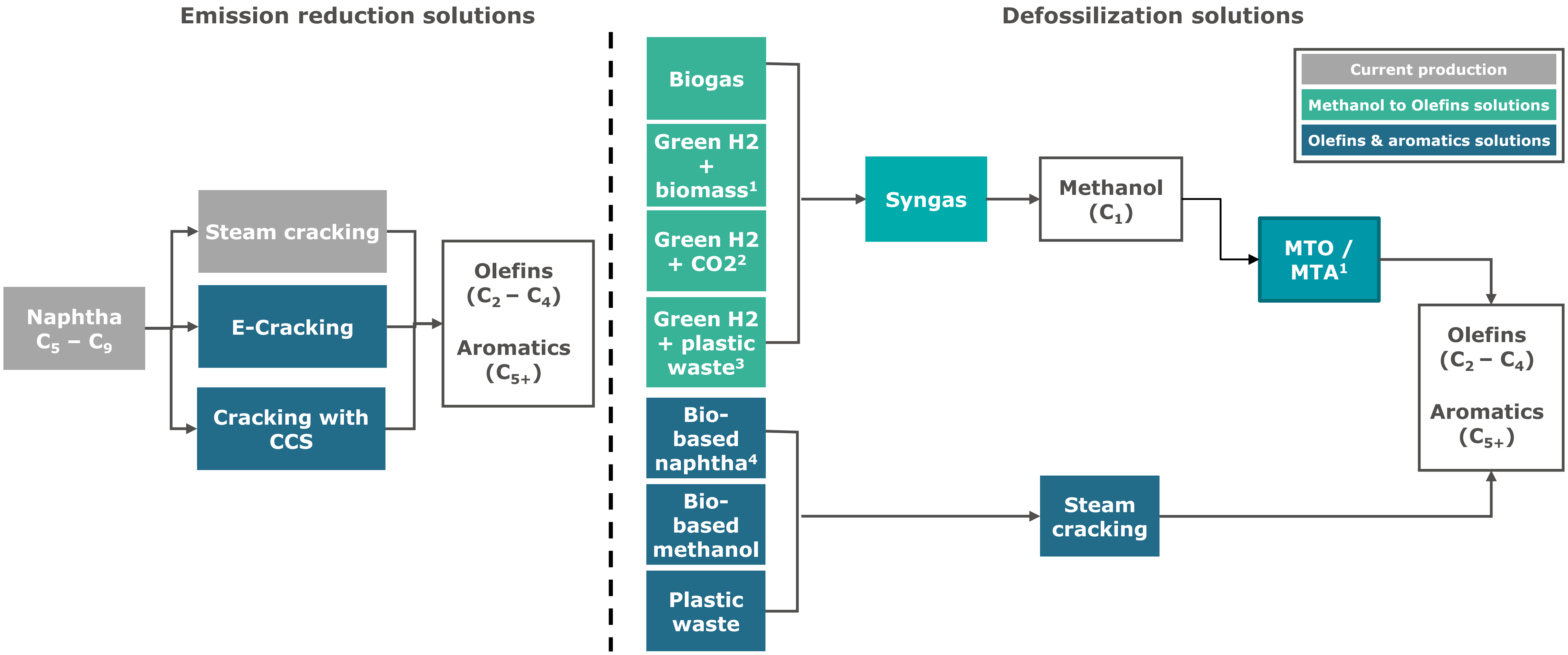
ILLUSTRATIVE



There is **no consensus** in the industry yet on the **targets and pathways** for **defossilization** towards 2050

Note: Defossilization will also reduce emissions in many cases

Perspectives of hydrogen in European HVCs sector



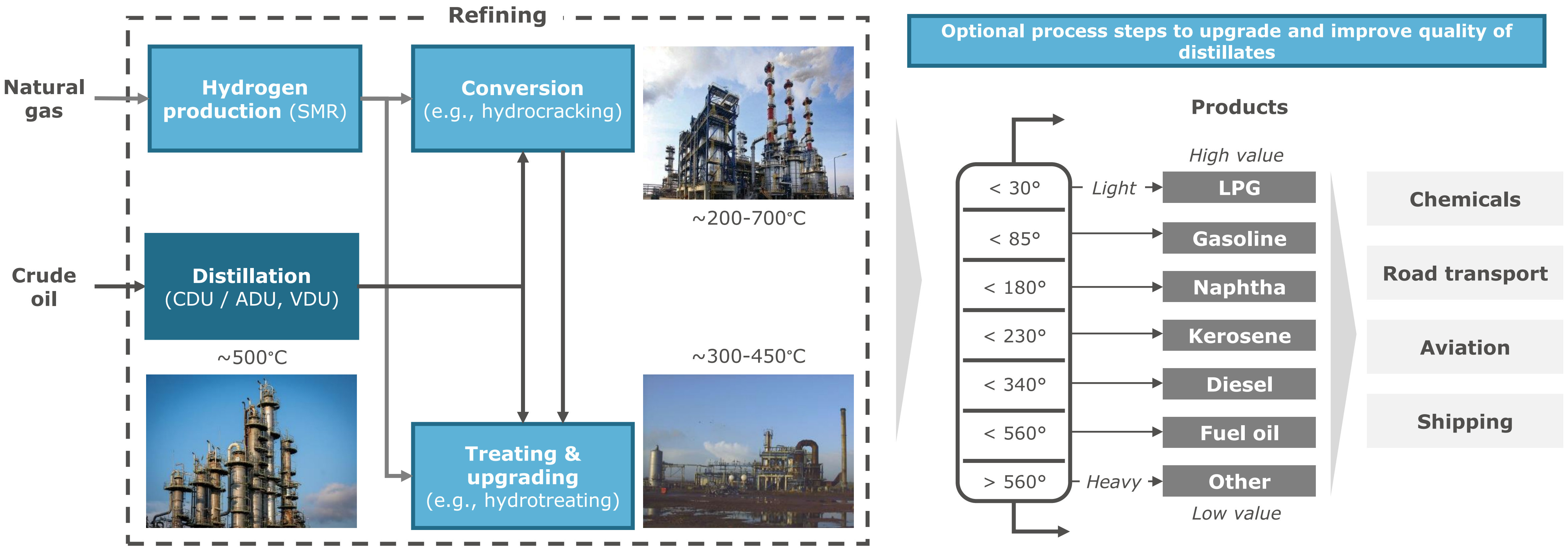
Note: 1) the Anaerobic Digestion (Green Hydrogen + Biomass) route requires 9.99 MWh of hydrogen/tonne of HVC (Material Economic, 2019); 2) The green e-methanol route requires 6.33 MWh of hydrogen/tonne of HVC (IRENA, 2021); 3) the gasification route (Waste-to-Methanol) requires 6.66 MWh of hydrogen/tonne of HVC (Material Economic, 2019); 4) bio-based naphtha requires 1.3 MWh of hydrogen/tonne of HVC (Guidehouse, 2021). Methanol-to-olefins / methanol-to-aromatics;

Mineral oil in refineries

Current use of hydrogen in refining activities

Refineries take crude oil as input and produce a range of fossil-based products, using Hydrogen to upgrade and improve the quality of these products

Refining process - SIMPLIFIED

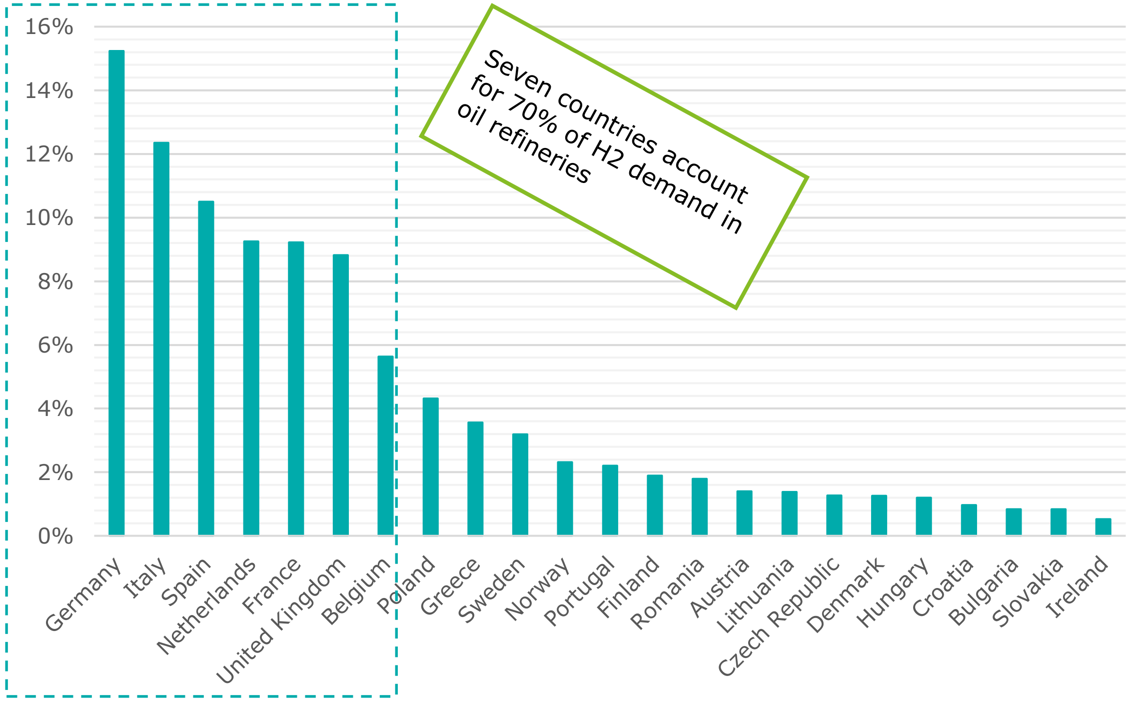


Source: Deloitte analyses

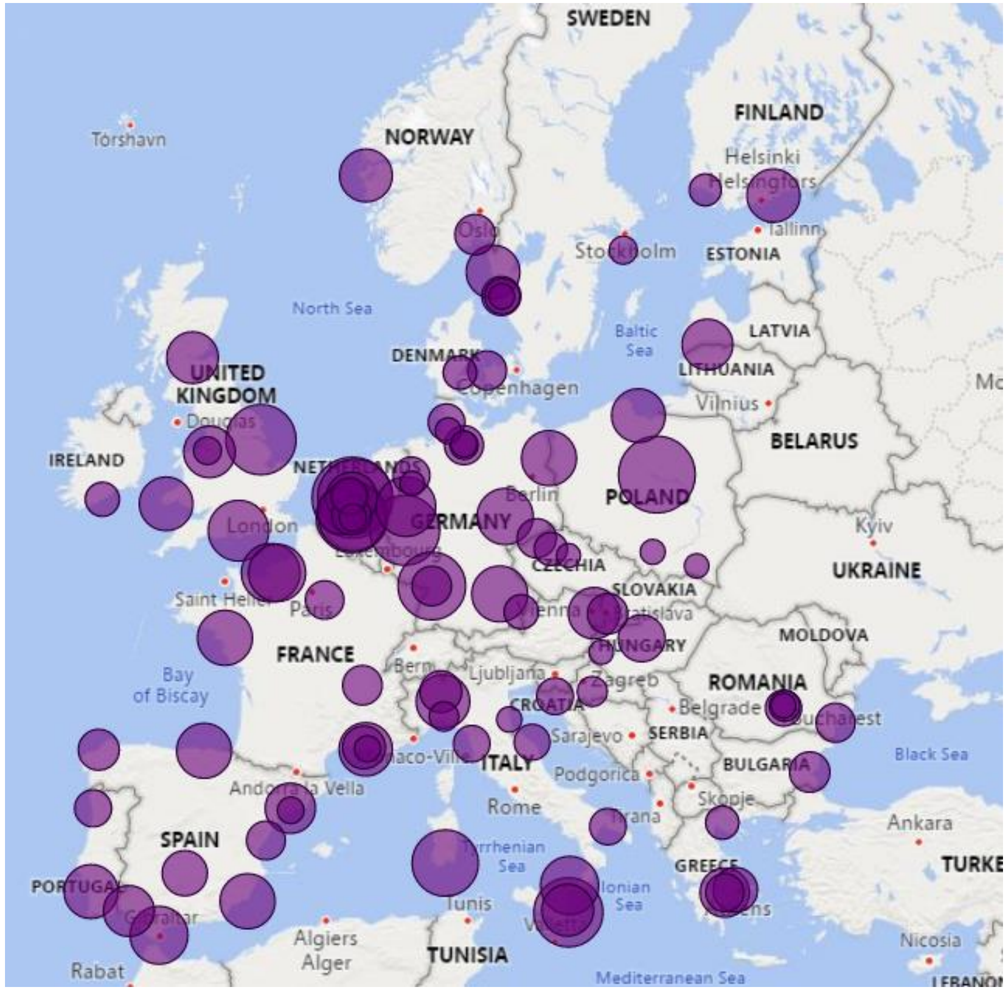
Overview of European oil refinery market (2019)

2019	Number of refineries	Capacity (Mt/year)[1]	Production (Mt/year)[2]	Hydrogen demand (in TWh/year)[3]
Total	~ 97	~ 690.4 Mt	~ 646 Mt	138 TWh

Share of H2 used in EU27+UK refineries



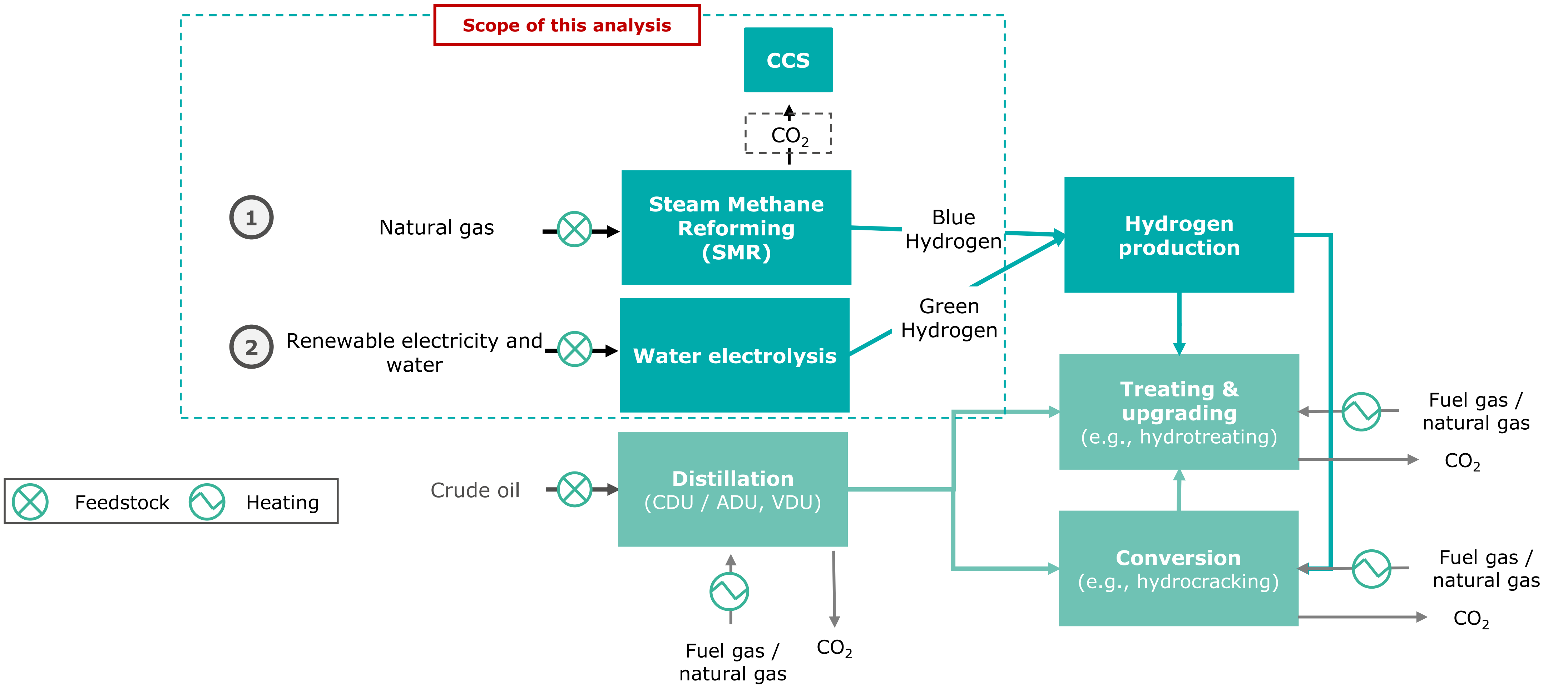
Location and relative size (in volume/year) of Europe refineries



Sources: (1) Concawe, 2019; (2) FuelsEurope, 2022; (3) Agora & AFRI, 2021; Deloitte analysis

Low-carbon hydrogen production in the hydrogenation process in oil refineries

Decarbonization of the refining production can be realized by CCS and / or substituting heating fuels and feedstock (e.g., green Hydrogen)



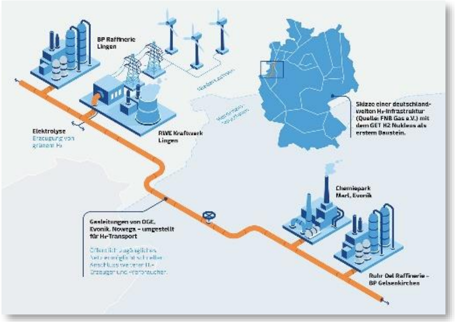
Source: Deloitte analyses

Examples of ongoing decarbonization roadmaps

Refinery Green Hydrogen initiatives

- The **Refhyne** initiative will install and operate a **10MW electrolyser** at the **Shell Rhineland Refinery** in Wesseling (DE), which will be able to produce approximately **1,300 tonnes of green Hydrogen** per year.
- This green Hydrogen can be **fully integrated** into refinery processes including the **upgrading** and **desulphurization** of conventional fuels

REFHYNE
CLEAN REFINERY HYDROGEN FOR EUROPE



- **BP** plans to jointly develop an industrial-scale **50 MW electrolyser** project with **Ørsted** for **green Hydrogen production**
- Powered by Ørsted **offshore wind**, the project will initially **replace 20%** of **natural gas-based hydrogen** used at **BP's Lingen** (DE) **refinery**

- **BP** is part of a **partnership** of seven companies, planning to build a **green Hydrogen grid** connecting **producers** of **green Hydrogen** with **industrial customers**
- The 130-kilometre grid from Lingen to **chemical** and **refinery** clients in Lingen and Gelsenkirchen (DE) is planned to **transport** first **green Hydrogen end of 2022.**

Source: Company websites

Examples of ongoing decarbonization roadmaps

Blue Hydrogen initiatives

- **ExxonMobil and Shell** have executed a joint development agreement in **Porthos**; the Port of Rotterdam **CO_2 Transportation Hub** and **Offshore Storage** project
- The Porthos project aims to **collect CO_2 emissions** from industrial sources and **transport** them by **pipeline** to depleted **North Sea offshore gas fields**

- **ExxonMobil**, **Shell** and **BP** participate in the **H-Vision study** looking into large-scale production of **blue hydrogen** in Rotterdam from **refinery fuel gasses**

- **ExxonMobil and Total Antwerp** are participating in the multi-stakeholder CCS project **Antwerp@C** at the Port of Antwerp
- The project would collect **CO_2** emissions from **industrial sources** for **local / international transport** and **storage** or **utilization**

Source: Company websites, Porthos, Antwerp@C, H-vision, Deloitte analyses

Shipping

When comparing fuelling options for international shipping, methanol and ammonia are the most promising

Biofuels

Pro's:
- Viable short-term option because current rules allow for fuel blends of up to 20% without engine modifications + tests have been conducted utilizing a maximum blend of 30%
- New ships can easily rely 100% on biofuels (proven technology)

Cons:
- Competition for suitable feedstocks and fuels from other sectors (e.g., road vehicles and aviation)
- Biomethane could play a role but is likely limited since production costs are highly dependent on feedstock availability and feedstock market price (high volatility)
- Still emits NOx and particulate matter

Ammonia

Pro's:
- While ammonia is corrosive and highly toxic if inhaled in high concentrations, ammonia has been handled safely for over a century

Cons:
- Requires modifications to engine

Methanol

Pro's:
- Requires little to no engine modifications
- No need for pressurized storage

Cons:
- Requires biogenic CO_2 as feedstock to be fully 'carbon-neutral'
- Cost related to biogenic CO_2 as feedstock result in higher cost of e-methanol compared to e-ammonia. However, if direct air capture and BECCS technology costs fall significantly in the next decade, it could be possible that methanol rather than ammonia will become the fuel of choice

Hydrogen

Pro's:
- Indirect use of hydrogen possible
- Green hydrogen has the possibility to become cost competitive in future

Cons:
- Major challenges due to the difficulty of storing it and its relatively low energy density (mainly for domestic shipping)

Main points:
- Medium to long-term: green hydrogen-based fuels will be foundation for decarbonization of international shipping sector
- Methanol and ammonia are most promising (ammonia more attractive due to its null carbon content)
- Hydrogen could be an option for short distances, for longer distances however, its role is rather limited due to large space required
- Renewable fuels production costs are currently high but will become competitive in the next decades
- Choice of fuel highly dependent on fuel price and availability, the supply chain, infrastructural adaptation costs of ships and ports, technological maturity, sustainability issues, net environmental performance and economic viability. Adoption of climate neutral sources could come earlier with government intervention
- Energy density of various fuels and implications in terms of onboard storage are elements that require further analysis (large storage space means less cargo capacity and less revenue)
- For domestic shipping, also batteries could be an option

Road freight

Hydrogen fuel cells have important advantages over electric batteries and biomethane as a fuel for long distance trucks

Relevant low-carbon fueling options:

1. Battery electric trucks
2. Hydrogen fuel cell trucks
3. Biomethane (bio-CNG/bio-LNG) trucks

Main points:

- Fast refueling times and high energy density leading to longer ranges make hydrogen and biomethane viable options for long-distance heavy road transport. However, by 2050, the majority of biomethane is expected to be used in other sectors where it has a higher societal value[1].
- Due to hydrogen's higher energy density than batteries, both in terms of volume and weight, given limitations in the weight and size of the energy storage in the vehicle, an FCEV can drive further and transport more payload than a BEV[2].
- The large size of required batteries for long-haul trucks is a significant cost driver[2].
- Fuel cells require significantly fewer raw materials compared to batteries and combustion engines[2].

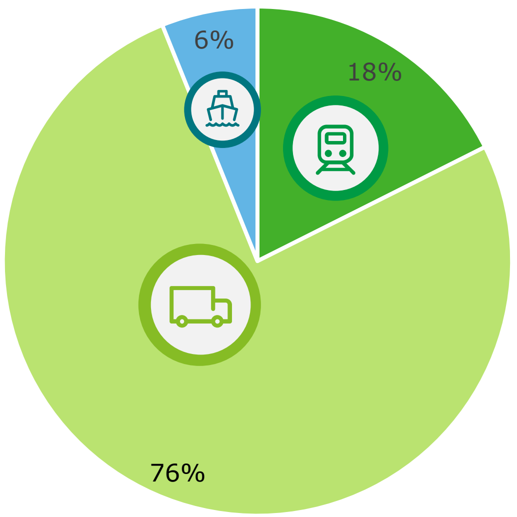
Sources: (1) Guidehouse, *European hydrogen backbone – Analysing future demand, supply, and transport of hydrogen,* 2021. (2) Fuel cells and hydrogen joint undertaking, *Hydrogen roadmap Europe*, 2019

I.2. Assessment of the ‘multimodality' functions of ports

Road transport might be partially replaced by more sustainable solutions such as railways in the future

Multimodality is the connection between vessels, trains and road transport and is of great importance to ports, since it is crucial for good connections, and it provides customers solutions to move goods cost effectively and efficiently.

Modal split of inland freight transport, EU, 2019 (% share in tonne-kilometers)[1]



Main observations:

- Currently, the largest part of goods are transported via the road (76%), followed by railways and finally by inland waterways.
- The modal split may change in the future, different stakeholders are looking into replacing road transport by more sustainable solutions such as railways. For example: a railway line opened between Vergèze and Fos sur Mer (Marseille) made it possible to subtract 27,000 trucks from road transport[2].

Adoption multimodality in model:

- In order to estimate the potential hydrogen demand, it is key to have an estimation of which transport mode will be used in the port areas and thus how large the potential hydrogen demand per transport mode can be. Transitions in volumes of the different transport subcategories were based on studies taking into account economic growth and change in model split.
- The modal split data was used to define the volumes of domestic shipping and road freight per port (railway is not taken into scope in the analysis)[3].

Sources and notes: (1) EUROSTAT (online data code: tran_hv_frmod, data available per country), (2) Port of Marseille (https://www.marseille-port.fr/en/Multimodality), (3) A shift in modal split towards the future was not directly taken into account, since for the different subcategories the individual volume evolutions were looked into.

Different assumptions were made when looking at the transport sectors to be able to make an estimation of future hydrogen demand

Assumptions:

- The role ports will play in bunkering of hydrogen (derivatives) is similar to their current bunkering role

→ Energy hubs of the future might evolve, and other ports could potentially play a large role

- Only the largest bunkering ports are taken into account due to lack of data.

Assumptions:

- To assign road freight to a port, it is assumed that 20% of road freight takes place in the vicinity of ports.

→ Depending on the country, more or less road freight should be assigned to ports

Assumptions:

- Trains are not taken into scope

→ The energy efficiency (i.e., MWh/m tonne-km) is more or less equal to the energy efficiency of shipping (27 MWh/m tonne-km)

→ There is 238,736 m tonne-km not yet electrified in Europe.

→ The max hydrogen demand coming from trains could be 6.5 TWh, which is not significant compared to the total hydrogen demand in Europe

APPENDIX II – Task 2

II.1. Distinction between existing and new supply of hydrogen in industrial subcategories

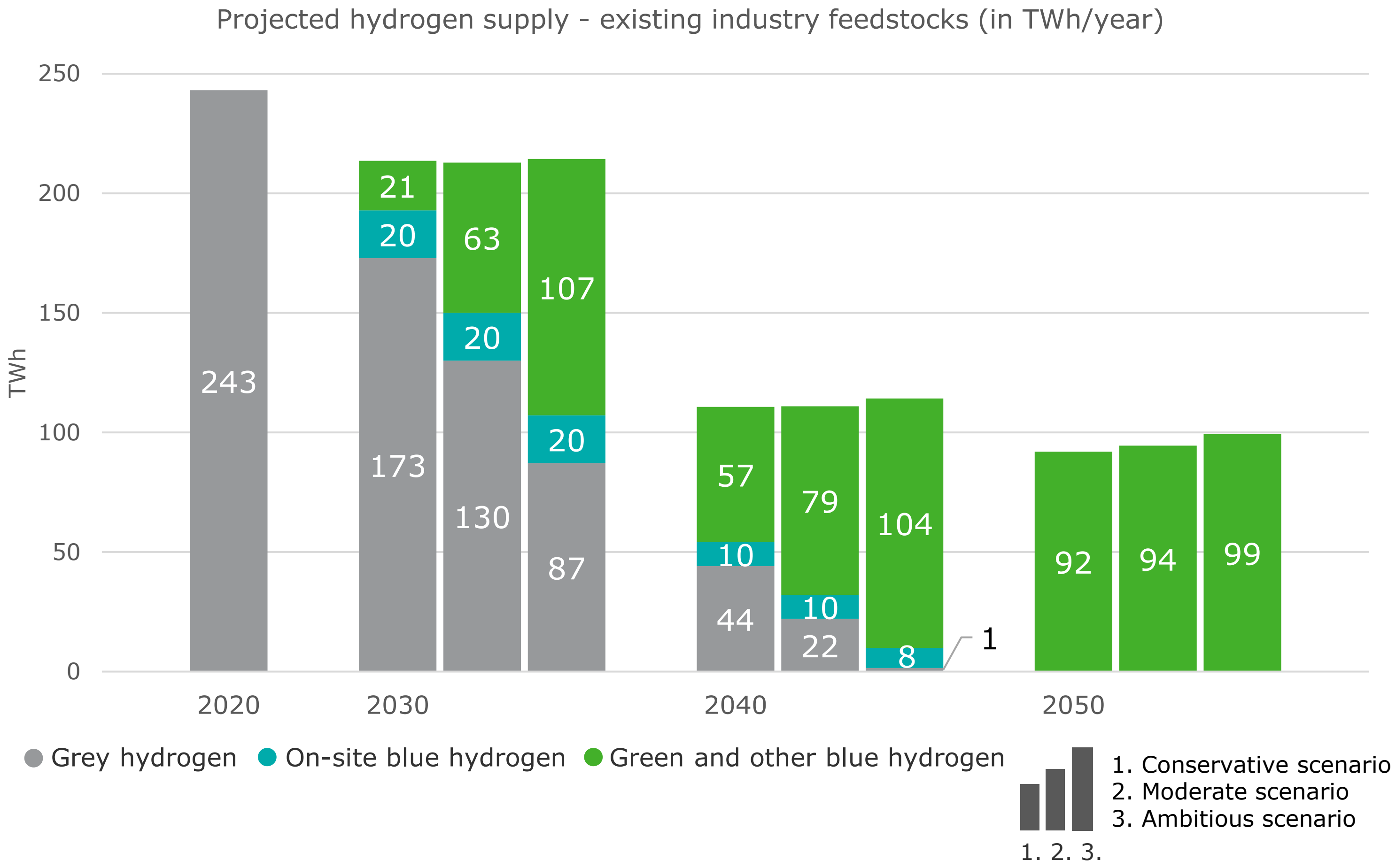
II.2. Hydrogen supply model assumptions and sources

II.1. Distinction between existing and new supply of hydrogen in industrial subcategories

Synthesis

Assessment of the hydrogen supply for industries from 2020 to 2050 (Synthesis – ammonia, methanol and hydrogenation of fossil fuel in refineries)

While on-site blue hydrogen is expected to be developed **in parallel** to green and other blue hydrogen **in the transition** away from grey hydrogen production for existing industries for which hydrogen is used as a feedstock, **all on-site blue hydrogen supply is replaced by green and blue hydrogen** to meet the long-term goal of a climate neutral European energy system.



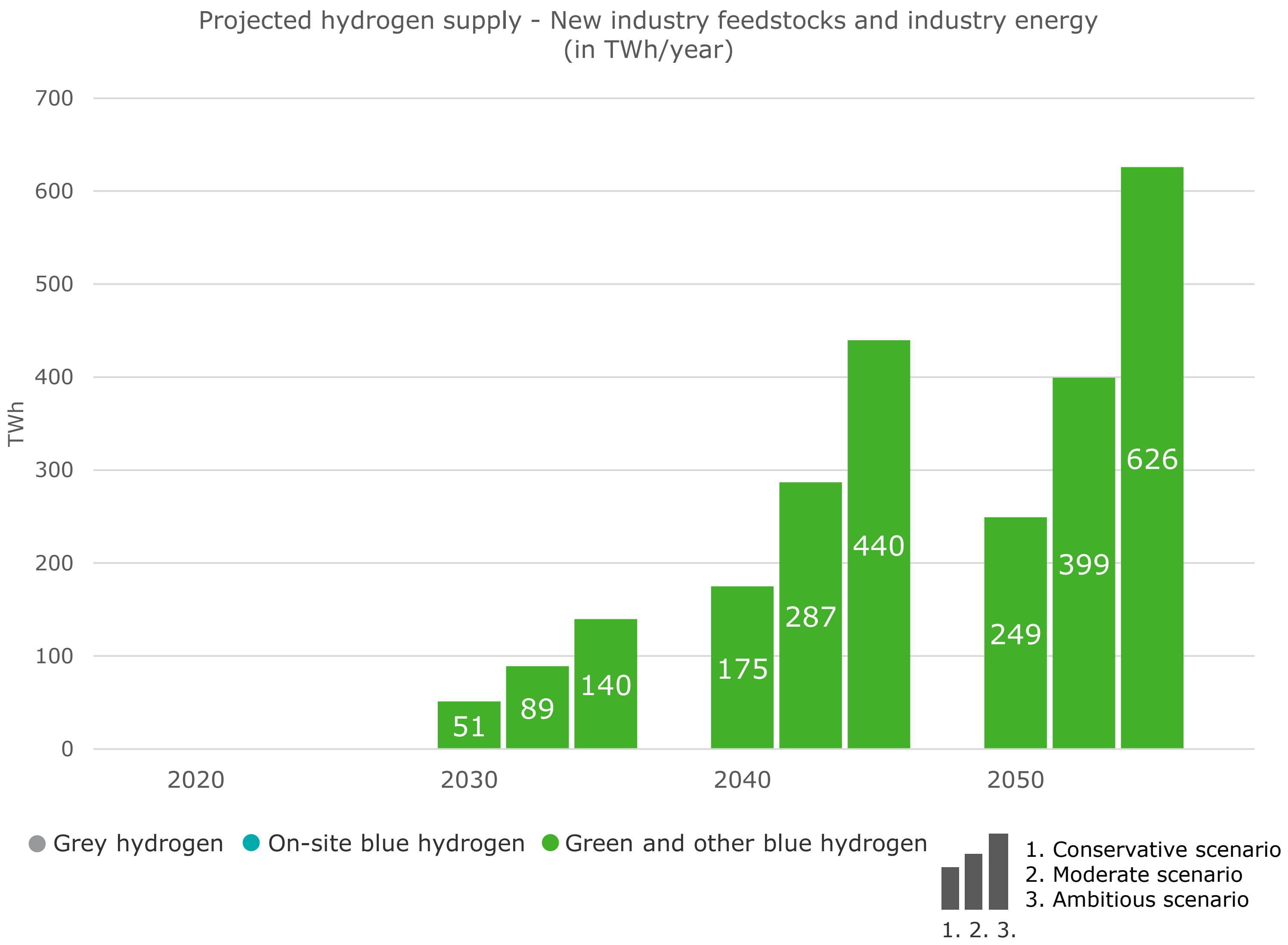
Narrative:

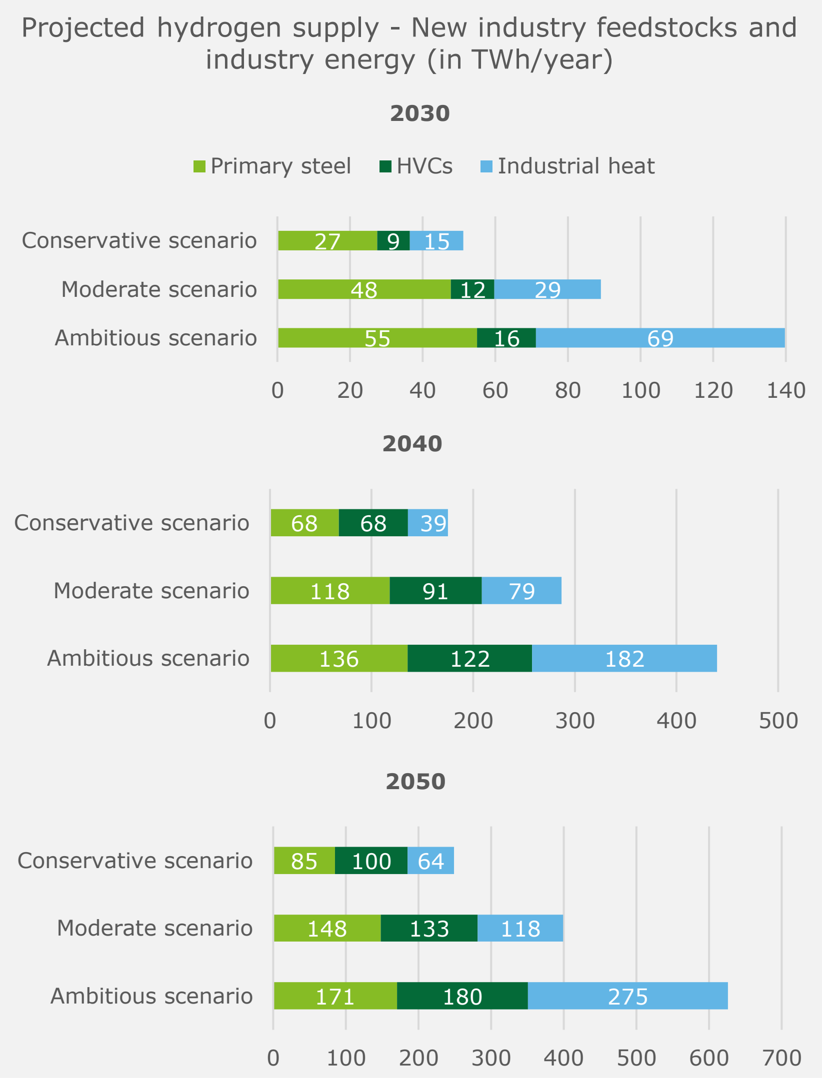
- By 2050, **100%** of hydrogen production for current uses has been replaced by green and blue hydrogen (or by non-hydrogen-based decarbonized production processes).
- In the transition, the study foresees that, between 2020 and 2040, **a minor share of the current grey hydrogen** use as feedstock for **fossil fuel hydrogenation** in refineries and **ammonia** production will be converted to **on-site blue hydrogen**.

Analysis of the scenarios:

- **Ambitious scenario**: The adoption rate of green and blue hydrogen as a replacement for grey hydrogen currently used in industries **increases rapidly** to **59% by 2030** and **99% by 2040**.
- **Moderate scenario**: The adoption rate of green and blue hydrogen as a replacement for grey hydrogen currently used in industry **increases rapidly** to **39% by 2030** and **80% by 2040**.
- **Conservative scenario**: The adoption rate of green and blue hydrogen as a replacement for grey hydrogen currently used in industry **increases slowly** (relatively to the two other scenarios) to **19% by 2030** and **60% by 2040**.

Assessment of the hydrogen supply for industries from 2020 to 2050 (Synthesis – primary steel, industrial process heat and HVCs production)

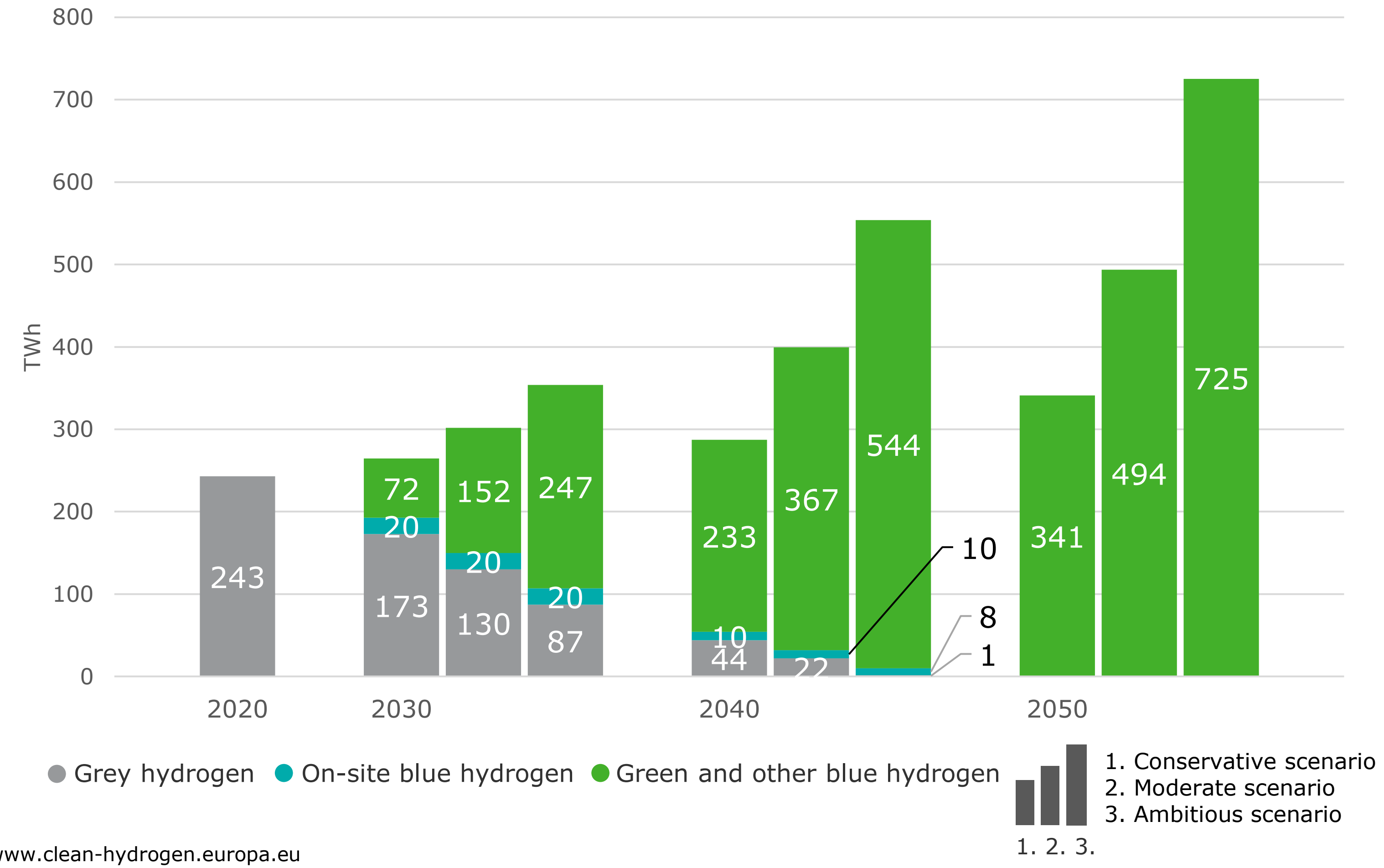




Assessment of the hydrogen supply for industries from 2020 to 2050 (synthesis)

This study assumes that, aside from refineries and ammonia production plants that will in part meet their hydrogen needs by on-site blue hydrogen production, the **future demand for green and blue hydrogen** from European industries will be met by **hydrogen not necessarily produced near industrial facilities**, based on a cost optimization rationale.

Projected hydrogen supply for industries (in TWh/year)



Synthesis of the scenarios:

- In this context, the results of our analysis show that, over time, the quantity of "green and other blue hydrogen" (excl. on-site) that will need to be supplied to EU+UK industrial facilities are the following:
  - Between **71 and 247 TWh** (or 2.1 to 7.4 Mt) per year in 2030;
  - Between **233 and 544 TWh** (or 7.0 to 16.3 Mt) per year in 2040;
  - Between **341 and 725 TWh** (or 10.2 to 21.8 Mt) per year in 2050.
- By **2030**, much of the green and blue hydrogen (excl. on-site hydrogen) can be expected to be supplied for primary steelmaking, medium and high temperature industrial process heat*, mineral oil hydrogenation and ammonia (for fertilizers).
- By **2040 and 2050**, much of the green and blue hydrogen can be expected to be supplied for primary steelmaking, medium and high industrial process heat* and HVCs production.

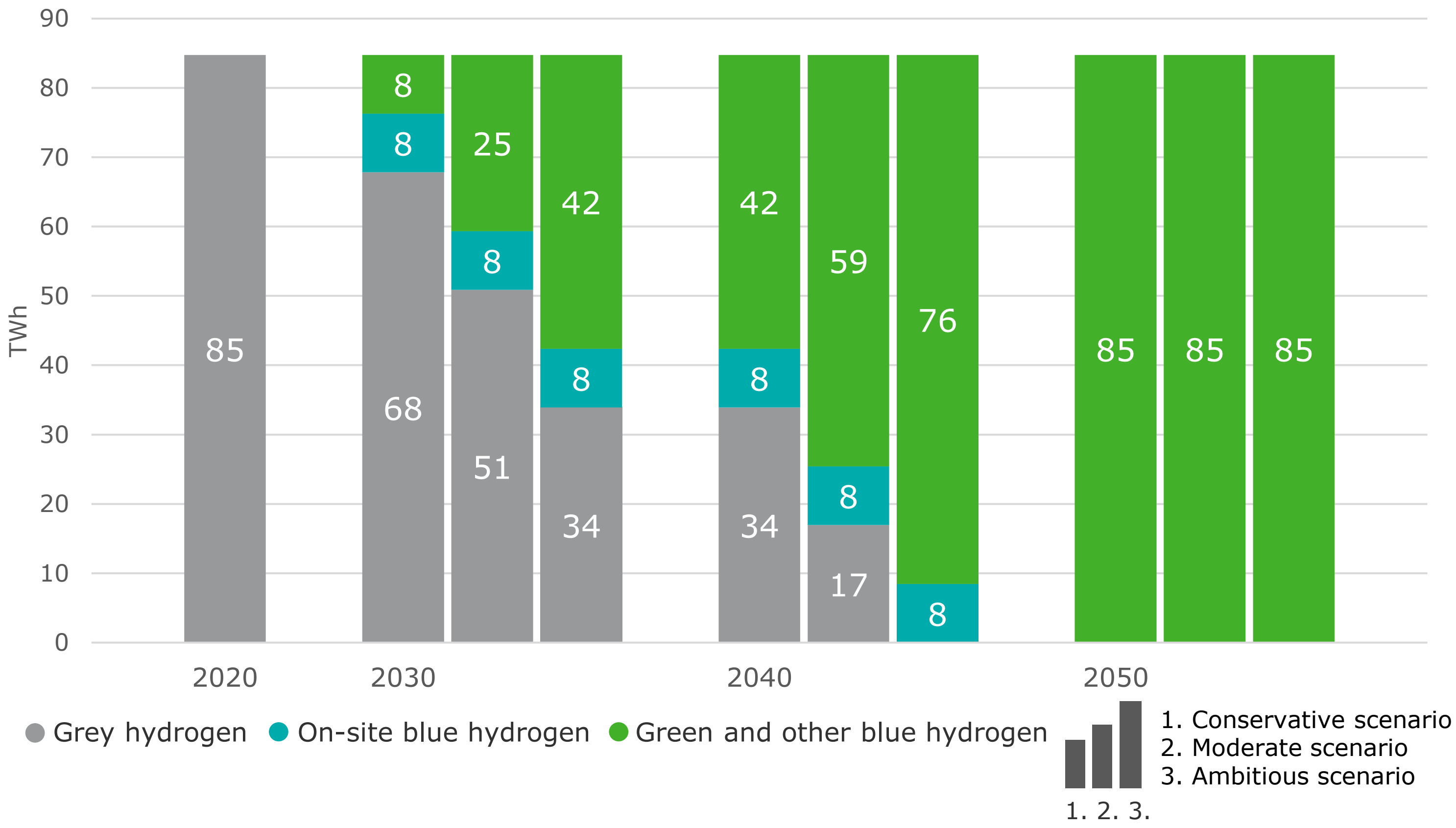
* only in the Ambitious scenario.

Individual assessment of the hydrogen supply for ammonia, methanol and hydrogenation of fossil fuel from 2020 to 2050

Assessment of the hydrogen supply for industries from 2020 to 2050 (ammonia for fertilizers)

With hydrogen already a key input to ammonia production process, one of the relevant dimensions to investigate in this study is **the extent to which current (grey) hydrogen production will be progressively replaced by green and blue hydrogen**. Indeed, depending on the rate of substitution, the future demand for **green and blue hydrogen will differ**. Therefore, the **scenarios** below **outline trajectories** in which the rate of adoption of green and blue hydrogen as an alternative to grey hydrogen is more or less sustained.

Projected hydrogen supply in the ammonia (for fertilizers) sector (in TWh/year)



Narrative

- Grey hydrogen in the production process of ammonia is progressively fully replaced by green and blue hydrogen.
- In all the three scenarios, it is assumed that there will be an equal split between on-site blue and green/blue hydrogen in the transition away from grey hydrogen.
- By 2050, all on-site blue hydrogen supply is replaced by green/blue hydrogen to meet the long-term goal of a climate neutral European energy system[1].

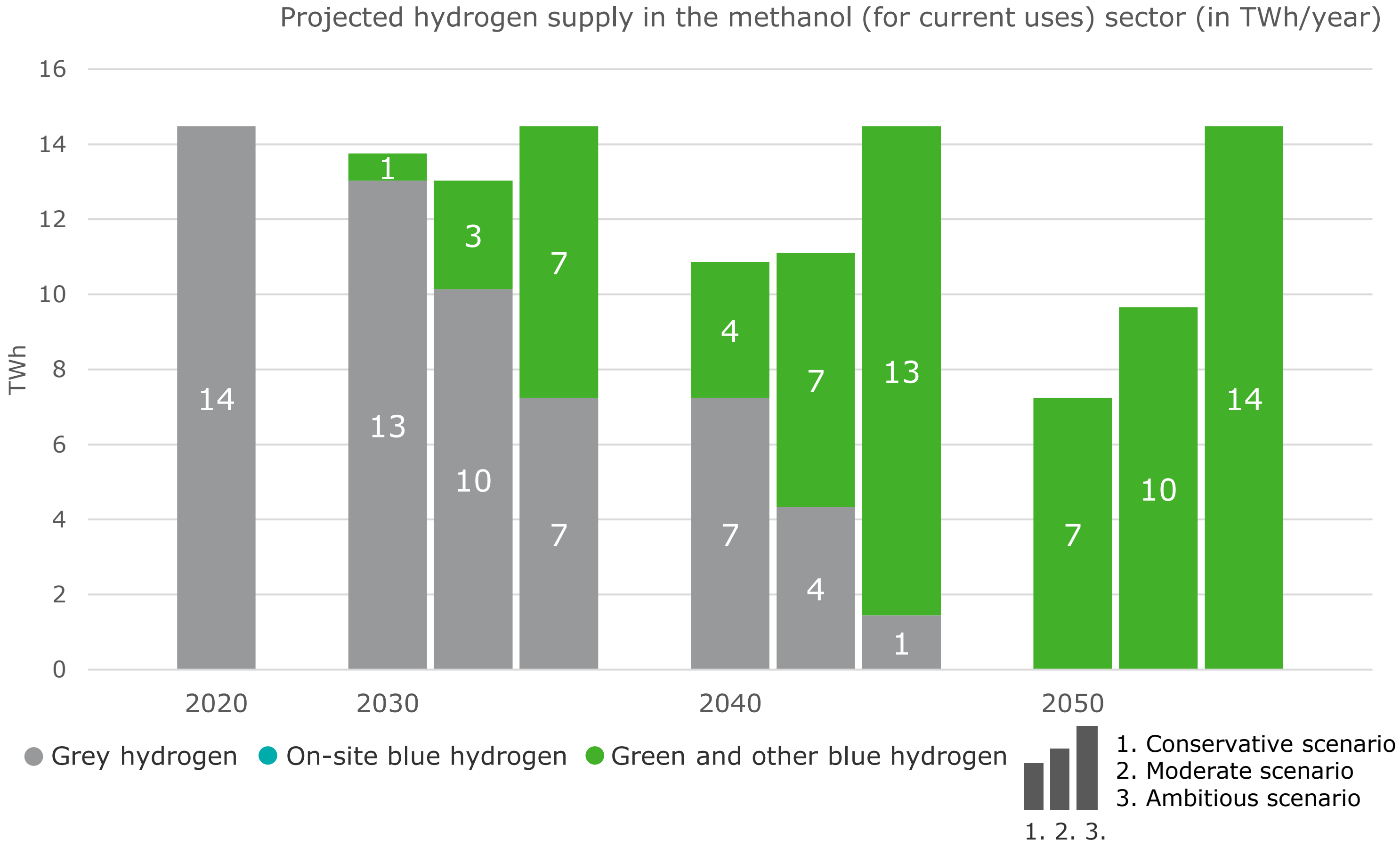
Description of the scenarios:

- **Ambitious scenario**: The adoption rate of green and blue (incl. on-site) hydrogen supply **increases very rapidly** to 60% in 2030 and 100% in 2040 (incl. 10% on-site). By 2050, **100%** of ammonia is produced with “green and other blue hydrogen”.
- **Moderate scenario**: The adoption rate of green and blue (incl. on-site) hydrogen supply **increases rapidly** to 40% in 2030 and 90% in 2040 (incl. 10% on-site). By 2050, **100%** of ammonia is produced with “**green and other blue hydrogen**”.
- **Conservative scenario**: The adoption rate of green and blue (incl. on-site) hydrogen supply **increases slowly** (relatively to the two other scenarios) to 20% in 2030 and 60% in 2040 (incl. 10% on-site). By 2050, **100%** of ammonia is produced with “green and other blue hydrogen”.

Note: (1) Guidehouse (2021) assumes that by 2050, there will be not blue hydrogen supplied to ammonia plants to meet the long-term goal of a climate neutral European energy system. Due to different assumptions regarding the future demand for ammonia (in Mt/year), hydrogen demand/supply in 2050 in the ammonia sector (for fertilizers production) slightly differs in comparative studies: 113 TWh/year in Guidehouse (2021), 88.5 TWh/year in Material Economics New Processes and Carbon Capture scenarios (2019), 71 TWh in Material Economics Circular Economy scenario.

Assessment of the hydrogen supply for industries from 2020 to 2050 (methanol for current uses)

Similar to ammonia, hydrogen is today a key input to the methanol production process. However, contrary to ammonia production, methanol production necessarily needs CO_2 input, which implies that blue hydrogen is not an option to decarbonize methanol production. The **scenarios** below **outline potential trajectories** in which the rate of adoption of green e-methanol as an alternative to SMR-based methanol is more or less or widespread.



Narrative

- The current production methanol process (based on SMR) is progressively replaced by green e-methanol (green hydrogen and CO_2) as well as by bio-methanol (biomass and CO_2).
- By 2050, all grey hydrogen supply is replaced by a shift to green e-methanol and bio-methanol production processes.

Description of the scenarios:

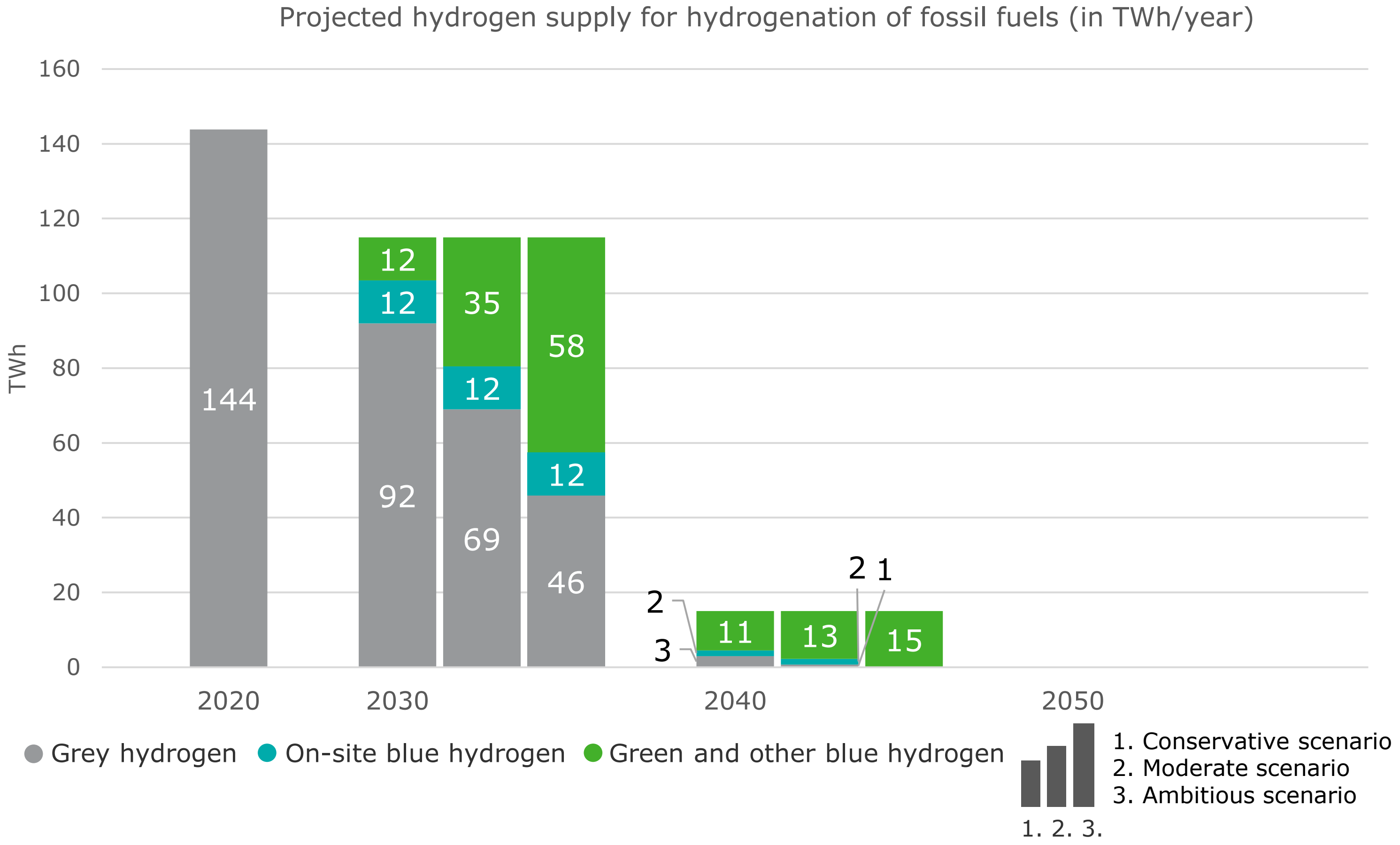
- **Ambitious scenario**: The adoption rate of green hydrogen supply (green e-methanol route) **increases very rapidly** to 50% in 2030 and 90% in 2040. By 2050, **100%** of European methanol production uses green hydrogen in the production process.
- **Moderate scenario**: The green e-methanol route is the **preferred decarbonization pathway (but not the only)** chosen by methanol producers. The adoption rate of green hydrogen supply **increases rapidly** to 20% in 2030 and 47% in 2040. By 2050, **2/3rd (67%)** of European methanol production uses green hydrogen in the production process.
- **Conservative scenario**: The pathway of **e-methanol is being considered as much as bio-methanol** by methanol producers. The adoption rate of green hydrogen supply **increases slowly** to 5% in 2030 and 25% in 2040. By 2050, **50%** of European methanol production uses green hydrogen in the production process.

Note: (*) Since blue hydrogen is not an option for decarbonizing methanol production, the above results should be interpreted as a green hydrogen supply only.

Distinction between existing and new supply of hydrogen in industrial subcategories

Assessment of the hydrogen supply for industries from 2020 to 2050 (hydrogenation of fossil fuel in refineries)

Similar to the ammonia and methanol produced processes, hydrogen is used by refineries in the hydrogenation of fossil fuel process. The **scenarios** below **outline potential trajectories** in which the rate of adoption of green and blue hydrogen as an alternative to grey hydrogen is more or less sustained.



Narrative

- Grey hydrogen in the hydrogenation of fossil fuel process is progressively replaced by green and blue hydrogen.
- In all the three scenarios, it is assumed that there will be an equal split between on-site blue and green/blue hydrogen in the transition away from grey hydrogen.
- By 2050, **no hydrogen is needed in refineries for the hydrogenation of mineral oil process[1].**

Description of the scenarios:

- **Ambitious scenario**: The adoption rate of green and blue hydrogen supply **increases very rapidly** to 60% in 2030 (incl. 10% on-site blue hydrogen) and 100% in 2040.
- **Moderate scenario**: The adoption rate of green and blue (incl. on-site) hydrogen supply **increases rapidly** to 40% in 2030 (incl. 10% on-site blue hydrogen) and 100% in 2040 (incl. 10% on-site blue hydrogen).
- **Conservative scenario**: The adoption rate of green and blue (incl. on-site) hydrogen supply **increases slowly** (relatively to the other scenarios) to 20% in 2030 (incl. 10% on-site blue hydrogen) and 85% in 2040 (incl. 10% on-site blue hydrogen site).

Note: (1) Aside from the difference between on-site blue hydrogen and green/blue hydrogen, Guidehouse (2021)'s scenario is similar to Deloitte's Ambitious scenario. While Agora & AFRI (2021)'s scenario assumes the same hydrogen demand over time as in Deloitte's three scenarios, it does not specify the green/blue hydrogen adoption rate.

Alternative view on blue hydrogen production in Europe

Blue hydrogen production in the EU (both from on-site and central hydrogen plants) could theoretically reach up to 396 TWh/year in 2040

Underlying assumptions to estimate blue hydrogen production potential in the EU:

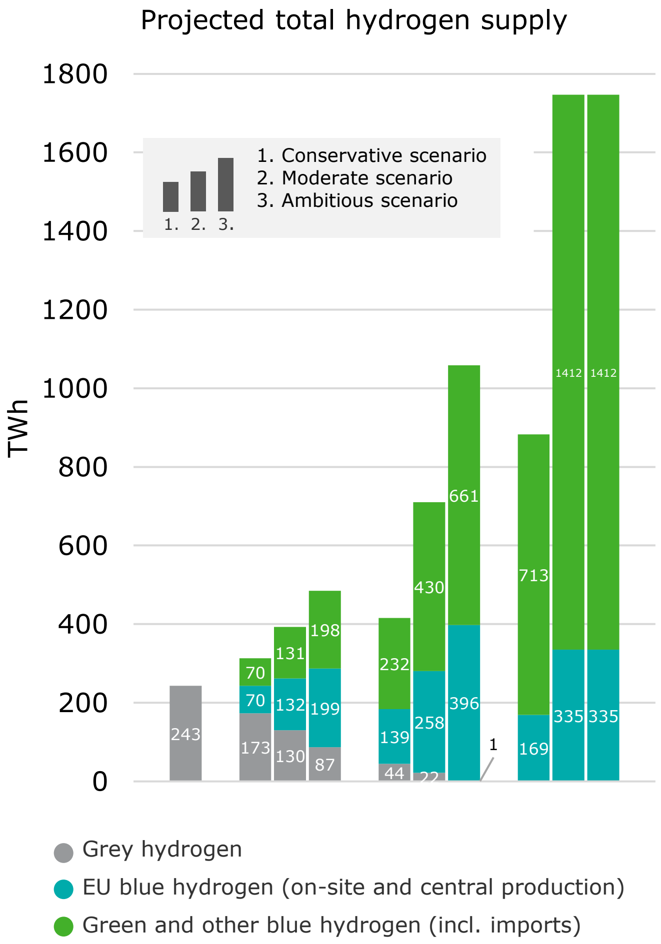
- Along with the production of on-site blue hydrogen and green hydrogen, it could be assumed that **EU countries develop in the 2020s and 2030s large-scale blue hydrogen projects** to supply feedstock and energy heat for **new industrial applications** (e.g., primary steelmaking, industrial process heat and HVCs production) and for **new non-industrial applications** (transport, urban areas, port activities).
- Assumptions on European blue hydrogen production uptake are based on the relative shares of blue hydrogen production in the overall Europe blue/green hydrogen supply mix for 2030, 2040, and 2050 from the Hydrogen4EU study (Renewable Push pathway scenario)[1]. These relative shares were then applied to the overall estimates of blue/green hydrogen supply requirements for this study's conservative, moderate and ambitious scenarios in 2030, 2040 and 2050 to determine total blue hydrogen production (both on-site and at central generation plants) in Europe. Blue hydrogen production estimates were then confronted with results in absolute value from the Guidehouse's study (2021) to check coherence and consistency with the latest literature[2].

Narrative:

- By 2050, **100%** of hydrogen production for current uses has been replaced by **green** and **blue hydrogen** produced both within and outside Europe.
- In the transition, both **green** and **blue hydrogen** play a role, with European production of blue hydrogen still providing about **20% of total Europe hydrogen supply in 2050**.
- Retrofitting of existing SMR plants with CCS units and development of new central blue hydrogen production sites are assumed to be **gradually deployed in the 2020s and 2030s**, reaching a **peak in 2040** and then decreasing due to increasing competition (due to lower costs) from green hydrogen production.

Outcome of the perspective:

- **Ambitious scenario**: The production of blue hydrogen **increases rapidly** to 200 TWh in 2030 (67% of the total green/blue hydrogen production) and 396 TWh in 2040 (40%), before decreasing to 335 TWh in 2050 (19%).
- **Moderate scenario**: The production of blue hydrogen **increases** to 132 TWh in 2030 (67% of the total green/blue hydrogen production) and 258 TWh in 2040 (40%), before decreasing to 169 TWh in 2050 (19%).
- **Conservative scenario**: Europe production of blue hydrogen **increases slowly** to 70 TWh in 2030 (67% of the total green/blue hydrogen production) and 139 TWh in 2040 (40%), before decreasing to 104 TWh in 2050 (19%).



Note: (1) Hydrogen4EU: Charting the Pathways to Enable Net Zero, 2021 (page 8); (2) Guidehouse, 2021: the study estimates that greenfield blue hydrogen supply potential in the EU+UK account for 167 TWh/year by 2030 and 244 TWh/year by 2035. Adding brownfield blue hydrogen production to this number leads to a total of 234 TWh/year by 2030 and 378 TWh/ year by 2035 and onwards.

II.2. Hydrogen supply model assumptions and sources

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/km	0,154	[1]
Liquified Hydrogen	Ships	kWh/kgHydrogen/km	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	EUR/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 – production cost (1/3)

		Unit	2030	2040	2050
Solar PV	CAPEX	EUR15/kW	720	580	500
	OPEX	%CAPEX	1,7	1,7	1,7
	Lifetime	year	25	25	25
	Efficiency	%	90	90	90
Onshore Wind	CAPEX	EUR15/kW	1260	1220	1102
	OPEX	%CAPEX	3	3	3
	Lifetime	year	25	25	25
	Efficiency	%	84	84	84
Offshore fixed	CAPEX	EUR15/kW	2940	2830	2710
	OPEX	%CAPEX	2	2	2
	Lifetime	year	30	30	30
	Efficiency	%	85	85	85
Offshore floating	CAPEX	EUR15/kW	4490	4330	4140
	OPEX	%CAPEX	2	2	2
	Lifetime	year	30	30	30
	Efficiency	%	85	85	85

Sources: Tsiropoulos I, Tarvydas, D, Zucker, A, Cost development of low carbon energy technologies - Scenario-based cost trajectories to 2050, 2017 Edition, EUR 29034 EN, Publications Office of European Union, Luxembourg, 2018, ISBN 978-92-79-77479-9, doi:10.2760/490059, JRC109894.

Cost assumptions for hydrogen supply model – production cost (2/3)

		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
	Efficiency	%	69	72	75
ATR + CCS	Capex	EUR/MW	680416	680416	680416
	CO2 capture rate	%	90	90	90
	Efficiency	%	71,429	71,429	71,429
	Fixed O&M	EUR/MW	20412	20412	20412
	Lifetime	years	25	25	25
	Variable O&M	EUR/MWh	0,245	0,245	0,245
GHR + CCS	Capex	EUR/MW	729017	729017	729017
	CO2 capture rate	%	95	95	95
	Efficiency	%	80	80	80
	Fixed O&M	EUR/MW	21871	21871	21871
	Lifetime	years	25	25	25
	Variable O&M	EUR/MWh	0,245	0,245	0,245

Sources: (1) IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen. (2) Blanco H., Nijs W., Ruf J., Faaij A., 2018a, Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization, Applied Energy 232, pp. 617-639. (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. (4) Hydrogen 4 EU study - https://www.hydrogen4eu.com/

Cost assumptions for hydrogen supply model – production cost (3/3)

		Unit	2030	2040	2050
Pyrolysis	Capex	EUR/MW	806449	806449	806449
	CO2 capture rate	%	97,5	97,5	97,5
	Efficiency	%	48,78	48,78	48,78
	Fixed O&M	EUR/MW	82739	82739	82739
	Lifetime	years	20	20	20
	Variable O&M	EUR/MWh	0,000	0,000	0,000
SMR + CCS	Capex	EUR/MW	1204000	1168500	1133000
	CO2 capture rate	%	74,6	74,6	74,6
	Efficiency	%	63,694	63,694	63,694
	Fixed O&M	EUR/MW	36100	35050	34000
	Lifetime	years	25	25	25
	Variable O&M	EUR/MWh	0,252	0,252	0,252

* WACC considered for European countries is 8% and for exporter countries are based on ease of doing business and own calculation

Sources: (1) IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen. (2) Blanco H., Nijs W., Ruf J., Faaij A., 2018a, Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization, Applied Energy 232, pp. 617-639. (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. (4) Hydrogen 4 EU study - https://www.hydrogen4eu.com/

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

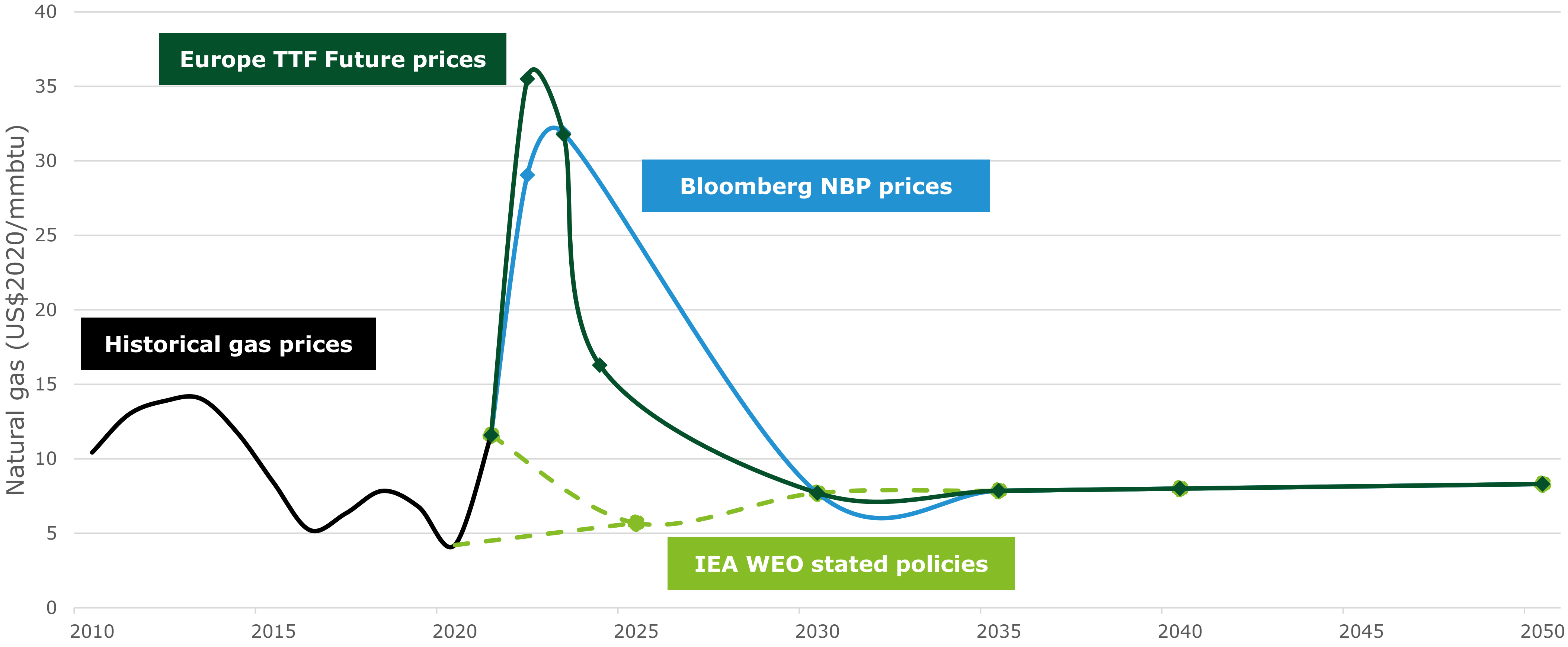
Transport fuel price[2]

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

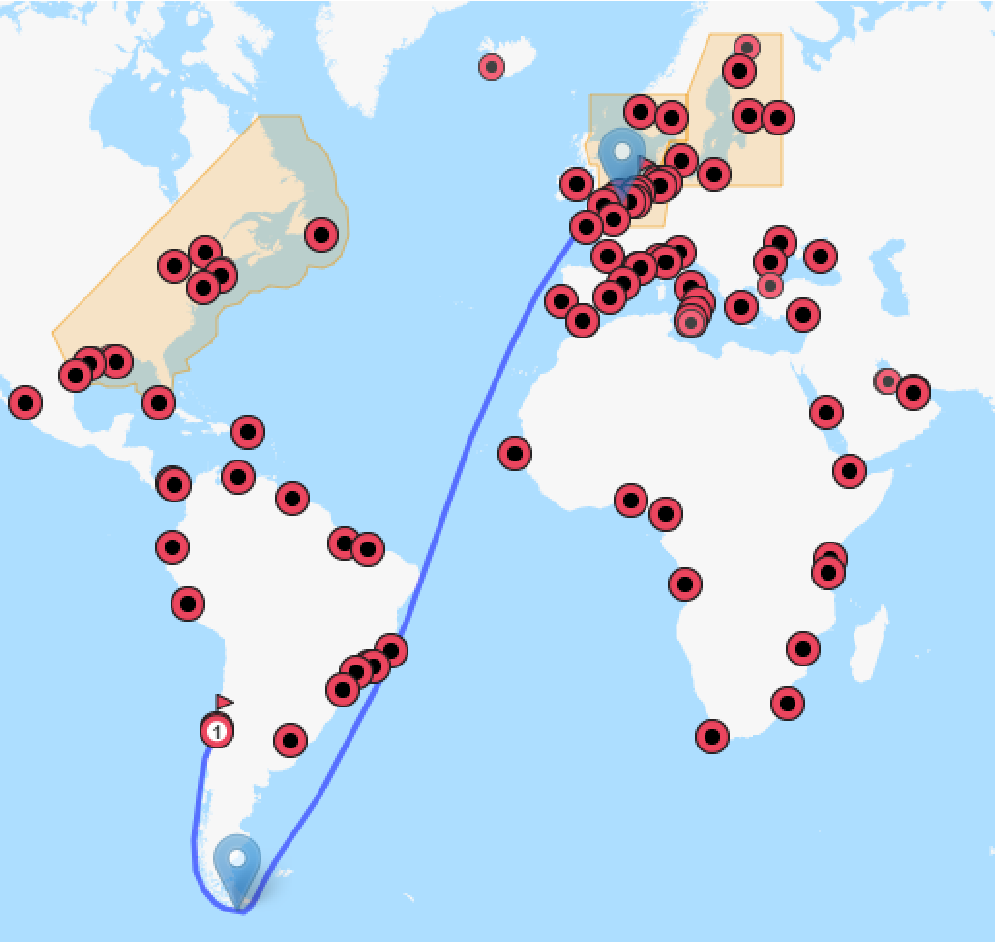
Sources: (1) "Data from the DNV Energy Transition Outlook report is included in this work, © DNV AS. 2021. All rights reserved. eto.dnv.com" This work is partially based on data developed by DNV AS, ©DNV AS. 2021, but the resulting work has been prepared by Deloitte and does not necessarily reflect the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

Natural price increase is a short-term bump in the prices, and in the long-term it shouldn't have a sustainable impact in the price projections

The HyPE model uses natural gas production cost in exporting countries, and not market price. However, even the natural gas market price is not expected to be impacted by recently experienced high prices in long run (2030 onwards).



Importing hydrogen from Chile will cost more than the most expensive imports from Middle-East and North Africa



- Ports: Valparaiso to Amsterdam
- Distance: 9,055 nautical miles (16,770 km)
- PV capacity factor: ***25%***
- Transport via ***ships in the form of ammonia***
- Considered costs: electricity production for electrolysis, electrolysis, conversion (including electricity consumption), shipping (fixed and variable), reconversion (including electricity consumption), import terminal and export terminal.
- Cost of ***local transport of hydrogen and electricity*** in Chile not considered.

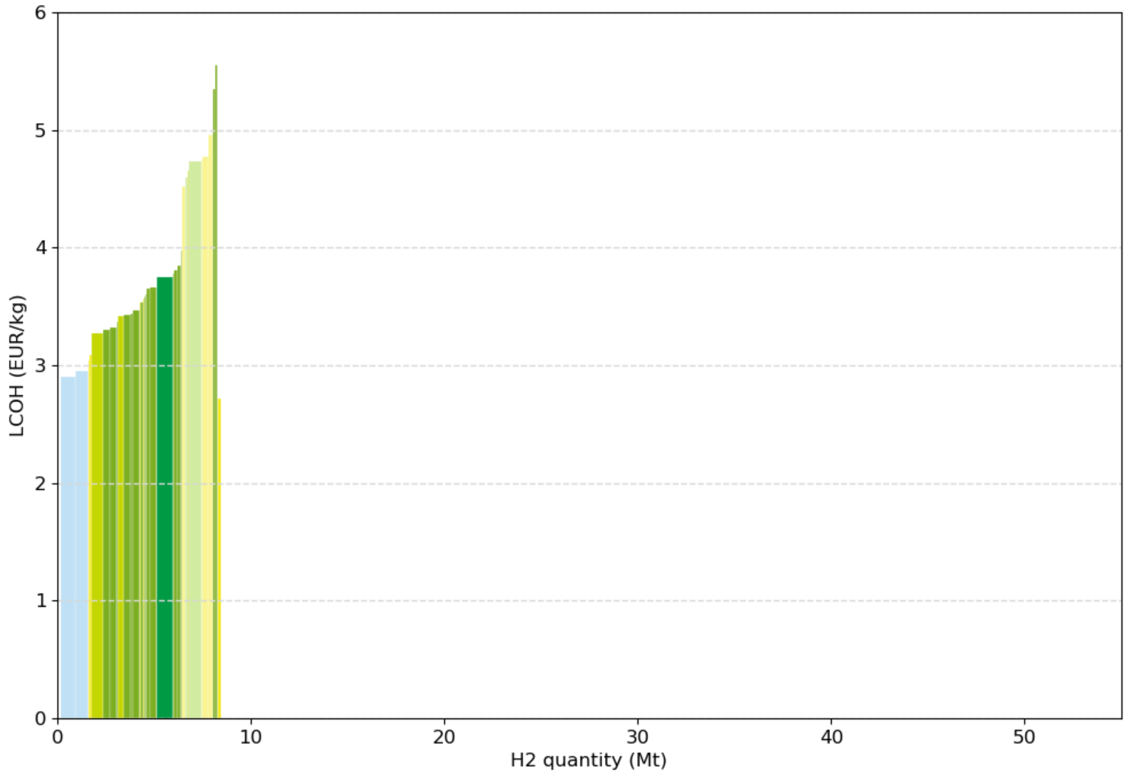
hydrogen origin	Cost in 2030	Cost in 2050
Chile - PV	€5.8/kg	€4/kg
Most expensive	€5.5/kg	€3.7/kg

- Allowing Panama will reduce it by around €0.1/kg

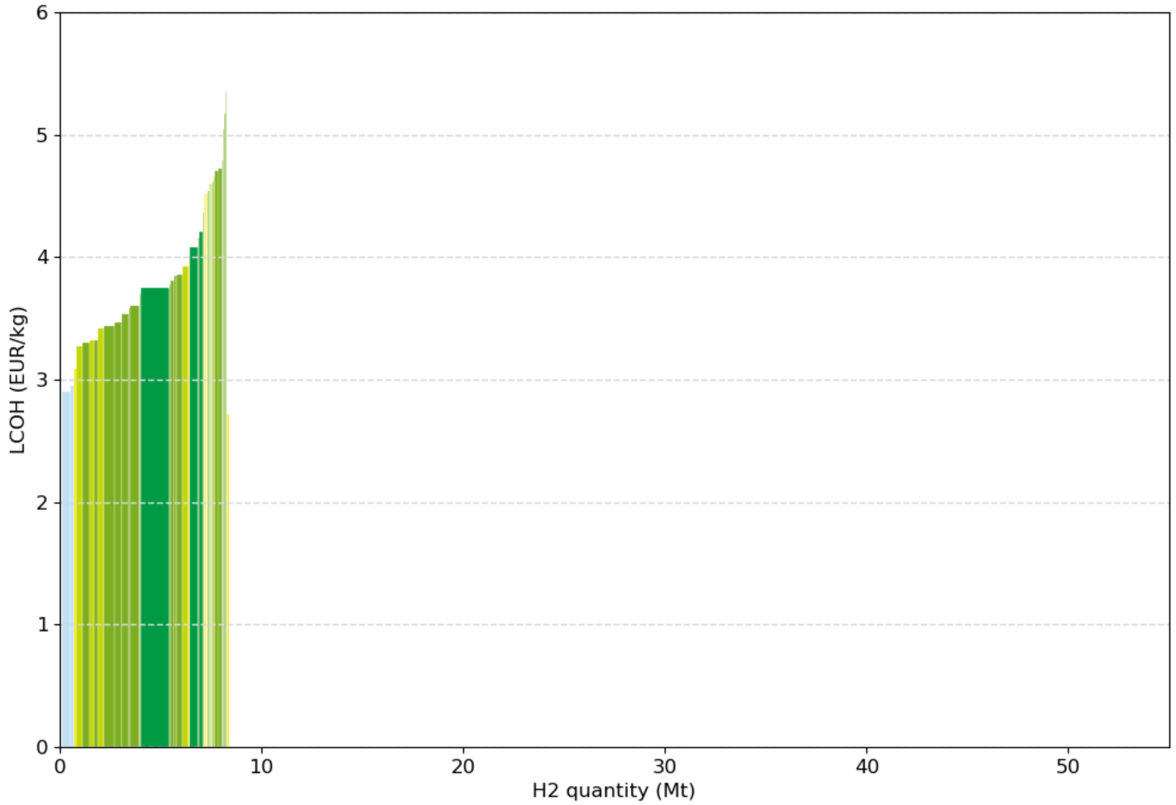
Sources: searoutes.com ; Renewables.ninja ; EU-JRC (2017) ; HyPE references

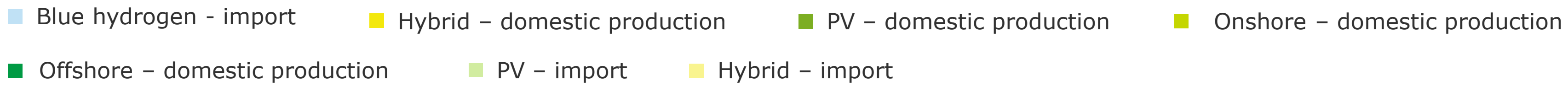
Merit order curve for hydrogen supply for the ambitious increased import scenario and ambitious base scenario in 2030

Increased import supply scenario



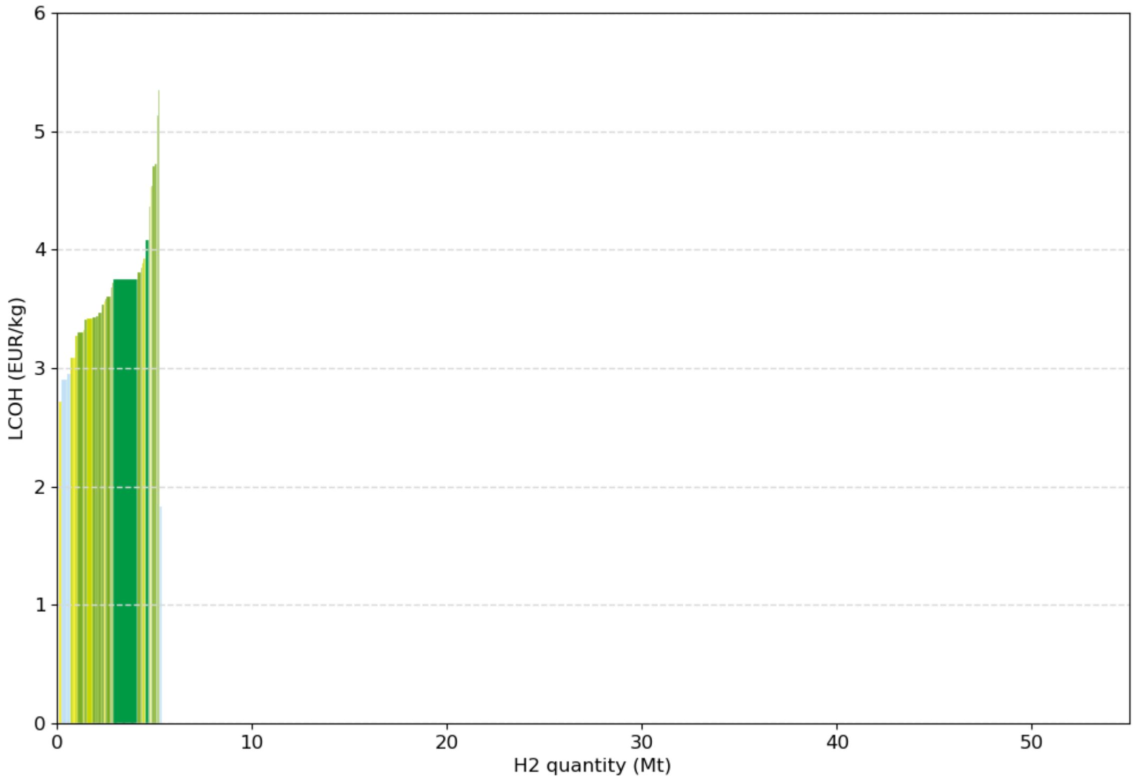
Base supply scenario



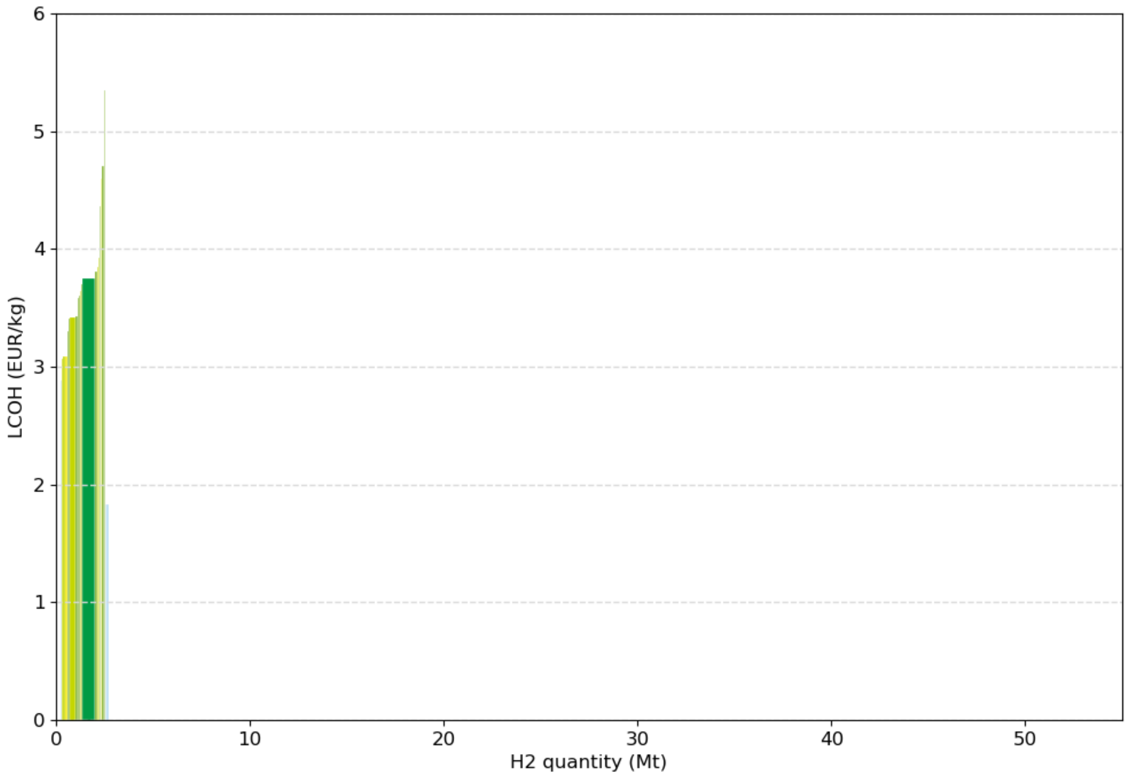


Merit order curve for hydrogen supply for the moderate and conservative base scenario in 2030

Moderate scenario



Conservative scenario



Blue hydrogen - import
Hybrid – domestic production
PV – domestic production
Onshore – domestic production
Offshore – domestic production
PV – import
Hybrid – import

APPENDIX III – Task 3
Role of ports in the hydrogen economy

At the moment, most ports take on the role of landlord or community builder and enabler concerning different aspects of the hydrogen value chain

Ports	Archetype	Reason of selection	Landlord	Community builder and enabler	Investor
Port of Valencia	Logistics and transport	Advisory board & pioneering port	Consumption	Across the value chain	
Port of Rotterdam	Logistics and transport, bunkering, industrial	Advisory board & pioneering port		Across the value chain	Transport and distribution
Port of Antwerp-Bruges	Logistics and transport, bunkering, industrial	Advisory board & pioneering port	Production, conversion/transport/storage and consumption	Across the value chain	Consumption
Port of Constanta	Logistics and transport	Advisory board & pioneering port		Across the value chain	
North Sea port	Logistics and transport, industrial	Pioneering port	Production	Across the value chain	
Port of Hamburg	Logistics and transport, bunkering, urban	Advisory board & pioneering port	Conversion/transport/storage	Across the value chain	
NorthSea Group		Geographical spread	Conversion/transport/storage and consumption	Across the value chain	Production and consumption

Conclusion: at this moment in time, most ports take on the role of landlord or community builder and enabler concerning the different aspects of the hydrogen value chain. The investor role is more limitedly adopted.

Deep-dive – Port of Valencia

valenciaport
Autoridad Portuaria de Valencia

Ambitions and role of ports including project examples concerning Hydrogen

Ambitions: The port of Valencia will be the first port in Europe to incorporate hydrogen technologies to reduce the environmental impact of its terminal machinery operations. They have the goal to become carbon neutral by 2030.

Roles:

Landlord:

- **Leasing of space** to consumers of hydrogen

Community builder and enabler:

- **HydrogenPORTS project**: test and validate hydrogen technologies for port machinery in order to achieve solutions that produce zero local emissions (funded by FCH JU and coordinated by Valenciaport Foundation and the PAV). Equipment tested: a reach stacker and a 4x4 tractor unit. Also installation of a hydrogen station. The station will be mobile and providing the necessary fuel to the port equipment
- Created an **advisory group** open to more than 65 members and 30 ports around the world to help to develop the hydrogen value chain in the port community
- Hydrogen technologies are being considered into the **Valenciaport 2030 Net Zero Emissions**

Buy/make Hydrogen

Focus on make

Link with archetype

Logistics and transport archetype: need for decarbonization of port equipment, domestic shipping and vehicles. Hydrogen can be part of the solution thus pilot projects are performed.

Deep-dive – Port of Rotterdam

Ambitions and role of ports including project examples concerning Hydrogen

Ambitions: The Port of Rotterdam wants to become a hydrogen hub with high amounts of hydrogen used in the industry and being the engine of the national economy

Roles:

Community builder and enabler:

- **Providing land for electrolysers**: 2 GW conversion park for green Hydrogen (hydrogen fabric together with Shell, Agreement between energy company Uniper and Port of Rotterdam to develop the production of green hydrogen on Uniper's Maasvlakte location, Hydrogen-Fifty project)
- **H-vision program** to produce blue Hydrogen partnering together with a.o. Equinor, BP, Shell, ExxonMobil, TAQA, Vopak and Gasunie
- Supporting the consortium Transhydrogen Alliance (technology company Protonne Ventures, trading company Trammo and energy company VARO) in their collaborations concerning production and import of green hydrogen and ammonia by **developing import terminal**
- Signed a Memorandum of Understanding with Western Australia agreeing to collaborate on the development of the hydrogen supply chain

Investor:

- **Coinvesting in infrastructure** a.o. hydrogen pipelines and investigating potential of hydrogen transport through pipeline of 40km from port to refinery in Pernis together with GasUnie
- **Joint venture for ports:** Sohar Port and Freezone, Oman is a 50-50 joint venture between port of Rotterdam and the Omani government. Pecém, Brazil is a 30-70 joint venture between the Port of Rotterdam and the state of Ceara Brazil. Both ports have a hydrogen production potential.

Buy/make Hydrogen

Combination of buy and make: ambition to let 20 Mt of hydrogen pass through the port, of which 90% import via ship and 10% produced in Rotterdam.

Link with archetype

Industrial archetype: having high hydrogen demand in the industry near the port motivates for a large production of green hydrogen. Transport and distribution infrastructure is required to obtain hydrogen at demand site

Logistics and transport archetype: High volumes pass through the port, leading to hydrogen required for handling and transport

Bunkering archetype: Largest bunkering port in Europe, leading to high amounts of hydrogen required for shipping

Deep-dive – Port of Antwerp-Bruges

Ambitions and role of ports including project examples concerning Hydrogen

Ambitions: Port of Antwerp-Bruges wants to play a pioneering role in the integration of carbon-neutral fuels and the hydrogen economy.

Roles:

Landlord:
- First **fuel station** capable of supplying green hydrogen directly to ships located at Port of Antwerp-Bruges and developed by CMB
- **NextGen District**: reserving an 88-hectare business park for the commercial development of initiatives concerning sustainability
- **Providing land for local electrolysis capacity build-up** to enable emerging green hydrogen consumer markets e.g. HyOffwind, Power-2-Methanol
- **Expansion of terminal capacity** for hydrogen carrier imports

Community builder and enabler:
- **CCUS and Hydrogen backbones**: innovation fund as game changer and PP-Partnership established (Rotterdam and Norway)
- **Power-to-Methanol demonstrator** (production of 8,000 tonnes of sustainable methanol): investment partnership established
- Transitioning to a **Multifuel Bunkering Hub** with renewable fuels
- **HyTrucks consortium** (Air Liquide, DATS 24 and Port of Antwerp-Bruges) joining forces with transport stakeholders aiming to have 300 **hydrogen-powered trucks** in Belgium by 2025
- **PIONEERS consortium**: 46 partners developing solutions to reduce GHG emissions in European ports led by Port of Antwerp-Bruges
- Signed **Memorandum of Understanding** with the Chilean Ministry of Energy to make green hydrogen flows between Chile and Western Europe a reality
- Signed cooperation agreement with the Port of Montreal to support the creation of the first green shipping corridor in the North Atlantic
- Part of the **Hydrogen Import Coalition:** actively facilitating the manifestation of imports flows/export projects

Investor:
- Initiated the construction of the world's first **tugboat powered by hydrogen**. This is realized by Compagnie Maritime Belge (CMB)
- Other projects: Hybackbone, PtmA and MethaTug

Buy/make Hydrogen

Combination of buy and make:
- Main focus on import of hydrogen
- Enabling first green hydrogen users by facilitating local electrolysis capacity
- Unlocking existing plant blue and white hydrogen to new hydrogen consumer markets (through backbone)

Link with archetype

Industrial archetype: having high hydrogen demand in the industry near the port motivates for having a large supply of hydrogen.

Logistics and transport archetype: need for decarbonization of port equipment, domestic shipping and road freight. Hydrogen can be part of the solution thus pilot projects are performed.

Bunkering archetype: second largest bunkering port in Europe, leading to high amounts of hydrogen (derivatives) required for shipping. Ways to fulfil this demand are looked into (e.g. import of hydrogen, becoming a multifuel bunkering hub).

Deep-dive – Port of Constanta

Ambitions and role of ports including project examples concerning Hydrogen

Ambitions: Become a clean hydrogen valley

Roles:

Community builder and enabler:

- In the **Pioneers consortium** coordinated by Port of Antwerp, Port of Constanta is one of three partner ports that will play an active role in maximizing the transferability of the solutions and are engaged to implement the best practices from the project
- There is the ambition to make **Dobrogea a hydrogen valley** with the Port of Constanta as its centrepiece
- Dobrogea could host most of the **electrolysers** in Romania
- The port wants to develop the idea of a **Danube Green Corridor**, where the ports along the Danube will contribute to the hydrogen economy.
- The port is looking at **offshore potential** and perspectives to them with the hydrogen in the port

Buy/make Hydrogen

Focus on make:

High potential for hydrogen production from onshore and offshore renewable energy. Romania could produce more energy than local demand, of which most production capacity is concentrated in Dobrogea

Link with archetype

Industrial archetype: Many potential hydrogen demand parties in the area such as refineries, combined plants, etc. and various transport sectors

Logistics and transport archetype: various transport sectors as potential hydrogen demand parties

Deep-dive – North Sea Port

Ambitions and role of ports including project examples concerning Hydrogen

Ambitions: North Sea Port has the ambition to become a hydrogen hub at European level

Roles:

Landlord:

Ambition to make land available for green hydrogen production projects (500 MW by 2025) such as:

- **VoltHydrogen Terneuzen and Vlissingen**: construction of 25 MW electrolysis unit in both places.
- **SeaHydrogenLand:** by 2030 Orsted expects the construction of a 1 GW sustainable hydrogen plant. The electrolyser can supply approximately 20% of current hydrogen demand in North Sea Port.
- **ELYgator** is a project of Air Liquide to construct a renewable hydrogen plant in Terneuzen
- **HydrogenBE project**: Engie and Equinor want to develop the production of low carbon hydrogen from natural gas and are launching a feasibility study for the suitability of a location in Ghent in North Sea Port

Community builder and enabler:

- North Sea Port forsees to facilitate and integrate where possible CO2 infrastructure at the port
- **Hydrogen Delta Network**: North Sea Port works together with Gasunie and Fluxys on the development of a hydrogen network
- **The hydrogen Delta Programme** sets the goal to replace grey hydrogen by low carbon hydrogen. North Sea Port reinforces this ambition by its connections, space available and presence of a significant industrial cluster. Within the project, North Sea Port, Fluxys and Gasunie are developing **local hydrogen infrastructure** in the port area, connected to the backbones.
- Gasunie and North Sea Port signed an agreement for the development of a **regional transport network for hydrogen** in Zeeland.
- **North-C-Hydrogen** foresees the reorientation of the **North-C-Methano**l project to green hydrogen production and no longer to focus on production of methanol exclusively (North-C-Methanol foresaw the construction of two demo plants, one with an electrolyser of 65 MW and one methanol plant, with 10 different parties working together on this).
- **Terranova Hydrogen**: Terranova Solar is the largest solar energy park in the Benelux and looks to hydrogen to store their solar energy. The hydrogen can be used in industrial applications in the port of Ghent and in freight transport.

Buy/make Hydrogen

Combination of buy and make:

Availability of large amounts of electricity from the sea leads to several green hydrogen production projects. Further also blue hydrogen will be produced.

Import potential of 2 – 6 Mt/year in 2050

Link with archetype

Industrial archetype: a lot of emissions present that need to be abated or captured. Further, knowledge concerning industries is present.

Deep-dive – Port of Hamburg

Port of Hamburg

Ambitions and role of ports including project examples concerning Hydrogen

Ambitions: The Hamburg Green Hydrogen Hub (HGHH) one of first projects worldwide to decarbonize an entire port economy.

Roles:

Landlord:

- Gasnetz Hamburg is **building a hydrogen pipeline** south of the river Elbe, also receiving hydrogen from the HGHH. The core network is about 60 km long and is designed to provide green Hydrogen to industrial companies in the South of Hamburg and the port.

Community builder and enabler:

- Shell, Mitsubishi Heavy Industries and Heat Hamburg are **building the Hamburg Green Hydrogen Hub (HGHH)** in close cooperation with Vattenfall on the site of the former power plant in Hamburg-Moorburg. If all permits are granted on time, hydrogen from renewable will be produced here from 2025 onwards. It will supply hydrogen to industries and the port as well as applications in transport in Hamburg and the surrounding area. With the HGHH different parties are brought together to support the energy transition in Hamburg. The port authority collaborates to accelerate the production, supply chain and consumption of hydrogen, leading to possible decarbonization of heavy-duty vehicles, port logistics and industry.
- The Hamburg Port Authority (HPA) is to work with Air Products to identify potential ways of **establishing a comprehensive hydrogen value chain** across the port.

Buy/make Hydrogen

Combination of buy and make:

- Development of green hydrogen production plant
- Hamburg recently presented their hydrogen import strategy

Link with archetype

- **Industrial archetype**: having a high hydrogen demand in the industry near the port motivates for a large production of green hydrogen.
- **Logistics and transport archetype**: need for decarbonization of port equipment and vehicles. Hydrogen can be part of the solution.

Deep-dive – NorSea Group

Ambitions and role of ports including project examples concerning Hydrogen

Ambitions: Establishing hydrogen supply hubs along the Norwegian coastline. This includes:
- Replacing fossil fuels by climate neutral energy carriers
- Be the missing link between producers and end-users through flexible solutions
- Developing hydrogen value chains with other partners and sister companies

Roles:

Landlord:
- **Enabling storage and bunkering of Hydrogen** through the infrastructure they own and operate
- Establishing and operating Yara-developed **floating ammonia filling stations** at their bases along the Norwegian coast

Community builder and enabler:
- **Pilot-E project enabling Hydrogen-powered transport** (ships and trucks): Development of Hydrogen Supply Hub and distribution concept with zero-emission fuel for maritime sector, together with partners such as Equinor, VikingCruises and Air Liquide. NorSea will will provide supply bases for storage and bunkering
- Offer **Hydrogen transport by ship, and last mile distribution** to end users outside of terminals.

Investor:
- **Development of pilot project producing Hydrogen:** small scale test project to produce small quantities of hydrogen together with other companies part of the same parent holding.
- **Hydrogen-powered Ro-Ro vessel** Topeka which is being constructed by parent company Wilhelmsen

Buy/make Hydrogen

Focus on make:
- Development of small-scale pilot project producing Hydrogen.
- Construction of Hydrogen vessel
- Hydrogen terminals for Hydrogen storage and bunkering

Link with archetype

Bunkering archetype: network of bases along the Norwegian coast which are leveraged to provide storage and bunkering services

Examples from other ports

Roles:

Landlord:

Port of Barcelona: hydrogenising Barcelona initiative: 20 MW electrolysers to power 200 fuel cell trucks and other Evs. Second phase: scale-up to 100MW. 3 to 4 hydrogen refuelling stations. Link archetypes: hydrogen chosen as ideal location due to several key industries present: heavy duty transport, port and maritime activities, grey hydrogen and general mobility such as public transport.

Port of Bremen: ‵Hydrogen – green gas for Bremerhaven‵, which involves setting up an electrolyser test field on the site of the former airfield at Luneort where green hydrogen will be produced with the help of wind energy.

Community builder and enabler:

Port of Duisburg: host Europe's first carbon neutral container terminal powered by hydrogen and intelligent operations: construct trimodal Duisburg Gateway Terminal together with other international partners. Project is being funded by the German Federal Ministry of Economics and Climate Protection

Associated British Ports (ABP): Toyota Tsusho, Uniper, Siemens Energy and Associated British Ports (ABP) launched a feasibility study looking at the decarbonization potential of hydrogen, dubbed Project Mayflower (the "Project"), at the Port of Immingham in the United Kingdom in September 2021. At the Port of Immingham, which handles the largest cargo volume in the U.K., the technological and economic feasibility of producing, supplying, and using hydrogen will be verified to create a decarbonization model within the port using hydrogen with the aim of formulating a plan for commercialization in the future. ABP will leverage its know-how gained from operating a total of 21 ports in the U.K. including Immingham to support the use of hydrogen at ports

Port of London Authority:

- Leading a new consortium aiming to develop a UK hydrogen highway network which consists of land, sea and ports. The hydrogen highway could significantly support the integration of hydrogen technologies into a range of different sectors with six projects planned for the highway. The six projects cover energy diversity research, trialing hydrogen power generation for vessels based at the PLA's Dentonne Wharf, establishing the business case for back hauling hydrogen into central London, ship design and health & safety requirements.
- An energy feasibility study has been conducted for the Port of London Authority (PLA) to identify opportunities to integrate low-carbon technologies across its sites and floating structures, bringing it closer to achieving its sustainability ambitions.

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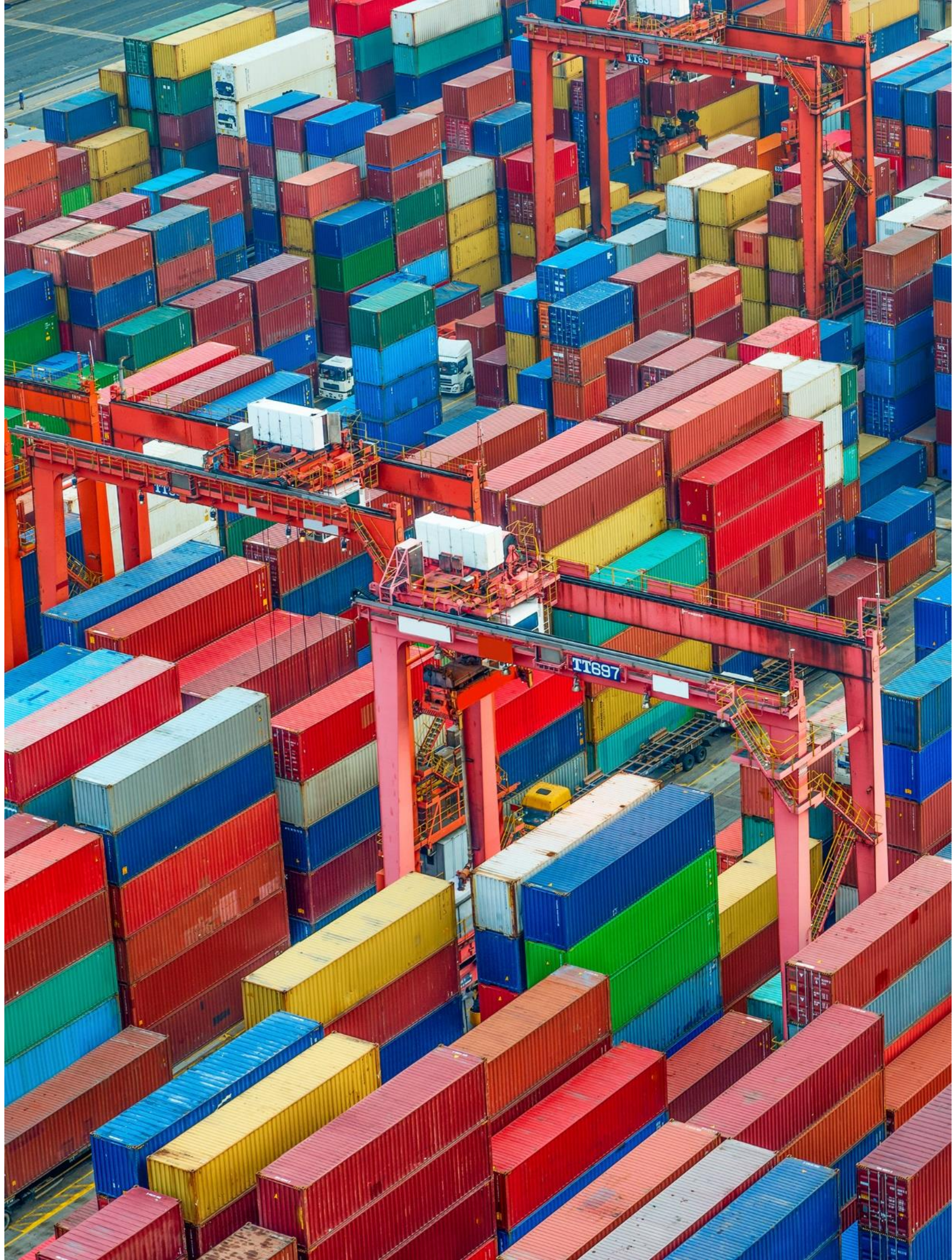
Co-funded by the European Union



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