MAGPIE

SMART GREEN PORTS

# Gaps and developments Hydrogen supply chain for future demand

Funded by the European Union

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# D3.4 - GAPS AND DEVELOPMENTS HYDROGEN SUPPLY CHAIN FOR FUTURE DEMAND

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# Abbreviation

AEL, Alkaline Electrolyser

AEMEL, Anion Exchange Membrane Electrolyser

CCS, Carbon Capture and Storage

CCUS, Carbon Capture, Utilisation and Storage

GH2, Gaseous Hydrogen

GHG, Greenhouse gas

kt, kilotonne

LCOE, Levelized Cost of Energy

LCOH, Levelized Cost of Hydrogen

LCOS, Levelized Cost of Storage

LH2, Liquid Hydrogen

LNG, Liquified Natural Gas

LOHC, Liquid Organic Hydrogen Carrier

Mt, Million tonnes

PEMEL, Proton-Exchange Membrane Electrolyser

PPA, Power Purchase Agreement

RES, Renewable Energy Sources

SMR, Steam Methane Reforming

SOC, State-of-Charge

SOEL, Solid Oxide Electrolyser

WP, Work Package

# Executive Summary

Commercial trades at a global level strongly rely on ports. They work as connection points between multiple stakeholders, who several times constitute large consumption hubs. Also, the ports themselves are huge consumption hubs. Particularly the so-called industrial ports typically characterized by the presence of hard-to-abate businesses (e.g., refineries, steel, alumina). Therefore, the impact of decarbonizing the port ecosystem will go far beyond its geographical area.

The MAGPIE project has a special focus on the reduction of the greenhouse gas (GHG) emissions associated with the different transport modalities that co-exist in a port. However, the energy requirements of a port are not only related with the transport sector. Industries and buildings are examples of two other demand streams. Having this overarching vision of the demand side is particularly important for the supply chain tasks (T3.2-T3.5). Analysing the supply chain, modelling it or sizing it has a dependency on the global demand. T3.3 focuses on the hydrogen supply chain and on identifying the supply gaps that might difficult the fulfilment of a growing demand for green hydrogen. By perceiving such gaps, it will also be possible to realize the needs and developments that need to be carried. Gaps might be identified, and developments might be needed across the entire supply chain. Supply & Production, Storage and the Distribution system compose the different streams of the hydrogen supply chain that are analysed throughout this deliverable. First, all these supply chain sectors are analysed in two dimensions: their current status (including within the MAGPIE ports) and their foreseen evolution. To do so, a comprehensive literature review was carried out and dedicated interviews with several MAGPIE partners were conducted, namely with Port authorities and demonstration leaders. Such analysis was the basis for identifying the existing gaps and consequently for structuring the modelling work of T3.3. Several models (associated with the different supply chain sectors) are detailed in this report, and they will help to shape the energy vectors of the future.

The main objectives of T3.3 are therefore settled. They respect the grant agreement requirements. However, and as already mentioned, achieving these objectives also depends on a complete vision of what will be the future demand for green hydrogen. D3.1[1] started this work and T3.2 continued it. Together, these two tasks design models capable to provide: 1) energy requirements estimation; 2) transition pathways towards green H2 for the transport and industrial sectors. Focus was given to these two demand sectors considering they will have a major impact on the future deployment of a green hydrogen supply chain. Considering that D3.1[1] and T3.2 took good care of accessing the future green hydrogen needs, T3.3 will focus on how the supply chain needs to evolve to cope with them. In a nutshell, the models designed in T3.3 try to provide an effective answer to the following questions.

*Table 1 - Modelling the green H2 supply chain*

| Sector | Questions |
|---|---|
| Supply & Storage | 1. Production in port VS Importing routes – what is the best option?<br>2. What is the optimal electrolyser/storage sizing? |
| Distribution System | 3. What options are available for hydrogen hinterland transport (energy carrier and transport modality)? What are the associated costs? |

T3.3 focuses on describing the H2-related models detailed in Table 1. Their development and testing will be carried during T3.6. Ultimately, during T3.6, the joint work of all models will allow to build long-term scenarios of energy demands and availability.

[1] MAGPIE Project, D3.1 – Transport Energy Requirements

## Supply & Storage sector

The results of D3.1[1] and T3.2 on the future demand for green hydrogen will be the starting point for the modelling of the supply and storage sectors. In other words, in order to identify what are the best production/storage options it is first required to have a view what the demand for hydrogen will be. Although with different characteristics, supply and storage planning/sizing studies cannot be dissociated. Indeed, sizing an electrolyser is influenced by the available/foreseen storage capacity. Therefore, D3.4 details a joint supply-storage model that has the following goals: 1) investigate how to optimally supply a specific demand for green hydrogen. Local production costs will be endogenously calculated while the import costs will be an input provided by another dedicated model - the PtX cost model. Import hydrogen using other energy carriers (e.g., ammonia) will also be considered; 2) size the electrolyser and storage systems; 3) generate hourly green H2 production time-series and the state-of-charge (SOC) control analysis.

## Distribution system

(Grey) Hydrogen transport is not a new topic. The use of hydrogen in hard-to-abate industries makes part of their Business-as-Usual. However, there is a changing factor that needs to be considered. The growing demand for hydrogen will lead to the arising of production centres that will not always be close to the consumption hubs. Consequently, the entire H2 distribution chain will need to be re-structured/upgraded. D3.4 looks into this new paradigm and studies which are the available options to transport green hydrogen. This assessment is carried in two different dimensions: focusing on the energy carrier and on the transport modality. Many different factors may influence these decisions ranging from the technical (e.g., H2 delivery constraints imposed by the off taker) to the more economic ones (e.g., need of conversion technologies). During the model's testing phase, emphasis will be given to the comparison between compressed hydrogen through long-distance pipes and liquid hydrogen using other transport means. Besides pipelines, other transport options are considered, namely trucks and barges. Concerning potential hydrogen carriers, ammonia will also be part of the analysis (linked with T3.4).

# 1. Introduction

The Green deal is an ambitious plan set out by the European Commission. Its main goals are: 1) achieving net-zero GHG emissions by 2050; 2) decouple economic growth from resource use; 3) ensure that all persons/places make part of the transition process. Accomplish 1) is a muti-sectoral problem (transports, industries, etc.) that requires adopting new green energy vectors or increasing the utilization of existing ones. Independently from which option is choose, it constitutes a broad and complex process that involves analysing all the sectors of a supply chain. Indeed, it is not possible to adopt a new green energy supply chain/vector (or increase the use of an existing one) without an assessment of what will be the infrastructure needs in terms of production, storage, and distribution.

The MAGPIE project is an international collaboration working on demonstrating technical, operational, and procedural energy supply and digital solutions in a living lab environment to stimulate green, smart, and integrated multimodal transport and ensure roll-out through the European Green Port of the Future Master Plan and dissemination and exploitation activities. The consortium, coordinated by the Port of Rotterdam, consists of 3 other ports (DeltaPort, Sines and HAROPA), 9 research institutes and universities, 32 private companies, and 4 other organisations. The project is divided in 10 main work packages which include energy supply chains, digital tools, 10 demonstrators for maritime, inland water, road, and rail transport, non-technological innovations, and the development of a Master Plan for European Green ports.

WP3 focuses on ports and on how these ecosystems can facilitate and accelerate the supply and the use of green energy carriers, particularly in the transport sector. The following energy carriers are analysed in depth: electricity (T3.2), hydrogen (T3.3), ammonia (T3.4), bioLNG (T3.5). Methanol will also be considered (particularly in the maritime transport sector), but no dedicated analysis of its supply chain will be carried out considering the already on-going projects in this topic.

D3.4 focuses on analysing and modelling a green hydrogen supply chain for port and hinterland transport demand. Building upon the outputs of D3.1[1] and T3.2, D3.4 focuses on accessing what changes/upgrades are required at the hydrogen supply chain level so that the future demand for green H2 can be attended. Although the main objective of MAGPIE is to green transports, highlight is also given to industries considering their role as major hydrogen consumers. All these topics are discussed following the report structure presented below:

- **Chapter 2** – A descriptive analysis of the existing gaps and needed developments across the hydrogen supply chain. Each sector of the supply chain is analysed in three dimensions: context, pathway towards decarbonization, deep dive on MAGPIE ports. The "context" section intends to provide a view on the current status of the hydrogen supply chain. The "pathway" section tries to anticipate the future challenges that it will face and discusses potential options to overcome them. The "deep dive" section will check if the MAGPIE ports are aligned with the present/future vision described in the previous sections. Here, inputs gathered from questionaries answered by port partners will be of utmost importance.

- **Chapter 3** – The gap analysis of Chapter 2 identifies which are the major operational/planning challenges that the hydrogen supply chain will face. Chapter 3 focuses on those and tries to provide answers on how to overcome them. Comparative assessment of different options/technologies and tecno-economic models will pave the way for a green and robust hydrogen supply chain. Chapter 3 contributions should thus enable: 1) an assessment on how the hydrogen supply chain should evolve given the foreseen demand growth; 2) the development and comparison between future energy scenarios.

- **Chapter 4** focuses on conclusions and on establishing the link with the second stage of T3.3.

# 2. Analysis of the Hydrogen supply chain

## 2.1 Introduction

Low-carbon and renewable hydrogen will play a prominent role in the energy transition, especially in the so-called hard-to-abate sectors like the heavy industry with processes that require high-temperature heating or the heavy transport sector such as aviation, trucking and shipping. Therefore, demand for hydrogen will theoretically ramp-up in the upcoming decades. To move from theory to practice and allow the upscaling of a hydrogen-powered economy, many uncertainties need to be tackled. Public and private stakeholders need long-term stability, certainty and balance between risk and return in hydrogen investments. Possessing a clear vision of how a mature and future-proof supply chain will look like is a first step in that direction. Several actions are important to achieve this vision, namely:

- Accurately estimate the future hydrogen demand
- Realize what are the best production strategies to minimize costs and emissions
- Identify distribution and storage options capable to guarantee a low-cost distribution and delivery of hydrogen

Accomplishing these objectives will allow to identify the gaps and developments needed throughout the hydrogen supply chain to ensure that future demand for green H2 will be met. Supported by an extensive literature review, chapter 2 analyses each sector of the hydrogen supply chain (i.e., production, storage, distribution) and presents their current status and future expectations on a global perspective in the context and the pathway towards decarbonization's subsections. In addition, and based on questionnaires answered by port partners, a deep-dive into the current situation of MAGPIE ports is carried out. Since it was not possible to collect answers from APS (Administração dos Portos de Sines e do Algarve) on time for this deliverable, the analysis focuses on the Ports of Rotterdam, HAROPA and DeltaPort.

## 2.2 Demand

### 2.2.1 Context

Transport and industrial activities are not exclusive from port ecosystems. Although ports are unique hubs where different sectors link and interchange goods, many processes that take place at ports are replicated in the hinterland. This allows to understand that the current situation at ports (in terms of hydrogen demand sectors) is in fact an extension of what happens in other locations. Nowadays, hydrogen consumption is mainly associated with industrial activities, such as fuel refining, biofuel, ammonia and methanol production and sponge iron production. Hydrogen can also be used for industrial heating and as feedstock or reactant in some chemical processes, such as synthesis gas production and organic chemical production. Despite these similarities between port and hinterland ecosystems, there is one important difference. Often, the hinterland hydrogen consumption is supplied by importing from ports. This is an additional demand stream for sea and inland ports that needs to be considered when planning/sizing the hydrogen supply chain. On the opposite side, the transport sector still represents a neglectable part of the global hydrogen demand.

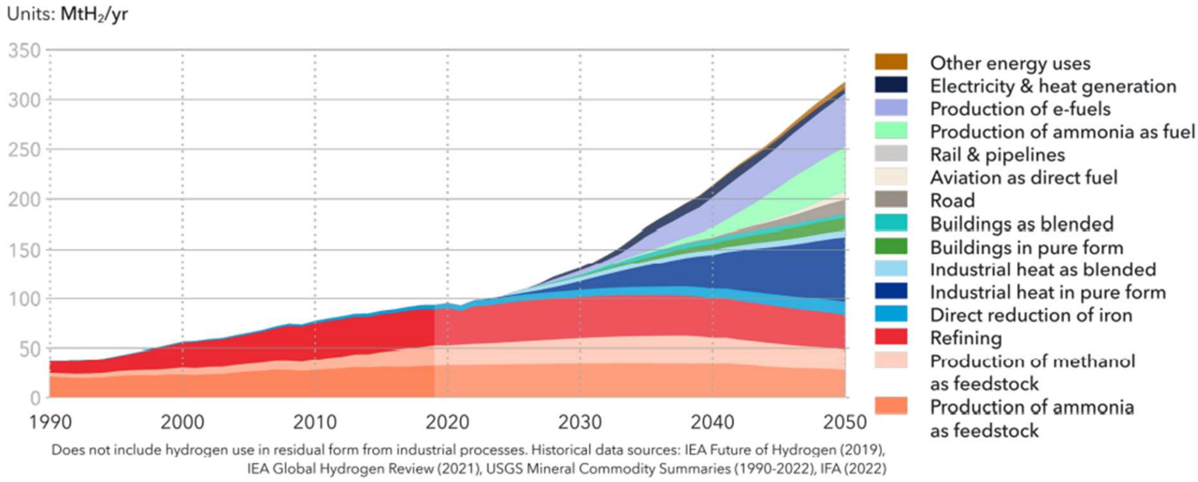



Figure 1 - Global hydrogen demand by sector[2]

Figure 1 provides a graphical vision of the hydrogen demand context. According to the several global energy outlooks available[3], this situation will change in the coming decades. The demand for hydrogen in seaports and inland ports will significantly grow as governments and industries around the world are setting ambitious targets for reducing GHG emissions in their logistic clusters. Sectors that are currently supplied by hydrogen will continue to be but will seek for a greener version of it. Other sectors like maritime shipping where electrification is not a viable option will start the transition from fossil fuels to hydrogen and its carriers. In fact, in many of these sectors, the use of low-emission hydrogen to satisfy some specific energy needs already ramped-up. Hydrogen-powered vessels and trucks as well as hydrogen for fuel refining are some examples of applications that already showed positive results.

This increase of the hydrogen demand will certainly take place. However, realizing when this growth will take-off, at what level and where is not yet clear. Understanding this is crucial for an accurate design of the future hydrogen supply chain. The demand-side models described in D3.2 focus exactly on this goal.

### 2.2.2 The pathway towards decarbonization

#### 2.2.2.1 *Transport modalities*

As previously mentioned, the demand for hydrogen and its derivatives in ports will grow as a result of the increasing focus on reducing GHG emissions. The transport sector will play an important role on this considering its ambitious decarbonization targets. Maritime and inland shipping companies are starting to adopt hydrogen and its derivates as fuel sources for their operations. Also, heavy-duty vehicles (e.g., trucks) and cargo handling equipment are future potential hydrogen consumers. On a different sector, but also worth mentioning, electricity production might also become a significant demand stream. Hydrogen has a high potential of becoming one of the X options used in the so-called Power-X-Power technologies thus allowing to store the excess of energy produced by non-dispatchable renewable sources.

Figure 1 also provides a view concerning the expected efforts to reduce emissions and increase sustainability in the transport, industrial and electricity production sectors. The MAGPIE project is orienting much of its manpower to support the transport sector in this

[2] Hydrogen Forecast to 2050, DNV
[3] Global Hydrogen Review 2022, IEA

transition process. Below, some of the H2-related demonstrators of the MAGPIE project are highlighted:

- Demo 7: Green Container – aims to demonstrate the use of green hydrogen and li-ion energy packs to provide electricity to an e-barge.
- Demo 9 (Work Package 6): Green Connected Trucking – aims to demonstrate electric driving with heavy-duty trucks (battery-electric and hydrogen).

In addition, T6.4 of WP6 aims to develop a logistical model for sustainable transport on hinterland corridors between ports, in this particular case between Rotterdam and DeltaPort, to demonstrate the feasibility of reducing last mile road transport and shifting last mile road transport partly to barge or rail. By doing that, the industry in the hinterland can be served via Rotterdam/DeltaPort.

Pilots and demonstration activities are vital to proof to the different stakeholders that their Business as Usual can be changed. However, it is not sufficient. Investors need predictability in terms of what will be the future H2 demand. D3.2 proposes dedicated approaches that by modelling technical and economic aspects of the H2 industry will allow to build reliable future demand scenarios. Thanks to such scenarios, the risk can be minimized, which will naturally lead to more investments. Below, a summary of the approaches proposed in D3.2 is provided:

- Global & Regional Transition Pathways – Although with a different geographical zoom, both approaches focus on perceiving how transports will shift from fossil fuels to new energy vectors (including hydrogen and its derivatives). These approaches use as input the energy requirements associated with the transport sector. Some of these energy requirements are obtained from literature inputs while others result from additional modelling work carried out within the MAGPIE project.

- Refuelling Requirements Assessment – This approach assesses the demand on refuelling (points) at the port or hinterland ecosystem. Rather than focus on volume, it tries to estimate where and when refuelling actions will occur.

#### 2.2.2.2 *Industries*

Although the MAGPIE project focuses on the transport sector, realizing the infrastructural needs of the hydrogen supply chain is an exercise that requires a global vision of the demand side. Figure 1 is self-explanatory in the sense that it highlights the relevance of industries in the hydrogen business. Currently, fuel refining together with ammonia/methanol production constitute the main (grey) hydrogen offtakers. In the coming decades, the industrial demand for hydrogen is expected to grow, primarily due to its potential to replace coal and natural gas as an industrial heat source. Present and future offtakers pursue the same objective i.e., become supplied by green hydrogen. However, the hurdles that will be faced are much different. While for current offtakers the gap is more related with supply side (i.e., moving from grey to green production), the future offtakers need to find a solution for every step of the supply chain (i.e., production, storage, distribution). Still, the major gap continues to be on the supply. This is related with the fact that storing and/or transporting hydrogen technologies are already mature. On the contrary, green hydrogen production is a recent technology that cannot take advantage (for now) of economies of scale. This situation might change soon as long as investors can make their decisions based on reliable estimations of the future H2 demand.

As well as for the transport sector, D3.2 details models focused on 1) estimating the present/future energy requirements associated with several industrial processes; 2) realizing what percentage of these requirements will become supplied by green hydrogen. Such models will be fine-tuned to consider the unique context that characterizes ports, particularly the ones with a strong industrial activity within their campus.

### 2.2.3 Deep-dive on MAGPIE ports

#### 2.2.3.1 *Transport modalities*

In order to deep-dive into the MAGPIE ports, a questionary was circulated among the port partners (Annex A). Despite their natural differences as the Port of Rotterdam is mainly a seaport, HAROPA comprises one seaport (Le Havre) and two inland ports (Paris and Rouen) while DeltaPort is exclusively an inland port, they are aligned with the general picture concerning the use of hydrogen in the transport sector. The following main conclusions were extracted from the questionary replies:

- Hydrogen consumption in the transport sector is currently inexistent or neglectable.
- Port actors anticipate that this situation will change. However, the fact that they do not have a clear vision of what will be the future demand for hydrogen is a significant obstacle to start the transition process (see "NAs" in Table 2).

As already mentioned, D3.2 provides important contributions to tackle this last point (i.e., to establish a reliable view on the future H2 demand).

Focusing now on the Port of Rotterdam context, hydrogen is directly used only to power two vessels for inland shipping purposes. Also, methanol (a hydrogen derivative) is used on a very small scale. In HAROPA port, only one barge is currently hydrogen-powered for inland shipping purposes and the consumption of hydrogen for road transport is barely null. Regarding DeltaPort, currently there is no consumption of hydrogen in the transport sector.

In terms of future scenarios, the Port of Rotterdam foresees that both compressed and liquified hydrogen will play an important role in the maritime and inland shipping businesses, more significantly by 2040. However, concrete estimations in terms of volume are not available. Moreover, and although not only related with the transport sector, hydrogen exports via pipeline are also expected to grow reaching 0.8 Mt in 2030 and 3.2 Mt in 2040. An increase on the exports is equal to an increase on the hydrogen-related activity in the hinterland. Consequently, is also a warning concerning the importance of studying how the hydrogen transport infrastructure needs to evolve in the coming decades. Regarding HAROPA, 20 to 35 barges in each port (Le Havre, Rouen, and Paris) are expected to be hydrogen-powered by 2030, resulting on a forecasted yearly consumption of 4 kt to 9 kt. For road transport a range from 66 kt up to 132 kt of hydrogen consumption is foreseen. Trains may also be a future hydrogen demand stream to face non-electrified railways between the HAROPA ports. The future scenarios in DeltaPort are expected to be similar to the ones planned for Rotterdam and HAROPA.

Table 2 sums up all these findings. The significant amount of "NA" information and the large H2 consumption ranges provided by some partners indicate that the future is still unclear. Even DeltaPort, where the forecasts seem more accurate, needs support in validating them.

*Table 2 - Present & future scenarios for Hydrogen-powered vehicles in MAGPIE ports*

| | | Present Demand (H2 kt) | Demand in 2030 (H2 kt) | Demand in 2040 (H2 kt) | Demand in 2050 (H2 kt) |
|---|---|---|---|---|---|
| Maritime | PoR | 0 | 0 | NA | NA |
| | HAROPA | 0 | NA | NA | NA |
| | DeltaPort | - | - | - | - |
| Inland Shipping | PoR | Neglectable | NA | NA | NA |
| | HAROPA | Neglectable | 4.000-9.000 | NA | NA |
| | DeltaPort | 0 | 4.950 | 15.000 | 25.000 |
| Rail | PoR | 0 | NA | NA | NA |
| | HAROPA | 0 | 0 | 0 | 0 |
| | DeltaPort | 0 | 31,68 | 31,68 | 31,68 |
| Road | PoR | NA | NA | NA | NA |
| | HAROPA | 0 | 66.000-132.000 | NA | NA |
| | DeltaPort | 0 | 392 | 1.100 | 3.300 |

#### 2.2.3.2 *Industries*

MAGPIE ports are also aligned with the global picture concerning the use of hydrogen in the industrial sector. As expected, fuel refining is currently the major hydrogen demand stream with a yearly consumption of almost 320 kt in the Port of Rotterdam and 200 kt in HAROPA Ports. Ammonia production industries are also relevant hydrogen consumers in HAROPA (130 kt). Other segments such as biofuel are currently minor hydrogen consumers, but this situation might change in the near future. Nowadays, in DeltaPort there are no relevant hydrogen consumers in the industrial sector. Together the inputs provided by port partners allow to establish the hydrogen demand baseline for the most significant industrial processes.

Establishing future scenarios for this same demand is a more challenging exercise, particularly for 2040 and 2050. Realize if the hydrogen demand will increase or decrease in some specific industry might be much easier than understand at which rate this will happen (see Table 3). Port authorities expect that the use of hydrogen for biofuel production and high temperature heat processes will grow significantly. Also, Power-H2-Power technologies might have an important role to play in the coming decades. On the opposite direction and as a consequence of a decrease in the use of fossil fuels, the H2 needs in the refining industry will decrease. At DeltaPort, the authorities foresee that the port might become an important exporter of compressed hydrogen via pipeline and liquid hydrogen via inland shipping. Thanks to the modelling work being carried in WP3 it will be possible to validate these estimations provided by port partners.

*Table 3 - Present & future scenarios for Hydrogen-powered industries in MAGPIE ports*

| | | Present Demand (H2 kt) | Demand in 2030 (H2 kt) | Demand in 2040 (H2 kt) | Demand in 2050 (H2 kt) |
|---|---|---|---|---|---|
| Fuel Refining | PoR | 318 | 318 | < 318 | << 318 |
| | HAROPA | 200 | 200 | NA | NA |
| | DeltaPort | - | - | - | - |

| | | | | | |
|---|---|---|---|---|---|
| Ammonia Production | PoR | 0 | 0 | 0 | 0 |
| | HAROPA | 130 | 130 | NA | NA |
| | DeltaPort | - | - | - | - |
| Biofuel Production | PoR | 45 | 100 | > 100 | > 100 |
| | HAROPA | 0 | 80 | NA | NA |
| | DeltaPort | - | - | - | - |
| Chemical Industry Production | PoR | 47 | NA | NA | NA |
| | HAROPA | - | - | - | - |
| | DeltaPort | - | - | - | - |
| Electricity Generation | PoR | 0 | Neglectable | NA | NA |
| | HAROPA | 0 | 9-15 | NA | NA |
| | DeltaPort | - | - | - | - |
| High Temperature Heat Industry | PoR | 300 | 400 | > 400 | >> 400 |
| | HAROPA | - | - | - | - |
| | DeltaPort | - | - | - | - |

## 2.3 Production

### 2.3.1 Context

Hydrogen can be produced through different methods with varying environmental impacts, efficiencies, costs, and depending on local resources and conditions. Currently, demand for hydrogen is satisfied almost entirely through steam methane reforming (SMR) without carbon capture, utilisation, and storage (CCUS). In SMR, hydrogen is produced from natural gas by a chemical reaction with steam resulting in high levels of GHG emissions:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

Additionally, the carbon monoxide is oxidated with water to produce carbon dioxide as well as additional hydrogen:

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

Coal can also be used as feedstock to produce hydrogen with even higher GHG emissions, as is exemplified in the following reaction:

$$C_{12}H_{24} + 6O_2 \rightarrow 12CO + 12H_2 \tag{3}$$

Another method to produce hydrogen is through the pyrolysis of natural gas using a molten metal catalyst at high temperature[4], with the advantage of generating no on-site GHG emissions since the produced carbon is solid and can be landfilled or used in other industrial processes. The methane is decomposed into solid carbon (named carbon black) and gaseous hydrogen through the reaction:

$$CH_4(g) \rightarrow C(s) + 2H_2(g) \tag{4}$$

[4] https://doi.org/10.1016/j.ijhydene.2022.12.169

The production of green hydrogen occurs through the electrolysis of water using RES to supply the required electricity:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (5)$$

The more mature electrolyser technologies that can be found at a commercial scale are Alkaline electrolysers (AEL) and Proton-Exchange Membrane electrolysers (PEMEL), with the first being responsible for roughly 70% of all installed electrolysis capacity in 2022[5]. While AEL tend to be less expensive, PEMEL is a more recent technology that is expected to match the cost of AEL in the coming years. Comparing AEL to PEMEL regarding technical characteristics, AEL have more restrictive operating limits (notably higher minimum load) and a lower energy density of the stack of the electrolyser, resulting in higher space requirements for the installation of AEL electrolysers[6]. Additionally, two other technologies are being researched at a laboratory level: Solid Oxide electrolysers (SOEL) and Anion Exchange Membrane electrolysers (AEMEL).

Indeed, the abundance of natural gas and coal in some regions aligned with well-established technology and infrastructure for hydrogen production and distribution and the high conversion efficiencies for both SMR and coal gasification have been important factors for the widespread use of these two methods. However, in order to comply with the announced pledges, the future hydrogen supply mix must become composed by lower-emission alternatives such as the production of hydrogen through methane reforming with CCUS, commonly referred to as blue hydrogen and, through electrolysis using RES (green hydrogen). Figure 2 shows that the previous statements are aligned with the international vision concerning the future of hydrogen supply.

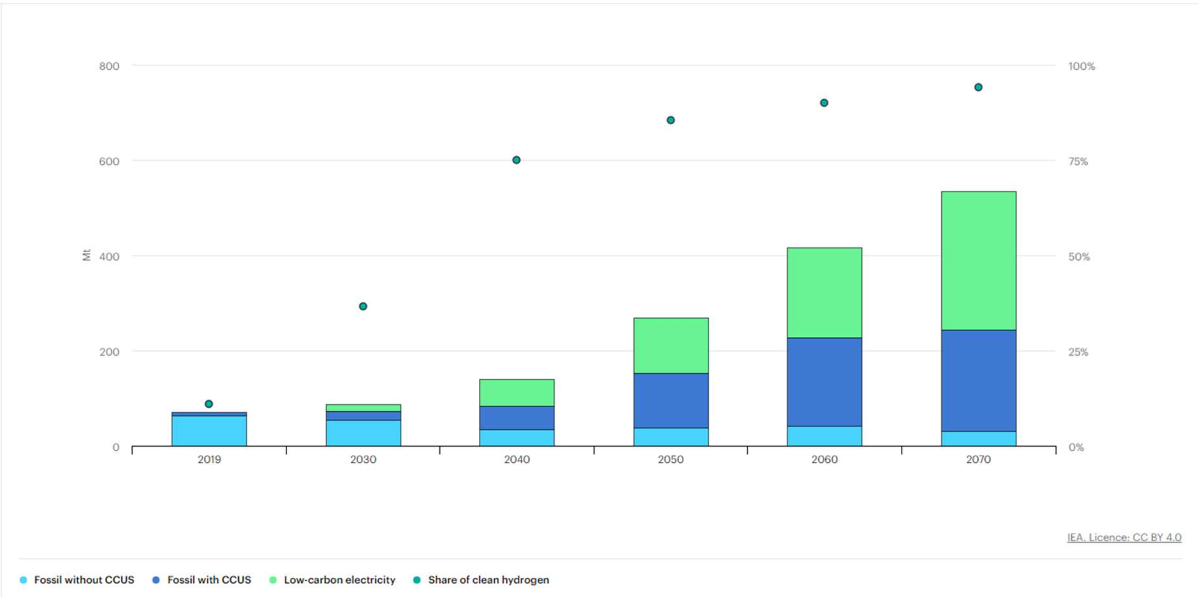



*Figure 2 - Global H2 supply mix[7]*

[5] Global Hydrogen Review 2022 – Analysis - IEA
[6] Green hydrogen cost reduction (irena.org)
[7] IEA, Global hydrogen production in the Sustainable Development Scenario, 2019-2070, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-hydrogen-production-in-the-sustainable development-scenario-2019-2070

Besides the foreseen changes in hydrogen supply mix, adjustments to the location of production facilities are also expected. Currently, a significant portion of hydrogen consumers are directly supplied by local production installations. However, the anticipated increase in hydrogen demand may change this situation. Large hydrogen production hubs may emerge far from consumption centres, thus leading to increased hydrogen transportation needs.

### 2.3.2 The pathway towards decarbonization

The future of hydrogen supply is likely to be diverse (Figure 2), with a mix of different production methods, including blue and green hydrogen. The exact mix will depend on factors such as the availability of feedstocks, the cost of energy, the demand for clean hydrogen, and the policies and regulations in place to support the growth of the hydrogen industry. Indeed, it is unlikely that one production method will completely replace the others, as each method has its own strengths and weaknesses, and the best approach will depend on the specific circumstances of each country and region.

Blue hydrogen can be seen as a transitional solution, as it can use existing natural gas infrastructure providing a faster deployment of cleaner hydrogen production while reducing the initial capital expenditure and time to build and operate new infrastructures. However, this method still produces some GHG emissions of around 2.1 to 7.6 CO2eq/kg H2 when accounting for emissions associated with natural gas sourcing[8]. In terms of on-site efficacy, while CCUS technology can reduce the emissions of SMR by roughly 90% (with studies estimating it can go up to 99% in the future)[9], it still produces some local GHG emissions and therefore cannot be considered a zero-emission alternative in the same sense as green hydrogen.

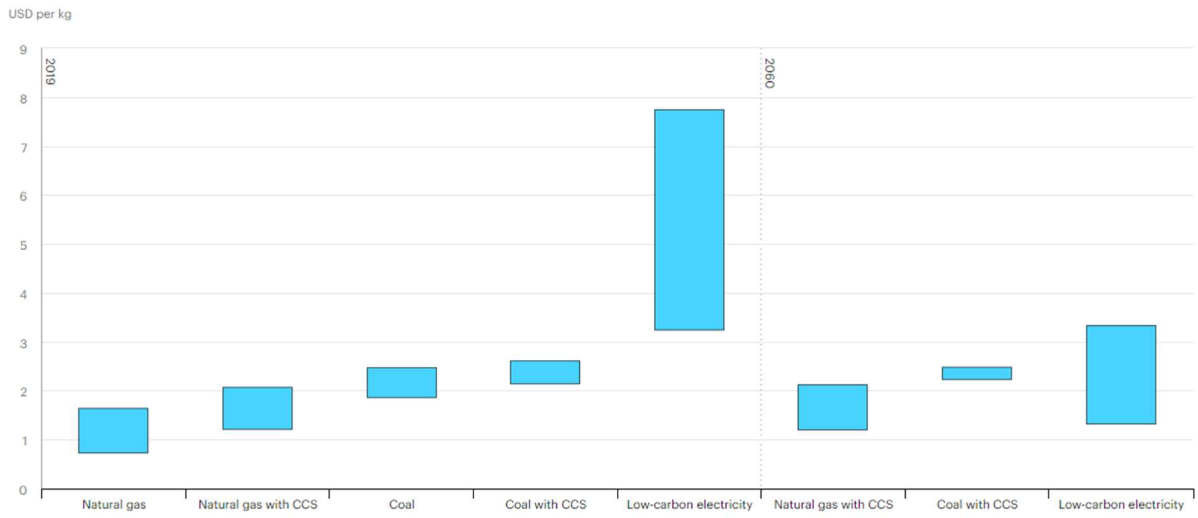



*Figure 3 - Global average LCOH production per technology (present & future scenarios)*[10]

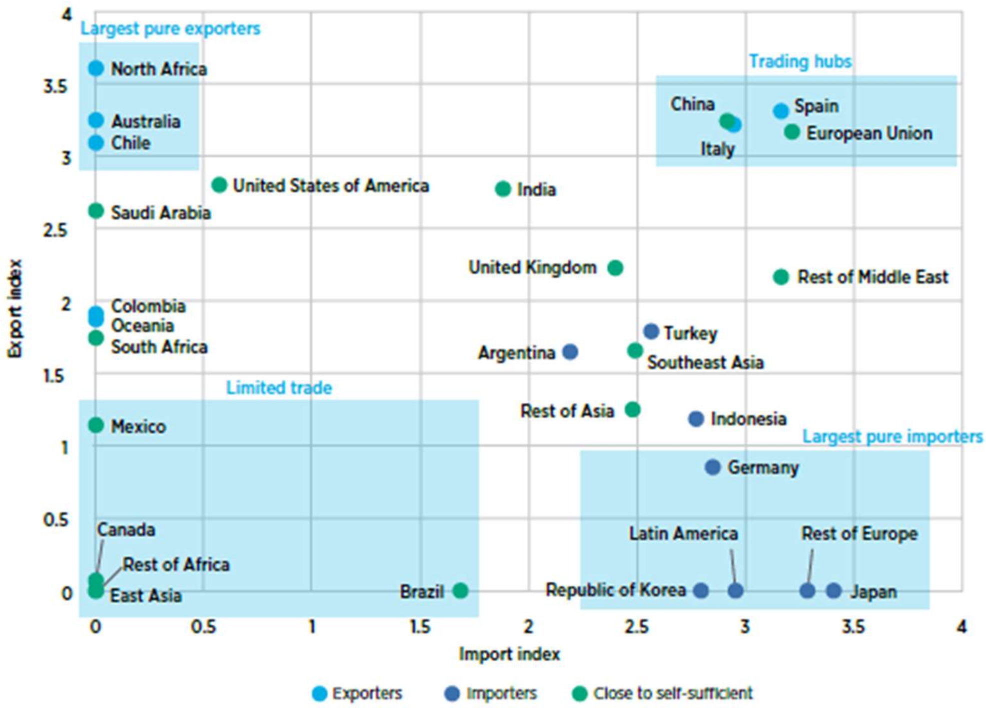
Figure 3 compares both alternatives in terms of costs per kg of hydrogen produced. Blue hydrogen can be produced at a lower cost than the green option, particularly in regions where the levelized cost of energy (LCOE) of renewable sources is high. However, for areas

[8] https://doi.org/10.1016/j.clet.2022.100552
[9] Global Hydrogen Review 2022 – Analysis - IEA
[10] IEA, *Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050*, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050

where there is a significant surplus of RES production, the opportunity cost increases and consequently the levelized cost of hydrogen (LCOH) decreases. In such cases, green hydrogen production may become the less costly option.

The associated GHG emissions and the costs of each production technology are therefore two factors that will impact on future investment decisions. Both aspects are still characterized by uncertainties that need to be tackled along the way. In the case of CCUS, some technological developments are still needed to increase the carbon capture rates. Concerning green hydrogen, the decrease of the LCOH has a strong dependency with the expansion of electrolyser manufacturing capacity thus allowing the deployment of large-scale applications.

Developing the international hydrogen trade is of utmost importance for the success of the global energy transition. As the worldwide demand for low-carbon hydrogen increases, kick-starting commercial trades in this sector will contribute for a secure, competitive, resilient, and sustainable energy system while enabling countries to share and benefit from their respective strengths and resources. Some regions have plentiful renewable energy sources to generate green hydrogen or can produce fossil fuel-based hydrogen with CCUS, yet their local hydrogen demand is limited. In other countries, the situation is exactly the opposite.




Note: Import and export flows use a logarithmic function to put the different orders of magnitude on a similar scale. This makes both axes dimensionless, and this could be interpreted as an index rather than as energy flows. The export index is the $LOG_{10}$ of the exported flow in PJ/year, and the import index is the $LOG_{10}$ of the imported flow in PJ/year.

*Figure 4 - Global importing needs & exporting opportunities*[11]

Figure 4 shows exactly what was previously mentioned. While some regions will be characterized by a hydrogen production potential that is higher than their internal demand, others will not be self-sufficient. Import-Export relations will therefore need to be established.

[11] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf?rev=f70cfbdcf3d34b40bc256383f54dbe73

Although a significant part of Europe is on the importing side, this does not mean that local production will be inexistent. Thus, it is important that each country can realize the most cost-effective mix (i.e., imports vs local production) to fulfil its own hydrogen needs. A dedicated model that considers the differences between domestic production and import costs is proposed in Chapter 3. As displayed in Figure 5, there are multiple aspects that influence these costs. As an example, factors such as scale, technological development or availability of resources may be capable to offset the transportation costs associated with import-export operations.

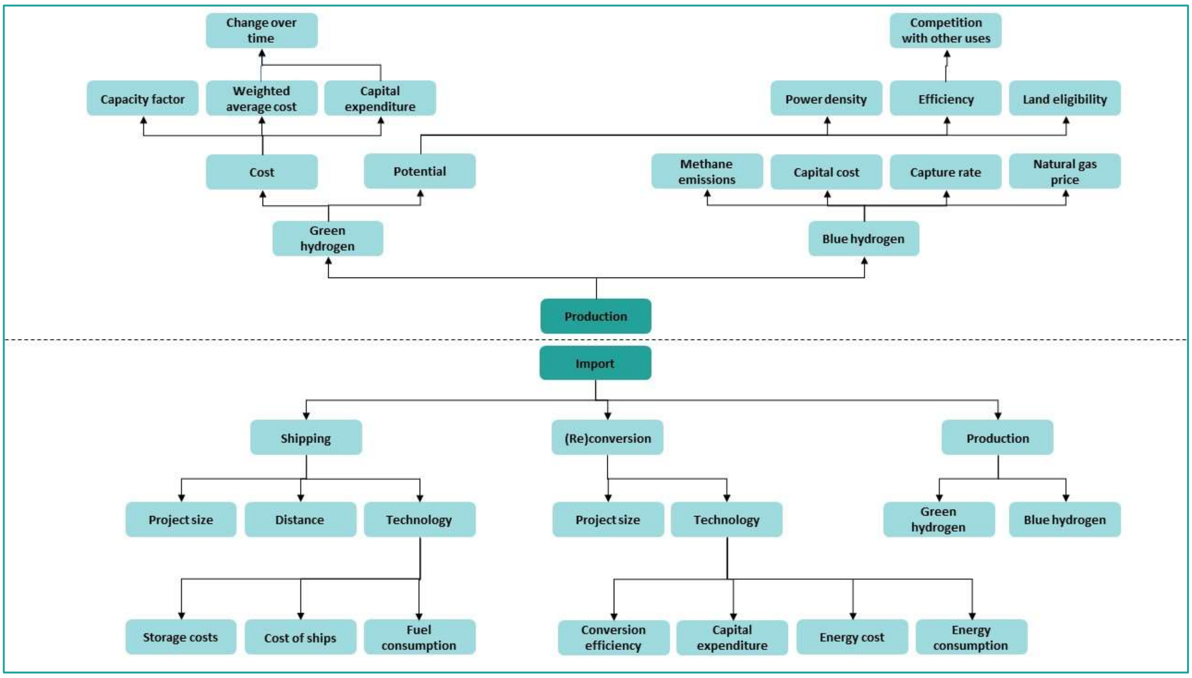



*Figure 5 - Import vs Local production (the influencing factors)*[12]

### 2.3.3 Deep-dive on MAGPIE ports

Aligned with the global hydrogen supply mix status, on MAGPIE ports, the supply of hydrogen is mainly assured by its grey variant. In HAROPA and Rotterdam conventional methods such as SMR and methane pyrolysis without CCS are extensively used. Additionally, in the port of Rotterdam, hydrogen is also produced as a by-product in chlorine, caustic soda, and sodium chlorate production as well as during operation of steam crackers, blast furnaces and coke ovens. Many of these processes are also responsible for GHG emissions.

The alignment of the MAGPIE ports with the global picture is also visible in terms of the future scenarios. Although grey hydrogen will remain present in MAGPIE ports for the next decades, the port authorities aim to gradually replace its production by lower-emission options, and so acting as first movers in the decarbonization process of the industry and logistics on a larger scale. As a result, the envisioned hydrogen supply mix in MAGPIE ports will most certainly be composed of green and blue hydrogen as both electrolysis and CCS technologies are attracting great interest from port authorities as well as external entities. Both options may be locally produced or imported in the form of liquified hydrogen or ammonia.

[12] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf?rev=f70cfbdcf3d34b40bc256383f54dbe73

There are already several initiatives going on in this direction. Porthos, which stands for *Port of Rotterdam CO2 Transport Hub and Offshore Storage*, is an on-going project aiming to capture industrial carbon emissions and store them under the North Sea[13]. This project is supported by the Dutch government, and it is expected to become operational in the coming year. H2-Fifty is another noteworthy project that is looking to produce 20,000 to 30,000 tons of hydrogen through electrolysis thus creating a zero-emission production hub at the port of Rotterdam[14]. Also, Air Liquide will continue its efforts to support the development of a green hydrogen supply chain. Currently, Air Liquide's hydrogen production site in the Rotterdam-Botlek area supplies a variety of customers, including chemical companies and other industrial users (within and outside the port premises). Despite all these local production efforts, future hydrogen demand will require the settlement of importing routes. Having this in mind, Shell New Energies, Engie, Vopak and Anthony Veder already signed an agreement to study the feasibility of establishing a renewable liquid hydrogen supply chain between Portugal and the Netherlands[15]. This study aims to assess the potential of producing green hydrogen and liquifying it in the industrial zone of Sines, and then, transport it via maritime shipping to the port of Rotterdam for distribution and sale.

All these initiatives are aligned with the current forecasts from the Port of Rotterdam. In the coming decades, a steady reduction of grey hydrogen production is expected (0.3 Mt – 2023; 0.4 Mt – 2040; 0.5 Mt – 2050). On the opposite direction, local hydrogen production through low-carbon forms will significantly increase. Blue hydrogen is expected to reach 0.3 Mt by 2030, 0.4 Mt by 2040 and 0.5 Mt by 2050 while green hydrogen production forecasts are 0.3 Mt by 2030, 1.2 Mt by 2040 and 2 Mt by 2050. As expected, this local production will cover a reduced portion of the total hydrogen demand (see Figure 4). The Port of Rotterdam foresees that 18 Mt of hydrogen will need to be imported by 2050.

The pathway towards a cleaner energy system is still characterized by lots of uncertainties, namely technical, economic, and regulatory. Naturally, the presented forecasts are also impacted by those. Chapter 3 tackles this topic by proposing a dedicated approach whose goal is to provide an accurate vision on the role that both local production and imports will have in fulfilling the hydrogen demand in ports.

Concerning the remaining ports, HAROPA envisions the installation of a 200 MW electrolyser by 2025 and of CCS technologies by the end of the decade. In terms of importing strategy, a similar situation as in the Port of Rotterdam is foreseen. DeltaPort is also considering both local production and imports (liquified hydrogen via inland shipping) in order to supply its own hydrogen demand.

## 2.4 H2 Storage

### 2.4.1 Context

Effective storage of hydrogen remains a significant challenge, as hydrogen has low volumetric energy density and is a high reactive gas. Nevertheless, several hydrogen storage options (with different maturity levels) are available, namely subsurface gas storage, compressed hydrogen tanks and pipelines when in gaseous state; liquid hydrogen tanks when in liquid state; metal hydrides when in solid state; ammonia and liquid hydrocarbon tanks when exploiting these energy carriers. Selecting the appropriate storage method is not simple

[13] Dutch government supports Porthos customers with SDE++ subsidy reservation - Porthos (porthosco2.nl)
[14] HyCC
[15] Renewable liquid hydrogen supply chain between Portugal and the Netherlands on the horizon | Shell Nederland

since many factors need to be considered: storing space requirements, energy consumption levels, safety issues, etc.

Currently, compressed hydrogen tanks are one of the most used methods to store hydrogen as it is a well-developed technology with low deployment timeframe. However, the associated low energy density can be a hurdle for scenarios with limited storage space. Pipelines are also widely used mainly for industrial applications due to their high technological maturity and low energy consumption needs. Like compressed hydrogen tanks, pipelines have some challenging safety requirements that must be safeguarded. Although these storage technologies are already mature and extensively used, major investments in storage facilities will be needed. Even with the repurposing of the current natural gas storage, the future GH2 storage requirements would not be met[2]. Considering this, several ports are already carrying advanced studies on this topic. For instance, under the H2Ports project, the Port of Valencia is exploring the development of a hydrogen mobile supply station that would store compressed hydrogen and transport it for locations with refuelling needs[16]. Similar initiatives are taking place in other ports like the Port of Long Beach[17] or Antwerp[18].

### 2.4.2 The pathway towards decarbonization

Looking at natural gas, the storage capacity currently stands at around 24% of the total yearly demand (TWh/year) of the European Union[19]. It can be deduced that hydrogen (and hydrogen carriers) will need a similar energy storage capacity to ensure a reliable and secure supply chain. Comparing to natural gas, hydrogen requires larger and more flexible storage units. Regarding flexibility, it is needed to accommodate intermittent/seasonal production patterns. Table 4 focus on the available hydrogen storage technologies and analyses their advantages and drawbacks.

*Table 4 - Hydrogen storage options (advantages and drawbacks)* [20][21][22][23]

| Hydrogen Storage Strategies | Advantages | Disadvantages |
|---|---|---|
| Compressed | High technological maturity; Low deployment timeframe; Practical; | Low energy density; Safety concerns; |
| Pipeline | High technological maturity; Low energy consumption; | Medium deployment timeframe; Safety concerns; |
| Liquid | Medium/high technological maturity; Medium/high energy density; | Energy consumption; High deployment timeframe; Safety concerns; |
| Ammonia | Medium/high technological maturity; High energy density; Medium/low deployment timeframe; | Energy consumption; Safety concerns; |

[16] https://h2ports.eu/about/
[17] https://polb.com/port-info/news-and-press/port-of-long-beach-joins-hydrogen-fueling-partnership-10-06-2022/
[18] https://www.offshore-energy.biz/port-of-antwerp-bruges-joining-h2global-in-energy-transition-move/
[19] https://www.gie.eu/wp-content/uploads/filr/3517/Picturing%20the%20value%20of%20gas%20storage%20to%20the%20European%20hydrogen%20system_FINAL_140621.pdf
[20] Techno-Economic Analysis of Hydrogen Storage Technologies for Railway Engineering: A Review;
[21] Hydrogen Forecast to 2050, DNV;
[22] Global Hydrogen Review 2022, IEA;
[23] Hydrogen storage methods: Review and current status;

| | | |
|---|---|---|
| LOHC | Medium/high energy density; Safety concerns; | Energy consumption; Low technological maturity; High deployment timeframe; |
| Solid (metal hydrides) | High volumetric energy density; No risk of H2 leakage | Low mass energy density; Water sensitivity (corrosion); Low kinetic for desorption |

Table 5 complements the information provided in the previous table by associating each option with the volume and time horizon of the storage needs. The geographical availability of each option is also shown in this table.

*Table 5 - Hydrogen storage options (volume, cycling and costs)*

| | Gaseous state | | | | Liquid state | | | Solid state |
|---|---|---|---|---|---|---|---|---|
| | **Salt caverns** | **Depleted gas fields** | **Rock caverns** | **Pressurized containers** | **Liquid hydrogen** | **Ammonia** | **LOHCs** | **Metal hydride** |
| Main usage (volume and cycling) | Large volumes, months-weeks | Large volumes, seasonal | Medium volumes, months-weeks | Small volumes, daily | Small medium volumes, days-weeks | Large volumes, months-weeks | Large volumes, months-weeks | Small volumes, days-weeks |
| Geographical availability | Limited | Limited | Limited | Not limited | Not limited | Not limited | Not limited | Not limited |

Besides the most common storage technologies (i.e., hydrogen compressed tanks and pipelines), ports are giving particular attention to the repurpose of LNG storage to LH2, and specially to NH3, due to the higher energy density shown when compared to GH2. Still, this repurposing process is technically complex and sometimes not feasible due to different chemical and physical properties of the carriers and the LNG. Concerning underground storage, repurpose potential also exists. However, within the available sites, not all are suitable for hydrogen[24], and some will be dedicated to other fuels. Another option currently under study is the use of Liquid Organic Hydrogen Carriers (LOHCs). These carriers are less complex to handle in terms of safety and require less capital investment. However, the reconversion from LOHCs is still at a relatively low level of maturity, and the process requires high energy consumption[25].

As a final remark, defining the best storage option is strictly linked with the rest of the supply chain. As an example, the choice of how to store hydrogen cannot be dissociated of how it is being produced. Otherwise, it will be impossible to find the optimal strategy for the whole supply chain. Having this in mind, section 3.2 proposes a model that jointly analyses production and storage options for hydrogen.

[24] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf?rev=3d707c37462842ac89246f48add670ba

[25] https://reader.elsevier.com/reader/sd/pii/S2589004221009342?token=118CA72B993F27FC5D3AEE1BECB655936F63352270189ED12C4CE39FD8ACAEB380AC98289BFF0164C3AEA54A88B2BBCA&originRegion=eu-west-1&originCreation=20230306151925

### 2.4.3 Deep-dive on MAGPIE ports

Like in other industrial clusters, the strategy adopted by the authorities of the Port of Rotterdam to store hydrogen is highly dictated by the technological readiness and pre-established infrastructures. Therefore, ammonia, liquified hydrogen and compressed hydrogen (linepack) are nowadays the preferred storage options. This strategy has been conducted over the years, especially for ammonia, as it is a relatively well-established storage option with existing infrastructure and high energy density. Additionally, due to its ease of use and immediate availability, liquid and compressed hydrogen has been used as backup in this port. Concerning DeltaPort and HAROPA, no hydrogen storage facilities are currently available.

Plans to expand the actual hydrogen carrier's capacity are ongoing in the Port of Rotterdam, where it is expected that ammonia could move from the actual 0.03 Mt storage capacity to 4 Mt by 2050 and, this way, all the demand should be easily satisfied. An increased storage capacity for liquified hydrogen may also be observed in the coming years as there are plans for two more LH2 tanks. In addition, a large diameter pipeline for gaseous hydrogen storage is expected in the future, while there are no plans for static gaseous hydrogen storage. Although DeltaPort and HAROPA have no hydrogen storage nowadays, their future plans tend to converge to the current status of the Port of Rotterdam.

Additionally, as research is ongoing to improve the performance of LOHC technology and its future looks promising, the authorities of the Port of Rotterdam, aligned with the general trends, are considering the deployment of this technology.

## 2.5 Distribution infrastructure

### 2.5.1 Context

As previously mentioned in this report, hydrogen can be distributed as pure hydrogen when submitted to a state-conversion process such as compression or liquefaction or by using a liquid hydrogen carrier such as ammonia or LOHC. Different modalities such as pipeline, truck, ship, rail and barge can be used to deliver hydrogen to end-users, but the choice of the best option may depend on the quantity and the purity level required by the consumers. Furthermore, transporting hydrogen is not an easy task due to its low energy density, low boiling point, safety concerns and energy consumption requirements.

Currently, hydrogen is mostly produced close to where it is used, especially in industrial and logistic clusters. When this is not the case, the distribution mean usually depends on the volume of hydrogen to be distributed:

- Large volumes over long distances - the usage of pipelines is currently the most cost-effective option. Major hydrogen users such as refineries and chemical plants are usually connected to a network of pipelines.
- Smaller volumes – the usage of pressurized containers transported by trucks is the most common option. It is flexible, versatile and allows the delivery of hydrogen to areas where pipelines are not available.

### 2.5.2 The pathway towards decarbonization

In the upcoming years, with an increasing and more widespread hydrogen consumption, the current distribution patterns will need to be adapted. The future distribution supply chain needs to consider the use of alternative carriers and various transport modalities, taking into account the advantages and disadvantages of each, as well as the unique characteristics of hydrogen offtakers (e.g., delivery frequency, location, hydrogen volume requirements). As previously mentioned, the transport of hydrogen is mainly carried in the form of GH2. This is related with the fact that hydrogen is produced in that same state and only requires compression to be transported to the offtaker. However, for larger demands, other carriers may prove to be more cost-effective.

Overall, the cost of transporting hydrogen greatly varies with the selected carrier. It has a direct impact on the vehicle technical specifications (e.g., the reference CAPEX of LH2 ships is around twice of LOHC[26]) and on the amount of hydrogen that can be transported per trip. Alternative carriers, such as LH2, NH3, and LOHC, have the capacity to carry more hydrogen for the same volume when compared to GH2. Moreover, the gravimetric hydrogen storage density of these carriers is larger, which means that for the same weight unit of storage/vessel more hydrogen is being transported. For instance, hydrogen storage densities of LOHCs typically range from 5 to 7 wt% (wt% stands for weight/mass percent; in this case, the weight of hydrogen stored per unit weight of the material used for storage), which means that a 40-tonne tanker trucks can transport around 1500 - 2000 kg of hydrogen[27]. A complete list of the advantages and drawbacks of each energy carrier was already detailed in section 2.4.2. Still, it is important to highlight the relevance of this list for the choice of the transport modality.

Although new links between energy carriers and transport modalities will arise, the ones that are already in place will continue to make part of the overall solution. Hydrogen pipelines are a highly efficient and appealing long-term option. Given the associated high investment costs, it is currently under analysis the possibility of repurposing the existing natural gas infrastructure. The main challenge is ensuring material compatibility with hydrogen. In the European Union, the extension of the existing pipeline infrastructure is being studied. The current plan aims to create a pipeline system spanning over 53,000km, with 60% of the system consisting of repurposed natural gas pipelines and 40% consisting of newly built pipelines[28].

There is no clear-cut answer on how distribution will be in the future. Therefore, decision support tools are vital to help hydrogen stakeholders in taking these decisions. In section 3.3, this topic is discussed, and a dedicated model is proposed.

### 2.5.3 Deep-dive on MAGPIE ports

Although not being directly responsible for the transport of hydrogen to the hinterland, the MAGPIE port authorities are aware that all transport means (carrier + modality) are being considered by transport operators. Regarding pipelines, concrete investment plans are already in place, particularly at the Port of Rotterdam where retrofitting the available natural gas grid is not seen as an option. In fact, a new dedicated network for hydrogen is under development in the port including an underground pipeline of 32 kilometres, connecting Maasvlakte to Pernis. This will integrate a national hydrogen distribution network that will be developed after the Dutch cabinet had expressed its importance for reaching the current decarbonization targets. Hynetwork Services (a 100% subsidiary of Gasunie, the natural gas grid owner) is responsible for the development (and conclusion by 2030) of this national network that will connect suppliers and users in the northern Netherlands and in the border points with Belgium and Germany.

As in Rotterdam, HAROPA also has a grid for the distribution of natural gas owned by GRT Gaz, a French natural gas transmission operator. However, there are no clear idea how the future hydrogen transport infrastructure will look like in HAROPA as studies are still being conducted to evaluate if a new dedicated hydrogen network must be constructed or if

[26] Analysing future demand, supply, and transport of hydrogen; EHB; 2021
[27] Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers, Markus et al., 2020
[28] European Hydrogen Backbone, 2022, April

retrofitting the existing natural gas grid to transport only hydrogen (or a blended variant) is a better option for the port and its stakeholders. In contrast, DeltaPort does not see a valid business case in constructing a dedicated hydrogen pipeline, which is understandable considering the type of operation of this port.

# 3. Modelling the hydrogen supply chain

## 3.1 Introduction

Chapter 2 relied on exogenous inputs (e.g., literature review) to investigate how the future hydrogen supply chain will look like. On Chapter 3, the objective is the same, but a different approach is followed. Dedicated models are proposed to endogenously realize how the hydrogen supply chain (supply, storage, distribution) will evolve in the coming decades. While some of these models are built from ground-zero, others depart from pre-existing studies that need to be adapted to the port context.

## 3.2 Production & Storage

### 3.2.1 PtX cost model

This section proposes to use a pre-existing open-source approach[29] to estimate the global production and supply costs of green (renewables-based) and blue (natural gas reforming with CCS technologies) hydrogen until 2050. The so-called PtX cost model is also able to estimate the costs of hydrogen international transport (by shipping or pipeline). Combining both costs is thus possible to create a ranking of cost-optimal importing sources/countries.

The model can be currently applied to 113 countries. For each of them, a minimization of the LCOH is carried while considering the production, storage, and conversion costs (if dimmed necessary). Figure 6 provides a global view concerning each step of the methodology.

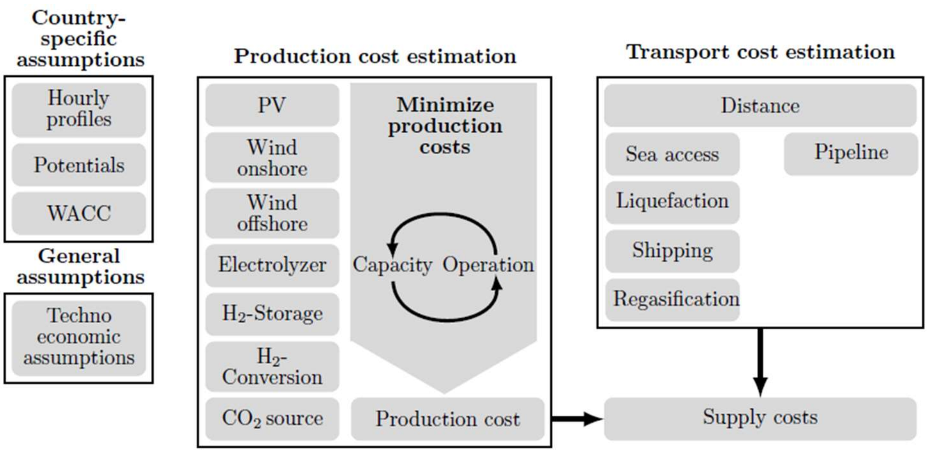



*Figure 6: PtX cost model*

As can be observed, the model also introduces country-specific weighted average costs of capital estimates to include the impact of differences in financing costs and country risk.

A thorough description of the mathematical formulation will not be carried in this report since it is well documented in the literature. Nevertheless, the objective function employed in this optimization problem is provided below:

[29] Gregor Brändle, Max Schönfisch, and Simon Schulte. Estimating long-term global supply costs for low-carbon hydrogen. *Applied Energy*, 302:117481, 2021. ISSN 03062619. doi: , 10.1016/j.apenergy.2021.117481.

$$\min Total\ Cost_{n,r,y}^{res,electr,sto,conv} \tag{6}$$

$$\begin{gathered} Total\ Cost_{n,r,y}^{res,electr,sto,conv} = \\ \left(CAPEX_{n,y}^{res} * a_{n}^{res} + OPEX_{n,y}^{res}\right) * C_{n,r,y}^{res} \\ +\left(CAPEX_{y}^{electr} * a^{electr} + OPEX_{y}^{electr}\right) * C_{n,r,y}^{electr} \\ +\left(CAPEX_{y}^{sto} * a^{sto}\right) * C_{n,r,y}^{sto} \\ +\left(CAPEX_{y}^{conv} * a^{conv} + OPEX_{y}^{conv}\right) * C_{n,r,y}^{conv} \end{gathered} \tag{7}$$

This proves what was mentioned before: for each country $n$ in year $y$ and considering RES resource class $r$, a linear optimization model tries to minimize the global costs. In other words, a joint minimization of the CAPEX/OPEX of a electrolyser $electr$, the CAPEX of a pressurized hydrogen storage tank $sto$, the CAPEX/OPEX of a hydrogen conversion plant $conv$ and the CAPEX/OPEX of renewable energy sources $res$ is carried. $C_{n,r,y}^{res}$, $C_{n,r,y}^{electr}$, $C_{n,r,y}^{sto}$ and $C_{n,r,y}^{conv}$ correspond to the installed capacity of each technology while $a_{n}^{res}$, $a^{electr}$, $a^{sto}$ and $a^{conv}$ are capital recovery factors used to convert investment costs into annual costs.

The value that the PtX cost model will bring to the MAGPIE project can be described by the following points:

- Calculate global ammonia production costs (already available in D3.6)
- Provide reliable import costs as an input to the model described in section 3.2.2. This model will together optimize imports and local production costs (endogenously calculated in order to account with dynamic electricity prices) thus allowing to create an optimal strategy to feed the hydrogen demand of a port.
- Complement the work described in section 3.3 (hydrogen hinterland transport) by providing an effective mean to calculate the costs of hydrogen international transport (e.g., by shipping).

### 3.2.2 Production and storage model

Departing from import costs provided by the PtX tool, the supply and storage model (SS model) will define the amount of hydrogen that is produced locally and imported on an hourly basis while minimizing the associated costs. In other words, the SS model is a techno-economic approach to simulate how to optimally match hydrogen supply and demand, taking into account, for example, the local RES profiles, component costs and available import routes for different hydrogen carriers.

Diving deeper into the SS model, regarding hydrogen production it allows for either the sizing of dedicated RES to provide electricity or for acquiring the electricity via power purchase agreements (PPAs). For importing hydrogen, it considers the available quantity and the corresponding price for several import routes. The optimization is performed on an hourly time step for 1 year to accurately model hydrogen production and the operation of the storage system. The obtained results are then extended to the entire lifetime of the project, resulting in an estimation on the full life operation of the local hydrogen production.

In order to properly evaluate the supply options for a port, the storage part of the supply chain had to be considered alongside the supply part as they are heavily dependent on one another. The required storage depends on how the hydrogen is supplied, either a more constant supply, such as hydrogen being produced locally, or a more fluctuating supply, like one based on importing hydrogen by ship. Moreover, the ability to receive large amounts of imported hydrogen in a short amount of time (e.g., a ship unloading hydrogen at the port) depends on the available storage, justifying why these two parts of the supply chain were modelled together.

Regarding the hydrogen carriers considered, three hydrogen carriers were chosen: gaseous hydrogen, liquified hydrogen and ammonia (denominated as GH2, LH2 and NH3, respectively). GH2 is the state in which hydrogen is produced and almost entirely consumed in, LH2 has a much higher energy density and can be produced relatively easily (albeit with a high energy consumption) and NH3 has a lower energy requirement with an even higher energy density, however, it is toxic and must be converted back to GH2 to be used for most applications.

For all three carriers, the SS model requires an hourly demand to properly estimate the storage based on the supply and demand rate of hydrogen. If a yearly profile with the hourly demand per carrier is available, the model can use it directly, otherwise, the demand per carrier is assumed to be constant throughout all the hours. With this assumption, the export of each carrier is done at a roughly continuous rate, even if it's not perfectly representative of reality, it is a valid assumption to allow the storage system to be modelled while being impartial.

In the model, while all three hydrogen carriers can be imported and stored, only GH2 can be produced directly. Since the hydrogen demand is provided per carrier, this would force the port to be fully dependent on imports for the sourcing of both LH2 and NH3. To overcome this, the following conversion technologies to transform one carrier into another were modelled:

- H2 liquifier -> cools GH2 down to its condensation point, generating LH2
- Haber-Bosch process -> combines GH2 and nitrogen to generate NH3
- H2 regasifier -> heats LH2 to generate GH2
- NH3 cracking -> uses heat and pressure to "crack" the NH3 into GH2 and other gases

The addition of these technologies allows the model to import/produce hydrogen as one carrier and convert it to another, covering more use cases and performing a more complete supply chain analysis.

### 3.2.2.1 Parameterization

In the modelling of the supply part, both local GH2 production and import for each carrier are considered. While the import per carrier can be simply provided as a list of available amount and cost for each carrier and location, being external to the model, the local GH2 production is dependent on the RES potential, electrolyser capacity, among others, making it more complex to model.

Focusing on the local production, the model considers offshore wind, onshore wind and solar PV as electricity sourcing options, receiving an hourly production profile for each. As the model is intended to either size RES or acquire the electricity via PPAs, two different sets of inputs are required depending on the electricity sourcing option. For sizing RES dedicated to hydrogen production, the cost of purchase and installation of the RES along with the yearly maintenance expenses, denominated as CAPEX (in €/MW) and OPEX (in €/MW/yr), respectively, must be provided. On the other hand, acquiring electricity via PPAs was modelled considering a pay-as-consumed agreement, where each MWh consumed by the electrolyser is paid according to a predetermined price. As inputs, this electricity sourcing option requires the available installed capacity (in MW) and the purchase cost (in €/MWh) for each RES technology to be considered.

Regardless of the model being capable of sizing the RES to supply electricity for the production of hydrogen, ideally the sizing of the RES for a port should take into consideration the global planning for the whole port ecosystem, not exclusively for hydrogen production. That problem was tackled in T3.2, where a model was developed to size the RES assess the RES potential and size them according to all of the port's electricity requirements. The option of modelling the RES as a pay-as-consumed PPA allows the SS model to use the sizing of RES from T3.2's model, making use of its more complete vision of the electricity supply chain for a more accurate sizing. Nonetheless, the model can also be run independently from the model developed in T3.2 by sizing the RES only considering hydrogen production.

Starting with the RES parametrization, both approaches to model the RES (sizing and considering PPAs) use an hourly capacity factor profile to take into account the renewables' variability and operational behaviour. A capacity factor profile is a profile ranging from 0 to 1, where 1 represents producing electricity at nominal capacity and 0 not producing any electricity, which can then be multiplied by the installed capacity to obtain an hourly production profile. Computationally, it's less expensive to then vary the installed capacity and assess the impacts on the system. For RES modelling, the inputs are:

- $cf_h^{RES}$ - Hourly capacity factor profile for each energy source
- $RES_{MODE}$ - Input to define whether to size RES or consider PPA, is set to SIZE_RES or PPA

If the RES should be sized, then $RES_{MODE}$ must be set to SIZE_RES and the following inputs must be provided:

- $CAPEX_{RES}$ - CAPEX for each energy source in €/kW
- $OPEX_{RES}$ - OPEX for each energy source in €/kW/yr

Otherwise, $RES_{MODE}$ must be set to PPA and the following inputs are required:

- $P_{RES}$ - Installed capacity of each RES in kW
- $pc_{RES}$ - Purchase cost of electricity for each RES in €/MWh

Purchasing electricity from the grid is also considered, where a fixed purchase price is considered and a limit on how much electricity can be consumed to the grid can be imposed. This limit can assist the hydrogen producing systems in continuing to generate hydrogen when the RES aren't generating electricity, while still ensuring the system doesn't acquire too much electricity from the grid and the hydrogen is still generated mostly from green electricity. Limiting electricity purchased from the grid is defined as a percentage of total yearly electricity demand. The inputs for grid electricity are:

- $pc_{grid}$ - Grid electricity price in €/MWh
- $lim_{grid}$ - Grid purchase limit in %

Electrolysers' efficiency typically depends on their load, achieving the highest efficiencies at lower loads and steadily decreasing as the load increases. Nonetheless, this difference in efficiency between the most efficient point and operating at full load is around 6%[30] and from a computational standpoint, considering this varying efficiency makes the optimization problem non-linear, which is significantly more difficult to solve on an hourly simulation. For

[30] Techno-economic analysis of hydrogen production from PV plants; Angelica Liponi et al.; 2022

these reasons, the electrolyser was modelled considering a fixed specific energy consumption. The inputs for the electrolyser are:

- $c_{sp,el}$ - Electrolyser specific energy consumption in kWh/kg
- $CAPEX_{el}$ - Electrolyser CAPEX in €/kW
- $OPEX_{el}$ - Electrolyser OPEX in €/kW/yr

The hydrogen imports per carrier are provided as a list for each carrier, where all commercial routes are provided as total available quantity of that carrier and its total import cost in €/kg. The imports were considered to be all transported by ship, so some assumptions on the frequency of the ships arriving had to be made for the model to capture the intermittency of a ship arriving, unloading a significant amount of the carrier it was transporting and the interval until the next ship arrives and unloads. In addition to the points raised above, the computational difficulty must be taken into account. If the model was given the ability to choose whether to receive a ship for each carrier and for each hour, finding an optimal solution would be significantly harder to solve and, most importantly, might not be representative of the real port conditions as a ship might not be able to be arranged to dock exactly as the model would prefer.

Ultimately, the imports for each carrier were modelled with a frequency of arrival for the ships, for example, considering that every NH3 ship would arrive every 72h. The model was given the minimum and maximum capacity of the ships for each carrier, so it maintains the ability to optimize for every ship how much should be imported. For each carrier $c$, the required storage inputs are:

- $p_i^c$ - Imported hydrogen purchase cost for route $i$ in €/kWh
- $h_i^c$ - Imported hydrogen available quantity for route $i$ in kg
- $ship_{min}^c$ - Minimum ship capacity in kg
- $ship_{max}^c$ - Maximum ship capacity in kg
- $ship_f^c$ - Ship frequency in hours

The storage was modelled with the CAPEX, OPEX and boil-off rate for each carrier. The developed model can then take these technical and economical parameters and size the storage capacity per carrier, however, it doesn't consider any compressors or additional equipment responsible for charging or discharging the storage. This was excluded due to the low impact in the overall result, high complexity of the system and increased computational difficulty. The only impacts in the simulations are excluding the compressors' cost and assuming the storage can be charged/discharged at any rate as long as the storage constraints are fulfilled. For each carrier $c$, the required storage inputs are:

- $CAPEX_s^c$ - Storage CAPEX in €/kg
- $OPEX_s^c$ - Storage OPEX in €/kg/yr
- $boil^c$ - Boil-off rate in %/day

The final inputs required are concerning the four conversion technologies, which are the systems that can convert GH2 into LH2 or NH3, and vice-versa Similar to the other components present in the model, they are sized in the simulations to reduce the total cost of supplying the required demand. To do so, the CAPEX, OPEX and electrical consumption for each unit converted are required.

While some conversions also require a significant amount of heat[31], the energy consumption in the form of heat wasn't modelled as its cost is dependent on the neighbouring industries and port ecosystem. Nonetheless, the heat requirement can be calculated based off the simulation results. It was also considered that the cost any other materials required for some conversions should be included in the overall CAPEX, OPEX and consumption for each technology. An example is the Haber-Bosch process that converts GH2 into NH3 but also consumes nitrogen, so the cost and consumption for an air separator unit to provide the nitrogen should already be included in this technology's inputs. For each conversion technology $ct$, the required inputs are:

- $c_{sp,ct}$ - Conversion specific energy consumption in kWh/kg of the output product of the reaction
- $\eta_{ct}$ - Conversion rate of the reaction in %
- $CAPEX_{ct}$ - Conversion CAPEX in €/kg/h
- $OPEX_{ct}$ - Conversion OPEX in €/kg/h/yr

Focusing on the demand per carrier, the model can either receive an hourly profile or consider that the demand is constant based off an annual value. In terms of inputs, the model is prepared to receive per carrier:

- $d_h^c$ - Hourly demand in kg
- $d_{total}^c$ - Annual demand in kg, where the hourly demand is calculated as:

$$d_h^c = d_{total}^c / 8760 \, , \forall_h$$

The remaining inputs the model requires are regarding the economics of the project, duration and annual demand per carrier:

- $l$ - Project lifetime in years
- $t_c$ - Project construction time in years
- $a$ - Project discount rate in %

#### 3.2.2.2 Optimization model

The developed optimization model is a Linear Programming (LP) problem, with an hourly granularity that finds a solution that satisfies the required demand per carrier and all the constraints that model the operation of the electrolyser, storage, hydrogen import, among others. This solution is determined by finding the optimal value for the variables defined for the problem that minimize the total cost of supply/storage, which are the following:

- $P_{el}$ – electrolyser capacity in kW
- $P_{RES}$ – installed capacity for each RES in kW
- $S_c$ – storage amount for carrier $c$ in kg
- $e_h^{RES}$ – hourly energy produced by each RES in kWh
- $e_h^{curt}$ – hourly energy curtailed in kWh
- $e_h^{grid}$ – hourly energy purchased from the grid in kWh
- $e_h^{el}$ – hourly energy consumed by the electrolyser in kWh
- $h_h^p$ – hourly GH2 produced in kg
- $i_h^{c,i}$ – hourly hydrogen imported for each carrier from each import route in kg

[31] Large-scale storage of hydrogen; Joakim Andersson et al.;2019

- $s_h^c$ – hourly hydrogen sold for each carrier in kg
- $sto_h^c$ – hourly hydrogen stored for each carrier in kg (negative value represents storage discharging)
- $soc_h^c$ – hourly state of charge of storage for each carrier in kg

If $RES_{MODE}$ is set to PPA, $e_h^{curt}$ isn't required by the model, however, a variable to determine the energy consumed from each PPA must be defined:

- $e_h^{pur,RES}$ – hourly energy purchased from PPA for each RES in kWh

If conversion technologies should be considered, the hourly flow rates of input and output for each technology along with the installed capacity must also be defined. The variables for the conversion are the following:

- $gh_h^{liq}$ – hourly GH2 to be liquified into LH2 in kg
- $lh_h^{liq}$ – hourly LH2 liquified from CH2 in kg
- $gh_h^{hb}$ – hourly GH2 to be processed by the Haber-Bosch process into NH3 in kg
- $nh_h^{hb}$ – hourly NH3 to be produced by the Haber-Bosch process from GH2 in kg
- $gh_h^{reg}$ – hourly GH2 regasified from LH2 in kg
- $lh_h^{reg}$ – hourly LH2 to be regasified into CH2 in kg
- $gh_h^{cra}$ – hourly GH2 generated from NH3 in kg
- $nh_h^{cra}$ – hourly NH3 to be cracked into CH2 in kg
- $P_{ct}$ – installed capacity per conversion technology in kg/h of output product

The optimization model is composed of an objective function to be minimized, which is the total supply and storage cost, and the constraints that model the operation of each component/sub-system: RES, electrolyser, storage, import and conversion technologies. Since the model is prepared to accept different simulations (with or without conversion technologies, sizing the RES or considering PPAs), the more complex simulation was chosen: with conversion technologies and with sizing of the RES. Mathematically, the problem is formulated as:

$$\min \; tc_{RES} + tc_{el} + tc_{grid} + tc_{imp} + tc_s + tc_{ct} \tag{8}$$

$s.t.$

$(Economic\ constraints)$:

$$tc_{RES} = \sum_{RES} P_{RES} \cdot CAPEX_{RES} \cdot k_c + P_{RES} \cdot OPEX_{RES} \cdot k_l \tag{9}$$

$$tc_{el} = P_{el} \cdot CAPEX_{el} \cdot k_c + P_{el} \cdot OPEX_{el} \cdot k_l \tag{10}$$

$$tc_{grid} = \sum_{h=1}^{8760} e_h^{grid} \cdot pc_{grid} \cdot k_l \tag{11}$$

$$tc_{imp} = \sum_{c} \sum_{i} h_i^c \cdot p_i^c \cdot k_l \tag{12}$$

$$tc_s = \sum_{c} S_c \cdot CAPEX_s^c \cdot k_c + S_c \cdot OPEX_s^c \cdot k_l \tag{13}$$

$$tc_{ct} = \sum_{ct} P_{ct} \cdot CAPEX_{ct} \cdot k_c + P_{ct} \cdot OPEX_{ct} \cdot k_l \tag{14}$$

$$k_c = \frac{\sum_{y=1}^{t_c}(1+a)^y}{t_c} \quad (15)$$

$$k_l = \frac{(1+a)^l - 1}{a \cdot (1+a)^l} \quad (16)$$

$(Hydrogen\ production\ and\ import\ constraints, where\ '\%'\ operator\ is\ the\ remainder\ operator)$:

$$h_h^p = \frac{e_h^{el}}{c_{sp,el}}, \forall h \quad (17)$$

$$e_h^{el} \leq P_{el}, \forall h \quad (18)$$

$$e_h^{RES} = \sum_{RES} P_{RES} \cdot cf_h^{RES}, \forall h \quad (19)$$

$$e_h^{RES} + e_h^{grid} = e_h^{curt} + lh_h^{liq} \cdot c_{sp,liq} + nh_h^{hb} \cdot c_{sp,hb} + gh_h^{reg} \cdot c_{sp,reg} + gh_h^{cra} \cdot c_{sp,cra}, \forall h \quad (20)$$

$$\sum_h e_h^{grid} \leq \sum_h e_h^{el} \cdot lim_{grid} \quad (21)$$

$$\sum_h i_h^{c,i} \leq h_i^c, \forall i, c \quad (22)$$

$$\sum_i i_h^{c,i} = 0, \forall h\%ship_f^c \neq 0, \forall c, h \quad (23)$$

$$\sum_i i_h^{c,i} \geq ship_{min}^c, \forall h\%ship_f^c = 0, \forall c, h \quad (24)$$

$$\sum_i i_h^{c,i} \leq ship_{max}^c, \forall h\%ship_f^c = 0, \forall c, h \quad (25)$$

$(Storage\ contraints)$:

$$h_h^p + \sum_i i_h^{gh,i} + gh_h^{reg} + gh_h^{cra} = s_h^{gh} + sto_h^{gh} + gh_h^{liq} + gh_h^{hb}, \forall h \quad (26)$$

$$\sum_i i_h^{lh,i} + lh_h^{liq} = s_h^{lh} + sto_h^{lh} + lh_h^{reg}, \forall h \quad (27)$$

$$\sum_i i_h^{nh,i} + nh_h^{hb} = s_h^{nh} + sto_h^{nh} + nh_h^{cra}, \forall h \quad (28)$$

$$soc_0^c = 0, \forall c \quad (29)$$

$$soc_h^c = sto_h^c + soc_{h-1}^c \cdot \left(1 - \frac{boil_c}{24}\right), \forall c, h > 0 \quad (30)$$

$$soc_h^c \leq S_c, \forall c, h \quad (31)$$

$$s_h^c = d_h^c, \forall c, h \quad (32)$$

$(Conversion\ technologies\ constraints)$:

$$lh_h^{liq} \leq P_{liq}, \forall h \quad (33)$$

$$nh_h^{hb} \leq P_{hb}, \forall h \quad (34)$$

$$gh_h^{reg} \leq P_{reg}, \forall h \quad (35)$$

$$gh_h^{cra} \leq P_{cra}, \forall h \quad (36)$$

$$lh_h^{liq} = gh_h^{liq} \cdot \eta_{liq}, \forall h \quad (37)$$

$$NH_3^{WT} \cdot nh_h^{hb} = gh_h^{hb} \cdot \eta_{hb}, \forall h \quad (38)$$

$$gh_h^{reg} = lh_h^{reg} \cdot \eta_{reg}, \forall h \quad (39)$$

$$gh_h^{cra} = NH_3^{WT} \cdot nh_h^{cra} \cdot \eta_{cra}, \forall h \quad (40)$$

Where equation (8) is the objective function, representing the sum of the costs in the supply and storage system: RES, electrolyser, grid electricity, hydrogen import, storage, and conversion, which are calculated by equations (9) to (14), respectively. For the calculation of the costs throughout the lifetime of the project, the discount rate and construction time must be taken into account. To facilitate their inclusion, $k_c$ and $k_l$ are calculated by equations (15) and (16), respectively, where $k_c$ represents the distribution of the initial CAPEX throughout the construction years and discounts the values from each construction year into year 0. Additionally, $k_l$ accounts for a constant expense throughout the lifetime of the project, discounting its value from each year into year 0.

Regarding the hydrogen supply and storage constraints: equation (17) sets the relation between hydrogen produced and electricity consumed by the electrolyser using the electrolyser's specific energy consumption; equation (18) limits the electricity consumed by the electrolyser to be equal or lower to the electrolyser's nominal power; equation (19) sums the renewable electricity produced from all installed RES; equation (20) states that all electricity production must be equal to all electricity consumption; equation (21) ensures that the electricity consumed from the grid stays below the imposed limit of $grid_{lim}$; equation (22) ensures the total imported amount of carrier $c$ from route $i$ is under or equal to the maximum available in that route; equations (23) to (25) define the hydrogen importing constraints, where hydrogen can only be imported at a certain interval ($ship_f^c$) and between a minimum and maximum value, for all carriers. In equations (23) to (25), the '%' operator is the remainder between the current hour and the ship frequency, only allowing for import of hydrogen when the current hour $h$ is a multiple of the frequency of ships arriving at the port, for each carrier, $ship_f^c$.

For the storage constraints: equation (26) states that the sum of gaseous hydrogen produced, imported and converted must be equal to gaseous hydrogen sold, stored or converted to other carriers; equations (27) and (28) are similar to equation (26), only for liquified hydrogen and ammonia, respectively; equation (29) sets the state of charge for the storage of each carrier to 0 for the first hour of operation; equation (30) calculates the current state of charge for each storage considering the previous state of charge, charge/discharge and boil-off rate; equation (31) ensures the state of charge is always under or equal to the storage's capacity; equation (32) ensures that the hourly demand is met for each carrier.

Lastly, regarding the conversion technologies constraints: equations (33) to (36) ensure that the hourly production of each conversion technology is under or equal to the installed capacity of that technology; equations (37) to (40) model the conversion reaction for each technology, considering its efficiency and, in the conversion to/from ammonia (the Haber-Bosch and NH3 cracking technologies, respectively), the $NH_3^{WT}$ represents the amount of hydrogen available in 1 kg of ammonia, which is 0.177 kg.

#### 3.2.2.3 Model outputs

The main contribution of this model is the analysis on producing hydrogen locally, importing hydrogen and how to store according to the indicated demand. The model also sizes the electrolyser, storage capacity for each carrier and capacity of the conversion technologies (should they be included in the optimal solution found). For local hydrogen production, the ideal capacity and LCOE of the RES is also presented as it is the most influential factor on the cost of producing hydrogen locally. A breakdown of how much hydrogen and the carrier in which is transported is also provided, along with the total quantities produced and imported.

On a more economical level, the LCOH of the local production and import by carrier is calculated and presented, along with a total LCOH. For storage, the Levelized Cost of Storage (LCOS) is calculated for each carrier, which represents the total investment in the storage divided by the total amount of hydrogen discharged. The total investment in the conversion technologies along with the cost per kg of the generated carrier is also calculated. At last, the total cost of supplying and storing the required hydrogen to fulfil the demand is presented.

The model also outputs the hourly values for all variables present in the optimization problem, allowing for the verification of the operation of each component in the modelled system. By analysing this output insight can be gained on the ideal operation of the entire SS system on an hourly basis.

## 3.3 Distribution grid model

Increasing hydrogen imports, in any carrier, and local production transform ports into important hydrogen distribution centres. This is similar to what occurs nowadays in the natural gas (NG) supply chain, where NG is imported in the liquid state (LNG) to the ports' LNG terminal and distributed through pipelines or vehicles to the offtakers. Contrary to natural gas, whose supply chain distribution technologies are implemented, mature, and efficient, comparable large-scale hydrogen distribution does not yet exist. Hydrogen can be transported via different transport modalities and multiple carriers, each with its pros and cons[32]. When choosing the transport-carrier combination, key factors to consider are carrier transport safety (e.g., ammonia toxicity), the maturity and cost-effectiveness of carrier technologies (e.g., conversion and reconversion), and the total cost of distributing the carriers by vehicle or pipeline. In addition, the offtakers' demand volume and distance from the port play an important role in selecting the best transport-carrier combination. Thorough planning is essential to determine the best option and minimize in the long-term the cost of hydrogen distribution.

### 3.3.1 Introduction to the model

A techno-economic model was developed to assist in the design and selection of the most cost-efficient hydrogen distribution from a port to an offtaker, for a given transport-carrier combination. It can, however, be repeatedly applied to compare the available transport-carrier combinations and identify the most cost-efficient option to an offtaker. The main elements that impact the distribution cost are the carrier, the transport modality (i.e., vehicle or pipeline), and the distribution complementary technologies (i.e., storage and carrier reconversion equipment for the vehicle, or the pipeline compressor).

A concept that can be applied to this model is not to look at individual offtakers, but rather at an offtakers' cluster with a central distribution centre - H2 Distribution Centre – which then satisfies the demand of the individual offtakers. The H2 Distribution Centre receives by vehicle/pipeline the respective carrier from the port, reconverts it to GH2 (if needed), and then distributes it to the surrounding offtakers. With this approach, the H2 Distribution Centre can benefit from economies of scale and take advantage of carriers that could be discarded if an individual offtaker was considered, e.g., ammonia due to high reconversion costs. When applying this "H2 Distribution Centre "concept, it is important to note that the model only considers distribution from the port to the H2 Distribution Centre. To analyse the distribution from an H2 Distribution Centre to the surrounding individual offtakers, the model would need to be applied at a more detailed level in that specific region.

[32] Analysing future demand, supply, and transport of hydrogen; EHB; 2021

From this point on in this section, the term 'H2 Hub' will be used to refer to either an individual offtaker or a H2 Distribution Centre.

Three transport modalities were considered to transport the carriers from the port to the H2 Hub: pipeline, barge, and truck. For each transport modality, the corresponding complementary technologies were modelled, and the carriers' properties were taken into account.

If a pipeline is set as a transport modality, only GH2 is considered as a carrier. Regarding complementary technologies for pipeline distribution, the model only considers a compressor station at the pipeline inlet in order to meet the required pipeline pressure (user can specify the pipeline output pressure in the model). The compressor costs are tightly dependent on the H2 demand, being very significant for large capacity pipelines, however rather negligible for medium and small capacity pipelines[33]. Nevertheless, the model includes the compressor station design so that the economic impact of this equipment in the total pipeline distribution costs can be assessed. Storage at the H2 Hub has not been considered, as it is expected that pipelines can continuously meet demand. This is acceptable because pipelines act as a buffer storage, ensuring that GH2 is always available to accommodate demand.

If a vehicle is specified as a transport modality, the carriers considered to be transported are: NH3, LH2, and GH2. As complementary technologies, one storage is always sized regardless of the carrier and, in the case of NH3 or LH2 as carriers, a reconversion technology is designed as well. When considering a vehicle, the amount of a carrier it can transport is dependent on the carrier properties, such as its volumetric density and/or hydrogen content (e.g., 1kg of NH3 has around 0.177 kg of H2), and the required vehicle technical features to transport it. In other words, this means that the carrier has meaningful impact on the vehicle features and number of trips required to meet the H2 Hub demand, thus impacting the total distribution costs.

At the H2 Hub, storage is considered when a vehicle is specified as a transport modality. The two main factors that affect storage sizing are: vehicle scheduling and guaranteeing demand fulfilment. While optimal vehicle scheduling is essential to reduce the storage size, it is not ideal to have the smallest possible storage. Analysing the last factor, since the H2 Hub will solely rely on vehicles, it is important to consider a storage size that guarantees to fulfil the demand for an acceptable time frame, e.g., 6h or 12h (depending on the H2 Hub demand and distance – user sets this parameter), reducing dependency on strict vehicle scheduling, and thus, the impact of possible schedule deviation.

A reconversion technology is also needed at the H2 Hub to reconvert NH3 and LH2 carriers into GH2, so that it can be utilized for its end-use. It is assumed that the reconversion of the carrier is done on-demand. If the H2 Hub is an individual offtaker, the reconversion of the carrier into GH2 is assumed to be either immediately used or stored in a second GH2 storage. If the H2 Hub is a H2 Distribution Centre, there is either a second storage, to which the reconverted carrier goes, and from where trucks then distribute to the individual offtakers, or it is directly discharged into pipelines to the H2 Distribution Centre consumers. This situation would be plausible, for example, for a maritime hinterland route where a large barge would transport NH3 to an H2 Hub, that would then be reconverted and discharged in a local pipeline system.

When comparing both transport modalities options, the pipeline infrastructure has a higher capital cost and is highly dependent on the geographical location/terrain, however, it can provide an on-demand hydrogen supply without the need for storage or reconversion technology at H2 Hub and has low maintenance costs. Choosing vehicles as a transport

[33] Analysing future demand, supply, and transport of hydrogen; EHB; 2021

modality usually requires less capital investment, only one storage and, in the case of LH2 or NH3 as a carrier, the reconversion technology. However, it presents high yearly variable costs since vehicles have limited transporting capacity, resulting in the need for several number of trips, which can mean a higher cost in the long term.

In the design of the hydrogen supply chain distribution, the importance of the granularity of the demand profile varies depending on the transport modality. To optimally design the pipelines, it is necessary to have an accurate hourly demand profile of the H2 Hub, so that they are neither under nor over-designed. On the other hand, when the distribution is performed by a vehicle, the demand profile can be given in larger time steps as previously explained. For the vehicle distribution, it is important to specify the profile granularity and to have the granularity equal to or lower than the number of hours of storage intended to meet the demand.

As a final remark, for vehicles, a cost per kilogram per kilometre transported is received as input for the model to compute the costs of truck transportation, while for the pipeline it was considered more suitable to design the pipeline and estimate its cost of operation. This distinction was made due to the interdependence of the transport modality and the H2 Hub. Vehicle characteristics, such as capacity, consumption, and investment cost, are predetermined and independent of any H2 Hub or demand characteristics. On the other hand, pipelines are designed to connect a port to a specific H2 Hub and must ensure that demand characteristics are met.

### 3.3.2 Parametrization

To analyse the distribution of hydrogen from the port to an H2 Hub, the carrier and transport modality must be provided. Furthermore, by default, for any H2 Hub the following parameters must be given:

- $d_h$ - H2 Hub demand profile [kg H2]
- $L_{off}$ – H2 Hub distance to port [km]

If the chosen transport modality is a pipeline, the pipeline's length is assumed to be equal to the offtakers distance to the port, except if the user provides a more accurate value. The pipeline's diameter is determined by the required flowrate, which is related to the hourly demand, and pipeline's pressure. To model the pipeline, the following parameters are required:

- $P_{PL,off}$ – pipeline pressure at offtaker [bar]
- $OPEX_{PL}$ – OPEX as a % of CAPEX [%]
- $coef_a$, $coef_b$, $coef_c$ - Coefficients for CAPEX polynomial equation (41)

Where $coef_a$, $coef_b$, $coef_c$ are the coefficients of the polynomial equation presented below, which provides the total investment cost in the pipeline (both coefficients and polynomial equation[34]).

$$CAPEX_{PL} = L_{off} \cdot (coef_a \cdot diam_{PL}{}^2 + coef_b \cdot diam_{PL} + coef_c) \tag{41}$$

For the pipeline compressor, the parameters are similar to the conversion technology described in the section 4.2. It is important to note that the economic parameters associated

[34] Seasonal storage and alternative carriers: A flexible hydrogen supply chain model; M. Reuß et al., 2017

with the compressor vary depending on the pressure required. The following parameters are considered:

- $CAPEX_C$ - Compressor CAPEX [€/kgH2/h]
- $OPEX_C$ - Compressor fix OPEX [€/kgH2/h/yr]
- $c_{sp,C}$ – Specific electricity consumption [kWh/kgH2/h]
- $c_{elect}$ – Electricity price [€/MWh]

If the chosen transport modality is a vehicle, parameters for storage and reconversion technology are required. Regarding the default data, a more accurate $L_{off}$ according to the vehicle can be provided, e.g., if it is a maritime or land route. Adding to the default data from the H2 Hub, it is also required to specify the number of hours for which the storage should be able to satisfy demand, as well as the maximum number of vehicles that can discharge within that timestep due to existent H2 Hub infrastructure restrictions. All the vehicle's parameters are carrier dependent and should be given accordingly. The inputs needed are:

- $n_{v,h,max}$ - Max number of vehicles per time step
- $h_S$ – Number of hours the storage should satisfy [h]
- $tcap_{v,c}$ – Total vehicle transporting capacity according to carrier [kg]
- $boil_{v,c}$ – Carrier boil-off rate in vehicle [%/km]
- $OPEX_{v,c}$ - Vehicle cost per km, according to carrier [€/km]

The boil of rate per km, $boil_{v,c}$, can be computed using the boil-off rate (in %/day), $boil_c$, and the average vehicle velocity (in km/h), $v_v$ , as,

$$boil_{v,c} = \frac{boil_c}{v_v \cdot 24} \tag{42}$$

For the reconversion technology and storage, similar parameters to ones used in the SS model are required. For the reconversion technology:

- $c_{sp,rt}$ – Reconversion specific energy consumption of the output product of the reaction [kWh/kg]
- $\eta_{rt}$ - Reconversion rate of the reaction [%]
- $CAPEX_{rt}$ - Reconversion CAPEX [€/kg/h]
- $OPEX_{rt}$ - Reconversion OPEX [€/kg/h/yr]

And for the storage:

- $CAPEX_S$ - Storage CAPEX [€/kg]
- $OPEX_S$ - Storage OPEX [€/kg/yr]
- $boil_{S,c}$ - Boil-off rate of storage [%/day]

### 3.3.3 Optimization model

Two models were implemented to analyse the distribution of hydrogen based on the type of transport modality: one for distribution by vehicle and the other for distribution by pipeline.

To model the supply chain distribution by vehicle, a Mixed Integer Linear Programming (MILP) problem was developed. This model finds the optimal vehicle scheduling that minimizes, for a transport-carrier combination, the distribution costs from the port to an H2 Hub while satisfying the required hydrogen demand and all the operational constraints. The optimal solution is determined by finding the values of the variables defined for the problem that minimize the total cost of distribution. The variables referred are the following:

- For the storage:
  - $S_c$ - storage amount for carrier [kg]
  - $stoc_h$ - hourly storage charging [kg]
  - $soc_h$ - hourly state of charge of storage [kg]
- For the vehicles:
  - $n_{v,h}$ - number of vehicles discharging at the port in one timestep
- For the reconversion technologies:
  - $P_{rt}$ - reconversion technology capacity [kW]

The optimization model is composed of the constraints that model the operation of each component and the objective function of minimizing total hydrogen distribution cost. Mathematically, the objective function of the problem is formulated as:

$$\min tc_s + tc_v + tc_{ct} \tag{43}$$

Where $tc_s$ ,$tc_v$ and $tc_{ct}$ represent the total cost of the storage, vehicle operation, and reconversion technology, respectively. The total costs of operation are discounted to year 0 (present year) of the simulation, as performed in section 3.3.3.

$s.t.$

$(Economic\ constraints)$:

$$tc_s = S_c \cdot CAPEX_s \cdot k_c + S_c \cdot OPEX_S \cdot k_l \tag{44}$$

$$tc_v = L_{off} \cdot OPEX_{v,c} \cdot k_l \cdot \sum_h (n_{v,h} \cdot tcap_{v,c}) \tag{45}$$

$$tc_{rt} = P_{rt} \cdot CAPEX_{rt} \cdot k_c + P_{rt} \cdot OPEX_{rt} \cdot k_l \tag{46}$$

$$k_c = \frac{\sum_{y=1}^{t_c}(1+a)^y}{t_c} \tag{47}$$

$$k_l = \frac{(1+a)^y - 1}{a \cdot (1+a)^y} \tag{48}$$

Eq. (45) represents the total cost of the trips from the port to the H2 Hub.

$(Storage\ contraints)$:

$$stod_h = d_h \cdot \eta_{rt}, \forall h \tag{49}$$

$$soc_h = stoc_h - stod_h + soc_{h-1} \cdot \left(1 - \frac{boil_{s,c}}{24}\right), h \geq 0 \tag{50}$$

$$soc_{h-1} \geq stod_h \tag{51}$$

$$soc_h \leq S_c, \forall h \tag{52}$$

Eq. (52) ensures that the storage contains enough hydrogen to fulfil the demand for the next time step. This is to replicate real-world operation, where it is essential to guarantee reliable hydrogen supply to meet the H2 Hub's demand.

$(Transport\ modality\ constraints\ - type\ vehicle)$:

$$stoc_h = cap_{v,c} \cdot \ n_{v,h} , \forall\ h \quad (53)$$

$$cap_{v,c} = \ tcap_{v,c} \ \cdot (1 - boil_{v,c} \cdot L_{off}) \quad (54)$$

$$n_{v,h} < n_{v,h,max}, \forall\ h \quad (55)$$

Eq. (54) considers the boil-off rate of the carriers that occurs during transportation, which can lead to the need of additional vehicle trips and increase the amount of carrier required at the port.

It is important to emphasize that additional constraints can be implemented to the model for specific logistical requirements of each offtaker.

To model the distribution of hydrogen through a pipeline, an iterative assessment model was developed to determine the most appropriate pipeline diameter and minimize the investment costs. To size the diameter, the model considers the required pressure on the pipeline's outlet, pressure losses along the pipeline, and the pipeline's technical specifications. The technical specifications and diameter are based on a steel pipelines catalogue that comply with the ASME B36.10 standard – commonly used for NG and that can be used for H2[35][36] The catalogue provides information on the pipeline's technical data, such as diameter, schedule, and maximum allowed pressure, which allow for more accurate pipeline design. It is important to note that the ASME B36.10 standard can be used for hydrogen transport, but special consideration must be given to prevent hydrogen embrittlement[37] and ensure safe transport. In addition, if the user wishes to analyse a pipeline standard other than the ASME B36.10, another pipeline catalogue can be applied to the model.

Now focusing on the model steps, initially a pipeline diameter and respective technical data are retrieved from the catalogue. Mathematically, the objective is to guarantee that the total pressure at pipeline inlet should be equal or inferior to the maximum allowed pressure of the pipeline being analysed. The pressure at the pipeline's inlet is given by,

$$P_{in} = P_{out} + \Delta P_0 \quad (56)$$

while at the pipeline outlet, the pressure, $P_{out}$, is given by the minimum allowed pressure on the pipeline, $P_{PL,off}$.

Applying the Darcy-Weisbach[38] equation, we obtain can obtain the pressure losses, $\Delta P_0$, through:

$$\frac{\Delta P_0}{L_{off}} = f_D \ \cdot \frac{\rho_{H2}}{2} - \frac{v^2}{D_H} \quad (57)$$

[35] https://www.engineeringtoolbox.com/astm-steel-pipes-working-pressure-d_775.html
[36] http://www.valveexpo.com/upload/201607/28/201607281625312942.pdf
[37] Hydrogen embrittlement of steel pipelines during transients; Zahreddine et al., 2018
[38] Howell, Glen (1970-02-01). "3.9.2". Aerospace Fluid Component Designers' Handbook. Vol. I. Redondo Beach CA: TRW Systems Group. p. 87, equation 3.9.2.1e.

To compute the friction factor, the Haaland[39] approximation was chosen, which considers a full-flowing circular pipe. The approximation is the following,

$$\frac{1}{\sqrt{f}} = -1.8\log\left(\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right) \tag{58}$$

where,

$$Re = \frac{\rho_{H2} \cdot v \cdot D}{\mu} \tag{59}$$

Considering a safety factor to avoid water hammer effect, the maximum velocity of hydrogen in the pipeline is:

$$v = 4\frac{Q}{A_{p,int}} \tag{60}$$

To compute the volumetric flowrate,

$$Q = \frac{Q_{max}}{\rho_{H2}} \tag{61}$$

After having computed all the variables, it is possible to determine the pressure at pipeline inlet, $P_{in}$, and to observe if it surpasses the pipeline maximum pressure allowed. If so, the remaining pipeline diameters and schedules from the catalogue are tested until the technical parameters are respected, and the minimum diameter pipeline is found.

By the end of the iteration, the most suitable diameter for the pipeline has been sized. The total costs of the pipeline are:

$$tc_{PL} = P_{rt} \cdot CAPEX_{PL} \cdot k_c + P_{rt} \cdot OPEX_{fix,PL} \cdot k_l \tag{62}$$

The costs associated with the pipeline compressor are the following:

$$tc_C = P_C \cdot CAPEX_C \cdot k_c + P_C \cdot OPEX_{fix,C} \cdot k_l + cost_{elec,C} \cdot k_l \tag{63}$$

Where $cost_{elec,C}$ is calculated as:

$$cost_{elec,C} = c_{sp,C} \cdot \frac{c_{elect}}{1000} \cdot \sum_h d_h \tag{64}$$

The total costs of distributing hydrogen to the H2 Hub by pipeline are computed as,

$$tc = tc_{PL} + tc_C \tag{65}$$

[39] Massey, Bernard Stanford (1989). Mechanics of fluids. Chapman & Hall. ISBN 978-0-412-34280-6

Similarly to the vehicle model, the total costs are discounted to year 0 (present year).

### 3.3.4 Model outputs

The main contribution of this model is the analysis of the cost of transporting hydrogen from a port to an H2 Hub, for a given transport modality and carrier. The model not only outputs technical parameters, such as sizing of equipment or logistic scheduling depending on the chosen transport modality, but also provides economic data for the solution.

To reiterate what was mentioned earlier in this section, the model is flexible in the sense that it can be applied to different combinations of transport-carriers, allowing for the identification of the most economical way to distribute hydrogen from the port to the H2 Hub. It is important to highlight that the comparison between models' results must always be for the same operational period. To ensure a fair assessment for the case of comparing the results of both vehicle and pipeline models to determine the most cost-effective option, the operational period should be considered as the lifetime of the pipeline.

# 4. Conclusions & Next steps

This deliverable provides the foundations for the remaining work to be carried in WP3 concerning the hydrogen supply chain. It presents a comprehensive review of the literature regarding the current status and future expectations for the several sectors that compose the hydrogen supply chain (production, storage, and distribution). Such a review was then oriented to the port context thanks to a dedicated survey that was conducted together with port partners. These two steps allowed to clearly identify the main gaps and obstacles that are hindering the uptake of a green hydrogen supply chain. By identifying these, it was then possible to propose dedicated models that should support port authorities in their transition process. Having now these models well described, the following steps are:

- Coordinate their implementation to enable the definition of a comprehensive long-term vision of energy demands and availability. The construction of a scenario-based vision might be vital to serve as input for some of the tools being developed in WP4. Moreover, this vision will feed into the MAGPIE Master Plan, which ultimately will support ports in understanding how they should move towards the decarbonization of their operations
- Develop and test them during T3.6 while providing important outcomes for the WP9 Master Plan

# Annex A

## H2 Supply Chain Questionnaire

1. **Are these H2 consumers relevant in a port environment? Do they already exist in your port (present), just in a future scenario (future) or they are not a possibility (No)?**

| | | Relevant? (Yes/No) | Present/Future/No |
|---|---|---|---|
| **Transport** | Maritime | | |
| | Inland Shipping | | |
| | Road | | |
| **Industry** | Fuel refining | | |
| | Ammonia production | | |
| **NG Grid** | - | | |
| **Export** | Pipeline | | |
| | Inland Shipping (LH2) | | |
| | Maritime (LH2) | | |
| | Trucks | | |

2. **Please indicate other H2 demand sectors that should be considered. Indicate also if they already exist in your port (present), just in a future scenario (future) or if they are not a possibility (No)?**

| | | Present/Future/No |
|---|---|---|
| **Transport** | ***Type A*** | |
| | **....** | |
| **Industry** | ***Type A*** | |
| | **....** | |
| **NG Grid** | **-** | |
| **Export** | ***Type A*** | |
| | **....** | |
| ***Sector A*** | ***Type A*** | |
| | **....** | |

3. **If yes & present/future, what is the current/forecasted H2 yearly consumption? If you do not have exact numbers, you can also provide growth %'s or just some forecasts (see examples below).**

| | | Demand Present (H2 tons) | Demand 2030 (H2 tons) | Demand 2040 (H2 tons) | Demand 2050 (H2 tons) |
|---|---|---|---|---|---|
| **Transport** | Maritime | | | | |
| | Inland Shipping | | | | |
| | Road | e.g., H2 consumption in road transport is currently neglectable | e.g., H2 consumption in road transport is expected to reach x MWh/year in 2030 | | |
| | Type A | | | | |
| **Industry** | Fuel refining | | | | |
| | Ammonia production | e.g., ammonia production consumes x tons of H2 per year | | e.g., ammonia production is expected to increase by x% until 2040. H2 needs will increase proportionally | |
| | Type A | | | | |
| **NG Grid** | - | | | | |
| **Export** | Pipeline | | | | |
| | Maritime (LH2) | | | | |
| | Inland Shipping (LH2) | | | | |
| | Trucks | | | e.g., the decentralization of H2 needs will lead to an increase of x% on the transport of LH2 by truck | |
| ***Sector A*** | Type A | | | | |

4. **For each one of the identified sectors, what will be the triggers that will ramp-up the transition to <u>green H2</u>? Which characteristics (e.g., location, size, types of activities, current consumption of H2, etc) might make a specific port more suitable/capable than other to start this transition? What are those characteristics?**

| | | Comment |
|---|---|---|
| **Transport** | Maritime | e.g., (inland shipping) - location of a maritime port close to an inland route with similar plans for H2 implementation thus promoting the availability of several bunkering spots. |
| | Inland Shipping | |
| | Road | |
| | Type A | |
| **Industry** | Fuel refining | e.g., Ports who are well located near industries consuming significant amounts of H2 |
| | Ammonia production | |
| | Type A | |
| **NG Grid** | - | |
| ***Sector A*** | Type A | ... |

5. **What are the main advantages/disadvantages of each export option?**

| | | Comment |
|---|---|---|
| **Export** | Pipeline | |
| | Maritime (LH2) | |
| | Inland Shipping (LH2) | |
| | Trucks | |

6. **H2 supply and demand will increase in the upcoming years. Matching these two sides (i.e., supply and demand) will require some flexibility. Particularly on the demand side, this might be associated with time shifting operations (e.g., shift intense demand activities to night periods). Do you see this as a viable possibility? Please specify what kind of flexibility actions can occur for each sector.**

| | | Yes/No | How? |
|---|---|---|---|
| **Transport** | Maritime | | |
| | Inland Shipping | | |
| | Road | | |
| | Type A | | |
| **Industry** | Fuel refining | | |
| | Ammonia production | | |
| | Type A | | |

| | | | |
|---|---|---|---|
| **NG Grid** | - | | |
| ***Sector A*** | Type A | | |

7. Focusing now on the **transport sector**. Although several different types of modalities operate in a port ecosystem, they do not rely entirely on the port to supply their own demand e.g., a diesel truck not always fuel its tank in the port (gas stations are spread throughout Europe). Having this in mind, what % of vehicles fuel their tanks in the port ecosystem?

| | | **%** | **Comment** |
|---|---|---|---|
| **Transport** | Maritime | | |
| | Inland Shipping | | |
| | Road | | |
| | Type A | | |

8. **And if instead of diesel-powered vehicles, we are speaking of H2-powered vehicles (characterized by higher limitations in terms of travel distances)? Is the same situation expected? How do you see the role that ports will have in making accessible H2 bunkering infrastructures?**

| | | **Comment** |
|---|---|---|
| **Transport** | Maritime | |
| | Inland Shipping | e.g., yes, all barges will continue relying on the ports infrastructure. |
| | Road | e.g., No. On a first moment we foresee an increase in the number of trucks bunkering their H2 tanks in the port (comparing to the number of trucks that nowadays fuel their tanks w/ diesel). This will be related with an initial lack of H2 bunkering infrastructures outside the port area |
| | Type A | |

9. **The availability of H2 consumption time-series that characterize the operation of the aforementioned sectors is vital for the success of the MAGPIE project. Who owns this data? Please specify the entity and, if possible, a direct contact point.**

   **Note:** In cases where H2 is not yet a reality, we would look to the current consumption patterns (i.e., fossil-fuel based)

| | | Contact points |
|---|---|---|
| **Transport** | Maritime | e.g., vessels manufacturers, terminal operators |
| | Inland Shipping | e.g., Demo 7 green Energy container; barges operators |
| | Road | e.g., Demo 9; truck operators |
| | Type A | …. |
| **Industry** | Fuel refining | |
| | Ammonia production | e.g., ammonia production industries, gas grid operators |
| | Type A | …. |
| **NG Grid** | - | |
| **Export** | - | …. |
| ***Sector A*** | Type A | …. |

## H2 Supply

10. **Are these H2 supply options relevant in a port environment? Do they already exist in <u>your port</u> (present), just in a future scenario (future) or they are not a possibility (No)?**

| | | Relevant? (Yes/No) | Present/Future/No |
|---|---|---|---|
| **Local production** | Grey H2 Conventional Methods (SMR, methane pyrolysis, etc) | | |
| | Blue H2 Conventional Methods w/ CCS | | |
| | Green H2 Electrolysis | | |
| | Hydrogen as by product (e.g., Some processes produce H2 as a by product, such as: chlorine/caustic soda/sodium chlorate production, operation of steam crackers, | | |

| | | | |
|---|---|---|---|
| | blast furnaces and coke ovens) | | |
| **Imports** | Pipelines | | |
| | Maritime (LH2) | | |
| | Inland Shipping (LH2) | | |

11. **Please indicate other H2 supply options that should be considered. Indicate also if they already exist in your port (present), just in a future scenario (future) or if they are not a possibility (No)?**

| | | **Present/Future/No** |
|---|---|---|
| **Local production** | Type A | |
| | … | |
| **Imports** | Type A | |
| | … | |
| **Option A** | Type A | |
| | … | |

12. **If yes & present/future, what is the current/forecasted H2 yearly production? If you do not have exact numbers, you can also provide growth %'s or just some targets (based on your growth plans).**

| | | **Supply Present (tons)** | **Supply 2030 (tons)** | **Supply 2040 (tons)** | **Supply 2050 (tons)** |
|---|---|---|---|---|---|
| **Local production** | Grey H2 Conventional Methods (SMR, methane pyrolysis, etc) | | | e.g., reduce the H2 production using conventional methods by 60% | |
| | Blue H2 | | | e.g., production of blue H2 is expected to | |

| | | | | | |
|---|---|---|---|---|---|
| | Conventional Methods w/ CCS | | | represent x% of the total H2 local production by 2040 | |
| | Green H2 Electrolysis | | e.g., planning on adding x MW or producing x green H2 tons by 2030 | | |
| | Hydrogen as by product | | | | |
| | Type A | | | | |
| **Imports** | Pipelines | | | | |
| | Maritime (LH2) | | | | |
| | Inland Shipping (LH2) | | e.g., LH2 imported by inland shipping is expected to grow 20% | | |
| | Type A | | | | |
| **Option A** | Type A | | | | |

13. **What are the main advantages/disadvantages of each option (General Drivers)? What are the specific characteristics of a port (Port Drivers) that might favor one option over the others (e.g., type and volume of demand requirements, existing assets, well established liquid bulk maritime routes)?**

| | | **General Drivers** | **Port Drivers** |
|---|---|---|---|
| **Local production** | Grey H2 Conventional Methods (SMR, methane pyrolysis, etc | | |
| | Blue H2 Conventional Methods w/ CCS | e.g., Lower CAPEX, GHG produced are captured but the whole process is not emissions free | |
| | Green H2 Electrolysis | e.g., no GHG emissions; high CAPEX | e.g., High RES in or around the port |
| | Hydrogen as by product | | e.g., existence of industrial processes (indicate which) that produce H2 as a by-product |
| | Type A | | …. |
| **Imports** | Pipelines | | …. |

| | | | |
|---|---|---|---|
| | Maritime (LH2) | e.g., important to transport H2 across long distances | .... |
| | Inland Shipping (LH2) | | e.g., existence of well-established inland routes for the transport of other liquids |
| | Type A | | .... |
| **Option A** | Type A | | .... |

14. **Do you see H2 production assets as potential flexibility providers? Please specify what kind of flexibility actions can occur (e.g., production curtailment/increase, time shifting of production actions)?**

| | | **Yes/No** | **How?** |
|---|---|---|---|
| **Local production** | Grey H2 Conventional Methods (SMR, methane pyrolysis, etc) | | |
| | Blue H2 Conventional Methods w/ CCS | | |
| | Green H2 Electrolysis | | |
| | Hydrogen as by product | | |
| | Type A | | |
| **Option A** | Type A | | |

15. **The availability of H2 production time-series is vital for the success of the MAGPIE project. Who owns this data? Please specify the entity and, if possible, a direct contact point.**

| | | **Contact Point** |
|---|---|---|
| **Local production** | Grey H2 Conventional Methods (SMR, methane pyrolysis, etc) | |
| | Blue H2 | |

| | | |
|---|---|---|
| | Conventional Methods w/ CCS | |
| | Green H2 Electrolysis | |
| | Hydrogen as by product | |
| | Type A | |
| **Imports** | - | |
| **Option A** | Type A | |

## Storage & Distribution

16. **Regarding the distribution infrastructure, does your port have a distribution grid for NG? Do you intend to 1) retrofit it to transport 100% H2 or 2) use it while blending NG with H2? Please comment on the chosen option.**

| | **Has NG grid? (Yes/No)** | **100% H2 transport? (Yes/No)** | **Blending? (Yes/No)** | **Comment** |
|---|---|---|---|---|
| **NG distribution grid** | | | | |

17. **If yes, is the Port authority the owner of the grid? If not, who is?**

| | **Grid owner** |
|---|---|
| **NG distribution grid** | |

18. **Has the port authority information on gas grid topology, gas grid measurements, etc? If not, who has?**

19. **Even if your port is going to exploit the NG grid to transport H2, there are any plans to build dedicated H2 pipelines? If yes, please provide a brief explanation on what are these plans (or if they already exist).**

| | **Yes/No** | **Comment** |
|---|---|---|

| | | |
|---|---|---|
| **H2 distribution grid** | | |

20. **Are these storage options relevant in a port environment? Do they already exist in <u>your port</u> (present), just in a future scenario (future) or they are not a possibility (No)? Please indicate other storage technologies that should be considered**

| | **<u>Relevant? Yes/No</u>** | **<u>Present/Future/No</u>** |
|---|---|---|
| **Liquified H2** | | |
| **Compressed H2** | | |
| **Type A** | | |

21. **<u>If yes & present/future</u>, what is the current/forecasted H2 storage capacity? If you do not have exact numbers, you can also provide growth % or just some targets (based on your growth plans).**

| | **<u>Storage Capacity Present (tons)</u>** | **<u>Storage Capacity 2030 (tons)</u>** | **<u>Storage Capacity 2040 (tons)</u>** | **<u>Storage Capacity 2050 (tons)</u>** |
|---|---|---|---|---|
| **Liquified H2** | | | | |
| **Compressed H2** | | | | |
| **Type A** | | | | |

22. **What are the main advantages/disadvantages of each option (<u>General Drivers</u>)? What are the specific characteristics of a port that might favor one storage option over the other (Port Drivers)?**

| | **<u>General Drivers</u>** | **<u>Port Drivers</u>** |
|---|---|---|
| **Liquified H2** | e.g., makes sense if the objective is a long term storage to inject into the H2 grid when needed | |
| **Compressed H2** | | |
| **Type A** | | |