PRE-FEASIBILITY FOR A HYDROGEN EXPORT PROJECT

Final Report

Inter-American Development Bank

Report No.: 10302204-ESZA-R-03 **Rev.:** A
Date: 9 May 2022

SAFER, SMARTER, GREENER

Project name:	Prefeasibility for a hydrogen export project	GL Garrad Hassan Ibérica S.L.
Report title:	Final Report	Plaza Antonio Beltrán Martínez, 1
Customer:	Inter-American Development Bank	Planta 9 Off D,
	1300 New York Avenue, N.W.	50002, Zaragoza, Spain
	Washington, D.C. 20577, USA	+34 976 43 51 55
Customer contact:	Natacha Marzolf	
Date of issue:	9 May 2022	
Proposal Reference:	211125-ESZA-P-01-A	
Report No.:	10302204-ESZA-R-03-A	
Document No.:		

Applicable contract(s) governing the provision of this Report:

Objective:

Prepared by:	Verified by:	Approved by:
Graham Nott, Robert Mellema, Claudia Pilas, Patricio Morales, Malte Nussberger, Miguel Sierra	Albert van den Noort	Carlos Albero

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Keywords:
Hydrogen, export, Chile, ammonia, liquid organic hydrogen carriers

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	9 May 2022	First version	Various	A. van den Noort	C. Albero

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List of abbreviations

The following table lists some of the abbreviations used in this Report.

Abbreviation	Meaning
AACE	Association for the Advancement of Cost Engineering
ALARP	As Low As Reasonably Possible
ASTM	American Society for Testing and Materials
ASME	American Society of Mechanical Engineers
BOG	Boil Off Gas
DIA	Declaración de Impacto Ambiental
EIA	Evaluación de Impacto Ambiental
EPC	Engineering Procurement and Construction
ESIA	Environmental and Social Impact Assessment
FEED	Front End Engineering & Design (study)
GIS	Geographic Information System
HAZID	Hazard Identification (study)
HAZOP	Hazard and Operability (study)
IBA	Important Bird Area
IDB	Inter-American Development Bank
LCOH	Levelised Cost of Hydrogen
LNG	Liquefied Natural Gas
LNGC	Liquefied Natural Gas Carrier
LPG	Liquefied Petroleum Gas
MTPA	Million Ton Per Annum
NIST	National Institute of Standards and Technology
PRIBCA	Plan Regulador Intercomunal del Borde Costero de Antofagasta
QRA	Quantitative Risk Assessment
VLGC	Very Large Gas Carrier

1 INTRODUCTION

DNV was selected by the Inter-American Development Bank as part of process #CH-T1235-P001 to perform a *Prefeasibility study for a hydrogen export project* in Chile. The beneficiary of this study is the Ministry of Energy of Chile.

The study aims to produce key information and recommendations for public and private stakeholders, including government authorities, on the optimal technologies, infrastructure, timings, sizing, location, and business models that would altogether englobe a new export terminal for hydrogen via maritime transportation in Chile. The findings of this study will be key for policy makers, industry and academia stakeholders and will provide the basis to develop a market in Chile for future exports of clean energy carriers such as hydrogen. The Government of Chile will play a key role in promoting the development of export infrastructure that tends to the optimal economic efficiency of markets as a whole and that can enable the export of clean energy produced via hydrogen by a wide variety of industrial stakeholders

The project consists of 16 activities:

1. Import markets
2. International benchmark
3. Maritime hydrogen supply chains
4. Pathway for Chile
5. Infrastructure description
6. Infrastructure key design variables
7. Infrastructure sizing
8. Analysis of coastal sites
9. Conceptual layout
10. Capex and Opex estimate Class 5
11. Levelized cost of infrastructure
12. High-level implementation plan
13. Local jobs and services
14. LNG terminal business models
15. Hydrogen terminal business model
16. Recommended actions

Results of Activities 1 to 4 are included as an annex to this report (Report 1).

2 EXECUTIVE SUMMARY

At the start of the project Europe and Asia were identified as the most promising future hydrogen import markets due to their reliance on energy imports, commitment to decarbonisation and explicit hydrogen roadmaps, targets and policies. Ammonia, steel, oil refining, shipping, aviation, heavy duty road transport and high temperature heat industrial processes were identified as key potential end users of green hydrogen or hydrogen derived products.

Ammonia was concluded to be the most feasible maritime hydrogen carrier in the short to medium term, due to its hydrogen density, technical maturity, existing infrastructure and vessels, existing market and future prospects. Interviews conducted to a group of 20 international stakeholders, including port authorities, shipyards, ship owners, industrial gas companies and energy companies suggested that there is not a clear winner amongst alternative carriers and that in the long term liquid hydrogen could emerge as the preferred option if technical and economic barriers can be overcome, particularly liquefied hydrogen ships.

Economic analysis shows that green ammonia produced in Chile could be competitive with green ammonia produced in the import markets even in a conservative scenario of hydrogen production costs. Competitiveness with respect to other potential exporting regions such as the Middle East and Australia was found to be largely determined by hydrogen production costs. The contribution of transport costs and shipping distance is very small in comparison to production costs.

The recommended pathway for Chile in the short-medium term is to prioritise green ammonia production to substitute fossil ammonia imports and export green ammonia to international markets, which include a very large and growing demand for fertilisers and potentially an even greater demand as a shipping fuel, a fuel for power generation and possibly a carrier to be converted back to hydrogen at the import markets. In parallel other hydrogen carriers should be further explored, particularly liquefied hydrogen; this was reflected in the interviews and is the long term vision of the Chile National Green Hydrogen Strategy. In this report generic ammonia export terminal infrastructure and technologies are described including pipelines, road and rail receiving facilities, storage tanks and port facilities. Ammonia is a gas at ambient temperature and pressure. Generally by pipeline, road and rail it is transported as a pressurised liquefied gas. For safety and economic reasons large volumes of ammonia are stored and transported by ship as a refrigerated liquefied gas at -33.3 ºC and atmospheric pressure. Special care must be taken when handling ammonia due to its toxicity.

The key design variables defining an ammonia export terminal can be grouped into input, storage and output conditions (volumes, gas/liquid state and transport modes), site conditions (ground conditions, bathymetry, seismicity, etc) and design parameters (design capacity, margins, lifetime, etc).

The design capacity was selected as 1 million tonnes/year of ammonia, roughly equivalent to an input of 180,000 tonnes/year of hydrogen. This is aligned with the ambitions set in the Chile National Green Hydrogen Strategy, can accommodate growth in the next decade, is technically feasible, has an acceptable safety risk, minimises levelized cost of transport and environmental impact and is generally aligned with the ambition of the private sector. A multi-modal terminal is proposed capable of receiving ammonia from a synthesis facility across the fence and from distant plants by pipeline, road and rail, catering for the needs of multiple upstream producers.

The coastal locations of Tocopilla, Mejillones, Taltal and Magallanes were analysed in terms of land use, existing infrastructure, marine traffic, environmental, cultural and social parameters, renewable resources, forecasted LCOH, renewable power and green hydrogen project pipeline and availability of local labour and suppliers. All four locations were found to have good attributes to host green hydrogen export infrastructure. For this particular pre-feasibility study, due to existing ammonia demand and existing ammonia storage and maritime terminal infrastructure Mejillones was proposed to continue with the study.

A conceptual layout, capex and opex estimate and high-level implementation plan was prepared for a greenfield ammonia export terminal. However, it is emphasized that reutilization of the existing ammonia infrastructure in Mejillones should be explored in future studies, as it may enable export of green ammonia from Chile in a very short time frame with minimum cost and environmental impact, at least for the period while a new, larger export terminal is developed.

A conceptual layout was prepared that includes two 60,000 m3 atmospheric, refrigerated ammonia storage tanks, a jetty for loading of fully refrigerated Very Large Gas Carrier ships, administrative and control buildings, compressor house, electrical substations, pipeline, road and rail receiving facilities and other auxiliary equipment. The area required is estimated to be 50,000 m^2.

Capex was estimated to be 480 million USD to AACE Class 4 (+30%/-25%), divided as follows: terminal area 278 million USD, jetty topsides, substructure and interconnection piping 102 million USD, owner's costs 20 million USD and owner's contingency 80 million USD. Opex was estimated as 2% of initial capex – approximately 10 million USD/year – plus electrical power costs of approximately 1 M USD/year.

These costs were found to be aligned with the estimates at the start of the pre-feasibility study. As an example, the levelized cost of green ammonia delivered from Chile to Japan was estimated at approximately 390 USD/ton in an optimistic LCOH scenario and 600 USD/ton in a more conservative LCOH scenario. The levelized cost of green hydrogen delivered from Chile to Japan in 2030 using ammonia as the carrier was estimated at 3.3 USD/kg in an optimistic LCOH scenario and 4.8 USD/kg in a more conservative LCOH scenario. It must be highlighted that the cost of ammonia cracking is still highly uncertain due to the low technical and commercial maturity of the technology.

Construction of the ammonia export terminal was estimated to take approximately 3 years from the start of detailed design to commissioning. Permitting was estimated to require 1 year in an optimistic scenario and up to 5 years or more if there are legal disputes.

Site construction was estimated to require approximately 450 people full time during 2 years with a peak of 725 people. Permanent jobs were estimated as 65 people with an additional 42 people as external services (security, cleaning, catering, mechanical, electrical and instrumentation)

Three commercial structures are addressed for setting up a hydrogen/ammonia export terminal: integrated, merchant and tolling. These are largely drawn from similarities with LNG trade. The LNG market commenced with a fully integrated setup and it gradually moved into a more merchant based market dynamic.

The role of the Government is crucial, articulating a close collaboration between different stakeholders such as end-users, producers and the regulators. Given the already existing Chile National Green Hydrogen Strategy, alignment with its key principles is desirable. Its main pillars are: 1) mission-oriented policy, 2) a balanced use of resources and land, 3) advancing towards a new economy based on clean exports, 4) building an efficient pathway towards a net-zero country, 5) harnessing green hydrogen as a catalyst for local growth and 6) openness to the world.

A future value chain and its commercial structure should promote market development, promote market competition, be investable, provide value for money, reduce support overtime, be suitable for future pipelines and infrastructure developments, be compatible with other support policies, technology agnostic, size agnostic, avoid unnecessary complexity, minimize environmental impact and promote sustainable development of local communities. Each commercial structure was scored against the aforementioned characteristics. Of these commercial structures, the tolling commercial structure is scored and selected as the most attractive for the bay of Mejillones. The most important elements to consider in a tolling structure are a tolling agreement, regulation of tariffs, export terminal license/permit, port use agreement, ownership structure, financing structure, ammonia sales purchase agreements and regulation and policy. Also, the tolling structure setup is discussed with special detail to the financing structure (e.g. special purpose vehicle).

Upstream production alignment is essential, for which four market designs are proposed and more public involvement will likely bring significant benefits. In order to establish value chain alignment, three instruments are essential: a national hydrogen and ammonia plan, open seasons for infrastructure development and tenders for renewable energy production in combination with green hydrogen and green ammonia production.

The project conclusions are summarized as follows:

- In the short-term ammonia export for use as ammonia is the most promising option that should be investigated further.
- Under the considered framework, Mejillones was deemed the most pertinent location to conduct this prefeasibility study for the export of green ammonia.
- DNV's first estimate is the ammonia export terminal will cost $480 million to build over a timescale of 39 months (permitting processes not included).
- A multi-modal terminal with a tolling business model is best suited to promoting market competition and development, while remaining technology neutral and agnostic on production project size and location for the export terminal.
- Reutilization of existing ammonia infrastructure at Mejillones could shorten the timeframe, cost and environmental impact of green ammonia export from Chile, at least in the initial stages of the industry while production capacity increases.

3 ACTIVITY 5 – ASSET AND INFRASTRUCTURE DESCRIPTION

Establishment of ammonia production and export facilities involves the design and construction of a wide variety of assets, within the scope of this study ranging from the ammonia production plant till the jetty for harboring the ammonia carriers. In this chapter a description of the required assets and infrastructure is provided. It must be noted that power production and transmission, and hydrogen production and storage are excluded from the scope of this study.

Starting with ammonia production, along the ammonia supply chain the following main elements may be identified:

1. Ammonia production plant (i.e. Haber Bosch process);
2. Ammonia storage (both on-site and in-port);
3. Ship loading facilities;
4. Truck and train loading facilities.

Although alternative ammonia production processes are currently being developed (e.g. Haldor Topsoe) the Haber-Bosch process is most commonly used in ammonia production today. We therefore will base our further analyses on this proven technology.

Before going into the details of the required infrastructure for transporting, handling, storing and exporting ammonia, it is important to establish some key assumptions and starting points. There are several options for transporting ammonia from its production facility to the envisaged export terminal, and each option will require a specific set of assets.

Key elements in the design of the ammonia value chain are the envisaged ammonia production rate and the way the produced ammonia is delivered into the market. In this study it is assumed that ammonia production eventually will arrive at roughly **1 million tons per year** and considering this large volume it is further assumed that the bulk of the produced ammonia will be exported by ship.

Since the bulk of the ammonia is expected to be exported by ship, the most obvious way to transport the ammonia from the production plant into the port is by pipeline. Nonetheless other import modalities will be possible as well like trucks or trains (basically for importing ammonia from inland production sites). Depending on the distances involved, it may be possible to load trucks and rail cars directly at the production site, or to establish an 'ammonia hub' in port having large storage tanks available already and avoiding other storage tanks to be in place at the production plant (especially for the loading of trains).

Another key observation is that currently ammonia is being imported in Chile by ship as a feedstock for the ammonia nitrate industry. For this purpose some ammonia import facilities are existing today which might provide an option for combining import and export functions at one location in future. This will also depend on the location of choice for establishing the ammonia production facilities, as will be discussed further into this report, but for now the description of the required assets and infrastructure in this chapter does not consider possible pre-existing structures.

In the figure below five possible scenarios are presented in which ammonia is handled along the transport route in different manners, especially depending on the location where hydrogen and ammonia are produced.

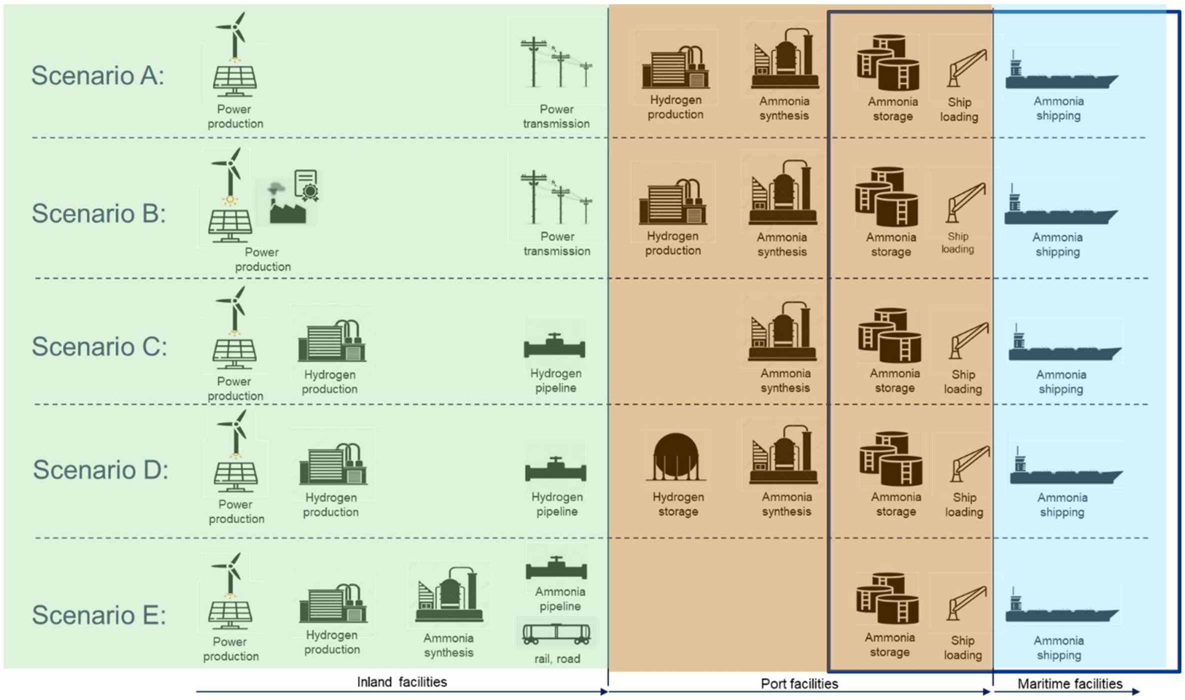

Figure 1. Five possible green hydrogen and ammonia production and transportation routes

Scenario A represents the situation where both hydrogen and ammonia are produced close to the shore and near the ammonia export terminal. Since no hydrogen storage is applied, both hydrogen and ammonia production rates depend on the available wind and/or solar energy. Notably, no fossil fuels are used to overcome periods with limited green power availability.

Scenario B is the same as Scenario A, but in times of failing wind and solar energy supply, power from the grid can be used to keep hydrogen and ammonia production at a steady level. In this scenario administrative arrangements need to be in place to compensate for the use of fossil fuels in the production of the additional power taken from the grid, e.g. by using green power certificates.

Scenario C, wind and solar farms are located in the hinterlands and hydrogen is produced locally, in close vicinity of the power production sites. Hydrogen is then transported by pipeline to the shore. Like in scenario A, hydrogen availability to the ammonia plant varies with wind or solar power production, and so does ammonia production. This option will require a high degree of ammonia production flexibility since the ammonia plant has to be ramped up and down continuously depending on actual hydrogen availability.

Scenario D is basically identical to Scenario C, but now intermediate hydrogen storage used. This implies that ammonia production can run continuously and plant size can be minimized. Hydrogen can be stored inland or at the port, depending on availability of suitable sites such as salt caverns, aquifers or depleted gas fields.

Scenario E is different to the others that ammonia is produced inland, close the renewable power production. Ammonia is then transported as pressurized liquified gas to the ammonia export terminal at the shore. Ammonia would be most economically and safely be transported by pipeline, but transport by rail car and road tanker is also possible. This multi-modal scenario is particularly interesting to cater for multiple ammonia producers as the industry develops.

Other scenarios are possible where energy to produce hydrogen is stored in some other form, such as pumped hydro or molten salt storage.

Hydrogen storage (Scenario D) is relatively hard to do in considerable volumes. Hydrogen can either be stored in depleted gas fields or underground salt caverns, or in pressurized tanks. We understand that no depleted gas fields or salt caverns are available, so the remaining option would be to use pressure vessels. Hydrogen may be stored at moderate pressures of 200-250 barg or at a high pressure of 700 barg using state of the art tanks made of composite materials. Either way, the storage capacity of individual tanks is limited to 0.2 m^3 or less due to physical restraints, so a large number of pressure vessels would have to be used for arriving at the required storage capacity. The storage capacity should suffice to overcome several days without hydrogen production in absence of solar and/or wind power. Such storage facility would have a large footprint and would be expensive.

There is a choice to be made between the (long haul) transmission of electrons versus transport of molecules (hydrogen or ammonia). Apart from differences in costs between pipeline and cable transmission, in case of ammonia another aspect is involved which is further discussed in section 3.1.1, Transport of ammonia over long distances is to be done in a pressurized state for physical reasons, but since ammonia is produced and stored in a cryogenic state, two phase shifts could be involved, introducing a significant loss of energy.

In scenario B grey power from the power grid may be used as a back-up in case of insufficient solar and/or wind power being available. This way, the hydrogen and ammonia production could be kept at a specific minimum rate. Such arrangement however would involve the use of grey power which does not comply with the intention of establishing fully green ammonia production.

In practice the actual development is a complex problem that will depend on the specific coastal location, existing power transmission, gas pipelines, gas storage possibilities, road, rail and port infrastructures, environmental constraints and feasible options for project developers. In this sense, this pre-feasibility study focuses on the ammonia reception, storage and ship loading facilities, referred to as the “ammonia export terminal”, receiving ammonia from a synthesis facility “across the fence” and from remote synthesis facilities by pipeline, road and rail, as will be detailed in subsequent chapters.

For a good appreciation of the required infrastructure, we have broken down the ammonia supply chain in its basic elements, being:

1. Power grid connection;
2. Electrolyzer plant;
3. Liquid or Gaseous Hydrogen Storage
4. Interconnecting hydrogen pipeline;
5. Air Separation Unit
6. Haber Bosch Ammonia plant
7. Ammonia pipeline;
8. Ammonia storage tanks;
9. Ammonia shore-to-ship transfer facilities;
10. Port facilities.

As requested by the Ministry of Energy and the IDB, this study has mainly focused on the required ammonia handling facilities upon the ammonia exiting the ammonia plant (points 7 to 10). These supply chain elements and the infrastructure to be involved will be discussed below.

3.1 Ammonia pipeline

3.1.1 Transmission conditions

Based on the typical Haber Bosch ammonia production process (Figure 2), typical outlet conditions are a pressure of some 25-30 barg and temperature of near 0°C temperature. These outlet conditions are determined by the final ammonia separation step (22).

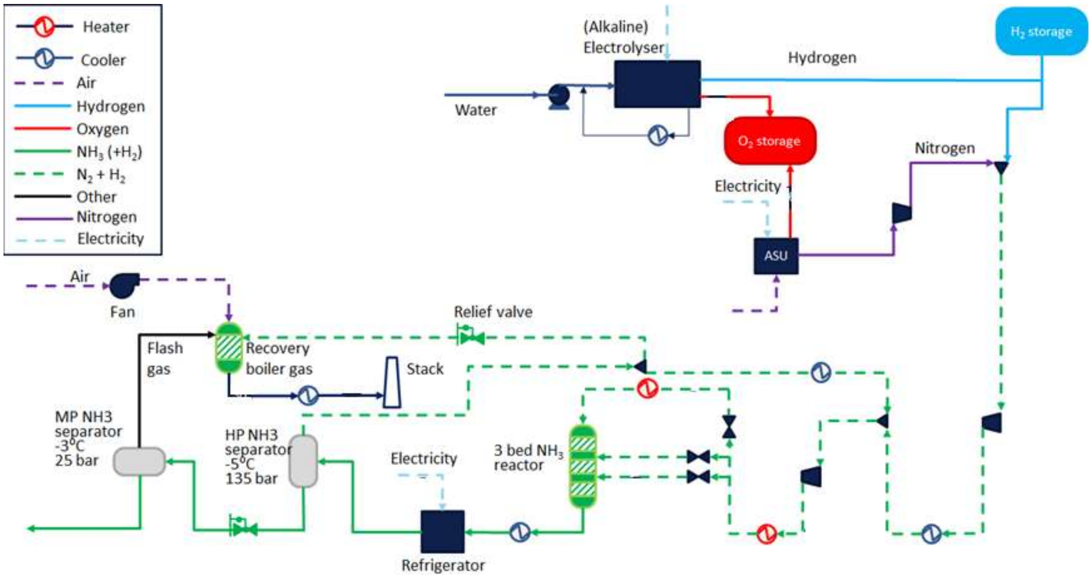

Figure 2. Schematics of the Haber-Bosch ammonia synthesis process.

Under such outlet conditions, ammonia is in the liquid phase, implying that it behaves like a fluid, provided the aforementioned pressure and temperature are maintained. In the below table, the ammonia boiling points as a function of pressure and temperature are shown.

Ammonia boiling point	
Pressure bar	Temperature °C
1.01325	-33.3
2	-18.8
3	-9.2
4	-1.9
5	4.1
10	24.9
15	38.7
20	49.4
25	58.2
30	65.7
35	72.4
40	78.4
45	83.9
50	88.9

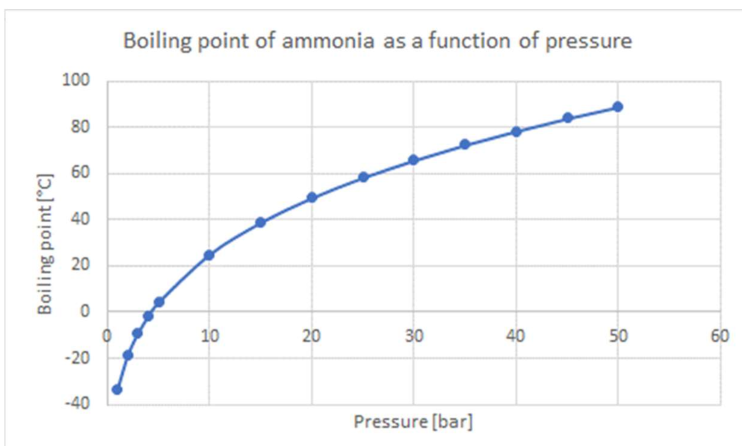

Figure 3. Ammonia boiling point at various pressures (Source: NIST Chemistry Webbook)

Evaporation inside the pipeline is to be avoided, so once in a liquid state it should be kept that way until the ammonia has reached its destination, i.e. the export terminal's storage tanks. A two-phase flow is unfavorable since it will reduce the pipeline transmission capacity and may cause cavitation damage on the inner pipe wall as a result of imploding vapor bubbles due to swirl. Pumps especially are affected by this phenomena The higher the pressure, the less cavitation will occur. Two phase flows also cause difficulties in flow measurement which will hamper process control and custody transfer metering.

The only way to avoid a multiple phase flow is ensuring that the pressure inside the pipeline never drops to a too low value, depending on local ambient temperatures and whether sunlight can cause the heating up of the pipe (in case of an overground pipeline). Assuming that the ambient temperature will not exceed 50°C, a pressure of at least 20 bar (21 barg) is to be maintained inside the pipeline (Figure 3).

For short lengths of pipe, pressure will not have dropped too much upon arrival at the ammonia storage facility, but in case of longer pipelines (tens to hundreds of kilometers), intermediate booster pumps may be required for keeping the pressure at the desired value and maintaining a high enough flowrate. Necessity of such would largely depend on actual flow rates and velocities, pipeline dimensions and applied materials.

Transport of ammonia by pipeline is done in a liquid state for limiting the pipeline diameter, and for the reason that ammonia is to be stored in storage tanks in a liquid state as well (see section 3.2). Transport of ammonia by ship, truck or rail car is done in a liquid state too for efficiency reasons. In some cases the ammonia is refrigerated during transport, but also pressure vessels are being applied or a combination of both (refrigerated tanks at kept at an elevated pressure).

3.1.2 Pipeline materials

Pipelines for transmitting ammonia are in use for decades already. Commissioned in 1981, the world's longest ammonia pipeline at 2,417kms and operated by Ukhrimtransammiak has averaged around 1.5m tonnes/year over the past 38 years, with nitrogen fertilizer from TogliattiAzot comprising about 75% of the 60 million tonnes transported until now. The pipeline runs between the Samara Oblast in the Russian Federation and the Ukrainian port of Yuzhny near Odessa.

Figure 4. An ammonia pipeline river crossing (Source: Ukhrimtransammiak)

From the above it may be clear that transporting ammonia by pipeline over longer distances is a common practice already. Given the corrosive nature of ammonia, only steel or ductile iron should be used for ammonia systems because ammonia will react rapidly with copper, brass, zinc and many alloys. In case of a pressurized pipeline with modest operating temperatures (above 0°C), common steel according to ASTM A106 grade B or API5L[1] can be used. In case of lower temperatures, below -29°C, ASTM A333 grade steel is to be applied by industrial standards and DNV expertise. The latter is especially relevant for cryogenic (liquefied, sub-cooled at atmospheric pressure) ammonia. The above does not only apply to the pipeline material itself, but also to flanges, connectors, online instrumentation and other appendages being used.

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[1] American Petroleum Institute, Pipelines for transmission of petroleum and natural gas.

Design and construction of ammonia pipelines is done according to ASME B31.3 (long distance) or B31.4 (plant based), and/or ISO 13623 (Category E fluid). The ammonia is required to contain some water with a maximum of 0.2% for inhibiting corrosion of carbon steel.

3.1.3 Pipeline dimensions

In the below table the specific gravity of ammonia under various conditions is presented.

Table 1. Specific gravity of ammonia under various conditions (NIST Chemistry Webbook)

Ammonia specific gravity [kg/m3]				
Pressure [barg]	Temperature [°C]			
	-33.3	0	20	50
1.01325	0.889 / 682	0.771	0.716	0.647
10	679	639	610	6.898
20	680	639	611	15.449
30	681	640	612	564
40	681	641	613	566

When considering an annual ammonia production of 1 million tons (average of 3014 tons/day) this would result in a nominal flow rate of 34.9 kg/s. When factoring in the intermittent ammonia production as a result of fluctuating hydrogen availability, for now it is assumed that the maximum flow rate may be five times that of the nominal flow, leading to a maximum mass flow rate of 174.5 kg/s.

At a pressure of 30 barg, and a (maximum) temperature of 50°C, the specific gravity is 564 kg/m3 (Table 3-1), and therefore the maximum volume flow of the ammonia would be 174.5 / 564 = 0.31 m3/s (1114 m^3/h).

Table 2. Typical gas and fluid velocities in pipeline systems (Source: Engineering Toolbox)

Fluid	Typical velocity	
	[ft/min]	[m/s]
Acetylene, steel pipe	4000	20
Air, 0-30 psi, steel pipe	4000	20
Ammonia liquid, steel pipe	360	1.8
Benzene, steel pipe	360	1.8
Ethylene, gas, steel pipe	6000	30
Hydrogen, gas, steel pipe	4000	20
Natural gas, steel pipe	6000	30
Water, steel pipe	180-480	0.9-2.4

Considering a fluid velocity of 1.8 m/s of liquid ammonia through a steel pipeline, it can be found that the minimum required pipeline diameter is some 0.55 m (550 mm or a 24” pipe). In the detail engineering process -at the FEED- the diameter should be calculated more precisely, also factoring in the required oversizing allowing for the actual intermittent hydrogen and ammonia production, pipe wall roughness, the allowable pressure loss and acoustic properties of the liquid, but the calculated 24” provides a first educated guess on pipeline dimensions.

The required pipe wall thickness is to be determined in the detailed engineering phase as well.

3.1.4 Pumping stations

Recompression of the ammonia during transport could be required. For this purpose, booster pumps are to be installed in pumping stations at regular distances (multiple pumps in parallel per station for improving operational ranges and for redundancy),

Given the corrosive and toxic nature of ammonia, loss of containment should be prevented at all times. Conventional, mechanically driven pumps tend to leak (small) amounts of liquid or vapor through seals which are not fully tight. For preventing ammonia from escaping the pump, so called ‘mag drives’ may be used (‘magnetic drives’). Such pumps have no mechanical connection between the pump's impeller and the motor, but instead the impeller is driven by means of a strong, rotating magnet on the opposite side of a membrane.

Figure 5. Picture of a mag-pump

Given the relatively low density of liquid ammonia, the total required power for boosting the pressure will be roughly 300 kWe per set of parallel pumps given the abovementioned flow rate of 1114 m^3/h and a maximum allowable pressure drop of 10 bar between pumping stations. This maximum allowable pressure drop depends on the discharge pressure provided by each of the pumping stations in connection with the minimum allowable pressure inside the pipeline for preventing evaporation (21 barg at 50°C as discussed in 3.1.1). In the light of the above assumption on allowable pressure drop, it must be noted that the ammonia pressure upon exiting the ammonia production plant must be at least 31 barg for keeping the ammonia in a liquid state till the next pumping station is reached. Pressure drop rate per kilometer of pipeline depends on the pipeline diameter, fluid velocity, the inner wall roughness and the dynamic viscosity (temperature and pressure) of the ammonia and should be established in the detail design phase using basic hydrodynamic principles. The pressure discharge pressure from each pumping station and the number of stations are to be determined based on a techno-economic evaluation.

3.1.5 Safety aspects

Pipelines represent a certain safety risk. Buried pipelines can easily be overseen in groundworks involving digging and dredging, and overground pipelines are exposed to external mechanical and chemical influences as well. Even the danger of sabotage cannot be ignored nowadays.

In case of a ruptured ammonia pipeline, and even in case of small leaks, there is a high risk of causing harm to the people and the environment in a close or not so close distance from the incident. Ammonia is very toxic and has a MAC (Maximum Allowable Concentration) of only 20 Parts Per Million (Sigma Aldrich Corporation) which implies that light work can be done in enclosed rooms with a concentration of 20 ppmV for a maximum duration of 8 hours.

Some physical and chemical properties of ammonia[2]:

[2] https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia

- Molecular Weight: 17.031
- Boiling point: -33.34 °C
- Melting point: -77.73 °C
- vapor pressure at 20°C: 8.56 bar
- Relative vapor density (air = 1): 0.6
- Solubility in water (at 20°C): 53 g/100 ml
- Flash point: not determined
- Explosion limits (at 20°C and 1.013 bar): 15-30 vol. % in air, 13.5-82 vol. % in oxygen
- Auto-ignition temperature: 630°C
- Minimum ignition energy: 100-1000 mJ
- Decomposition temperature: 450°C; in the presence of iron, nickel, zinc, uranium and osmium this decomposition can occur from 300°C

Some further safety considerations:

- Ammonia is a combustible gas (zoning, hot work permit system required)
- The dissolution of ammonia in water is accompanied by a large development of heat. Do not spray water on a puddle of liquid ammonia.
- Ammonia vapor is quickly absorbed in water (1 volume unit of water absorbs approximately 200 volume units of ammonia vapor). A water curtain is therefore used for the capture of ammonia vapors. But one has to watch out for water intrusion. in the vapor phase in tanks, this can create a vacuum with the tank imploding as a consequence.
- A leak of 1 liter of liquid NH3 produces 125 liters of gaseous ammonia.
- The relative density of the ammonia cloud depends on the temperature and the concentration. Ammonia can therefore also behave heavier than air.

3.1.5.1 Incident report no. 1: Potchefstroom (South Africa) in 1973

The release of approx. 38 tons liquid ammonia due to a sudden rupture of a fixed, horizontal ammonia tank killed 18 and injured 65 people at Potchefstroom (South Africa) in 1973. Welding had been done on the tank prior to the accident, but the vessel was not stress relieved after the work was completed (and not during initial fabrication either). The situation escalated further as a result of the chilling effect of the escaping ammonia due to pressure relieve, causing embrittlement of the tank material. Ammonia was released under very unfavorable conditions, namely stable weather and low wind speed. The ammonia was spread in a heavy cloud and drifted to a residential area located only 200 m from the storage tank.

3.1.5.2 Incident report no. 2: Kingman, Kansas (USA) in 2004


Figure 6. A picture of the Kingman incident

In October 2004 near Kingman, Kansas (USA), an ammonia pipeline ruptured after being damaged. The National Transportation Safety Board determined that the probable cause of the pipeline rupture was a pipe gouge created by heavy equipment damage to the pipeline during construction in 1973 or subsequent excavation activity at an unknown time that initiated metal fatigue cracking. Approximately 4,858 barrels (204,000 gallons) of anhydrous ammonia were released into the atmosphere. Nobody was killed or injured due to the release, but the ammonia leaked into a creek and killed more than 25,000 fish including some from threatened species.

Notably, the visible cloud in the picture is not ammonia itself, but water vapor from the surrounding air being condensed due to the low temperature of the escaping gas.

3.1.5.3 Incident report no. 3: Railway accident, Minot, North Dakota (USA) in 2002

Another accident happened near Minot, North Dakota in 2002. During a railway accident 31 railroad tank cars derailed, 15 of them carrying anhydrous ammonia. Five of the fifteen tank cars catastrophically failed (ruptured) and were propelled over distances up to 1200 ft (366 meter). The rupture led to the instantaneous release of 146,000 gallons (about 370 tons) of anhydrous ammonia. Over several days a total of almost 221,000 gallons (about 560 tons) of ammonia were released. One resident was killed from exposure to the gas. Over 300 people were injured, and the vapor plume covered an area that affected about 11,600 residents with related irritation to the eyes and lungs.

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Figure 7. Ammonia tank cars derailed near Minot, and a ruptured tank car at some distance from the scene

It is of great importance to avoid any leakage of anhydrous ammonia. Pipeline design and construction are to be done adequately and much attention should be paid to leak prevention, detection, containment and repair. Accidents cannot always be avoided. Safety measures during design, construction and operations should be aimed at minimizing the risks of accidents happening in the first place, but also at mitigating any adverse effects to life, property and the environment. In an early stage of the design phase (pre-FEED), a Quantitative Risk Analysis (QRA) is to be done to determine the safety distances (e.g. to nearby communities) to be applied once the pipeline or other transport modalities are in operation. Also a HAZID study (Hazard Identification) is to be done to inventory possible dangers connected to the operations, and to develop ideas on possible mitigating measures. Shortly prior to the detailed engineering phase, a HAZOP (Hazard and Operability Study) study which in detail focuses on specific parts of the production and transport chain is advised as well.

3.2 Ammonia storage tanks

Tank type selection criteria

Ammonia storage, either at the ammonia production plant and/or in the export terminal will be required for managing the irregular ammonia production and shipping schemes. Ammonia will be produced intermittently, and the ammonia carriers will only be loaded once in a while, making it necessary to keep a certain volume of ammonia in stock.

In further sections the required capacities of the applied tanks will be established. For now, only the various tank types that could be considered will be discussed. An important factor when selecting the most appropriate tank type is the state in which the ammonia is to be stored.

Ammonia can be kept in tanks at either:

1. Low pressure (<10 barg) at ambient temperature in a gaseous state;
2. Low pressure (<10 barg) in a refrigerated tank in a liquid state;
3. High pressure at ambient temperature (30 barg at a maximum of 50°C) in a liquid state;
4. Low pressure at low temperatures (atmospheric at -33.3°C) in a liquid state.

It may be expected that rather large volumes of ammonia need to be handled annually, with carriers taking in their loads in wide time intervals (weeks rather than days). The first option would require at least 100 times the tank volumes that are needed in case of liquid storage (options 3 and 4 so storage in a gaseous state cannot be done in a practical and economical viable way.

For instance: The density of ammonia under atmospheric pressure at 20°C is 0.716 kg/m^3 (Table 3-1). So, a 1 m^3 tank can hold 0.716 kg of ammonia. When applying a 1 m^3 tank at 30 barg and 20°C, the density of the liquid ammonia is 612 kg/m^3. So instead of 0.716 kg, the pressurized tank can hold 612 kg, 855 times more.

The low pressure refrigerated tank would provide a possibility in case of short lasting storage (e.g. on board a Liquid Gas Carrier), but for semi-permanent storage much energy would be required to keep the ammonia from vaporizing and associated pressure build up inside the tank at higher ambient temperatures.

The choice then remains between the high pressure hot, and the atmospheric cold tank fill. Pressure resistant storage tanks are relatively expensive and due to mechanical strength limitations of the materials available in tank construction, tanks can be of limited volumes each. Instead of one or two larger tanks, when applying pressurized tanks, the number of tanks would be significantly larger than in case of the atmospheric cryogenic state.

Another consideration is that large ammonia carriers are not equipped with pressurized tanks either for the same reasons as raised for land-based tanks. Loading capacities would simply end up being too small to allow for economic shipping. Since ammonia is to be shipped in a cryogenic state anyway, it would make most sense to store the ammonia in the onshore tanks in the same way. This is the reason why large ammonia storage tanks at ammonia import and export terminals are of the cryogenic type.

3.2.2 Pipe-to-tank transfer

As discussed in the previous chapter, ammonia will arrive in a liquid state at around 25 barg at the tank farm in the export terminal. It is still at an ambient temperature, but before being introduced into the storage tank, it must be brought into a cryogenic state. This would imply that the pressure is to be reduced to the atmospheric pressure and simultaneously, the temperature is to be lowered to -33.3°C. Since no change of phase is occurring in the process, the cooling down of the ammonia has to be done by means of compression, cooling and expansion whilst pressure release may be done using an expansion valve system. The proposed methodology is depicted below.

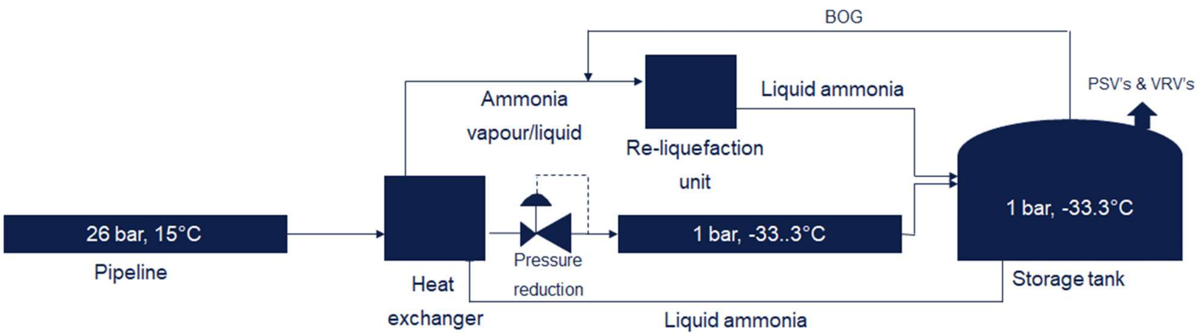

Figure 8. Proposed ammonia conditioning process

In Figure 8, ammonia arriving by pipeline at 25 barg (26 bar) and 15°C is fed through a heat exchanger where liquid ammonia from the tank is introduced from the opposite side. The temperature of the pipeline ammonia will be lowered to -33.3°C. Part of the cryogenic ammonia supplied from the storage tank will evaporate due to the heat exchange, but the liquid / vapor mixture is sent to the tank's boil-off handling unit where it will be cooled down to -33.3°C again and returned into the tank. Meanwhile the pressure of the pipeline ammonia is reduced to atmospheric, so it can be introduced into the storage tank having the same state as the ammonia already kept inside.

Like any cryogenic fluid, liquid ammonia tends to heat up due to imperfect thermal insulation of the tank, causing a small part of the fluid to reach a temperature of over -33.3°C and causing it to evaporate. The ammonia vapor migrates to the top of tank where it is being removed in order to keep the tank pressure at a low enough level. This vapor or Boil Off Gas is then introduced into the aforementioned re-liquefaction unit (along with the liquid/vapor mixture returning from the heat exchanger) and through a compression / expansion / cooling process returned into a fully liquid state at -33.3°C again. For enabling the pipeline ammonia to be cooled down sufficiently, the capacity of the re-liquefaction unit should be (significantly) larger that in case of the unit being used for handling BOG only. Additional energy consumption will be a consequence as well.

3.2.3 Tank types

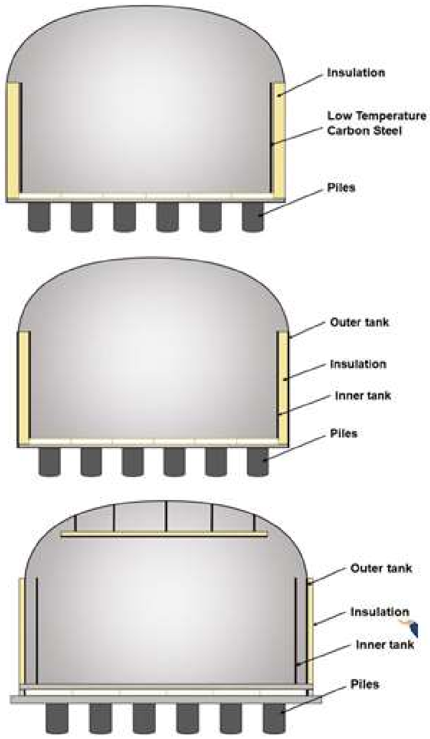

Figure 9. Tank types

A wide variety of cryogenic ammonia tanks exists. Most applied are the so called flat bottomed tanks which, in case of ammonia, can have a storage capacity of up to 75,000 m^3. The range of flat bottom tanks can be further broken down into types representing various containment properties, some of which are:

- Single wall tanks;
- Double wall (double containment) tanks;
- Full containment tanks.

In ascending order, the tanks offer improved specifications regarding robustness and loss of containment in case of incidents. The two former tank types need to be placed in a tank pit, or are to be surrounded by a dyke, whilst the full containment tank can rely on its sturdy design and construction making use of several barriers for escaping ammonia.

Flat bottom tanks are placed on piles, not only for distributing the load of the tank more evenly, but also for thermal insulation purposes preventing the soil beneath the tank becoming a permafrost area.

Making a selection out of these tank types is a trade-off between specific required properties, local conditions and safety requirements, the cost of tanks and additional safety measures to consider.

Figure 10. Two 50,000 MT ammonia tank and the tank foundation piles during construction in Qatar (Source: McDermott)

Besides flat bottom tanks, also spherical tanks are being used, especially in areas with increased seismic activity. Chile is especially infamous for its tremors and earthquakes. The Atacama Fault Zone (AFZ) is an extensive system of faults cutting across the Chilean Coastal Cordillera in Northern Chile between the Andean Mountain range and the Pacific Ocean. The fault system is North-South striking and runs for more than 1100 km North and up to 50 km in width through the Andean forearc region. Considering this, tank types and tank design should be carefully selected in the detail engineering phase.

Figure 11. Spherical tanks

Being able to withstand higher pressures, spherical tanks can hold liquid ammonia at relatively high temperatures and are frequently used in areas with increased seismic activity.

3.3 Port facilities

For reloading the ammonia from the onshore storage tanks into ammonia carriers, specific port facilities will be required, like:

- Docking facilities;
- Shore-to-ship pipeline and pumping systems;
- Cryogenic system from the onshore ammonia tanks to the offshore ammonia loading facilities in the jetty
- Port service providers;
- Road and railroad connections

In the below sections, these specific requirements will be further discussed.

3.3.1 Docking facilities

In many ports, the available shore length for docking vessels is rather limited and as a result quite expensive. For this and other reasons, the capacity of the docking facilities is frequently enlarged by the application of jetties stretching into the water for hundreds of meters and allowing multiple vessels to be docked simultaneously, occupying only a relatively small part of the available shore side and not necessarily requiring quays to be in place.

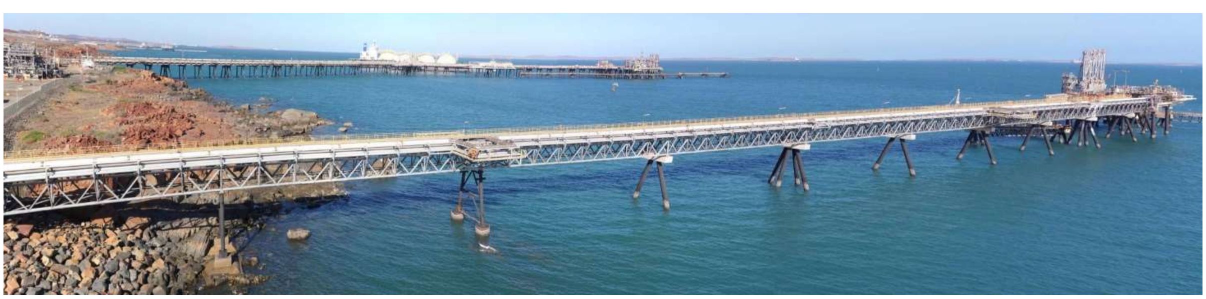

Figure 12. LPG and LNG export jetties at the Karratha Gas Plant in Mermaid Sound, near Dampier, WA

Jetties are connected to the shore by means of a pipe bridge, which may also hold power lines and pipelines for the ship's fuel supply. Another aspect related to the use of jetties, and especially where ammonia is concerned, is the fact that a jetty provides a certain safety distance between the carrier and the shore. In case of accidents happening on either side of the jetty like a fire or explosion, the other side will be relatively safe for adverse effects.

Figure 13. Two carriers docked alongside one pier

In the selection of the location for the export terminal the options for establishing jetties or other means for docking vessels is a very important factor. Vessels, and especially the smaller ones should be protected against high winds and swell; jetties are mainly constructed in sheltered areas. Water depth at the proposed location should be determined with a full bathymetric assessment including bathymetric maps, and this data should be sufficient to allow vessels to manoeuvre into place without running ashore.

A relatively new development allowing carriers to be kept away from the shore side is the application of so called Single Mooring Point (SMP) mooring systems. The mooring system, consisting of a floating buoy containing connectors for the carrier to be hooked on to, is connected to the shore by a (partial) flexible pipeline. The undersea pipeline allows for both loading and unloading of carriers.

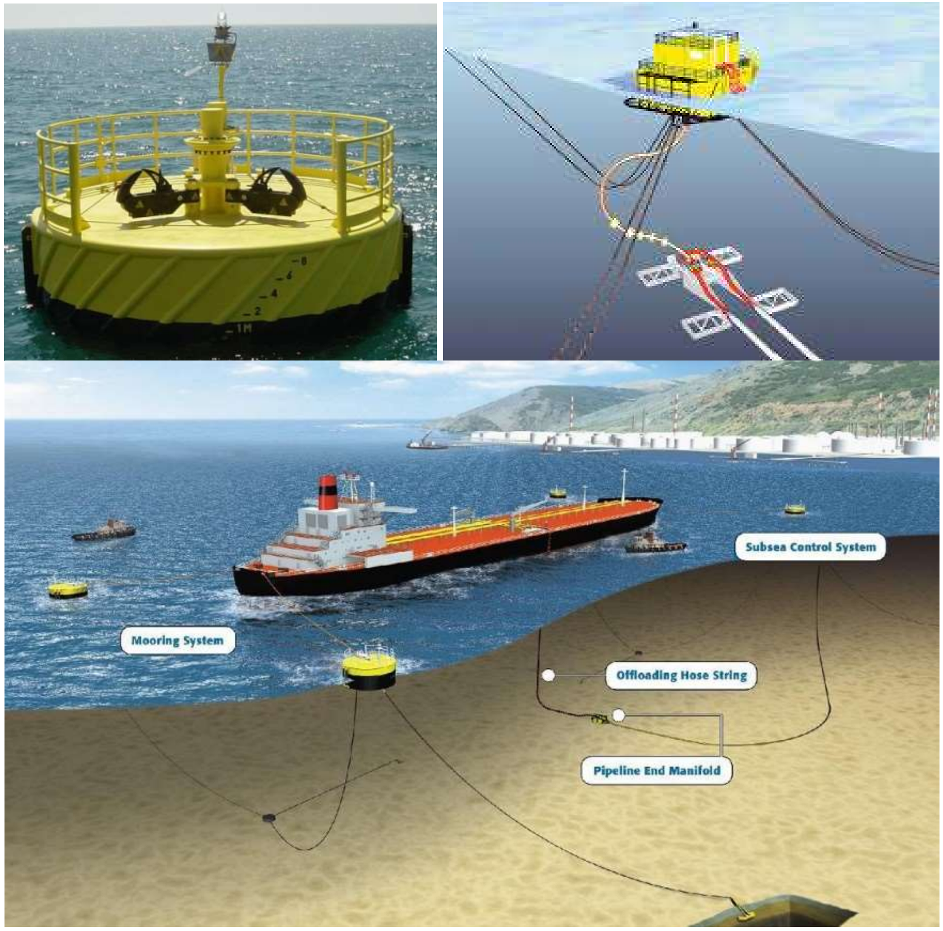

Figure 14. Concept of an SMP (Source: Bluewater)

The most appropriate docking methodology is to be determined based on port location and conditions, available docking space and environmental considerations.

3.3.2 Shore-to-Ship pipeline and pumping systems

Although the jetties carry the main supply pipelines from the shore to the ship, an additional land-based piping system will be required for connecting the pipelines to the onshore tanks. Such system will allow for doing the carrier loading from various tanks and especially in case of multi-purpose jetties, the onshore pipeline facilities may present a true spaghetti of larger and smaller pipelines.

Figure 15. Example of a 'busy' terminal pipeline system

Typically in loading carriers, onshore pumps are being used, but in many cases the liquid flow is established using gravitational force alone depending on the level of the fluid inside the storage tanks. Additional pumping may be required to overcome frictional loss inside the pipes.

In this context, also the firefighting systems are to be mentioned. Throughout the terminal, desalinated water pipelines and jockey pumps are installed for providing water to sprinklers and fire hoses. In specific places like truck or railcar loading platforms canapes are used for providing an overhead supply of water for spraying water in case of emergencies. In ammonia plants water curtains are to be applied for preventing ammonia to be spread in case of incidents involving loss of containment. Also, a nitrogen purging and blanketing system must be in place allowing pipelines and tanks to be purged safely, e.g. at start-ups or shutdowns.

Figure 16. Photograph illustrating typical emergency ammonia spill deluge spray systems

The onshore ammonia handling system should also include the custody transfer equipment, allowing for the accurate metering and billing of the transferred ammonia.

Regardless that both the jetties and the onshore piping systems are most probably not all the time in use, they require regular 24/7 surveillance, with inspections and maintenance.

3.3.3 Port service providers

Apart from the parties directly involved in the transfer of gases and liquids like the terminal and the carrier operators, daily business also relies on various other service providers for allowing a safe, efficient and effective port operation.

Port tugs should be available for manoeuvring the sometimes huge carriers into place and assisting the vessels upon departure as well. A **port traffic control** must be in place to safely guide the traffic in and out the port using facilities like radar and communication stations. A **pilot service** will be required for assisting the skippers in and out the port and a **bunker station** (either onshore or barge based) must be in place for refuelling the carriers. The **port authority** has an important task in recording and coordinating ship movements and supervising the docking and loading/unloading procedures, including the permitting and HSE aspects.

3.3.4 Road and railroad connections

The reloading of ammonia into or from road tankers or railway cars are to be done via dedicated platforms. In case of high ammonia transfer rates, a truck loading station may be comprised of multiple docks allowing for the simultaneous loading of several trucks at a time. In case of railway transport, an extensive loading system is to be used capable of loading several train cars simultaneously. Of course, both the truck and train loading stations should have a good accessibility with the road and railway routes avoiding populated areas as much as possible.

Figure 17. Typical ammonia road tanker / trailer unloading station arrangement

3.3.5 Ammonia specific requirements

From interviews with European port authorities, it was learned that no specific requirements, other than already posed to large fuel carriers, will be applicable to ammonia carriers. Despite this, DNV recommends strongly to allow ammonia handling only at a sufficiently large distance from inhabited zones, to be determined by means of Quantitative Risk Assessment, proceeded and followed up by HAZID and HAZOP studies. Serious accidents with ammonia like the ones mentioned in Chapter 3.1.5, prove the potential danger to people and the environment in case of accidental releases of ammonia.

3.3.6 Liquid hydrogen handling infrastructure

At some moment in time it may be more economical to start exporting liquid hydrogen rather than ammonia. This possibility was indicated in Activity 4 of this study and is the vision of Chile National Green Hydrogen Strategy. A key question would be whether existing (ammonia) infrastructure could be re-used for storing and transporting liquid hydrogen. The short answer to this is no, although there are some nuances to make.

Although hydrogen is used for the production of ammonia, there is a significant difference in the way both substances can be stored and transported due to different chemical and physical properties. Hydrogen at atmospheric pressure has a boiling point of -252.8 °C, very close to the absolute minimum temperature of -273.15 °C. In comparison, the atmospheric boiling point of ammonia is -33.3 °C. Although gases with even lower boiling points can be liquefied (helium, -268.95 °C) it has to be noted that metals to be used for containing such liquids need to be made of a special alloy. For obtaining low-temperature specifications an alloy of steel and nickel is to be used.

Anecdotic evidence for this is an accident that happened in Cleveland Ohio in 1944. An LNG storage tank containing some 5,500 m^3 liquid gas ruptured, releasing its content into the sewer system of the nearby town. Here the LNG evaporated and at some moment the gas was ignited, resulting in huge explosions and fires. The fire destroyed 79 homes, 2 factories, 217 cars, 7 trailers, and 1 tractor; the death toll reached 130. The fire and subsequent analysis of its cause led to new and safer methods for the low-temperature storage of natural gas. During the investigation of the accident it was found that the tank had ruptured as a result of the use of inappropriate materials, since nickel by the end of World War 2 had become very scarce and expensive.

Although the gas carrying parts of the transmission and storage system would need to be replaced, other structures like roads, railways, jetties and pipe bridges could be re-used. Thermal insulation of tanks and pipelines would have to be enhanced and BOG handling and re-liquefaction capacity would have to be adapted to the new situation. Replacement of (major parts of) such equipment would be inevitable.

4 ACTIVITY 6 – INFRASTRUCTURE KEY DESIGN VARIABLES

In report #1 DNV identified ammonia as the energy vector connecting Chilean renewable energy resources with Western and Asian energy markets likely to be most successful and widely adopted by project developers in the short to medium term. In the long term it is possible that liquified hydrogen becomes the carrier of choice, particularly if the shipping technology develops, as perceived by many of the stakeholders interviewed as part of Activity 3.

It is expected that private companies supported by the capital markets are likely to be able to economically develop comparatively small power-to-ammonia projects based upon the green premium for e-Ammonia and the relatively simple and modular nature of the projects that do not have the economies of scale characteristic of conventional grey ammonia made by reforming of fossil fuels. However, storing and shipping of the e-Ammonia produced to western markets requires an investment in an export terminal infrastructure that only very large projects could support. DNV has identified the following characteristics of the ammonia export terminal that define its function and cost:

- Feedstock/input state: ammonia may be received for shipping in a number of its forms including as a gas, a pressurized liquified gas or as a refrigerated liquified gas.
- Input transport mode: ammonia may be received by multi-modal transport (road, rail, pipeline).
- Input transport / throughput volumes.
- Export transport state.
- Export transport mode.
- Export transport volume.
- Topography.
- Bathymetry and MetOcean data.
- Ground conditions and Seismicity.
- Climatic conditions and availability of cooling medium.
- Site location and proximity to centers of population.
- Availability of utilities (water, power etc.).
- Regulatory regime and emission standards.
- Design capacity, margins and turndown.
- Design philosophy and novelty.
- Design life.
- Construction strategy.
- Operations philosophy.

Each of these elements is further explored below.

4.1 Feedstock / input state

As illustrated in Figure 3-1 above, ammonia exists as either a gas or liquid at ambient temperatures depending upon the pressure at which it is stored. Alternatively, if refrigerated to -33.4 ºC, anhydrous ammonia can be stored as a liquid at atmospheric pressure in insulated tanks. However, because the refrigerated liquid will be subject to the ingress of heat from the surrounding environment, ammonia is either transported under pressure (to prevent it boiling off) or else must be transported in highly insulated containers or pipes to avoid the ingress of heat.

Generally ammonia is stored and transported as a liquified gas under pressure at small scale (for example in road and rail cars) and in pipes due to the cost and electrical power demands of the Boil-Off Gas (BOG) condensation equipment. Because of the high pressures and the required thickness of the storage tank walls, ammonia is more economically stored as a gas liquified by refrigeration in very large tanks where the additional costs and complexity of the BOG condensation equipment outweigh the costs of construction high pressure tanks.

The state of the ammonia arriving at the export terminal is important since it will always be stored as a refrigerated liquid at scale, and therefore equipment must be provided to receive the warm pressurised liquid ammonia and cool it down suitable for long term storage.

4.2 Mode of delivery to the terminal

Ammonia might arrive at the export terminal by a number of different transport modes including:

- Road - in either articulated tanker truck or else in ISO-containers conveyed by truck.
- Rail – in rail tank car.
- Sea – by ship from other coastal manufacturing plant.
- Pipeline – from manufacturing plants and received either as a refrigerated liquid 'across the fence' for a local plant or else as a pressurised (warm) liquid from more distant manufacturing sites.

Depending upon the scale and distance of the ammonia manufacturing plant from the export terminal different transport modes are likely to be used. For example, for a pilot facility road transport is likely to be the lowest cost option since the only equipment required to ship the ammonia product are loading pumps, hoses and the required safety systems. Road transport is viable for remote manufacturing sites where the hydrogen / ammonia plant is sited locally to the renewable power resource, but away from other transport infrastructure. The disadvantage of a road transport scheme is likely to be the elevated risk profile for making / breaking multiple hose connections and from the increased traffic of ammonia tankers on the local roads and highways.

Rail offers the opportunity to export ammonia in larger volumes and potentially in a safer way due to the safety systems established by railway operators, however the infrastructure cost for a rail siding and rail car loading gantry are higher and a rail connection is only viable where the manufacturing plant is located near to existing rail infrastructure.

The transport of ammonia by sea is common and a fleet of liquified gas carriers (LGC's) exists. These ships are either refrigerated, pressurised or semi-refrigerated (like pressurised but using some refrigeration to reduce the cargo pressure). Where the ammonia manufacturing facility is situated close to the sea, the transport of ammonia from manufacturing site to the export facility by coastal freighter is economic but requires investment in either a loading buoy or jetty.

Pipelines are used to transport large volumes of ammonia as a pressurised liquified gas over long distances. The installation of a dedicated pipeline connection is the highest capital cost option due to the need to purchase land easements along the pipeline route and is also likely to take a protracted period of time to obtain the required environmental and social permits for construction. However, once installed a buried pipeline connection will offer the highest levels of safety together with lowest operating costs per tonne of ammonia delivered.

In the event that an ammonia manufacturing plant is built adjacent to the export terminal, ammonia can be transported by insulated pipeline between the facilities as a refrigerated gas in liquid form. As a refrigerated liquified gas the ammonia can be diverted to the storage tanks directly without the need for additional equipment to cool the gas down that would be needed for pipeline ammonia received in its warm state from more distant facilities.

4.3 Volumes delivered to the terminal by each mode

The volumes of ammonia delivered by each mode is important since it will dictate the type and number of receiving facilities to be able to process the targets volumes by the selected modes. For example if large volumes were expected to be received by road tanker, multiple road tanker unloading stations would be required to process the number of trucks since each truck would be expected to take at least 60 - 90 minutes to unload. If very large numbers of trucks were expected then a single weighbridge might be insufficient resulting in queues and therefore two weighbridges would be required to process the throughput. Similarly if large volumes were expected to be received as a warm pressurised liquified gas then the receipt and refrigeration facilities would need to be able to process this volume and would require suitable electrical supply to power the large compressors necessary to refrigerate the received ammonia.

4.4 Export state

It is likely that long term most of the ammonia handled by the terminal will be exported to distant markets. However, in the short and medium term ammonia might be used domestically to offset imports. It is essential that the export terminal facilities be matched to the intended export mode since refrigerated ammonia will need to be warmed before it can be loaded onto rail car, pressurised liquified gas ships and some types of road tanker.

Since the terminal is likely to receive some ammonia as a warm pressurised liquified gas, it is common practice to have a warm ammonia pressurised buffer storage 'bullet' since ammonia can then be reloaded, for example from rail car to road car, without the energy penalty of being refrigerated and then re-warmed.

4.5 Export mode

Similarly to the import mode, it is important to understand the export mode to ensure sufficient facilities are provided to service the expected type of export. The required equipment might include loading pumps, fiscal metering, boil-off gas handling, additional rail sidings etc.

4.6 Export volumes

Similarly to the import mode, it is important to understand the expected export volumes by each mode to ensure sufficient facilities are provided to service the expected throughput. This might require duplication or increase in some facilities to service the required throughput.

An example of this might be the size of the warm ammonia buffer (day) tank. If large volumes of warm ammonia were expected to be received by rail car or pipeline and exported by road car then a large warm (pressurised) storage tank would be required to balance the flows between the large intermittent train (rail car) receipts and the smaller more frequent road tanker fills.

4.7 Topography

The topography of the proposed ammonia export terminal refers to the flatness of the terrain and presence of any hills, valleys, river beds etc. that would need to be taken into account in the layout of the terminal. The more steep the slope of the terrain the more soil and rock that would need to excavated to create level foundations for the storage tanks and rail sidings by a 'cut and fill' method. Some topographical features such as dry river beds or small hills can be incorporated into the layout without significant additional costs using bridges, culverts and other structures. Some landscaping features can improve the design, for example by providing natural shelter for the offices, maintenance warehouse and control room protected from the processing facilities by berm or similar or alternatively raised above the local terrain providing natural defences against flood, tsunami or other natural disaster. However, in general the lowest cost construction site will be flat land and construction costs will increase as the site topography deviates from this.

4.8 Bathymetry and MetOcean data

The bathymetry of the site refers to the underwater topography of the sea floor. In general the following features are desirable:

- Deep water shipping lane from open ocean to the site for transit of very large gas carrier ships.
- Some natural features protecting the site from deep water waves and storms such as a headland or bay to provide shelter to the ships whilst berthing and alongside at the jetty or cargo transfer facilities.
- Deep water at berth, close to the terminal on land. When the terrain slopes very gently into the sea it may be many hundreds of meters or even several kilometres before there is sufficient water depth to accommodate the under keel clearance (draught) of the very large gas carrier ships. It is desirable to have deep water close to the terminal to minimise the length of the jetty servicing gas carrier ships.

The MetOcean conditions refers to the ocean metrological conditions adjacent to the site. The significant wave height, direction and period is a key design parameter as are site wind and current speeds and directions. In general a large gas carrier ship will only be able to berth at the terminal when the significant wave height is below a threshold (typically 1.5

meters) and might need to disconnect and move away from the berth if wave heights exceed a higher threshold (typically 2.5 meters), so as to avoid damage to ship or jetty as a result of mooring forces.

Similarly, high prevailing wind speeds or water currents will impose restrictions on when a gas carrier ship can approach the berth and when it must move away to a safe anchorage.

If the MetOcean conditions at the site are predicted to exceed the permitted thresholds, either regularly or in the event of a storm, then additional measures will be required that might impose restrictions upon when a gas carrier can approach or remain at berth (and hence when ammonia can be exported) or might require construction of infrastructure to protect the berth such as a breakwater. Depending upon the frequency and seasonality of such exceedances the high costs of the additional infrastructure might be essential or avoidable.

4.9 Ground conditions and Seismicity

Since the facilities will incorporate heavy industrial equipment (compressors, pump skids) and equipment that cannot tolerate subsidence (such as the liquid ammonia storage tanks), solid and substantial foundations will be required to provide the necessary support. The design of the foundations will be predicated upon the ground conditions and presence of load bearing strata. In addition to the main equipment foundations, any marshy or poorly drained soil will require general soil improvement techniques to be appropriate for roads, rail sidings, buildings etc. An ideal site would be one with a top layer of well draining sand with load bearing bedrock or strong soil close to the surface. A poor site would be one in a marshy area with a deep layer of sedimentary or silty soil that would require very deep piled foundations to be able to support the expected loads. Any ground faults must be identified and avoided during the detailed design process.

The seismicity (seismic rating) of the site will also dictate the design of the foundations and will require specialist civil engineering solutions where the seismic accelerations are severe, such as seismic isolation of the ammonia storage tank. However, the seismic rating is general to an area and not the site so is therefore unavoidable unless another more distant site can be selected.

4.10 Climatic conditions and availability of cooling medium

The climatic conditions will determine additional protective measures necessary for the plant. For example the following measures might be necessary:

- In very cold climates frost / freeze protection and enclosed processing facilities will be required to protect operators and equipment from extreme cold.
- In very hot climates solar heat gain might be substantial, potentially leading to high levels of boil-off gas formation and better cold insulation of pipes and equipment.

The cold sink temperature (temperature of cooling water or ambient air that heat is rejected to) is important for the design of the warm ammonia receiving and refrigeration facilities. If the atmospheric wet bulb temperature is low then a low cooling water temperature is assured or alternatively if the summer ambient temperature is low air can be used as the cooling medium. The lower the cooling medium temperature available, the lower the compressor power that is necessary for refrigeration and liquefaction of the received pressurised ammonia import.

For very large facilities such as power plants and LNG facilities it is often economic to construct seawater intake and treatments facilities to use the sea as the cooling medium, however for simple facilities such as the ammonia export terminal it is unlikely that the additional cost and permit complexity for seawater abstraction would be economic.

The climatic conditions can also affect construction standards, materials selection and design life. For example it is likely that an ammonia export facility will be constructed close to open ocean / sea so that ammonia can be transported by ship to higher value overseas markets. Construction of the facility in a coastal and marine location can lead to accelerated corrosion due to salt water spray in the air and high humidity. Other environments such as warm and humid tropical locations can also lead to accelerated corrosion unless materials or coating systems are selected to provide protection.

4.11 Site location and proximity to centers of population

Ammonia is a toxic and flammable substance. It is also detectable (by odor) at very low concentrations. It is therefore essential that the ammonia export terminal be constructed:

- In an area that is designated and regulated as an industrial zone and familiar with the demands of the chemical industry.
- Away from centres of population that would be sensitive to odors due to low level emissions from the plant.
- Away from centres of population that might be affected in the event of an incident at the plant.

Some infrastructure solutions can be applied to mitigate the effects of minor leaks (such as vapour fences or firewalls), however the safest and lowest cost solution is to ensure safety by separation and to locate the ammonia export facility away from an area inhabited or visited by the public with controls such as industrial zoning to ensure that in future public buildings such as schools, churches or hospitals will not be built resulting in changes in the risk profile of the facilities.

4.12 Availability of utilities (water, power etc.)

In an industrial zoned area it is likely that the utilities required by the facility would be available, such as water, electrical power etc. For an industrial cluster additional services might be available such as pipeline nitrogen and fuel gas. In the most remote locations the ammonia export facility would need to be completely self-sufficient, for example in generating potable / process water from seawater by reverse osmosis or generating electrical power from imported diesel or natural gas connection. The presence and reliability of utilities would be considered in the design of the export terminal to determine which utilities must be under the direct control of the facility / operator to ensure safe and commercially viable operation.

As an example, a 1 million tonne/year ammonia export terminal might require utilities in the following quantities:

- Electrical power – 5 to 6 Mwe
- Cooling water – 2000 m3/hr at 5 ^{o}C differential

4.13 Regulatory regime and emission standards

The regulatory regime should be appropriate for the risk that the facilities present. Where the regulator is not familiar with the hazard the regulatory regime may be inadequately defined or too stringent. Either scenario is problematic for a developer since it can lead to investment uncertainty, cost creep or enforcement of actions that incur costs disproportionate to the risks mitigated.

The environmental challenges of developing a green hydrogen / ammonia industry in Chile and regulation have been addressed in a study commissioned by the Ministry of Energy under the Renewable Energy Programme and is referenced below.[3]

4.14 Design capacity, margins and turndown

The design capacity is determined by the volumes of ammonia received and exported via the different modes indicated in sections 4.3 & 4.6 above. However it is likely that the required capacity of the terminal will grow as the renewable ammonia industry develops in Chile. Some elements of the design are more economically delivered (as a lifecycle cost) if they are incorporated or considered in the beginning of the project such as size and draught of gas carrier ships, cargo volumes

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[3] Study: Identification of environmental, sectoral and territorial aspects for the development of green hydrogen projects throughout their value chain

and ammonia storage volume. For example if the facility targets future exports by the largest ocean going very large gas carriers (VLGC's) with a cargo volume of ~ 87,000 m^3 of ammonia then an ammonia storage strategy capable of delivering this volume based upon the largest economic tank size should be considered (such as 2 x 50,000 m^3 tanks). If a smaller ammonia tank such as 25,000 m^3 is initially constructed it is likely to require additional overall investment to meet the VLGC cargo export volumes in the future, for example by construction of two additional tanks of 25,000 m^3 and 50,000 m^3 to permit such large export cargo volumes. The total costs of the final three tank strategy (2 x 25,000 m^3 + 1 x 50,000 m^3) is likely to be much higher than the equivalent 2 x 50,000 m3 alternative.

The relative volumes of each ammonia stream received by the terminal is uncertain. For example it may transpire that a larger number of small ammonia manufacturing terminals are eventually constructed than initially expected and ammonia receipts at the export terminal by road exceed initial expectations. A design margin would be applied to the concept to account for such uncertainty that would be calculated to ensure that both the required functionality and additional functionality that might reasonably be expected to counter uncertainties is incorporated, without burdening the project with unnecessary costs. As the project matures and approaches investment it would be expected that such design uncertainties are reduced and hence the design margins can be reduced.

In a manner similar to determining ultimate capacity, minimum capacity must also be considered. For example the Boil-Off Gas compressors could operate on a recycle basis to operate at low gas volumes but would be inefficient and a loading system might not be able to run the main pumps if the receiving ship or rail car cannot accept the intended flow rate. The minimum expected flow or turndown conditions must be defined to permit an equipment sizing and operating philosophy.

4.15 Design philosophy and novelty

The design philosophy would be expected to provide definition of the way the terminal is expected to operate and the risks the operator is willing to accept and those that must be mitigated by technical solution. For example the operator might specify that there must be a minimum of one or two facilities elsewhere in the world operating with the intended equipment of technical solution to avoid taking design risks. Such design risks might include using a jettyless loading station with a floating cryogenic hose that, whilst technically feasible, might not have been proven in operation in a similar environment and therefore might carry undisclosed risks that would prevent proper function in the future or need additional investment or retrofit to work as intended.

4.16 Design life

The required design life will determine equipment specifications such as pipework corrosion allowance, allowable mechanical stress for fatigue assessment or running hours for large rotating equipment etc. In general setting a long design life, even with a requirement for intermediate maintenance CAPEX spending to achieve this economic life will require additional upfront CAPEX and, in the event that a very long design life such as 50 years be specified, might lead to unnecessary conservatism in the design. In general a design life of 20 – 30 years is specified for similar installations and, based upon the experiences of the LNG industry, the upside of extended asset life is identified and capitalised late in the plant's operations.

4.17 Construction strategy

The construction of the facilities requires that equipment, skills and materials be available at the site. Where site conditions are inhospitable such as extremes of climate or remote location, some of the construction can be undertaken under controlled conditions at shipyards and off-site as pre-assembled modules ready to ship to the site. For extreme conditions the facilities might be fabricated as an autonomous floating facility that can be transported to the site and used with minimal infrastructure. At the opposite end of the spectrum governments might dictate a local labour and materials obligation on the developer forcing them to use local services, irrespective of then quality, capability or capacity of available service.

The selection of an appropriate construction strategy accounting for stakeholder requirements, technical complexity and site characteristics can significantly influence the final CAPEX and facility function.

4.18 Operations philosophy

The operations philosophy will determine how much is done by the operator and how much is outsourced. The operations philosophy makes a trade-off between automation, cost of local labour, the benefits of installed against capital spares, local skills, the required facility availability etc.

5 ACTIVITY 7 – INFRASTRUCTURE SIZING

Earlier work undertaken as part of this assignment has identified Ammonia as the preferred energy vector for export of hydrogen made from renewable power. The following sections indicate an outline design of a facility to receive and export ammonia made from hydrogen sourced from renewable power generated within Chile, based upon a target throughput of 1 million tonnes ammonia/year, roughly equivalent to an input of 180,000 tonnes/year hydrogen.

This export capacity is based on the following criteria:

- **Alignment with the Chile National Green Hydrogen Strategy:** the Strategy has the ambition to produce 200 kton/year of hydrogen in 2025 in two hydrogen valleys. An ammonia capacity of 1 million tonnes/year corresponds to approximately 180 kton/year of hydrogen, close to the aforementioned target

- **Growth:** This capacity should be sufficient to handle growth until the end of this decade, whether in the North or South of Chile.

- **Technical feasibility:** the world largest ammonia plants are approximately 1 million tonnes/year. There is no precedent of much larger plants.

- **Risk:** For safety and security reasons it would be advisable to build additional terminals in other locations rather than increase the capacity (e.g. accidents or earthquakes).

- **Cost efficiency:** such a large capacity and economies of scale minimises the levelized cost of transport, enabling the largest gas carriers to load and minimising the number of round trips.

- **Environmental impact:** a multi-modal terminal with this capacity will be able channel the exports of multiple upstream producers, avoiding the need for smaller, individual terminals and minimizing the environmental impact

- **Alignment with the private sector:** in general this capacity is aligned with the project pipelines of private developers, considering also the risk and uncertainty of a nascent industry.

5.1 Feedstock/input state

Ammonia may be received for shipping in a number of its forms including as a gas, a pressurized liquified gas or as a refrigerated liquified gas. For the purposes of the initial terminal design, it is assumed that ammonia is only received in liquid form either refrigerated or pressurized since the conveyance of ammonia as a gas is uneconomic and technically challenging since:

- At 25° C ammonia will be a vapour below a pressure of 10 Bar absolute with a density of 6.87 kg/m3
- At 25° C and above 10 Bar absolute ammonia will be a liquid with a density of around 600 kg/m3
- Ammonia is therefore a factor of 87 times more dense in the liquid phase than in the vapour phase and therefore the size of the pipeline may be reduced.
- It is common practice in the design and construction of natural gas pipelines to use a high gas pressure (typically around 1000 psia) in order to maximise fluid density and to allow for a pressure drop of 1.5 – 2.0 psi/km to provide a spacing between compressor stations of 80 – 100 km. If ammonia were conveyed as a gas the pressure would need to be kept low and the pipeline would need to be constructed with many compressor stations at short spacings to avoid two phase formation and flow instability.

5.2 Input transport mode:

It is assumed that ammonia may be received by multi-modal transport namely road, rail and pipeline in order to maximise the value of the export terminal to the nascent renewable ammonia industry in Chile.

5.3 Input transport / throughput volumes

As stated at the beginning of this chapter, the desired capacity of the ammonia export facility shall be 1 million tones/year. The volumes received through each of the major vectors for the purposes of the study has been defined as:

- 350,000 tonnes/year 'across the fence' as a refrigerated liquified gas (i.e. in the liquid phase below -33 ^oC) from an adjacent ammonia manufacturing facility.
- 350,000 tonnes/year by pipeline from remote production site as a pressurised liquified gas (i.e. in the liquid phase at less than 250 psig).
- 300,000 tonnes/year by railcar and road tanker as a pressurised liquified gas (i.e. in the liquid phase at +40 ^oC / 225 psig). The split between railcar and road tanker deliveries is notionally assumed to be:
  - 200,000 tonnes/year by railcar, equivalent of 2857 railcars/year at 152,700 lbs load each. It is assumed that ammonia trains comprise 12 railcars each and therefore the terminal will receive approximately 238 trains/year assumed to be one every weekday for ~ 48 weeks of the year. The railcar unloading system must be capable of processing a train of 12 railcars within a 12 hour day shift to allow turnaround.
  - 100,000 tonnes/year by road tanker, equivalent of 4184 vehicles/year at 23.9 tonnes load each. It is assumed that the road tanker unloading will operate weekdays only for 48 weeks per year and therefore 240 service days/year. Based upon 240 days the road tanker unloading system must be capable of processing up to 18 tankers/day within a 12 hour day shift.

This distribution of import streams:

- Is a conservative scenario because it considers the Capex, Opex and footprint of 4 different receiving facilities (refrigerated pipeline, pressurized pipeline, road tanker and rail car unloading facilities)
- Caters for the need of multiple upstream producers, pilot and demonstration projects in the initial stages of the industry
- Due to the lower cost and lower safety risk profile the trend will be to increase ammonia delivered by pipeline and to decrease ammonia delivered by road and rail. However, spare road and rail capacity will give maximum flexibility to the terminal, which could eventually be used to distribute ammonia to an expanding base of local customers.

5.4 Export transport state, mode and volume

It is anticipated that ammonia shall be exported by ship as a refrigerated liquified gas in fully refrigerated very large liquified gas carrier (VLGC's) ships.

The current fleet of ammonia compatible liquified gas carriers include classes of ships at 60,000 m^3 and 81,000 m^3 of fully refrigerated vessels and will typically require a jetty with 14 m of water to allow for a draft of ~13 m with an under keel clearance of 1 m. The current maximum size VLGC can transport 87,000 m^3 of ammonia and this has been selected as the design basis since we have seen in the parallel LNG industry that the size of gas carrier ships only ever increases as the supply chain (shipbuilders) respond to demands for lower cost shipping by implementing economies of scale.

It is assumed that the ammonia export facility shall be designed to accommodate the largest currently available VLGC's since the project will target distant markets of Europe and Asia and therefore the economy of scale for international shipping will have a material effect upon the delivered commodity price.

It is anticipated that excess ammonia produced above domestic demand will be shipped to higher value distant markets in Asia and Europe. It is noted that the South China Sea basin is around 9500 nautical miles from the West coast of Chile and therefore at an average cruising speed of 15 – 18 knots this represents a voyage of around 22 – 26 days with a round trip of 48 – 56 days once an allowance has been made for loading and unloading. The voyage to European markets is shorter (perhaps only 7000 NM), however the voyage also attracts Panama Canal fees that are substantial (up to $800K to 1 MM). The Time Charter Equivalent (TCE) cost for a Large Gas Carrier (LGC) is typically of the order of $ 50,000 per day and therefore the cost of each ammonia shipment to remote markets is high; up to $2.4 – 2.8 million depending upon prevailing charter rates and other costs. Because of the high cost of shipping it is desirable to leverage the economy of scale and to send the minimum number of shipments which are therefore by necessity large cargo volumes.

Figure 18 (below) indicates the three main types of ammonia compatible gas carriers and their cargo volume and draft. The early gas carriers used pressurized tanks and were able to transport LPG and ammonia at ambient temperature under pressure as a liquified gas. Because of the thick cargo tank walls the early pressurized gas carriers (Pressurized Ammonia Compatible class) were limited to a cargo volume of typically only a few thousand cubic meters. By chilling the ammonia / LPG cargo the vapour pressure is reduced and a thinner or larger cargo tank can be used allowing greater cargo volumes in the class designated as Semi-Refrigerated Ammonia compatible up to 23,000 m^3. With the development of boil-off gas re-liquefaction systems it is possible to ship ammonia over long distances as a fully refrigerated cargo at -33.4 ^oC and atmospheric pressure. This Fully Refrigerated class of ammonia carrier is capable of transporting cargo volumes up to 87,000 m^3.

Looking at the LNG industry it is noted that in general the size of gas carriers gets bigger at each evolution of the technology and therefore it is recommended that for an ammonia export terminal of 1 million tonnes/year capacity that the initial design considers the largest gas carrier currently available (i.e. 87,000 m^3). Because the ammonia shipping 'packet' sizes are large and the charter fees make it uneconomic to have an VLGC in port for any length of time it is necessary to store this large ammonia volume upon completion of production/gathering ready for loading and export.

The ammonia industry has experience of design and construction of double and full containment, insulated atmospheric pressure storage tanks for the storage of anhydrous ammonia at -33.3ºC in tanks up to 60,000 m^3 (~41,000 tonnes). It is therefore recommended that the ammonia storage and export facility be designed with 120,000 m^3 of nominal storage (i.e. 2 tanks) to allow for a loading volume of 87,000 m^3. The calculation is illustrated below:

- Ammonia shipping packet size - 87,000 m3
- 'Heel' - namely an essential volume of ammonia in the tank to flood the pump suction that is not useable (i.e. does not contribute to the working volume) but must be accounted in the gross volume. This volume is typically up to 5% of the tank volume (6,000 m^3) depending upon tank diameter and pump type.
- Production safety buffer – Because the ammonia carrier undertakes long voyages with uncertain weather conditions there must be a buffer volume in the tank to mitigate the effects of a ship arriving a couple of days early (upside risk) or a couple of days late (downside risk) without having to interrupt or stop operations because the tank is full or the gas carrier cannot load because there is insufficient volume stored. Based upon a nominal volume of 120,000 m3 less 6,000 m3 heel the working volume is 114,000 m3 and therefore deducting an export packet size of 87,000 m3 leaves a production safety buffer of 27,000 m3, equivalent to 18,500 tonnes or 6.7 days at the design import rate of 1 million tonnes/year.

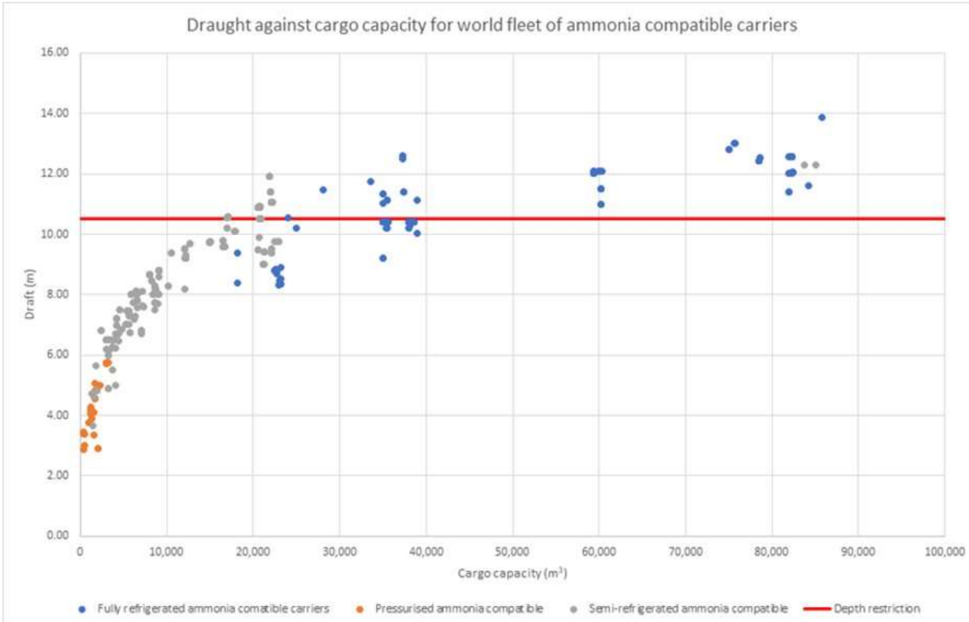


Figure 18. Draft against cargo capacity for world fleet of ammonia compatible carriers

It is assumed that up to the full 1 million tonnes/year of ammonia received shall be exported to international markets by sea. If the domestic market can accept a proportion of this flow, then it is expected that it will be transported by coastal freighter by sea, reducing the number of port calls required by international gas carrier vessels.

5.5 Topography

For the purposes of the study a flat site location has been assumed.

5.6 Bathymetry

Public data for a typical LNG import terminal (example used in Figure 19 below of GNL Mejillones) indicates that a terminal able to accommodate LNGC's of 165,000 m^3 uses a jetty head 600 m from the shore connected to the shore by trestles. The arrangement uses breasting dolphins at the jetty head and mooring dolphins extending to 750 m from shore. It is anticipated that a similar arrangement will be adopted for an ammonia export terminal accommodating Very Large Gas Carrier (VLGC's) for ammonia of 87,000 m^3 due to similar draft requirements (i.e. 13 - 14 m draft with under keel clearance of 1 – 1.5 m).

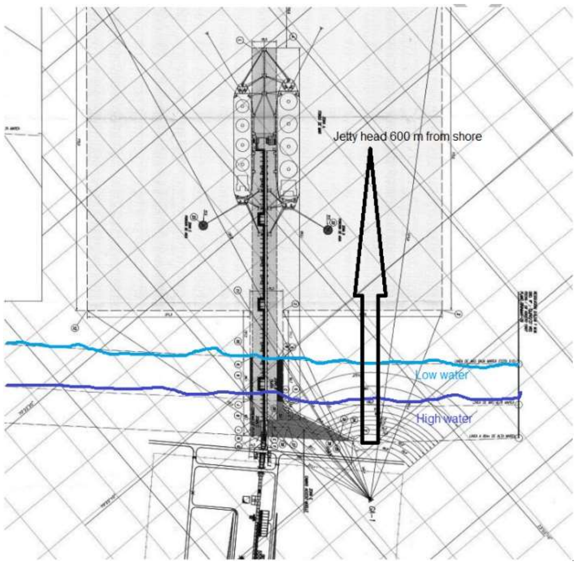


Figure 19 Jetty

No MetOcean data is available at this time until a location is fixed. The addition of an artificial feature such as a breakwater to provide a sheltered loading jetty is noted as a significant additional cost. The Energia Costa Azul offshore caisson breakwater to provide shelter for LNGC ships whilst un-loading at the LNG regassification terminal in Mexico has been estimated to add $875 Million of additional CAPEX.[4]

5.7 Ground conditions and seismicity

It is noted that Chile is situated on the Pacific “ring of fire”. Chile runs along a seismic zone where tectonic plates rub up against each other. It is one of the most earthquake-prone countries in the world and in 1960 was hit by a 9.5 magnitude quake. For the purposes of preliminary concept development, a typical peak ground acceleration of 3.92 m/s^2 shall be applied (Figure 20). Where high seismic loads are imposed special civil engineering construction must be used such as the use of seismic isolators to ensure the survivability of ammonia storage tanks in the event of a large earthquake.

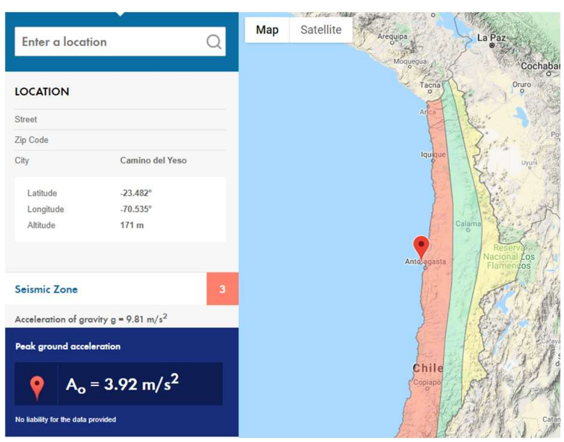


Figure 20. Ground conditions and seismicity at example location in Chile (Mejillones)

4 AECOM: Energia Costa Azul breakwater

5.8 Climatic conditions and availability of cooling medium.

The wet and dry bulb temperature will; inform the maximum cooling medium temperature available for cooling water and air cooling respectively and is subject to location and weather.

5.9 Site location and proximity to centers of population.

A location away from residential areas and centres of population is preferred.

5.10 Availability of utilities (water, power etc.).

Based upon the low demand for process water from the ammonia export facility it has been assumed that a supply of potable and process water shall be available to the facility from the municipal supply and no fresh water production shall be required.

It is assumed that electrical power supply will be grid selected and of adequate availability to meet the process needs of the terminal.

5.11 Regulatory regime and emission standards.

It is anticipated that a risk based regulatory approach will be taken to the design, construction and commissioning of the ammonia storage and export facility whereby the developer must demonstrate that all risks to workers and the general public have been evaluated and reduced to a level that is As Low As Reasonably Practicable (ALARP) without disproportionate cost.

It is expected that the facilities would be design and constructed in accordance with Chilean standards[5] and mature chemical industry standards such as those listed in the following table:

Codes/Standard No.	Title
API-520, Part-I & II	Sizing, Selection and Installation of Pressure relieving devices in refineries
API-521	Pressure relieving and de-pressurisation System
API Std-618	Reciprocating Compressors for General Refinery Service
API 610	Centrifugal Pumps for Petroleum Petrochemical and NaturalGas Industries
API 617	Axial and Centrifugal Compressors and Expander- Compressors for Petroleum, Chemical and Gas Industry Services
API 661	Air Cooled Heat Exchangers
API 620 R	Field fabricated storage tank
API 537	Flares
API 2000	Venting Atmospheric and Low-Pressure Storage Tanks
API RP 651	Cathodic Protection of Aboveground Petroleum StorageTanks

[5] SUPPORT GUIDEFOR REQUEST FOR AUTHORIZATION OFSPECIAL HYDROGEN PROJECTS

ASME Sec. VIII	Rules for Construction of Pressure Vessels
ASME B31.3	Process Piping
ASME B31.12	Hydrogen Piping
IEC 60038	IEC Standard voltage
IEC 60076	Power Transformer
IEC 60079	Electrical apparatus for explosive atmosphere
IEC 60364	Electrical Installations of Buildings
IEC 60502-2	Power cables with extruded insulations and theiraccessories for rated voltages
IEC 60529	Degree of Protection provided by enclosures (IP Code)
IEC 62040	Uninterruptible Power System (UPS)
ACI 318	American Concrete Institute (ACI) 318, Building Code Requirements for Reinforced Concrete
ACI 350	ACI 350, Code Requirements for Environmental Engineering Concrete Structures
NACE TM 284	Evaluation of Pipeline and Pressure Vessel Steels forResistance to Hydrogen- Induced Cracking
NFPA 2	2020 Hydrogen Technologies Code
NFPA 30	Flammable and Combustible Liquids code
NFPA 1	Fire code 2018 (Chapter 53)
NFPA 59	Utility LP-Gas Plant Code
ISPS	International Ship and Port Facility Security Code (from SOLAS)

5.12 Design capacity, margins and turndown.

In absence of any other data regarding use of the terminal in the early years it is assumed that the terminal will be designed based upon the following parameters:

- Design throughput – 1 million tonnes per year received via modes as defined in section 5.3
- Design margin – the equipment and facilities shall be designed for a maximum flow of 110% of the design throughput.
- Turndown - the equipment and facilities shall be designed for a minimum flow of 50% of the design throughput.
- Availability – the terminal and facilities shall be designed for a target availability of >95% (i.e. planned maintenance and unplanned failures shall be less than 438 hours per year (i.e. 5% of 365.25 days x 24 hours per day = 8766 annual terminal operating hours)

5.13 Design philosophy and novelty.

It is anticipated that the facility will not incorporate any major equipment or systems that has not been proven in a similar facility on the same application at similar scale. Such technical novelty might include:

- Membrane type storage tanks.
- Floating jettyless loading systems and hoses.

5.14 Design life.

The facilities shall be designed for an initial economic lifetime of 30 years.

5.15 Construction strategy.

In the North of Chile it is anticipated that a predominantly site built (stick built) facility with packaged equipment where appropriate would be the most economic solution due to:

- Mature services industry catering to the chemical, power, gas and mining industries.
- Favourable climate.
- Nature of the equipment (large storage tanks, rail sidings, trestles and jetty) that cannot be economically modularised.

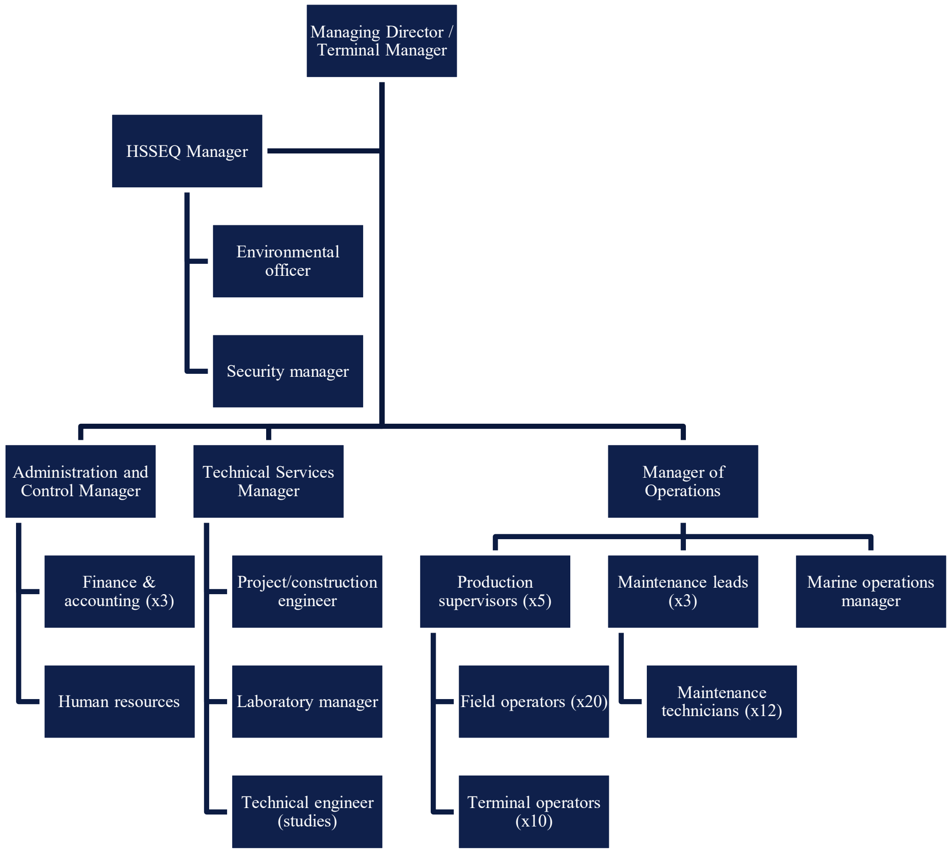
For the same reasons it possible that in the South of Chile a partly modularised strategy could be preferred.

5.16 Operations philosophy.

It is anticipated that a minimally manned facility would be provide the most safe and economic operation. A minimally manned facility typically comprises:

- High degree of process automation and remote control of pumps, compressors etc. from a control room on site manned 24/7.
- Road car token system whereby road tankers and drivers must have pre-qualified and approved equipment and training to enter the facility. Once within the facility the provided token reconciles field data to the road car, for example taking empty / full weight from the weigh bridge and subtracting known tare weight to provide allowed cargo weight to be loaded / unloaded. Hose hook up can be completed by the road tanker driver and approved by a terminal field operator before ammonia flow commences.
- The facility will train and retain a skeleton staff of technicians and engineers to attend to breakdowns and equipment / instrument failures. Additional support would be provided by mechanical, electrical and instrumentation contractors retained on a service agreement. For larger projects the maintenance leads would prepare a scope of works and tender to the preferred contractors. Once scope, price and schedule is agreed the terminal engineering and operations staff would ensure a safe way of working, monitor progress and re-instate production once the works are complete.

Based upon a 3 x 8 hour shift system (with 4 shift teams) it is anticipated that the following typical organisation chart shall apply:


Managing Director / Terminal Manager
HSSEQ Manager
Environmental officer
Security manager
Administration and Control Manager
Technical Services Manager
Manager of Operations
Finance & accounting (x3)
Human resources
Project/construction engineer
Laboratory manager
Technical engineer (studies)
Production supervisors (x5)
Maintenance leads (x3)
Marine operations manager
Field operators (x20)
Terminal operators (x10)
Maintenance technicians (x12)

6 ACTIVITY 8 – ANALYSIS OF COASTAL LOCATIONS

6.1 Introduction

This section seeks to identify the most important aspects for evaluating the coastal sites selected as part of this pre-feasibility study and determine their viability for installing a new ammonia plant and exportation facilities. The proposed coastal locations are shown in the map below: Tocopilla, Mejillones, Taltal and Cabo Negro.

Figure 21. Coastal locations for hydrogen export terminal

6.2 Methodology and assumptions

An analysis was conducted to identify opportunities and constraints at each site. The methodology is divided into four main stages:

- Site analysis and mapping: Geographic Information System (GIS) data was obtained from public sources and websites to analyze the characteristics of the proposed sites and create maps showing key geographical features relevant for the Project development.
- Definition of criteria: A variety of criteria was identified and used to characterize and compare sites. The criteria are grouped into five main categories: land use, infrastructure, marine traffic, environmental and social considerations. These criteria represent a combination of spatial restrictions or technical barriers for the development of the Project.
- Site ranking and evaluation: A scoring system was developed to weight each criterion to indicate its relative importance and impact on the Project. It should be noted that the weighting of criteria was based on previous sitting experience and the expertise of the professionals involved in the analysis.
- Key considerations of the selected site: The are several key considerations for the site selected in the prefeasibility study that need to be addressed in the next stage of the Project.

The GIS information was obtained the following sources:

- Chilean Ministry of National Assets (*Ministerio de Bienes Nacionales*): https://www.ide.cl/
- Chilean Ministry of Energy (*Ministerio de Energía*): https://arcgis2.minenergia.cl/
- Chilean National Energy Commission (*Comisión Nacional de Energía*, CNE): https://energiamaps.cne.cl/
- Chilean National Monuments Council (*Consejo de Monumentos Nacionales*, CMN): https://www.monumentos.gob.cl/
- Chilean Corporation for Indigenous Development (*Corporación Nacional de Desarrollo Indígena*, CONADI): https://siic.conadi.cl/
- Red CEDEUS: http://datos.cedeus.cl/
- UNESCO World Heritage List http://whc.unesco.org/en/list/
- Marine Traffic: https://www.marinetraffic.com/

It is assumed that GIS files are the most updated information. DNV has not undertaken direct consultation with agencies or local authorities, and no site visit was completed to verify the GIS data.

6.3 Geospatial Analytics

A constraint analysis was completed for all four sites using GIS data. The investigation focused on the adjacent port, between 3 and 5 km radius to give a sense of distance. The proposed sites were examined at high level for any potential constraints that compromise the development of the Project. The maps included in Appendix A show constraints and geospatial features identified at the sites.

Table 3 summarizes key findings for each site.

Table 3- Key sites findings

Category	Sub-category	Criteria / Description	Findings and observations			
			1.Tocopilla	2. Mejillones	3. Taltal	4. Cabo Negro
Land Use	Land zoning/ use considerations	Identification of land use designation/zoning taking into consideration the characteristics of the coastal and adjacent area.	The surrounding land of the Tocopilla port area is used for residential and industrial purposes, mainly along the coast. Once outside the urban area, the terrain becomes more complex with some surrounding hills with very little vegetation and without apparent agricultural use	The Mejillones site is located within an industrial area along the bay, with a plan of extending the port and industrial area to an adjacent area, as identified on the map in Appendix A. The proposed Project will be located in the industrial extension area with no apparent interference from existing or future zoning or land use.	An urban area surrounds the Taltal port. Outside the boundaries of the Taltal town, the terrain is barren with little to no vegetation.	The Cabo Negro port contains an industrial area, surrounded by wide empty areas to the north-west side of the Cabo Negro Peninsula. Other smaller industrial facilities are located to the south side of the Cabo Negro Peninsula and along Route 9.
	Risk of conflictual land use or planning considerations	Identification of potential conflict with existing zoning and/or surrounding land uses (e.g., industrial, agriculture, mining activities)	• The proximity to towns and limited land available for the project development is a constraint for the Project.	• Since the industrial zone is concentrated in one area and the residential/urban area is on the other side, there is no actual risk of zoning or land use conflict. However, a new regional land use regulation (*Plan Regulador Intercomunal del Borde Costero de Antofagasta,* PRIBCA) could limit the development of industrial areas in the region.	• With proximity to towns/ densely populated areas, there is potential for conflict for zoning/land use.	• The zone has been established for industries; therefore, no risk of zoning or land use conflict is anticipated.
	Sensitive receptors[6]	Buildings, where sensitive receptors (e.g., children, elderly,) are congregated include residences, schools, hospitals.	• Few schools and health centers are located at less than 2 km (from a potential Project facility location)	• Few schools and health centers are located at more than 2 km (depending on the distance to the location of the Project facility).	• Few schools and health centers are located at less than 2 km (from a potential Project facility location)	• No schools and health centers are located within the study area

[6] The United States Environmental Protection Agency define sensitive receptor as occupants of hospitals, schools, daycare facilities who are more susceptible to the adverse effects of exposure to toxic chemicals and other pollutants https://www3.epa.gov/region1/eco/uep/sensitivereceptors.html

DNV

Infrastructure	Transport infrastructure	Availability of transport infrastructure, comprising both passenger and freight modes (i.e., road, railway, airport, and pipelines), and its capacity to connect with terminals Project facilities, terminals and ancillary facilities that support Project operations.	• Road infrastructure: Routes 1 and 24 connect coastal areas with sparsely population centers • Rail infrastructure: a railway line reaches the surroundings of the port area • Airport: The closest aerodrome is located at 8.5 km (Punta Blanca) • Gas pipeline and high voltage transmission network are available	• Road infrastructure: Road network running from the coast to the main road (Route 1), • Rail infrastructure: a railway network connects the industrial zone with the population center and externally with Antofagasta and other population centers • Airport: The closest aerodrome is located at 15 km (Hornitos) • Gas pipeline and medium and high voltage transmission network are available	• Road infrastructure: Route 1 runs along the boundaries of the industrial zone. • Rail infrastructure: There is no current railway network. • Airport: The closest airport is located at 18 km (Las Breas) • Gas pipeline and high voltage network are available	• Road infrastructure: Road 9 connects the industrial zone to other population centers, running from North to South. • Rail infrastructure: There is no railway • Airport: The closest airport is located at 6 km (Ibáñez del Campo) • ENAP network of oil and gas pipelines • ENAP depleted fields may be used for hydrogen storage
	Onshore facilities	Availability of onshore facilities that can be efficiently optimized to provide continuous production and reduced operating cost. These include but is not limited to wind and solar power plants, fertilizer production facility, LNG plants, and O&G facilities.	• AES Gener and Engie's coal-fired power plants and gas-fire combined cycle plants	• Engie's coal-fired power plant • Kelar's gas fired combined cycle power plant • Enaex's ammonium nitrate production plant, including desalinization plant • Codelco's LNG plant and molybdenum treatment plant	• Enami's copper refinery. • Planned 778MW wind farm (Horizonte) • High hybrid wind and solar potential recognized in Chile long term energy plans	• Methanex's methanol synthesis plant. • Methanex's wind farm Cabo Negro.
	Port and marine facilities	Availability of marine facilities (e.g., unloading system, storage tanks, piping, pumps, control system, safety system)	• Few storage tanks, breakbulk and cranes	• Few storage tanks, breakbulk and cranes	• Three berths and an offshore Conventional Buoy Mooring (CBM) system	• One bulk cargo berth is available. • Methanol and LPG export terminals
Environmental	Ecological sensitive areas	Proximity to natural protected areas, national parks, nature reserves or other designated critical habitat for protection of birds, fishes and marine species.	• No major environmentally protected areas have been identified within the area of interest. • Designated areas for aquaculture, fishing and or exploitation of benthonic resources (*Areas de Manejo y Explotacion de Recursos Bentonicos*,	• The Mejillones Peninsula is a nationally designated priority site for biodiversity. The protected area covers 7,215 hectares of terrestrial ecosystem extending from Punta Angamo to Caleta Herradura. The Mejillones Peninsula has also been	• No environmentally protected areas have been identified within the area of interest. • Suitable areas for artisanal fishing and aquaculture designated areas (AMERB) are located at the East and West coast.	• No environmentally protected areas have been identified within the study area of interest. • No AMERB areas have been identified.

			AMERB)[7] are at approximately 4km from the town.	recognized as an Important Bird Area (IBA) supporting coastal bird species. • Few designated artisanal fishing and aquaculture areas (AMERB) are located at the east and west side of Mejilllones Bay.		
	Water Resources	Proximity to surface water bodies (e.g., rivers, streams, lakes) or other alternatives that can be used as in-take water supply for the facility operation or discharge of treated effluent.	• There is no surface water suitable for the Project.	• There is no surface water suitable for the Project. However, the existing seawater desalination plant can meet Project requirements as an alternative water source.	• There is no surface water suitable for the Project.	• Few waterbodies with potential for the Project are located within a 5km-radius area (Cabo Negro Lagoon and Pescado river).
Cultural and Social	Archaeology and Cultural Heritage	Presence of cultural heritage or archaeological sites, including resources with cultural or traditional value to Indigenous peoples (e.g., landscape, sacred place or object)	• No protected cultural heritage places or resources have been identified within the area of interest. Historical monuments are located within urban areas.	• No protected cultural heritage places or resources have been identified within the area of interest.	• No protected cultural heritage places or resources have been identified within the area of interest.	• No protected cultural heritage places or resources have been identified within the area of interest.
	Closest communities	Proximity to communities (Potential exposure of the public to the accidental release of toxic gases)	• The closest community is within a 2 km radius of the industrial zone.	• The closest community is outside of a 2 km radius of the industrial zone. (between 2 to 12 km depending on the location of the facility)	• The closest population center is within a 2 km radius of the industrial zone.	• The closest inhabited town is Punta Arenas, located at 20 km of the industrial zone.
	Indigenous Peoples	Presence of collective lands, water and territories of Indigenous peoples that are formally recognized[8] within study area for each site.	• No indigenous communities were identified.	• No indigenous communities were identified.	• No indigenous communities were identified.	• No indigenous communities were identified.
Marine Traffic	Marine routes and traffic	Identification of maritime routes and type of vessels regularly visiting the port – commercial shipping traffic (e.g., propane gas tankers, ammonia carriers) and fishing routes (i.e.,	• Existing routes for bulk carriers. There are no LPG/LNG routes • High traffic of fishing vessels	• Existing routes for LPG, LNG, bulk carriers, container ship, general cargo • High traffic of fishing vessels	• No LPG/LNG carriers arrive at this port • Low traffic of fishing vessels	• Only LPG carriers arrive at Cabo Negro Port. • There are no fishing or pleasure activities in this port.

[7] The Chilean National Undersecretariat of Fisheries (*Subpesca*) regulates aquaculture activities and allocates exclusive rights to small-scale fishermen organizations for exploitation of marine resources, called Management and Exploitation Areas for Benthic Resources (*Areas de Manejo y Explotacion de Recursos Bentonicos*, AMERB)

[8] The Corporation for Indigenous Development (*Corporación Nacional de Desarrollo Indígena*, CONADI) is responsible for representing the interest of indigenous people in Chile.

		commercial, artisanal or recreational)				

6.4 Additional considerations

This section provides a high-level analysis for additional considerations, such as local labor, suppliers, development of green hydrogen projects in the region, LCOH, etc. The analysis by DNV is presented in terms of barriers, which are aimed to identify potential risks for the development of projects in bays included in the DNV review.

Table 4.- High level review of Barriers for the development of Green Ammonia projects

Barrier	Other considerations analyzed by DNV in terms of Barriers			
	Tocopilla	**Mejillones**	**Taltal**	**Cabo Negro**
Presence of Wind /PV on the area	Antofagasta region leads the developments of renewable energy in Chile, considering that over 1.6 GW have been installed in the region, which represents 19% of the total installed capacity in Chile. ***DNV notes that the current development of renewable energy in Antofagasta region is positive for the development of green hydrogen projects and also for the synthesis of ammonia, considering the energy consumption that these projects will demand in the future.***			The Magallanes region is not connected to the national electrical system (SEN) and the main source of electric generation are fossil fuels. No major wind farms have been installed, however, considering the potential wind resource in the area it will attract the development of wind farms in the region.
Forecast levelized cost of Hydrogen (data provided by Ministry of Energy)	As of 2025 it is expected that levelized cost will be 2.0 USD/kg H2 and by 2050 be close to 0.8 USD/ kg H2. ***DNV notes that by 2030, the northern region will be more attractive in terms of levelized cost.***			It has been projected that Magallanes region will have the most attractive levelized cost of hydrogen by 2025 (1.7 USD/kg H2). The cost is expected to decrease by 2050 (1.0 USD/ kg H2), however, based on this projection the northern region will be more attractive in terms of LCOH.
Green hydrogen projects	No track record of green hydrogen projects located at the bay (except the Hyex pilot project) ***DNV notes that considering the Tocopilla bay has a limitation in terms of surface available for the***	Hyex project, which is being developed by Engie and Enaex will synthesis ammonia in a pilot plant located 25 km away from Tocopilla. Then the ammonia will be transported to Mejillones through trucks. In a second phase the project is expected to generate	No track record of green hydrogen projects located at the bay ***DNV notes that considering the Taltal bay has a limitation in terms of surface available for the development of***	Currently the Haru Oni project is under construction. This project consists in a pilot project in order to produce hydrogen and then to synthesis this product into e-fuels.

Barrier	Other considerations analyzed by DNV in terms of Barriers			
	Tocopilla	**Mejillones**	**Taltal**	**Cabo Negro**
	development of this kind of projects. Further details about preliminary layout detailed in section 7	ammonia close to Mejillones.	***this kind of projects***	
Distance to import markets	Asia (Osaka): 9366 nm Europe (Rotterdam): 6900 nm (Via Panama Canal)	Asia (Osaka): 9464 nm Europe (Rotterdam): 6965 nm (Via Panama Canal)	Asia (Osaka): 9467 nm Europe (Rotterdam): 7055 nm (Via Panama Canal)	Asia (Osaka): 9407 nm Europe (Rotterdam): 7416 nm
Potential integration with other companies	DNV notes that the personnel from the coal fired power plant have a potential to be re-skilled in order to support the development of ammonia in the region.	Potential integration with Enaex ammonium nitrate plant and also with power generation companies	No major industrial activities in the area, therefore, DNV notes that no major integration with companies in Tal Tal bay is expected.	Main industries located in Punta Arenas are Enap and Methanex. It is still uncertain if these companies will integrate joint ventures with other companies to use current infrastructure for the development of green ammonia projects.
Availability of local labour	Despite the professionals and technicians from the coal fired power plant, it is noted that no major institutes or research centres are located in the area regarding the development of ammonia projects. Despite this issue, DNV notes that it is possible to re-skill personnel from the power plants into the hydrogen field.	Along Mejillones Bay, there are several industrial companies, such as Enaex, Power plants and a desalination plant, among others. Based on this scenario it is expected that no major barriers be presented to find local labour in the area. In addition, considering the decarbonization process, this can be seen as an opportunity for companies to instruct the personnel from coal fired power plants into hydrogen field.	Tal Tal city has over 13,000 Inhabitants. Therefore, it is expected that if ammonia projects are developed in the bay, it seems more probable that the labour will not come from local personnel.	HIF (Developer of Project Haru Oni) signed a cooperation agreement with Magallanes University in order to promote research projects for H2. DNV notes that in the region there are already professionals with similar process industry profiles needed (Methanex, Enap)

Barrier	Other considerations analyzed by DNV in terms of Barriers			
	Tocopilla	Mejillones	Taltal	Cabo Negro
Availability of local suppliers	Mining and desalination suppliers in the region. Most of the suppliers are located in Antofagasta City, which is positive for the Mejillones Bay considering the distance form this industrial complex to the city. DNV notes it is likely that the hub for the supply in the Antofagasta region will be located in Antofagasta city.			DNV notes that the location of the Magallanes regions presents a challenge due to distance from main Chilean cities. However, it is noted that the current interest in developing green hydrogen projects in the region will have an impact in the development of suppliers to be located in the region.
Feasibility of underground storage	Lack of data/ uncertainty about potential underground hydrogen storage in salt caverns or acquifers.			Potential feasibility of using the Enap oil & gas fields for underground storage of Hydrogen. To be confirmed.

6.5 Recommended coastal location

As per Table 4, a summary of the high-level review performed by DNV is analyzed. In general terms it is noted that the bays located in Antofagasta Region (Taltal, Tocopilla and Mejillones) are mostly dedicated to the mining industry. In addition, the region is currently leading the development of renewable energies in Chile. These facts are positive in terms of development of suppliers and also for local labor as the current industries are currently demanding specialized manpower and suppliers. Nevertheless, as the development of suppliers and local labor are still not specialized for green hydrogen and ammonia projects, it is expected that this barrier be overcome once the development of these projects start in the region. From the three bays located in this region, it is expected that Mejillones will have an advantage considering the current developments of the industrial sector on the bay and also considering that it is close to the city of Antofagasta, which leads the industrial services and also potential education and training centers (universities located in the city) Despite the positive overview of the Antofagasta region, it is noted as a concern the proposed legislation (PRIBCA) could limit the development of industrial areas on the bays located along this region. Still further details need to be analyzed in order to advise the potential impacts in the development of green ammonia projects, as discussed in the following sections.

Cabo Negro bay, which is located in Magallanes region, it is noted that there is currently interest in the development of green hydrogen projects (already one pilot project in construction), despite the region is located at the extreme south of Chile which naturally causes connectivity issues with main Chilean cities. It is expected that the development of suppliers and specialized manpower barriers be decreased once the development of green hydrogen projects are materialized. In addition, no major environmental issues are evidenced as there is no record of legislation to limit the industry development along the bay (Subject to environmental approval by SEIA) (the main difference with the Antofagasta region considering the PRIBCA).

Based on the review conducted by DNV, all bay locations presents potential to overcome current barriers for suppliers and manpower, however, considering that in the short term the hydrogen projects are expected to be located close to Magallanes and Mejillones bay, it is noted that these areas present the most potential in the short term. In terms of LCOH, both regions present exceptional forecast scenarios, however, it is expected that by 2050, the northern region will be more attractive in terms of LCOH. Regarding distance to import markets, it is noted that all regions presents similar distances for Asia, however, the Northern region is closer to European import markets through Panama Canal.

Based on the previous analysis and recognizing the potential of both the North and South regions of Chile to export green hydrogen and derived products, DNV recommends to continue this pre-feasibility study with Mejillones as the preferred coastal locations for development of the ammonia export terminal in the short term.

6.6 Key considerations for Mejillones

Figure 22 shows the constraints map for Mejillones.

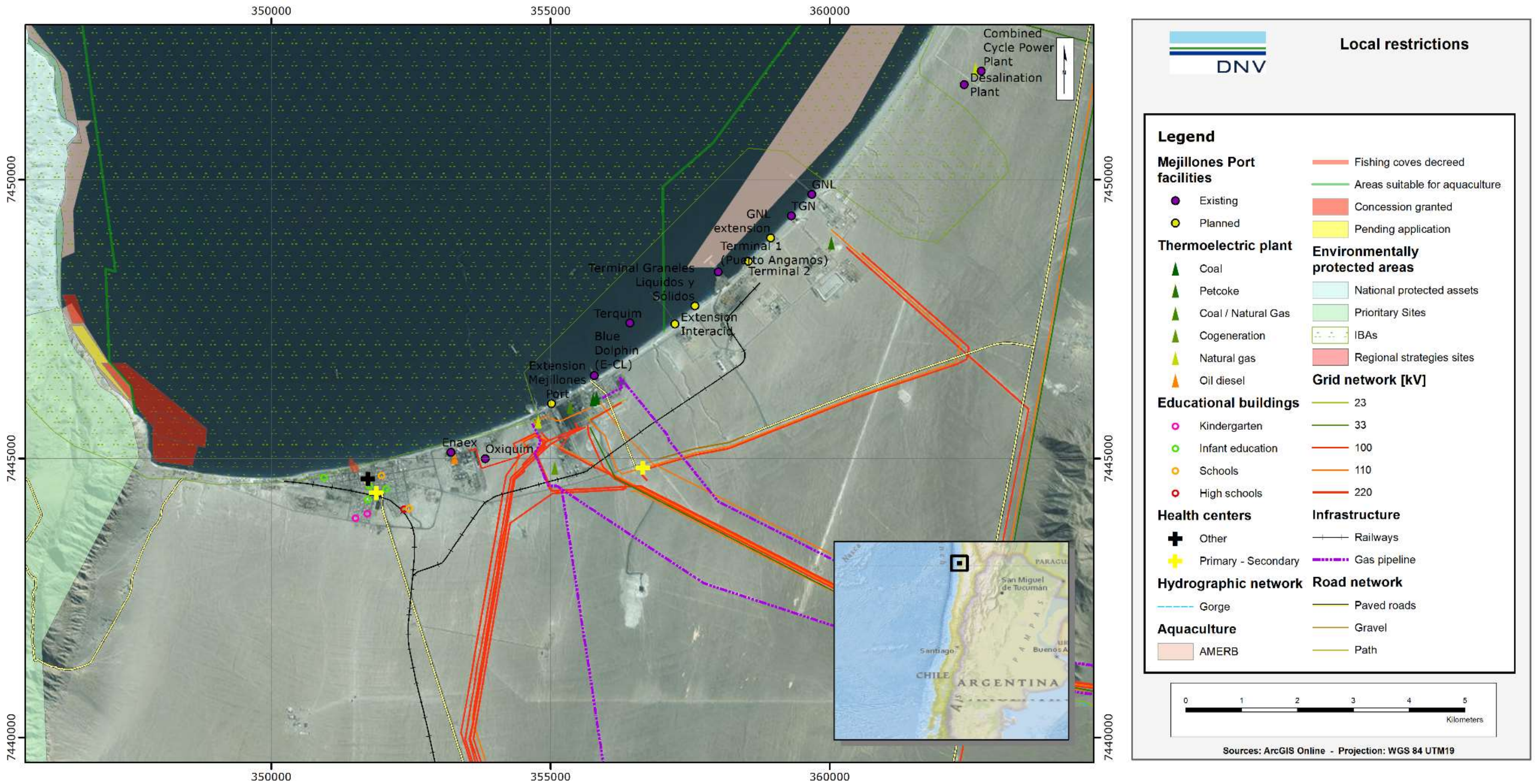


Figure 22 - Mejillones Constraint Map

6.6.1 Land Use

Mejillones is zoned as an area of multiple uses, based on the Mejillones land use plan (*Plan Regulador Comunal del Puerto y Bahia de Mejillones,* PRC)[9]. It regulates economic activities in the coastal areas such as port-related activities, industrial activities to support port operations, urban areas, and ecological protection of the coastal area. A large adjacent area is reserved for expanding the port and industry-related activities, which would be suitable for the new ammonia facility or required infrastructure (See Figure 51 – Appendix A). In addition, an area adjacent to the Mejillones town has been designated for a future expansion of the urban area. Available information was used to identify and map land use areas; however, there are several land use planning instruments designed that regulate the sustainable use of the territory and port in Mejillones, including the regional and local regulatory plans (*Plan Regulador Intercomunal del Borde Costero de Antofagasta,* PRIBCA[10]) and PRC. Further considerations regarding the compatibility of the proposed Project site in terms of land use should be developed. The next study should also identify minimum distances to any land use constraints (e.g., urban areas, green areas, cultural protected areas).

6.6.2 Infrastructure

An analysis of the infrastructure available in Mejillones is discussed in 6.3. In addition we include here information received from ENAEX and reproduced with their permission.

6.6.2.1 ENAEX ammonia import terminal

ENAEX manufactures and supplies ammonium nitrate and explosives for the mining industry and provides rock fragmentation services in Chile and worldwide.

The Prillex plant in Mejillones has a current production capacity of 850 kton/year of ammonium nitrate. ENAEX imports approximately 350 kton/year of refrigerated ammonia via its own import terminal at the bay of Mejillones. The terminal is a private port belonging to ENAEX.

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[9] Mejillones Municipality, Ordinance No.33, Communal Regulatory Plan (Ordenanza Plan Regulador Comunal del Puerto y Bahia de Mejillones (PRC), 11 November 2000. Amended by Exempt Decree 445 as of 3 October 2013.

[10] Regional Secretariat of the Ministry of Housing and Urban Planning (Secretaría Regional Ministerial, (SEREMI) del Ministerio de Vivienda y Urbanismo, (MINVU), Study on the Regional Regulatory Plan Update (Estudio Actualizacion Plan Regulador Intercomunal del Borde Costero de Antofagasta, PRIBCA) - Executive Summary, April 2021

Figure 23. ENAEX Prillex plant in Mejillones (image courtesy of ENAEX)

Refrigerated ammonia is typically imported in ships with a capacity of 25,000 ton every 3 weeks, taking approximately 3 days to unload. Utilization of the terminal and unloading equipment is therefore only about 15%. The terminal is capable of receiving ships with larger capacity.

Figure 24. Ammonia carrier unloading at ENAEX Prillex plant in Mejillones (image courtesy of ENAEX)

The terminal was rebuilt in 2013 and is designed for a 50 year lifetime. It is understood that the Enaex terminal consists of a marine island with a hose line platform suitable for 12.5 m draft vessels with an unloading rate of 250 m3/hr[11]. The transfer line from the marine island is assumed to run below the sea and therefore must be insulated and waterproofed since the facility regularly receives fully refrigerated ammonia cargo.

Total ammonia storage capacity at the plant is 30,000 ton in three tanks with a capacity of 10,000 ton each. Two tanks are single wall and date back to 1982 and 1992. A more modern double wall tank was built in 2010. The tanks are surrounded by dykes for containing the outflow of ammonia in case of leakages and ruptures.

ENAEX does not have facilities to receive and liquify ammonia transported by rail, road or pipeline.

ENAEX is jointly developing with Engie a green ammonia project called HyEx. This will be the first green ammonia production plant in Chile with an annual production of 18,000 tons per year. In the long term ENAEX has the ambition to replace ammonia imports with domestic green ammonia.

ENAEX is also open to the possibility of using its existing infrastructure at Mejillones for green ammonia export by third parties.

The feasibility of this possibility should be analysed in future studies directly with ENAEX so that their normal operations are not impacted. Reutilization of the terminal seems feasible but in the long term additional storage capacity could be required.

6.6.3 Environmental

The development of green ammonia production and exportation involves many on-shore and off-shore activities likely to produce changes in the biophysical or social environment. The Project boundaries need to be defined to determine whether an impact can be reasonably expected. Nevertheless, the constraint analysis identified the following key environmental aspects associated with the installation and operation of an ammonia plant and export terminals:

Ecological sensitive areas

There is an ecologically sensitive area at 4 km from the industrial zone, where the proposed ammonia plant would be located. Mejillones Peninsula has been designated a priority site for biodiversity at a national level. The protected area covers 7,215 hectares of terrestrial ecosystem extending from Punta Angamos to Caleta Herradura (See Figure 22). The Mejillones Land Use Plan (PRC)**Error! Reference source not found.** also designated this area with a special restrictive provision (*Area Especial de Restricción Punta Angamos* (ER), where only a few uses are permitted (e.g., non-permanent structures, tourism-related activities).

A search of a global database on biodiversity areas indicates the Mejillones Bay as an Important Bird Area (IBA) key biodiversity area, extending from the territorial coastal limits to the high seawater mark. The Mejillones Bay provides a habitat for coastal bird species such as the endangered Peruvian tern (*Sternula lorata*), Peruvian diving petrel (*Pelecanoides garnotii*) and Northern royal albatross (*Diomedea sanfordi*). The Peruvian tern is a migratory bird that winters on the coast of Mejillones Bay and nests in the spring season. It is important to note that the IBA's designation of the Mejillones Bay does not have complementary protection at national level.

Biological studies focusing on sensitive coastal bird species need to be completed for the Project, once the Project site is defined. These studies will help determine both Project impacts and those impacts that already occurred from the industrial facilities in the area. Further studies are required to determine if breeding and nesting habitats for these species, which may have diminished across the coast due to urbanization and industrial activities.

Air Quality

[11] https://agental.cl/en/port-manual/chile/enaex/

As noted in section 3.1.5, the effect of air emissions is a major concern as it will have an impact on the environment and the people. Once the air pollutants like SO_2, NO_x, NH_3, PM_{10} are emitted into the atmosphere, the pollutants dispersion is controlled by different meteorological parameters (e.g., wind speed, temperature). An atmospheric dispersion modelling and the prediction of ground-level pollutant concentrations are essential studies required to estimate the impacts of the new plant on the surrounding environment and identify areas of maximum ground-level concentrations. The best available technology and pollution control measures adequate for the Project should be further explored.

Water

Information regarding availability of water resources has been assessed. No water bodies were observed within the Mejillones site. Understanding that a large quantity of water is required to produce green ammonia using electrolysis, desalination is an alternative source of water. For an ammonia production of 1 MTPA it is estimated that the electrolysis plants would require approximately 1.6 MTPA of desalinated water. It should be noted this is much lower than the water requirements of the existing mining industry in the North of Chile. However, as with any desalination plant, the brine generated from the process when discharged into the sea may adversely affect the marine ecosystem if not handled correctly. The potential impacts of the desalination plant on the marine environment should be further investigated.

6.6.4 Cultural and Social

This study assumed a location for the proposed Project within the industrial zone or its extension. There are no designated indigenous people territory or cultural resources on the industrial zone. It is assumed that this area is completely developed, and therefore the chance of discovering subsurface archaeological resources. Although significant impacts are unlikely, an archaeological/cultural assessment for the proposed Project site should be completed at feasibility level.

Although the Project site has not been defined, the distance between the land suitable for the Project and the nearest community or residence is more than 2 km. This distance increases to the east side by 6 km until the eastern boundary of the industrial zone and by 12 km until the existing combined cycle power plant. As indicated in Section 3.1.5, the operation of the ammonia production plant poses direct risks to surrounding communities or public health from the exposure to toxic gases or vapours. Therefore, a Quantitative Risk Analysis (QRA) and Hazard Identification (HAZID) is recommended to be done at the feasibility stage of the Project to determine safety distances to nearby communities. Moreover, if communities' health and safety concerns are not addressed, this perception of risk can quickly turn into an objection to the Project development. It is recommended that engagement and dialogue with stakeholders starts early in the Project development to obtain buy-in from government agencies and local communities. The following section provides an overview of different methods to support the community engagement process for the Project.

Methods for community engagement

There is not one single method for community engagement. It is necessary to recognize that community engagement will depend on a number of factors such as location, size of the community, cultural identity, type of proposed development, etc. In general, engagement methods can be considered in three categories as shown in Table 5 illustrates each level of engagement, including details in which situation is applicable.

Table 5- Community Engagement Methods

Type of Engagement	Description	Main characteristics

1. Information Sharing	It involves one way of communication providing timeline information to communities through notices, sustainability or environmental reports, community newsletters, open houses, public meetings,	• Provide technical information, Project updates • Present certain aspects of construction, operations, decommissioning or other processes at local public meetings. For example, the implementation of emergency protocols, coordination among different port areas.
2. Consultation	Consultation is a two-way dialogue; it is a process rather than standalone events and it involves people in affected communities and other relevant stakeholders. Consultation offers an opportunity to present project information to resolve issues and concerns. Consultations are carried out through public meetings, workshops, roundtables, surveys, etc.	• Enable greater understanding of concerns, opportunities and expectations from the public, including vulnerable community groups (e.g., Indigenous peoples, women, children) • Obtain the opinion and input from governmental agencies NGOs, academic or scientific institutions, on wildlife conservation.
3. Collaboration	Providing opportunities for shared decision-making, through partnerships, collaboration agreements, multi-stakeholder forums. In this method of engagement, communities work with private and public organizations to find a solution, and share responsibilities in the implementation of actions	• Develop a trusting relationship with local communities throughout planning and monitoring activities of the Project. • Collaborate with private and public organizations to develop and implement environmental, safety and social actions within the Mejillones Port Complex.

6.7 Further studies

DNV recommends the following activities to support the feasibility phase for the development of the ammonia plant and export terminal in Mejillones.

General recommendation:

- Analyse the feasibility of reusing existing ammonia import and storage infrastructure in Mejillones for green ammonia export
- A full Environmental and Social Impact Assessment (ESIA) for the project shall be prepared following the requirements of the IDB's Environmental and Social Policy Framework (ESMF) and the applicable requirements set out in the WBG's Environmental, Health and Safety (EHS) Guidelines.
- Perform a regulatory compliance analysis addressing regulatory permits and other notable requirements, that may be required for the Project.

Recommendations for Land Use

- Ensure that the Project is aligned with the current and planned territorial planning strategies applicable to the Mejillones Port, including but not limited to Regional Regulatory Plan for the Antofagasta Coast (PRIBCA), Local Regulatory Plan (PRC), Mejillones Port Complex Master Plan.
- Validate Project compatibility with designated management areas in the context of landscape, cultural, or ecological values.
- Confirm the minimum distance from the selected Project site to existing and planned urban areas or other non-compatible land use.

Recommendations for Environmental

- Complete a wildlife characterization study to provide an overview of natural features and habitats to assess species with the potential to occur in the area.
- Ensure that the feasibility study identify avian breeding and overwintering areas along the coast, particularly nesting areas for the Peruvian tern (*Sternula lorata*).
- Engage with environmental organizations/groups such as Bird Life International and any local groups active in the area looking at protecting the shores.
- Prepare a biodiversity management plan as part of ESIA study, considering proactive conservation measures, support to initiatives to further protect the area, and ensuring avoidance of conversion/degradation of critical natural habitats.
- Perform an atmospheric dispersion modelling to define a buffer distance for public safety and estimate the efficiency of mitigation measures.
- Assess the environmental impacts of the desalination plant (including brine discharge modelling) that will be used by the Project. A seawater quality baseline assessment should be performed during Project planning / ESIA phase .
- Identify possible measures to ensure efficient use water resources and mitigate potential impacts from wastewater generation.
- Perform a screening to predict and identify the Project's potential environmental impacts and whether an environmental impact statement (*Declaracion de Impacto Ambiental*, DIA) or a more comprehensive environmental impact assessment (*Estudio de Impacto Ambiental*, EIA) report would be required.[12] This study

[12] Guidance about DIA and EIA can be found here: https://www.sea.gob.cl/sites/default/files/imce/archivos/2021/06/30/revista_4.pdf. The environmental impact assessment regulation can be found here: https://www.sea.gob.cl/sites/default/files/imce/archivos/2016/01/12/dto-40_12-ago-2013.pdf

should also be able to anticipate any potential risk in the environmental assessment process as to whether the proposed development will be approved and expected timeline.[13]

Recommendations for Cultural and Social

- Complete a socio-economic analysis of the communities (social baseline) in the area of influence of the project (port and associate facilities).
- Complete stakeholder mapping and stakeholder engagement plan. It is recommended that this analysis integrates the view from stakeholders who represent diverse community interest. It should also integrate a gender-oriented approach and communication strategy to identify relevant stakeholders of the proposed development and address potential barriers to green hydrogen development in the area, including a grievance redress mechanism.
- Complete a cultural assessment of the proposed Project area.

Recommendations for Health and Safety

- A Quantitative Risk Analysis (QRA) and Hazard Identification (HAZID) and/or HAZOP as applicable is recommended to be performed to define a buffer distance for public safety and identify mitigation measures to acceptable risk levels.
- A Natural Disaster Risk Analysis (DRA) and Disaster Risk Management Plan (DRMP) following the *Disaster and Climate Change Risk Assessment Methodology for IDB Projects* (2019).

Additional recommendations:

- Develop an analysis on socio-environmental liabilities, cumulative and indirect impacts, and any risks and impacts from Associated Facilities related to the project development.

13

Guidance for environmental assessment of green hydrogen projects in Chile can be found here: https://www.4echile.cl/publicaciones/estudio-identificacion-de-aspectos-ambientales-sectoriales-y-territoriales-para-el-desarrollo-de-proyectos-de-hidrogeno-verde-en-toda-su-cadena-de-valor/

![DNV logo]

7 ACTIVITY 9 – CONCEPTUAL LAYOUT

Based upon the infrastructure sizing basis defined in Section 5 above, DNV developed a process simulation (heat and mass balance) in order to develop an equipment list and specifications suitable in order to prepare a conceptual CAPEX cost estimate consistent with AACE Class IV (+30%/-25%).

The conceptual layout and the cost estimates and high-level implementation plan in subsequent activities are for a greenfield ammonia export terminal. In this way results of this prefeasibility study may be reused for other export projects. As reiterated throughout this report, in the case of Mejillones there is existing ammonia infrastructure that could be partially reutilized for ammonia export, with the advantages of reducing costs, time and environmental impacts, at least in the initial phases of the industry.

A warm ammonia day tank of 1500 m3 volume was incorporated into the design in order to buffer the peak flows of warm ammonia into the system and hence reduce the flash gas rates. Based upon current industrial practice a Boil-Off Gas (BOG) rate of 0.05%/day of the refrigerated ammonia storage was used in the calculation of the BOG compressor sizing.

A conceptual layout based upon a plot size of 700 x 700 m was developed and used as the basis of estimate.

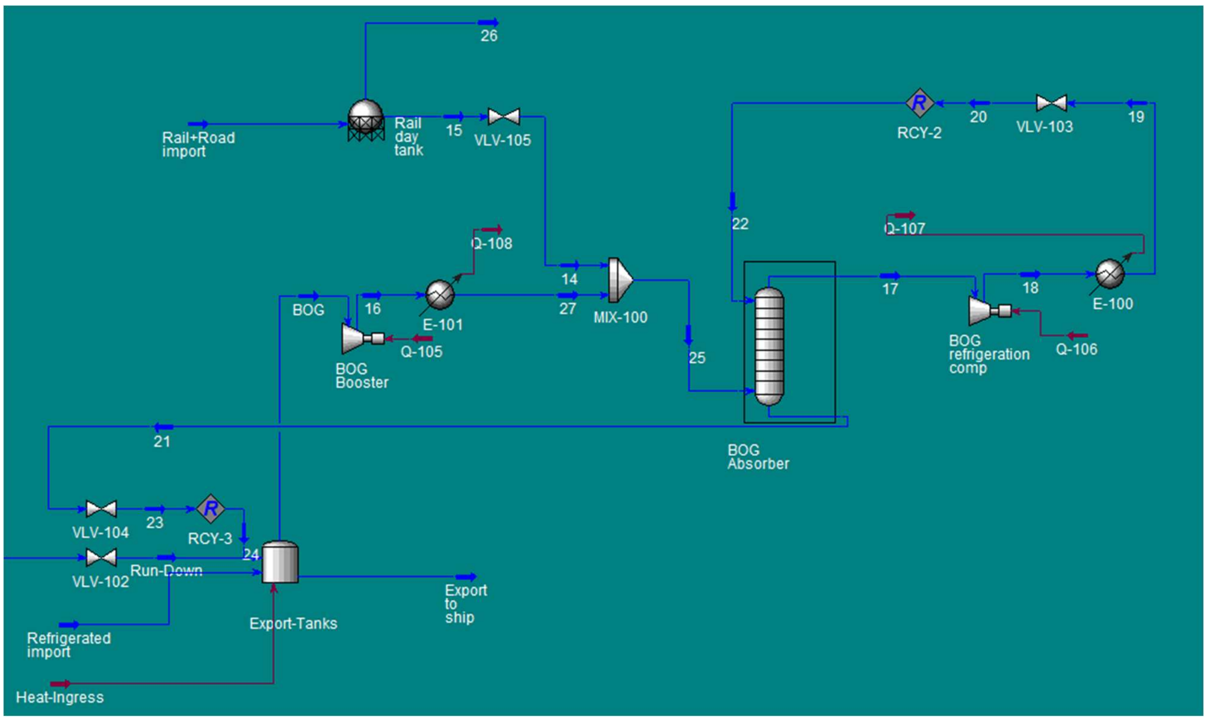
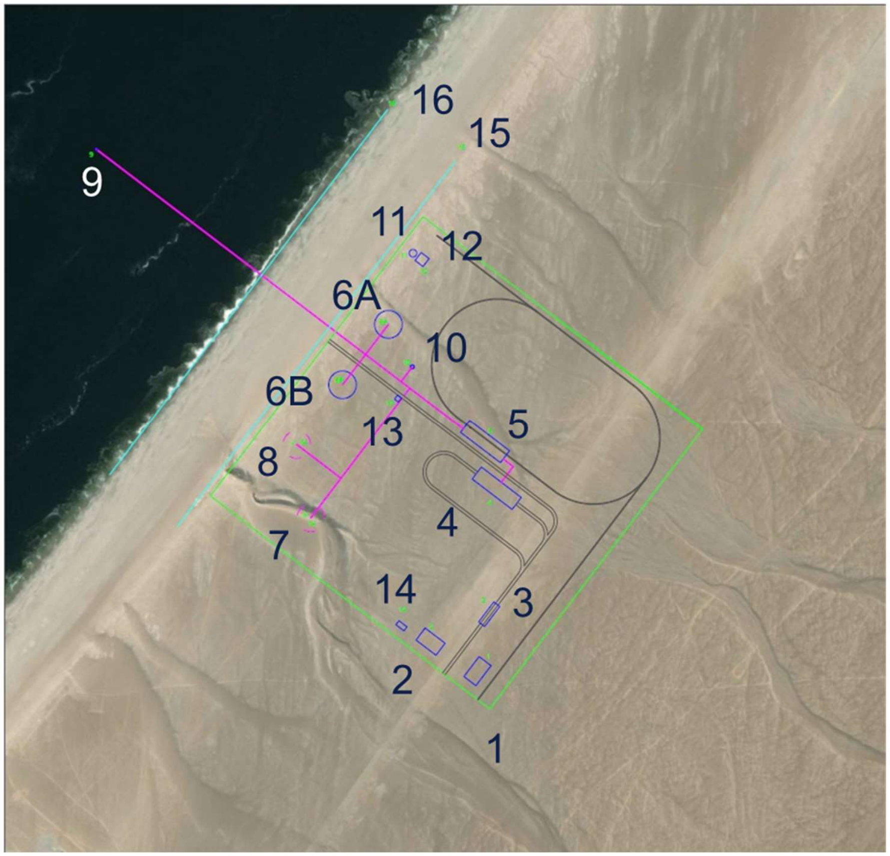


Figure 25. Process simulation

7.1 Conceptual site layout

The following figure shows a conceptual layout of the ammonia export terminal in a generic location along the coast of Mejillones. The space required is a square of approximately 700 x 700 m. The length of the jetty is 600 m.



	Legend
1	Administrative / Control building
2	Maintenance building
3	Weighbridge
4	Road tanker loading station and pumps
5	Rail car loading station and pumps
6A	Ammonia tank (ambient pressure full refrigerated)
6B	Ammonia tank (ambient pressure full refrigerated)
7	Marine loading LP flare
8	Main process flare (2 flare tips / flare lines)
9	Jetty head with loading arms and drain drum
10	Ammonia day tank (pressurized)
11	Fire water tank and pumps house
12	Water treatment / rain run off impounding
13	Compressor house
14	Electrical import and sub-station
15	High water level
16	Low water level

Figure 26. Conceptual site layout

7.2 Equipment list

Equipment name	*Quantity*	*Config.*	*Type*	*Capacity/duty*	*Size*	*Electrical load*	*Design pressure*	*Design temperature*	*Comment*
Warm pipeline pig receiver	1	1W	Horizontal vessel with quick opening closure	8" line	36" dia. x 72" T/T	N/A	250 psig/FV	-35/+85 C	LTCS ASME VIII U
Warm pipeline flash drum	1	1W	Vertical vessel with demister pad	12" inlet line	2000 mm dia. x 10,000 mm T/T	N/A	100 psig / FV	-35/+85 C	LTCS ASME VIII U
Warm pipeline flash gas compressor	1	1W	Two stage reciprocating compressor with interstage air cooled	10,400 Am^3/hr from atmospheric to 15 Bar.G		1.5 MW	250 psig/FV	-35/+85 C	LTCS
Warm pipeline flash gas compressor cooler	1	1W	Forced draft fin fan	4.3 MW.Th			250 psig/FV	-35/+85 C	LTCS
Fully refrigerated ammonia storage tanks	2	2W	Flat bottom site constructed tanks. Insulated double wall construction	Each 60,000 m3	Est. 55 m dia x 26 m HOS	N/A	+70 mBarG / -5 mBarG	-35/+55 C	LTCS. API 620 App. R
Refrigerated ammonia tank pumps	6	4W + 2S	Deep well submersible / long shaft pumps	1800 m^3 into 150 m head		60 kW	10 BarG/FV	-35/+55 C	
Warm ammonia day tank	1	1W	Above ground Liquified gas storage bullet with	1500 m^3	8.5 m Dia x 26 m T/T		250 psig/FV	-35/+85 C	LTCS ASME VIII U

			hemispherical ends on concrete saddles.						
BOG gas booster compressor	2	1W + 1S	Two stage reciprocating compressor with interstage air cooled	8,500 Am^3/hr from atmospheric to 3.6 Bar.G		0.6 MW	250 psig/FV	-35/+85 C	LTCS
BOG gas booster compressor cooler	2	1W + 1S	Forced draft fin fan	300 kW.Th			250 psig/FV	-35/+85 C	LTCS
BOG absorber	1	1W	Vertical vessel with demister pad	12” inlet line	2000 mm dia. x 13,000 mm T/T	N/A	250 psig/FV	-35/+85 C	LTCS ASME VIII U
BOG gas refrigeration compressor	2	1W + 1S	Two stage reciprocating compressor with interstage air cooled	4,600 Sm^3/hr from 3.4 Bar.G to 19 Bar.G		1.5 MW	300 psig/FV	-35/+85 C	LTCS
BOG gas refrigeration compressor cooler	2	1W + 1S	Forced draft fin fan	6100 kW.Th			300 psig/FV	-35/+85 C	LTCS
Rail tank car unloading station	2	2W	Covered rail tank car unloading station with bottom connections. C/W deluge/scrubbing water curtains		4” liquid and vapour connections		250 psig/FV	-35/+85 C	LTCS

			Fiscal (mass flow) metering						
Rail tank car unloading pumps	3	2W + 1S	Unloading pumps with piping manifold/controls	120 m3/hr into 150 m differential head	4" liquid and vapour connections	55 kW	250 psig/FV	-35/+85 C	LTCS
Road tanker unloading station	2	2W	Covered road tanker unloading station with Top connections. C/W deluge/scrubbing water curtains Fiscal (mass flow) metering		3" liquid and vapour connections		250 psig/FV	-35/+85 C	LTCS
Road tanker unloading pumps	3	2W + 1S	Unloading pumps with piping manifold/controls	30 m^3/hr into 150 m differential head	4" liquid and vapour connections	15 kW	250 psig/FV	-35/+85 C	LTCS
Weighbridge	1	1W	Suitable for 44T, 18 wheeler or equiv.						
Marine loading arms	4	3W + 1S	Hydraulic articulating loading arms with QCDC		12"		250 psig/FV	-35/+85 C	LTCS
Ship access tower / gangway	1	1W							
Jetty drain drum	1	1W	Horizontal pressure vessel on saddles.		3 m dia. X 5 m HOS		250 psig/FV	-35/+85 C	LTCS

Firewater tank	1	1W	Flat bottomed site constructed tank with cone roof		15 m dia. X 12 m HOS		Full hyd. Head	0 / 55 C	CS coated in and out.
Electric firewater pumps	2	2W		1000 m3/hr at 80 m					CS
Diesel firewater pumps	2	2W		1000 m3/hr at 80 m					CS
Diesel storage tank	1	1W	Flat bottomed site constructed tank with cone roof	20,000 litres with outer bund tank @ 110% volume					CS coated externally
Nitrogen supply package	1	1W	Vacuum insulated vertical vessel	20 m3					c/w vaporisers
Warm flare	1	1W	Freestanding flare tower c/w flare line and flare tip		12”		250 psig/FV	-35/+85 C	LTCS
Cold flare	1	1W	Freestanding flare tower c/w flare line and flare tip		12”		250 psig/FV	-35/+85 C	LTCS
Cold flare K/O drum	1	1W	Horizontal pressure vessel		2500 mm diameter x 8000 mm T/T		250 psig/FV	-35/+85 C	LTCS
Marine flare	1	1W	Freestanding flare tower c/w flare line and flare tip		12”		250 psig/FV	-35/+85 C	LTCS

Refrigerated storage tank spill containment pit	1	1W	Below ground pit c/w rainwater pump out		20 x 20 x 5 m (L x W x D)				Foamed R/C concrete
Warm ammonia day tank spill containment pit	1	1W	Below ground pit c/w rainwater pump out		20 x 20 x 5 m (L x W x D)				Foamed R/C concrete
RTC loading stations spill containment pit	1	1W	Below ground pit c/w rainwater pump out		10 x 10 x 5 (L x W x D)				Foamed R/C concrete
Road tanker spill containment pit	1	1W	Below ground pit c/w rainwater pump out		5 x 5 x 5 m (L x W x D)				Foamed R/C concrete
Effluent holding pit	1	1W	Below ground pit c/w chemical dosing skid for pH control.		10 x 10 x 5 (L x W x D)				R/C concrete
Emergency generator	1	1W				500 kW			Diesel gen set
Power import / transformer / harmonic filters	1	1W				5 MW			
Admin / control building	1	1W			30 x 50 x 10 m (L x W x H) 2 floors				Steel framed building with block wall construction.

									Not blast / fire hardened.
Maintenance / operators building	1	1W			30 x 50 x 10 m (L x W x H) 1 & 2 floors				Steel framed building with block wall construction. Not blast / fire hardened. Half building double height with roller shutter door and O/H crane.

8 ACTIVITY 10 – CAPEX AND OPEX ESTIMATE CLASS 4

DNV engaged the Project Control Partnership (PCP Ltd) to prepare to a conceptual CAPEX cost estimate consistent with AACE Class IV (+30%/-25%) for a greenfield ammonia export terminal. Potential savings from reusing existing ammonia infrastructure in Mejillones are discussed below.

The estimate was prepared based upon:

- Major equipment estimated using PCP proprietary software based upon equipment key technical data provided by DNV
- Bulk materials (piping, instrumentation, electrical materials, civil works, structural steel) have been pro-rated from the equipment costs using factors from the PCP Cost Estimating Manual, based upon historic costs from similar units.
- Construction costs have been pro-rated from the equipment costs using factors from the PCP Cost Estimating Manual, based upon historic costs from similar units. Man-hours have been back-calculated using average labour rates for Northern European projects and the construction estimate then corrected for Chile based upon a factor of 0.791 (i.e. $100 construction cost in Europe would cost $ 79.10 in Chile).
- Indirect costs and engineering costs have been developed based upon historic norms assuming an international engineering contractor with an average blended man-hour rate of $ 100/hour.
- Owners costs have been pro-rated against indirect costs as a percentage of EPC costs.
- An owners contingency of 20% has been applied based upon the current early stage project definition.

The project estimate specifically excludes:

- Pre-FID engineering development (FEED) costs
- Forwards escalation.
- Import duties and local taxes
- Capital spares
- Feedstock and utilities costs
- Decommisioning costs

DNV and PCP has estimated a Total Cost for the proposed facilities as described in Section 7 of $ 480 Million USD. The high level summary of the cost estimate is reproduced on the following page:

Table 6. Ammonia storage & export facility capital cost estimate

DESCRIPTION	MATERIALS Total (USD)	FABRICATION Total (USD)	SUBCONTRACT Total (USD)	LABOUR Total (USD)	INDIRECTS Total (USD)	TOTAL COST (USD)
Terminal Area	77,984,585	3,649,126	107,377,670	32,374,202	56,133,546	277,519,130
Jetty Topsides	4,757,250	180,755	848,002	1,485,134	1,924,532	9,195,672
Jetty Substructure			70,220,940		9,830,932	80,051,872
Interconnecting Piping	2,285,370		2,682,530	5,968,500	2,460,690	13,397,090
Total EPC Cost	**85,027,205**	**3,829,881**	**181,129,142**	**39,827,836**	**70,349,700**	**380,163,764**
Owner's Costs					20,199,472	20,199,472
Forward Escalation						*Excluded*
Owner's Contingency	16,972,795	770,119	36,270,858	7,972,164	18,150,828	80,136,764
TOTAL COST	**102,000,000**	**4,600,000**	**217,400,000**	**47,800,000**	**108,700,000**	**480,500,000**

In case ENAEX's existing maritime infrastructure could be reused (buoy, mooring, subsea hose) this could translate to significant savings.

ENAEX's limited ammonia storage capacity could in principle be used for pilot or early stage projects, but eventually new storage tanks would have to be built. Additionally, further import facilities by pipeline, rail and/or road would have to be built.

Opex has been estimated as 2% of initial capex – approximately 10 million USD/year – plus electrical power costs of approximately 1 M USD/year (a constant power consumption of 4 MW at a cost of 25 USD/MWh).

9 ACTIVITY 11 – TOTAL LEVELIZED COSTS

9.1 Introduction

The calculation of total levelized costs serves the purpose of deriving a unique production and transportation cost value over the project's lifetime. It further allows to identify the unique cost segments and their respective contribution to the total levelized costs. Finally, competing projects may be assessed against each other from an economic perspective. Thereby, the project's competitiveness can be identified in production cost terms.

In order to calculate total levelized costs, a Microsoft Excel-based tool has been developed. It allows to compare different options of the project specifications. Additionally, sensitivities can be analyzed. Thereby, comparisons both of project specifications (i.e. by differentiation of the energy carrier for ship transport) and of project locations (i.e. the comparative advantage of production in Chile rather than in Australia) can be undertaken. The calculation tool uses DNV-internal, research, and project specific data as input.

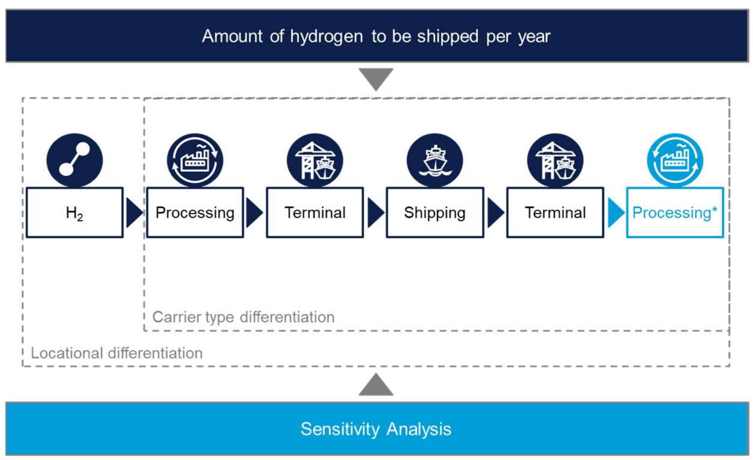


Figure 27. Cost model

Figure 27 shows on a conceptual level the different steps and options that are calculated in the bottom-up tool. Processing after import (in blue) is considered as optional step, as the use of ammonia as end product is next to hydrogen as end product equally used for comparison purposes.

Conscious of different project uncertainties, the total levelized costs depicts the expected cost given a set of assumptions. It does not account for or reveal eventualities unless included in the assumptions. As such, changed assumptions may, depending on the cost segment's contribution to the total levelized costs, have a larger or smaller impact on the final total levelized costs.

9.2 Methodology

Fundamental to the calculation of levelized costs is the normalization of value by use of an annuity factor. This factor is derived by the expected lifetime of the project and the discounting factor. Apart from this factor, recurring cost such as operating and fuel costs and one-off costs, first and foremost capital expenditure, are included in the calculation.

The specific input data for the different steps along the supply chain are depicted in Figure 28, Figure 29 and Figure 30.

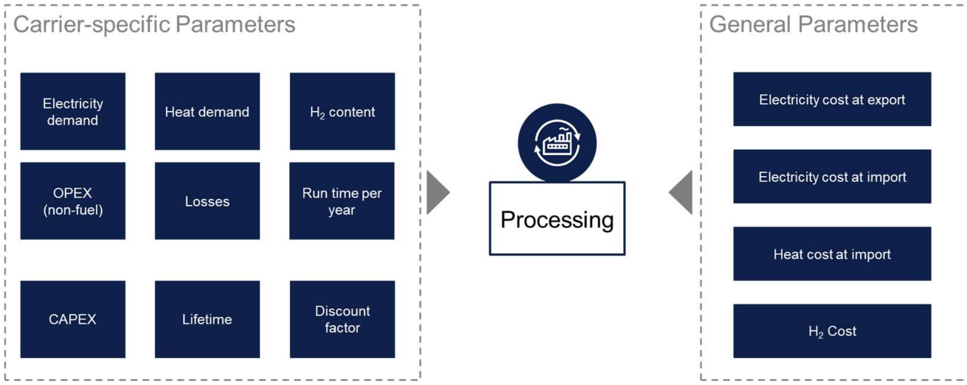


Figure 28: Processing parameters

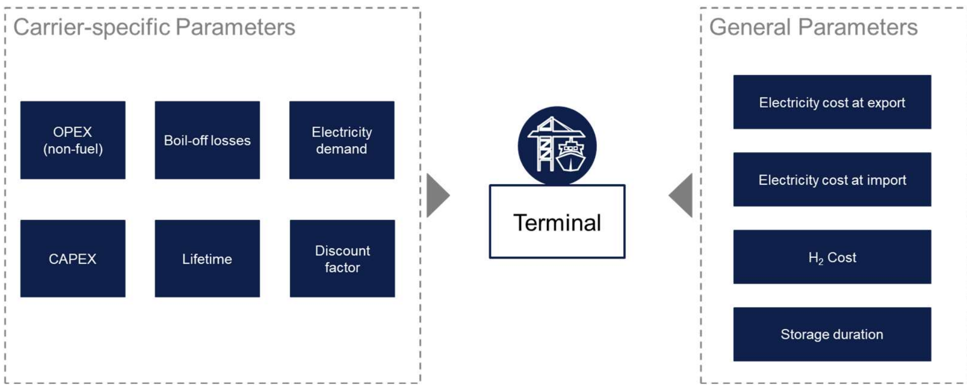


Figure 29: Terminal parameters

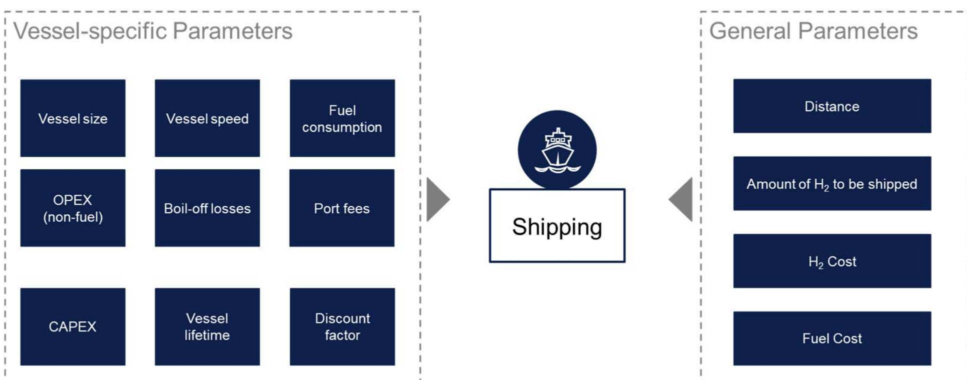


Figure 30: Shipping parameters

In Activity 11, the parameters for the terminal have been refined on the basis of the results from the preceding activities. The major base assumptions are as follows:

- LCOH of hydrogen production is 1.39 $/kg as provided by the Ministry, or the average LCOH cost figure for the respective origin country provided by Brändle et al 2020[14], if cross-country comparisons are made. The latter LCOH are as follows: For Australia 3.15 $/kg, for Chile 2.64 $/kg, for Morocco 2.76 $/kg, for Saudi Arabia 2.56 $/kg. These LCOH correspond to the averages of the available cost figures per country.
- The production volume is 200 kt H2 per year. The volume for the terminal differs, as other sources of hydrogen are stored and loaded there as well. This difference is also used to determine the permissible size of the shipping vessel.
- The electricity price for processing and terminal operation is half in Chile compared to the assumed price in the import country, because of the exceptionally good locational factor for renewable energy sources in Chile.
- The terminal costs are estimated at USD 480,500,000. 2% of these CAPEX are recurring operating costs. Required electricity is assumed to be a constant load of 4 MW. The terminal is sized for 1 million tons of ammonia per year throughput. This results in 0.03504 kWh per throughput kg NH_3 electricity demand.
- Shipping costs are assumed at USD 75,500,000 for the ammonia carrier vessel, but idle time of the ship needs not be paid. This specification of the assumption is relevant, as the pre-set shipping distance and shipped amount results in idle time during which the ship could be used for other purposes. Therefore, only a part of the CAPEX for the ship is attributable to the transportation of ammonia as included in the project cost. In addition, fuel prices and CO_2 are assumed as constant throughout the project period.
- Import terminal costs are derived from IEA 2019
- The discount factor is 8%. The reference year is 2030.

9.3 Results

The results from the cost calculation show a strong competitiveness of the envisioned projects. The cost segmentation as set out in picture Figure 31 and Figure 32 reveals that export terminal costs are minimal compared to the other cost segments, particularly the production cost. Transportation costs (being the sum of export terminal, shipping, and import terminal costs) account for about 9% of the total levelized costs for ammonia. Given the expected low LCOH of 1.39 $/kg by 2030, total ammonia costs are strongly competitive in Europe.

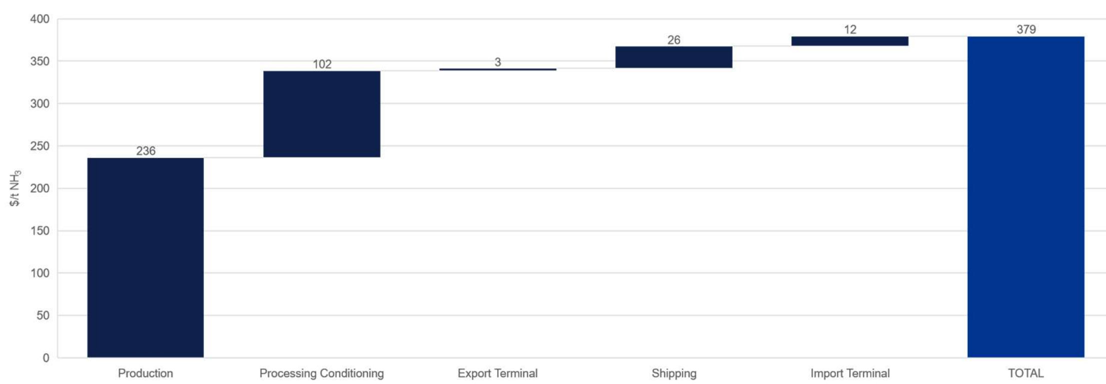


Figure 31: Ammonia cost segmentation Chile – Europe

[14] Gregor Brändle, Max Schönfisch, Simon Schulte, Estimating Long Term Global Supply Costs for Low Carbon Hydrogen, EWI Working Paper, No 20/04, 2020

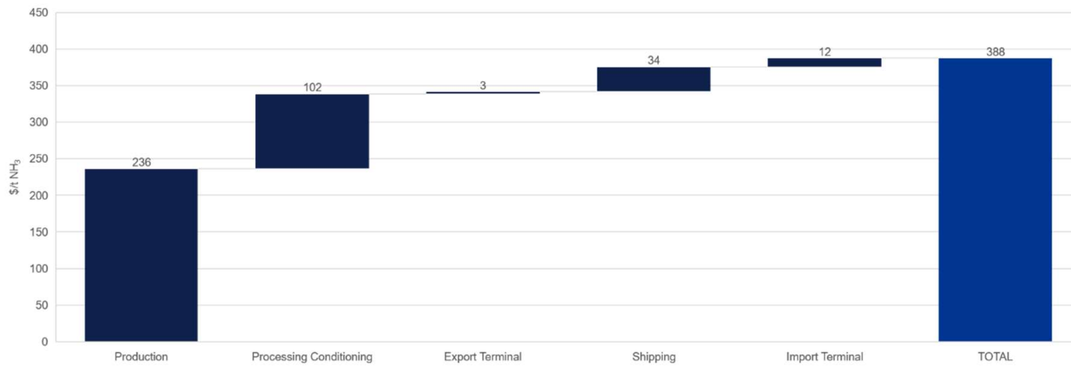
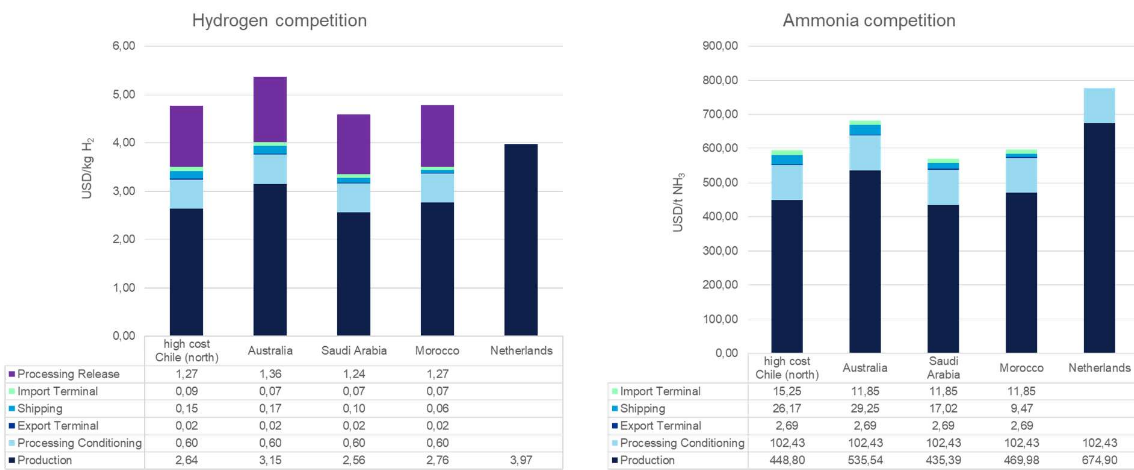


Figure 32: Ammonia cost segmentation Chile – Japan

Figure 33 and Figure 34 show the cost competition to Europe and Japan using LCOH estimates from Brändle et al 2020 (2.64 $/kg for Chile). For hydrogen as an end product, the expected release costs in the importing country have a significant impact on cost competitiveness. This impact can be perceived from the purple-colored release costs in Figure 33 and Figure 34 (left hand side). For example, hydrogen from Chile could be delivered in Europe at 4.77 USD/kg while hydrogen could be produce in Europe at 3,97 USD/kg. However, assuming 1.39 USD/kg for hydrogen production as per the Ministry's forecast instead of 2,64 USD/kg as per the forecast in Brändle et al 2020, hydrogen from Chile could be delivered in Europe at 3.52 USD/kg imply cost competitiveness to domestic production. In any case, the export of ammonia appears to be cost competitive to domestic production in Europe even in the case of conservative hydrogen production costs (as shown on the right hand side in Figure 33).



	high cost Chile (north)	Australia	Saudi Arabia	Morocco	Netherlands
Processing Release	1,27	1,36	1,24	1,27	
Import Terminal	0,09	0,07	0,07	0,07	
Shipping	0,15	0,17	0,10	0,06	
Export Terminal	0,02	0,02	0,02	0,02	
Processing Conditioning	0,60	0,60	0,60	0,60	
Production	2,64	3,15	2,56	2,76	3,97

	high cost Chile (north)	Australia	Saudi Arabia	Morocco	Netherlands
Import Terminal	15,25	11,85	11,85	11,85	
Shipping	26,17	29,25	17,02	9,47	
Export Terminal	2,69	2,69	2,69	2,69	
Processing Conditioning	102,43	102,43	102,43	102,43	102,43
Production	448,80	535,54	435,39	469,98	674,90

Figure 33: Cost competition to Europe

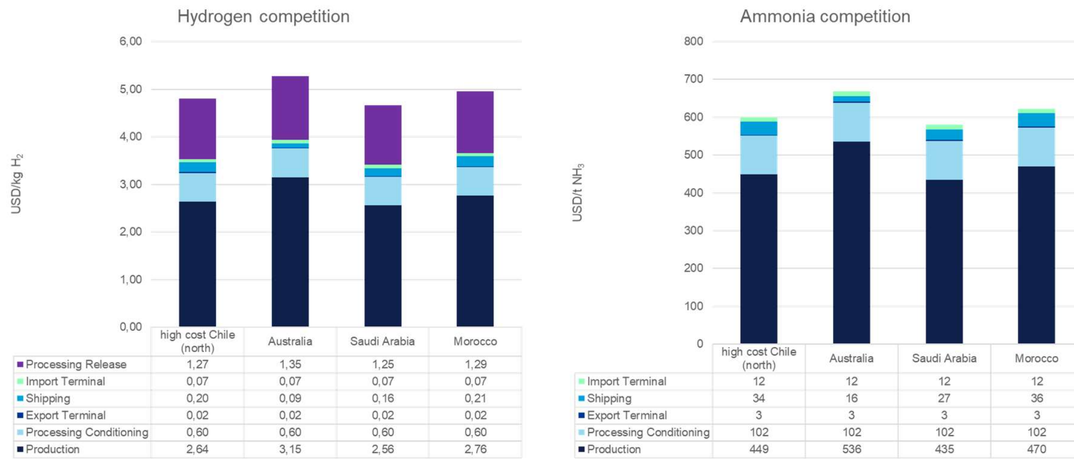


Figure 34: Cost competition to Japan

When comparing total levelized cost from Chilean production and export to production and export from Australia, Saudi Arabia and Morocco, Chile scores – depending on the condition if the importing country is in Europe or Japan – second or third. Notwithstanding, the cost differences are limited. Noting this narrowness as well as the conservative LCOH estimates in Brändle et al 2020 compared to 1.39 $/kg estimate provided by the Ministry of Energy, it may be followed that the contribution of the transportation cost to the likelihood of project success is minor. However, given high release costs, ammonia as the final end-product is, in cost terms, the better option.

Note: due to harmonization requirements across all hydrogen carriers in the shipping model cost model the actual levelized export terminal costs are significantly higher, please refer to section 13.3.3 of this report

10 ACTIVITY 12 – HIGH-LEVEL IMPLEMENTATION PLAN

It is expected that the overall design and construction of the ammonia storage facilities and export terminal will take around 40 months, including some preparatory work and EPC activities. In the below chart a break down into different activities is presented.

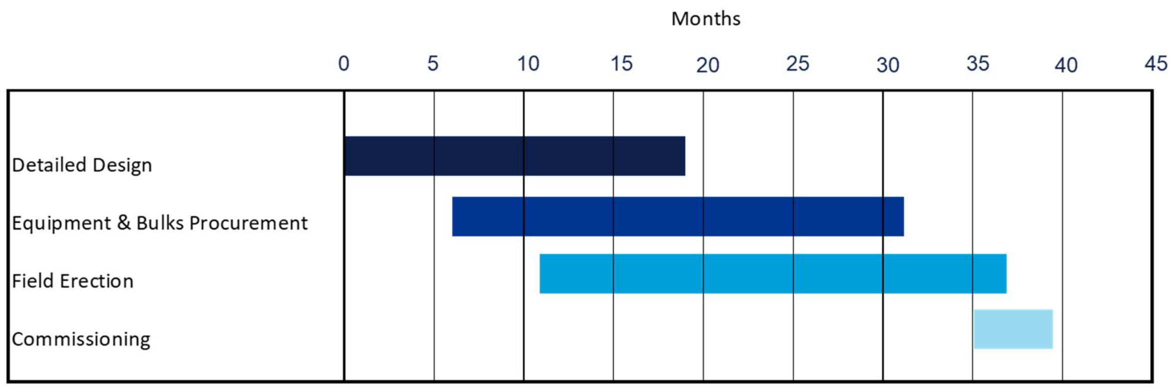


Figure 35: Overall high level implementation schedule.

It must be appreciated that the above schedule is exclusive of other (time consuming) activities like commercial negotiations, contracting, permitting and HSE-studies. In the next sections the various process steps in the establishment of the storage and export facilities will be further elaborated upon.

10.1 Preparations

An important limiting aspect of new business development is the so-called chicken and the egg dilemma, which especially goes for energy related projects. The issue here is that at the beginning of an energy transition process there is little demand for alternative forms of energy, but as long as demands remains low, asset owners are not very keen on investing in new infrastructure. This situation may last for a long period of time; it may take years before any movement on either the demand or the supply side may be noticeable. It should be very well considered what the actual demand for ammonia/hydrogen in the receiving countries really is; for now only very few users of green hydrogen can be found in North West Europe awaiting a promised reduction of hydrogen tariffs, although many companies have expressed their interest in a fuel transition toward hydrogen some time ago already.

In such phase, market parties typically meet and discuss business plans, but it will take a bold move by a few of them to actually put matters into motion on a relatively small scale at first, but again, before this will lead to delivery and offtake contracts to be signed may take a few years. Final investment decisions must be based on a thorough feasibility study including advanced cost / yield calculations to be underpinned by a cash flow analysis. Attracting capital for financing the project has also to be done at this stage.

Then, after having unfolded and shared business plans, preparations for the establishment of the required infrastructure are to be made, in the beginning leading to a Basis of Design containing all the functional requirements and capacities of the planned assets and infrastructure, followed by Front End Engineering & Design and Detailed Engineering phases. Geotechnical surveys must be carried out for exploring the soil composition and mechanical strength and an environmental impact report has to be prepared as well.

At this stage, also permits need to be applied which may be a time consuming process as well, depending on local governmental structures and legislation. Local and federal authorities must be involved, and plans may need to be adjusted based on specific demands that are being raised in the process, so it's back to the drawing board then. In other cases the permitting procedures can go quite smoothly without causing hardly any delay at all. For now it is unknown how governmental bodies would appraise the permit applications and how swiftly they are in issuing the permits. This of course will also depend on the impact the project has on the environment and possible hazardous aspects involved.

Depending on local conditions and market prospects, the preparatory phase will take between one and five years. This phase is proceeding the other phases shown inFigure 35.

10.2 Detail design and procurement phase

More or less in parallel with the permitting process, the detail engineering phase can start. At first based on some preliminary assumptions, but further on in the process the design will become more certain, leading to the phase when all kinds of system components, parts and equipment can be defined, followed by the actual procurement of the goods. In this phase also the contracting out of specific parts of the design and the construction work is done and working meetings amongst contracting parties about specific topics will be arranged on a regular basis. Typically at this stage a QRA will be done to learn about the design criteria regarding safety distances and other measures to be taken.

Drawings will be made, and remaining design and construction issues are to be resolved before the actual construction of the facilities can start. Especially regarding the procurement of materials it must be noted that delivery times are prolonged nowadays due to shortage of raw materials and products as a result of COVID-19 restrictions.

10.3 Field erection and commissioning

Already in the previous stages of the project, land procurement and some plot preparation can be done, but the main on site ground works can only commence once the detail design is more or less completed. Pipelines, power cables, drainage and other utilities must be installed and the foundations for the various installations will be laid. Once the plot preparation is completed the actual construction can start, and once underway the pace of construction will accelerate enabling the whole plant to be erected within a period of 25 weeks or half a year.

At the end of the construction phase, the plant is to be commissioned, implying that over a period of several weeks all kinds of test are ran, like pressure resistance and performance tests of specific pieces of equipment. At the end of this period a commissioning certificate is issued, and the plant is ready to be taken into operation.

10.4 Conclusion on the envisaged time schedule

Although the construction of an ammonia storage and exporting facility can be done in a manageable timeframe, especially the duration of the preparatory phase cannot be easily predicted. From start to finish the whole project may take everything between two and ten years.

It is estimated that the permitting phase can last between 1 year and up to 5 years or more if there are legal disputes and court cases

The possibility of reusing existing ammonia infrastructure in Mejillones at least in the initial industry phases could minimise the permitting times and enable exports in the minimum time frame possible.

11 ACTIVITY 13 – LOCAL JOBS AND SERVICES

11.1 Permanent jobs

Based upon the conceptual organization chart presented in Section 5.16 (Operations Philosophy), DNV estimates that the ammonia export terminal will directly employ 65 personnel.

The Operations Philosophy also assumes that external service providers will provide security services together with mechanical, electrical and instrumentation technical services and also cleaning and catering services. It is anticipated that these additional jobs service contracts might result in 42 additional jobs in the Mejillones area:

- Security – five shifts each of four personnel – 20 jobs
- Mechanical – estimated to be ~ 6 jobs
- Electrical - estimated to be ~ 6 jobs
- Instrumentation - estimated to be ~ 4 jobs
- Cleaning and catering - estimated to be ~ 6 jobs

11.2 Construction jobs

The PCP / DNV CAPEX estimate has estimated the following site hours expended over a 25 month construction period and levelized into person equivalents based upon 2000 hours/year.

Table 7. Construction jobs

Description	**Total site hours over 25 months**	**Equivalent in job years based upon 2000 hours/year**
Equipment setting	55,922	27
Piping installation	340,456	170
Control systems installation	13,923	6
Field instruments installation	72,079	36
Electrical equipment installation	2,598	1
Electrical cables installation	51,714	25
Telecom systems installation	13,183	6
Site preparation	13,431	6
Civil works	168,707	84
Road, rail, paving and fencing	57,093	28
Buildings	218,496	109
Steelwork	63,224	31
Insulation	111,485	55
Painting	40,513	20
Scaffolding	158,061	79
Commissioning support	81,678	40
TOTAL		**723 job years**

12 ACTIVITY 14 – EXPORT TERMINAL BUSINESS MODELS

In this Chapter, the potential export terminal business models are discussed in greater detail.

12.1 Background LNG trade

The first LNG cargo was shipped in 1958 from the United States to the United Kingdom. Shortly after, LNG shipments from Algeria started to Europe. However, the gas market reforms in the United States slowed down this increase in LNG trade in the Atlantic Basin. Simultaneously, more interest in the Pacific market started to emerge driven by import countries as Japan, South Korea and Taiwan.

In the early days of the LNG market these value chain projects were underpinned by long-term sales contracts between large IOCs or NOCs (international oil companies and national oil companies respectively) and state-owned utility companies (often 20 years or longer). The ownership of the utilities resulted in low counterparty credit risk. In these structures the volume risk of the project was taken by the utility company. These companies could often rely on regulated home markets where the contract price would be part of the regulated tariff. The price risk was taken by the upstream producers by linking the price formula to oil. The contract structures were often point-to-point dedicated to the specific value chain.

The emergence of the United States as a major producer of shale gas and the liberalization of the European market has created a radical change in this traditional business model. The access to a liquid market to source and offload significant volumes allowed the tolling model for liquefaction plants to emerge. In this model the LNG liquefaction plant would be rented out to different producers or traders who wanted to convert their gas into LNG and export to other regions. Also, the access to a deep and liquid market allowed other LNG producers to sell their excess gas or replace shortfalls in supply. These developments increasingly opened up the LNG market for smaller non-traditional players and this is often called a merchant market.

Further, substantial changes in the pricing mechanism for LNG have taken place. In the beginning of the LNG trade all contracts were indexed against oil. Currently, more and more contracts are indexed against gas prices, which is the case with grey hydrogen contracts as well. An overview of the main import and export markets is provided in Figure 36.

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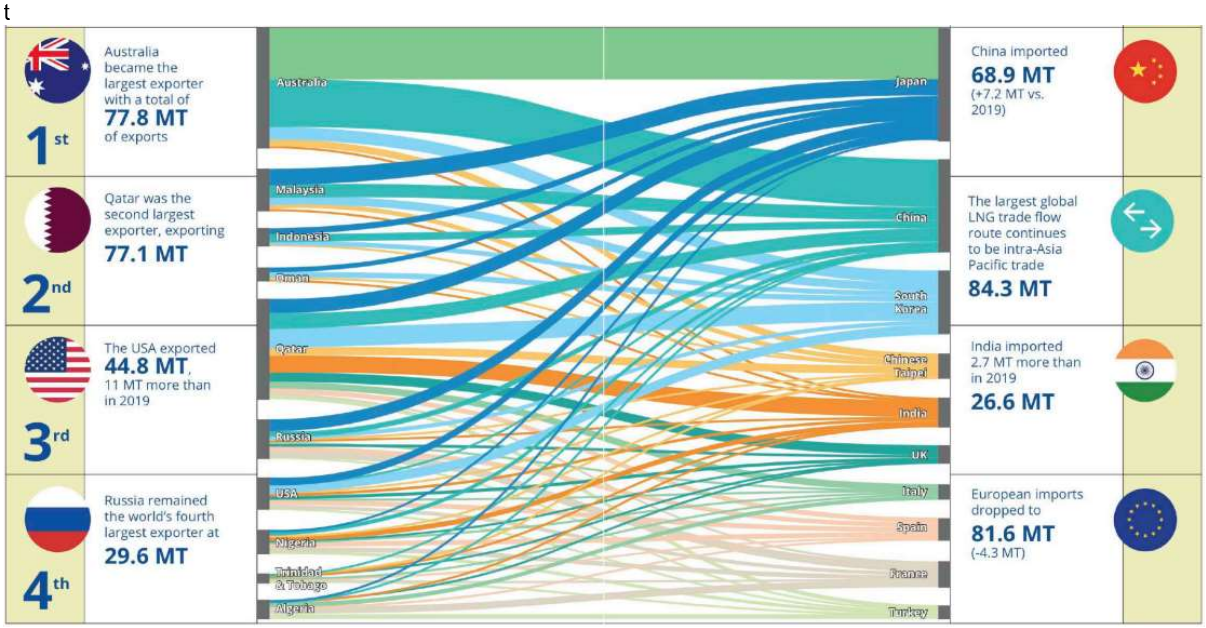


Figure 36: Qatar and Australia are responsible of ~50% of global LNG trade.[15]

[15] IGU World LNG Report 2021 | IGU (2021). Retrieved February 17, 2022, from IGU website: https://www.igu.org/resources/world-lng-report-2021/

12.2 Overview of LNG terminal models

Several terminal business models could be considered, in which different parts of the supply chain are operated by either one or multiple parties. Each terminal model has an ownership structure as well as a contract structure. The building blocks for the ammonia supply chain are similar to the LNG supply chain. Due to the choice of ammonia as energy carrier, these are used interchangeably. In Figure 37, the supply chain for renewable ammonia is depicted with the three different business models that could be opted for.

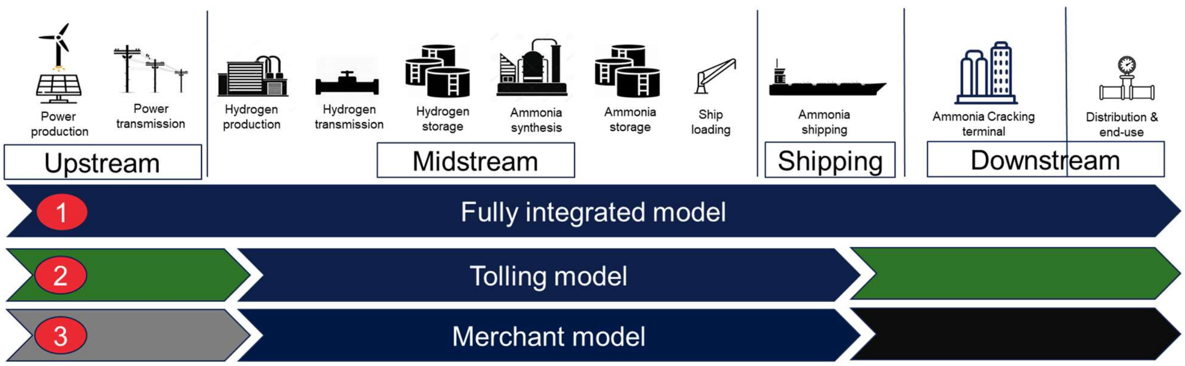


Figure 37: Three different business models: blue indicates included in the business model, green indicates it is the same entity at both sides of the ammonia plant, grey and black indicate the upstream entity is different from the downstream entity.[16]

12.2.1 Commercial Structure 1: Fully Integrated Model

Under the fully integrated structure the ownership of upstream assets, transportation and liquefaction plant is held by one joint venture company, or has the same shareholders as the upstream assets. The upstream assets are fully integrated into the LNG export facility.

LNG export terminals are often perceived as medium to low-risk projects. This is mainly due to the sound economics, strong sponsors and reliable long-term contracts with creditworthy buyers. Therefore, typically these projects have been financed on a project basis up to 70% debt. This allows for the minimization of the high-priced cost of capital from the sponsors. The absence of commodity price risk in the tolling model or the merchant model can even result in debt levels up to 90%.[17] The projects rely on the revenues from the sales to repay the loans.

The typical lenders to LNG projects are commercial banks, export credit agencies, multilateral agencies, debt capital markets, buyer country institutions and sponsor co-lending. Since mid-2000s large buyers have also been entering the upstream fully integrated projects (such as Kogas).

A long-term dedicated sales contract or multiple sales contracts (SPAs) between the upstream joint venture (or the individual shareholders) to a-listed creditworthy utility companies are typical. The credit of the buyer(s) is underpinning the capital-intensive upstream investments. Long term price review clauses included in the SPA were intended to protect both buyer and seller to alignment with potential changing market conditions.

Delivery of LNG was often either as Free-on-Board (FOB) at the liquefaction terminal or Delivery-ex-Ship / Delivery-at-terminal (DES/DAT) at the receiving terminal. The delivery contracts offered limited flexibility for diversion to other

[16] Gas Processing Liquefaction Production Exploration and Development Transport Understanding Natural Gas and LNG Options Global Edition. (n.d.). Retrieved from https://www.energy.gov/sites/prod/files/2017/09/f36/Understanding%20Natural%20Gas%20and%20Lng%20Options_general%20no%20appendix.pdf

[17] LNG Finance - will lenders accommodate the changing environment? (n.d.). Retrieved from https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Insight-78-LNG-Finance-will-lenders-accommodate-the-changing-environment.pdf

destinations and contained take-or-pay clauses with some volume flexibility on the buyer's side. National governments are often actively involved through national oil & gas companies in higher risk countries. An overview of the commercial structure is given in Figure 38.

Examples of fully integrated projects are: Qatar Qatargas and RasGas, Russia's Sakhalin, Norway's Snohvit, Australia's North West Shelf and Darwin LNG, and Indonesia's Tangguh.

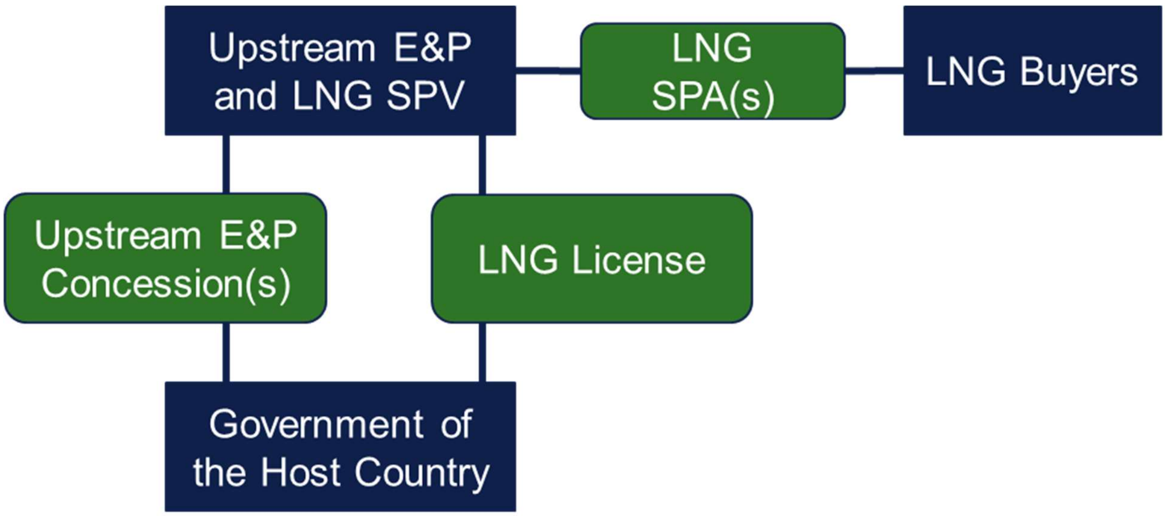


Figure 38: Overview of integrated business model: fully integrated model, with blue indicating the stakeholders and green the contracts and or permits.[18]

12.2.2 Commercial Structure 2: Tolling Model

Under the tolling structure, the ownership of upstream assets, transportation and liquefaction plant are under different entities. The liquefaction plant is not part of the fully integrated value chain but acts as an independent service provider by providing liquefaction services to the owners of the upstream gas assets (producers, merchants or utilities). This also means that the liquefaction company does not take title of the gas.

The financing of the tolling structure is like that of the fully integrated structure. The main difference is the lower capital that is required for the project since the upstream assets don't have to be financed. The credit of the off-takers is underpinning the financing.

The capacity in the LNG liquefaction plant is usually tolled under long-term contracts to creditworthy counterparties. These would generally be either large IOCs with a broad supply portfolio or merchants with access to deep and liquid traded markets.

The fee for the tolling would often consist of a two-part tariff. One fixed monthly payment that would cover the fixed operation and maintenance costs, debt servicing, and return on equity. The other part would cover the variable costs such as power purchases when gas is processed into LNG cargoes. Due to this structure the owner of the liquefaction plant is not exposed to any commodity price risk. This commercial tolling structure paved the way for the first LNG aggregator models and allowed for more diverse pricing mechanisms. The natural gas purchase and sales agreement (GSA), is set

[18] https://www.energy.gov/sites/prod/files/2017/09/f36/Understanding%20Natural%20Gas%20and%20Lng%20Options_general%20no%20appendix.pdf

up between the upstream project company and the tolling customer. An overview of the commercial structure is provided in Figure 39.

Tolling structure examples include Trinidad's train 4, Egypt's Damietta, Indonesia's Bontang, and the US' Freeport LNG, Cameron LNG, and Cove Point facilities.

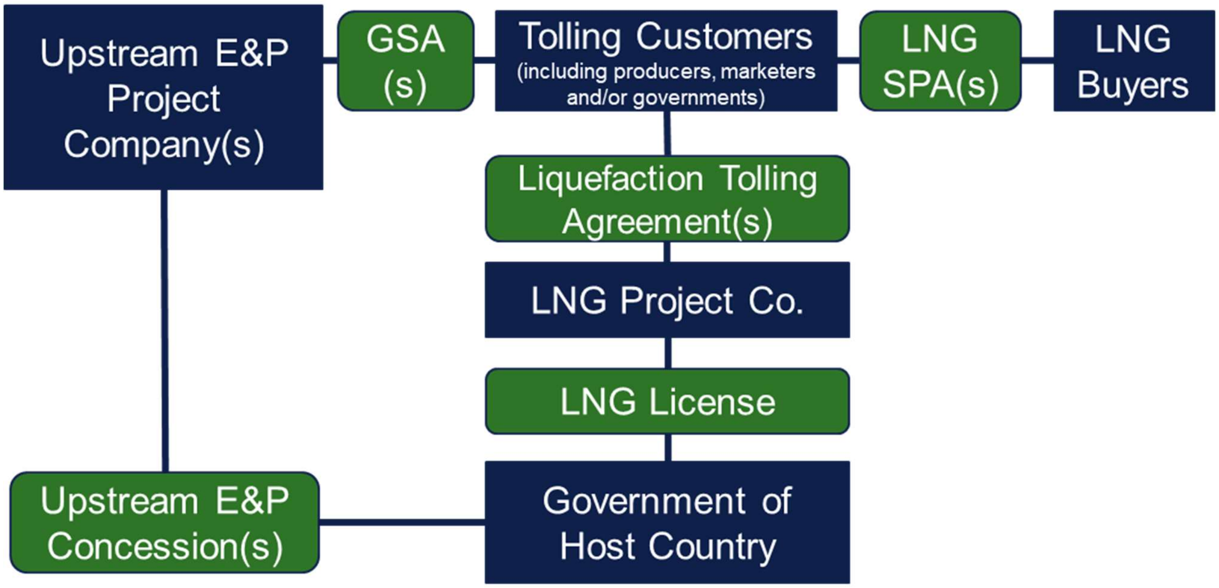


Figure 39: Overview of an tolling business model: tolling model, with blue indicating the stakeholders and green the contracts and or permits.[19]

12.2.3 Commercial structure 3: Merchant Model

Like the tolling structure, under the merchant structure the ownership of upstream assets, the transportation and liquefaction plant are under different entities. However, contrary to the tolling structure the LNG Project Company is buying the natural gas upstream and taking title of the natural gas. Often this is done under a long-term GSA.

The financing of the merchant commercial structure is like the other two models. However, opposite to the other two models the price risk between the purchase price of the natural gas and the sales price is one of the key project risks. The profit of the liquefaction plant is derived from the margin between the sales price and the cost of liquefaction and purchase of the natural gas. The credit of both the LNG buyer(s) and the upstream seller(s) are used to underpin the financing.

Depending on the ability to source short term upstream gas usually around 80%-85% of the liquefaction capacity is contracted by long-term upstream GSA contracts and sold back-to-back to LNG buyers. The remaining capacity can be utilized taking advantage of short-term price opportunities and shorter duration contracts.

With the development of the Henry Hub in the US and the TTF in Europe the major challenge with the merchant business model is to what extent long-term contracts remain necessary to underpin investments. Price convergence in the global LNG market could provide such a deep and trusted market that investors are confident that volume and price risk can be managed throughout the project lifetime. The energy transition and the currently increased volatility puts pressure on this trend. An overview of the commercial structure is provided in Figure 40.

[19] Gas Processing Liquefaction Production Exploration and Development Transport Understanding Natural Gas and LNG Options Global Edition. (n.d.). Retrieved from https://www.energy.gov/sites/prod/files/2017/09/f36/Understanding%20Natural%20Gas%20and%20Lng%20Options_general%20no%20appendix.pdf

Examples of merchant business models are Trinidad trains 1, 2, and 3, Angola, Nigeria, Equatorial Guinea, and Malaysia.

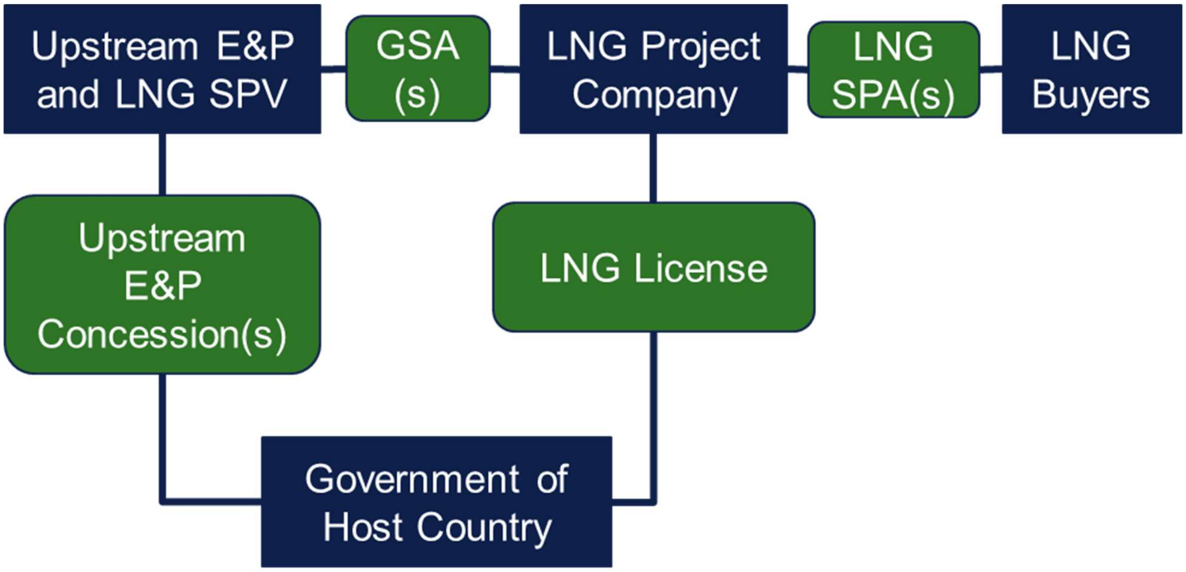


Figure 40: Overview of an commercial business model: merchant model, with blue indicating the stakeholders and green the contracts and or permits.[20]

12.2.4 Advantages and disadvantages

Some of the advantages and disadvantages of each commercial structure are listed in Table 8. In reality it is possible to create a hybrid model by combining different elements from these models to tailor to the needs of the project stakeholders.

Table 8: Overview advantages and disadvantages.[21]

Commercial structure	Advantage	Disadvantage
1. Integrated	Commercial parties are aligned between the upstream and LNG liquefaction project	Does not allow for different upstream projects with different ownership to come together in one LNG project
	No need to determine a transfer price	Does not allow for other entities, including the host government, to also have ownership in the plant
		Complex to expand for non-concession production
2. Tolling	No price or market risk for the LNG project investor	Requires additional project agreements with government
		Potentially different fiscal and tax regime

[20] Gas Processing Liquefaction Production Exploration and Development Transport Understanding Natural Gas and LNG Options Global Edition. (n.d.). Retrieved from https://www.energy.gov/sites/prod/files/2017/09/f36/Understanding%20Natural%20Gas%20and%20Lng%20Options_general%20no%20appendix.pdf

[21] Gas Processing Liquefaction Production Exploration and Development Transport Understanding Natural Gas and LNG Options Global Edition. (n.d.). Retrieved from https://www.energy.gov/sites/prod/files/2017/09/f36/Understanding%20Natural%20Gas%20and%20Lng%20Options_general%20no%20appendix.pdf

	Reduced environmental impact (one terminal serving several upstream producers versus each producer building their own terminal)	
3. Merchant	Flexibility to allow non-concession investors in the LNG plant	Requires additional project agreements with Government
		Potentially different fiscal and tax regime
		Requires negotiation of gas transfer price to manage price and volume risk

12.2.5 Evolution of LNG business models

As stated, the emergence of a fully liquid LNG market reduces the necessity for long-term contracts to secure funding for a project. The confidence in the ability for short- and spot trading to manage volume and price risk enables developers to lend without impacting gearing levels.

In the US and in Europe such market conditions are present, but the Asian market is still in its infancy. Major importers like Japan, China and India are dominated by a few state backed companies. However, there are signals that the JKM (which is the price marker for Asia) is being used (partially) in some of the new LNG contracts. Consequently, the liquidity of this benchmark is increasing.

In recent years the amount of receiving terminals for LNG has increased substantially just as the number of ships available (~650) to transport the LNG. Globally, this potential access to a fast network of existing LNG receiving terminals and ships is offering merchant players flexibility to build customized portfolios.

One of the major issues surrounding the evolution towards a fully merchant business model is the allocation of the price risk. For example, with some of the US export models the price risk is allocated to the buyer. The base price of the LNG is derived from the Henry Hub where a liquefaction fee is paid on top. Especially, in the Asian market this makes these projects only competitive if the US market remains substantially lower than the European or Asian market. Competing projects from countries where there is no apparent alternative for the feed gas can offer more attractive terms where the price risk is eliminated from the buyer.

In the US, Cheniere has been partially successful in some of the newer contracts and seem to be willing to offer feed gas at the buyers' market prices. That means buyers can source their gas at the Henry Hub but have it indexed against domestic (Asian or European) price indices. The market evolution is depicted in Figure 41, where the global (liquid) market is depicted in Figure 42.

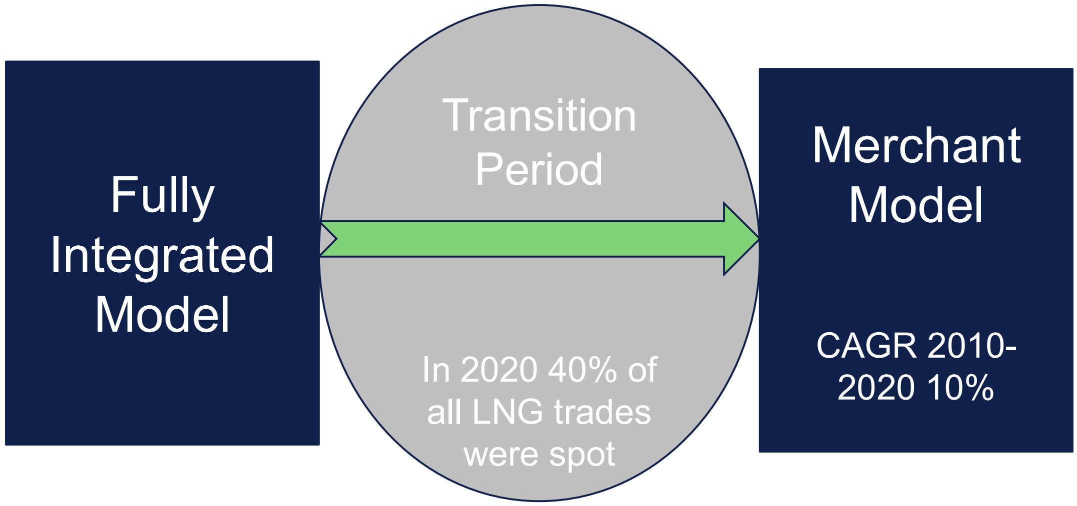


Figure 41: Evolving LNG market: from a structure market to a merchant market (adapted).[22]

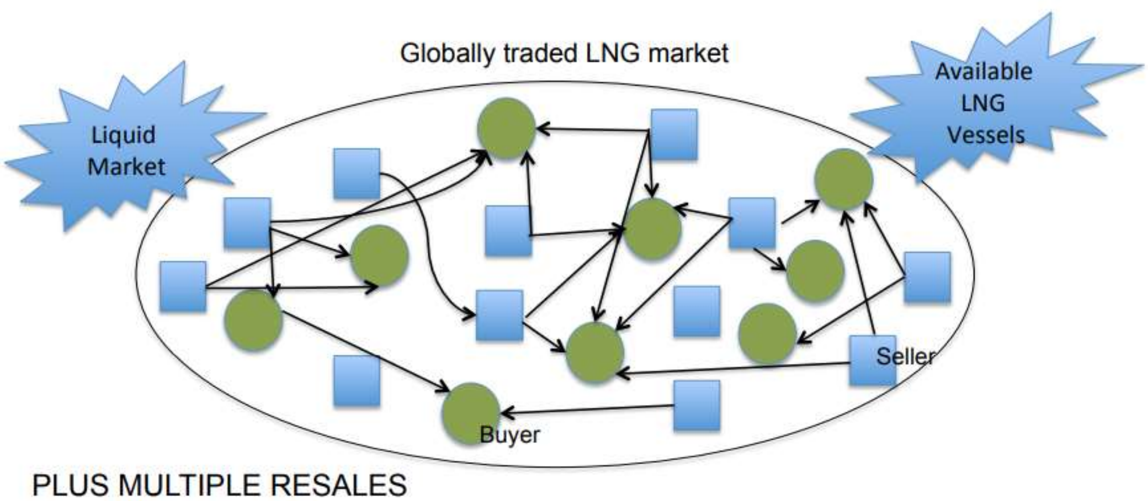


Figure 42: Fully flexible value chain starting to emerge.[23]

12.3 Overview of Ammonia Trade

The key role of ammonia today is as the basic feedstock for inorganic fertilizers that currently support food production for around half of the world's population. This accounts for around 77% of today's annual ammonia use.

Regarding the industrial use that makes up the remaining 23%, ammonia is the key component in the production of AdBlue (Urea) for vehicle NOx control, and in the pharmaceutical, textile and explosives industries. Furthermore, in this area, ammonia is an efficient refrigerant that has been used extensively since the 1930s in industrial cold stores, food processing industry applications and increasingly in large scale air conditioning.

[22] New Players, New Models A research think piece. (2019). Retrieved from https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/04/New-Players-New-Models.pdf

[23] New Players, New Models A research think piece. (2019). Retrieved from https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/04/New-Players-New-Models.pdf

Use cases potentially possible but (large scale) not applied today include:

1. As a transport fuel, by direct combustion in an engine or through chemical reaction with oxygen in the air in a fuel cell to produce electricity to power a motor (especially in the maritime sector).
2. As a medium to store and transport chemical energy, with the energy being released either by directly reacting with air or by the full or partial decomposition of ammonia to release hydrogen.
3. To store thermal energy through the absorption of water and through phase changes between material states (for example liquid to gas).

Most ammonia is traded in converted forms as fertilizers and urea but 11% of global ammonia production, or 18.5 million tons, is still traded as ammonia. The main centre for ammonia trade is Yuzhne in the Black Sea, where most spot trades take place. The relative pricing in other geographies is typically consistent with prevailing freight rates. The main global trade flows of ammonia are shown in Figure 43 and Figure 44.

Ammonia export terminal business models are comparable to LNG liquefaction terminals. It has the same value chain components and capital-intensive character. The main difference is that the different independent ammonia producers are not active in the upstream natural gas market (for example: CF Industries, Yara, Nutrien, Group DF, Qafco, TogliattiAzot, Eurochem and Acron). Therefore, the fully integrated model is not common in the ammonia market.

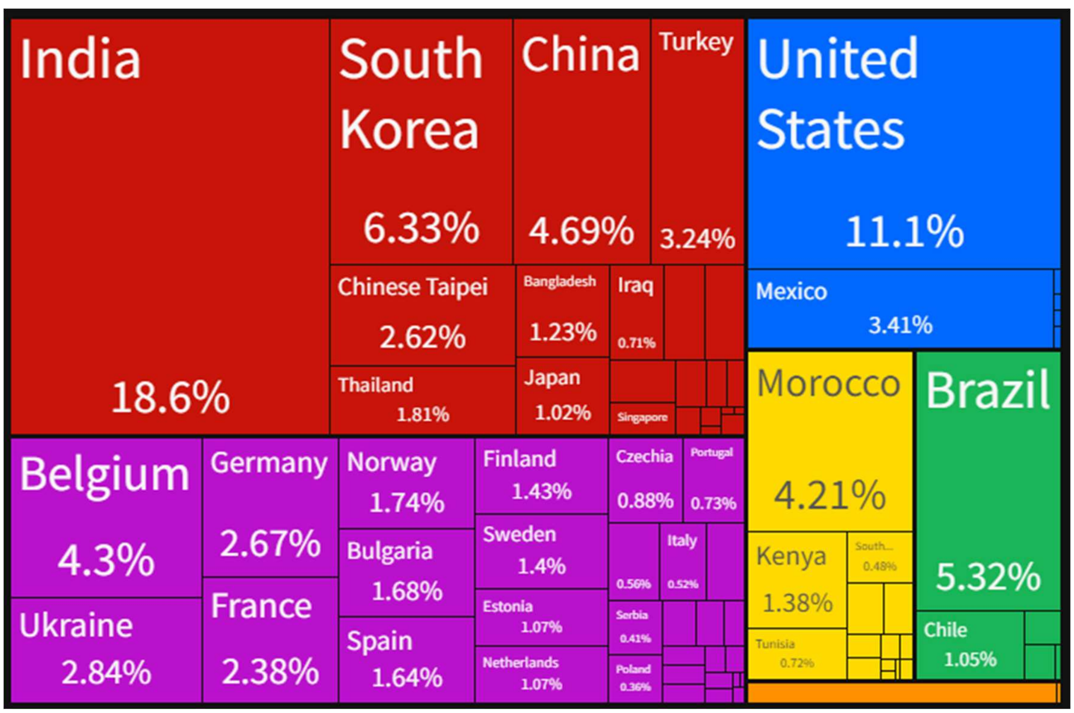


Figure 43: importers of ammonia in 2019. The colours refer to: red (Asia), blue (North-America), purple (Europe), yellow (Africa), green (South-America).[24]

[24] OEC - The Observatory of Economic Complexity | OEC. (2022). Retrieved February 1, 2022, from OEC - The Observatory of Economic Complexity website: https://oec.world/en

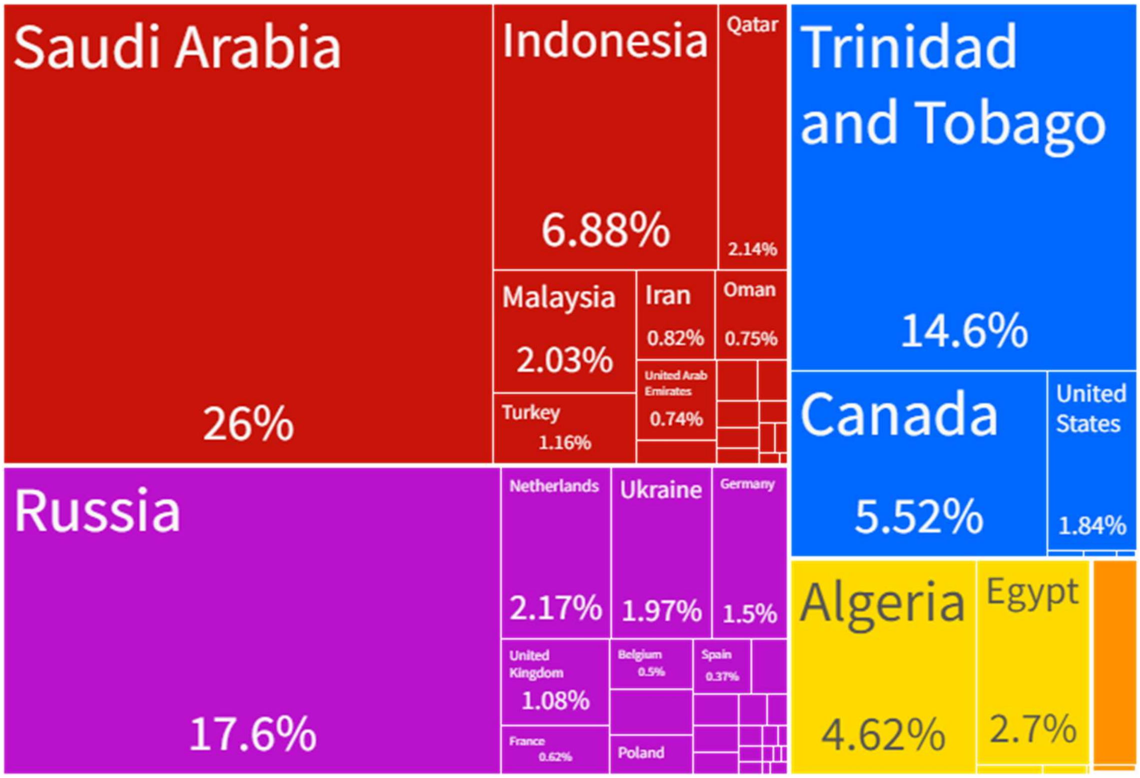


Figure 44: exporters of ammonia in 2019. The colours refer to: red (Asia), blue (North America), purple (Europe), yellow (Africa).[25]

12.3.1 Role of the Chilean government

General role of governments in hydrogen projects

The US Department of Energy identifies the general role of a government as to set policies that define development objectives for the relevant energy sector, establish institutions that set priorities, establish legal and fiscal frameworks governing the relevant energy carrier and infrastructure development and monitor governmental entities and private sector companies to ensure that all priorities and rules are followed. These developments are hardly ever done by a government on its own. Most of these energy and infrastructure projects require specialistic knowledge for which external partners are required.

These large scale and capital intensive infrastructure projects cover a broad range of policies and therefore require broad consensus within different governmental organizations. Also, the development of local applications is key to successful export projects.

Government participation

Strategic government participation in large scale energy projects is key for a successful outcome. Support is often critical in obtaining land ownership rights and the right permits and approvals. Also, direct (equity stake) or indirect (state-owned

[25] OEC - The Observatory of Economic Complexity | OEC. (2022). Retrieved February 1, 2022, from OEC - The Observatory of Economic Complexity website: https://oec.world/en

company equity stake) participation in the project might improve the (external) credibility of a project and improvement along the value chain.

In LNG projects active government participation is common around the globe[26]. This active participation is often executed through national oil and gas companies. Examples are: Qatar Petroleum Company or Sonangol. The form and extent of participation will depend on the nature of the host country.

Also, for the internal country transmission infrastructure, government involvement or coordination is beneficial. Especially, if there is limited existing infrastructure. Once a project or sector has become self-sufficient a divestment of the Government interest is possible.

Hydrogen policy and regulatory framework

The successful development of a hydrogen market requires, at least, three fundamental pillars:

- A national hydrogen policy (e.g. National Green Hydrogen Strategy)
- A hydrogen act or law that provides the overall legal basis (e.g. with respect to market structure)
- A hydrogen master plan that sets out the plan to monetize the national renewable resources, with the aim to develop a hydrogen industry (the implementation of the strategy)

One of the main challenges is to align the speed of infrastructure development to match demand and supply for both the export and the internal market. The important outcomes of an effective hydrogen policy are:

- Hydrogen deliverability
- Affordable power and hydrogen supply
- Commercialization of supply
- Availability of power
- Access to the market
- Regulations

The above criteria will set the tone for necessary regulatory and policy frameworks for domestic and export hydrogen supply through the hydrogen master plan as well as the national hydrogen policy. All these frameworks should start with clear objectives as captured in the hydrogen master plan.

The features of an effective hydrogen policy are:

- Facilitate effective project development/operation for all stakeholders
- Provide transparency, clarity of roles/responsibilities and ease of doing business
- Minimum complexity
- Monetary policy (exchange rate/repatriation of profits, etc.)
- Facilitate local hydrogen utilization projects
- Facilitate development of local infrastructure, either by government, public/private partnership, or private investors

[26] https://www.energy.gov/sites/prod/files/2017/09/f36/Understanding%20Natural%20Gas%20and%20Lng%20Options_general%20no%20appendix.pdf

- Economic and social development outcomes for local communities
- Stakeholder consultation

12.3.2 Design criteria of a hydrogen/ammonia business model

The needs of the three main parties

In the design of a hydrogen business model the different needs of the main parties involved (producers, government and end-users) must be considered. This is reflected in Figure 45**Error! Reference source not found.**.

The producers' needs are:

- Sufficient visibility and predictability over returns on capital invested and operational costs to justify making the investment now
- To demonstrate to investors that revenues will be sufficient to pay a return on any capital provided to the producer, in line with similar type of projects
- To be able to price competitively in comparison to counterfactual fuels to attract end users
- To be able to supply hydrogen in the market regardless of the technology they have used to produce hydrogen or the size of their operations

The Government needs are:

- To achieve strategic objectives such as decarbonization targets, security of supply, affordability, job creation, economic development etc.
- To keep the subsidy to a minimum to reduce distortions created by government intervening in the market, and the right duration necessary to trigger investment and establish a self-sustaining market
- To be comfortable that projects represent value for money. Funding is limited – if it has been allocated to one project to achieve a particular objective, it will not be available to another if the first project does not deliver on that objective
- To ensure all subsidy control requirements have been met and be comfortable with any balance sheet implications

The end-users' needs are:

- Sufficient visibility of costs and availability of hydrogen to justify switching
- The cost of hydrogen to be no more than the cost of the counterfactual fuel that it is replacing to justify switching to hydrogen or any additional cost to be matched by achieving a higher value for a low carbon product
- To be able to secure long-term supplies of hydrogen and find alternative sources of low carbon hydrogen should producers cease production.

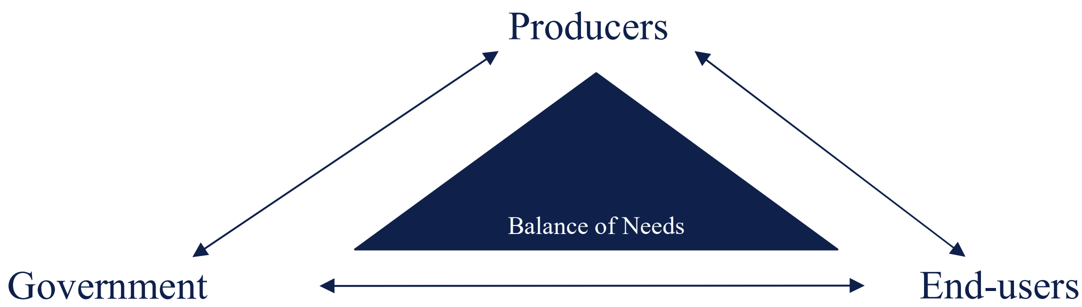


Figure 45: Balancing the needs of the different stakeholders is key in the business model, with the Government representing the needs of civil society and the environment.

A 'good' business model should provide a stable contractual framework, that avoids both unnecessary complexity and excessive simplicity.

- It should incentivize the private sector to allocate capital to the construction of hydrogen/ammonia production plants, incentivize that plant to produce hydrogen/ammonia only when there is demand for it, incentivize the producer to promote and develop end-use markets, and incentivize them to sell that production at a price that fairly reflects its intrinsic value in various applications.
- It should protect the plant from bearing the full uncertainties of an immature market but reduce/remove those protections as they cease to be necessary.
- It should ensure that in the case of subsidies returns to the producer are not excessive, and tightly control overall cost to the government by enabling subsidy to reduce both within the contract life and across different rounds of contract awards. It should effectively reduce the subsidy to zero when the market has sufficiently developed to a point that the value of hydrogen/ammonia reflects the cost of producing it.
- It should enable investment in projects based on low carbon hydrogen production technologies, and for progression from 'first of a kind' (FOAK) to 'Nth of a Kind' (NOAK) to be supported with only minor adjustment to the model rather than a more fundamental redesign.
- In future it should be able to function in a competitive allocation process.

12.3.3 Key design criteria for the assessment of options

In Table 9, an overview is provided of the key design criteria and its principles.

Table 9: Overview of principles for the evaluation of configurations.[27]

Principle	Description
Promotes market development	Model should incentivize producers to seek and develop sources of demand for hydrogen and promote its use

[27] Low Carbon Hydrogen Business Model: consultation on a business model for low carbon hydrogen. (n.d.). Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011469/Consultation_on_a_business_model_for_low_carbon_hydrogen.pdf

Promotes market competition	Model should not create barriers to market entry, enable abuse of market power, or provide an enduring competitive advantage to first movers compared to later market entrants
Investable	Model should provide sufficient predictability over revenues and returns to investors and mitigate risks which investors are not best able to bear
Value for money	Model should be effective in achieving its intended purpose at the lowest possible cost to society and prevent excessive returns to developers
Reduces support over time	In the case of revenue support the model should allow for revenue support to producers to reduce over time (within and between contracts) by being responsive to evolving market conditions and encouraging learning, innovation, and cost reductions over time
Suitable for future pipeline	Model should be fit for purpose for FOAK projects as well as NOAK projects with minor or reasonable adjustments
Compatible	Model should be compatible with other policies across the value chain and should not result in double subsidization of the same units
Technology agnostic	Model should be applicable to a range of production technologies (provided they meet the low carbon hydrogen standard and do not create an enduring competitive advantage for one technology over another)
Size agnostic	Model should be applicable to a range of project sizes and should not incentivize inefficient sizing of production plants
Avoids unnecessary complexity	Model should avoid unnecessary complexity in its design, implementation, and administration, and be transparent for producers to comply with

13 ACTIVITY 15 – AMMONIA TERMINAL BUSINESS MODEL

In this Chapter, the hydrogen/ammonia terminal business models are be evaluated. First, in Section 13.1 the business models are scored along the key principles and design criteria. Second, in Section 13.2 the design requirements are further clarified. Third, in Section 13.3 the chosen business model are elaborated upon, detailing market development, financing and regulation. Then, Section 13.4 addresses the upstream connections (production of ammonia) and in Section 13.5 certification is taken into account. Finally, Section 13.6 addresses the value chain alignment.

13.1 Selection of business model

In Activity 14, three main business models for an LNG/ammonia export terminal were identified together with the criteria to evaluate the business models under the framework of the Chilean National Green Hydrogen Strategy. Based on DNV's own assessment and discussions with the Chilean Ministry of Energy and the Ministry of Transport and Telecommunications, the criteria are evaluated.

Promotes market development

Compared to the oil & gas market, the energy density of renewable projects is lower. This probably means that the development of a hydrogen market requires multiple projects. From this perspective it is important that a green ammonia export terminal stimulates the development of multiple projects and is not just focussed on a few. Therefore, a fully integrated model is less effective in the renewable energy market from this point of view. The tolling- and merchant model would more efficiently stimulate different upstream projects.

Promotes market competition

In the discussion with the Ministries it became apparent that one of the main goals of the Chilean government is to prevent the forming of an export monopoly by one market participant, supported by the ambition of the Chilean National Green Hydrogen Strategy of achieving highly competitive exports in a short window of time (5-10 years). It is important to have all upstream project developers of ammonia production to have equal conditions to access a potential export terminal. The risk that a private export terminal of a first mover blocks or hinders the development of other projects is seen as undesirable. A fully integrated business model poses the highest risk in this respect where the whole value chain is operated by one entity. The tolling- and merchant model offer better opportunity for different upstream developers to access the export market. This in turn would promote the most cost-efficient upstream projects to be favoured by export terminal developers since they are able to pay the most competitive processing fees.

Investable

All of the business models rely on the sales of long-term offtake commitments to secure investments. However, the fully integrated model has the lowest dependency between the different elements of the value chain as they are all aligned by the vertical integrated project organization. Also, in general the number of actors in this model are lower compared to the other models. In the merchant model the project organization has to independently source purchasing contracts and the sales contracts and manage the price risk in between. This will take much more effort to coordinate and align these transactions. The tolling model is in between where it takes more effort to align between the export terminal and the upstream developments. However, it is not faced with the downstream price risk as is the case with the merchant model.

Value for money

The fully integrated model offers limited opportunities for economies of scale with respect to the pooling of volumes. The export terminal will most likely be dimensioned on the size of the upstream resource development. In the case of the tolling and merchant model, for the size of the export terminal, the effect of pooling multiple individual projects can be leveraged. From this point of view the latter two can generate better value for money if economies of scale can result in lower export terminal fees and subsequently need less of government support, as well as potentially benefitting the environment by reducing the relative environmental footprint.

Reduces support over time

As presented in activity 5 the ammonia export terminal cost of around 58 $/tonne NH3 represent a relatively small part of the total levelized cost of the value chain. Therefore, the reduction of support over time for this part of the value chain has limited importance. In the fully integrated business model the costs for the export terminal might be more difficult to separate from the rest of the value chain. For the tolling- and the merchant business model the cost of the export terminal can be made more explicit as it can be seen as a stand-alone service. In this respect any support on these processing fees can be ring fenced more easily.

Suitable for future pipeline

The export terminal can be expanded or copied in future based on the upstream developments. It is important that the export capability can grow in coordination with the developments of ammonia production capacity. The fully integrated model is mainly suitable for large upstream projects and not well suited to fulfil an aggregator role. This also means that the structure and agreements tend to be more project specific. Therefore, this model is less likely to be easily copied to other projects. The tolling- and merchant model can be copied better to future alternatives. Especially, the ability to aggregate smaller projects provides these models with advantages over the fully integrated model.

Compatible

Support schemes for hydrogen production are generally directed at CAPEX or OPEX support. In designing these schemes the export terminal doesn't impact any other CAPEX support that is given. Also, in respect to OPEX support there is little risk for double support as long as any support for the export terminal is deducted from any other support schemes. All three models have limited risk of double subsidization.

Technology agnostic

The hydrogen that is used in the production of ammonia can be produced in different ways. Electrolysis, reforming, partial oxidation and pyrolysis are the most predominant production routes. Since Chile doesn't have large natural gas reserves, the natural gas based routes are not the most logical ones and it is expected that electrolysis will be the main production method for all projects. In that sense the technology agnostic route is a less important criteria. However, principally by decoupling production and exports the merchant- and tolling model offer a more technology agnostic approach, as long as the conditions of CO2 reduction are met.

Size agnostic

Ammonia export terminals require a certain scale to become economical. This means that smaller individual projects can only access export markets if they can pool volumes with other projects. On the other hand, the fully integrated business model can only operate economically at scale and cannot combine multiple upstream projects from different owners. Therefore, the merchant- and tolling model are relatively more resilient against the range of project sizes. However, particularly in the merchant model the transaction costs will increase with the number of projects that need to be contracted. The coordination and maintenance of all these contracts is complex.

Avoids unnecessary complexity

Setting-up a new supply chain unavoidably involves a certain degree of complexity to coordinate all the elements in the value chain. The fully integrated model involves the least complexity. However, in this model the transparency is most limited due to the vertical integration of the different value chain steps. The merchant and tolling model are more complex due to the value chain coordination. The merchant model has limited transparency due to the bilateral agreement(s) of the project company and the suppliers/off-takers of the ammonia. In this respect the tolling model offers the most transparent model where access to the terminal can be arranged on a regulated transparent basis.

Table 10: Scoring potential business models against criteria.

	Fully integrated Model	Tolling Model	Merchant Model
Promotes market development	2	5	4
Promotes market competition	2	5	4
Investable	4	3	2
Value for money	4	5	5
Reduces support over time	3	5	5
Suitable for future pipeline	2	5	4
Compatible	3	4	4
Technology agnostic	3	5	4
Size agnostic	2	5	3
Avoids unnecessary complexity	5	4	2
Total score	**28**	**45**	**34**

The scoring of the criteria has been done by DNV expert judgement. Based on the above scoring of the three business models and taking the specific requirement of the Chilean government into account the tolling business model comes out as the preferred choice of business model. In the remainder of this Activity, this model shall be further detailed.

13.2 Design requirements for the Chilean government

In further detailing the tolling business model structure it is important to understand the requirements the design has to meet. The following pillars are identified in the national hydrogen strategy of Chile and translated into design principles for the tolling business model for the ammonia export terminal:

- **Mission oriented policy.** The Chilean government should facilitate but also be in the driver seat and coordinate along the value chain. Being able to align between the different building blocks in the value chain is important.
- **Balanced use of resources and land.** Developing the national resources in harmony with the environment means that national coordination in the development of infrastructure and upstream resources needs to go hand-in-hand and fragmentation needs to be prevented.
- **New economy based on clean exports.** Non-discriminatory access and a stable predictable policy framework are key for attracting diverse international investors and project developers. This international pluriform environment is key in developing to a recognised hydrogen market.
- **Efficient pathway towards a net-zero country.** The local utilization of green energy is important in a pathway towards net-zero. From this perspective developing a national hydrogen market that also facilitates domestic uptake of the use of green hydrogen or ammonia is important. This is also important from a social acceptance perspective.

- **Green hydrogen as a catalyst for local growth.** The development of a national hydrogen and ammonia market should also provide the incentive to develop higher value-added products or services to be developed in parallel to exporting solely the commodity.
- **Openness to the world.** The access for third parties, large and small, to the national infrastructure and export capabilities will drive the openness to the world. A consistent and well-designed legal, fiscal, regulatory and commercial market design will be crucial.

13.3 Tolling structure setup

The tolling business model for the ammonia export terminal has to be structured by taking the interrelationship with other elements of the value chain into account. In the picture below it can be seen that the terminal has to align with the upstream developments, the hydrogen and ammonia transportation, and the international shipping. Also, it has to be consistent with the Chilean hydrogen framework of financing, governmental policy, regulation, legislation and fiscal regime, the coordination of the value chain and risk management. Standalone design of the export terminal without taking this wider perspective into account could result in overall suboptimal outcomes for the development of hydrogen value chains in Chile. The terminal is a small piece that has to fit within a broader puzzle.

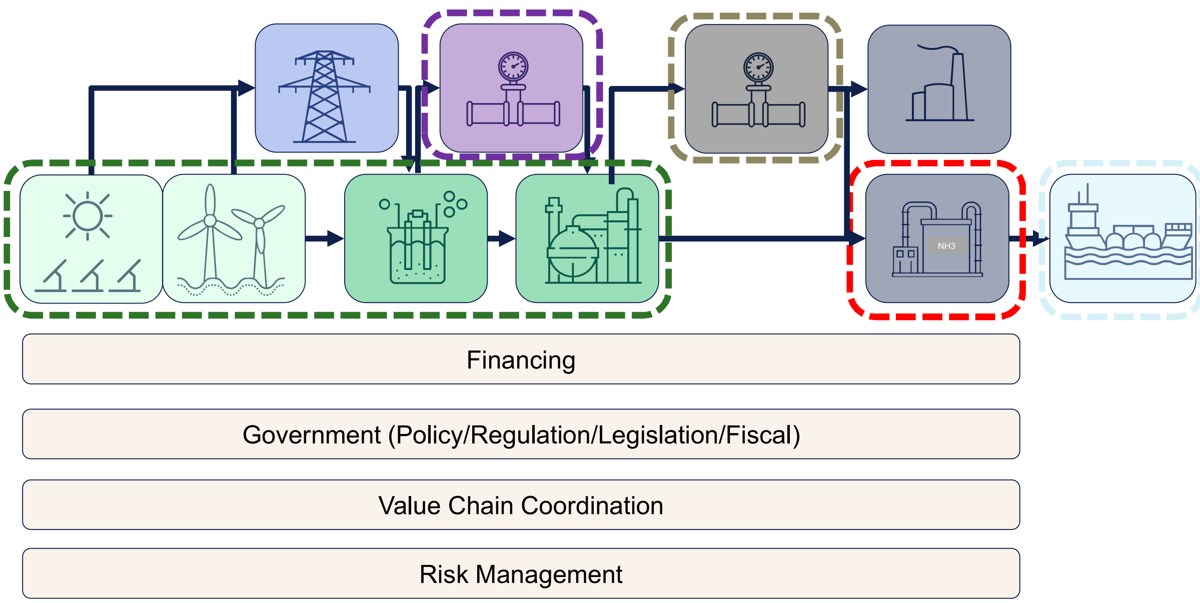


Figure 46: Tolling structure aspects to take into account across the value chain.

Besides the interfaces between the different steps in the value chain the internal elements of the sub-categories of the business model structure for the export terminal are the following (see Figure 47):

1. **Tolling agreement.** The project structure will have to set up contracts with upstream suppliers of ammonia to determine the conditions and pricing of the service provided.
2. **Regulation of tariffs.** The tariffs of the terminal will depend on the regulatory framework that is applicable to the port concession. This can either be a regulated access model, a negotiated access model or a hybrid form.
3. **Export terminal license/permit.** The export terminal will have to secure a license from the national government and apply for a permit to operate within all legal requirements.

4. **Port use agreement.** The terminal will have to conclude a port use agreement with the relevant port authority to arrange a concession for the project duration.
5. **Ownership structure.** The organizational set-up of the export terminal is considered as a project organization. This means that the ownership structure of the export terminal can be structured as a private entity, a public entity or a combination of both.
6. **Financing structure.** The financing structure of the investment in the export terminal will be a combination of equity financing from the shareholders and debt from the international lending market.
7. **Ammonia SPAs.** The shipping logistics for the offtake of the ammonia have to be arranged. Normally, the upstream counterparties to the tolling agreement will organize their own shipping logistics and these requirements will be taken care off in the tolling agreement.
8. **Regulation and policy.** The terminal might be subject to specific regulation or support schemes from the Chilean government.

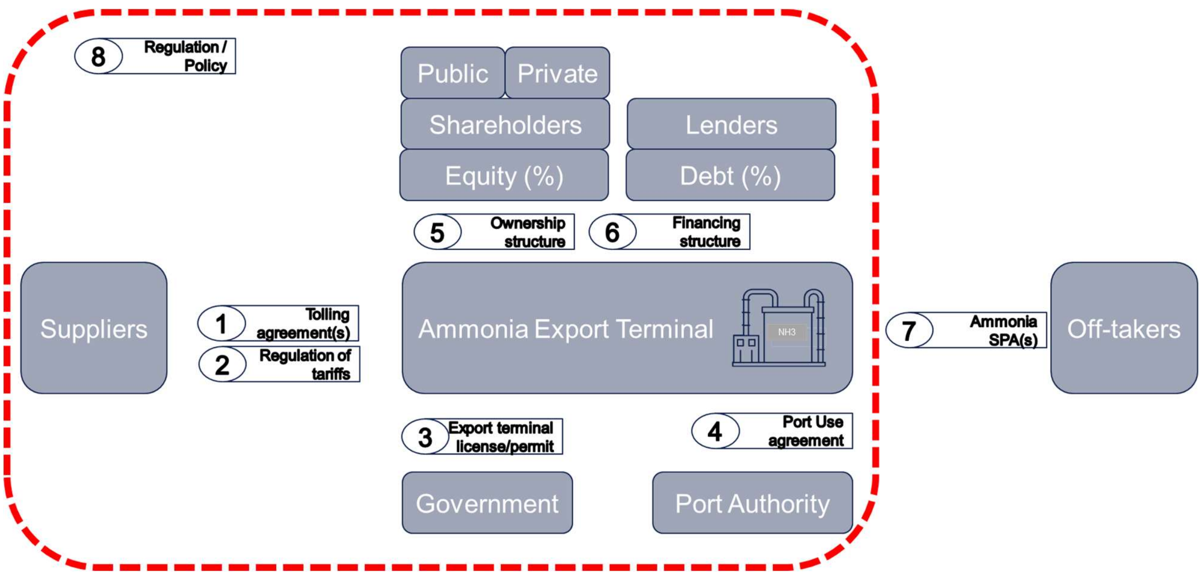


Figure 47: Illustration of a tolling structure setup.

13.3.1 Upstream market development and value chain coordination

The ammonia export terminal company has to conclude tolling agreements with the upstream suppliers. The main characteristics of the tolling agreement are:

Element	Term	Explanation
Duration (years)	15-20	The terminal will pursue long-term take-or-pay contracts in order to underpin the investment. The contracts will need to cover approximately 80% of the total capacity.[28]

[28] Gas Processing Liquefaction Production Exploration and Development Transport Understanding Natural Gas and LNG Options Global Edition. (n.d.). Retrieved from https://www.energy.gov/sites/prod/files/2017/09/f36/Understanding%20Natural%20Gas%20and%20Lng%20Options_general%20no%20appendix.pd

Fee structure	Fixed and variable	The fee structure of the terminal usually consists of a fixed processing fee that covers the fixed OPEX and financing cost of the terminal. On top of the fixed cost a variable fee is payable when executing the option to use the export facility. Power prices are the main component of this variable fee.
Indexation	Consumer Price Index (CPI)	The fixed part of the fee is usually indexed to a consumer price inflation index as published by the national statistical authority.
Guarantees	Potential Parent Company Guarantee	Customer credit ratings are a proxy for the risk of non-payment during the term of the contract. They are key in determining the investment grade of the project.
Delivery point of ammonia	Ex-FOB or DES	Ammonia can either be delivered to the tolling customer ex-FOB at the jetty or at the destination terminal
Receiving point of ammonia	Terminal	At the moment the receiving point of the ammonia would be at the terminal. However, depending on transportation model design this could change.
Sourcing of ammonia	Customer or Parent Company	Most likely model to process the ammonia of the customer as a service

As a result of the choice for a tolling model the development of the export terminal, the production of ammonia and the transport of ammonia to the export terminal are separated. This means that the transportation of the ammonia from the inland production plant to the terminal has to be arranged. The organization of this activity can be handled in two different ways. The first option is to allocate this responsibility to the producer. This means that the producer is responsible to construct an ammonia pipeline, rail or road carrier to the export terminal connection point. The advantage of such a solution is that the capital requirement and operating risk is for the upstream producer. However, a main disadvantage is that this results in a fragmented pipeline market and potentially loss in economies of scale (efficiency). Also, the timing of the construction in combination with the permitting is more challenging to align with the start-up of the export terminal.

Alternatively, the pipeline construction can be part of the project company that operates the export terminal or a separate independent ammonia pipeline operator. The advantage of such a model is that the coordination and equal access to the pipeline system can be aligned with the main goals of developing a competitive hydrogen market.

13.3.2 Financing

As with previously mentioned perspectives, the ammonia market resembles attributes of the LNG market. LNG projects are typically set up by means of a Special Purpose Vehicle (SPV). An illustration of the structure is provided in Figure 48. From the figure it becomes clear that there are certain cash inflows and outflows. The inflows are dominated initially by the financing with debt- and equity providers, typically having a gearing (debt- to equity ratio) of 70:30. Obviously, the tolling revenues are also cash inflows to the SPV. The outflows are merely the EPC, O&M and royalties & taxes. A detailed cashflow model provides insights into the different stakeholder cashflows and assumptions (see Appendix B). The outcome of the model is that a tolling fee of 44 $/t before tax is needed for the ammonia export terminal to break-even. The total capital expenditure is $ 481 million with a gearing of 70/30. The WACC is assumed at 8% and the interest rate on the loan at 4.6%. The annual OPEX is assumed at 2% of the total CAPEX.

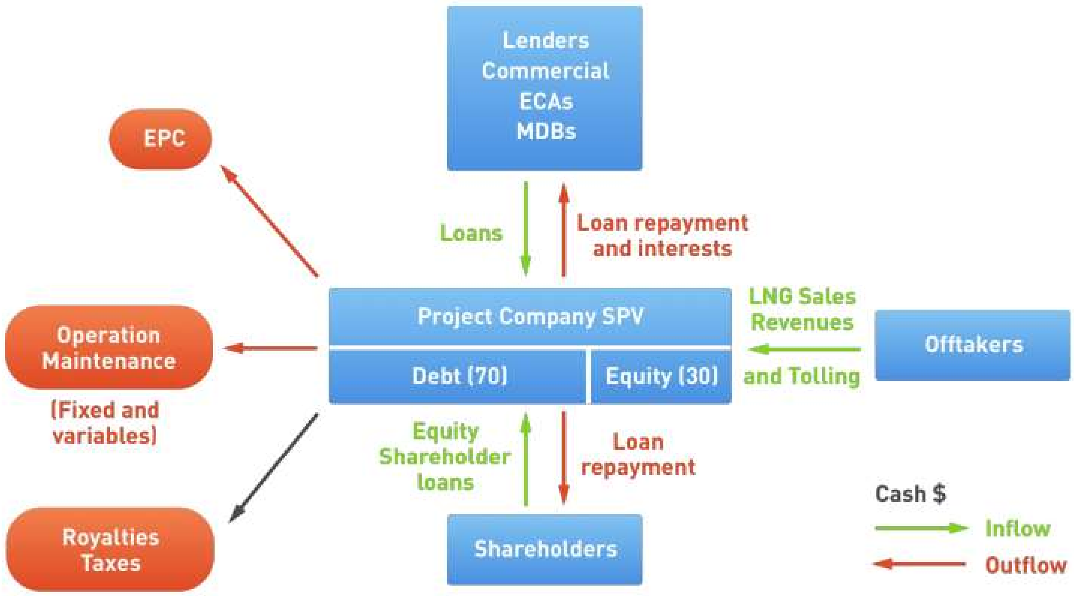


Figure 48: Overview of financing structure for a typical LNG project.[29]

In the development of LNG terminals, de-risking is key to bring down capital costs. One of the primary drivers in de-risking is long term contracts with buyers that are creditworthy. Instead of using the creditworthiness of the project company, the creditworthiness of the counterparties (customers) is used. The rationale is that the debt must be repaid from the cash generated by the project, also known as off balance sheet financing. The creditworthiness is often determined by rating agencies like S&P, Moody's and Fitch. The various customers are pooled, and the share of different types of creditworthiness is determined.

The duration of these contracts is also key in assessing the risk associated with investing in a terminal project. It is especially the combination of long duration contracts with creditworthy customers that translate into an investment grade project. With both these attributes, the cost of raising debt is further reduced as well as allowing for an increased share of debt in a project.

The time required to develop the financing of an SPV depends on various characteristics (e.g. country, complexity). At an early stage, it is important to have soundings with potential investors to gauge interest in the project. First, equity providers are sought for the project determining the gearing, and afterwards debt providers. It is especially on the debt side where the tolling contracts are important to consider since these will (as mentioned earlier), determine the ability to service debt.

Typical financiers of projects are international commercial banks, domestic banks, export credit agencies, development banks, the World Bank, sponsor co-loans and other providers (e.g. raising bonds after construction of the project). Export credit agencies have a particularly important role since they typically not only provide loans, but also political and commercial risk cover. Noticeable is the role of development banks, who typically come in at an early stage. Development

[29] Gas Processing Liquefaction Production Exploration and Development Transport L N G Regasification Distribution and Transport Marketing and Sales Global LNG Fundamentals Liquefaction Gas Processing Liquefaction Production Exploration and Development Transport L N G Regasification Distribution and Transport Marketing and Sales. (n.d.). Retrieved from https://www.energy.gov/sites/default/files/2018/03/f49/Global%20LNG%20Fundamentals%2C%20Updated%203.15.18.pdf

banks support ranges from loans, equity, due diligence etc. Especially their softer role comes in as an important means to mitigate risk in projects. Similar approaches could be used in ammonia business models.

13.3.3 Note on export terminal levelized costs

In Activity 9 the contribution of the export terminal was estimated as only 3 $/ton of ammonia, whereas in the cash flow model presented in Appendix B this is estimated as 44 $/ton. This discrepancy is mainly due to the following reasons:

- In the shipping cost model used in Activities 3 and 11 there is an assumption on 3 days of storage in order to make a uniform comparison across all carriers. However, the design of the terminal in Activities 7, 9 and 10 considers approximately 31 days of storage. For a given capacity (1 million tonnes/year) this results in a much higher throughput (numer of cycles) and hence much lower unit or levelised costs.
- The shipping cost model used in Activities 3 and 11 assumes 1 storage tank. The design of the terminal in Activities 7, 9 and 10 storage terminal consists of 2 storage tanks to be able to load the largest ammonia vessels currently available.
- The electricity costs for the terminal in Activities 7, 9 and 10 are also significantly higher due to the relatively lower number of cycling times. The consumption is mostly independent of throughput but based on the storage capacity to keep the ammonia in the tanks cooled.

These are aspects of the shipping cost model to be improved in future studies to better reflect the full terminal costs.

13.3.4 Tariff regulation

The tariffs for the export terminal can be set up in two different ways. The first method is a regulated access model in line with common practice in many European countries. The second is a model based on negotiated tariffs.

In the regulated model the tariffs are determined on the basis of a regulatory framework that is overseen by an independent regulatory body. This independent body determines the value of the regulated asset base and the allowed return on capital. These two drivers then determine the transportation fee that can be charged to the customers. Under and over recovery of allowed revenues is corrected in future regulatory periods. The advantage of such a model is a clear and predictable pricing model towards customers and equal access to all interested parties. Towards the investors in the terminal, it provides a clear outlook on the ability to recover their investments throughout the regulatory periods.

The other model is based on negotiated tariffs. Here the project company negotiates with every individual customer on their tariffs. Usually the project company sets its tariffs on the basis of the levelized cost of the project increased by a consumer inflation index. In this model the project company is not protected against loss-making tariff setting with its customers. If not all of the capacity is sold or if the duration of the term is expiring there is no guarantee on return of investment. On the other hand, the company has more flexibility to determine the level of its tariffs as the pricing methodology applied.

13.3.5 Export terminal license and permit

In many countries an export license is required for certain specific goods to be exported. Depending on the legislation in Chile it could be the case that the owner of the ammonia export terminal has to apply for an export license. The procedure often comprises an assessment of the demand and supply balance for the good in question in order to determine how exports would compare to domestic needs. Some countries only issue export licenses if the source for the export is causing a surplus on the demand and supply balance. In Chile this might be a relevant consideration from a national perspective due to the ammonia imports that are currently taking place.

In addition to the export license the terminal itself has to apply for a building and operating permit. The competent national authority will determine the applicable legislation and criteria the ammonia export terminal has to comply with. The environmental impact assessment is often an important element of this process.

13.3.6 Ownership structure

The ownership structure of the export terminal can be either a privately owned company, a publicly owned company or a public / private partnership (where the share split can vary). The choice of ownership structure can be considered on the basis of the overall Chilean government goals for the hydrogen market development, the stage of development the market is in, the specific regulation of the port (public or private) and the risk profile of the project.

One of the main goals of the Chilean government is to develop a competitive upstream hydrogen market with equal access to all counterparties. From this perspective the involvement of a public company can facilitate the development of the product offer and the non-discriminatory access for all market participants. Also, the hydrogen market is in its infancy. Therefore, the capital investments are large and infrastructure needs to be developed as well as repurposed. This might limit the accessibility of the resources by smaller project developers compared to larger more capital backed developers. Without the access to a larger export terminal these smaller developers might otherwise struggle to develop their projects. In any case it might be a consideration of the Chilean government to have an active share in an infrastructure project of strategic importance.

As described in more detail below the Chilean port system has two different possibilities for development. In the case of a private port all ownership structures are possible. However, in the case of a public port the structure will be limited to a public company. The establishment of an export terminal in a private port in combination with public ownership participation might guarantee the non- discriminatory access by preventing the blocking of other export terminals by a private one.

The involvement of a public Chilean shareholder in the export terminal will also positively influence the risk profile of the project. It will increase the thrust the market has in the value chain development and also reduce the credit risk within the project.

13.3.7 Port access agreement / concession

Chile has two different port systems: public ports and private ports. In each system a different ministry is in charge. This is in contrast with other countries, where a single ministry is in charge of both port models. Two different regulatory frameworks exist regarding different port models (OECD, 2016).

On the one hand, there are ports for public use, where there are two main principles: to provide permanent services to all types of cargo, and to develop competitively, efficiently and in competition between service providers. An important attribute is that contracts are being awarded via tenders where the lowest bid is decisive. Thereby, the requirement exists to publish the rates that are awarded.

On the other hand, there are ports that are governed by the regime of maritime concessions on the coastline. These are not only applicable to ports, but any activity (restaurant or port terminal). This framework, a priori, can provide greater flexibility, but has less regulatory density in the case of having a terminal that is used by more than one single actor. It is especially being used by vertically integrated supply chains and industries (e.g. mining, hydrocarbons or aquaculture terminals). An overview of the main attributes of each regulatory framework is provided in Table 11.

Table 11: Overview regulatory framework ports in Chile.

	Public ports	Private ports
Law + year	N 19.542 (1997)	N 0340 (1960)

Ministry	Ministry of Transport and Telecommunications	Ministry of Defense	
Concession	Terminals are awarded to private companies in tenders	Application of maritime concession without tender and without consideration to efficient use of the bays	
Duration	Maximum concession period of 30 years	Maximum concession period 50 years	
Services	Obliged to provide public services without discrimination, continuously and under service standards	Provide services without tariff regulation, defined only by the general legal framework	
Declared Use	May be declared as of	May be declared as of:	
	Public use	Public use	Private use

Complejo Portuario Mejillones (CPM) is an interesting case due to its structure and openness in spite of being under the private ports frameworkEven though the owner and operator of the port is Codelco (a public company), the port still required to go through a private maritime concession for its opening. With Codelco closely collaborating with the public sector, while being the owner of the port, it brings the advantage of both integration with the public sector as well as the responsiveness of a private actor. However, CPM is only one of several ports operating in the Bay of Mejillones.

It is, however, important that there is no price discrimination amongst actors that would like to make use of the terminal. As such, the goal is to achieve competitive rates throughout the supply chain. Therefore, only the public- and the public/private use frameworks are deemed relevant.

13.4 Connecting the upstream projects with the export terminal

One of the consequences of choosing a tolling business model (compared to the fully integrated model) is that the transportation of ammonia from the production facility to the export facility is the responsibility of the individual upstream project developers. This is in line with the current situation in Chile for other commodity markets. For example, all of the natural gas transmission pipelines are in the hands of private companies. In general, there are four possible market design principles for hydrogen/ammonia transportation:

- In a liberalized market private companies have the ability to develop pipelines on a commercial basis. There are no specific rules and the general competition rules are applicable.
- The market concentration and abuse of power are monitored by an independent regulatory authority. Periodic analyses are made. Based on the outcomes certain obligations can be given to transportation companies (i.e. third party access).
- A public transportation company can operate alongside private investments which have to comply to certain access requirements. However, only the tariffs of the public company are regulated.
- A public transportation company is mandated by legislation to operate as the exclusive transmission system developer. In such a system in principle there is no room for privately owned transmission networks.

However, in view of the coordinated domestic market development of hydrogen in Chile the following considerations are important that could result in the choice for more public involvement:

- The private development of pipelines can result in a more fragmented market that doesn't have a national coverage and/or increases transaction costs. The public involvement could support the development of a national network. Such a network would enable the establishment of a physical marketplace where demand and supply are balanced. This will increase the size of the market and increase competitiveness. In the long run this would benefit the affordability and security of supply.

- Private pipeline development has the risk of inefficient parallel development with lower utilization of the assets. A more national approach could result in better utilizing economies of scale and reduce the risk of inefficient operation (where pipelines are operated at reduced capacities due to lack of supply).
- A national coordinated network development could better unlock vital system roles. For example, the access to large scale storage locations, the utilization of flexibility for balancing the network, the coordinated development of certain renewable power areas etc.
- Private developers do not have to evaluate explicitly the system benefits of pipeline transport versus electricity transport, and between hydrogen or ammonia transport. For the production of hydrogen, one of the main considerations is the location of the electrolyzer. This can be done close to the power generation source which can result in pipeline transport to the export terminal. Alternatively, the electrolyzer can be built closer to the export facility which can result in longer electricity transmission line from the generation source to the export location. This socio-economic consideration might be better coordinated or guided by the public sector.

13.5 Certification

Certification of renewable energy is key for exporting countries. The challenge in this area is to design certification schemes that are recognized globally and facilitate intercontinental trade. An example initiative is the CertifHy standard development. In the trade of commodities there is no physical differentiation between fossil and renewable or low carbon fuels with respect to the carbon emission intensity. This distinction is only made by certificates that can be traded to track a production batch through the value chain from production to end-consumption. The commercial premium for the renewable product on top of its fossil alternative is valorised through the certificates. For the tolling business model it is therefore important for the processed ammonia to be certified according to international standards and accepted by the main trading partners. The export terminal operator needs to have a system in place to make sure that the origins of the supplied ammonia can be verified according to chosen standards.

13.6 Value chain alignment

Setting-up a new capital-intensive energy value chain requires coordination along such value chain. If there is no fully integrated value chain business model this coordination becomes more urgent. In liberalised markets this coordination is the prime responsibility of market players. The role of national governments is to design the playing field by efficient predictable legislation and regulation. The following instruments are key in such an approach:

- A national hydrogen and ammonia master plan would support coordination along the value chain. A master plan serves the purpose of identifying and evaluating different hydrogen and ammonia options. The plan is a guidance for policy development and decision making. It also provides a good opportunity to identify any potential anchor projects.

  Also, the wider system integration with other sectors are a key consideration such as the decarbonization of ports.[30] In ports DNV has identified ten green transitions for port decarbonization: electrification of port-connected activities, fuel switch for maritime transport, electrification of industry, integration with offshore wind, energy system integration, hydrogen as a feedstock and energy vector, phase-out of fossil fuelled power plants, carbon capture and storage, new regulations and circular and bio-based economy. Four transitions are relevant in a master plan. First, the fuel switch for maritime transporter. The hydrogen or ammonia could be used as a

[30] Ports: green gateways to Europe DNV. (2021). Retrieved February 1, 2022, from DNV website: https://www.dnv.com/Publications/ports-green-gateways-to-europe-179372

transport fuel for shipping with the associated bunkering infrastructure. Second, energy system integration where different energy vectors combined are used for deep decarbonization. Third, the use of hydrogen as a feedstock or energy vector to decarbonize industrial activity. Fourth, the phase-out of fossil fired power generation where hydrogen or ammonia could be used for back-up power to support a high level of renewable power generation.

- Open-seasons[31] to underpin network developments. Open season procedures can be used for two different purposes. Firstly, they can be used to test the potential interest in the market for transportation or export capacity. In this way the development of the national infrastructure can be coordinated in time. Secondly, they can be used as a means to provide non-discriminatory access to infrastructure to all market participants.
- Combined tenders of renewable energy development plots in combination with electrolyzers and ammonia conversion, like the one recently arranged by CORFO that awarded 50 million USD to green hydrogen production projects[32]. The integrated tendering of ammonia production can facilitate competitive bidding on identified lots of development potential and help to minimize costs to society.

[31] https://www.entsog.eu/sites/default/files/entsog-migration/publications/incrementalcapacity/ERGEG%20Guidelines%20of%20Good%20Practice%20-%20Open%20Season%20Procedures%20%28GGPOS%29.pdf

[32] Corfo press release, 27 December 2021, Corfo adjudica propuestas de Hidrógeno Verde que atraerán inversiones por 1.000 millones de dólares

14 ACTIVITY 16 – CONCLUSIONS AND RECOMMENDED ACTIONS

14.1 Summary project conclusions

Through our pre-feasibility work over the last 6 months, we have drawn the following key summary conclusions:

1. **Ammonia:** In the short term, ammonia export, for use as ammonia, is the most promising option that should be investigated further.
2. **Mejillones:** Under the proposed framework, Mejillones was selected as the most appropriate bay to conduct the pre-feasibility study for a green ammonia export terminal. Mejillones has strong solar resources, existing ammonia use that can be decarbonised, and available land that can be used for ammonia export terminal construction. The ammonia terminal design can be extrapolated to a certain degree to other promising bays, such as Tocopilla, Taltal and Cabo Negro.
3. **$480 million:** Our first estimate is that the ammonia export terminal and associated infrastructure will cost $480 million to build over a timescale of approximately 3 years from start of detailed design to commissioning (39 months). Permitting times are estimated to be between 1 year and up to 5 years or more if there are court cases against the development of the project.
4. **Tolling model:** We recommend a tolling model for the export terminal, as it is best suited to promoting market competition and development, while remaining technology neutral and agnostic on production project size.

Overall, DNV concludes that:

- Green ammonia export from Chile offers a promising market in the coming years, meeting a requirement to decarbonise fertiliser production and with potential in other end-use applications.
- Given the expected hydrogen production costs in Chile, and our calculated export costs (including ammonia production, port facilities, shipping etc), export of ammonia from Chile, to be used as ammonia, will be competitive against green ammonia production in key target markets.

As we have also shown, other hydrogen export options have potential, and should also be investigated further. For example, liquid hydrogen exports are seen by many to be the long-term winner, and investigating liquid hydrogen does not hinder the development of ammonia.

14.2 Recommendations: Key pillars

In order to develop green ammonia exports from Mejillones, we recommend a series of next steps actions across 5 key pillars. This will ultimately become a full feasibility study and Front End Engineering Design (FEED), and will require a cross-government effort, including:

- Close cooperation between various departments;
- A strong dialogue with the private sector, including to preserve competition;
- Close engagement with local communities;
- A focus on good environmental protection.

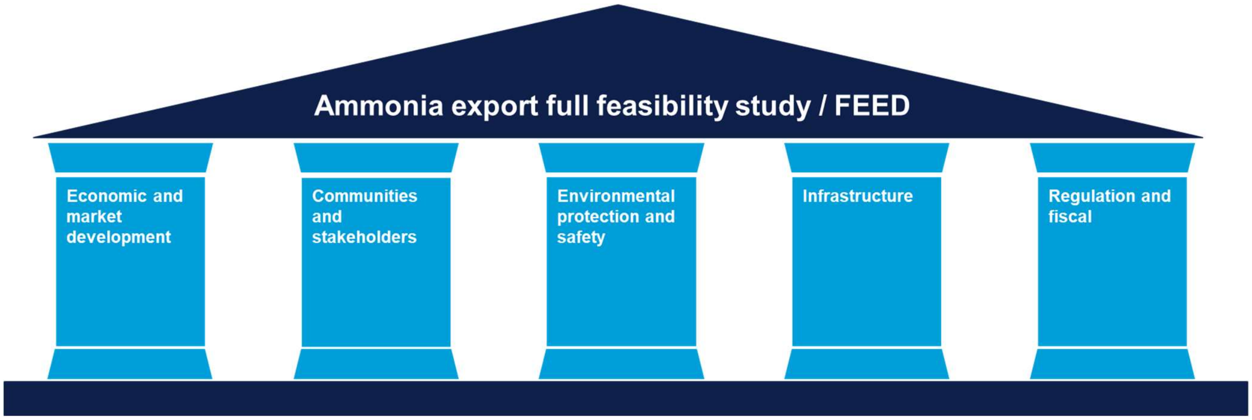


Figure 49 Five key pillars to develop green ammonia

14.3 Recommendations: Economic and market development

In this pillar, we recommend that a hydrogen and ammonia master plan is developed to guide policy making; that local end-use is built up to provide local decarbonisation and economic benefits, and avoid an over-reliance on exports; and that work continues to build export markets.

Table 5: Economic and market development recommendations

Recommendation	Details
1. **Develop a hydrogen and ammonia master plan**	• A national hydrogen and ammonia master plan would support coordination along the value chain, including production, transport, storage, domestic end-use, and export. A master plan serves the purpose of identifying and evaluating different hydrogen and ammonia options, and would deepen the analysis presented in this pre-feasibility study. • The plan is a guidance for policy development and decision making, including strategic land planning for production projects (similar to auctioned offshore wind license blocks). It also provides a good opportunity to identify further potential anchor projects. • It is important for the hydrogen and ammonia master plan to be developed in a timely way. It could be included as part of the Long Term Energy Planning Process[33], if respective timeframes allow, as inclusion would support consistent planning across the energy sector as a whole.
2. **Build up local hydrogen and ammonia use to ensure local emissions reduction and economic development, and avoid an over-reliance on exports**	• **Ammonia:** This will include substituting local green ammonia for imported grey ammonia, developing local fertilizer production, ammonia as a shipping fuel, and seasonal energy storage for the power sector. • **Hydrogen:** This will including continuing to develop local hydrogen use to decarbonize mining, industry and transport. • **Products:** Continue to promote local production of green synthetic fuels, green methanol and other green products.
3. **Work to build export markets**	• Continue strengthening dialogue and relationships with stakeholders in importing countries, including governments, port authorities and end users (fertilizers, steel, power, etc).

[33] Planificación Energética de Largo Plazo | Ministerio de Energía. (2020). Retrieved February 1, 2022, from Energia.gob.cl website: https://energia.gob.cl/panel/planificacion-energetica-de-largo-plazo-0

	• Develop a clear narrative on the value to importers of using green ammonia from Chile. • This also links to recommendation 7 on developing an internationally compatible certification scheme.

14.4 Recommendations: Communities and stakeholders

Here we recommend that a comprehensive stakeholder engagement programme is developed to ensure that local concerns are properly taken account of.

Table 6: Communities and stakeholder recommendations

Recommendation	Details
4. **Develop a comprehensive stakeholder engagement framework, focused above all on local communities**	A stakeholder engagement framework with a gender-oriented approach and communication strategy should be developed as part of the next phase to identify relevant stakeholders and address potential barriers to green hydrogen development in the area. In Activity 4, we set out more details of how a stakeholder engagement programme should be designed, including the following: • **Communities:** The plan should note that there will be local impacts from project development, that local jobs and community support schemes are essential, and that incorporating local knowledge into project design can be very beneficial. • **Local engagement:** Early and transparent engagement should include awareness raising before project applications are submitted, engagement through the overall Strategic Environmental Assessment (SEA) and project-specific Environmental Impact Assessment (EIA) processes, and engagement during the project planning application stage. • **Wider engagement:** It is also important that other key stakeholders are contacted at regular intervals, including port authorityies, H2 Chile and other operators. • **Respect:** At all stages, the views of local communities need to be listened to and respected. It is important for project developers to be willing to make reasonable modifications to projects based on community feedback. It is also important that job opportunities are provided for local people and that any community benefit schemes are well-designed and relevant to local issues.

14.5 Recommendations: Environmental protection and safety

It is important that a Strategic Environmental Assessment (SEA) is carried out to make sure that cumulative environmental impacts are properly considered and mitigated.

Table 7: Environmental protection and safety recommendations

Recommendation	Details
5. **Carry out a Strategic Environmental Assessment (SEA) of the green hydrogen and ammonia development programme in strategic regions such as**	• Strategic Environmental Assessment (SEA) is a systematic process for identifying, reporting, proposing mitigation measures and monitoring environmental effects of plans, programmes and strategies. It aims to ensure that environmental issues are taken into account at every stage of the programme. • SEA helps to better protect the environment, aims to ensure that any development is sustainable, and increases opportunities for public participation in decision-making. It ensures that expert views are

Antofagasta and Magallanes, analysing key bays such as Mejillones, Taltal, Tocopilla and/or Cabo Negro	sought at various points in the preparation process from the public and the consultation authorities. The SEA process links closely to the stakeholder engagement process, and includes the following steps: 1. An environmental report is prepared in which the likely significant effects on the environment and the reasonable alternatives of the proposed programme are identified. 2. The public and the environmental authorities are informed and consulted on the draft programme and the environmental report. 3. The environmental report and the results of the consultations are taken into account before adoption. 4. Once the programme is adopted, the environmental authorities and the public are informed and relevant information is made available to them. In order to identify unforeseen adverse effects at an early stage, significant environmental effects of the programme are monitored. • The advantage of this process is that it can assess cumulative impacts of numerous potential projects within the region, ensuring that the environment is protected during the first and subsequent phases of development. For example, in the case of Mejillones, specific issues that an SEA for green hydrogen and ammonia development could consider include: ○ **Biodiversity:** The marine area is overlapping within a Key Biodiversity Area (Bahia de Mejillones) which has important biodiversity features for birds and marine mammals. A biodiversity management plan should consider proactive conservation measures, and discussions should be held with relevant environmental and local community groups. ○ **Water and wastewater:** Possible measures to ensure efficient use of water resources and potential impacts from wastewater generation, providing information on pollution levels from wastewater plumes and applicable pollution control strategies. ○ **Additional environmental and social considerations:** Analysis on socio-environmental liabilities, cumulative and indirect impacts, and the associated facilities related to the proposed development. • Other issues that should be covered alongside the SEA include community and occupational health and safety. For example, the Mejillones area is prone to high risk of earthquake, tsunami and flooding. Applicable mitigation measures on natural disaster risks should be identified, as well as possible mitigation measures to minimize the safety risk of exposure to ammonia and other hazardous materials including requirements for the development of Quantitative Risk Assessments and other relevant safety studies.

14.6 Recommendations: Infrastructure

An infrastructure study is required to identify opportunities for and savings from shared infrastructure.

Table 8: Infrastructure recommendations

Recommendation	Details
6. **Carry out a study of the required enabling infrastructure for green hydrogen and ammonia development in strategic regions such as Antofagasta and**	• Enabling infrastructure, including electricity grid, hydrogen and ammonia pipelines, extension of road and rail to the export terminal, central hydrogen and ammonia storage, water desalination etc, is of critical importance to the success of projects. • In many cases, individual projects can secure or construct their own enabling infrastructure, but economies of scale from shared infrastructure are likely to be significant. Shared infrastructure can also support competition by allowing smaller projects to connect,

Magallanes, analysing key bays such as Mejillones, Taltal, Tocopilla and/or Cabo Negro	without having to build their own infrastructure, and reduces the chance of wasteful duplicated pipelines or other physical assets. Hence the government has a key role in decision-making in this area. • The pipeline construction can be part of the project company that operates the export terminal or a separate independent ammonia pipeline operator. The advantage of such a model is that the coordination and equal access to the pipeline system can be aligned with the main goals of developing a competitive hydrogen market. • Based on plausible scenarios for the development of projects, the study would: o Identify the options for shared infrastructure. o Quantify the likely savings. o Examine options to finance shared infrastructure. o Set out how to promote open access and support competition, including smaller projects. • In the case of Mejillones, the company ENAEX owns and operates a maritime terminal with capacity to import and store refrigerated ammonia. Using this infrastructure for export could potentially mean that the first ammonia exports would not require a new terminal – in this scenario a new terminal would be built to handle export growth. However, the technical feasibility of this solution and economic savings would have to be analysed in cooperation with ENAEX.

14.7 Recommendations: Regulation and fiscal

In this pillar, we recommend that a standard and certification scheme is developed that is compatible internationally; that a review of fiscal incentives is carried out to ensure that any government support is proportionate and well-targeted; that the involvement of public companies is considered; and that "open seasons" are carried out to underpin network developments.

Table 9: Regulation and fiscal recommendations

Recommendation	Details
7. **Develop a standard and certification scheme for green hydrogen and ammonia that is compatible internationally**	• A standard in Chile to define green hydrogen and ammonia is necessary to ensure that only truly green projects are developed and supported (for example, avoiding the development of electrolyser projects using coal-fired electricity). • Together with a certificate scheme, this will support decarbonisation for end-users within Chile and provide them with confidence in the credentials of the hydrogen and ammonia they purchase. • Such a standard and certification scheme needs to be compatible with international schemes in key export markets, including the EU, North America and Asia, and potential global schemes through the International Renewable Energy Certificate Standard (I-REC). Many of these schemes are still in development, so close attention should be paid to how these schemes progress. Examples include: o The EU's emerging hydrogen standards and certification, including the EU Taxonomy for Sustainable Investment[34], implementation of the REDII directive, and CertifHy.[35] o The UK's Low Carbon Hydrogen Standard, which has been consulted on but not yet finalised.[36] o The I-REC Standard Foundation and Avance Labs have finalized an MOU to develop a Product Code for hydrogen

[34] EU Taxonomy https://ec.europa.eu/sustainable-finance-taxonomy/
[35] CertifHy https://www.certifhy.eu/
[36] UK Low Carbon Hydrogen Standard https://www.gov.uk/government/consultations/designing-a-uk-low-carbon-hydrogen-standard

	that will adhere to the strict requirements of the I-REC Standard's International Attribute Tracking Standard.[37]
8. **Carry out a review of fiscal incentives**	• It is important that any government support is limited, supports competition and does not allow excess profits to be made. Given the favourable costs of green hydrogen production in Chile, it is likely that large-scale support schemes will not be needed, but there may be useful enabling measures, including carbon prices, tax policies, regulatory mandates, and infrastructure financing. • The review should analyse the fiscal options in detail, and make recommendations to support the goals of development of the sector without an undue burden on the state.
9. **Consider business models with the involvement of public companies**	• Consider the involvement of public companies in the development, construction and operation of the ammonia export terminal to reduce financial costs.
10. **Carry out "open seasons" to underpin network developments**	• An open season is a procedure where a transparent and non-discriminatory call for binding commitments of any party for capacity is made by a group of Transmission System Operators (TSOs) together spanning two or more market areas, which may be preceded by non-binding expressions of interest of any party, in order to base an investment decision for a capacity expansion on the obtained commitments. • Open season procedures can be used for two different purposes. Firstly, they can be used to test the potential interest in the market for transportation or export capacity. In this way the development of the national infrastructure can be coordinated in time. • Secondly, they can be used as a means to provide non-discriminatory access to infrastructure to all market participants.

[37] I-REC Foundation https://www.irecstandard.org/news/press-release-the-i-rec-standard-foundation-signs-mou-with-avance-labs-for-the-development-of-a-i-rec-standard-accredited-product-code-for-hydrogen/#/

APPENDIX A – SITE CONSTRAINTS MAPS

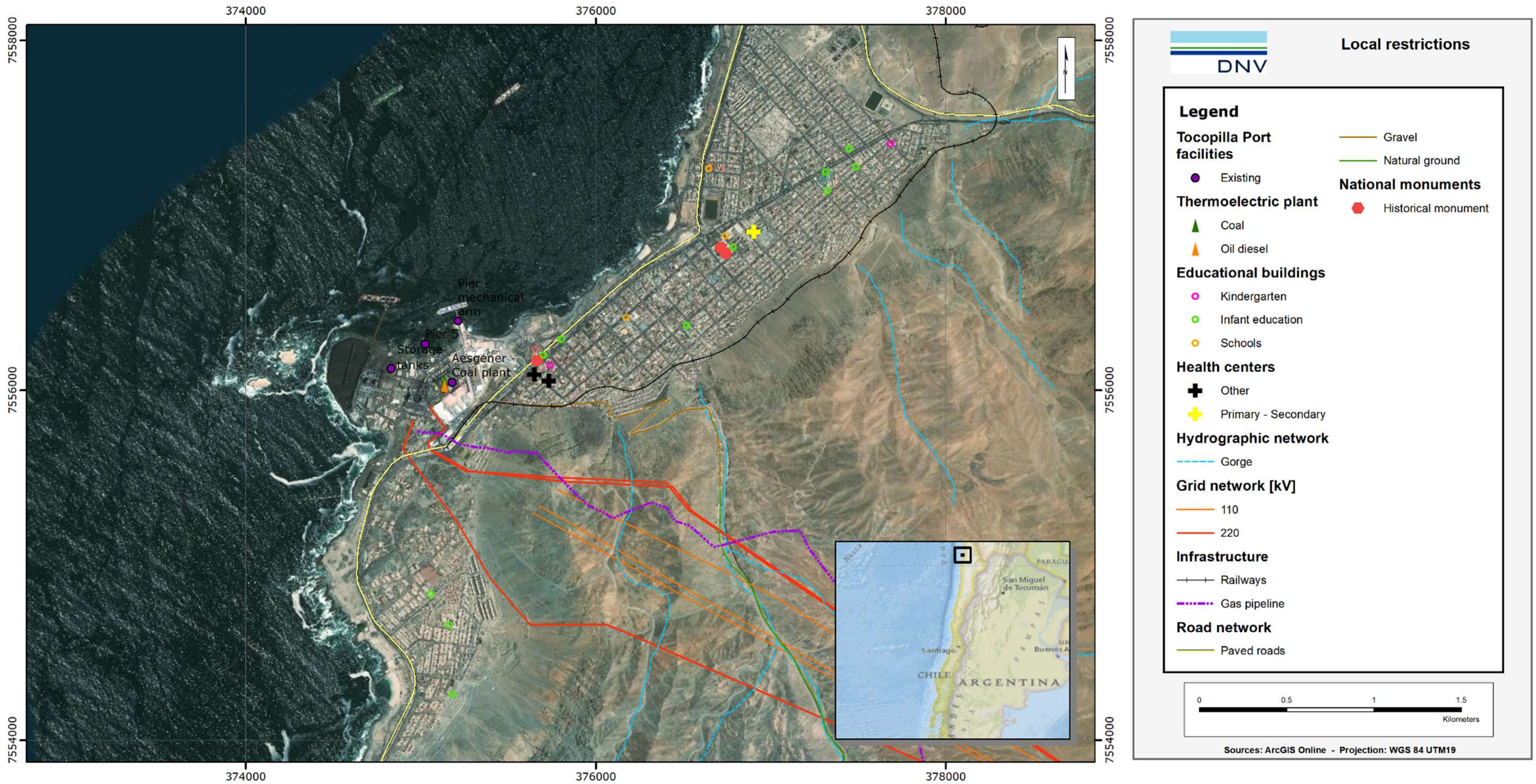


Figure 50 Constraint map - Tocopilla

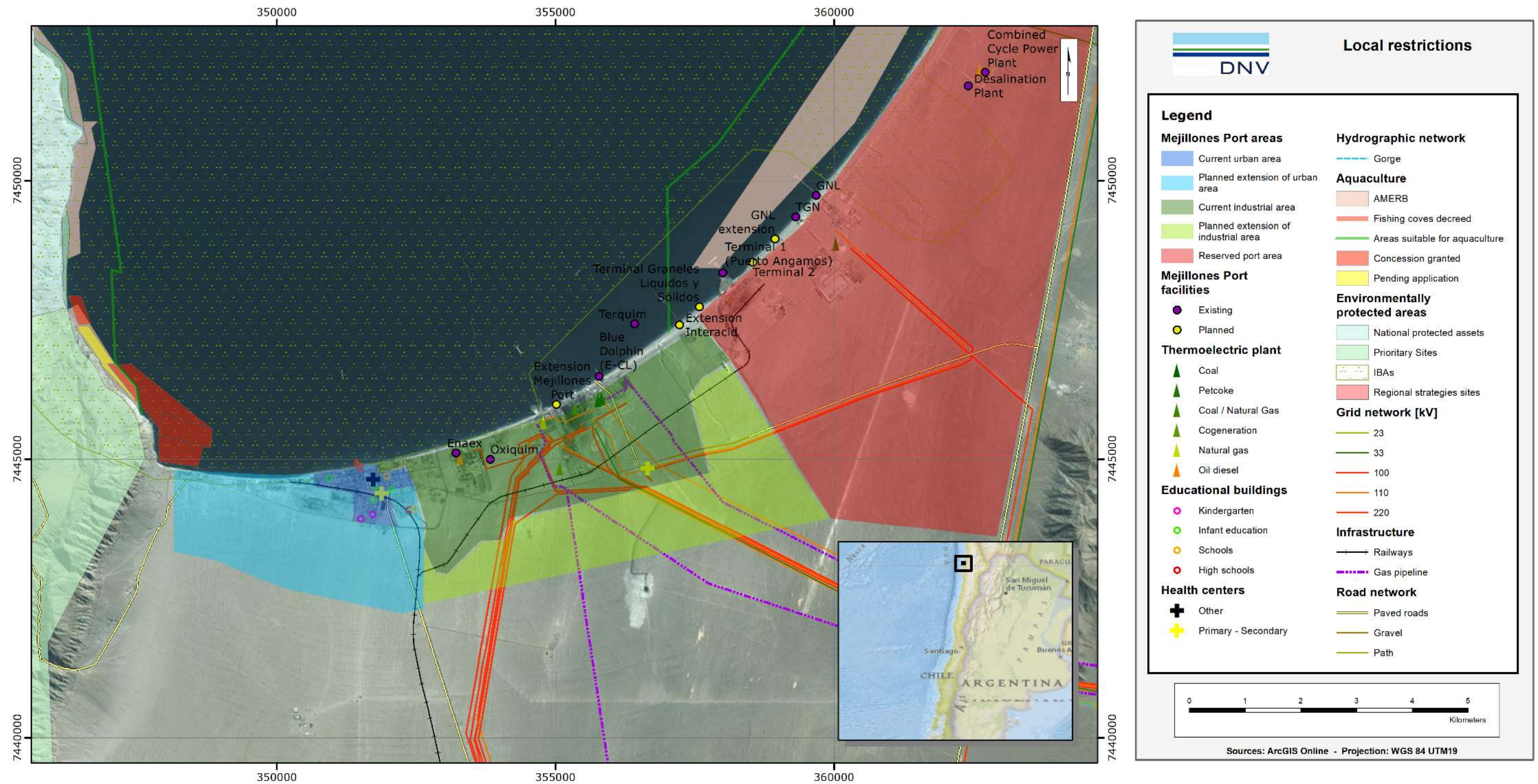


Figure 51 - Constraint Map – Mejillones

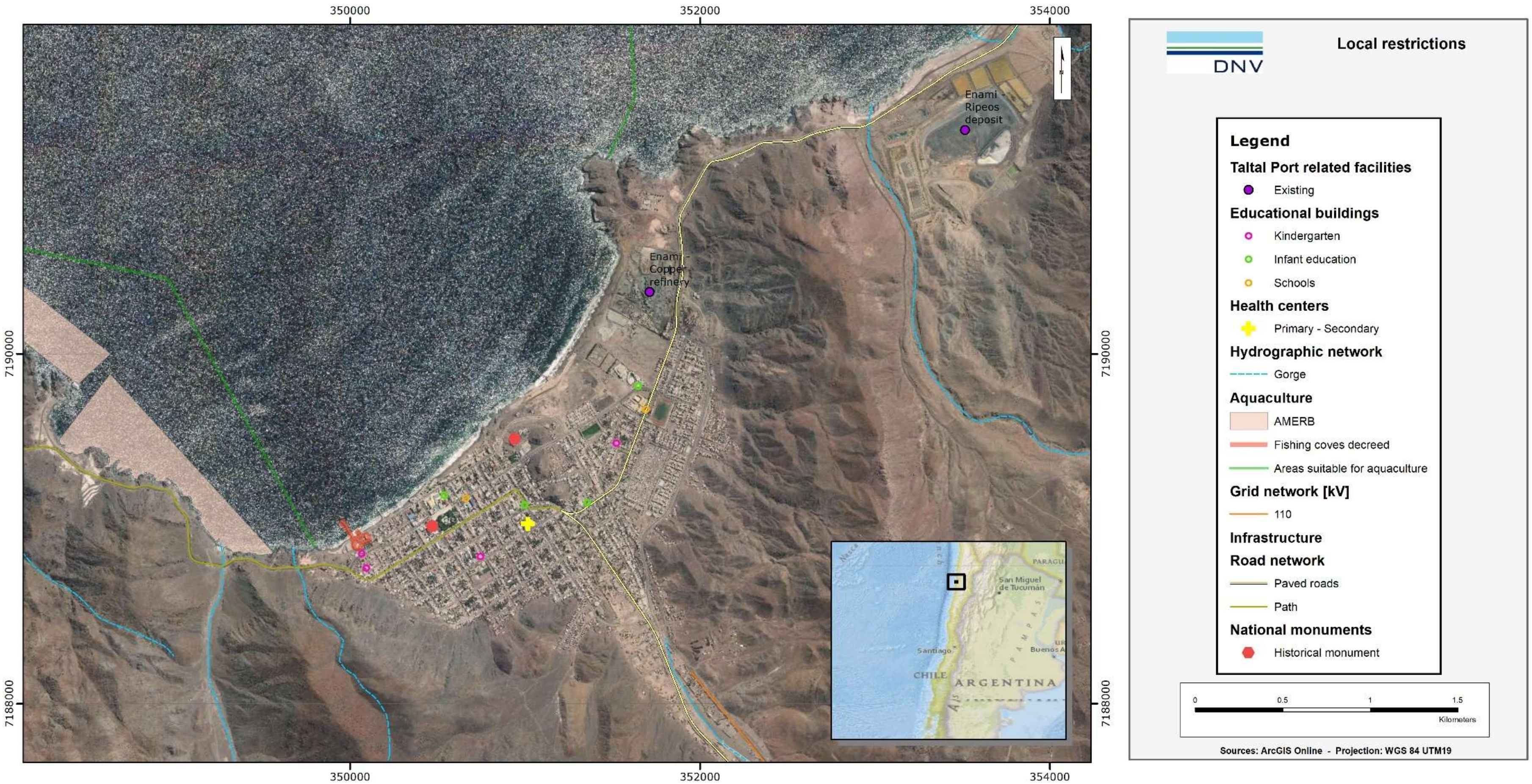


Figure 52 - Constraint Map - Taltal

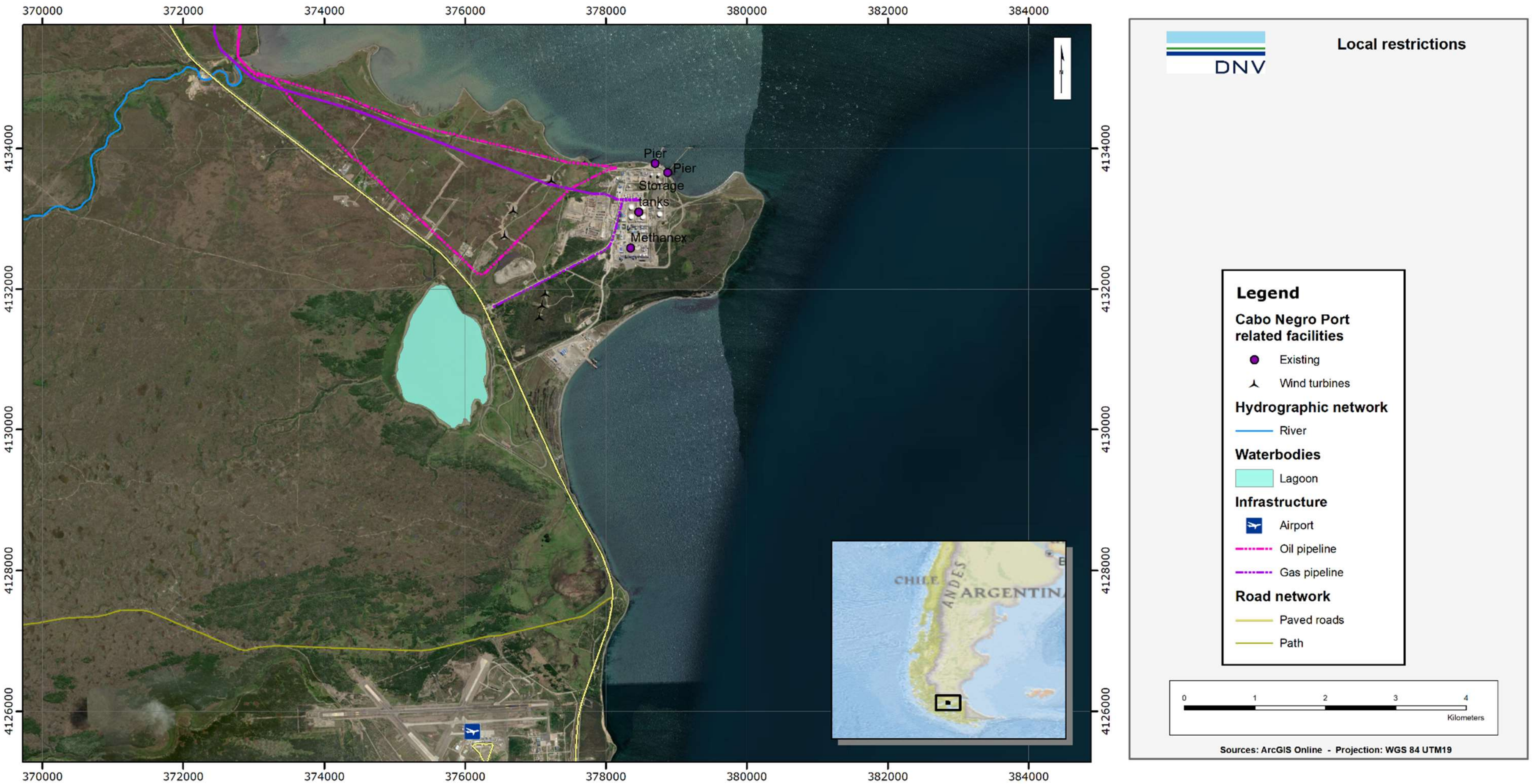


Figure 53 - Constraint Map - Cabo Negro

APPENDIX B – BUSINESS MODEL

Input parameters

	Unit	Active Case
Financial		
Inflation	%	0,00%
Discount rate nominal	%	8,0%
Discount rate real	%	8,0%
Discount date	Year	2022
Capital structure		
Debt	%	30%
Cost of debt	%	4,63%
Equity	%	70%
Cost of equity	%	8%
Tax		
Tax rate	%	21%
Taks consolidation	[-]	Yes
CAPEX		
Ammonia export terminal	MUSD	481
Year 1	%	25,0%
Year 2	%	25,0%
Year 3	%	25,0%
Year 4	%	25,0%
OPEX		
Total opex	% of CAPEX	2%
Ammonia Export Terminal Characteristics		
Start construction	Year	2024
Start operation	Year	2027
Months of operation first yea	Nb. Months	12
Project Life	Nb. Years	30
Depreciation	[-]	2
Capacity	tonnes NH3/year	1.000.000
Availibility	%	96,0%
Operating hours	Hr	8.410
Efficiency	% (LHV)	100,0%
Power consumption	MW	4
Exchange rates		
GBP to EUR	GBP/EUR	1,15
USD to EUR	USD/EUR	0,9

Levelised Cost

Nominal				IRR
Ammonia	**SUM**	**NPV**	**$/tonne**	7,0%
CAPEX	336,7	248,4	33,7	
OPEX	313,8	77,1	10,5	
Total	**650,5**	**325,5**	**44,2**	
			44,2	

Nominal				IRR
Ammonia	**SUM**	**NPV**	**$/tonne**	11,2%
CAPEX	336,7	248,2	33,7	
OPEX	313,8	77,1	10,5	
Tax	127	29	4	
Total	**651**	**354**	**48**	

Real			
Ammonia	**SUM**	**NPV**	**$/tonne**
CAPEX	336,7	248,4	33,7
OPEX	313,8	77,1	10,5
Total	**650,5**	**325,5**	**44,2**

Real			
Ammonia	**SUM**	**NPV**	**$/tonne**
CAPEX	337	248	34
OPEX	314	77	10
Tax	127	29	4
Total	**651**	**355**	**48**

Cash flow model (2022-2040)

Year					Units	SUM	NPV Nominal	NPV Real	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Inflation index									100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
WACC factors																												
Ammonia export terminal									100%	93%	86%	79%	74%	68%	63%	58%	54%	50%	46%	43%	40%	37%	34%	32%	29%	27%	25%	23%
Exchange rates																												
GBP to EUR									1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15
USD to EUR									0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Energy flows	Operating start	Operating end																										
Flags	2028	2057			[-]				0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Throughput					tonnes NH3	30.000.000	7.372.626	7.372.626	0	0	0	0	0	0	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000
Throughput					tonnes H2	5.295.000	1.301.269	1.301.269	0	0	0	0	0	0	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500
Power consumption					MWh	1.009.152	248.003	248.003	0	0	0	0	0	0	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638
Revenues																												
Flags					[-]				0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Tolling revenue					MUSD	1.325	326	326	0	0	0	0	0	0	44	44	44	44	44	44	44	44	44	44	44	44	44	44
CAPEX	From	To	Depreciation	Oper. life																								
Ammonia Terminal Flag	2024	2027	30	30	[-]				0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CAPEX phasing					%				0%	0%	25%	25%	25%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
CAPEX					MUSD	337	248	248	0	0	84	84	84	84	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPEX	From	To																										
Ammonia Terminal Flag	2028	2057			[-]				0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fixed OPEX					MUSD	289	71	71	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Variable OPEX					MUSD	25	6	6	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Cash flows																												
Capex					MUSD	337	248	248	0	0	84	84	84	84	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Revenue					MUSD	1.325	326	326	0	0	0	0	0	0	44	44	44	44	44	44	44	44	44	44	44	44	44	44
Opex					MUSD	314	77	77	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10
D&A					MUSD	337	83	83	0	0	0	0	0	0	11	11	11	11	11	11	11	11	11	11	11	11	11	11
EBIT					MUSD	674	166	166	0	0	0	0	0	0	22	22	22	22	22	22	22	22	22	22	22	22	22	22
Debt outstanding					MUSD	1.447	612	612	0	0	25	51	76	101	101	95	89	83	78	72	67	63	58	54	50	46	42	39
Interest expense					MUSD	67	28	28	0	0	1	2	4	5	5	4	4	4	4	3	3	3	3	2	2	2	2	2
Principal payment					MUSD	101	32	32	0	0	0	0	0	0	6	6	6	5	5	5	5	4	4	4	4	4	4	3
Levelized debt service					MUSD	168	60	60	0	0	1	2	4	5	11	10	10	9	9	8	8	7	7	7	6	6	5	5
Cashflow (pre-tax)					MUSD	607	-28	-28	0	0	-85	-87	-88	-89	29	29	30	30	30	30	31	31	31	31	31	32	32	32
Taxable income					MUSD	607	137	137	0	0	-1	-2	-4	-5	18	18	18	19	19	19	19	20	20	20	20	20	21	21
Defererred tax loss start					MUSD	23	15	15	0	0	0	1	4	7	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Positive taxable income					MUSD	607	139	139	0	0	0	0	0	0	6	18	18	19	19	19	19	20	20	20	20	20	21	21
Deferred tax loss end					MUSD	23	16	16	0	0	1	4	7	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cash Tax					MUSD	127	29	29	0	0	0	0	0	0	1	4	4	4	4	4	4	4	4	4	4	4	4	4
Taxes					MUSD	127	29	29	0	0	0	0	-1	-1	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Cashflow (post-tax)					MUSD	970	89	89	0	0	-83	-82	-81	-80	48	48	47	47	46	46	46	45	45	44	44	44	43	43

Cash flow model (2041-2057)

Year					Units	SUM	NPV Nominal	NPV Real	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057
Inflation index									100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
WACC factors																									
Ammonia export terminal									23%	21%	20%	18%	17%	16%	15%	14%	13%	12%	11%	10%	9%	9%	8%	7%	7%
Exchange rates																									
GBP to EUR									1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15
USD to EUR									0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Energy flows	Operating start	Operating end																							
Flags	2028	2057			[-]				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Throughput					tonnes NH3	30.000.000	7.372.626	7.372.626	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000	1.000.000
Throughput					tonnes H2	5.295.000	1.301.269	1.301.269	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500	176.500
Power consumption					MWh	1.009.152	248.003	248.003	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638	33.638
Revenues																									
Flags					[-]				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Tolling revenue					MUSD	1.325	326	326	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44
CAPEX	From	To	Depreciation	Oper. life																					
Ammonia Terminal Flag	2024	2027	30	30	[-]				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CAPEX phasing					%				0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
CAPEX					MUSD	337	248	248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPEX	From	To																							
Ammonia Terminal Flag	2028	2057			[-]				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fixed OPEX					MUSD	289	71	71	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Variable OPEX					MUSD	25	6	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Cash flows																									
Capex					MUSD	337	248	248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Revenue					MUSD	1.325	326	326	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44
Opex					MUSD	314	77	77	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
D&A					MUSD	337	83	83	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
EBIT					MUSD	674	166	166	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
Debt outstanding					MUSD	1.447	612	612	39	35	32	29	26	24	21	19	16	14	12	10	8	6	4	3	1
Interest expense					MUSD	67	28	28	2	2	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
Principal payment					MUSD	101	32	32	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	1	1
Levelized debt service					MUSD	168	60	60	5	5	5	4	4	4	3	3	3	3	3	2	2	2	2	2	1
Cashflow (pre-tax)					MUSD	607	-28	-28	32	32	32	32	32	33	33	33	33	33	33	33	33	33	33	34	34
Taxable income					MUSD	607	137	137	21	21	21	21	21	21	21	22	22	22	22	22	22	22	22	22	22
Defererred tax loss start					MUSD	23	15	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Positive taxable income					MUSD	607	139	139	21	21	21	21	21	21	21	22	22	22	22	22	22	22	22	22	22
Deferred tax loss end					MUSD	23	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cash Tax					MUSD	127	29	29	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5
Taxes					MUSD	127	29	29	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5
Cashflow (post-tax)					MUSD	970	89	89	43	43	43	42	42	42	42	41	41	41	41	41	41	40	40	40	40

APPENDIX C – REPORT 1 (ACTIVITIES 1 TO 4)

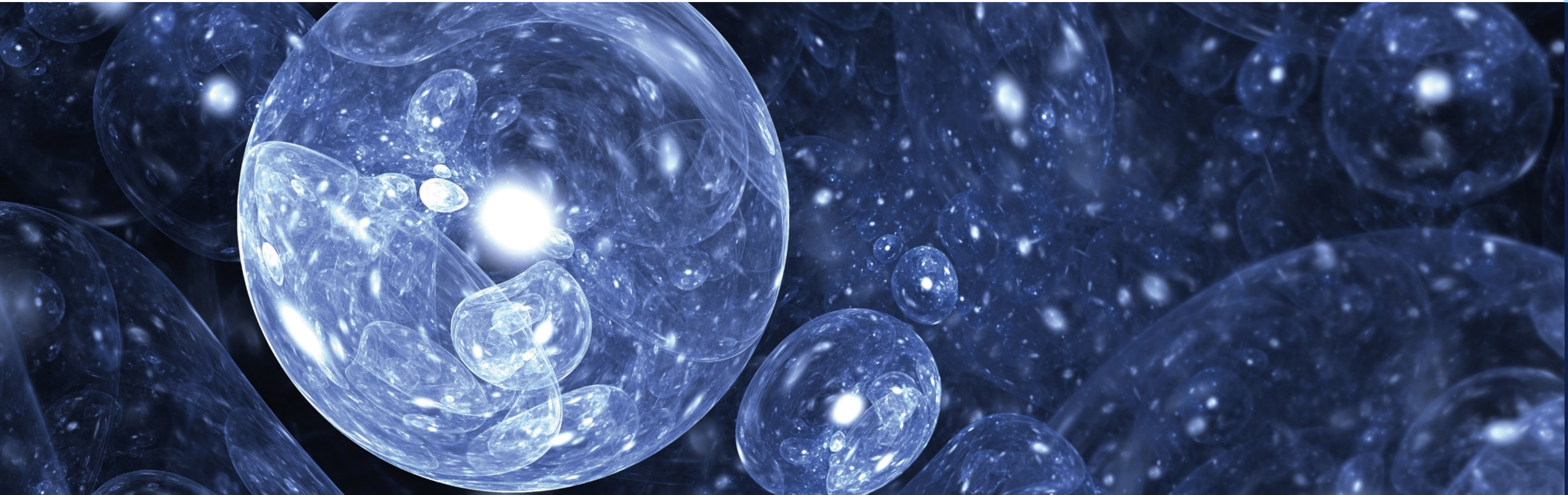
DNV

WHEN TRUST MATTERS

Prefeasibility study for a hydrogen export project

IDB Selection Process #: CH-T1235-P001

Activities 1 to 4 – Report 1



Project name	Prefeasibility study for a hydrogen export project	GL Garrad Hassan Iberica SL Plaza Antonio Beltrán Martínez, 1 Planta 9 Off D, 50002 Zaragoza Spain
For	Inter-American Development Bank	
Client reference	CH-T1235-P001	

Date of issue	10 November 2021	**Project number**	10302204
Report number	10302204-ESZA-R-01	**Organizational unit**	Energy Systems
Contract number	L2C 211125	**Subject group**	Advisory

Prepared by	Wouter van der Goot, Danillo Marques, Malte Nussberger, Jan-Henrik Hübner, Alan Alexander, Corin Taylor, Miguel Sierra	*Signature*
Verified by	Oyvind Sekkesaeter	*Signature* Øyvind Sekkesaeter
Approved by	Carlos Albero	*Signature*

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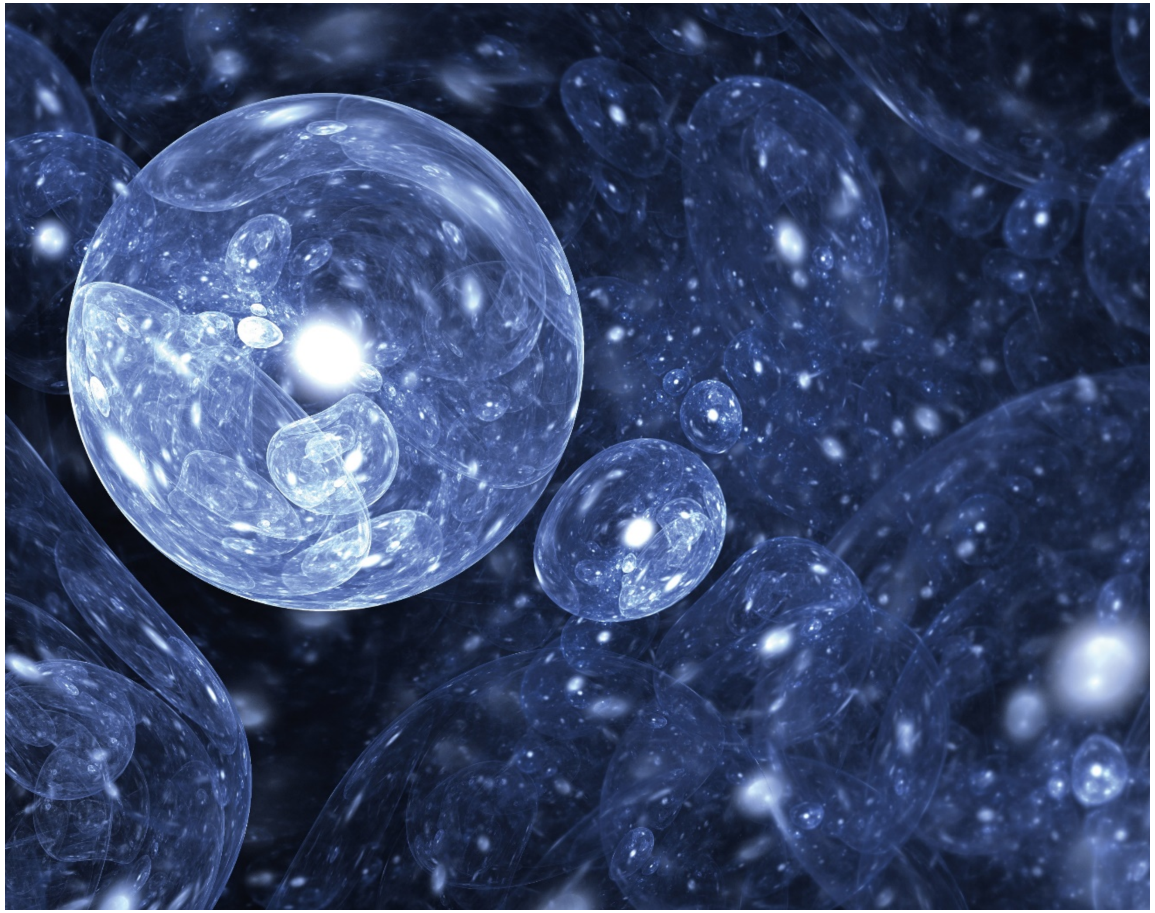
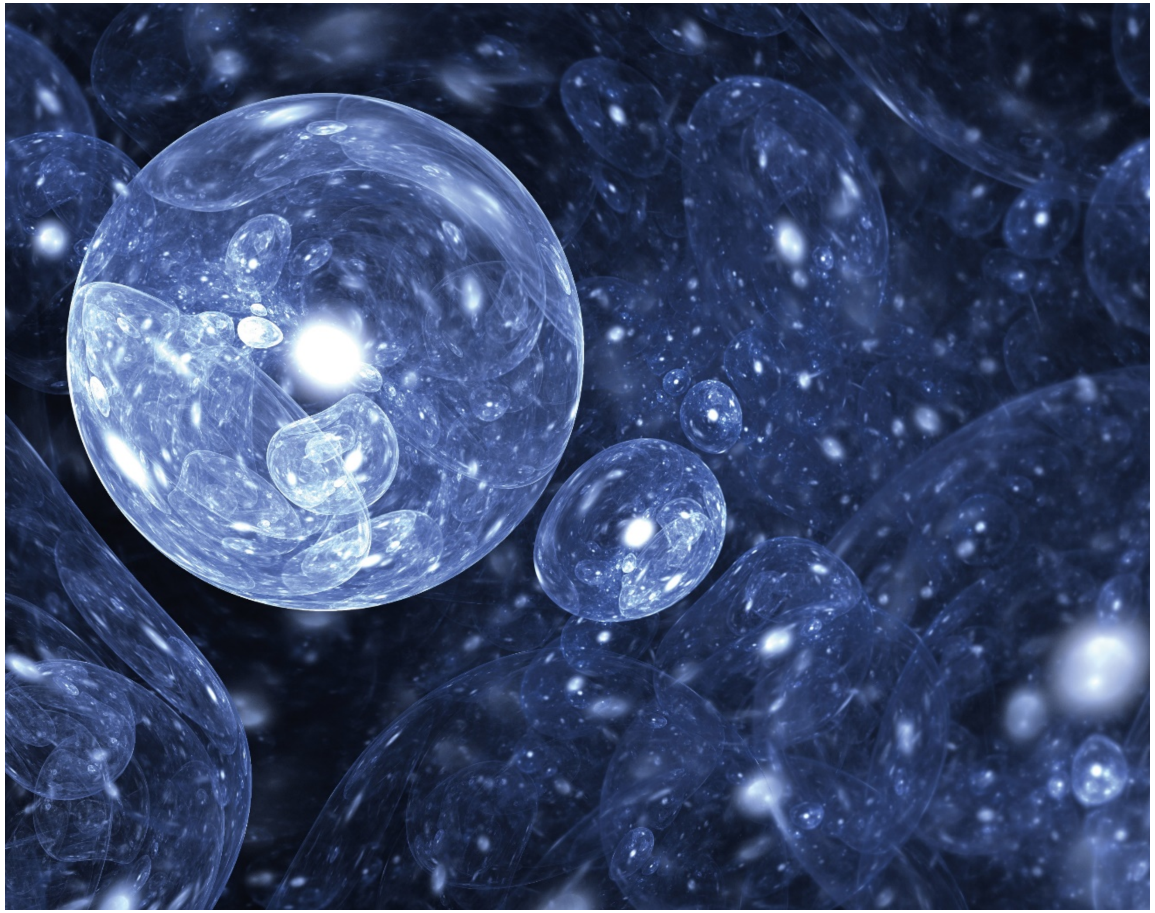
☐	Unrestricted distribution	**Market Segment**	Hydrogen

Content



Content



2020s – Recommendations for Chile: Ammonia

North Chile

The first step should be to investigate further **Option 1: Ammonia direct use**, as there is existing ammonia demand, it is the cheapest export option and most likely to be competitive earliest – before 2030. Pursuing this option allows for **Option 3: Ammonia conversion into H2**, if ammonia cracking is scaled up, with no changes required in Chile. Given the existing infrastructure and ammonia demand, this option should be investigated around Mejillones.

South Chile

The first step should also be to investigate further **Option 1: Ammonia direct use**, given the lower cost of wind electricity compared to solar in the 2020s and the existing LPG export plant in Cabo Negro, although there is no large-scale domestic demand in this location. Similar to North Chile, this option allows for **Option 3: Ammonia conversion into H2** in future.

This approach would promote H2 export through ammonia in the main solar and the main wind regions in Chile, and make use of existing infrastructure and skilled labour. Large ammonia tankers are also already in operation. This approach would maintain flexibility to scale up ammonia production as the 2020s progress. Key export markets to target are Japan and North West Europe.

Given a) the need to scale up hydrogenation and dehydrogenation for LOHC, and the large cost gap between grey and green methanol, and b) the views of interviewees, we think that these are possible, but less promising options for the 2020s. Focusing on ammonia also provides greater optionality, with the potential for direct use in more than one sector and cracking into H2.

The case for ammonia beyond 2030

As per the schematic on the previous slide, we also think that ammonia is the most promising strategic way ahead in the 2030s:

Technology

Ammonia for direct use in fertiliser is the only option that does not need technology development (retrofits to fertiliser plants may be needed, but with existing, proven technology). All of the other options require some technology development, including:

- Liquid H2 requires development of new cargo-ships
- LOHC requires hydrogenation/dehydrogenation to be scaled up
- Methanol requires Direct Air Capture to be scaled up

Versatility and optionality

Ammonia is likely to become a green fuel for ships, which is an advantage over LOHC. Existing ammonia use will face pressure to decarbonise. Both of these trends suggest an increasing demand for green ammonia. In the EU Fit for 55 package an amendment to the Renewable Energy Directive is proposed (not yet adopted):

- A binding target of 50% renewable hydrogen consumption for industry by 2030 (i.e. replacing existing grey H2). This will be a significant enabler of green ammonia.
- Bringing the shipping sector into the EU-ETS (completely for intra EU shipping and 50% for international shipping). Again a game changer for ammonia.

Equally, there is a high degree of uncertainty in the development of the carrier market for hydrogen. The cost levels for LOHC and ammonia are similar (considering the uncertainty in the cost estimates). In this case, ammonia provides Chile with a relatively cheap option to mitigate potential technological or market risk – ammonia can be converted into gaseous hydrogen whereas the LOHC route does not give the option to enter the ammonia market.

Cost and competition

The cost difference between imported and locally produced hydrogen is greater than the difference between imported and locally produced ammonia, which tends to favour ammonia imports. Our analysis suggests that (assuming cost of hydrogen production in Chile is 2.64 $/kg from Brändle et al 2020):

- Green ammonia exported from Chile is cheaper than green ammonia produced in the Netherlands ($379 per tonne of ammonia from Chile freight included, versus $777 per tonne in the Netherlands).
- For green H2, the overall costs are slightly higher from Chile ($4.77 per kg from Chile versus $3.97 per kg in the Netherlands), given the transport costs and the need for the processing of the H2 carrier (assuming ammonia as the export carrier).

Government support

For LOHC and liquid hydrogen, the main issues are global technological, which limits the Ministry's ability to lower the barriers. On methanol, the biggest issue is Direct Air Capture – widespread deployment in Chile could help to reduce the costs of DAC, but at a high cost to Chile.

For ammonia, the biggest hurdles may be the current lack of a global certification scheme for green ammonia, and planning and environmental permitting issues at the export terminal – in Australia, the Asian Renewable Energy Hub was rejected on local environmental grounds. Both of these issues suggest an important role for the Ministry:

- International cooperation to certify green ammonia for export, with certificates accepted by the importing country.
- Strong engagement with export projects to ensure appropriate facility design and strong environmental controls.

Pathway for ammonia

As described above, the option that appears to be lowest risk (or most versatile) is the production of ammonia (preferably in Mejillones or Cabo Negro), with a potential phasing of production. Timelines could be brought forward depending on demand for green ammonia in different sectors and the development of ammonia cracking technology.

Illustrative schematic for ammonia production development in Chile

Project phases	Phase 1	Phase 2	Phase 3
Illustrative timing	Operation by 2025	Operation by 2030	Operation by 2035
Description	Ammonium nitrate plant for decarbonised mining industry	Export for direct use in green fertiliser production	Export for direct use as a marine fuel AND/OR for cracking into H2
Chile infrastructure	• Green H2 production • Ammonia production	• Expanded green H2 and ammonia production • Ammonia terminal repurposed for export	• Expanded production and export capacity • Ammonia bunkering facility
Risk mitigation	No dependency on export markets or green certificates	• No dependency on expanded ammonia cracking capacity • Likely competitive position by 2030	Opportunities for both marine fuel and H2, depending on new marine vessels and ammonia cracking technology

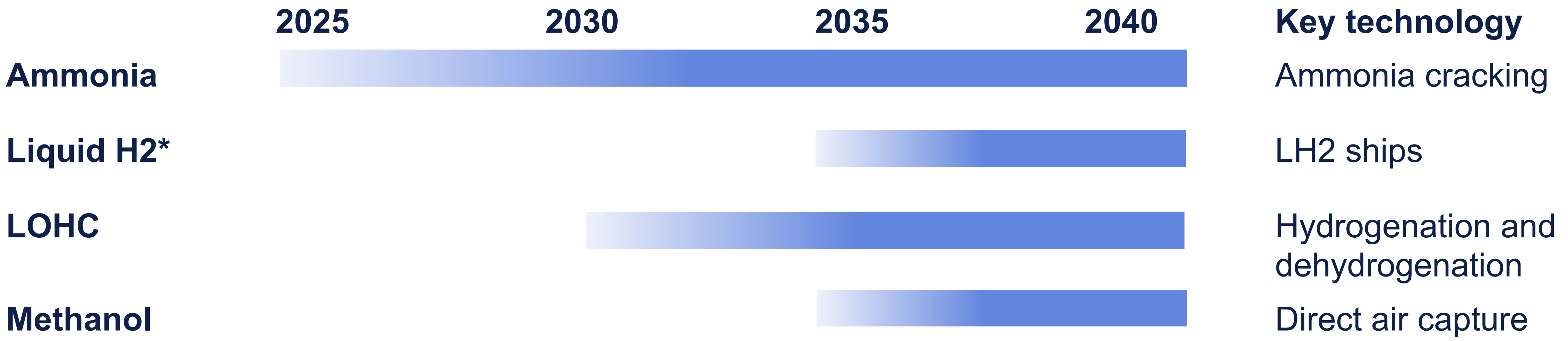
Tonnes NH3 →

2030s – The importance of flexibility

Given the uncertainties in the precise timeframes for the development and scaling of key enabling technologies for the various hydrogen carriers, retaining flexibility in Chile's strategy is essential. We recommend:

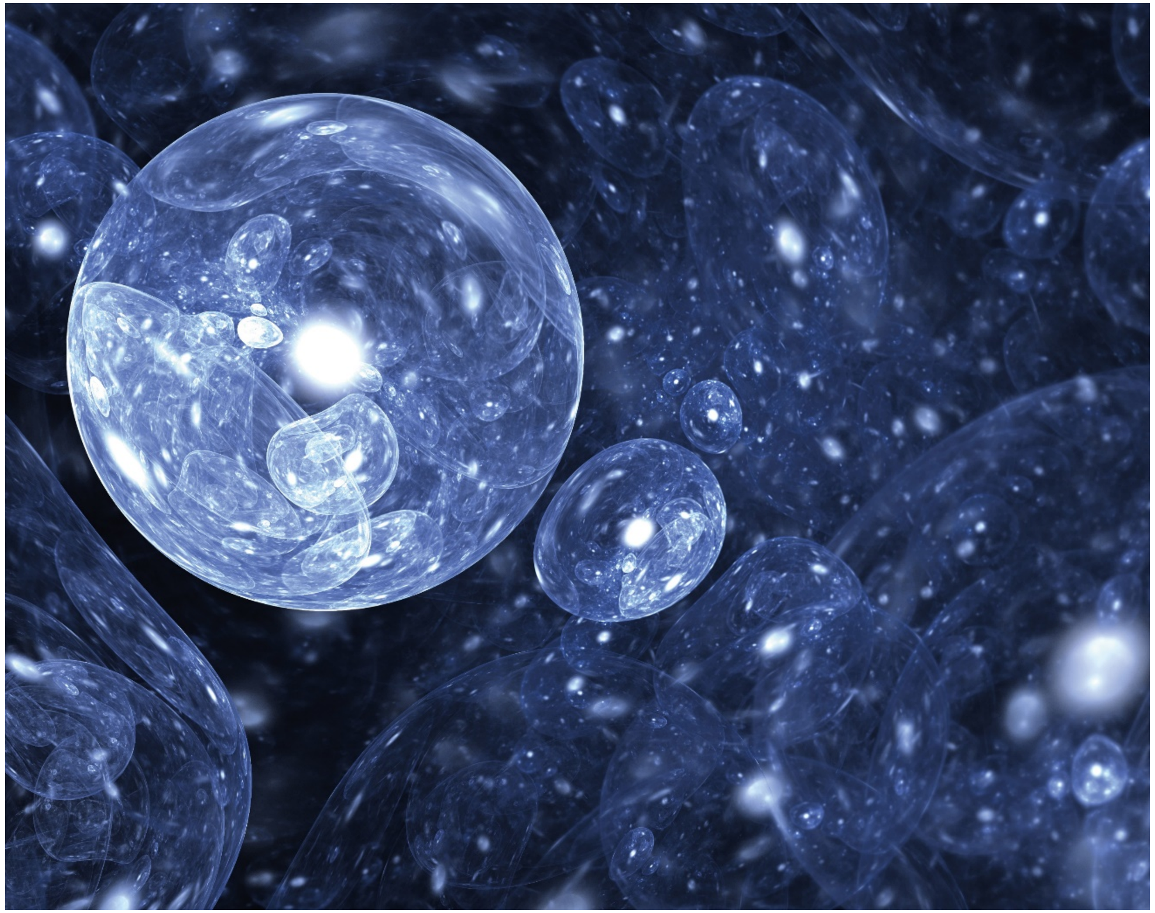
- Providing regular updates on the technology developments relevant to the various carriers, together with the enabling regulations (such as procedures for using ammonia as a maritime fuel and hydrogen guarantees of origin that enable international trade).
- Refreshing the strategy every 2-3 years to reflect regulatory and technology developments.
- Depending on how technology develops in practice, be ready to expand beyond ammonia and add other hydrogen carriers in the 2030s and 2040s – including potentially liquid hydrogen if ships are sufficiently advanced.

Potential strategic pathways for hydrogen carrier establishment



* The Chile National Green Hydrogen Strategy envisages LH2 exports to begin by 2030. DNV believes this indeed may be the case if the development and implementation of the shipping technology is accelerated.

Content



Technical overview of most promising hydrogen applications and alternatives (1/2)

The application of hydrogen has most added value in sectors where electrification is difficult or too costly. These are mostly refining, ammonia, iron & steel, high temperature heating and aviation/shipping

Sector	Opportunity to switch to hydrogen	Alternatives
Direct Heating (High Temperature Heat)	• Direct heating exposes the product directly to the flame and/or combustion products (flue gases). Typical processes are drying processes, production of ceramics, calcination processes, glass production, steel production. • These processes can be converted to hydrogen, but additional research is needed on the impact of the product quality and the product appearance.	• Electrification is possible for most processes. However, modification of existing processes is capital expensive and might be more appropriate for new build. • CCS can also be an option. However, due to the capture rate on existing processes this might be challenging to achieve full decarbonization.
Iron & Steel	• Steel production is split-up between primary and secondary steel making. In the primary process either BF-BOF or DRI-EAF is used. In secondary steel making Scrap-Electric Arc Furnace (ScrapEAF) is used. • Hydrogen can replace the energy carrier and reducing agent in the DRI process or admixed in the BF-BOF.	• In Europe, the HIsarna process offers potential to significantly reduce CO2 emissions. Coupled with CC(U)S this could be a potential competing decarbonization route. • Admixing hydrogen to existing BF-BOF furnaces coupled with CC(U)S could also be a potential alternative decarbonization route.
Ammonia	• Ammonia is mostly produced in large scale plants using the Haber-Bosch process, in which ammonia is synthesised from hydrogen and nitrogen. The current hydrogen is made from reforming natural gas or coal. • Hydrogen can easily replace natural gas or coal in the production of ammonia. However, for urea production another source of CO2 is necessary.	• The existing SMR units can be retrofitted with CC(U)S where 60-65% of CO2 can be captured against relatively low costs. • Also, biomethane could be used as an alternative feedstock. For urea production biomethane might be the only viable pathway due to the requirement of carbon.
Heavy Duty Trucking & Aviation & Shipping	• Most of the heavy transport use liquid fossil fuels which have a high energy density and fast refueling times. • Hydrogen can play a role in fuel cell electric trucks. Also, ammonia is a potential option for long distance shipping. For aviation synthetic fuels are one of the few options.	• For trucks either direct electrification by BEV, indirect via hybrid catenary systems or bio-LNG are possible solutions. • For aviation bio-jet fuels are one of the few alternatives. • Next to ammonia also methanol could provide an alternative for shipping.

Sources: Internal DNV analysis, Wang et al 2021, IEA 2019

Technical overview of most promising hydrogen applications and alternatives (2/2)

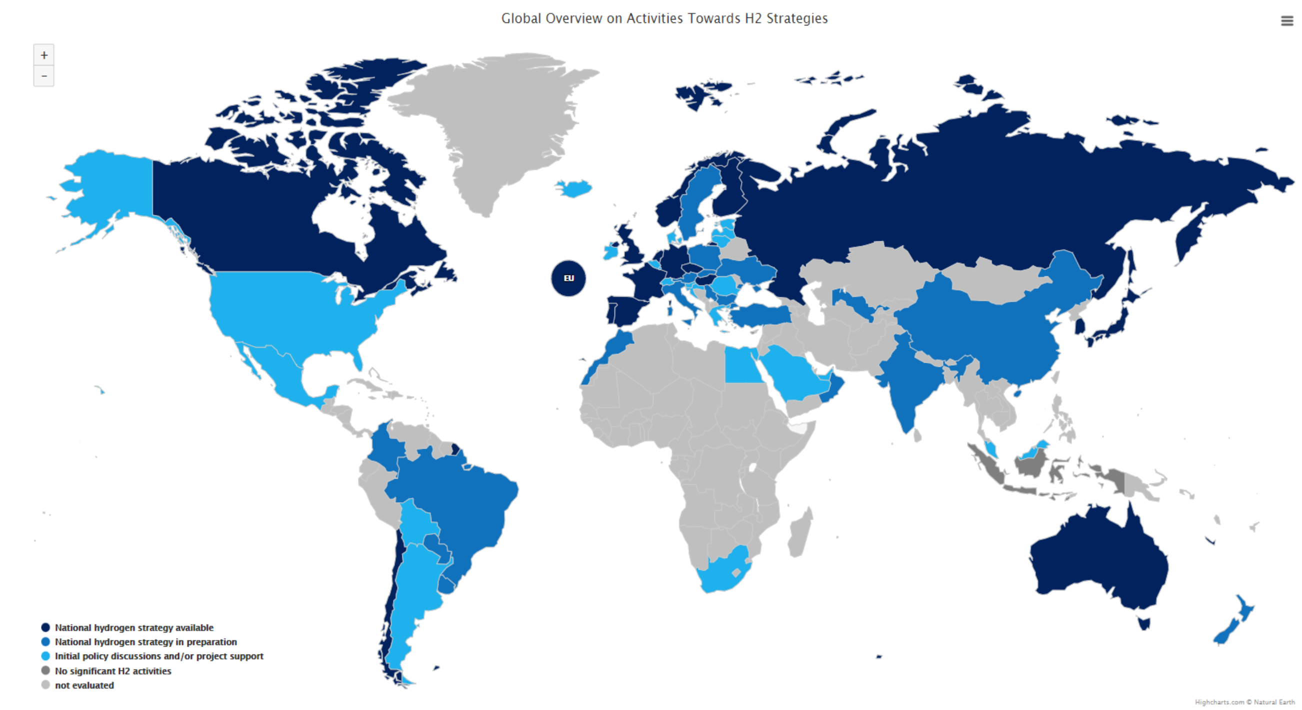
The application of hydrogen has most added value in sectors where electrification is difficult or too costly. These are mostly refining, ammonia, iron & steel, high temperature heating and aviation/shipping

Sector	Opportunity to switch to hydrogen	Alternatives
Refineries	• In a refinery, hydrogen is an important feedstock that is used in several processes (e.g., hydrocracking, hydrodesulfurization). Usually, hydrogen is produced on site and imported from merchant producers. • The easiest application of green hydrogen is the replacement of merchant hydrogen. Also, the production of synthetic kerosine or upgrading of biofuels to biokerosene.	• For onsite hydrogen production and fluidized catalytic cracking at refineries CC(U)S is an alternative to using electrolytic hydrogen. • Electrification of furnaces is possible. However, by-product gasses need to be handled • Biomass admixing up to 10% is possible .
Power Generation	• Natural gas turbines are widely used for electricity generation. Hydrogen (or ammonia) can replace natural gas used in these turbines. • However, due to increase in flame speed and flame temperature gas turbines currently cannot be easily be retrofitted to use hydrogen or ammonia.	• Natural gas in combination with CCS based on an Allam cycle could offer an alternative. The pure CO2 stream facilitates the efficient capture of CO2. • Biomethane could easily replace natural gas in existing gas turbines. • Ammonia is tested to be co-fired with coal in existing coal fired or in gas turbines.
High Value Chemicals	• HVCs are produced in steam crackers, where long-chain hydrocarbons are cracked into short-chain hydrocarbons. The main HVCs are ethylene, propylene, butadiene, benzene. The main feedstocks used in steam cracking are naphtha, gas oil, ethane, butane and propane. • Due to the requirement of carbon methanol is an interesting feedstock replacement.	• Chemical recycling where pyrolysis oil from non-recyclable plastics or waste is turned into feedstock for the cracking process. • Electric cracking processes. However, currently no electric crackers exist.

Sources: Internal DNV analysis, Wang et al 2021, IEA 2019

Analysis of hydrogen strategies

Since 2017 the number of countries which have published a dedicated hydrogen strategy has increased rapidly. Based on these strategies a comparative analysis has been performed on the targeted demand sectors and the (preferred) sources of hydrogen.



Source: World Energy Council

Development of Hydrogen Strategies

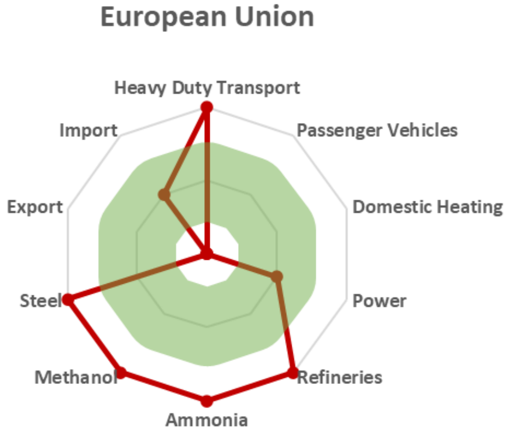
- Since Japan in December 2017 published the worlds first hydrogen strategy an increasing number of countries have followed and published a dedicated hydrogen strategy. Currently 20 countries have such a strategy.
- The World Energy Council expects that by 2025 the number of countries will increase further representing around 80% of global GDP.

Methodology

- A more detailed analysis of the hydrogen strategies and policies of the following countries/states has been performed:
  - Europe, the Netherlands, Germany, the United Kingdom, United States, California, Canada, Japan and South Korea
- For each strategy it has been analysed which demand sectors are targeted by the strategy. This has been done on the basis of three categories which are represented in a spider diagram:
  - **Inner circle:** Not mentioned in the strategy;
  - **Central circle:** Mentioned in the strategy but not the main focus of the strategy;
  - **Outer circle:** Mentioned in the strategy and classified as the main focus of hydrogen demand applications.
- Further, it has been analysed which production methodologies of hydrogen are within the scope of the strategy. This has been indicated by the colour(s) within the spider diagram. The colour(s) represent:
  - **Green:** hydrogen production based on electrolysis using renewable power (wind and solar);
  - **Pink:** hydrogen production based electrolysis using nuclear power;
  - **Blue:** hydrogen production based on fossil fuels in combination with carbon capture utilization and/or storage

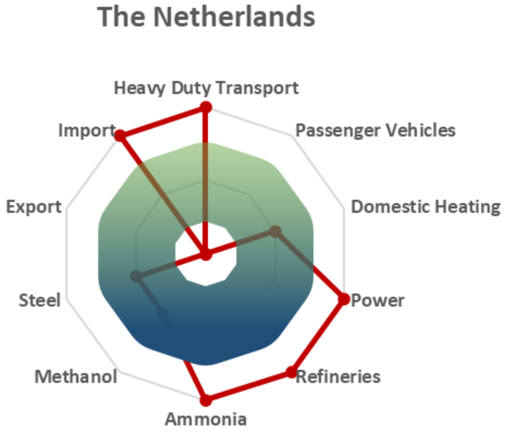
European hydrogen strategies

The European hydrogen strategies have a strong focus on developing the internal EU production capabilities. Although, the Netherlands and Germany also focus on large scale imports. Except for the UK 'blue' hydrogen has a temporary role.



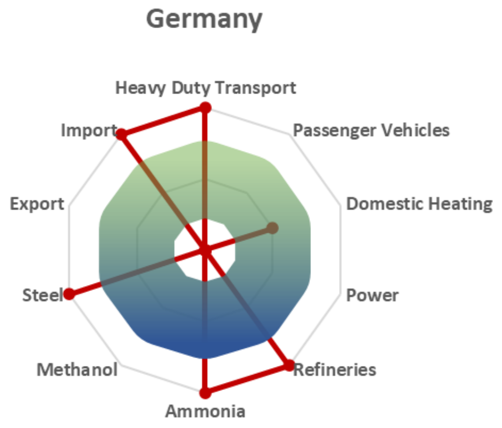
Source: European Commission 2020

- Just as the USA and Japan, the EU has increased its emission reduction target for 2030 to 55% compared to 1990 levels.
- The European hydrogen strategy focusses on the hard to decarbonize segments industry and transport where the short term targets are refining and ammonia to replace current fossil hydrogen.
- In order to promote the use of hydrogen specific (blending) targets and supporting measures for individual markets are considered.
- The importance of a global market and partnerships for the import of hydrogen are explicitly mentioned.
- There are subtle differences between EU countries but refining, ammonia, steel and aviation are common markets in most strategies.



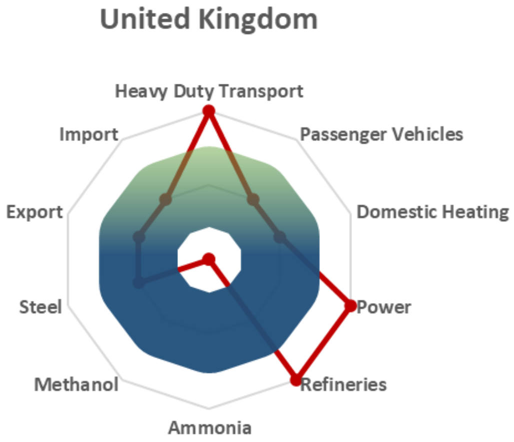
Source: Dutch Hydrogen Strategy

- The Netherlands has a emission reduction target for 2030 of 49% compared to 1990 levels.
- In March 2020 the hydrogen vision and accompanying policy was published.
- The hydrogen program is a commitment that follows the signing of the national Climate Agreement and envisages and stepped approach up to 2030 to reach 3-4 GW of hydrogen electrolysis production capacity.
- For 'Blue' hydrogen a phase-out schedule will be published in a road map for hydrogen that will be published in 2022.
- The main focus is on the industrial clusters, transportation, power generation and heating
- Large scale import and transit is an important element in the Dutch hydrogen strategy.



Source: German Hydrogen Strategy

- Germany has increased its emission reduction target for 2030 to 65% compared to 1990 levels.
- In June 2020 the German Government has published its hydrogen strategy.
- The strategy is focussing on reaching 5GW of hydrogen production capacity by 2030 increasing to 10GW by 2035/40 with a focus on 'green' hydrogen but not excluding 'blue' as a transition fuel.
- The most important market segments are industry (refining, ammonia, steel, cement), transport and heating.
- Due to the domestic resource restriction Germany recognizes an important role for the imports of hydrogen (although mainly focused within the EU internal market).



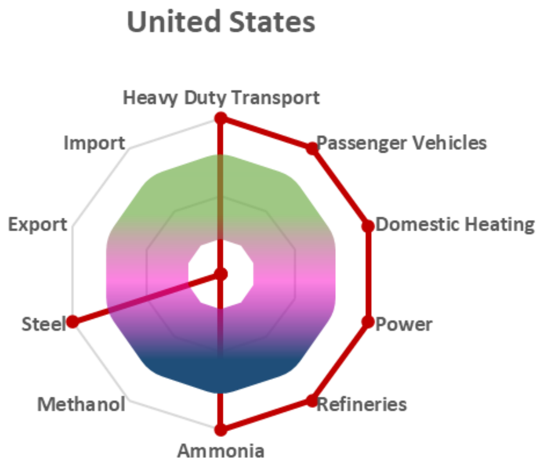
Source: UK Hydrogen Strategy

- The UK has a emission reduction target for 2030 of 68% compared to 1990 levels.
- On August 17th 2021 the UK has published its first hydrogen strategy.
- The strategy is focusing on reaching 5GW of hydrogen production capacity by 2030 and has adopted a twin track to support the development of both 'blue' and 'green' hydrogen.
- The major target market segments are industry, power generation and transport (with pilots in other segments) where the priority is on replacing 'grey' hydrogen with low carbon hydrogen.
- The strategy has a strong focus on developing a domestic hydrogen industrial capability but does see the potential for an international market.

Refer to slide 13 for interpretation of the diagrams

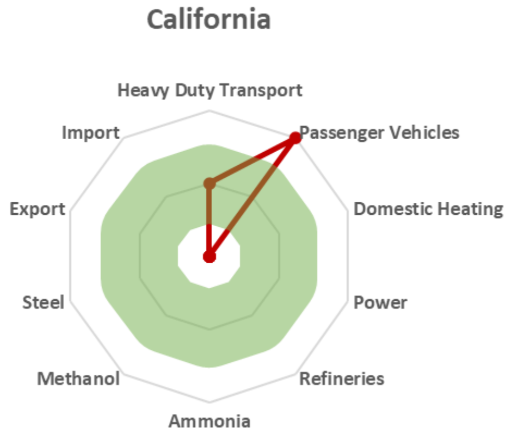
North American hydrogen strategies

Hydrogen strategies in North America have a strong focus on domestic production capacities and potential export. Nuclear, natural gas in combination with CC(U)S are alternative production methods. California stands out with the focus on mobility.



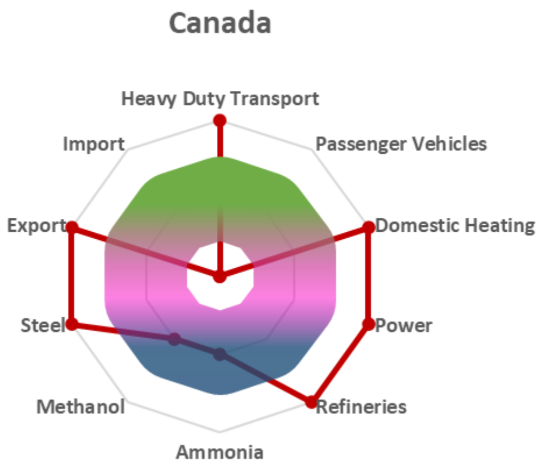
Source: USA Infrastructure Bill 2021

- On April 22nd 2021 the US has announced a new emission reduction target for 2030 of 50%-52% compared to 2005 levels.
- Additionally, the Bipartisan US infrastructure bill allocates $9.5bn to push down the costs of clean hydrogen.
- Included in the $550bn bill are plans for a national hydrogen strategy and roadmap, at least four regional H_2 hubs and billions of dollars for research and development.
- The US strategy focusses on domestic production of hydrogen and imports is not included.
- The Bill addresses demonstration of end-use in power generation, domestic heating, transport and industry.



Source: California 2021

- On February 2021 California's Governors Office of Business and Economic Development published the California Zero-Emission Vehicle Market Development Strategy.
- It highlights that in line with Japan and South Korea also California targets the mobility sector for hydrogen usage.
- The strategy aims to accelerate large scale, affordable, and equitable ZEV market development to achieve a zero emission by 2035 for passenger vehicles and by 2045 for heavy duty trucks.
- The strategy focusses on the local production of hydrogen by means of renewable electrolysis.
- Large part of the strategy is also focussed at expanding the hydrogen refuelling infrastructure.



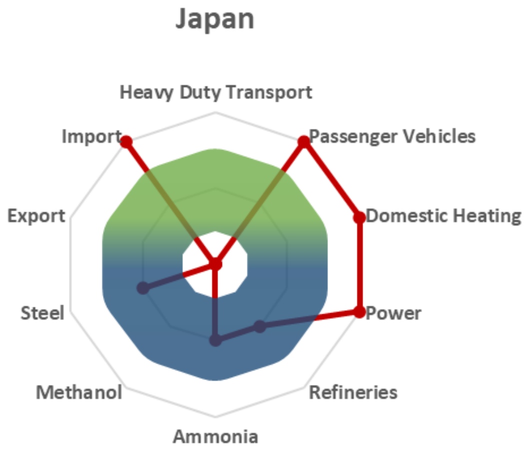
Source: Canadian Hydrogen Strategy

- Canada has increased its emission reduction target for 2030 to 40–45%% compared to 2005 levels.
- In December 2020 Canada has released its national hydrogen strategy.
- The strategy is focussing on establishing Canada as one of the world biggest hydrogen economies and has a particular emphasis on hydrogen exports.
- On the production side Canada is focussing on low carbon hydrogen from a variety of its domestic resources including natural gas with CC(U)S, nuclear power and large scale renewables.
- The main demand is foreseen in transportation and feedstock usage.

Refer to slide 13 for interpretation of the diagrams

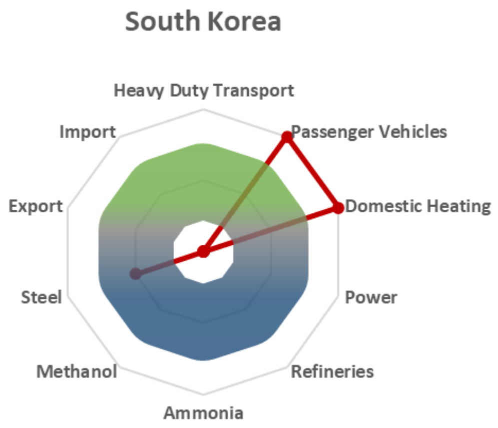
East Asian hydrogen strategies

Driven by domestic fuel cell manufacturing capabilities Asian hydrogen strategies have a strong(er) focus on light vehicle mobility compared to many European strategies. Also, Japan has a strong focus on blending hydrogen/ammonia in power generation.



Source: Japanese Hydrogen Strategy

- On the same summit as the USA, Japan has announced a more ambitious emission reduction target for 2030 of 46% compared to 2013 levels.
- The Japanese hydrogen strategy focusses predominantly on the mobility and the power sector.
- Japan targets 0.3 Mt of hydrogen demand by 2030 to replace natural gas and coal in power generation, and specific pilot projects dedicated to implement this target.
- In the medium term admixing green ammonia in the coal power plants is an important goal and in the short term using ammonia or hydrogen in CCGT.
- The import of hydrogen is an important element in the Japanese strategy. Japanese companies are active in overseas partnerships.



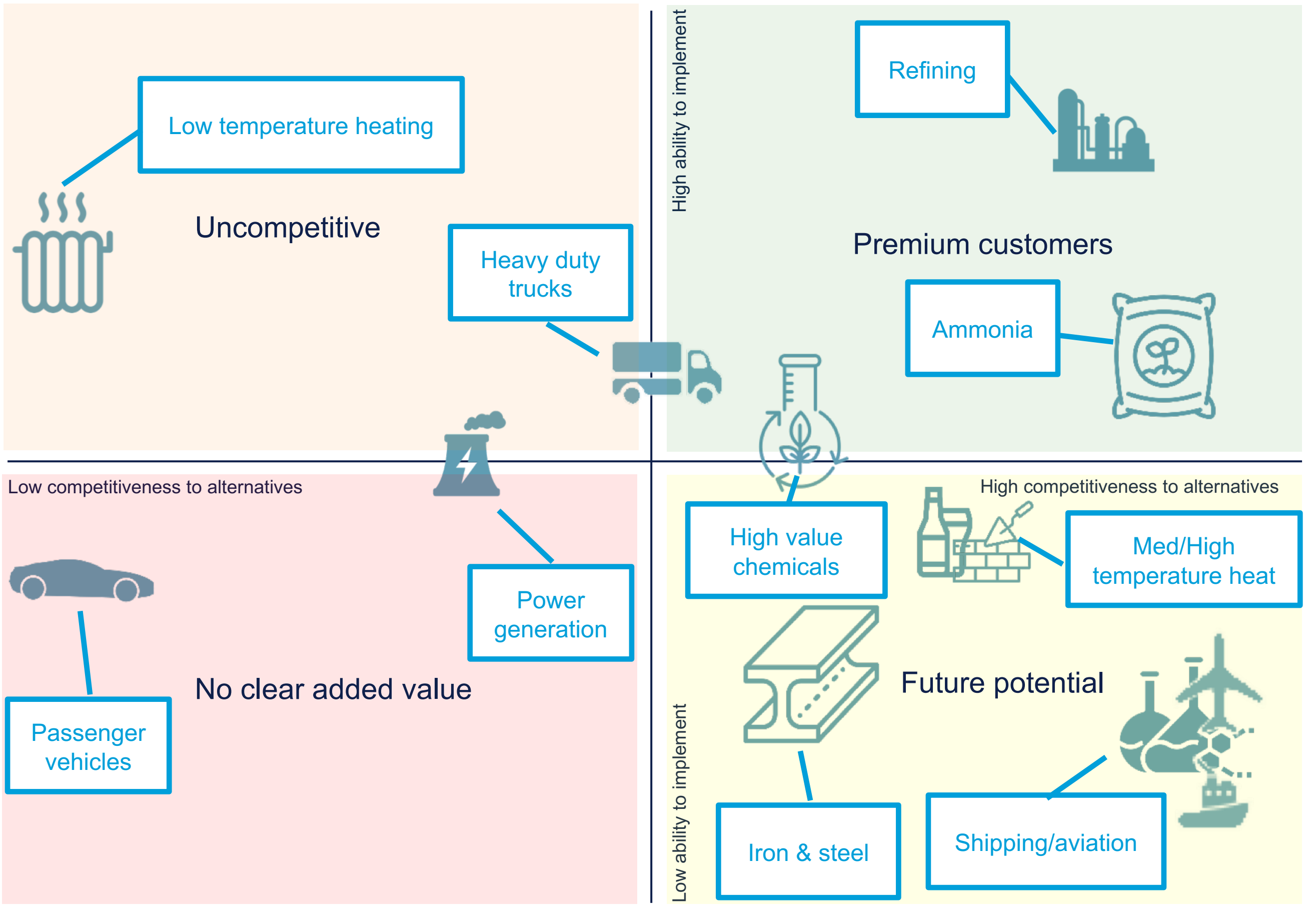
Source: Korean Hydrogen Roadmap

- The South Korean emission reduction target has also been increased for 2030 to 40% compared to 2017 levels.
- The South Korean hydrogen strategy focusses on the mobility and the power sector.
- South Korea targets a hydrogen demand and supply of 1.94 Mt by 2030.
- Contrary to the Japanese strategy South Korea is researching the use of offshore wind power to produce domestic green hydrogen.
- Just as Japan, South Korea has a substantial steel sector. However, this is not addressed explicitly in the strategy.
- The import of hydrogen is foreseen to play a role from 2040. The main focus is on the development of the domestic hydrogen industry (especially fuel cell development but also water electrolysis).

Refer to slide 13 for interpretation of the diagrams

Identifying target market segments

Proximity to harbors, existing hydrogen eco-systems, high concentrated volume demand and in some geographies driven by blending targets a high willingness to pay make refineries a premium customer to replace imported grey hydrogen by green.



Sources: Internal DNV analysis and Liebreich 2021

Premium customers for hydrogen

- The most promising launching market segments for **green** hydrogen are **refining** and **ammonia**. The key enablers are:
  - No real alternatives
  - Existing hydrogen users (limited equipment adaptation necessary) with high concentrated volumes of demand
  - Embedded in existing hydrogen eco-systems
  - Willingness to pay a premium in refining due to blending targets in transportation

Future potential

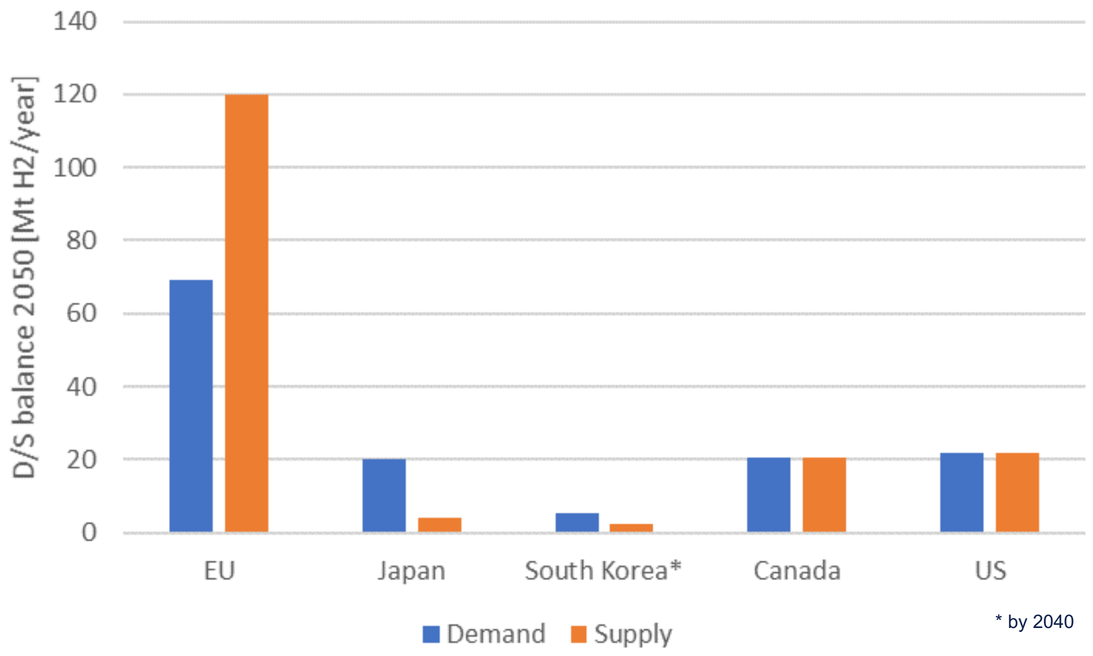
- In addition to the premium customers there are some segments where hydrogen could play an important decarbonization role. In these segments there are alternatives (all-electric or biomass) but hydrogen has a good competitive position:
  - **Steel:** An all electric option is relatively expensive compared to hydrogen and is mainly used in recycling of steel. Hydrogen could start to be blended into the existing blast furnaces (30%). However, developing the TRL of hydrogen BF-DRI could move the segment to premium customers.
  - **HTH:** In sectors like cement, glass and bricks where high temperature heat is required hydrogen could be a cost competitive alternative. Pilots need to be developed.
  - **Aviation/shipping:** Except biofuels the production of synthetic hydrogen based fuels is one of the view alternatives to decarbonize these segments.

No clear added value/uncompetitive

- Especially, in passenger vehicles hydrogen doesn't provide a clear benefit compared to electrification. TCO outlooks provide similar levels for both alternatives and for infrastructure roll-out hydrogen is significantly behind compared to BEV. Hydrogen has more benefits in the other segments.
- In low temperature heating electrical heat pumps provide in the majority of cases a better solution compared to hydrogen (after boundary requirement like insulation are met).

Demand and supply balance

In North America and to a lesser extent in Europe there is strong focus on developing internal production capabilities to meet future hydrogen demand. In Japan and South Korea there is a stronger focus on meeting part of demand through imports



* by 2040

Sources

Europe: European Backbone, Analysing future demand, supply, and transport of hydrogen 2021

Canada: Canadian Hydrogen Strategy

USA: The Technical and Economic Potential of the H2@Scale Concept within the United States

Japan: Japanese Hydrogen Strategy

European demand and supply outlook

- Within Europe there are significant differences between local markets. In North West Europe (The Netherlands, Germany, Belgium and the UK) there is more demand for green hydrogen than there is potential supply. However, especially in Southern and Eastern Europe there is a surplus in production potential. On top of the potential for green hydrogen there is additional 'blue' hydrogen potential.
- Hydrogen exports to Europe will have to compete on price to gain market share. Competitive prices could be advantageous taking into account issues around public acceptance in Europe. Prices for imports will probably have to be in the range of 1.5 – 2.0 €/kg.

North American demand and supply outlook

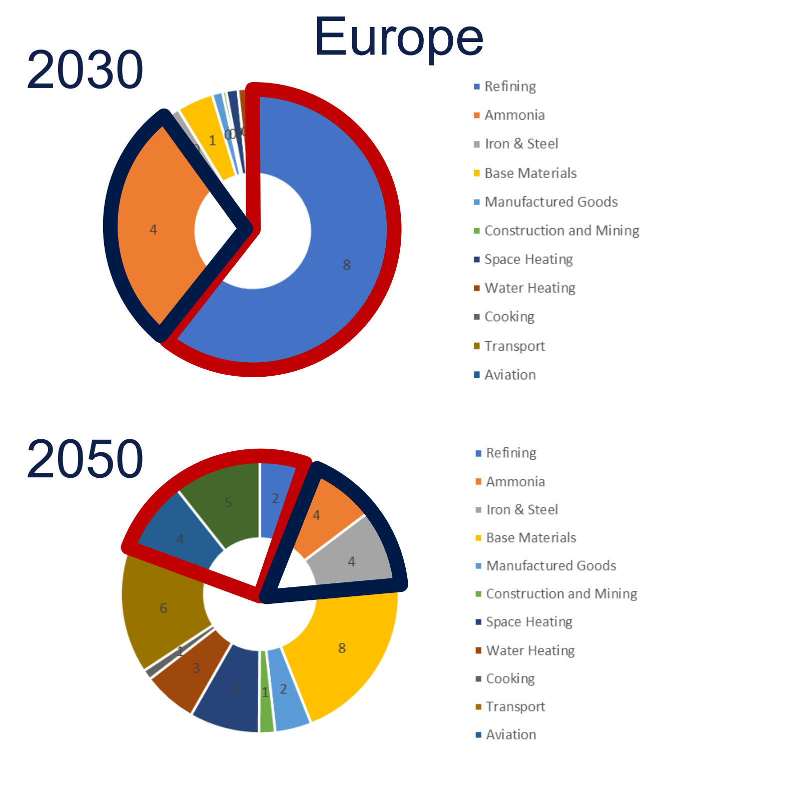
- In the US the theoretical demand for hydrogen is estimated at around 106 Mt per year where in the base case 22 Mt of economical accessible demand is assumed which is served completely by SMR production. In the case of low cost renewables the economic potential could be increased to 41 Mt of hydrogen demand being serviced mostly by electrolysis. Similar to Europe large difference exists between the geographical hydrogen balances across the different states.
- Hydrogen exports to the US will have to compete on price to gain market share. Prices for imports will probably have to be in the range of 1.5 – 2.0 $/kg.

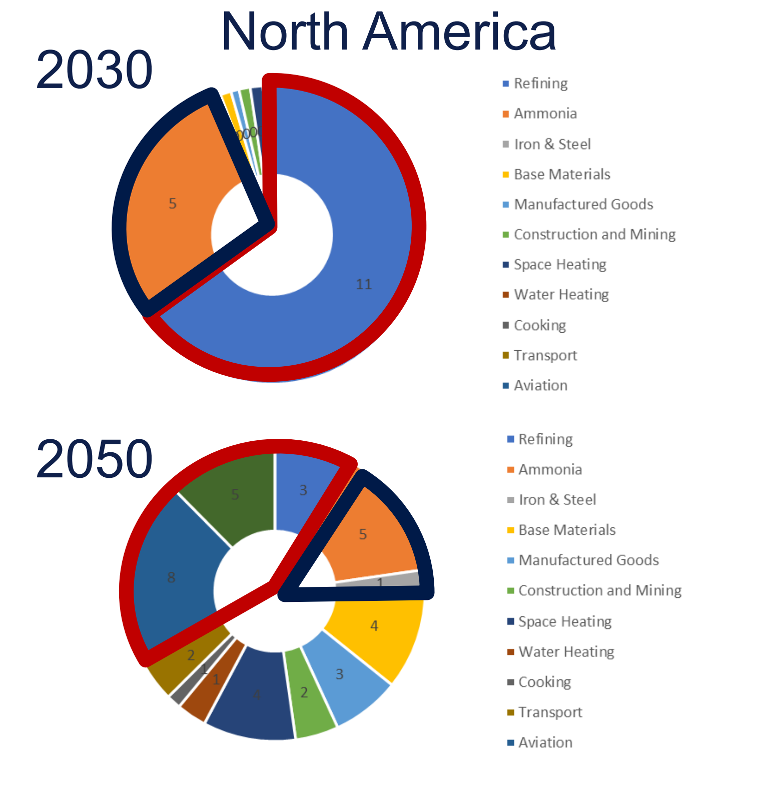
Asian demand and supply outlook

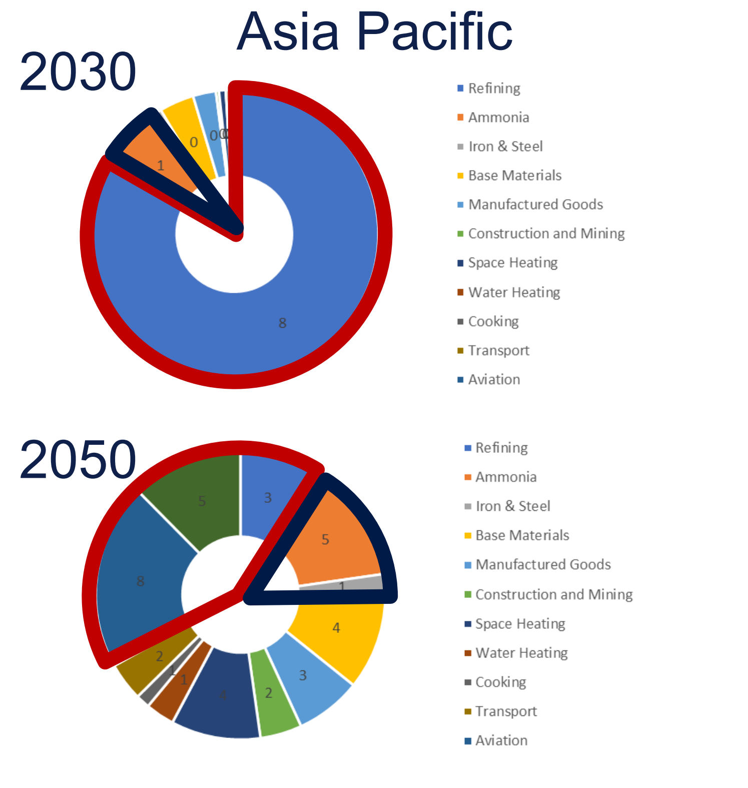
- Asian countries (Japan and South Korea) are less resource self sufficient (have a lower renewable resource potential) compared the US and Europe. Also, for hydrogen substantial imports are foreseen. For Japanese imports an important production technology could be lignite gasification in combination with CCS.
- In order to gain market share the Japanese hydrogen strategy foresees a hydrogen price of around 1.8-2.2 €/kg to unlock market potential.

Sectoral overview hydrogen demand

Globally a similar shift in (expected) hydrogen demand can be observed. The refinery sector which is the current major driver of hydrogen demand will decrease and be replaced by new demand from iron & steel, aviation, shipping and transportation.







- The demand for hydrogen in the refinery sector is expected to decline over time due to a shift from ICE combustion vehicles towards BEV/FCEV. However, this demand is partly replaced by new demand for hydrogen/synthetic fuels for the shipping and aviation sector.
- The demand for hydrogen in ammonia production across all three regions is expected to remain in line with current hydrogen demand.
- The demand for hydrogen in refining, ammonia, shipping, aviation, iron & steel all have high degree of clustering around port areas.

Port Based Occasionally port adjacent

Ranking demand attractiveness

Policy alignment is the main driver for Europe as the most attractive hydrogen market. The most attractive market segments are refining, ammonia production and aviation/shipping due to the lack of alternatives and the good fit with port infrastructure.

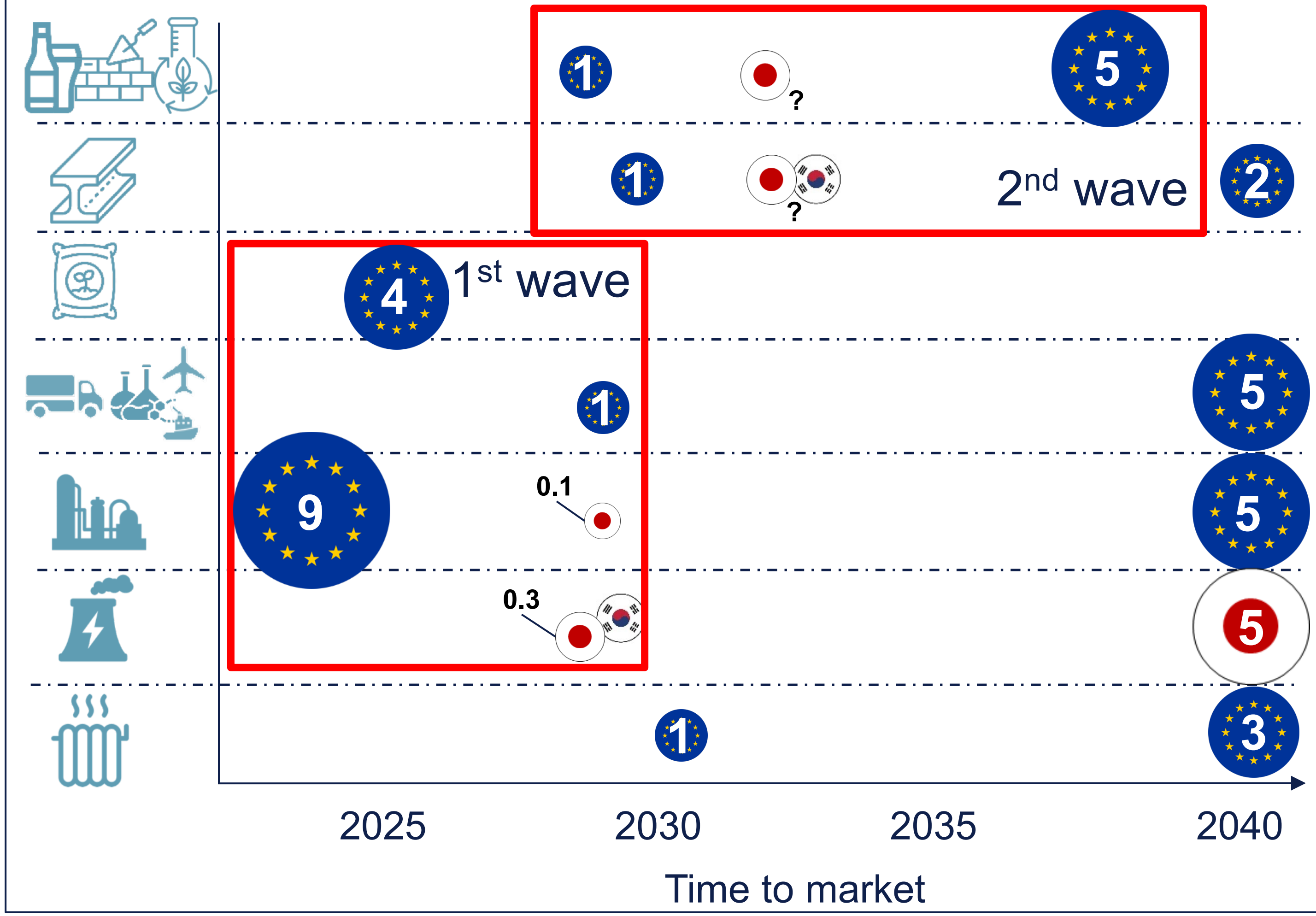
	Ease of infrastructure access			Competition with alternatives			Ability to switch to (green) hydrogen			Aligned with policy			Overall Score		
	EU	NA	AP	EU	NA	AP	EU	NA	AP	EU	NA	AP	EU	NA	AP
Refinery	5	5	5	4	5	5	4	4	4	5	3	1	18	17	15
Ammonia	3	4	4	5	5	5	3	3	3	5	3	1	16	15	13
Iron & Steel	3	2	4	4	4	5	2	2	2	5	3	4	14	11	15
High temperature heating	2	2	2	4	4	4	3	3	3	4	3	1	13	12	10
Low temperature heating	2	2	2	1	1	1	4	4	4	2	3	4	9	10	11
Power generation	5	5	5	2	2	3	2	2	2	3	3	5	12	12	15
Aviation (incl. synthetic fuels)*	5	5	5	4	4	4	2	2	2	5	3	1	16	14	12
Shipping	5	5	5	4	4	4	3	3	3	5	1	1	17	13	13
High value chemicals	3	3	3	4	4	4	2	2	2	4	3	1	13	12	10
Light duty vehicles	2	2	2	3	3	3	3	3	3	2	4	5	10	12	13
Heavy duty vehicles	3	3	3	3	3	3	2	2	2	4	4	5	12	12	13

- The most relevant demand sectors have been ranked on a scale ranging from 1 to 5 based on a qualitative assessment of the previous slides. Adding up the point results in a total score. The segments per continent which score above 14 points are seen as the most promising.
- The most promising market segments are accessible through existing or close proximity to port infrastructure, have limited competition from alternatives (mainly electrification), have the ability to relatively easy switch to hydrogen and are supported by the relevant hydrogen strategy.

* Includes the use of hydrogen for the production of biofuels

Market development and drivers

Driven by blending targets and low implementation costs, the European refining market will be the 1st off-taker of green hydrogen replacing existing imports. In the medium term the European and Asian steel market will become large hydrogen off-takers.



Drivers:

Short term (before 2030):

- The first driver of hydrogen demand will be the refining sector in Europe due to Increasing renewable blending obligations. Replacing existing hydrogen imports requires no modifications. Japan, Korea and the USA don't have binding obligations (yet) in the transportation sector.
- The second driver in Europe will be the decarbonization of ammonia production. However, direct use of ammonia could require additional equipment modifications.

Medium Term (after 2030):

- Steel is one of the largest emitters of CO_2 and limited decarbonization alternatives exist. Blending hydrogen in existing BF could kick-start emission reduction in the short term coupled with CCS. Building new factories based on hydrogen DRI-EAF would create substantial hydrogen demand after 2030. In Europe, Germany stimulates steel companies to implement hydrogen for decarbonization.
- For aviation and shipping either hydrogen, synthetic fuels, biofuels or ammonia are likely to create increasing hydrogen demand to decarbonize these sectors.
- In Japan, Jera & Mitsubishi have started pilot projects to use ammonia/hydrogen in its existing generation units. Depending on the outcome of the pilots this could open a substantial market for hydrogen demand.

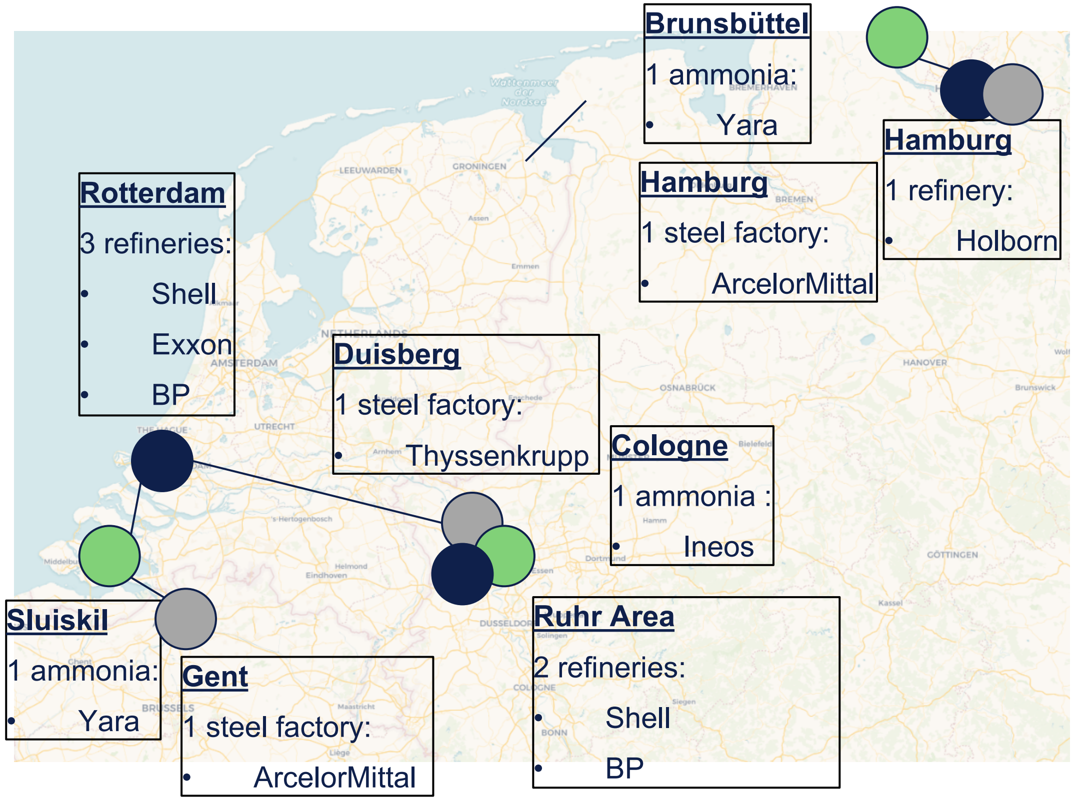
Number and bubble size indicate hydrogen demand in Mt/Yr

Sources

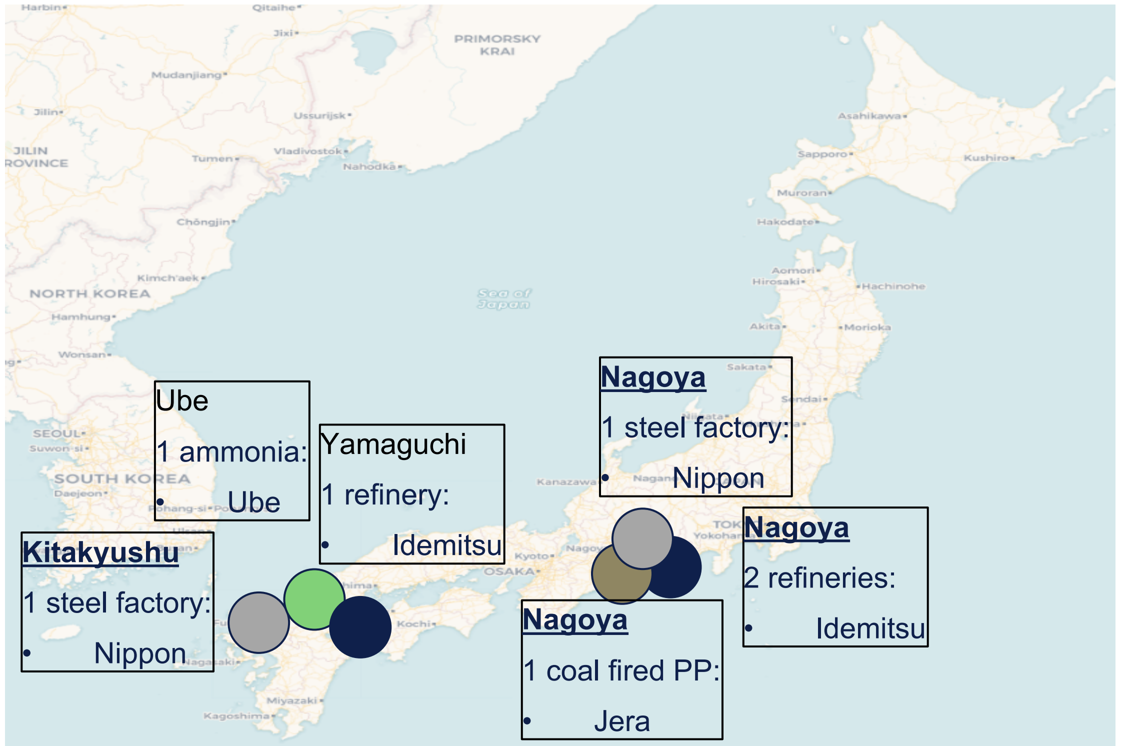
DNV ETO, Japanese Hydrogen Strategy

Identification of potential importers Europe and Japan

The ports of Rotterdam and Hamburg offer the opportunity to launch green hydrogen supply to refineries and expanding through the European hydrogen backbone to ammonia and steel. In Japan, the port of Nagoya offers access to power, steel & refinery.



- The ports of Rotterdam and Hamburg offer locations that are in close proximity to multiple refineries. These refineries could be premium off-takers of imported green hydrogen. Also, in the ARA region an existing hydrogen infrastructure exists.
- Further, these ports offer the potential for ammonia bunkering for the shipping sector.
- In a second phase the ports offer potential to connect through the European hydrogen backbone to iron & steel and ammonia demand centres.

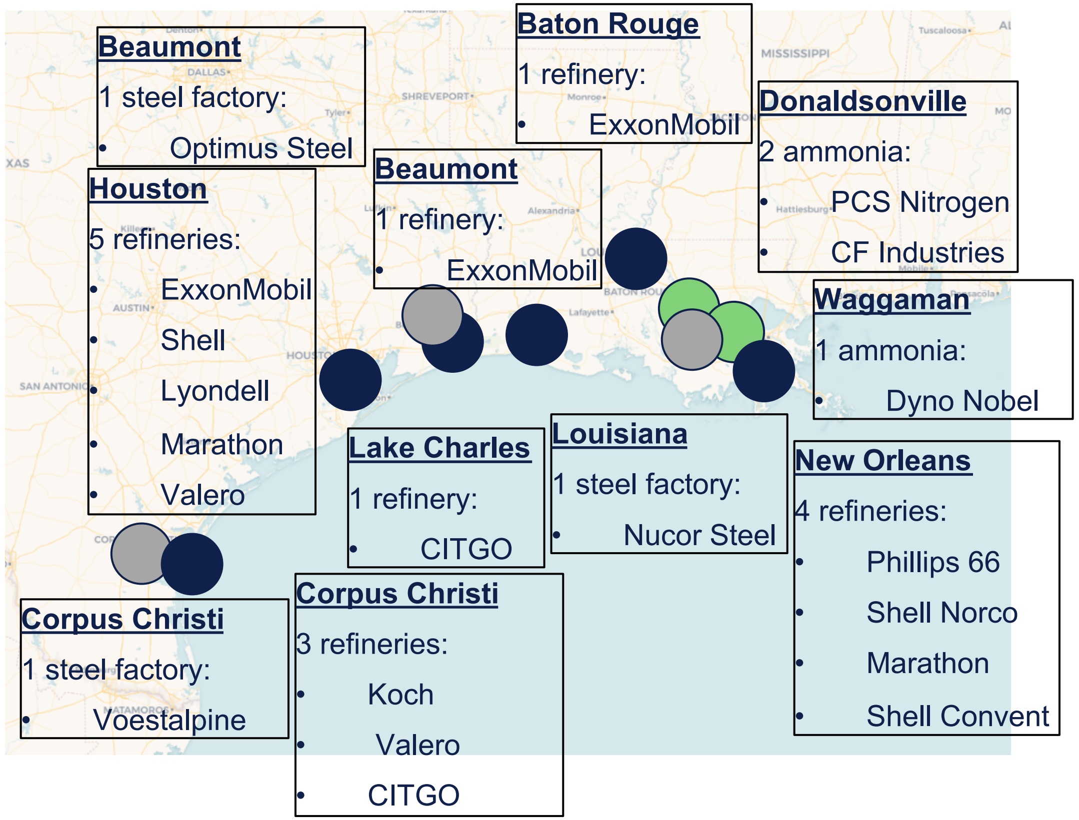


- The ports of Nagoya and Kitakyushu offer locations that are in close proximity to multiple current and future potential demand centres. These demand centres consist of power generation, refineries and steel production.
- Also, these harbours offer potential for ammonia bunkering for the shipping sector.
- In Nagoya Jera is setting-up a pilot project to admix ammonia into their coal fired power plant and the Hydrogen Utilization Study Group in Chubu has already been performing hydrogen feasibility studies

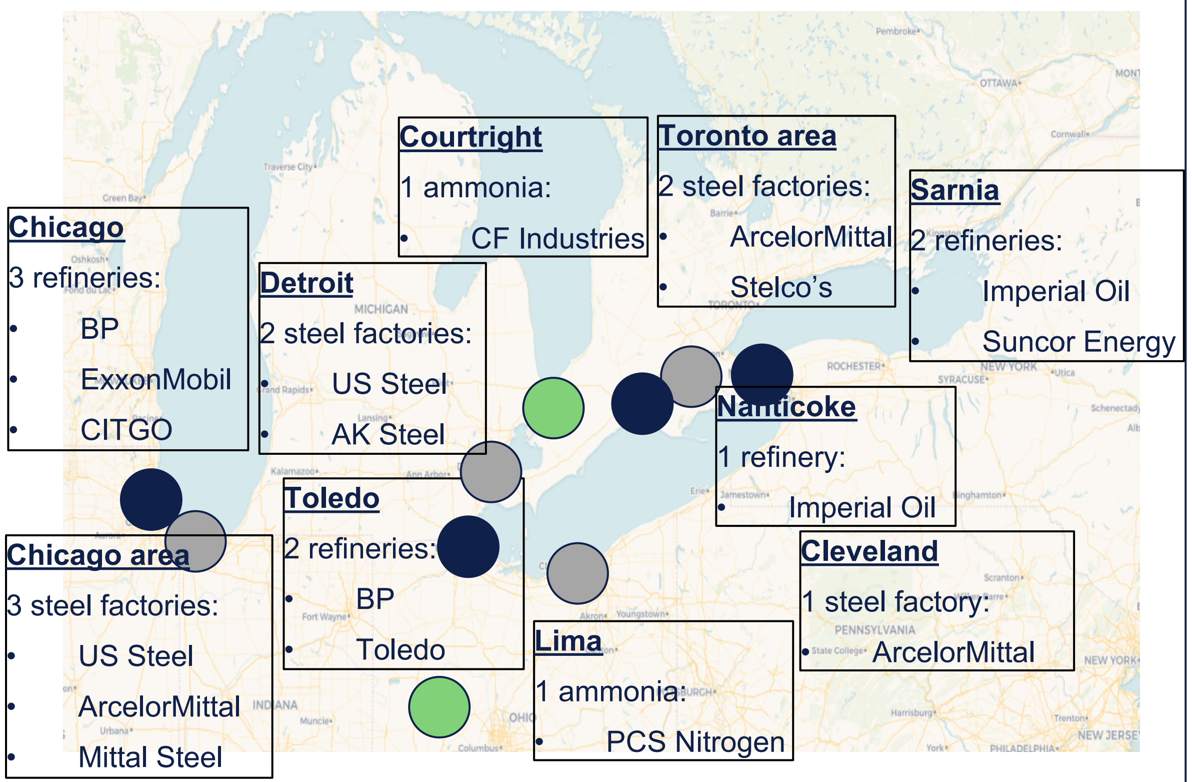
Ammonia Iron & Steel Refinery Power Generation

Identification of potential importers North America

The ports along the coast of Texas and Louisiana offer access to a large potential customer base connected to an existing hydrogen eco-system. The Great Lakes offer a similar opportunity and can connect US and Canadian potential demand.



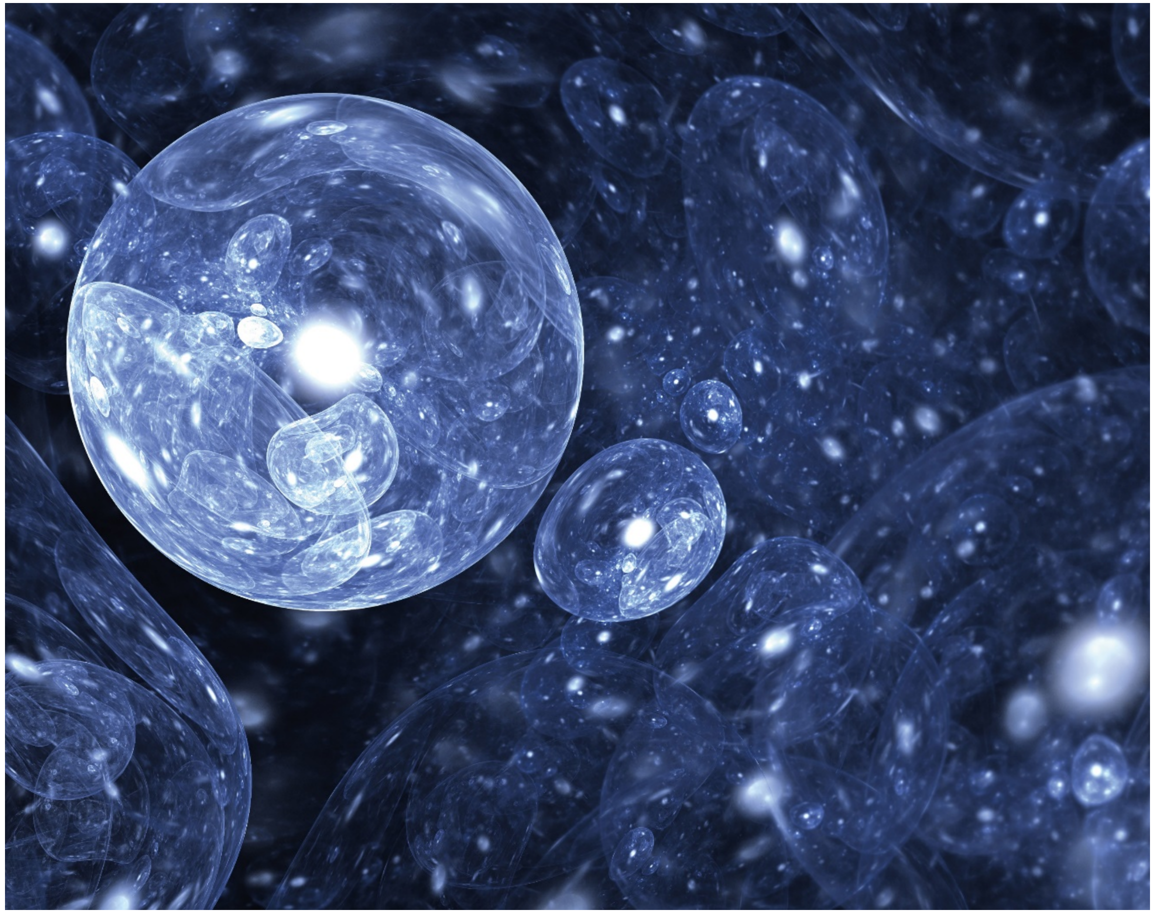
- Multiple ports offer access to large eco-system of refineries, ammonia and iron & steel manufacturing where currently the Gulf Coast Hydrogen System is currently operated.
- However, there is strong competition from current and potential local hydrogen production by SMR (eventually coupled with CC(U)S).
- Multiple ports along the coast provide opportunities for ammonia as ship bunkering.



- The ports of Hamilton, Detroit, Chicago (where an existing hydrogen network is present) & Toledo offer locations that are in close proximity to multiple demand centres. These demand centres consist of refineries, ammonia and iron & steel.
- Especially, areas of Chicago, Detroit and Toronto have a large steel industry which potential for hydrogen demand when these industries have to decarbonize.
- In this area there is potential strong competition from nuclear high temperature electrolysis.

Ammonia Iron & Steel Refinery

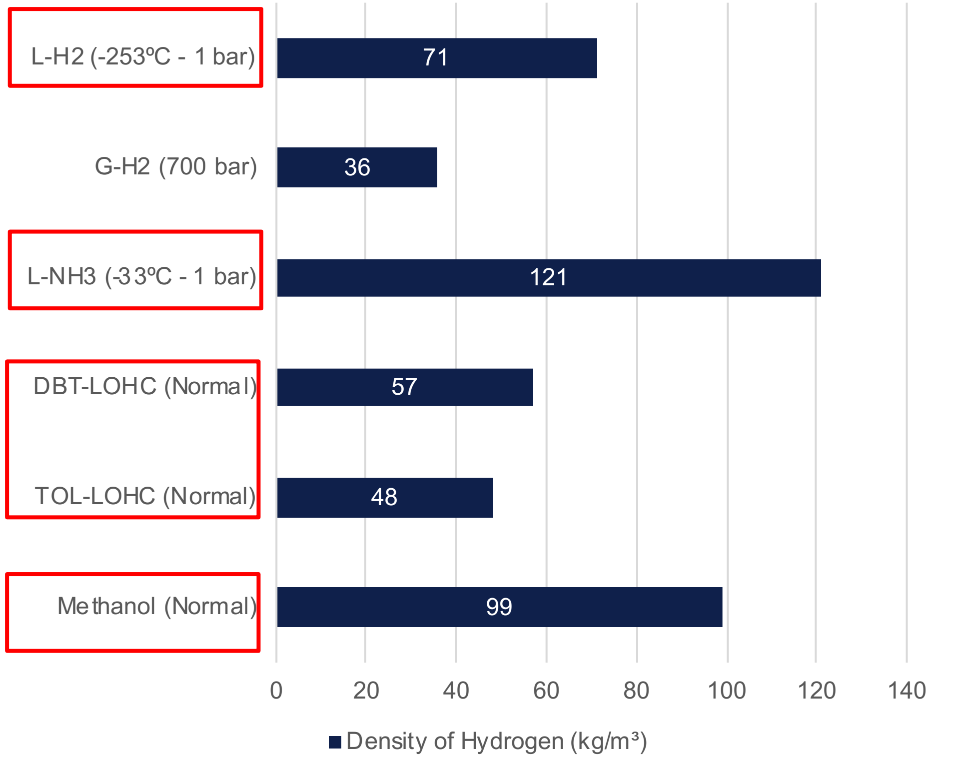
Content



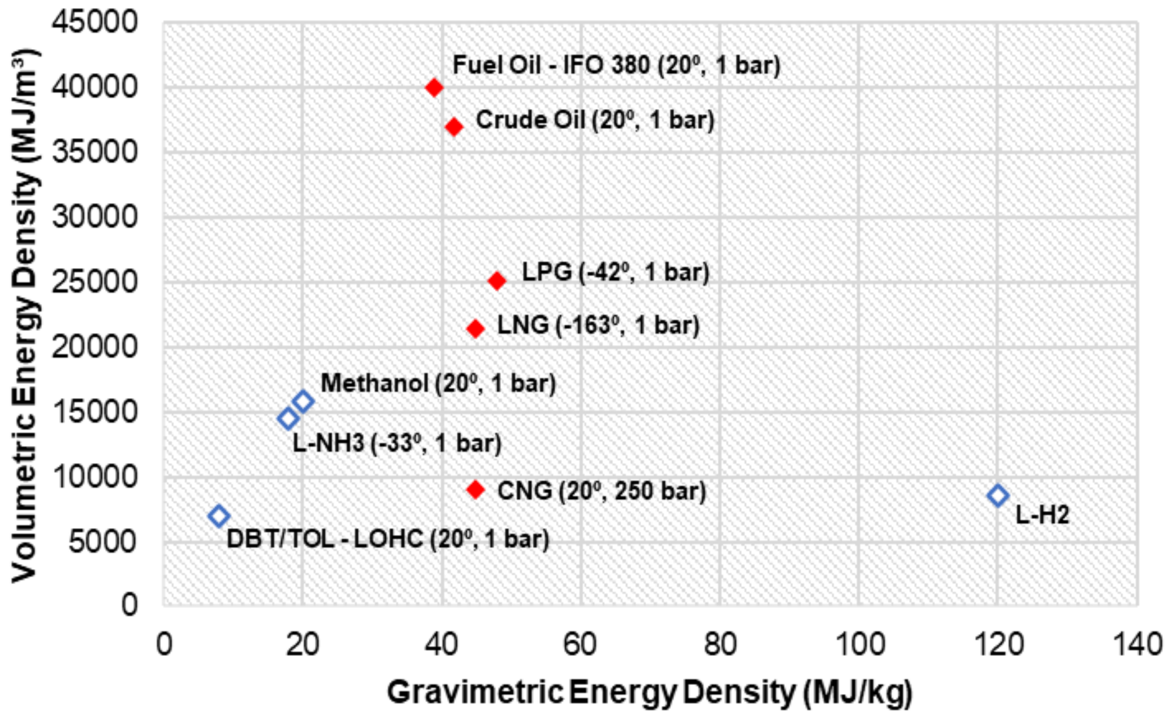
Hydrogen Carriers

Hydrogen can be transported and stored in pure form or as an intermediate energy carrier that can be charged and de-charged with H2.

Each hydrogen carrier has different physical and chemical properties. Hydrogen density is one of the most important physical properties in a hydrogen carrier. Compressed hydrogen has the lowest hydrogen density of all the hydrogen carriers considered. Ammonia (L-NH3), on the other hand, has the highest hydrogen density, followed by Methanol and Liquefied hydrogen (L-H2).



The figure below shows a comparison of energy content of different fuels both with respect to volume and mass (the fuel only, and not the entire storage system). The energy density is taken to be the LHV of each fuel. Hydrogen carriers are shown in blue, and fuels based on hydrocarbons in red. All hydrogen carriers have a significantly lower volumetric energy density compared to conventional fuels such as LNG and fuel oil. It also shows that ammonia and methanol has a higher volumetric energy density than L-H2 and LOHC. On the other hand, L-H2 exhibit a very high gravimetric energy density more than twice that of LNG. Needs to be considered that when storing e.g. LH2 in a tank, the practical energy density (including tank system) will decrease significantly.



Hydrogen Carriers

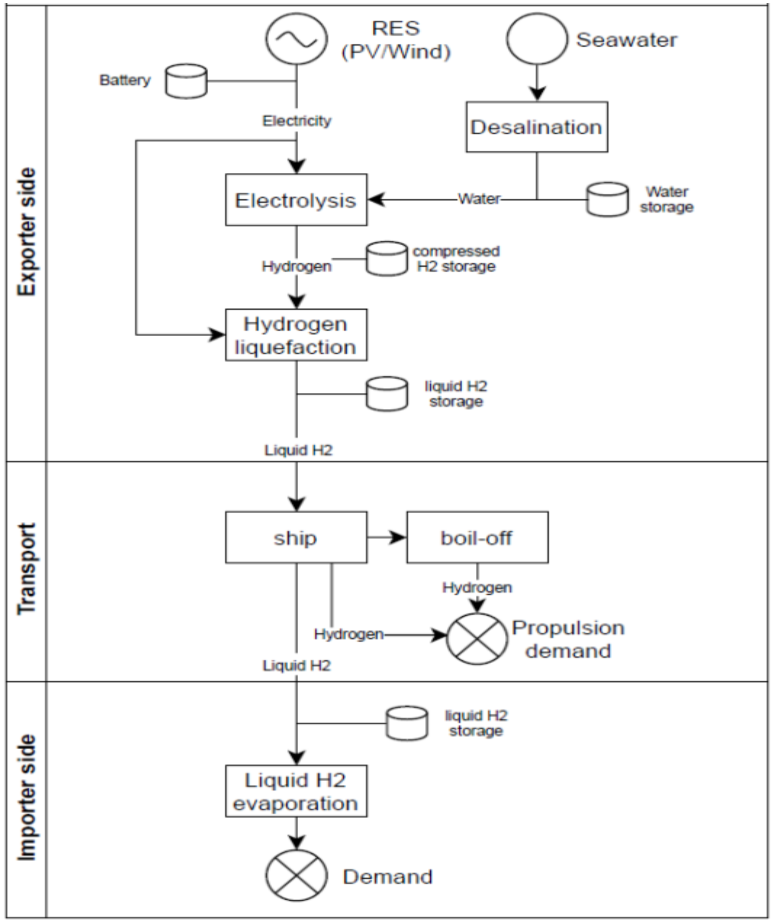
Liquid Hydrogen

L-H2 is the most straightforward method of transporting this renewable energy and possesses the major advantage of not needing chemical transformation steps throughout the supply chain. However, the low volumetric energy density and the very low boiling point (-253 °C) present major technical challenges. For instance, while L-H2 has a higher energy density than compressed hydrogen, more energy is required to liquefy hydrogen than for compressing it to relevant pressures. Furthermore, L-H2 has different safety characteristics than compressed gaseous hydrogen. For example, a leak into open air from compressed hydrogen tanks will rise due to buoyancy and will generally dissipate quickly. In contrast, a leak of L-H2 into open air will freeze the surrounding air, become a heavy gas, and may accumulate on the ground for some time. This is relevant when, for instance, transporting hydrogen either by ship or truck, or when storing it in tanks. The figure on the right presents a macro transportation chain associated to L-H2.

Shipping of pure hydrogen: According to Hydrogen Council 2021, the long-term optimal choice of carrier depends on a range of factors. L-H2 is most efficient if the destination requires liquid or high-purity hydrogen, and has benefits if hydrogen needs to be distributed with trucks after landing at port. This is typically the case for hydrogen refueling stations for cars or trucks, for example. In contrast to L-NH3 and LOHC, L-H2 does not require cracking or dehydrogenation to convert into gaseous hydrogen, which not only saves costs but also avoids purity challenges caused by carrier residues. L-H2's main drawback is its relatively low volumetric energy density compared with ammonia, which limits the amount of hydrogen per ship, and the boil-off losses that occur with every day of storage. While liquefaction is a proven and commercialized technology, L-H2 shipping and large-scale storage – which requires suppliers to manage the boil-off losses – remain in the early stages of deployment.

The Suiso Frontier, the world's first liquid hydrogen carrier (Source: Nikkei Asia, World's first liquid hydrogen carrier ship launches in Japan. Accessed in July 2021).

There are only experimental tankers in operation today (see figure above). Since shipping of L-H2 has only to a small degree been tested in real-life, with demonstrational and industrial pilot projects coming up in a few years, it is given a TRL of 4. Because of the cryogenic state of L-H2, many special considerations will need to be taken for shipping. (Sekkesæter, 2019).



Macro transportation chain associated to LH2 (Johannes Hampp, 2021).

Hydrogen Carriers

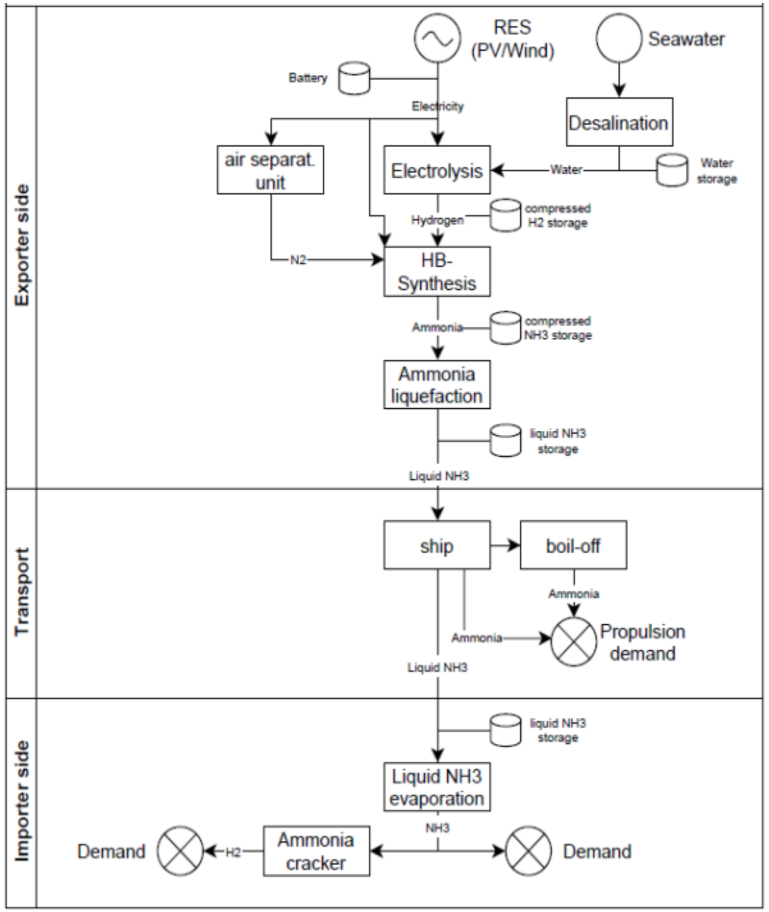
Ammonia

Ammonia is a compound of nitrogen and hydrogen with formula NH3 and has a higher energy density per volume than liquefied hydrogen and can be stored and transported as a liquid at low pressures or in cryogenic tanks at around -33°C at 1 bar. This implies that ammonia can be transported at low cost by pipelines, ships, trucks and other bulk modes. One drawback is that the ammonia synthesis and its subsequent cracking to release hydrogen require significant energy. This molecule has the advantage of not needing CO2 in the production process and having a moderate boiling temperature, however its high toxicity and the fact that it is difficult to use it directly in energy applications comes with big challenges. Reconversion of ammonia into hydrogen is feasible although the technology is not yet fully mature, and it adds costs. The figure on the right presents a macro transportation chain associated to Ammonia.

Shipping of Ammonia: Ammonia can be directly utilized as a feedstock for some applications (such as fertilizers, shipping fuel, co-firing or ammonia combustion for power generation), avoiding the need to crack NH3 back into hydrogen. A similar approach could be used for other hydrogen carriers, e.g. methanol. Ammonia benefits from a higher volumetric energy density than L-H2 and thus suppliers can ship it more cost efficiently than L-H2 using commercially available ammonia cargo ships. However, two drawbacks of using ammonia as a hydrogen carrier are the high costs of cracking it back into hydrogen and the achievable purity levels. Furthermore, because ammonia is toxic, it may face handling and storing restrictions in residential areas as well as limited options for in-land distribution (Hydrogen Council, 2021). Otherwise, ammonia as a carrier is gaining momentum globally in announced projects, as it offers the lowest costs, existing infrastructure is available, and no carbon is involved. It may be a promising market for the purpose of kick-starting the import chain, with large initial volumes, but the number of applications seems to be limited, as shipping and fertilizers are the main or only application areas in which it is applied directly (Hydrogen Import Coalition, 2020).

The Yara Kara was the first of three new Yara handysize ammonia carriers to hit the water in 2016. Source: Richard Ewing, Yara's new ammonia tanker fleet complete as 'Sela' sets sail, December 2016. Image Source: Yara

Ammonia tankers with capacities of up to 84,000 m3 are in operation today. Since shipping of ammonia is already largely in operation and with competitive cost in many places, it's given a TRL of 9.



Macro transportation chain associated to NH3 (Johannes Hampp, 2021).

Hydrogen Carriers

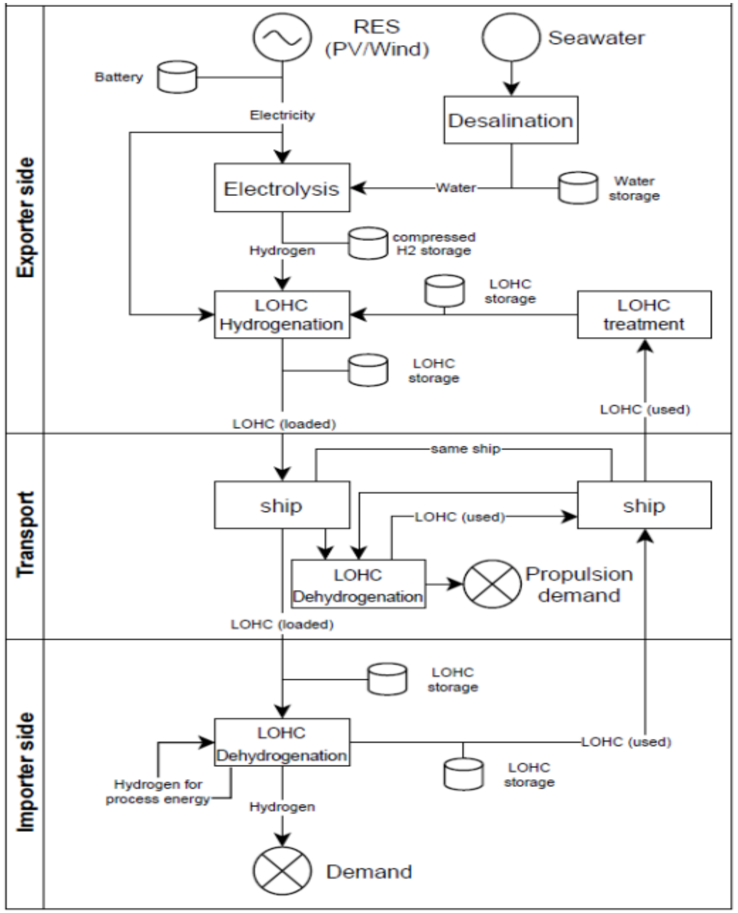
Liquid Organic Hydrogen Carriers - LOHC

Through the formation of chemical bonds, hydrogen may be combined with various organic compounds to produce liquid organic hydrogen carriers (LOHCs). A number of different materials have been proposed as potential LOHC materials. These include toluene, N-ethyl carbazole, dibenzyltoluene, formic acid, and naphthalene. However, research suggests that dibenzyltoluene (DBT) and toluene (TOL) are the LOHC materials with highest potential (Sekkesæter, 2019). Hydrogenation and dehydrogenation of a LOHC, such as toluene and Dibenzyltoluene, requires less energy, but the gravimetric density of the hydrogen that can be extracted from the hydrogenated liquid (methylcyclohexane for the LOHC toluene) is 50%–70% lower than the gravimetric hydrogen density of ammonia. The figure on the right presents a macro transportation chain associated to LOHC's.

Shipping of LOHC: Liquid organic hydrogen carriers can use existing diesel or other hydrocarbon products infrastructure and safely store hydrogen over long periods without loss. When using non-flammable and non-toxic carrier materials, LOHC can use existing industry-scale hydrocarbon infrastructure without any additional safety regulations. The main drawbacks of LOHC are the novelty of the dehydrogenation process, which requires large amounts of heat to release the hydrogen from the carrier, and the limited hydrogen carrying capacity compared with LH2 and NH3. The ability to use cheaper storage tanks than those needed for other carriers partly outweighs these issues (Hydrogen Council, 2021).

No dedicated LOHC tankers currently exist for this purpose, despite some experimental. The AHEAD (Advanced Hydrogen Energy Chain Association for Technology Development) project has set up a large-scale piloting project investigating use of TOL-LOHC as a hydrogen carrier. LOHC (both TOL-LOHC and DBT-LOHC) also exhibit similar properties with regards to transport, as conventional cargoes such as distilled oils and crude oil. Toluene for example is already shipped today. Marine transport of DBT/TOL-LOHC is assigned a TRL of 7.

Typical oil tanker that can be used for LOHC transport. Image Source: Engineering channel, Oil Tankers. Accessed in July 2021



Macro transportation chain associated to LOHC (Johannes Hampp, 2021).

DNV

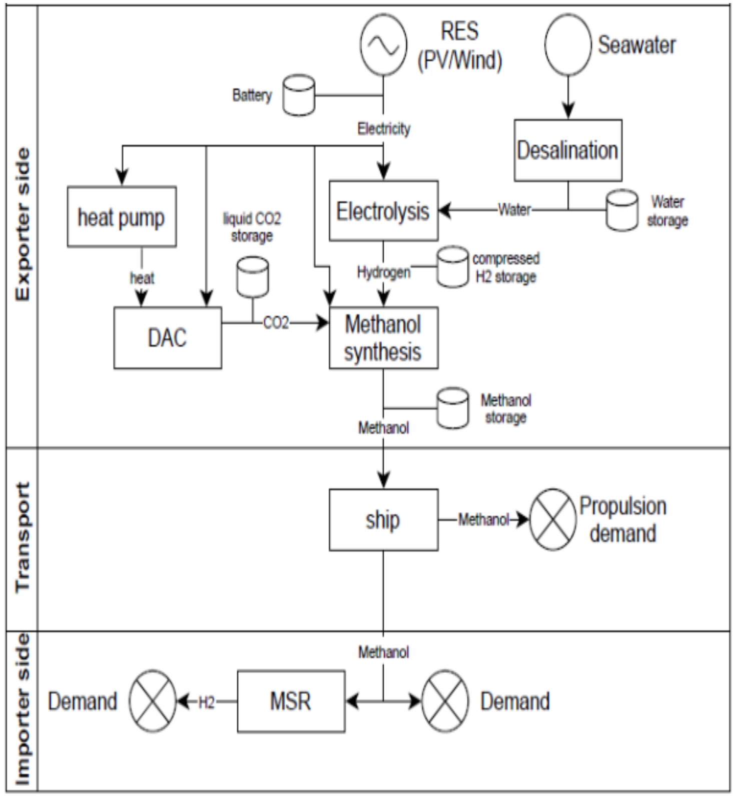
Hydrogen Carriers

Methanol

Methanol (MeOH) is a liquid organic compound with favorable properties for transport, storage and use as a fuel or energy carrier. Methanol plays an important role in the chemical industry and is an emerging fuel currently mostly produced from fossil fuels. A transition to renewable methanol – derived from biomass or synthesized from green hydrogen and carbon dioxide (CO2) – could expand methanol's use as a chemical feedstock and fuel while moving industrial and transport sectors toward net carbon neutral goals. The cost of renewable methanol production is currently high and production volumes are low. But with the right policies, renewable methanol could be cost competitive by 2050 or earlier (IRENA, 2021). The methanol-molecule has the advantage of already widespread infrastructure and being liquid in atmospheric conditions. The carrier is not carbon free, as CO2 is required in the production process. The figure on the right presents a macro transportation chain associated to Methanol.

Shipping of Methanol: Shipping methanol is already carried out on a large scale today, with a number of methanol tankers using methanol as a fuel for propulsion. Methanol transport over sea takes place on a much smaller scale than conventional fuels at the moment, but the existing shipping technology can easily and quickly be enlarged if the demand turns out to be there (Hydrogen Import Coalition, 2020). Said that, methanol shipping is assigned a TRL 9.

Example of a typical tanker for the transport of liquid substances. It is a type of vessel designed and built to transport any liquid product, such as methanol. Image Source: https://www.marinelog.com/news/nyk-takes-delivery-of-methanol-fueled-methanol-tanker/. Accessed in August 2021.



Macro transportation chain associated to Methanol (Johannes Hampp, 2021).

Summary of Shipping Technologies

The preferred option for transport and storage will depend on the distance, state and the end user to determine the most cost-optimal solution. No universal solution would be expected

Liquefied Hydrogen (Suisso Frontier)

Methanol – typical tanker for the transport of liquid substances

Ammonia tanker (Yara)

LOHC – typical oil tanker

Carriers	TRL*	Comments
Liquefied Hydrogen	4	There are only experimental tankers in operation today (Ex.:Suisso Frontier)
LOHC	7	No dedicated LOHC tankers currently exist for this purpose, despite some experimental. However, LOHC can be transported by conventional cargoes such as distilled oils and crude oil. Toluene for example is already shipped today.
Ammonia	9	Shipping of ammonia is already largely in operation and with competitive cost in many places
Methanol	9	Methanol transport over sea takes place on a much smaller scale than conventional fuels at the moment, but the existing shipping technology can easily and quickly be enlarged if the demand turns out to be there

Images Source: Fazcomex, Tipos de Navios. Accessed in July 2021.; Mitsou OSK Lines, Newbuilding LNG Carrier for JERA Named Sohshu Maru.; Engineering channel, Oil Tankers. Yara; AHC Member Meeting, March 9th 2021; Nikkei Asia, World's first liquid hydrogen carrier ship launches in Japan.
**TRL = Technology Readiness Level*

DNV

Infrastructure Overview

The objective of this chapter is to present an overview of existing infrastructure for import and/or export hydrogen carriers, considering those under discussion in this report. In general, the infrastructure needed for import and/or export of these carriers are basically a berth for the ships, a transfer system (loading/unloading arms, flexible hoses, pipelines), storage tanks and truck/train loading/unloading stations. Each equipment is designed specially for the product to be transferred. For example, carriers like L-H2 and LNG (cryogenic) and Ammonia (low-temperature) would require specific equipment to keep them liquefied, while LOHC and methanol would require typical hydrocarbon equipment (tanks, pipelines, pumps, etc) as they can be transferred and storage in ambient pressure and room temperature. The discussion regarding the infrastructure needed for conversion of carriers into hydrogen (cracking, dehydrogenation, others) is not part of the scope of this chapter.

Pure hydrogen terminals for import and export are still under study and have only experimental projects undertaken. Due to the current techniques used in the manufacturing of double-walled, vacuum-insulated spheres, facilities for the storage of L-H2 are limited to a maximum size of about 20,000 m³. Here, a scale-up of technology will be needed to meet the large energy requirements in the future. The most likely scenario will involve industry migrating to a concept of atmospheric storage tanks, which are also well known in the LNG business (Hydrogen Import Coalition, 2020).

There are some potential alternatives for re-utilization of LNG terminals as hydrogen import/export infrastructure, but still under study. The very low temperature for hydrogen liquefaction (-253ºC) and a very small size of hydrogen molecule are the main challenges.

Japan's Kawasaki Heavy Industries has completed construction work on the world's first liquefied hydrogen receiving terminal, the Kobe LH2 Terminal, also called "Hy touch Kobe". Hy touch Kobe Terminal consists of a loading arm system (LAS) transferring liquefied hydrogen as its cryogenic temperature of -253℃, a liquefied hydrogen storage tank with 2,500 m³ and related facilities. The storage tank enables long-period storage of cryogenic liquefied hydrogen reduced to a temperature of -253°C and one eight-hundredth its initial volume. The tank features a double-shell vacuum-insulation structure, comprising inner and outer shells with a vacuum-sealed layer in between to prevent heat transfer from the outside. The L-H2 terminal is now undergoing the world's first technology demonstration.

Kobe Liquefied Hydrogen Receiving Terminal "Hy touch Kobe". Source: Kawasaki Heavy Industries

Kobe Liquefied Hydrogen Storage Tank. Source: Kawasaki Heavy Industries

Infrastructure Overview

In general, large-scale terminals already exist for hydrogen carriers such as LOHC, ammonia and methanol and this existing infrastructure could therefore be readily reused for the decarbonized alternatives. Large-scale storage of LOHCs can be done in internal floating roof tanks, such as the ones used for hydrocarbon fuels. For methanol, there is already a significant existing infrastructure, as shown in the figure below, as well as typical liquid chemical storage plants with internal floating roof tanks can easily be used for this substance.

Existing infrastructure for methanol. Source: DNV, Alternative Fuels Insight (AFI), status 17 July 2021.

Infrastructure Overview

An increase in the ammonia demand globally is expected for the next decades mainly due to the hydrogen and decarbonization markets growing and then more infrastructure will be necessary to enable this expanding market. The good news is that ammonia's current infrastructure can be adapted, new infrastructure can be built and operated cheaply and lessons from existing operations can be taken on board. As a bonus, conversion of existing LNG-focused maritime assets into ammonia analogues can be done with some modifications, but with lower working capacity.

The required modification depends on the current design as the configuration of the LNG import facility could impact the systems, but in general, the storage tank need to be converted (i.e., reduced capacity, change of tank accessories such as in-tank pumps, instrumentation and safety valves), BOG system needs to be evaluated in detail to identify the proper compressor configuration to avoid inefficient BOG compressor operation. The piping system and supports need to be enforced for ammonia service. The instrumentation and measuring devices need to be evaluated in detail to ensure their functionality with ammonia and identify the components which need to be replaced.

Existing infrastructure for ammonia. Source: DNV, Alternative Fuels Insight (AFI)

Existing infrastructure for LNG. Source: DNV, Alternative Fuels Insight (AFI)

Safety: An important aspect worth mentioning when discussing the reutilization of LNG terminals for hydrogen or ammonia storage is the safety distances for the internal facilities as well as the surrounding population. A possible loss of containment scenario of LNG, hydrogen and ammonia will have different levels of consequence. A hydrogen leakage can lead to a significant overpressure due to explosion in case of contact with an ignition source and even a small leakage of ammonia, for example, can generate an extensive vulnerability area due to its toxicity. The impacts will depend not only by the material and operational conditions, but also the surroundings where the facility is located. Hence, it is important to highlight that performing a safety risk analysis before the decision of any reutilization is essential to guarantee the safety and consequently the project viability.

Summary of Infrastructure Overview

In general, pure hydrogen terminals for import and export are still under study and only experimental projects have been undertaken. On the other hand, large-scale terminals already exist for the others hydrogen carriers such as LOHC, ammonia and methanol and this existing infrastructure could therefore be readily reused for the decarbonized alternatives.

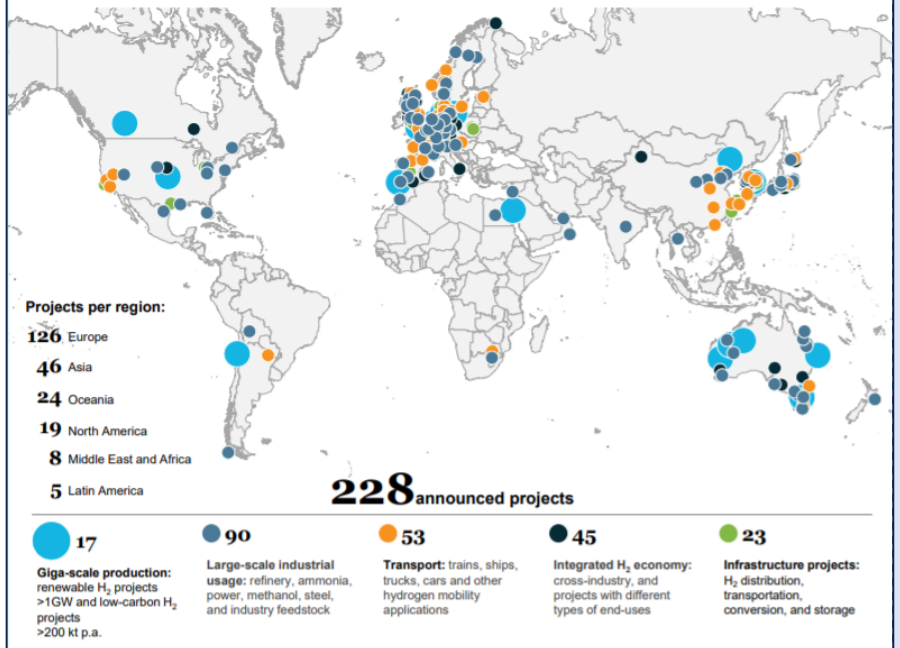
Carriers	TRL* Export	TRL* Import	Comments
Liquefied Hydrogen	3	4	**Import**: Though an established commercial process, liquefaction of hydrogen gas has never been performed at such high quantities and high efficiency. There are only experimental export terminals in operation today (Ex.:Hi Touch Kobe – Kawasaki Heavy Industries). **Export:** Regasification of LH2 is done at small scale.
LOHC	4	4	**Import:** Hydrogenation process is still in the early stages of development, although it has been tested commercially in small-scale. Can easily use existing operational technology and infrastructure for typical hydrocarbon products, such as oil, gasoline, and others. **Export:** Dehydrogenation plants are still in their early phase of development. Can easily use existing operational technology and infrastructure for typical hydrocarbon products, such as oil, gasoline, and others.
Ammonia	9	4	**Export:** Numerous cryogenic air separation plants and ammonia plants are in operation, worldwide, as well as the terminals and storage units. **Import**: There are large scale import and storage units for ammonia worldwide, but ammonia cracking process has still low maturity.
Methanol	4	7	**Export:** Methanol synthesis is a known and mature process, but CO2 direct air capture has low maturity. **Import**: Methanol reforming for hydrogen production has still a medium maturity.

**TRL = Technology Readiness Level*

Overview of Projects Worldwide

According to the Hydrogen Council 2021, There are over 30 countries with hydrogen roadmaps, and 228 large-scale hydrogen projects announced across the value chain, with 85% located in Europe, Asia, and Australia. If all projects come to fruition, total investments will reach more than $300 billion in spending through 2030, including $80 billion which can be considered “mature” – meaning that these projects are in the planning stage, have passed a final investment decision (FID), or are under construction, already commissioned, or operational. Governments worldwide have committed more than US $70 billion in public funding. The aim of this chapter is to present an overview of the most significant hydrogen import/export projects under development around the world.

Of these, 17 are already-announced giga-scale production projects (i.e. more than 1 GW for renewable and over 200 thousand tons a year for low-carbon hydrogen), with the biggest in Europe, Australia, the Middle East and Chile.



Source: Hydrogen Insights, Hydrogen Council, Feb 2021

A relevant project in Europe is the Hamburg hydrogen hub in Germany. It came about with the signing of a letter of intent between the giants Shell, Mitsubishi Heavy Industries, Vattenfall and Wärme Hamburg. In order to enable the production of green hydrogen on a large scale and the decarbonization of the energy system and basic industries by 2025, the feasibility study for this project plans the transformation of a coal-based plant for the production of green hydrogen with an initial potential of 100 MW, powered by photovoltaic and wind power plants. Also in Europe, the Dutch government estimates that the green hydrogen sector has similar regulations to the electric and natural gas sectors. The country is carrying out research into the use of existing gas networks for the transport of hydrogen, connected to neighboring countries. This structural advantage is expected to position the Netherlands as a relevant hub in northwestern Europe.

In the UK, the North of Scotland Hydrogen Programme at the Port of Cromarty Firth is aimed at developing a state-of-the-art hub to produce, store and distribute hydrogen to the region and other parts of the UK and Europe. The nearest distilleries and ports should be the first to benefit from this clean fuel.

In Saudi Arabia, a green hydrogen project is underway with an investment estimated at US$ 5 billion. The proposal is to produce around 650 tons of green hydrogen per day, in an integrated manner with the Neom smart city project, close to Egypt’s and Jordan’s borders.

The most relevant project in Asia is developed by state-owned Sinopec, China's biggest hydrogen producer. The launch is scheduled for 2022 in Inner Mongolia. The estimated production of the project, whose approximate investment is 2.6 billion yuan, is 20,000 tonnes of green H2. The initial phase of production is estimated at 10 thousand tons and supported by a solar energy station with a capacity of 270 MW and a wind farm of 50 MW. Sinopec also plans to develop a green hydrogen plant with the same annual capacity in China's northwest region of Xinjiang, supported by a 1,000 MW solar power station.

In South America, Chile has already demonstrated its intention to become an internationally recognized green hydrogen hub, having presented its National Green Hydrogen Strategy in 2020. The Chilean Ministry of Energy hopes that the Magallanes region, in the south of the country, can take advantage of its great wind potential and its petrochemical and port experience to become a hub in the production and export of green hydrogen. The northern region, focused on solar energy production, is also expected to be a hub in the production of green H2.

Also in Brazil, it is possible to notice the formation of the first productive clusters dedicated to the production, distribution and export of green hydrogen. Despite the still incipient regulation of the activity in Brazil, the recent initiatives led by the Port of Pecém/CE and by the Port of Suape/PE gain relevance among them.

Source: Recharge, Jul 2021

DNV

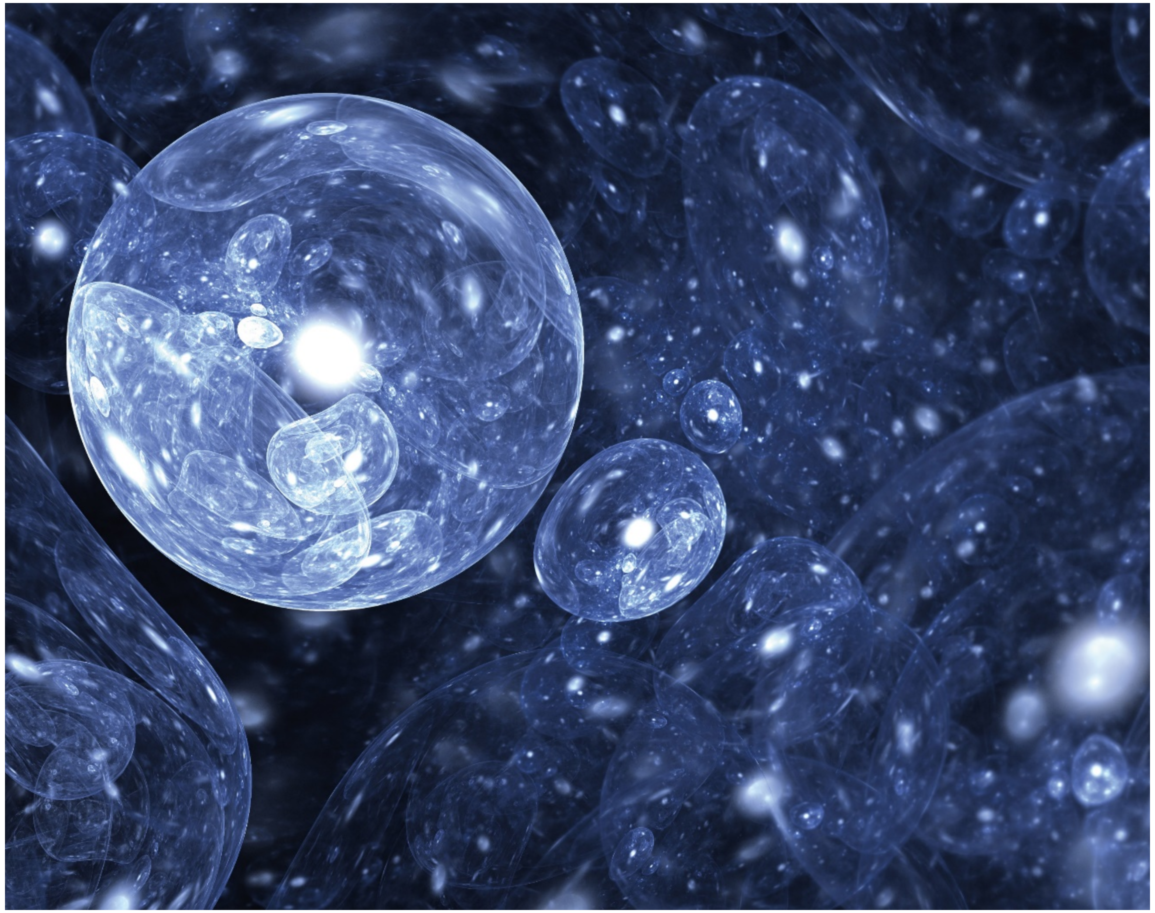
Carriers Comparison

(red)	Major barrier/s
(yellow)	Moderate barrier/s
(green)	No significant barriers

A comparative table with main KPIs for each type of carriers selected is presented below. Note that these assessments show the current state of technology readiness and market development, which could change in the future

	Liquefied Hydrogen	Ammonia	LOHC	Methanol
Hydrogen density	71 kg/m³	121 kg/m³	48-57 kg/m³	99 kg/m³
Energy efficiency	High purity hydrogen Less conversion losses	Energy losses for hydrogen conversion	Energy losses for hydrogen conversion	Energy losses for hydrogen conversion
Technical maturity - export infrastructure	Nonexistent (only experimental), even though liquefaction process is relatively mature for other liquefied gases	Existing and mature	Nonexistent but can easily use existing technology for hydrocarbon products	CO2 direct air capture has low maturity (methanol synthesis in itself is mature)
Technical maturity - shipping	Nonexistent (only experimental)	Existing and mature	Toluene is already shipped in a large scale	Existing and mature
Technical maturity - import infrastructure	Regasification of LH2 is done at small scale	Existing infrastructure, but ammonia cracking has low maturity	Nonexistent but can easily use existing technology for hydrocarbon products	Methanol reforming has still a medium maturity
Cost	In general, the most expensive mainly for long distances	In general, medium costs compared to the others	In general, medium costs compared to the others	In general, the lowest costs
Environmental, Social, Health and Safety (ESHS)	High Flammability Carbon Free	High Toxicity	High flash point. Not flammable in room temperature. Medium toxic effects	High flammability Biodegradable
Re-utilisation of existing infrastructure	Potential for LNG infrastructure, but still under study	LPG infrastructure can be used. Only some modification needed for LNG infrastructure.	Can easily use existing liquid hydrocarbons infrastructure	Can easily use existing liquid chemicals infrastructure
Existing market as commodity	Only niche applications	Existing	LOHC carrier material needed for hydrogen transportation	Existing

Content



Overview on stakeholder interviews conducted

Status: 2021-07-30							
# of candidates	**21**						
Stakeholder	**Company**	**Region/Location**	**First Name**	**Last Name**	**Status**	**Date**	**Time CET**
(1) Shipyard	Nihon Shipyard	Japan	Katsunori	Sakaguchi	(3) Done	21/07/2021	08:00
(1) Shipyard	KSOE - Korea Shipbuilding & offshore engineering (part of HHI)	South Korea	Byeongyong	Yoo	(3) Done	21/07/2021	10:00
(1) Shipyard	Kawasaki Heavy Industries Ltd	Japan	Sohei	Inatsu	(3) Done	27/07/2021	08:30
(2) Ship owner	Schulte Group	Germany	Christoph	Schulte	(3) Done	08/07/2021	17:00
(2) Ship owner	Exmar	Belgium	Fredrik	Van Nuffel	(3) Done	22/07/2021	11:30
(2) Ship owner	NYK Line	Japan	Tsutomu	Yokoyama	(3) Done	28/07/2021	09:00
(2) Ship owner	Ultranav	Chile	Christian	Csaszar	(3) Done	28/07/2021	16:00
(3) Port Authority	Hamburg Port Authority - HPA	Germany	Ingo	Fehrs	(3) Done	19/07/2021	15:00
(3) Port Authority	Wilhemshaven Hafenwirtschaftliche Vereinigung	Germany	Hans-Joachim	Uhlendorf	(3) Done	12/07/2021	15:00
(3) Port Authority	Port of Vancouver	Canada	Gary	Oleszewski	(3) Done	15/07/2021	17:00
(3) Port Authority	Port of Long Angeles	US	Jacob	Goldberg	(3) Done	19/07/2021	18:00
(3) Port Authority	Port of Rotterdam	Netherlands	Monica	Swanson	(3) Done	21/07/2021	13:00
(3) Port Authority	Port of Kobe	Japan	Michito	Aoi	(3) Done	27/07/2021	09:45
(3) Port Authority	Hamburg Port Authority - BWI	Germany	Rüdiger	Hintze	(3) Done	28/07/2021	10:00
(3) Port Authority	Ultramar/Neltume Ports	Chile	Fernando	Reveco	(3) Done	30/07/2021	16:00
(4) Energy provider	Uniper	Germany	Thomas	Pock	(3) Done	19/07/2021	12:30
(4) Energy provider	Itochu Corporation	Japan	Takeo	Akamatsu	(3) Done	20/07/2021	08:30
(4) Energy provider	Shell	Netherlands	James	Helliwell	(3) Done	20/07/2021	14:00
(5) Tech. Provider	Corvus Energy	Norway	Kristian	Holmefjord	(3) Done	09/07/2021	12:30
(5) Tech. Provider	Air Liquide	France	Dominic	Walter	(3) Done	12/07/2021	09:00
(3) Port Authority	Port of Antwerp	Belgium	Tom	Monballiu	(1) Inquired		

DNV

20 stakeholder interviews conducted in Europe, Asia, and America

- **Semi-structured interviews** of 25-60 minutes over MS Teams
- **Focus areas**: Perspective on different carriers and company's position/preparedness for hydrogen economy

- **3 shipyards**
  - Kawasaki Heavy Industries, Japan
  - Nihon Shipyard, Japan
  - Korea Shipbuilding and Offshore Engineering (part of Hyundai Heavy Industries), Korea

- **2 technology providers**
  - Air Liquide, France
  - Corvus, Norway

- **4 ship owners**
  - Exmar, Belgium
  - Ultranav, Chile
  - NYK, Japan
  - Schulte, Germany

- **8 Ports/terminals**
  - Hamburg, Germany
  - Wilhelmshaven, Germany
  - Rotterdam, Netherlands
  - Kobe, Japan
  - Los Angeles, USA
  - Vancouver, Canada
  - Neltume (Meijllones etc.), Chile

- **3 energy companies**
  - STASCO (part of Shell), Netherlands/UK
  - Uniper, Germany
  - Itochu, Japan

Summarizing perspective on the carriers

LH2

The potential long term winner
- First test vessel being built, 20-50,000 m³ expected for 2030, 160,000 m³ for early 2030s
- Lowest energy loss from conversion (liquefaction ~20%) compared to other carriers
- Challenges on tank, boil-off management, engine, purging, gas detection to be overcome yet

Ammonia

The likely short term winner
- Vessels of 40-90,000 m³ available, scale up to 175,000 m³ possible without major problems
- Some market for ammonia as feedstock and fuel for co-firing
- Disadvantage of ~50% energy loss from Haber-Bosch and cracking, if ultimately needed as H2 (e.g., steel industry, heating, mobility)

Methanol

Perceived as less relevant
- Vessels of 60-120,000 m³ available, scale up to 200,000 m³ possible without major problems
- Market for methanol as feedstock and fuel
- Tailpipe CO2 emissions, besides 20% energy loss in methanol synthesis further energy loss for cracking, if ultimately needed as H2 (e.g., steel industry, heating, mobility)

LOHC

Perceived as less relevant
- Vessels of 60-120,000 m³ available, scale up to 200,000 m³ possible without major problems
- No use for LOHC as feedstock, i.e. dehydrogenation required (process not proven on large scale)
- Limited use of waste heat from hydrogenation, energy intensive dehydrogenation at destination

Most interviewees recommend openness for more than one energy carrier, typically ammonia and LH2

LH2 – potential long term winner

- **Technology readiness**: Low, one "test" vessel of 1,250 m³ currently being built
- **Key challenges**
  - **Tank**: It appears that **small vessels** can be built with vacuum insulated cylindric or bilobe type C tanks of 3-4 bar design pressure. The maximum tank size is estimated between 5,000 and 10,000 m³. **Mid sized vessels** could be built using 2-4 of such tanks. **Larger vessels** will realistically be build with self-supporting, foam insulated spherical (or prismatic?) type B tanks of atmospheric pressure. Kawasaki Heavy Industries (KHI) plans with 4 x 40,000 m² spherical tanks (see picture above).
  - **Boil-off**: Today there are no reliquefication units for hydrogen for marine applications (vibration, bending). Type C tanks can afford some days boil-off until the design pressure is reached. Atmospheric tanks require extraction of the boil-off. As the hydrogen is expensive it is likely not feasible to vent or flare it, and it needs to be consumed by the vessel.
  - **Engine**: To deal with the boil-off, the propulsion system need to be able to run on hydrogen. Due to limited size and maturity of fuel cells (up to 3 MW with class approval) and 2-stroke hydrogen combustion engines, KHI plans to have a hydrogen-fired boiler operating a steam turbine, a technology similar to old LNG carriers. A design speed of 20 knots is planned. As the efficiency of steam turbines are limited, it is expected that fuel cells or 2-stroke combustion engines will be the preferred propulsion option in the long term.
  - **Purging**: LNG carriers use nitrogen for purging of pipes. As nitrogen (N2) would freeze in contact with LH2, helium might need to be used.
  - **Gas detection**: Gas detection system of LNG carriers use nitrogen. As N2 would freeze in contact with LH2, other solutions will be needed.
- **Scale**: Most interviewees assume vessels of 20-50,000 m³ by 2030, KHI plans a first demonstration vessels with the new tank concept by about 2026 and first commercial ships by 2030. 160,000 m³ shall be possible in the early 2030s.
- **CAPEX:** No liquid market, newbuilds only against long contracts. While some assume CAPEX of initial vessels to be factor 2.5-3 compared to LNG (i.e. ~400 MUSD for 160,000 m³), it may be drop to 20-40% above Moss-type LNG carriers as soon as scale is reached. High CAPEX limits the liquidity of the market (fewer shipping companies).

Ammonia – perceived as short term winner

- **Technology readiness**: Very high, fully refrigerated liquefied petroleum gas (LPG) carriers can carry ammonia, currently shipped typically as feedstock for fertilizer industry in vessels of 40-50,000 m³
- **Key challenges**
  - **Transportation**: In volumes of 40-90,000 m³ **not a challenge**. First choice energy carrier, if energy shall be shipped in the short term. Next development will be vessels fuelled by ammonia and vessels of larger scale (if needed by the market). Ammonia fuelled engines yet a challenge due to nitrogen oxides (NOx), corrosiveness and lacking lube oils. Need for >10% diesel as pilot fuel. Toxicity to be addressed. First engines presumably ready in 2024 and first vessel applications in 2025.
  - **Conversion losses at Haber-Bosch**: Possibly 40% **energy loss in conversion from H2** gas to ammonia, just 10% for compression and 20% for liquefaction.
  - **Conversion losses at cracking**: As need for ammonia as feedstock (e.g. fertilizer) and for co-firing is somewhat limited, other applications require **cracking of** ammonia to gain hydrogen, which consumes about 10% of the energy. While technology is known, large scale crackers do not exist yet. Hydrogen derived from ammonia cracking has impurities, which hinder application in proton-exchange membrane (PEM) fuel cells. Though, future high temperature fuel cells and other applications (e.g. in steel and chemical industry) can deal with impure H2.
  - **Scale**: Ammonia is shipped in fully refrigerated LPG tankers @-34°C. Typical vessel sizes are 40,000 and 82,000 m³. Large newbuilds have 93,000 m³. Vessels of up to 175,000 m³ will be possible, if the market requires such batch volumes.
- **CAPEX:** CAPEX for 40,000 m³ approx. 50 MUSD, for 90,000 m³ approx. 85 MUSD, for 175,000 m³ possibly 145 MUSD.

Methanol – perceived as less relevant

- **Technology readiness**: High for shipping, dedicated methanol carriers of 60 up to 120,000 m³ existing
- **Key challenges**
  - **Transportation**: In volume of 60-120,000 m³ **not a challenge,** vessels existing. Newbuild vessels already fuelled by methanol. Next development will be vessels of larger scale (if needed by the market).
  - **Conversion losses at methanol synthesis:** Possibly 20% **energy loss in conversion from H2** gas to methanol, just 10% for compression and 20% for liquefaction.
  - **Use of methanol**: Significant demand for methanol as fuel and feedstock, but applications requiring H2 (fuel cells, steel industry, …) would require energy intensive cracking.
  - **GHG balance**: Combustion of methanol causes tail pipe CO2 emissions. In current international carbon accounting systematic, the CO2 capture from carbon capture and storage (CCS) is credited to the source (e.g. cement or steel plant), while tail pipe emissions are a burden for the consumer of methanol.
- **Scale**: Interviewees assume that Methanol can be shipped in dedicated product tankers and, if needed, vessels up to Very Large Crude Oil Carrier (VLCC) size (200,000 m³).
- **CAPEX**: Some methanol carriers of 60-120,000 m³ on the market. CAPEX of larger vessels may be assumed to be just 5-10% higher CAPEX than crude carriers (VLCCs) of same size .

LOHC – perceived as less relevant

- **Technology readiness**: High for shipping, shipped in product tankers, low for hydrogenation/de-hydrogenation
- **Key challenges**
  - **Transport**: In volume of 60-120,000 m³ **not a challenge,** vessels existing. Next development will be vessels of larger scale (if needed by the market). Overall question of **(limited) efficiency** when shipping 94% carrier and 6% hydrogen head-haul and 100% carrier back-haul.
  - **Carrier:** Need for large amounts of organic carrier as toluene. Some conversion losses requires replacement of lost carrier.
  - **Hydrogenation**: Exotherm reaction creating a lot of waste heat of 150-200 °C, typically in countries with limited use for such heat. Successfully tested by NYK in Brunei. Then shipped to Japan in ISO containers.
  - **Dehydrogenation**: Endotherm reaction requiring significant energy in countries, which are scarce of (renewable) energy. Process not proven at large scale. Safety challenges. Successfully tested by NYK.
- **Scale**: Interviewees assume that LOHC can be shipped in product tankers and, if needed, vessels up to VLCC size (200,000 m³).
- **CAPEX**: Can be carried is existing product/chemical tankers. CAPEX of dedicated larger vessels may be assumed to be just 5-10% higher CAPEX than crude carriers (VLCCs) of same size. Some interviewees assume that costs of produced H2 in destination country may be higher than via ammonia route.

Summarizing perspective on the countries/ports

Japan
Kobe

- Strong demand for import due to power plants, steel, fertilizer industry and mobility; market for ammonia and H2
- 20 LPG import terminals in Japan with some potential for conversions to ammonia, Kobe as first with import of LH2, governmental push for import; currently little extra price willingness for green vs. blue vs. grey hydrogen

Korea

- Korea is interested in importing both LH2 and ammonia for steel industry and power generation
- Ammonia import terminals existing

Germany
Hamburg/WHV

- Strong governmental incentives for hydrogen economy, need for import of green hydrogen (or other carriers) for steel industry, industrial heat, potentially heating and some power generation
- Hamburg and Ruhr area will be consumption clusters, Ruhr area served via Wilhelmshaven or NED or BEL

Netherlands
Rotterdam

- Netherlands with own demand for hydrogen and transit country to Germany, own H2 produc. from offshore wind
- Rotterdam will be key energy hub, with hydrogen production and import, open for any carrier in parallel

Belgium
Zeebrugge/Antwerp

- Belgium with own demand for hydrogen and transit country to Germany, limited potential for own H2 production
- Hydrogen import via Zeebrugge (yet LNG), pipelines (CH_4, CO_2, H_2) to Gent (steel) and German Ruhr area

USA
Los Angeles

- Significant potential to generate green electricity and hydrogen domestically, yet more distribution than generation
- Some early stage discussion of importing H2 to LA, but port currently more focused on H2 as maritime fuel

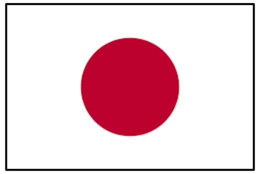
Canada
Vancouver

- Significant potential to generate green electricity and hydrogen domestically
- Limited potential for significant H2 import via Vancouver, port more focused on H2 as fuel

Japan and Germany apparently most promising import markets, with Germany strongly favouring green hydrogen; Netherlands and Belgium important too

Interview insights

Demand by country, infrastructure by port – Japan: Kobe



- Total Japanese **LPG import** amounts to 14 million tons per year with about 20 receiving terminals. Some of them could be converted for ammonia, if needed. Total **ammonia consumption** amounts to about 1 million tons per year, whereof 200,000 tons are imported.
- **Key hydrogen demand** could arise from **power plants** (co-firing of ammonia in coal and of H2 in gas power plants), **steel industry** (hydrogen), **fertilizer industry** (replacing conventional ammonia) and **mobility** (as hydrogen in fuel cells, but competing with electric vehicles), possibly synthetic CH4 for gas grid (heating)
- Today the **Port of Kobe** and nearby Sakai/Osaka in densely populated area have 4 LPG import terminals for energy use. By no Japan follows a strategy of domestic decarbonization and has **no clear preference** (of price willingness) **for green hydrogen** compared to blue or brown/grey hydrogen.
- Driven by Japan's strive for domestic decarbonization and the related HySTRA programme Port of Kobe is currently **modifying a pier for import of liquid H2 via the vessel Suiso Frontier**, which is currently being build as demonstration vessel by Kawasaki Heavy Industries. The hydrogen is to be imported from Australia. First cargo operation is expected for fall 2021/early 2022. The hydrogen will be used for a test project with public buses.
- If hydrogen demand will increase significantly in Japan and in the proximity of Kobe, Port of Kobe is prepared to **upgrade import facilities to deal with larger volumes up to a size of 160,000 m^3**, which is currently planes by Kawasaki Heavy Industries. Power plants and steel mills in/near Kobe can be major consumers. MOL is developing a container terminal to be operated based on fuel cells running on hydrogen.
- By now Kobe is not a major import port for **Ammonia**, but Ammonia is high on the agenda for use as feedstock (fertilizer) and as hydrogen carrier respectively for co-firing in power plants. At the moment there is no space foreseen for an Ammonia import terminal, but existing facilities could be restructured, if needed.
- **Trading houses like Itochu** could play a role as hydrogen importer. Itochu is active in ammonia business (ship fuel and plant in Siberia) and hydrogen business (fuelling stations, local generation for industry together with Air Liquide)

Demand by country, infrastructure by port – Korea

- **Korea is interested in importing both LH2 and ammonia** rather than in importing methanol (due to tailpipe emissions) and LOHC (technical challenge)
- Drivers of demand will be **steel industry** (Posco), requiring hydrogen, **power generation** (requiring ammonia), to limited degree mobility (requiring hydrogen in fuel cells)
- **Ammonia terminals** operated by the Lotte group make up for about 70% of all current ammonia import

Demand by country, infrastructure by port – Germany: Hamburg

- The **port of Hamburg** is located upstream the river Elbe about 90 km from the North Sea in the densely populated city of Hamburg. It is a significant container port with a number of terminals but also imports coal (still), oil products, copper concentrate and other goods.
- **Hamburg Port Authority as landlord and authority** is committed to support companies establishing hydrogen related activities in the port area. Authority for economy and innovation (**BWI)** is leading the hydrogen cluster. 8 IPCEI hydrogen projects are supported.
- In Hamburg and the vicinity there is a number of **potential off-takers** of hydrogen, e.g. an Arcelor Mittal steel mill, Aurubis copper plant (for heat), Trimet Aluminum plant (for heat), possibly Yara fertilizer production in Brunsbüttel (note also planned import of green Ammonia for fertilizer in port of Rostock).
- There are activities to **convert a coal fired power plant** into a hydrogen energy hub with a 500 MW electrolyser. But also **import of hydrogen** (in different forms) is being planned for by different companies. 5 **locations** are **being evaluated**
- There are plans by the local gas grid operator GasNetz Hamburg for HH-WIN, a **hydrogen grid** in the port of Hamburg, connecting major energy consumers with an import terminal. A connection to the gas grid is being considered too.
- Hamburg is open for all carriers, but due to dense population around the port, **safety aspects** will play a role at planning import facilities. Liquid carriers might be easier than carriers that are gaseous at ambient temperature. An Aquaventus/ Air Products project plans **importing LOHC** produced at offshore wind parks in the North Sea and dehydrogenation in Hamburg. Even if an import terminal for e.g. LH2 or ammonia could not be build in Hamburg, Hamburg shall be **connected via a H2 pipeline** (possibly a converted gas pipeline) due to its consumers.
- Currently there is no empty space, but **areas could be converted** for hydrogen import if needed and regarded safe.
- Germany will focus on importing **green hydrogen**. Grey/brown can be ruled out. Blue is seen critically.

Demand by country, infrastructure by port – Germany: Wilhelmshaven

- The **port of Wilhelmshaven** is a deep water port with a container and an oil terminal. An existing coal fires power plant will be closed in 2021.
- An **LNG terminal** with an FSRU was planned by German utility company Uniper but cancelled in spring 2021 due to demand uncertainty.
- Meanwhile **Uniper** is considering a new project of an **ammonia import terminal with a cracker** to supply hydrogen to steel manufacturer **Salzgitter Steel**, which considers converting 4 ovens to methane firing (later on possibly hydrogen). CO2 shall be captured and transported to Wilhelmshaven via pipeline. Considerations are being made to produce DRI (directly reduced iron) in Wilhelmshaven and transport it to Salzgitter via rail. Considerations also to supply hydrogen via pipeline to **ThyssenKrupp steel mills** in Ruhr area. No FID made yet. – Besides this Uniper is piloting electrolyser and methanization projects and considers blue hydrogen production by steam methane reforming. Furthermore Uniper is **experienced in energy and commodity trading** and seeks a role in the hydrogen economy.
- Besides that investor **Atlas Invest** is considering to set up a **4 GW electrolyser** to make use of offshore wind in peak times and 1.4 GW **direct current from UK** plus a production facility for **synthetic CH4** following the Sabatier process. The synthetic CH4 may be stored in **existing storage caverns** in 20 km distant Etzel and ultimately fed into the domestic gas grid (currently being negotiated). CO2 pipelines may be build from Salzgitter and potentially from Ruhr area and cement plants. 40 inch oil pipelines to Ruhr area and Hamburg are available and may be used for CH4 or CO2. A H2 pipeline is currently not foreseen in this project. No FID made yet.
- Besides these “local” projects Wilhelmshaven would offer **space and deep water access** for **hydrogen import** facilities.

Demand by country, infrastructure by port – Netherlands: Rotterdam

- Currently about **40% of the energy consumption of the Netherlands** and 13% of the energy demand of the EU are **imported via Port of Rotterdam.** Furthermore Rotterdam is the key port for bunkering of ships in Europe.
- **Port of Rotterdam is a landlord port** with many oil and gas companies using areas in the port. Some Ammonia is currently being handled in the port. Overall the port has enough space to become a hydrogen hub for Western Europe.
- The Port of Rotterdam has a clear agenda of participating in the **green transition**. It is carrier-agnostic and believes all 4 carriers (Ammonia, LH2, Methanol and LOHC) will play some role in the future.
- **Ammonia export terminal** existing in Port of Rotterdam (belonging to OCI, producing Ammonia in Geleen). Potential for importing green Ammonia to use as feedstock rather than intention for cracking to produce H2.
- First investment being made for **production and storage of LH2** in the Port of Rotterdam with 200 MW electrolyser operated by Shell and Eneco from 2026 onwards (first part of it in 2023). For 2030 a 2.5 GW electrolyser cluster is being planned.
- A **H2 pipeline** will be built to the German Ruhr Area (with steel manufacturer Thyssen Krupp) as likely anchor customer. Furthermore a **connection to the European gas grid** is being planned with households as consumers of H2 (as co-firing with CH4).
- **Import facilities for Methanol** are being considered. Intention is to replace grey Methanol.
- **Import and de-hydrogenation of LOHC** shall be tested. TRL is regarded as low and costs per imported MWh appear high.

Demand by country, infrastructure by port – Belgium: Antwerp/Zeebrugge

- **Belgium's hydrogen imports** of estimated 70 TWh in 2035 and 700 TWh in 2050 will be used 50% domestically and 50% transported by pipeline to Germany (Ruhr area). Belgium has limited potential for own production of green hydrogen (in North Sea wind parcs)
- **Port of Antwerp** is Belgium's largest port with a strong chemical cluster. It is located upstream river Scheldt, i.e. inland and populated area. In the port of Antwerp BASF is handling about 1 million tons of Ammonia per year as feedstock for chemical processes. About 600,000 tons are produced on site, while about 400,000 m^3 are imported. Permissions limit the annual Ammonia volume in Antwerp to 1 millions tons.
- If additional ammonia were to be imported to Belgium, it needs to be done via **Port of Zeebrugge**, where also an LNG terminal is located. Zeebrugge does not have significant local off-takers, but a pipeline street is being planned by energy company Fluxys from Zeebrugge via Ghent (Arcelor Mittal steel mill) to German Ruhr area. The pipeline street shall transport CH_4 and H_2 from Zeebrugge and CO_2 back from the industrial areas. Zeebrugge shall become port for CO_2 export.
- A **Hydrogen Import Coalition** constituting of 7 stakeholders (energy companies, ports, shipping companies) has formed to drive the development of hydrogen import. They regard Ammonia as most viable short/mid term solution, but are open for other carriers (esp. LH_2) longer term.

Demand by country, infrastructure by port – USA: Los Angeles

- **Port of Los Angeles** and neighbouring Port of Long Beach are the key ports of the southern US west coast (California). Besides container terminals there are several smaller tank terminals for crude and products operated by Shell, Vopac, Conocophilips etc. No LNG terminal. Hardly/few potential industrial off-takers of hydrogen or Ammonia.
- With the **Clean Technology Action Plan** and subsequent activities Port of LA has defined its ambitions and plans to gradually decarbonize port activities (ships, harbour crafts, trucks, locomotives, terminal operation etc.) with a target of 90% GHG reduction from 2019 to 2050
- Among the first hydrogen projects there are first **heavy duty trucks** operated on hydrogen and fuel cell as well as a hydrogen fuelled **tug.** For such equipment Port of LA has strong interest in green hydrogen.
- Overall California could **produce** significant shares of required **green electricity and hydrogen domestically**, but this has limited progress yet. Today California is rather setting up **hydrogen distribution infrastructure** for transportation
- Neighbouring state of Utah plans the Advanced Clean Energy Storage project for **storing electricity in form of hydrogen** in salt domes.
- With regard to **hydrogen import** there are some early stage discussions, but no infrastructure in place yet. Space could be made available, if it makes sense for the city and the region.

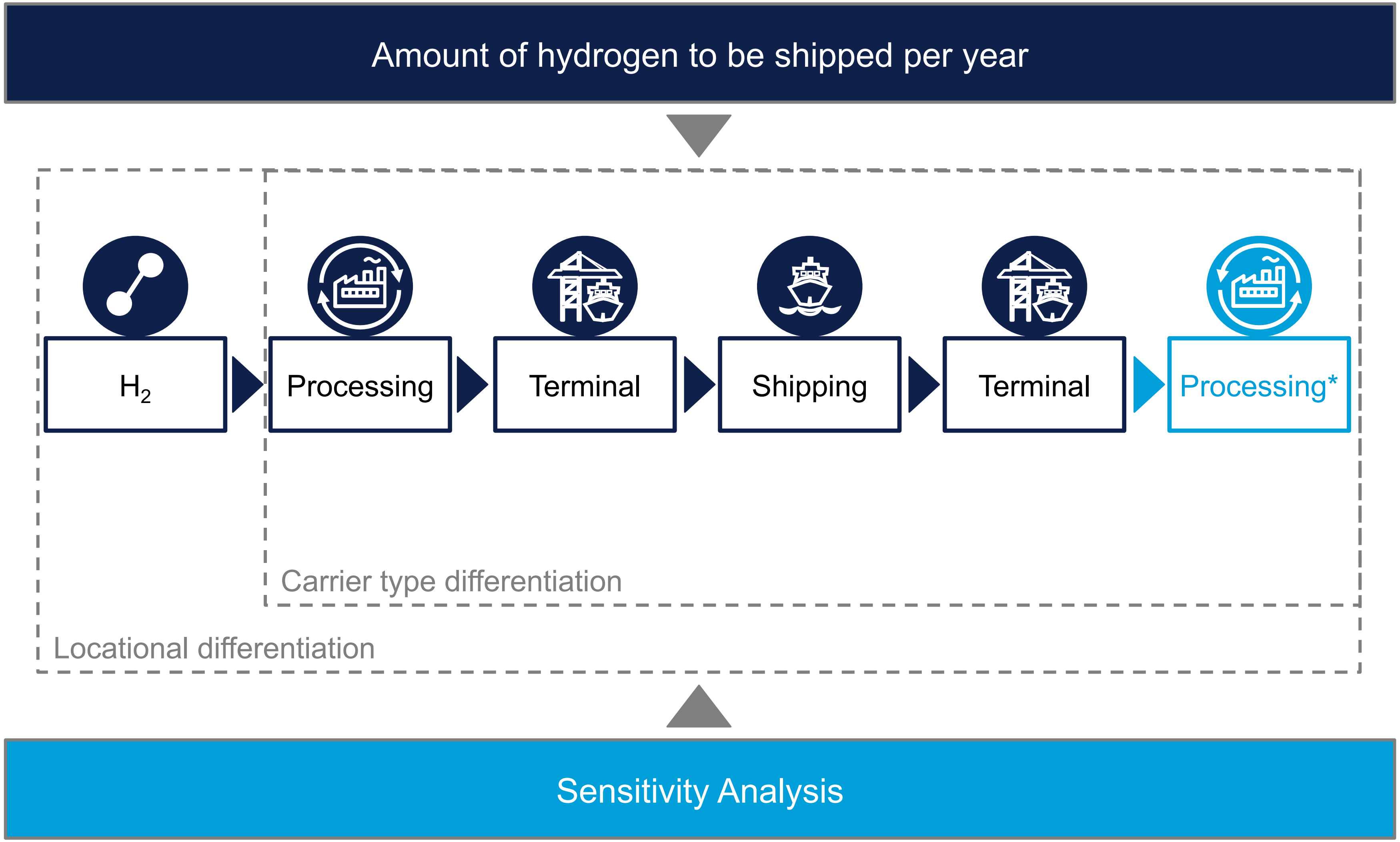
Demand by country, infrastructure by port – Canada: Vancouver

- **Port of Vancouver** is the key west coast port of Canada, providing access of British Columbia and Alberta to the Pacific ocean.
- Traditionally the port of Vancouver is an **export port** for dry bulk; **grain exports** have outpaced coal exports (from Alberta). Beyond that it is the main container port for shipments from China etc. LNG export facilities are available, operated by industrial players (not the port authority)
- Majority of **electricity** in British Columbia (and Quebec) originates from **hydro power**, while other provinces generate electricity from coal and nuclear power.
- With the **low carbon fuel standard** in British Columbia increasing shares of car fuels need to be from renewable origin with the distributers being responsible for safeguarding the required mix. It is expected that on the longer term these drop-in fuels will be produced in Canada (e.g. from forest residues), whereas in a transition period some import may be required.
- **CCS** could become relevant for Canada, especially in the oil fields of Alberta; However, the business case is not yet strong enough for investments.
- An **H2 import** terminal might be established, if there were a business case for private companies, but there seems to be little incentive and interest yet
- Overall the Port of Vancouver is more interested in **H2 as ship fuel for local/coastal traffic** (e.g. dredger, tug, ferries) than in H2 or Ammonia imports

Infrastructure by port – Chile: Mejillones and vicinity of Punta Arenas

- **Neltume Ports** is operating 17 port facilities in Latin America, 1 in North America. Types of cargo comprise among others containerized cargo, dry bulk, liquid bulk, breakbulk, pulp, copper concentrate, sulphuric acid etc.
- **Neltume Ports** is active in developing and operating ports and terminals. This comprises greenfield projects as well as expansions of existing facilities and conversions in line with applicable regulations. Experience with chemical goods is demonstrated by the existing business with copper concentrate and sulphuric business.
- The four existing terminals in **Mejillones** could be expanded by an **export terminal for green ammonia** produced from electricity generated in the desert nearby. **Additional land** and access to deep water would be available. A **conversation** of one of the existing terminals can be considered (which might save time in the permission and construction process). In this context Neltume has been approached by a number of companies (incl. Japan and EU).
- In the south of Chile **near Punta Arenas** Neltume is investigating a further export terminal for green ammonia together with an unnamed international company. As this might be a greenfield project more time (overall 4-5 years?) might be required for the permission process, engineering and construction.

Model Structure



- The Microsoft Excel-based bottom-up model is constructed to compare different supply chains for H_2 via shipping routes
- The basic **input** parameters are:
  - Amount of H_2 to be shipped
  - Cost of H_2 production at export location
  - Distance port-to-port
- The **output** comprises:
  - Total costs of H_2 at import market
  - Costs of H_2 transport per supply chain segment and H_2 carrier
- Necessary cost and process parameters are taken from academic literature and expert industry insights (i.e. the interviews conducted for this project activity)
- A VBA-based sensitivity analysis allows to identify impacts of deliberate parameter changes

** Processing: optional step as ammonia and methanol may be used directly*

Processing parameters

Carrier-specific Parameters

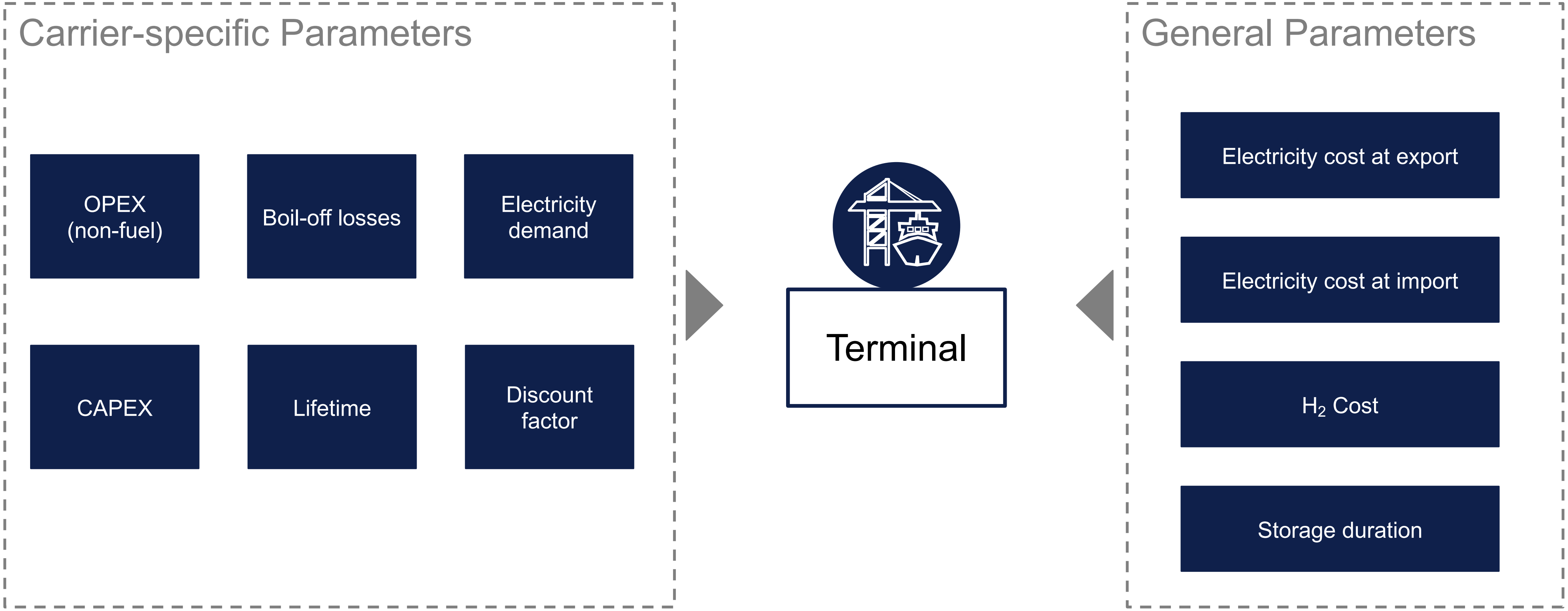
- Electricity demand
- Heat demand
- H_2 content
- OPEX (non-fuel)
- Losses
- Run time per year
- CAPEX
- Lifetime
- Discount factor

Processing

General Parameters

- Electricity cost at export
- Electricity cost at import
- Heat cost at import
- H_2 Cost

Terminal parameters



Shipping parameters

Vessel-specific Parameters

- Vessel size
- Vessel speed
- Fuel consumption
- OPEX (non-fuel)
- Boil-off losses
- Port fees
- CAPEX
- Vessel lifetime
- Discount factor

Shipping

General Parameters

- Distance
- Amount of H_2 to be shipped
- H_2 Cost
- Fuel Cost

Model Assumptions for base scenario

H_2

- Same production cost in northern and southern Chile* (1.39 USD/kg H_2)
- 200 kt H_2 to be shipped per year

- Chile MoE; Brändle et al 2020

Processing

- Scaling factor of 1 (i.e. no economies of scale)
- Electricity price in Chile half the assumed price at import market*

- Niermann et al 2021; Ikäheimo et al 2018; Brändle et al 2020; Guerra et al 2020

Terminal

- Uniform storage time for all carriers (3 days)
- Uniform terminal costs at all locations

- Brändle et al 2020; IEA 2019

Shipping

- Constant shipping fuel prices (i.e. ships do not run on H_2 (carrier) as fuel)
- Additional costs of 50 \$/t CO_2
- Idle time for vessels needs not be compensated*

- Port of Rotterdam fees; Drewry; expert Interviews; Clarkson Intel.

Terminal

- Uniform storage time for all carriers (20 days)
- Uniform terminal costs at all locations

- Brändle et al 2020; IEA 2019

Processing

- Heat and electricity prices are equal
- LOHC and methanol uses own energy from carrier without use of distributed heating

- Niermann et al 2021; Brändle et al 2020; Guerra et al 2020

Timing

- Reference year = 2030 for cost data

Carrier

- DAC = 100 USD/t CO_2
- Toluene = 0.73 USD/kg

Others

- 8% interest rate
- 1 USD = 0.82 EUR

Note: *subject to sensitivity analysis
Processing: optional step as ammonia and methanol may be used directly

DNV

Model Assumptions for scenario differentiation

- **The parameters selected for scenario differentiation were identified with regard to a) relevance for the overall costs and b) uncertainty in the prevalent cost assumptions**
- **A high case is used for cost uncertainty of novel technologies. A low case considers potential to decrease costs by supply chain optimization.**

H_2	Processing	Terminal	Shipping	Terminal	Processing
• As in base case	• 30% increase compared to base case for LOHC processing and direct air capture • As in base case for other carriers	• 30% increase terminal costs for LH2 transport • As in base case for other carriers	• 30% increased costs for LH2 • As in base case for other carriers • Cost coverage of idle time for ships	• 30% increase terminal costs for LH2 transport • As in base case for other carriers	• 30% cost increase for ammonia, methanol and LOHC processing • As in base case for other carriers
• As in base case	• As in base case	• As in base case	• As in base case	• 50% cost reduction compared to base case	• 20% cost reduction compared to base case

Timing	Carrier	Others
• As in base case	• As in base case	• As in base case

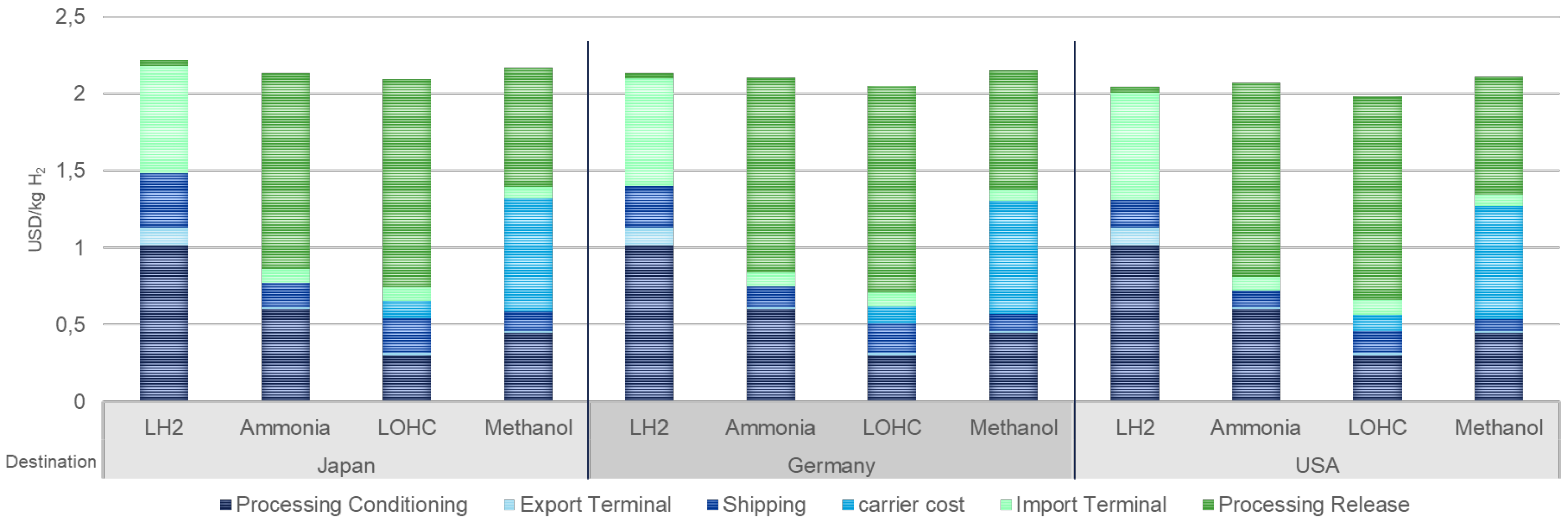
Note: *Scenario differentiation made to account for cost uncertainty of novel technologies (high case) and to account for faster distribution of H_2 and increased process efficiency (low case)*

DNV

Carrier analysis for Chile

- The cost drivers for the supply chains widely differ per carrier. While costs for methanol are driven by Direct Air Capture (DAC) and for LH2 by liquefaction and storage at the import terminal, costs for supply chains based on ammonia and LOHC are dominated by costs for the H_2 release process.
- LOHC is the cheapest option, followed by ammonia. All supply chains revolve within a narrow cost range, irrespective of the destination.

Comparison of cost of transportation by segment

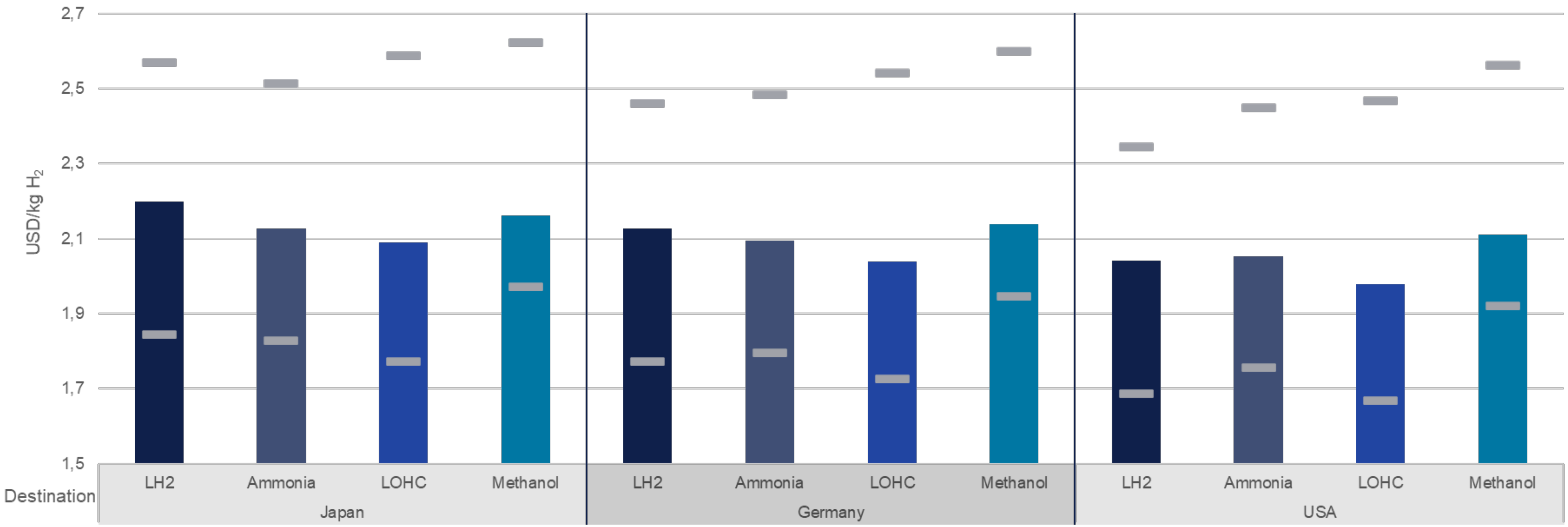


Note: The analysis is calculated for northern Chile with the base scenario assumptions and hydrogen production costs of 1.39 USD/kg H_2.The results for southern Chile match the analysis as shipping cost differences have only little impact.

Carrier scenario analysis

- **The scenario analysis strengthens the finding that the methanol base supply chain is comparatively expensive; LOHC remains the cost competitive option in the low cost scenario but sees extensive cost increases in the high cost scenario.**
- **Ammonia and LH2 are generally on a level playing field – LH2 loses out in more distant supply chains.**

Comparison of cost of transportation by scenario

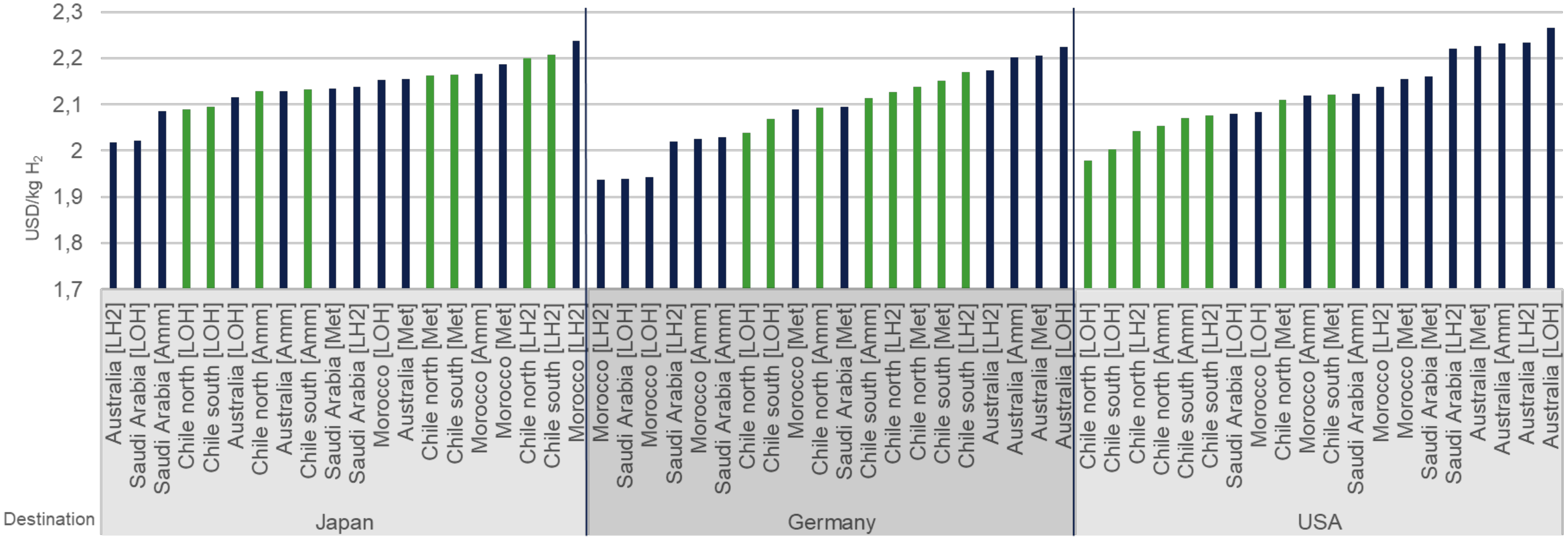


Note: The analysis is calculated for northern Chile with hydrogen production costs of 1.39 USD/kg H_2. The results for southern Chile match the analysis as shipping cost differences have only little impact. The coloured bar shows the base scenario while the upper (lower) lines depict the costs in the higher (lower) scenario.

Competitor Analysis in the base scenario

- The analysis in the base scenario shows a clear competitive advantage for H_2 export to the USA. Middle Eastern countries appear to be better suited for export to Germany in terms of costs. Competition for export to Japan is comparatively dense; Australia may play a role here.
- The transportation cost range is limited compared to the potential cost differences for H_2 production which are, thus, driving competitiveness.

Comparison of cost of transportation by H_2 origin



Note: To guarantee comparability, hydrogen production costs were taken from Brändle et al 2020. The underlying production cost data is, hence, about 1.3 USD/kg H2 higher than estimated for Chilean Ministry.

Brändle et al (2020)

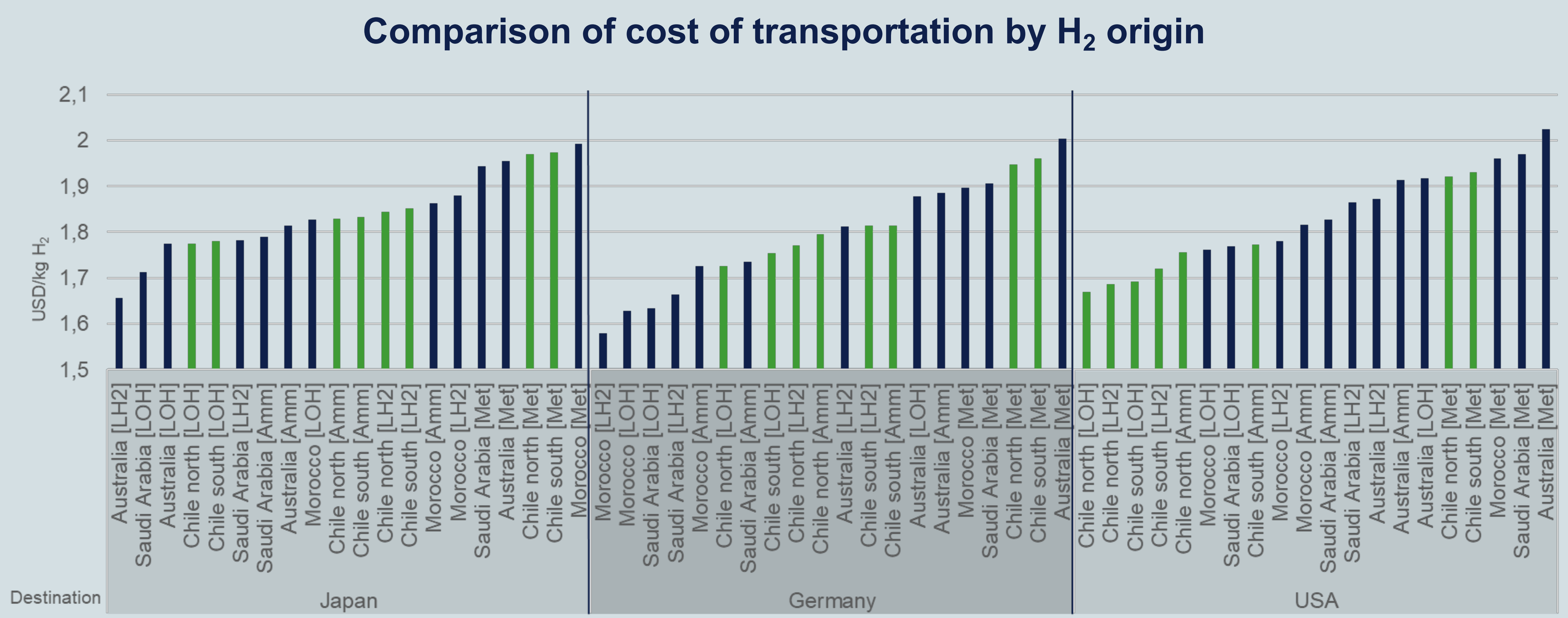
Origin	*$/kg*	*Origin*	*$/kg*
Australia	3,15	Chile	2,64
Morocco	2,76	Saudi Arabia	2,56

Chile National Green Hydrogen Strategy

Origin	*$/kg*
Chile (North)	1,39
Chile (South)	1,33

Competitor Analysis in the low cost scenario

- **The ranking and competitive advantages in the low cost scenario remain by and large the same as in the base scenario**
- **The variation of supply chain costs in comparison to the base scenario increase marginally.**



Note: To guarantee comparability, hydrogen production costs were taken from Brändle et al 2020.
The underlying production cost data is, hence, about 1.3 USD/kg H2 higher than estimated for Chilean Ministry.

Brändle et al (2020)

Origin	*$/kg*	*Origin*	*$/kg*
Australia	3,15	Chile	2,64
Morocco	2,76	Saudi Arabia	2,56

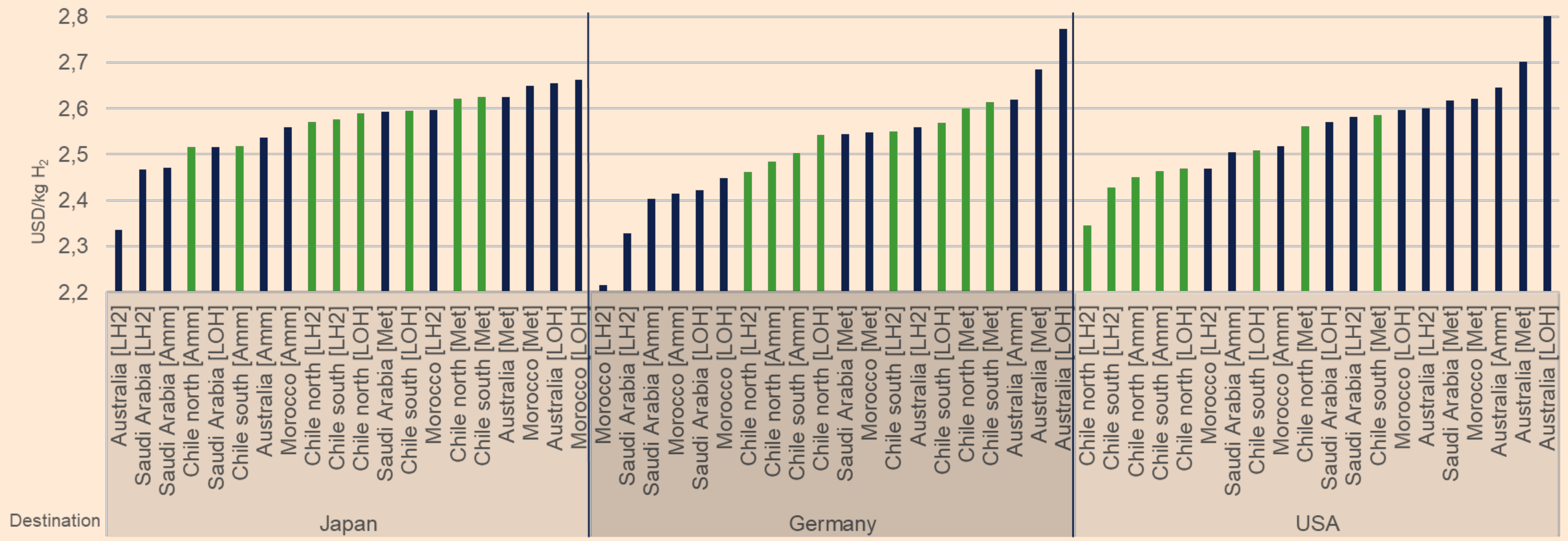
Chile National Green Hydrogen Strategy

Origin	*$/kg*
Chile (North)	1,39
Chile (South)	1,33

Competitor Analysis in the high cost scenario

- **The ranking and competitive advantages in the high cost scenario remain by and large the same as in the base scenario**
- **The variation of supply chain costs in comparison to the base scenario increase marginally.**

Comparison of cost of transportation by H_2 origin



Note: To guarantee comparability, hydrogen production costs were taken from Brändle et al 2020.
The underlying production cost data is, hence, about 1.3 USD/kg H2 higher than estimated for Chilean Ministry.

Brändle et al (2020)

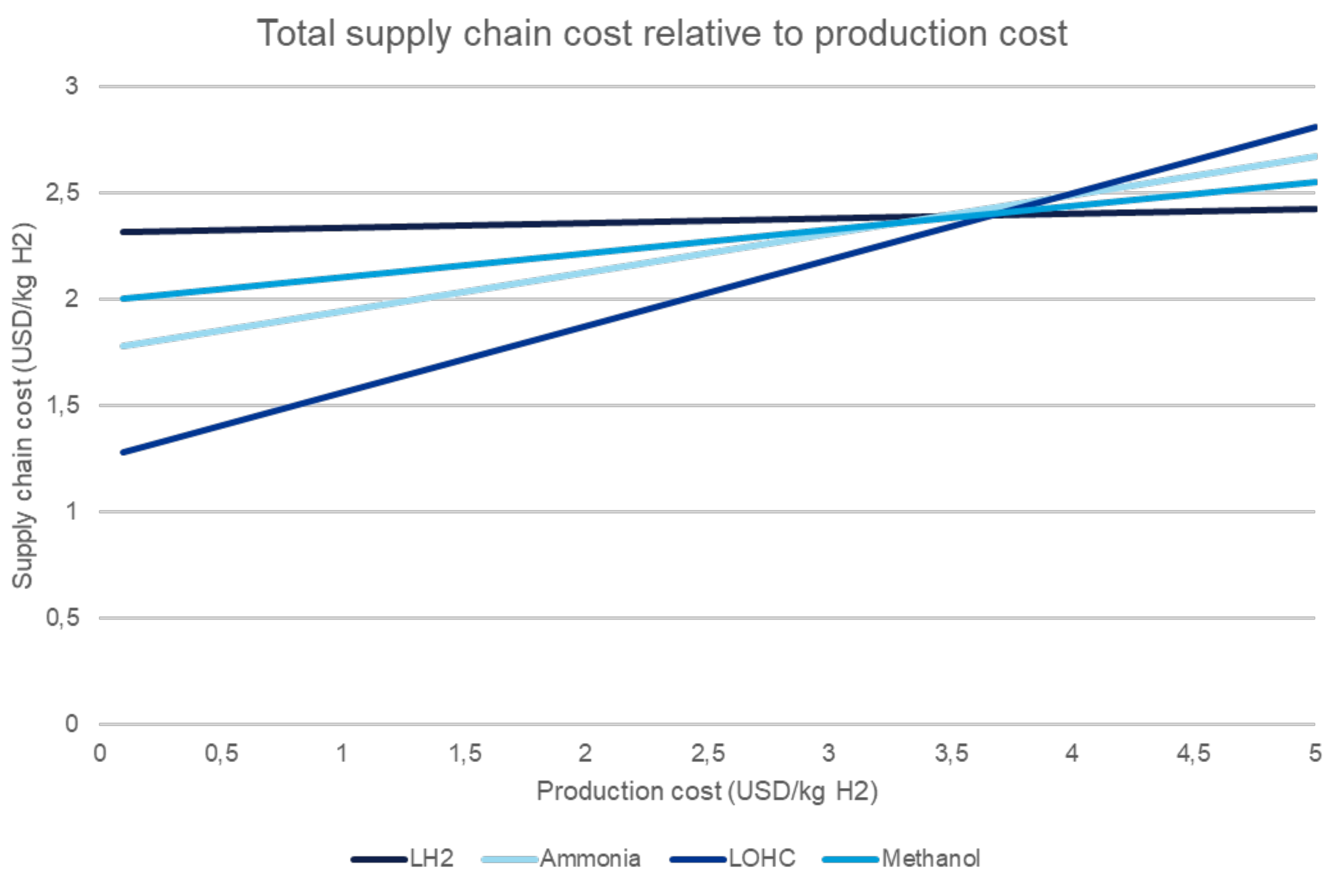
Origin	*$/kg*	*Origin*	*$/kg*
Australia	3,15	Chile	2,64
Morocco	2,76	Saudi Arabia	2,56

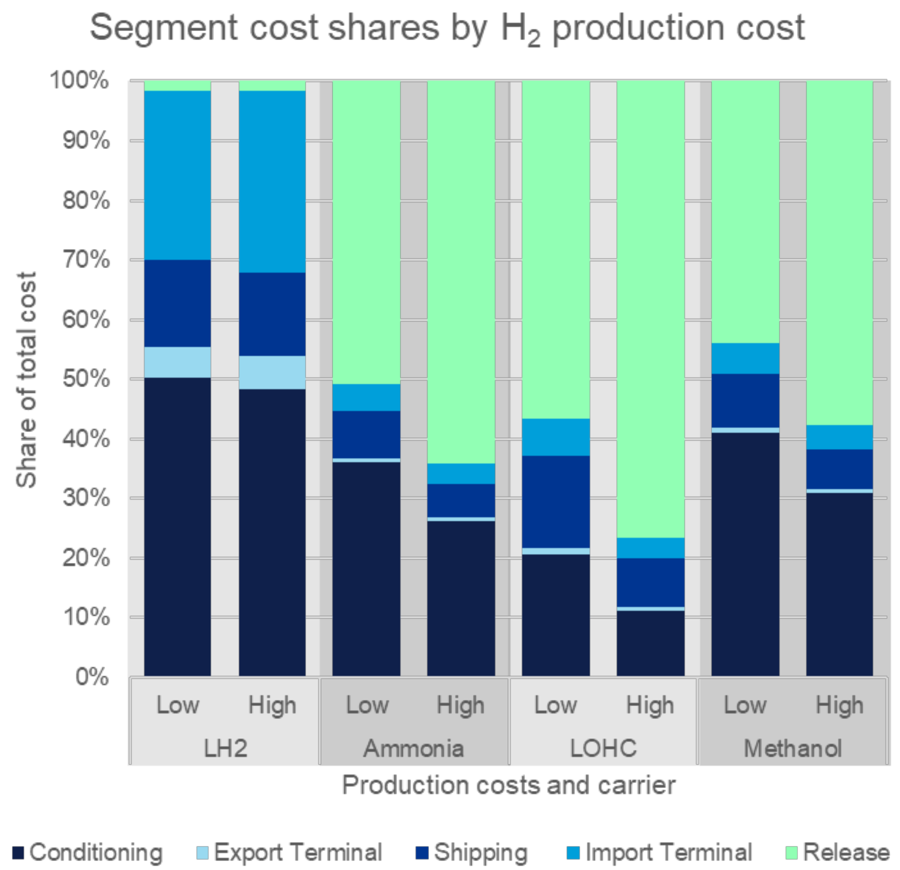
Chile National Green Hydrogen Strategy

Origin	*$/kg*
Chile (North)	1,39
Chile (South)	1,33

Sensitivity to H_2 production cost

- The LOHC supply chain is particularly sensitive to hydrogen production costs as large shares are used for the hydrogen release process.
- LH2 is the least sensitive carrier to H_2 production costs, given that H_2 is not used as shipping fuel but as energy carrier for the release process.



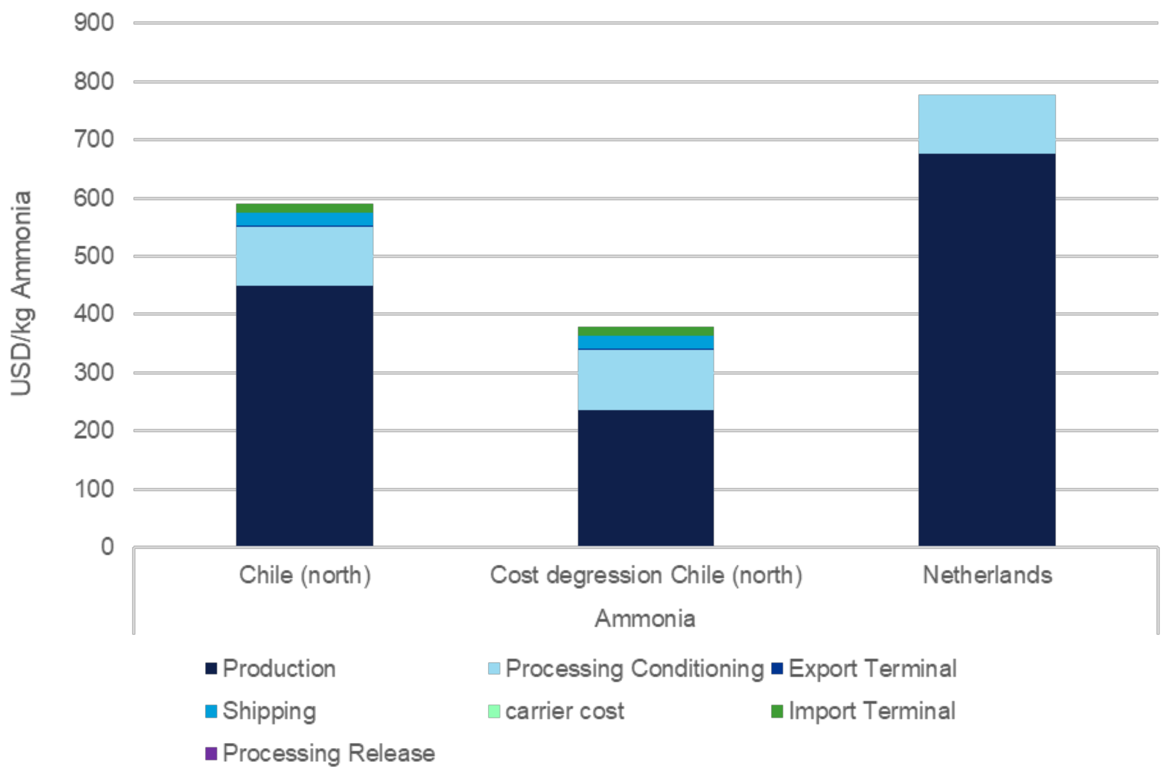


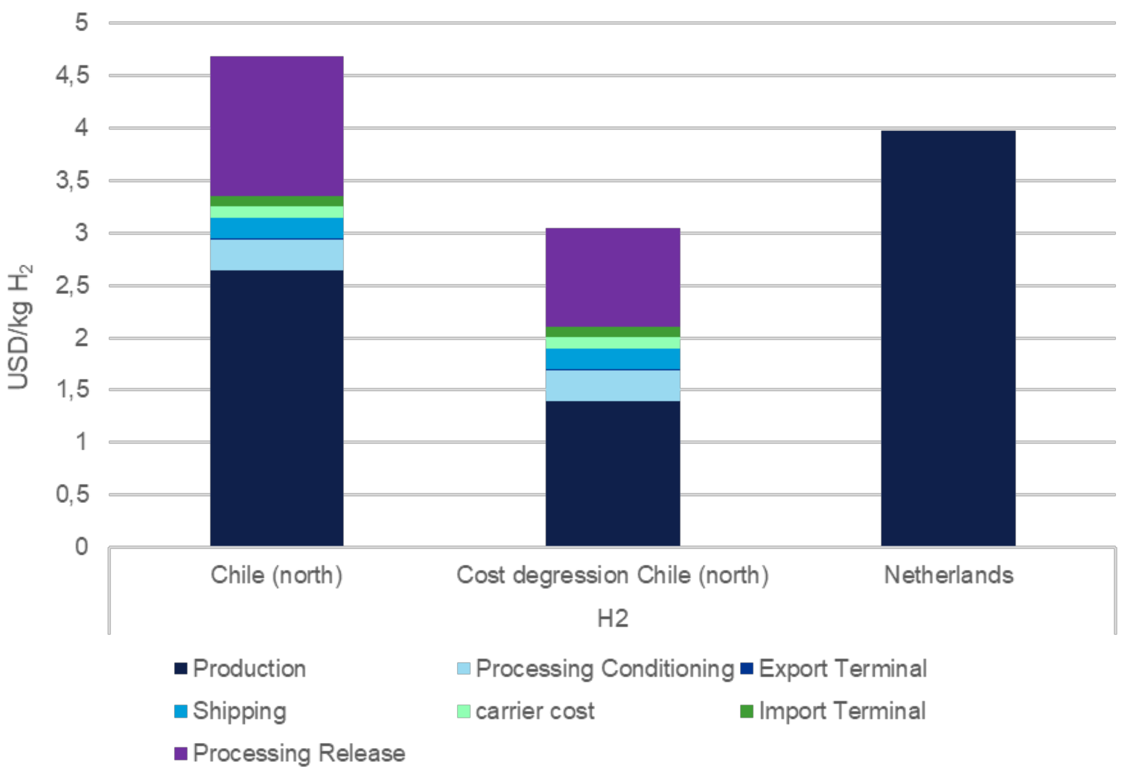
Note: representative supply chain calculated for Northern Chile-Japan route in the base scenario

Cost comparison with domestic production

- **A direct comparison with domestically produced hydrogen and ammonia shows the strong benefit of directly selling ammonia rather than (released) hydrogen: While domestically produced hydrogen is cheaper than the cheapest imported hydrogen if production costs in Chile do not decrease as envisioned, lower H_2 production cost as well as processing costs for green ammonia imply a competitive advantage for imported green ammonia.**

Supply chain cost comparison





Note: representative supply chain calculated for the cheapest Northern Chile-Germany route in the base scenario (LOHC as carrier for H2 comparison) with production cost data from Brändle et al 2020 and in the cost degression case with hydrogen production costs of 1.39 USD/kg H_2.

Literature comparison of supply chain costs

- **Parameter comparison with recent hydrogen economy literature is not robust, as supply chains differ with regard to the reference year, the location, the granularity of parameter segmentation and others. However, direct comparison of available parameters locate the model's results at the lower end of the cost parameter range.**

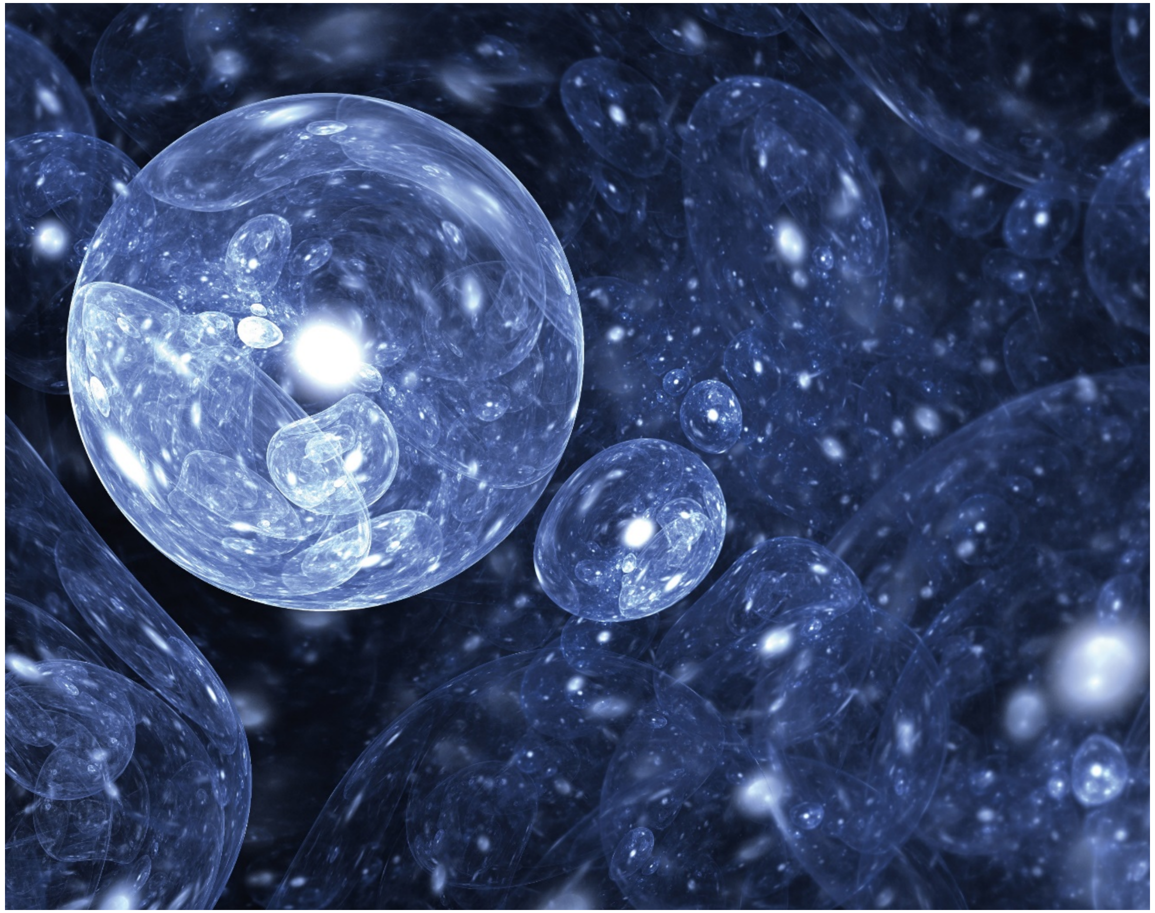
	LH2				**Ammonia**				**LOHC**			
($/kg H_2)	Costa Rica 2021 (to EU)	Hydrogen Council 2019	IEA 2019	DNV	Costa Rica 2021 (to EU)	Hydrogen Council 2019	IEA 2019	DNV	Costa Rica 2021 (to EU)	Hydrogen Council 2019	IEA 2019	DNV
Liquefaction / conversion	<2	0.7-1.0	1	1	~ 1.5	0.8-0.9	1	0.6	~0.4	0.3-0.5		0.3
Loading	~1			0.1	~0.2			0.01	~0.1			0.01
Shipping	~0.5	1.0-1.2	1.0-1.3	0.3	~ 0.1	0.3-0.4	0.1-0.2	0.15	~0.1	0.3-0.4		0.2
Release	~ 0.1	0.2		0.04	~1	0.9-1.6		0.85	~1.5	1.2-1.8		1
Note:	DNV assumes high cost for storage at import terminal in line with IEA											

Literature comparison of shipping parameters

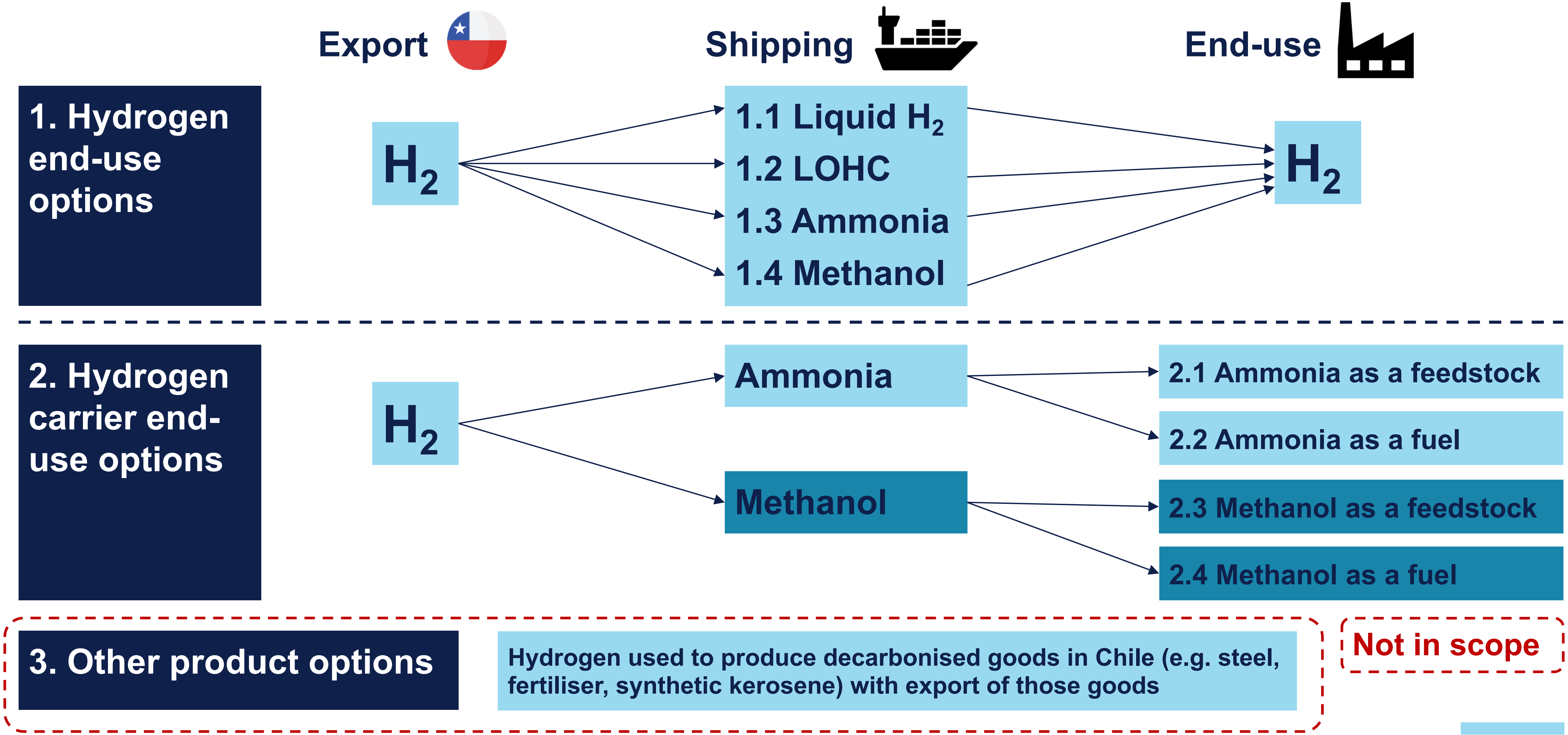
- **Parameter comparison with recent hydrogen economy literature is not robust, as supply chains differ with regard to the reference year, the location, the granularity of parameter segmentation and others. However, direct comparison of available parameters identify a significant difference in the assumption for LH2 ship sizes. Our interview results and industry insights show that LH2 ship assumption on sizes has often been overconfident.**

	LH2 Ship				Ammonia Ship		
	Gallardo et al	IEA	Niermann et al 2021	DNV	Gallardo et al	IEA	DNV
Capacity	160,000 m^3	11,000 t (~155,000 m^3)	173,400 m^3	50,000 m^3	53,000 m^3	53,000 t (~85,000 m^3)	82,000 m^3
CAPEX M$/ship	412	412	146	105	85	68	75.5
$/m3	2575	2658	841	2100	1603	800	920
Speed kn	16	-	18	18	16	-	18
Boil off %/day	0,2	0,2	-	0,2	0	0	0
O&M %/Capex	4	4	11,500 €/day	6,464 $/day	4	4	8,600 $/day

Content



Overall options for hydrogen export (1/2)



Overall options for hydrogen export (2/2)

1. Hydrogen end-use options	Options where hydrogen is liquified or converted into a carrier, and then converted back into hydrogen at the destination terminal for end-use. These options can help to meet the projected large growth in hydrogen demand, but they are more costly and require more energy, given the need to convert back into hydrogen at the destination terminal.
2. Hydrogen carrier end-use options	Options where hydrogen is converted into fuel or feedstock for direct use at the destination. These options are cheaper and require less energy, given that there is no need to convert back into hydrogen at the destination terminal, and they can also help to decarbonise the large global demand for these fuels and feedstocks. However, in some cases there are issues of international carbon accounting, if combustion of the fuel in the destination country leads to CO_2 emissions.
3. Other product options	Although this is not in scope for this project, it is worth noting that hydrogen can also be used in Chile to make decarbonised goods, such as steel, fertiliser and synthetic kerosene, with these goods then exported. Advantages include no energy losses from international transport of hydrogen / hydrogen carriers, and possibly higher-value product exports. However, the production of many of these goods would require other resources in Chile, or imported, which might offset some of these advantages. Further investigation would be required.

Not in scope

Key considerations for each option

ISSUE	CONSIDERATIONS
1. Cost of transport	Cost of transport from Chile to end-user, including liquefaction/conversion from hydrogen and reconversion to hydrogen if necessary. Potential for cost reduction
2. Demand	Likely growth in demand in key end-use markets, including appetite for imports and policy required to bridge cost gap between green hydrogen and incumbent alternative
3. Timing	Likely speed of growth in demand and timescales for overcoming weak points in the hydrogen export value chain, depending on carrier
4. Infrastructure	Potential to re-use/scale up existing infrastructure for export from Chile, for shipping, and for receiving at the overseas terminal
5. Environmental, Social, Health and Safety (ESHS)	Environmental and health/safety factors, including toxicity and explosion/large release impacts, together with social and local community issues

Note that the assessments in the following tables provide a current view of the state of technology readiness and market development, which is likely to change in future

Colour key to following tables:

Colour	Meaning
Red	Major barrier/s
Orange	Moderate to major barrier/s
Yellow	Moderate barrier/s
Green	No significant barriers

Hydrogen end-use options (1/2)

	Liquid hydrogen	LOHC	Ammonia	Methanol
Cost of transport	• Most expensive option: ~$2.00-2.20 per kg H2	• Cheapest option: ~$1.55-1.65 per kg H2	• Second cheapest option: ~$1.80-1.90 per kg H2	• Second most expensive option: ~$2.00 per kg H2
Demand	• Refineries account for around half global hydrogen use (~38 million tonnes), and green H2 can be a drop-in replacement for grey H2. However, refinery business may decline in e.g. Europe, as less crude oil is refined given the shift to electric vehicles. • Strong growth in hydrogen projected, particularly in heavy transport and industrial sectors, given net zero targets (excludes use of hydrogen for ammonia etc production). Over 30 countries with hydrogen strategies. • Hydrogen Council project pipeline envisages more that 10 million tonnes low-carbon H2 production by 2030; DNV Energy Transition Outlook envisages only modest low carbon hydrogen demand before 2030, with strongest growth in 2040s. • Green hydrogen will compete with blue hydrogen produced locally in some markets e.g. UK, US, although preference for green hydrogen in Germany. • Cost gap vs grey hydrogen, which will fall as CO2 prices rise, and possibly locally produced blue hydrogen. Green hydrogen costs may be similar with higher electricity prices in target markets, offsetting higher transport and processing costs for imports. • Currently unclear how cost gap will be overcome for imports. Domestic production will be subsidised, but subsidy may not be extended to imported hydrogen. Coalition forming in Europe for a carbon border tariff on (grey) hydrogen imports. • For **methanol**, issue of IPCC carbon accounting rules, which deem non-biogenic carbon to be fossil, even if directly captured from the air. EU adopts these IPCC carbon accounting rules – the rules will need to change to support H2 imports via methanol. • For all carriers, internationally-recognised green certification (e.g. guarantees of origin) is required.			
Timing	• **Weak point is LH2 ships**, which are only at the experimental stage today (TRL 4). We don't expect to see large scale LH2 ships before 2030. • LH2 regasification is also only carried out at small scale today.	• **Weak point is small pilot scale for hydrogenation and dehydrogenation**. • Marine transport of LOHC assigned a TRL of 7 – no dedicated LOHC tankers currently exist, apart from experimental, but LOHC exhibits similar properties to conventional cargoes such as distilled oils and crude oil.	• **Weak point is ammonia cracking.** Ammonia cracking into H2 is still at small scale: 1-2 tonnes per day. • Questionable that the required scale will be reached by 2030, although likely that industrial application will develop in the 2030s.	• **Weak point is Direct Air Capture** for the production of green methanol, with CO2 captured from e.g. industrial sources not fully green. • Would also compete with bio-methanol with CCS. • Methanol cracking into hydrogen is also not fully mature.

Hydrogen end-use options (2/2)

	Liquid hydrogen	LOHC	Ammonia	Methanol
Infrastructure	• Potential alternatives for re-utilization of LNG terminals as hydrogen import/export infrastructure, but still largely under study • **Chile** – LNG import terminal in Mejillones – potential to repurpose for export • **Worldwide** – extensive LNG import and export infrastructure	• Potential to re-use existing liquid hydrocarbons infrastructure • **Chile** – Oil refinery in Cabo Negro • **Worldwide** – Extensive hydrocarbons infrastructure	• **Chile** – NH3 import terminal in Mejillones and LPG export plant in Cabo Negro • **Worldwide** – Extensive ammonia infrastructure (although not for cracking into H2), with 18.5 million tonnes traded each year	• **Chile** – Methanol plant in Cabo Negro • **Worldwide** – Extensive methanol infrastructure and global trade

Environmental, Social, Health and Safety (ESHS)	• DNV hazard study: 0.1 bar overpressure from explosion (irreversible damage to health: 0.175 bar, broken glass: 0.05 bar):
	    • Large LH2 release (100mm opening) – 849 metres max distance
	• DNV hazard study: 50% of the concentration for the lower flammability limit of hydrogen
	    • Large LH2 release (100mm opening) – 704 metres max distance
		• High flash point. Not flammable in room temperature.
		• Medium toxic effects
			• NH3 has a toxic effect on the human body. Irreversible damage occurs at concentrations above 300 ppm. Exposure for 10 min to 2,700 ppm can be lethal.
			• High concentrations of ammonia both in air and water can form a serious threat for all living organisms in its surroundings.
			• DNV hazard study: Acute Exposure Guideline Levels (AEGLs) were applied for an exposure time of 10 minutes: Level 2: Irreversible or other serious, long-lasting health impairments or impaired ability to escape:
			    • Large NH3 release (100mm opening) – 3,940 metres max distance
				• Medium toxic effects – comparable to gasoline or diesel
				• Biodegradable

DNV

Hydrogen carrier end-use options (1/3)

	Ammonia: Feedstock	Ammonia: Fuel	Methanol: Feedstock	Methanol: Fuel
Cost of transport	• Significantly cheaper (>50%) to transport if no cracking back into H2 required • Cost of ~$0.80-0.85 per kg of H2 in the carrier – just over half the cost of the cheapest carrier (LOHC) with conversion back into H2		• Cheaper (> one third) to transport if no processing back into H2 required • Cost of ~$1.35-1.40 per kg of H2 in the carrier – around 10-15% cheaper than the cheapest carrier (LOHC) with conversion	
Demand	• Current demand of ~200 million tonnes (~180 million tonnes for fertiliser production). • Fertiliser demand expected to grow to 250 million tonnes by 2040.	• Not in significant use as a fuel today. • Biggest opportunity is **maritime fuel** – current maritime fuel demand around 4x total global ammonia production. • DNV expects over 40 million tonnes of ammonia use as a shipping fuel by 2040, but it will take time to develop, with only around 200,000 tonnes used in 2030. (Note the points on toxicity in the ESHS section below.) • Opportunities for use in **power generation**, including co-firing in coal power stations, but direct fuelling of 100% ammonia in gas turbines is an immature technology – Mitsubishi Power targets commercialisation of a 40 MW 100% ammonia gas turbine around 2025.	• Current demand of ~100 million tonnes – around 60% used as feedstock. • Overall demand expected to reach more than 120 million tonnes by 2025 and 500 million tonnes by 2050. • China is world's largest producer and consumer – over half of global demand, 75% of which used as feedstock.	• Current demand of ~100 million tonnes – around 40% used as fuel. • Overall demand expected to reach more than 120 million tonnes by 2025 and 500 million tonnes by 2050. • China is world's largest producer and consumer – over half of global demand, 25% of which used as fuel.

Hydrogen carrier end-use options (2/3)

	Ammonia: Feedstock	Ammonia: Fuel	Methanol: Feedstock	Methanol: Fuel
Timing	• Key issue is when green ammonia becomes cost-competitive with grey ammonia. • Given expected natural gas and CO2 prices, DNV expects cost competitiveness to be reached in early 2030s on average, and by earlier than 2030 in Europe and OECD Pacific Asia	• Ammonia not being used as a shipping fuel today. • 44 ammonia ships expected by 2030, using 215,000 tonnes ammonia per annum. • Mid/long-term, the majority of the demand for ammonia as a maritime fuel is expected to come from new builds, as retrofits from conventional oil-fuelled systems are expensive. Retrofits from LPG systems are less complex and costly. • Given slow pace of shipping turnover, significant growth in ammonia demand for maritime fuel only expected from mid-2030s. Only 10% of current newbuilds are ordered with alternative fuel systems, most of which are LNG.	• Key issue is when green methanol becomes cost-competitive with grey methanol. • The production cost of grey methanol is around \$100-250 per tonne. IRENA estimates that the production cost of green methanol with Direct Air Capture, which is currently over \$1,000 per tonne, will fall to around \$250-630 per tonne in 2050. (Bio methanol is projected to have cheaper production costs.) • The price of CO2, and of renewable electricity (for the Direct Air Capture and green H2 production) are critical to projections of when green methanol will be cost-competitive – but we expect that this will be considerably later than for green ammonia.	**Shipping** • Around 30 methanol-fuelled vessels are either in operation today, or in the orderbook (fossil methanol). • Given slow pace of shipping turnover, significant growth in methanol demand for maritime fuel not expected in the short term. Only 10% of current newbuilds are ordered with alternative fuel systems, most of which are LNG. • Currently, the shipping industry faces large uncertainty with respect to selecting the right fuel technology for assets lasting ~25 years • Methanol has higher volumetric energy density than ammonia, and could fuel an ultra large container vessel (ULCV) for 13,000 nm, compared to 10,000 nm for ammonia – very relevant for distances such as Europe-Far East (around 23,000 nm). **Road** • Methanol is used in gasoline blends, mainly in China, at low (3-5%), mid (15-30%) and high (50-100%) volume percentages, although not yet at a nationwide scale.

Hydrogen carrier end-use options (3/3)

	Ammonia: Feedstock	Ammonia: Fuel	Methanol: Feedstock	Methanol: Fuel
Infrastructure	• Extensive global infrastructure for existing grey ammonia, which is compatible with green ammonia. • However, ammonia plants with integrated urea production may need some retrofits to shift away from natural gas (with proven technologies).	• Comparable to LNG (which comes at -162°C), ammonia due to its toxicity will require more complex bunkering operations than today's fuel, but with little cost impact. • Fuel quantities needed by seagoing ships require dedicated ammonia bunker vessels; these do not exist yet. • It is expected that all ammonia terminals could be used as a reload terminal for an ammonia bunker vessel. This would include the NH_3 import terminal in Mejillones.	Extensive global infrastructure for existing grey methanol, which is fully compatible with green methanol.	• Can re-fit existing global marine bunkering infrastructure. • Around 100 ports with methanol availability. • Can also be used in existing marine engines after retrofit.

Environmental, Social, Health and Safety (ESHS)	No differences from current grey ammonia feedstock	• Versus existing conventional marine fuel:
		  • 100% SOx reduction
		  • 0% NOx reduction (more research needed)
		• Ammonia has significant hazards when compared to other fuels in the maritime market and requires careful handling, including the installation of onboard detection systems; measures to cope with leakages to reduce concentrations; and onboard safety systems, including shut-off valves.
		• Currently major companies from across all the segments of the maritime industry are coming together in a project managed by Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping to develop the safety parameters and protocols necessary to accelerate the safe adoption of ammonia as a fuel for the shipping industry.
		• We expect that the toxicity challenges of ammonia as a maritime fuel will be overcome, as effective mitigation measures do exist, but proof is yet outstanding.
			No differences from current grey methanol feedstock	• Versus existing marine fuel:
				  • 100% SOx reduction
				  • 30-60% NOx reduction
				• Much lower toxicity in marine environment than conventional fuels. LC 50: Lethal Dose: Fish:
				  • Gasoline: 8.2 mg/l
				  • Methane: 49.9 mg/l
				  • Diesel: 65 mg/l
				  • Heavy fuel oil: 79 mg/l
				  • **Methanol: 15,400 mg/l**

Key comparisons (1/3)

ISSUE	COMPARISONS
1. Cost of transport	• Ammonia for direct use is the cheapest, followed by methanol for direct use. • All options that convert the carrier back into H2 are more expensive – LOHC cheapest in this category, followed by ammonia.
2. Demand	• Largest current demand is ammonia as a feedstock (mainly fertiliser – although this may require plant retrofits to shift away from natural gas), followed by methanol. Methanol also has considerable demand growth forecasted. • Major growth expected in hydrogen use, although dependent on policy. • Ammonia as a marine fuel has large potential, but again dependent on policy.

3. Timing	• For options that convert the carrier back into H2, the biggest issues are weak points in the supply chain, in particular:
	  • For LOHC – scale of hydrogenation and dehydrogenation
	  • For methanol – Direct Air Capture
	  • For ammonia – scale of ammonia cracking technology
	  • For liquid H2 – a lack of ships
	• For the direct use options, the key issue is when the green route becomes cost-competitive with the grey route, which we expect to be reached much sooner for ammonia than for methanol. Ammonia also has greater potential as a shipping fuel, but scale up will take time given the slow rate of ship turnover and uncertainties over shipping fuel choice.

Key comparisons (2/3)

ISSUE	COMPARISONS
4. Infrastructure	• Most options have good potential to re-use existing infrastructure. • Ammonia bunkering for marine fuel use and possible LNG infrastructure re-purposing for liquid H2 require the most work.
5. Environmental, Social, Health and Safety (ESHS)	• The most challenging option, safety-wise, is ammonia, due to its highly toxic nature, which needs the largest safety distances. However, ammonia is used and traded extensively today with good safety controls. • Liquid H2 presents explosion risks, although safety distances are around one quarter those of ammonia. • LOHC and methanol present the lowest safety risks. • For direct use as a fuel, ammonia and methanol provide an almost 100% reduction in SOx, but unlike methanol, ammonia does not lead to a reduction in NOx.

Key comparisons (3/3)

Note that these assessments show the current state of technology readiness and market development, which could change in the future

Comparison issue	Liquid hydrogen	LOHC	Ammonia	Methanol	Ammonia direct use	Methanol direct use
Cost of transport	Major barrier/s	No significant barriers	Moderate barrier/s	Moderate to major barrier/s	No significant barriers	No significant barriers
Demand	Moderate barrier/s	Moderate barrier/s	Moderate barrier/s	Moderate barrier/s	No significant barriers	No significant barriers
Timing	Major barrier/s	Moderate barrier/s	Moderate to major barrier/s	Moderate barrier/s	Moderate barrier/s	Major barrier/s
Infrastructure	Moderate barrier/s	No significant barriers	No significant barriers	No significant barriers	No significant barriers	No significant barriers
Environmental, Social, Health and Safety (ESHS)	Moderate barrier/s	No significant barriers	Moderate to major barrier/s	No significant barriers	Moderate barrier/s	No significant barriers

Colour key :

- Red: Major barrier/s
- Orange: Moderate to major barrier/s
- Yellow: Moderate barrier/s
- Green: No significant barriers

2020s – The main options

From the above analysis, no carrier option is perfect. There is an opportunity for first-mover advantage, but equally a risk of technology lock-in. The following are potentially viable options for the 2020s.

Option 1: Ammonia direct use

- The most promising early option is ammonia for direct use in fertiliser production, with a large global demand, existing infrastructure for trading ammonia, a potential cost cross-over point with grey ammonia before 2030, and an ammonia import terminal in Mejillones and LPG terminal in Cabo Negro that could be repurposed.
- The upside potential for this option is the adoption of ammonia as a marine fuel at scale in the 2030s, although it is not dependent on this occurring.*
- There is also existing ammonia demand in Mejillones, which could be met alongside the development of exports.

Option 2: LOHC conversion into H2

- Based on our model, this is the cheapest option for H2 end-use, with global demand for green H2 likely to grow substantially. There is potential to use the oil refinery infrastructure in Cabo Negro.
- However, the applicability of supportive policies for imported H2 will need to be verified, and scale up of hydrogenation and dehydrogenation will be required.
- H2 for refining in Europe is a promising market in the short term, but for other regions is uncertain.

Option 3: Ammonia conversion into H2

- Based on our model, this is the second cheapest option for H2 end-use, and the option that interviewees felt was the most promising. It can also make use of the ammonia import terminal in Mejillones and LPG terminal in Cabo Negro.
- Ammonia cracking technology, however, would need to scale up substantially, and stringent safety protocols to manage toxicity and safety risks are needed.
- But for Chile, there is no need for additional infrastructure beyond that needed to export ammonia for direct use. Pursuing Option 1 therefore allows for Option 3.
- Given the high versatility of ammonia, the slightly higher transport cost compared to LOHC could be seen as an ‘insurance premium’ for a lower risk option.

Option 4: Methanol direct use

- Overall, this is the second cheapest option, behind ammonia direct use, and can make use of the methanol plant in Cabo Negro, existing global infrastructure and strong and growing demand for methanol for various applications.
- There will be a need for liquid fuels and feedstocks for many decades, and green methanol can be used to help decarbonise the hard-to-abate sectors.
- The main barrier is the high cost of green methanol relative to grey, given the need for Direct Air Capture, and it will take longer for this gap to be bridged than for ammonia.

*Toxicity of ammonia is not expected to be an insurmountable barrier to adoption as a marine fuel. The main barriers are related to the source and cost of ammonia.

2020s – Recommendations for Chile: Ammonia

North Chile

The first step should be to investigate further **Option 1: Ammonia direct use**, as there is existing ammonia demand, it is the cheapest export option and most likely to be competitive earliest – before 2030. Pursuing this option allows for **Option 3: Ammonia conversion into H2**, if ammonia cracking is scaled up, with no changes required in Chile. Given the existing infrastructure and ammonia demand, this option should be investigated around Mejillones.

South Chile

The first step should also be to investigate further **Option 1: Ammonia direct use**, given the lower cost of wind electricity compared to solar in the 2020s and the existing LPG export plant in Cabo Negro, although there is no large-scale domestic demand in this location. Similar to North Chile, this option allows for **Option 3: Ammonia conversion into H2** in future.

This approach would promote H2 export through ammonia in the main solar and the main wind regions in Chile, and make use of existing infrastructure and skilled labour. Large ammonia tankers are also already in operation. This approach would maintain flexibility to scale up ammonia production as the 2020s progress. Key export markets to target are Japan and North West Europe.

Given a) the need to scale up hydrogenation and dehydrogenation for LOHC, and the large cost gap between grey and green methanol, and b) the views of interviewees, we think that these are possible, but less promising options for the 2020s. Focusing on ammonia also provides greater optionality, with the potential for direct use in more than one sector and cracking into H2.

The case for ammonia beyond 2030

As per the schematic on the previous slide, we also think that ammonia is the most promising strategic way ahead in the 2030s:

Technology

Ammonia for direct use in fertiliser is the only option that does not need technology development (retrofits to fertiliser plants may be needed, but with existing, proven technology). All of the other options require some technology development, including:

- Liquid H2 requires development of new cargo-ships
- LOHC requires hydrogenation/dehydrogenation to be scaled up
- Methanol requires Direct Air Capture to be scaled up

Versatility and optionality

Ammonia is likely to become a green fuel for ships, which is an advantage over LOHC. Existing ammonia use will face pressure to decarbonise. Both of these trends suggest an increasing demand for green ammonia. In the EU Fit for 55 package an amendment to the Renewable Energy Directive is proposed (not yet adopted):

- A binding target of 50% renewable hydrogen consumption for industry by 2030 (i.e. replacing existing grey H2). This will be a significant enabler of green ammonia.
- Bringing the shipping sector into the EU-ETS (completely for intra EU shipping and 50% for international shipping). Again a game changer for ammonia.

Equally, there is a high degree of uncertainty in the development of the carrier market for hydrogen. The cost levels for LOHC and ammonia are similar (considering the uncertainty in the cost estimates). In this case, ammonia provides Chile with a relatively cheap option to mitigate potential technological or market risk – ammonia can be converted into gaseous hydrogen whereas the LOHC route does not give the option to enter the ammonia market.

Cost and competition

The cost difference between imported and locally produced hydrogen is greater than the difference between imported and locally produced ammonia, which tends to favour ammonia imports. Our analysis suggests that (assuming cost of hydrogen production in Chile is 2.64 $/kg from Brändle et al 2020):

- Green ammonia exported from Chile is cheaper than green ammonia produced in the Netherlands ($379 per tonne of ammonia from Chile freight included, versus $777 per tonne in the Netherlands).
- For green H2, the overall costs are slightly higher from Chile ($4.77 per kg from Chile versus $3.97 per kg in the Netherlands), given the transport costs and the need for the processing of the H2 carrier (assuming ammonia as the export carrier).

Government support

For LOHC and liquid hydrogen, the main issues are global technological, which limits the Ministry's ability to lower the barriers. On methanol, the biggest issue is Direct Air Capture – widespread deployment in Chile could help to reduce the costs of DAC, but at a high cost to Chile.

For ammonia, the biggest hurdles may be the current lack of a global certification scheme for green ammonia, and planning and environmental permitting issues at the export terminal – in Australia, the Asian Renewable Energy Hub was rejected on local environmental grounds. Both of these issues suggest an important role for the Ministry:

- International cooperation to certify green ammonia for export, with certificates accepted by the importing country.
- Strong engagement with export projects to ensure appropriate facility design and strong environmental controls.

Pathway for ammonia

As described above, the option that appears to be lowest risk (or most versatile) is the production of ammonia (preferably in Mejillones or Cabo Negro), with a potential phasing of production. Timelines could be brought forward depending on demand for green ammonia in different sectors and the development of ammonia cracking technology.

Illustrative schematic for ammonia production development in Chile

Project phases	Phase 1	Phase 2	Phase 3
Illustrative timing	Operation by 2025	Operation by 2030	Operation by 2035
Description	Ammonium nitrate plant for decarbonised mining industry	Export for direct use in green fertiliser production	Export for direct use as a marine fuel AND/OR for cracking into H2
Chile infrastructure	• Green H2 production • Ammonia production	• Expanded green H2 and ammonia production • Ammonia terminal repurposed for export	• Expanded production and export capacity • Ammonia bunkering facility
Risk mitigation	No dependency on export markets or green certificates	• No dependency on expanded ammonia cracking capacity • Likely competitive position by 2030	Opportunities for both marine fuel and H2, depending on new marine vessels and ammonia cracking technology

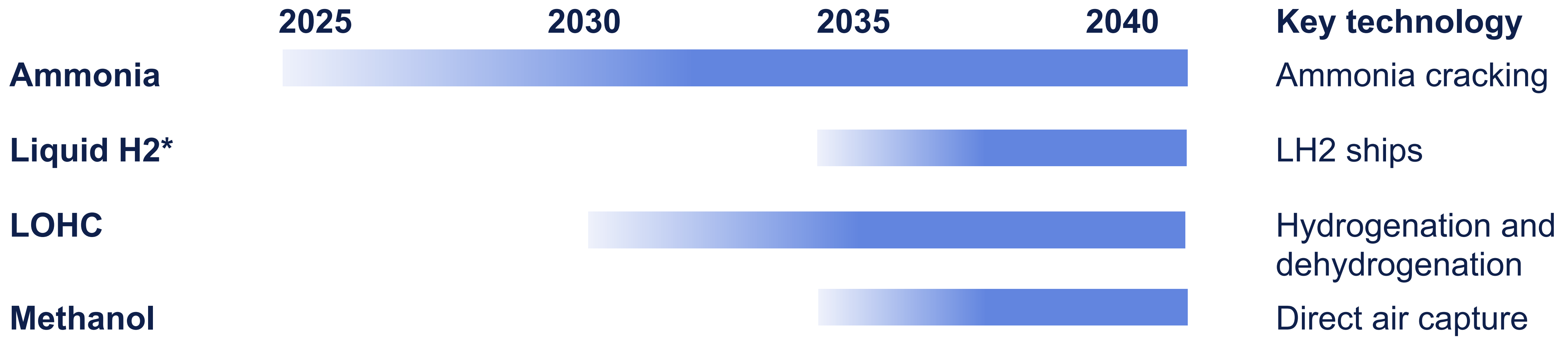
Tonnes NH3

2030s – The importance of flexibility

Given the uncertainties in the precise timeframes for the development and scaling of key enabling technologies for the various hydrogen carriers, retaining flexibility in Chile's strategy is essential. We recommend:

- Providing regular updates on the technology developments relevant to the various carriers, together with the enabling regulations (such as procedures for using ammonia as a maritime fuel and hydrogen guarantees of origin that enable international trade).
- Refreshing the strategy every 2-3 years to reflect regulatory and technology developments.
- Depending on how technology develops in practice, be ready to expand beyond ammonia and add other hydrogen carriers in the 2030s and 2040s – including potentially liquid hydrogen if ships are sufficiently advanced.

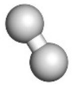
Potential strategic pathways for hydrogen carrier establishment



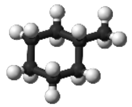
* The Chile National Green Hydrogen Strategy envisages LH2 exports to begin by 2030. DNV believes this indeed may be the case if the development and implementation of the shipping technology is accelerated.

2030s – Recommendations on other carriers

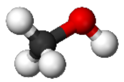
Technology developments in the 2020s could change the picture radically by 2030, and we think it is important that options are kept open for Chile, with an eye to the same export markets – North West Europe and Japan. We therefore recommend that the Ministry maintains a close eye on technology developments for the other carriers, and prepares to facilitate the following, including through international cooperation on green certificates:



Liquid hydrogen. Liquid H2 could be a promising long-term option, as noted in the interviews. It is not currently at the stage where it can compete against the other carriers, but we expect this situation to change in the coming years, and we note that the organisations we interviewed generally expected that liquid hydrogen would be the potential long term winner. There is existing LNG infrastructure in Mejillones that could potentially be repurposed, and similar in destination countries. This option also avoids the need for ammonia or LOHC conversion technology at the destination port, and has a smaller safety footprint than ammonia.



LOHC conversion into H2. This is likely to take longer to scale than ammonia. Given the existing oil refinery, this option should be investigated around Cabo Negro. Existing liquid hydrocarbons infrastructure worldwide could also potentially be repurposed.



Methanol direct use, in particular investigating whether it can genuinely become cost-competitive with grey methanol, the potential for scale up of Direct Air Capture, and the potential to ship bio-feedstock from the forestry industry north of Cabo Negro for the production of bio-methanol, which is likely to be cheaper to produce. This option should also be investigated for Cabo Negro, given the existing methanol plant. Globally, infrastructure for transporting and storing methanol, including ships, is extensive.

In the above analysis, and on previous slides, we have highlighted areas of existing infrastructure in Chile that could potentially be repurposed for hydrogen or hydrogen carrier export.

There are, however, limited opportunities to repurpose infrastructure from one carrier to another. For instance, it is unlikely to be feasible to repurpose ammonia facilities and ships for liquid hydrogen, although of course port jetties could be reused. For LOHC and methanol, there may be greater complementarity, with both potentially able to use existing liquid hydrocarbons infrastructure.

Developing a stakeholder engagement framework

We recommend that a comprehensive stakeholder engagement framework is developed at an early stage, focused above all on local communities.

Local communities

There are three key issues for local communities living near planned hydrogen export projects:

Local impacts:

- *Project construction impacts, including traffic*
- *Long-term visual and other impacts from the new facilities*

Economic issues:

- *Local jobs, including to support a Just Transition for communities reliant on fossil-fuel jobs*
- *Community benefits and support schemes*

Local knowledge

- *Incorporating local knowledge into project design is critical. Local communities will have specific local knowledge that national and/or international project developers and engineers may not*

Local engagement

Early and transparent engagement with local communities is essential to build support and help ensure a well-designed project. Renewable energy has strong support in principle, but excessive local impacts arising from an insensitively-designed project could undermine this.

Pre-engagement

- *Awareness raising at an early stage – before environmental permit and planning applications are submitted – is needed to start to build local support and gain initial feedback that can be incorporated into project design*

Environmental impact assessments

- *Engagement through the environmental impact assessment (EIA) process is needed to help project developers understand local environmental conditions; ensure well-designed environmental monitoring programmes; and design effective mitigation measures to keep local impacts to acceptable levels and reduce safety risks to as low as reasonably practical (ALARP).*

Detailed planning

- *Detailed planning applications also require community engagement to help answer questions such as how construction will be managed, how visual impacts will be minimised, and how projects that are designed to benefit the global environment will also provide a positive impact locally.*

Respect

At all stages, the views of local communities need to be listened to and respected. It is important for project developers to be willing to make reasonable modifications to projects based on community feedback. It is also important that job opportunities are provided for local people and that any community benefit schemes are well-designed and relevant to local issues.

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WHEN TRUST MATTERS

Prefeasibility study for a hydrogen export project

IDB Selection Process #: CH-T1235-P001

Activities 1 to 4 – Report 1

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Appendix A
Overview of Projects

Overview of Projects Worldwide

BRAZIL	
PROJECT NAME: BASE ONE (3.4GW)	
LOCATION	Pecém, Ceará state, northeast Brazil
POWER SOURCE	Combined baseload wind and solar power
DEVELOPERS	Enegix Energy, in conjunction with Italian wind turbine maker Enerwind, EPC provider Black & Veatch, and the Ceará state government
PLANNED USE OF H2	Green hydrogen for "major international markets via ocean freight"
H2 OUTPUT	600,000 tonnes per year
PLANNED DATE OF COMPLETION	2025
EXPECTED COST	$5.4BN
STAGE OF DEVELOPMENT	Project was announced on 1 March 2021, but Enegix says it has "contracted" the 3.4GW of solar and wind capacity through its partnership with Enerwind

CHILE	
PROJECT NAME: HYEX (1.6GW)	
LOCATION	Antofagasta, Chile
POWER SOURCE	Solar
DEVELOPERS	Engie and Enaex
PLANNED USE OF H2	Green ammonia, half of which will be used at Enaex's ammonium nitrate plant; the remainder will be targeted for fuel, green fertiliser and export markets.
H2 OUTPUT	124,000 tonnes per year (700,000 tonnes of green ammonia)
PLANNED DATE OF COMPLETION	26MW pilot by 2024
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Early stage, project was announced in October 2020

Source: Recharge, Jul 2021

DNV

Overview of Projects Worldwide

CHILE	
PROJECT NAME: HNH (1.4GW)	
LOCATION	Southern Chile
POWER SOURCE	1.8-2GW of onshore wind to power ,1.4GW of electrolysers connected to a Haber-Bosch system for ammonia production
DEVELOPERS	Austria Energy and Ökowind EE
PLANNED USE OF H2	Green ammonia for export via a new international port (which is part of the project)
H2 OUTPUT	850,000 to one million tonnes of green ammonia per year
PLANNED DATE OF COMPLETION	2026
EXPECTED COST	$3,000.000,000
STAGE OF DEVELOPMENT	Wind measurements are under way, topography studies have been done and work on environmental license application and wind farm design have begun

EUROPE (MULTIPLE SITES)	
PROJECT NAME: HYDEAL AMBITION (67GW)	
LOCATION	Multiple sites across Western Europe, starting in Spain and southwest France, then extending to eastern France and Germany
POWER SOURCE	95GW of solar across multiple locations to power 67GW of electrolysers
DEVELOPERS	A group of 30 energy players, including gas distributors Snam, Enagás and OGE; electrolyser maker McPhy; EPC provider Vinci Construction; and solar developers Falck Renewables and Qair.
PLANNED USE OF H2	To deliver green hydrogen across Europe at €1.50/kg before 2030 (ie, to be cheaper than unabated grey hydrogen)
H2 OUTPUT	3.6 million tonnes per year
PLANNED DATE OF COMPLETION	Before 2030
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Early stage, project was announced in February 2021.

Source: Recharge, Jul 2021

Overview of Projects Worldwide

NETHERLANDS	
PROJECT NAME: NORTH2 (10GW)	
LOCATION	Eemshaven, northern Netherlands
POWER SOURCE	Offshore wind
DEVELOPERS	Shell, Equinor, RWE, Gasunie, Groningen Seaports
PLANNED USE OF H2	To help power heavy industry in the Netherlands and Germany
H2 OUTPUT	One million tonnes per year
PLANNED DATE OF COMPLETION	2040 (1GW by 2027, 4GW by 2030)
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Feasibility study under way, to be completed by July 2021

NETHERLANDS	
PROJECT NAME: SEAH2LAND (1GW)	
LOCATION	Industrial clusters near North Sea ports in the Netherlands and Belgium
POWER SOURCE	A 2GW offshore wind farm in the Dutch North Sea powering 1GW of electrolysers
DEVELOPERS	Orsted, in conjunction with ArcelorMittal, Yara, Dow Benelux and Zeeland Refinery
PLANNED USE OF H2	For use at industrial clusters for the production of steel, ammonia, ethylene and transport fuel
H2 OUTPUT	Not stated, but the industrial clusters currently consume 580,000 tonnes of grey hydrogen annually
PLANNED DATE OF COMPLETION	Not stated
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Early stage, project was announced at the end of March 2021

Source: Recharge, Jul 2021

DNV

Overview of Projects Worldwide

GERMANY	
PROJECT NAME: AQUAVENTUS (10GW)	
LOCATION	Heligoland, Germany
POWER SOURCE	Offshore wind
DEVELOPERS	A consortium of 47 companies, research institutions and organisations, including RWE, Vattenfall, Shell, E.ON, Siemens Energy, Siemens Gamesa, Vestas, Northland Power, Gasunie and Parkwind
PLANNED USE OF H2	General sale via a European hydrogen network
H2 OUTPUT	One million tonnes per year
PLANNED DATE OF COMPLETION	2035 (30MW by 2025, 5GW by 2030)
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Early stage, project was only announced in August

GERMANY	
PROJECT NAME: ROSTOCK (1GW)	
LOCATION	Rostock, Germany
POWER SOURCE	Offshore wind and other renewable sources
DEVELOPERS	Consortium led by RWE
PLANNED USE OF H2	All avenues being explored
H2 OUTPUT	Not stated
PLANNED DATE OF COMPLETION	Not stated
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Very early stage

Source: Recharge, Jul 2021

Overview of Projects Worldwide

GREECE	
PROJECT NAME: WHITE DRAGON (1.5GW)	
LOCATION	Region of West Macedonia, northern Greece
POWER SOURCE	Solar
DEVELOPERS	A plethora of Greek companies: government-controlled electricity company Public Power Corporation, state-owned gas utility DEPA (the project co-ordinator), gas grid operator DESFA, oil company Hellenic Petroleum, refiner and petrol marketer Motor Oil, steel pipe manufacturer Corinth Pipeworks, long-distance gas pipeline operator TAP, renewables developer Terna Energy, fuel-cell maker Advent Technologies and power plant builder Damco Energy
PLANNED USE OF H2	Baseload power generation via fuel cells (to replace existing lignite power plants), with waste heat potentially used for district heating or by heavy industry. The project also includes the planned construction of a hydrogen pipeline to deliver H2 to the transport sector, heavy industry and possibly for export
H2 OUTPUT	About 250,000 tonnes per year for power generation, with 58,000-71,000 tonnes for other sectors
PLANNED DATE OF COMPLETION	2029
EXPECTED COST	€8,000,000,000 ($9,700,000,000)
STAGE OF DEVELOPMENT	Stage of development: Plan submitted to the Greek government and the European Commission with a view to it becoming an Important Project of Common European Interest, which would it give it access to public funds

PORTUGAL	
PROJECT NAME: H2 SINES (1GW)	
LOCATION	Sines, southwest Portugal
POWER SOURCE	Undecided, but likely to be onshore wind and solar
DEVELOPERS	EDP, Galp, Martifer, REN, Vestas
PLANNED USE OF H2	Domestic consumption and export
H2 OUTPUT	Not stated
PLANNED DATE OF COMPLETION	2030
EXPECTED COST	€1,500,000,000 ($1,840,000,000)
STAGE OF DEVELOPMENT	Stage of development: Feasibility study under way

Source: Recharge, Jul 2021

Overview of Projects Worldwide

DENMARK	
PROJECT NAME: GREATER COPENHAGEN (1.3GW)	
LOCATION	Greater Copenhagen area, Denmark
POWER SOURCE	Offshore wind preferred
DEVELOPERS	Orsted, Maersk, DSV Panalpina, DFDS, SAS
PLANNED USE OF H2	Hydrogen for buses and trucks, e-fuel (derived from green hydrogen and captured CO2) for shipping and aviation
H2 OUTPUT	Not stated, but it would produce “250,000 tonnes of sustainable fuel” per year
PLANNED DATE OF COMPLETION	2030 (10MW pilot as soon as 2023, 250MW by 2027)
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Feasibility study under way, with a view to a final investment decision in 2021

DENMARK	
PROJECT NAME: ESBJERG (1GW)	
LOCATION	Esbjerg, Denmark
POWER SOURCE	Offshore wind
DEVELOPERS	Copenhagen Infrastructure Partners,in conjunction with shipping giants Moller-Maersk and DFDS, and food companies Arla, Danish Crown and DLG
PLANNED USE OF H2	Green ammonia for fertiliser production and as a shipping fuel.
H2 OUTPUT	Not stated
PLANNED DATE OF COMPLETION	Between 2025 and 2027
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Early stage, announced in February 2021

Source: Recharge, Jul 2021

Overview of Projects Worldwide

KAZAKHSTAN	
PROJECT NAME: UNNAMED (30GW)	
LOCATION	Steppes of western and central Kazakhstan
POWER SOURCE	45GW of wind and solar
DEVELOPERS	German developer Svevind Energy and Kazakhstan's investment promotion agency
PLANNED USE OF H2	For export or local use
H2 OUTPUT	About three million tonnes per year
PLANNED DATE OF COMPLETION	Not stated, but with a final investment decision between 2024 and 2027
EXPECTED COST	Not stated.
STAGE OF DEVELOPMENT	Stage of development: Very early stage, memorandum of understanding signed in late June 2021

MAURITANIA	
PROJECT NAME: AMAN (ABOUT 16-20GW)	
LOCATION	Northern Mauritania
POWER SOURCE	30GW of wind and solar
DEVELOPERS	CWP Global
PLANNED USE OF H2	Green steel, long-distance shipping, decarbonising ammonia fertiliser nationally and internationally
H2 OUTPUT	Not stated
PLANNED DATE OF COMPLETION	Not stated
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Stage of development: Very early stage, memorandum of understanding between CWP and the Mauritanian government signed in June 2021.

Source: Recharge, Jul 2021

DNV

Overview of Projects Worldwide

OMAN	
PROJECT NAME: UNNAMED (14GW)	
LOCATION	Oman
POWER SOURCE	25GW of wind and solar (with turbines making up two thirds of the capacity) to power 14GW of electrolysers
DEVELOPERS	InterContinental Energy, Omani oil & company OQ, and Kuwaiti state-owned tech company EnerTech
PLANNED USE OF H2	For sale on international markets
H2 OUTPUT	Not stated
PLANNED DATE OF COMPLETION	2038, with about a third of the full capacity up and running in 2028
EXPECTED COST	Not stated, but the first phase (accounting for about one third of the full capacity) would cost about $10,000,000,000
STAGE OF DEVELOPMENT	Project was announced on 17 May 2021, but partners had been collaborating on it for "more than three years"

SAUDI ARABIA	
PROJECT NAME: HELIOS GREEN FUELS PROJECT (4GW)	
LOCATION	Neom, a planned city in northwest Saudi Arabia
POWER SOURCE	Onshore wind and solar
DEVELOPERS	Air Products, ACWA Power, Neom
PLANNED USE OF H2	To produce green ammonia (NH4), which would be transported around the world and converted back into H2 for use as a transport fuel.
H2 OUTPUT	About 240,000 tonnes per year (to create 1.2 million tonnes of green ammonia annually)
PLANNED DATE OF COMPLETION	Not stated, but first ammonia production due in 2025
EXPECTED COST	$5,000,000,000
STAGE OF DEVELOPMENT	Early stage, project was announced in July 2020

Source: Recharge, Jul 2021

Overview of Projects Worldwide

CHINA	
PROJECT NAME: BEIJING JINGNENG INNER MONGOLIA (5GW)	
LOCATION	Eqianqi, Inner Mongolia, China
POWER SOURCE	Onshore wind and solar
DEVELOPERS	Chinese utility Beijing Jingneng
PLANNED USE OF H2	Not known
H2 OUTPUT	400,000-500,000 tonnes per year
PLANNED DATE OF COMPLETION	2021
EXPECTED COST	$3,000,000,000
STAGE OF DEVELOPMENT	Due to be under construction this year, but not confirmed

CHINA	
PROJECT NAME: YELLOW SEA (2GW)	
LOCATION	Qingdao, Shandong province, China
POWER SOURCE	Floating wind
DEVELOPERS	Qingdao Blue Valley Industrial Development Zone, Shandong Zhongneng Integration Offshore Wind Turbine Manufacturing Corp (an affiliate of Fujian-based vertical-axis wind turbine maker Tonex) and PowerChina's North West Engineering Institute
PLANNED USE OF H2	Not stated
H2 OUTPUT	Not stated
PLANNED DATE OF COMPLETION	Not stated
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Very early — the only concrete development so far seems to be a signed co-operation contract between the co-developers

Source: Recharge, Jul 2021

Overview of Projects Worldwide

AUSTRALIA	
PROJECT NAME: HYENERGY ZERO CARBON HYDROGEN (8GW)	
LOCATION	The Gascoyne region of Western Australia
POWER SOURCE	Wind and solar
DEVELOPERS	Province Resources
PLANNED USE OF H2	Green hydrogen and ammonia "for heavy transport and industry", and potentially for blending into a local natural-gas pipeline. And later on, for export to Asian markets
H2 OUTPUT	Not stated
PLANNED DATE OF COMPLETION	2030
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Early stage, project announced in February 2021

AUSTRALIA	
PROJECT NAME: MURCHISON RENEWABLE HYDROGEN PROJECT (5GW)	
LOCATION	near Kalbarri, Western Australia
POWER SOURCE	Onshore wind and solar
DEVELOPERS	Hydrogen Renewables Australia and Copenhagen Infrastructure Partners
PLANNED USE OF H2	A demonstration phase would provide H2 for transport fuels; an expansion stage would produce H2 to blend into local natural-gas pipelines; and a final, large expansion would produce H2 for export to Asia, with a focus on Japan and South Korea
H2 OUTPUT	not stated
PLANNED DATE OF COMPLETION	2028
EXPECTED COST	$12,000,000,000
STAGE OF DEVELOPMENT	Early stage

Source: Recharge, Jul 2021

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Overview of Projects Worldwide

AUSTRALIA	
PROJECT NAME: PACIFIC SOLAR HYDROGEN (3.6GW)	
LOCATION	Callide, Queensland, Australia
POWER SOURCE	Solar
DEVELOPERS	Austrom Hydrogen, a start-up
PLANNED USE OF H2	Export to Japan and South Korea
H2 OUTPUT	More than 200,000 tonnes per year
PLANNED DATE OF COMPLETION	Not stated
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Early stage, project was announced in June 2020

AUSTRALIA	
PROJECT NAME: H2-F	
LOCATION	Gladstone, Queensland, Australia
POWER SOURCE	Renewable energy, but not otherwise specified
DEVELOPERS	The Hydrogen Utility (also known as H2U)
PLANNED USE OF H2	Green ammonia for export to Japan and other countries
H2 OUTPUT	Not stated, but developer says it would produce “up to 5,000 tonnes of green ammonia per day”
PLANNED DATE OF COMPLETION	Not stated, but initial operations due to begin in 2025
EXPECTED COST	$1,600,000,000 (not including sources of power)
STAGE OF DEVELOPMENT	Feasibility study under way, targeting approvals by 2023

Source: Recharge, Jul 2021

Overview of Projects Worldwide

AUSTRALIA	
PROJECT NAME: GERALDTON (1.5GW)	
LOCATION	Geraldton, Western Australia
POWER SOURCE	Onshore wind and solar
DEVELOPERS	BP/BP Light source
PLANNED USE OF H2	Production of green ammonia for domestic and export markets
H2 OUTPUT	Not stated, but about one million tons of green ammonia per year
PLANNED DATE OF COMPLETION	Not stated
EXPECTED COST	Not stated
STAGE OF DEVELOPMENT	Stage of development: Feasibility study under way

Source: Recharge, Jul 2021

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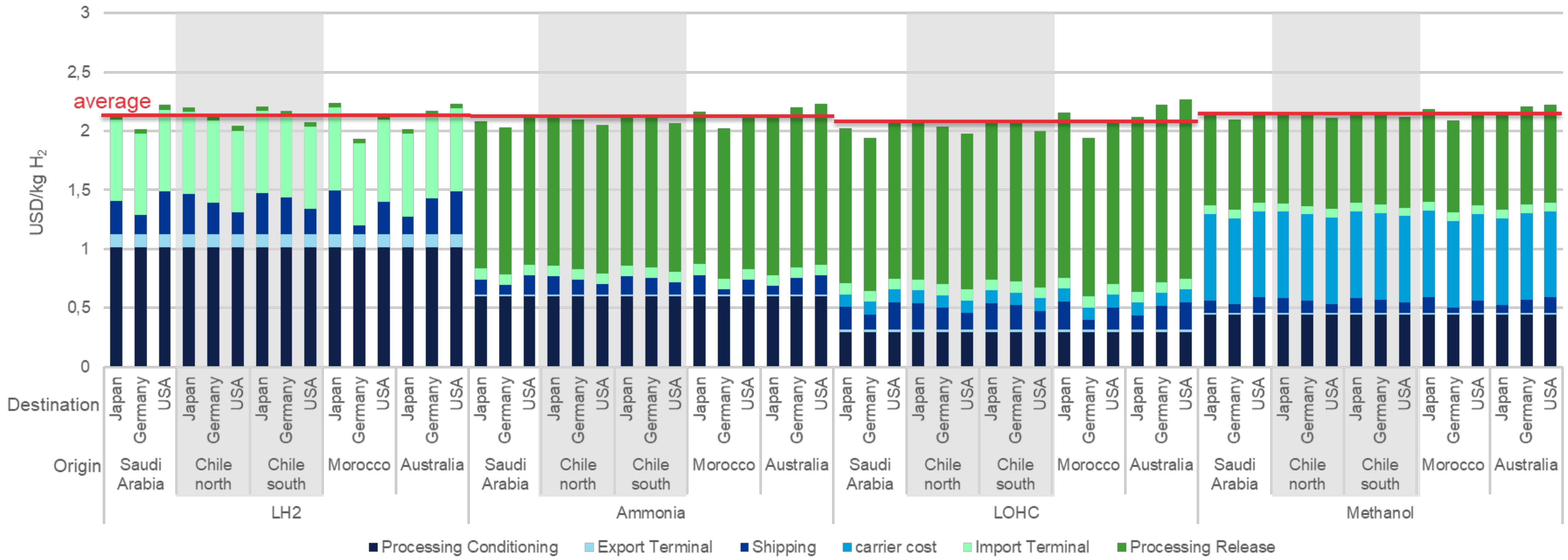
Appendix B
Transportation Overview

Base scenario overview

- The supply chain costs range between 1.93 USD/kg H_2 (Morocco – Germany with LH2) and 2.27 USD/kg H_2 (Australia – USA with LOHC).
- While all supply chains lie within a narrow range, the costs rank on average as follows: 1. LOHC, 2. Ammonia, 3. Methanol, 4. LH2.

Transportation cost comparison



Note: To guarantee comparability, hydrogen production costs were taken from Brändle et al 2020.
The underlying production cost data is, hence, about 1.3 USD/kg H2 higher than estimated for Chilean Ministry.

Brändle et al (2020)

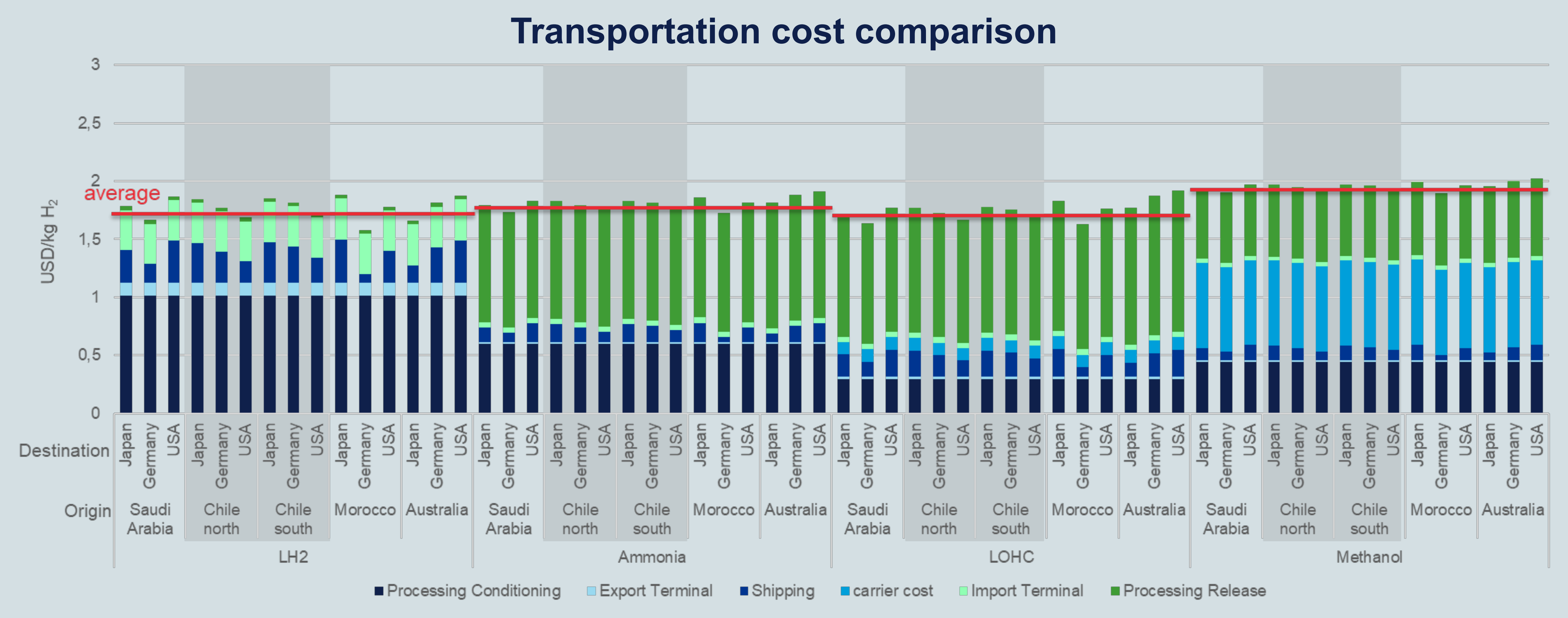
Origin	*$/kg*	*Origin*	*$/kg*
Australia	3,15	Chile	2,64
Morocco	2,76	Saudi Arabia	2,56

Chile National Green Hydrogen Strategy

Origin	*$/kg*
Chile (North)	1,39
Chile (South)	1,33

Low cost scenario overview

- **The low cost scenario shows reduced import terminal costs (50% reduction) and reduced processing-release costs (20% reduction) to account for faster distribution of hydrogen as well as process efficiency increases in hydrogen release from the carriers.**
- **LOHC remains the top performing carriers on average as in the base case. LH2 becomes the preferred carrier compared to ammonia.**



Note: To guarantee comparability, hydrogen production costs were taken from Brändle et al 2020.
The underlying production cost data is, hence, about 1.3 USD/kg H2 higher than estimated for Chilean Ministry.

Brändle et al (2020)

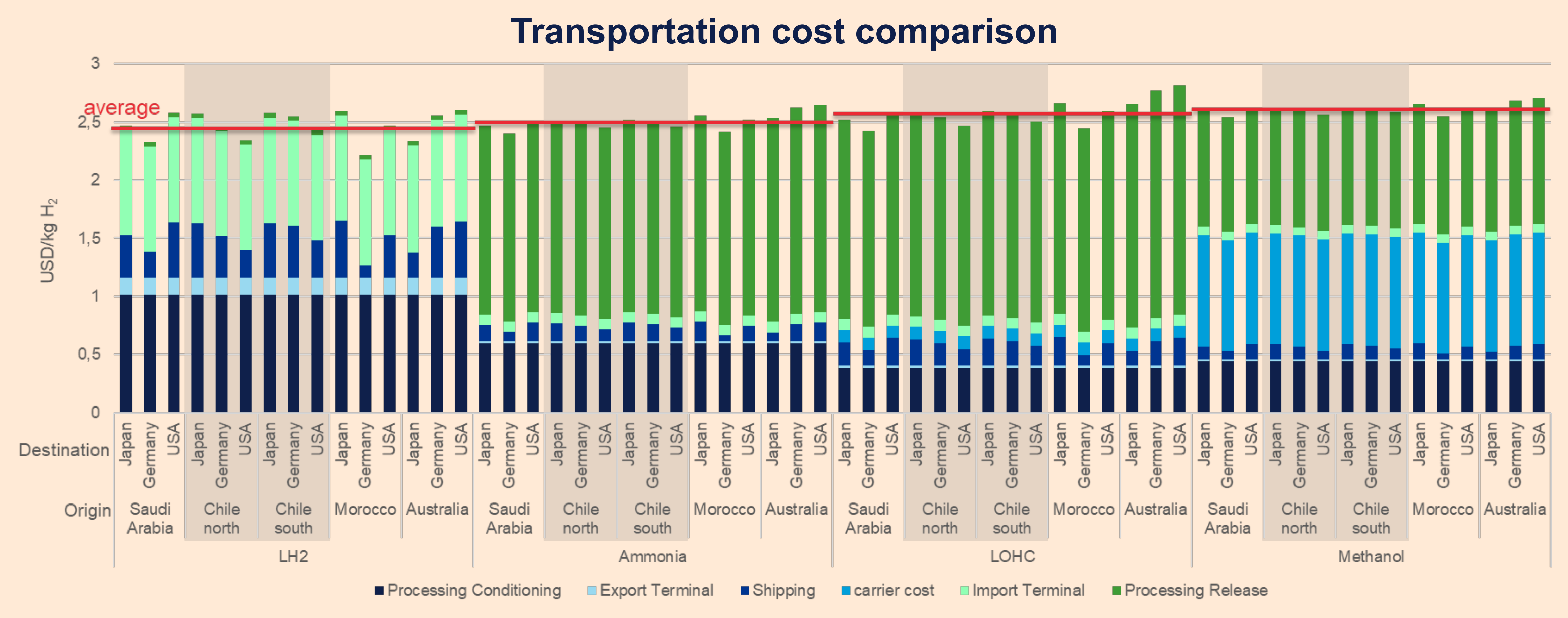
Origin	*$/kg*	*Origin*	*$/kg*
Australia	3,15	Chile	2,64
Morocco	2,76	Saudi Arabia	2,56

Chile National Green Hydrogen Strategy

Origin	*$/kg*
Chile (North)	1,39
Chile (South)	1,33

High cost scenario overview

- **The high cost scenario shows increased costs for novel technologies (30% increase for LH2 terminals and shipping, Ammonia and Methanol cracking, LOHC processing, and DAC*) to account for costs arising from technical impediments as well as cost coverage of idle time for ships.**
- **In this scenario, LH2 becomes the cost optimal choice – ammonia ranking second and LOHC third.**



Note: To guarantee comparability, hydrogen production costs were taken from Brändle et al 2020.
The underlying production cost data is, hence, about 1.3 USD/kg H2 higher than estimated for Chilean Ministry.
**DAC = Direct Air Capture for methanol production*

Brändle et al (2020)

Origin	*$/kg*	*Origin*	*$/kg*
Australia	3,15	Chile	2,64
Morocco	2,76	Saudi Arabia	2,56

Chile National Green Hydrogen Strategy

Origin	*$/kg*
Chile (North)	1,39
Chile (South)	1,33

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