First Workshop ARENHA project:
"Introduction to novel technologies related to ammonia-based energy storage"

Expected impact when using ammonia for H2 storage

Álvaro RAMIREZ SANTOS
ENGIE CRIGEN
Contact: alvaro.ramirezsantos@engie.com

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862482

Index

ENGIE Lab CRIGEN is part of the ENGIE Research ecosystem (23 thematic labs)

€35 million revenues

1,2 M€ subsidies

100 Patents in portfolio

Unique testing facilities
30 active POC
20 pilots

ISO 9001 certified

180 employees

37 years Average age

37% / 63%

27 nationalities

50 PhD,
25 thesis,
60 scientific publications/year

NEW ENERGY RESOURCES LABS
- Biogas, Biomass & waste
- Small Scale Liquefaction
- Hydrogen

NEW ENERGY USES LABS
- Future Industry
- Environment & Society
- Future Buildings & Cities

EMERGING TECHNOLOGIES LABS
- Drones & Robots
- Computer Science & AI
- Nanotech, Sensors & Wireless

ENGIE Lab Singapore

H2 LAB : We pave the way for a competitive zero-carbon hydrogen economy

LOWER THE COSTS OF THE WHOLE GREEN HYDROGEN VALUE CHAIN TO ENABLE 100% GREEN GAS BY 2050

- Technological innovations
- Tools
- Demonstrators and operations

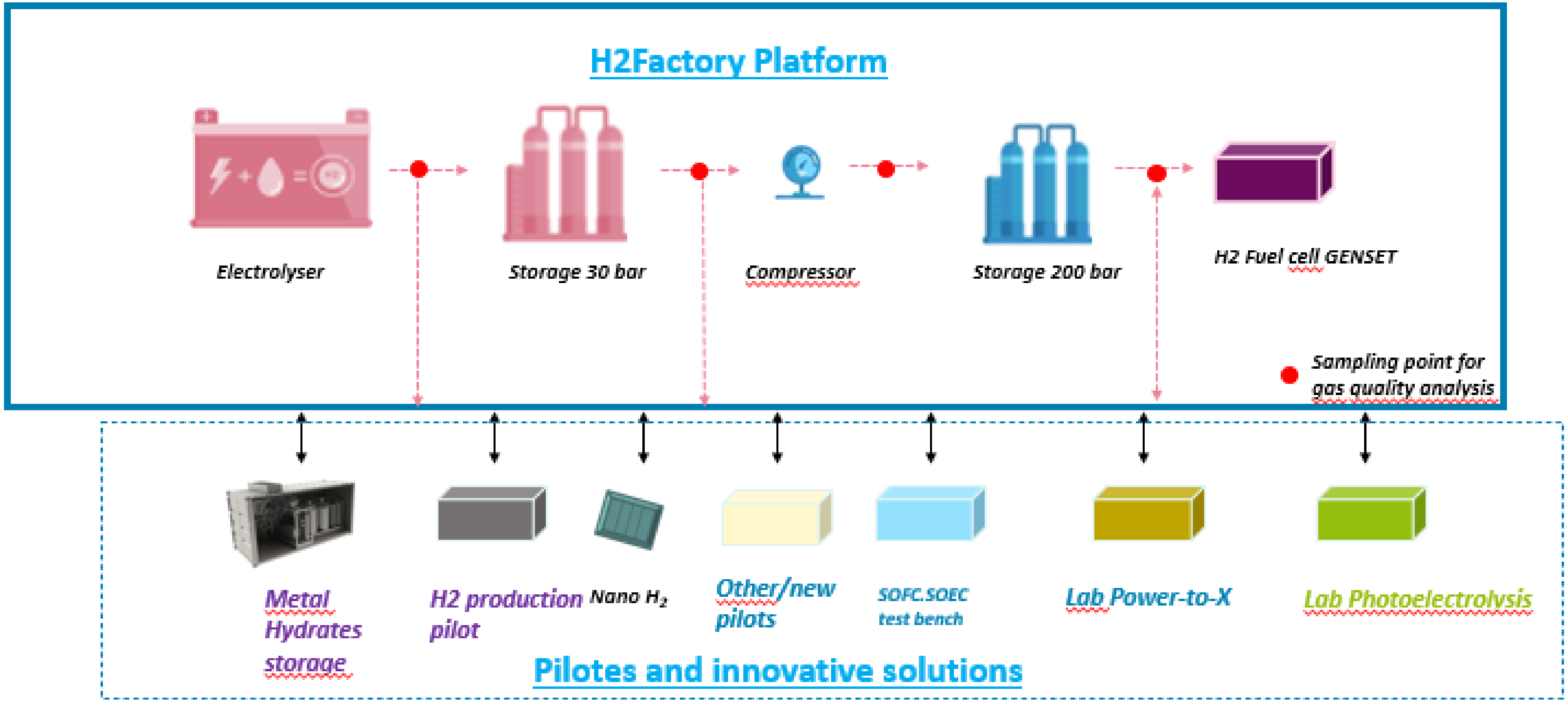
IDENTIFY, ASSESS AND INTEGRATE INNOVATIVE SOLUTIONS TO ANSWER THE NEW NEEDS OF OUR CLIENTS TOWARD A ZERO CARBON TARGET

- Green Hydrogen for industrials
- Green Hydrogen mobility
- Green Hydrogen for territories

VALORIZE EXISTING INFRASTRUCTURES BY PROVIDING ENERGY TRANSITION SOLUTIONS TO ASSETS OWNERS

- Power to Gas
- Networks conversion with hydrogen injection

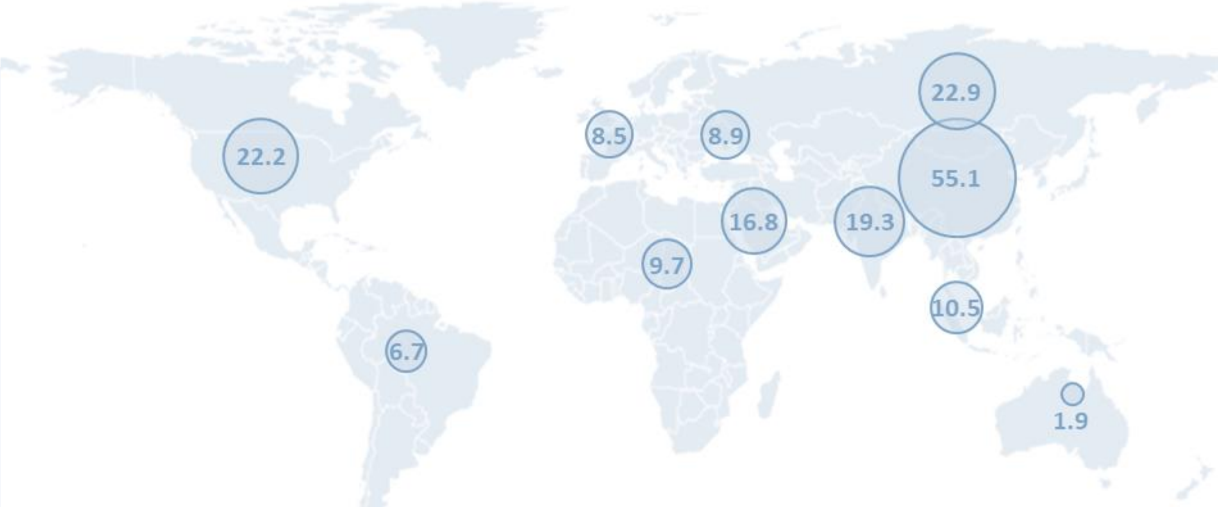
H2FACTORY : a R&D platform for innovative solutions developing and testing



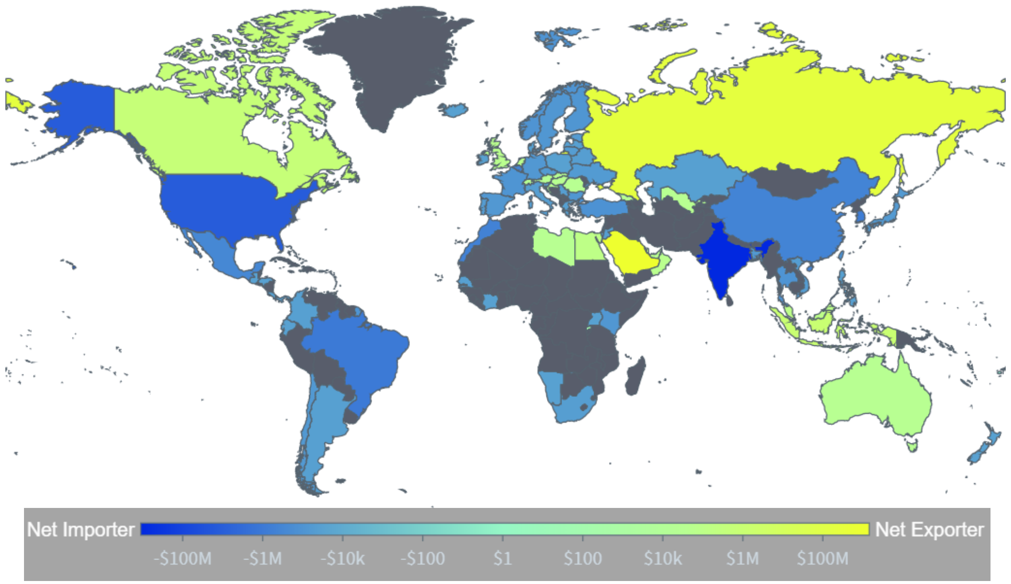
1. Ammonia production today

Ammonia Market Key Insights

- Ammonia is captively consumed on-site. Still, there is a significant merchant market (around 17.5 Mt or 5.35B€ in 2019).
- Ammonia trade routes are dictated by countries with lower-cost gas.
- Gross production reached 182 Mt in 2020 with a third located in northeast Asian countries.
- Europe is a net importer of ammonia with Belgium (242M€), Ukraine (162M€), Germany (147M€) and France (124M€) as top importers in 2019. Top exporters to EU are Russia, Trinidad and Algeria.
- In today's market, South America, Africa, East and South Asia are net importers of ammonia.
- In the last two decades, ammonia capacity has grown by a net capacity of 58 Mt. More than 190 new production lines were added. There is still an estimated 42 Mt spare capacity concentrated in the Northeast Asian region.



Ammonia gross production by region in 2020 (million tons) – Data: Argus Media



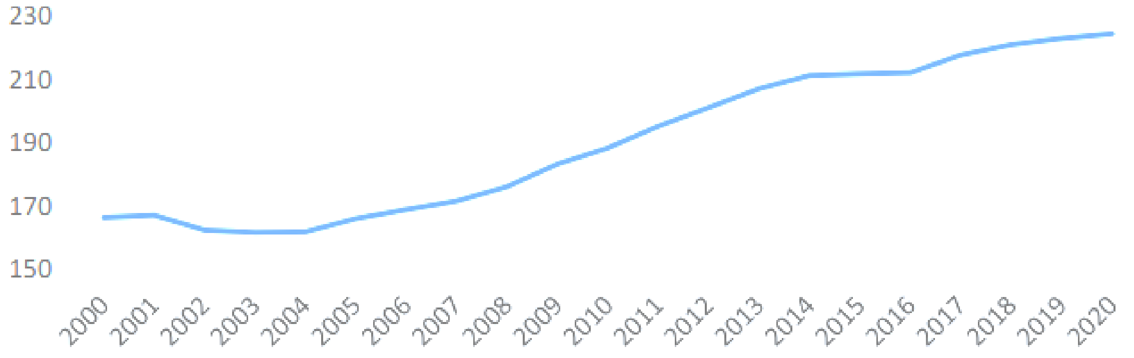
Net trade of Anhydorus Ammonia in 2019 – Source: World Bank

areNH$_3$a

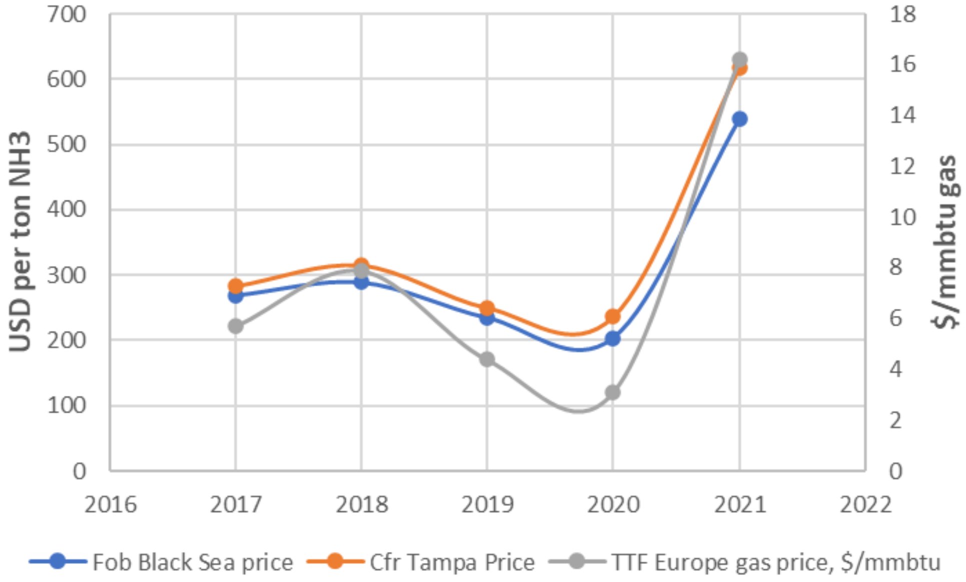
1. Ammonia production today

Ammonia Market Key Insights

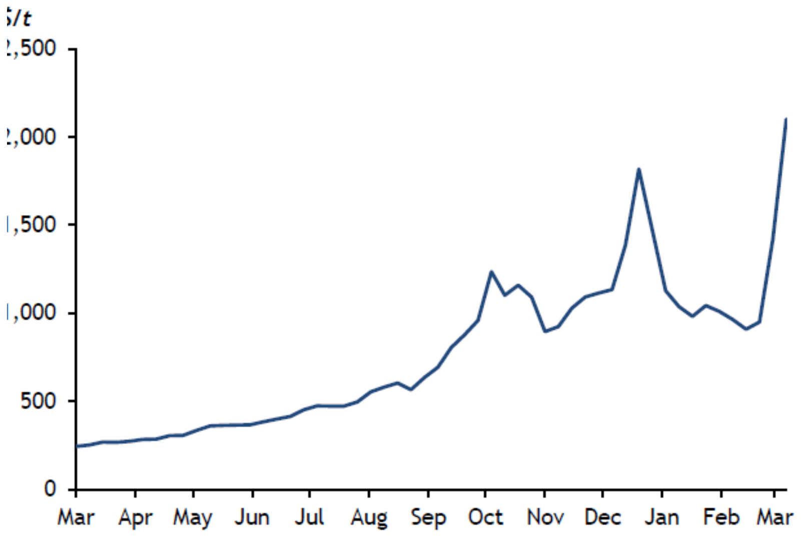
- Ammonia market is facing a supply disruption with the potential to affect global trade flows. Price volatility ahead.
- Spot trade is growing in relevance
- Discussion on evolution of pricing mechanisms to accompany expected demand in years to come (Argus Media 2022)
- Current prices: 118 €/MWh TTF (38,2 USD/mmbtu) gas and >1100 USD/ton NH3



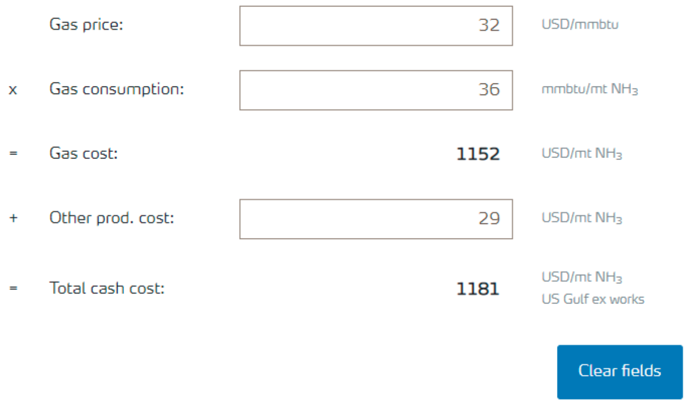
Ammonia growth in capacity for the last two decades (million tons) –Source Argus Media 2020



Ammonia and natural gas prices



European ammonia production costs – Source Argus Media 2022



Ammonia cost calculator – Source yara.com

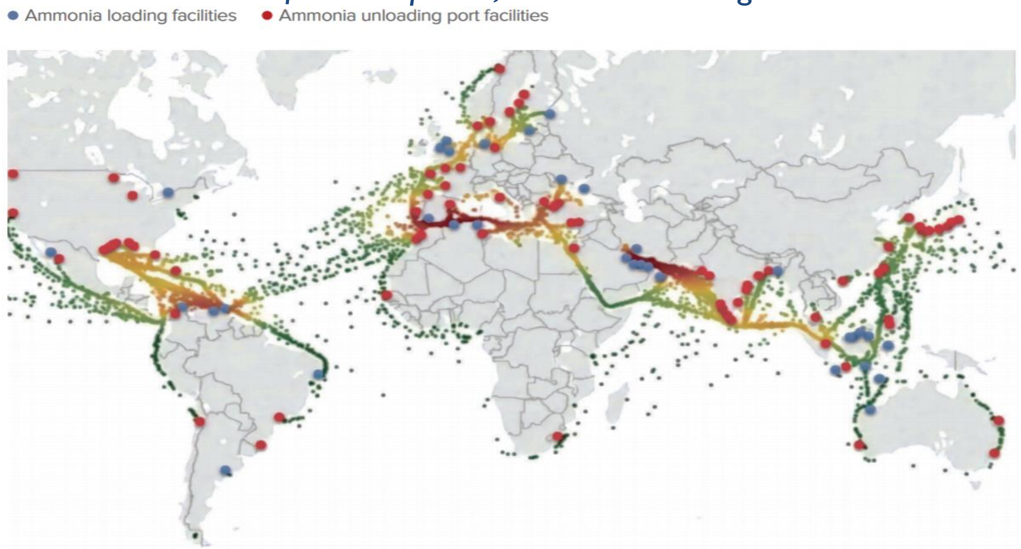
ENGIE Lab

II. Ammonia Infrastructure

Ammonia Infrastructure Key Insights

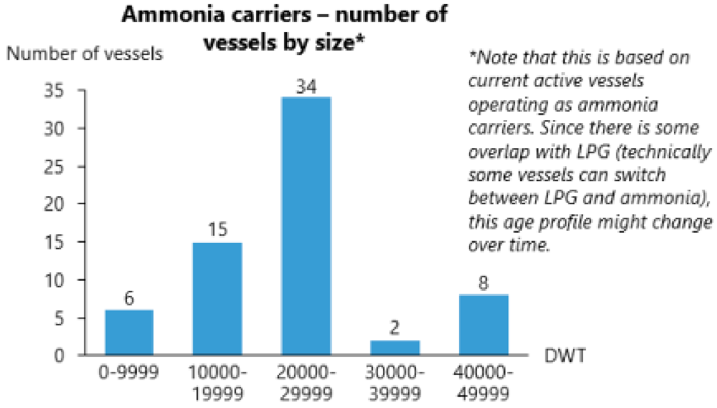
- The supply chain and logistical infrastructure for ammonia trade is mature and very well developed. Global maritime trade of ~18 million ton per year.
- Wide network of ports (over 120) and storage facilities worldwide that handle ammonia in large volumes, and international shipping routes are well-established.
- Ammonia transportation can be done by road, train and ship. As well as by pipeline (e.g., in the USA, 4,800 km of carbon steel pipes transport around 2 Mt/yr of ammonia).
- Over 200 lpg tankers that can take ammonia with >40 deployed with ammonia cargo at any point in time.

Global fertilizer plants, 2020 – Data: Argus Media



Ammonia shipping infrastructure, including a heat map of liquid ammonia carriers and existing ammonia port facilities – Source: The Royal Society, 2020

LPG tanker - Source gcaptain.com

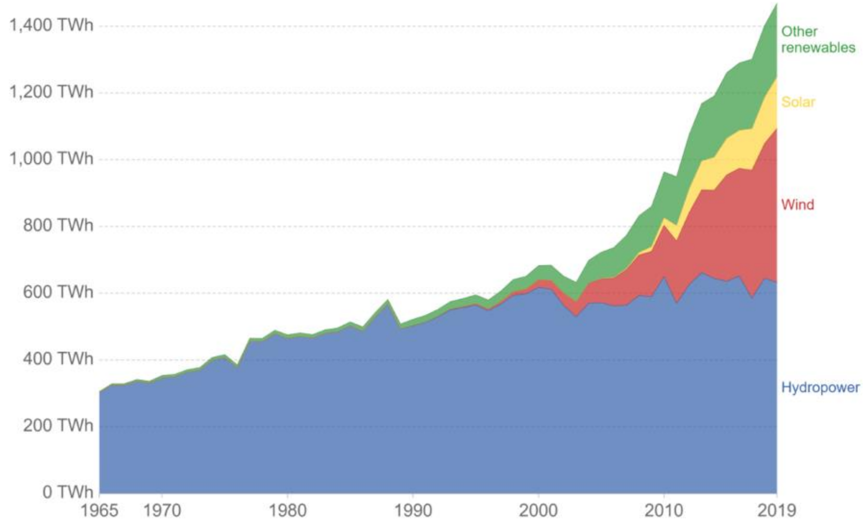


Global ammonia shipping fleet - Source Argus Media 2021

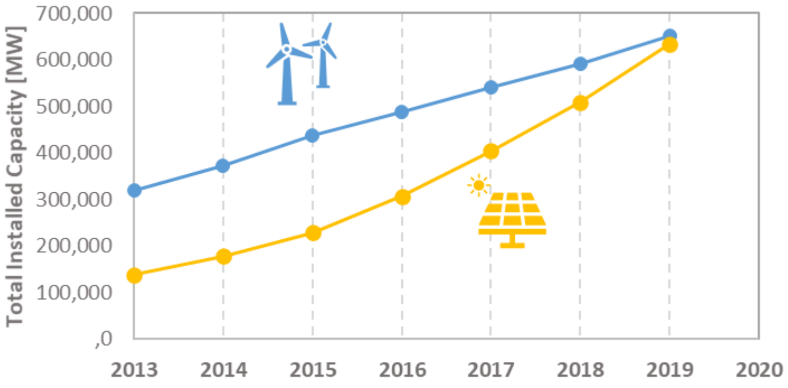
III. Green power to green ammonia

Renewable Energy Market Key Insights

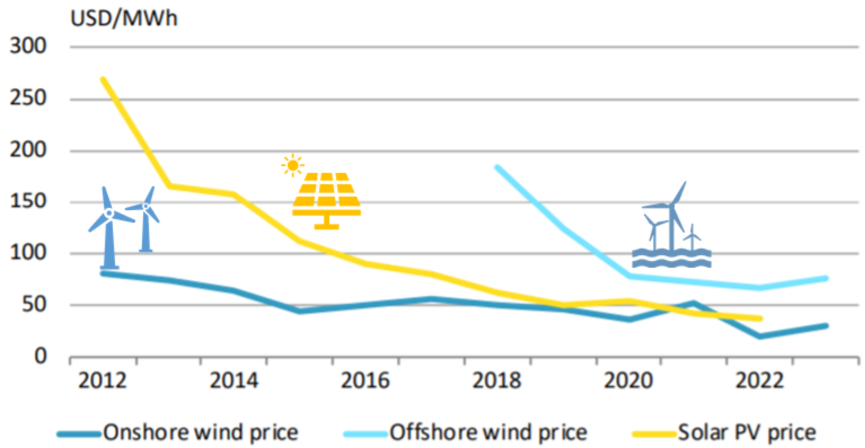
- **Solar power**: 634 GW of installed power as of 2019. Led by China (32%), USA(12%) and Japan (10%). PV's growth is exponential with a rate of 20 to 30% per year (124 GW of added capacity in 2019).
- **Wind power:** 650 GW of installed power as of 2019. Led by China (36%), USA (16%) and Germany (9.5%). Global wind power is witnessing a steady growth rate of 10% per year (60 GW of added capacity in 2019).
- Europe is no exception, with a strong growth of wind energy.
- The cost decline of solar and wind power opens new possibilities for global decarbonization through electrification of energy end-uses directly of via hydrogen production by electrolysis.



Installed capacity of Renewable energy in EU – Source: BP statistical review of Global energy



Global wind and solar installed power – Source wwindea.org Statista 2021



Average auction prices by commission dates – Source: IEA 2017

III. Green power to green ammonia

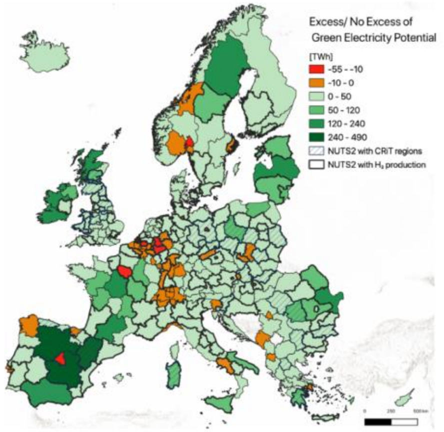
Offshore Wind Markets Key Insights

- In Europe, the estimated potential of offshore wind resource ranges between 600 and 1,350 GW for a cost of 50 to 65€/MWh.
- By 2030, the potential of offshore wind could possibly represent between 80% and 180% of the EU's total electricity demand.
- Higher technical potential is located at >20 km, this creates high associated transmission over-costs if undersea cables are used.

Curtailment Key Insights

- EU countries with large shares of intermittent renewables and low interconnection capacity will heavily rely on the adoption of energy storage solutions.
- While enhancing grid interconnections is a tool to improve renewable electricity integration, large-scale energy storage is a cornerstone to leverage the high offshore wind potential in Europe.
- The German case: Germany relies on 40 GWh of pumped-storage power as the only seasonal storage solution. So

Curtailed renewable electricity in Germany– Source Tractebel ENGIE 2018

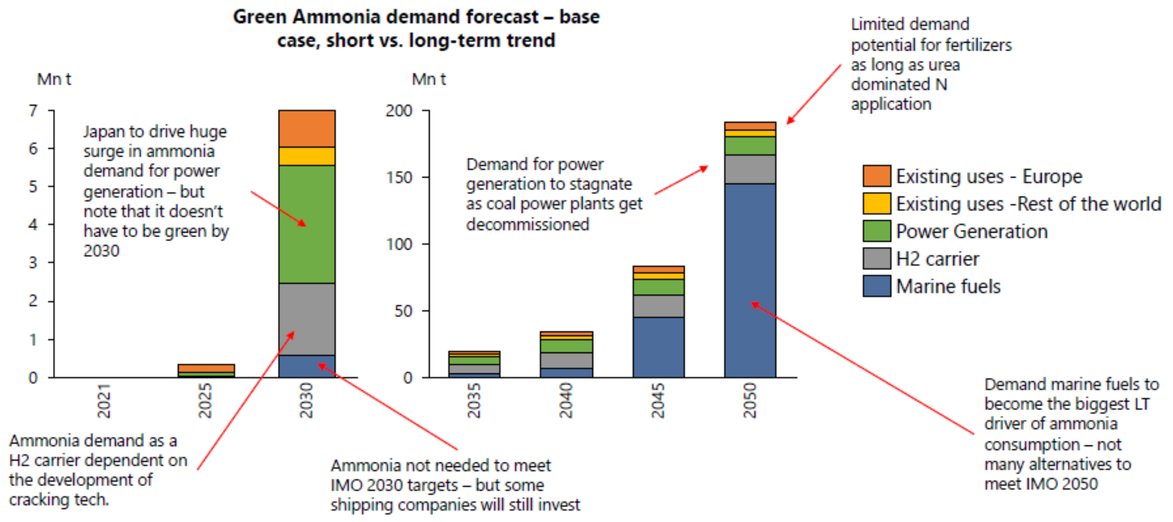


Regions with an excess or deficit of technical potential for green electricity after subtracting the current consumption for all sectors and that needed for moving from existing hydrogen production from grey to green– Source Kakoulaki et al. 2021

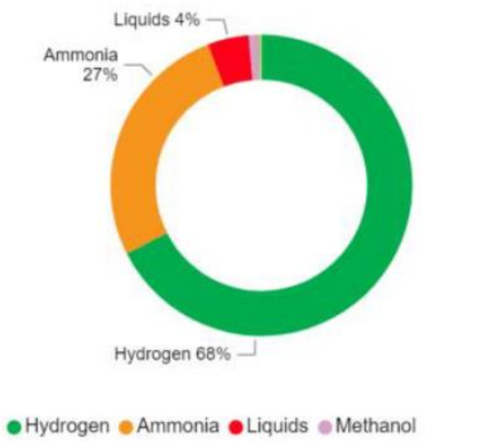
IV. Green ammonia production

Green Ammonia demand forecast key insights

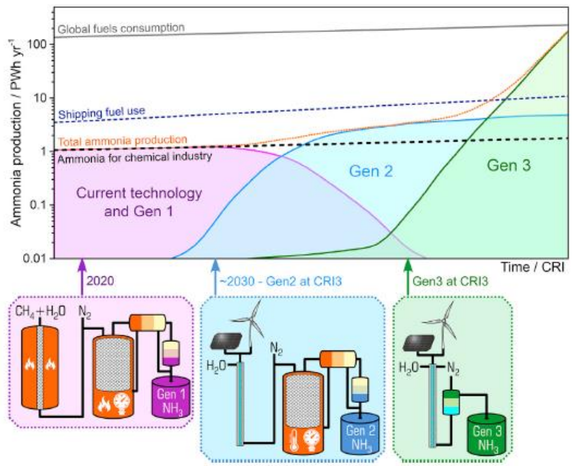
- >25% of currently intended electrolysis capacity is to be used in power-to-ammonia projects located mainly in Australia.
- Green ammonia will start on the short-term replacing existing uses and its projected to continue its expansion as H2 carrier and marine fuel.
- Current HB with or without carbon capture to continue the transition towards green electrolysis-based HB in the 2020's and 2030's. Electrochemical synthesis of ammonia represents the ultimate goal, but no commercial relevance before 2030/2040.



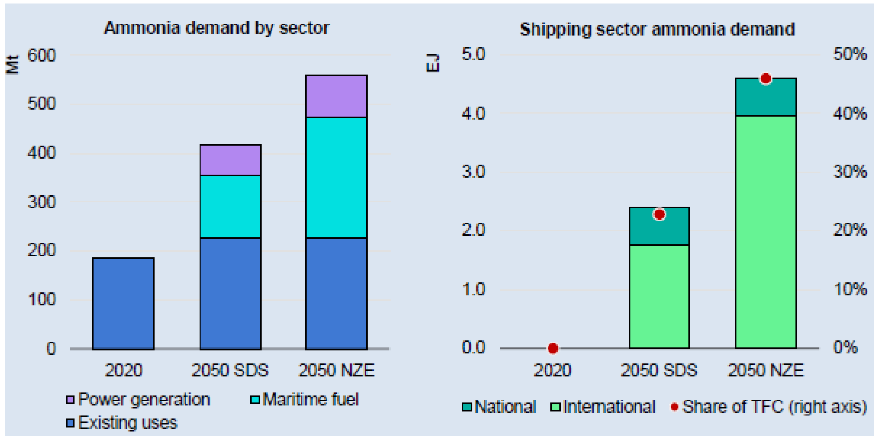
Green ammonia demand forecast - Source Argus Media 2021



Electrolysis capacity by end product - IHS Markit 2021



Ammonia economy roadmap by technology- Source: MacFarlane et al. 2020

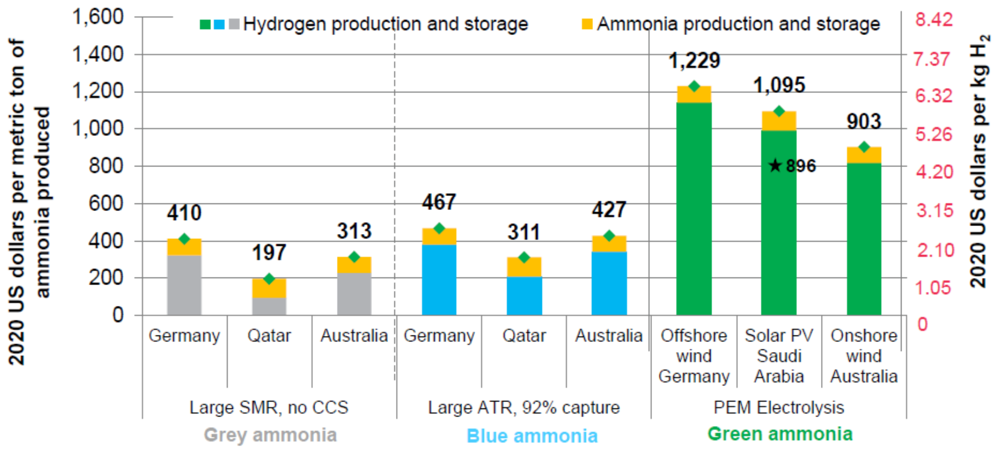


Ammonia use as energy carrier in SDS and NTE scenarios- Source: IEA 2021

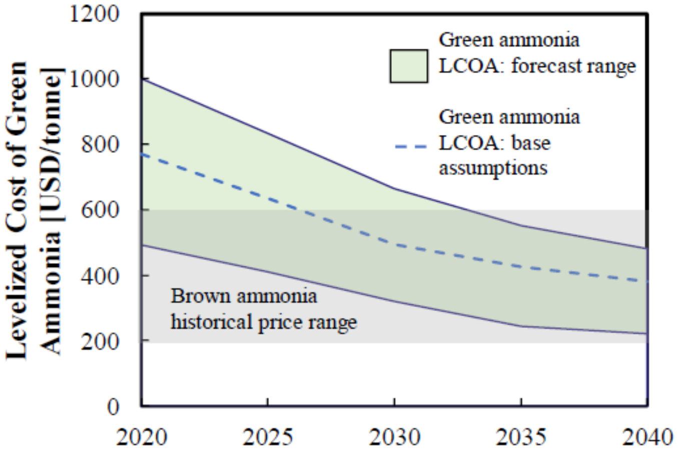
IV. Green ammonia production

Green Ammonia price key insights

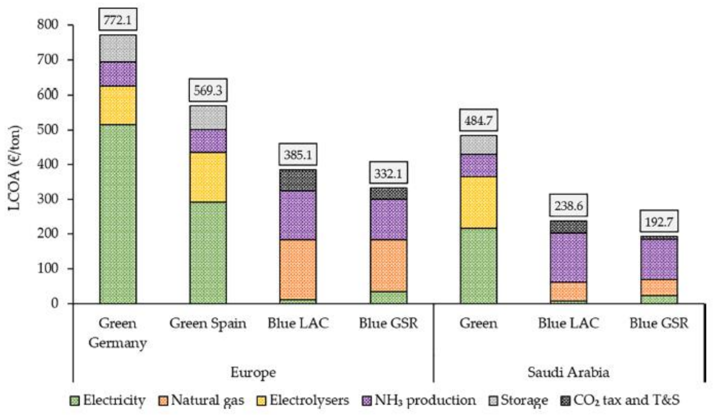
- Green ammonia costs are driven by green hydrogen costs, translated into electrolyzer CAPEX and electricity costs.
- Green ammonia is more geographically independent than blue ammonia, since no nearby underground storage or CO2 transportation
- Lower capital costs to come will enable to combine smaller scale ammonia production with remote renewable generation.
- More active HB catalysts must be developed to operate at lower temperature and absorption enhanced HB can lead to lower pressure
- SOEC can be coupled to HB synthesis to profit from waste heat and increase energy efficiency. SOEC can also produce ammonia synthesis gas (H2+N2) directly.



Levelized cost of ammonia production for a ~2500 ton/day plant- Source: IHS Markit 2021



Green ammonia production cost foreast - Source: Cesaro et al. 2020

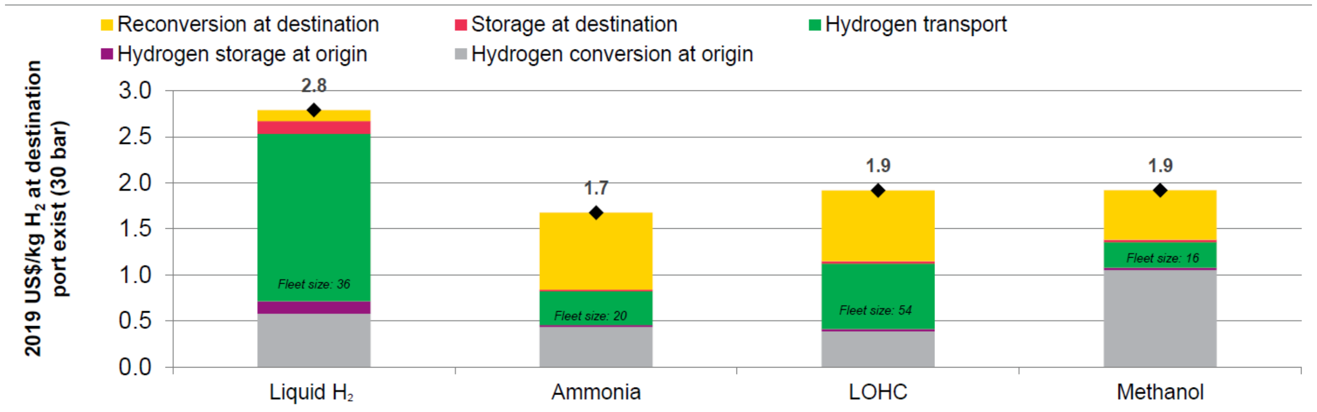


Comparison of green and blue ammonia by 2050 - Source: Arnaiz del Pozo et al. 2022

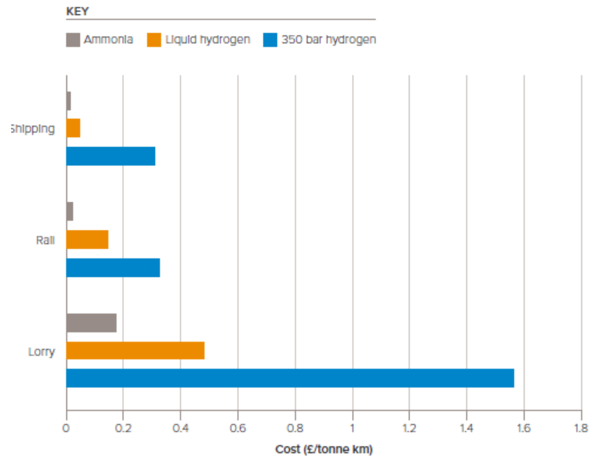
IV. Ammonia as hydrogen carrier

Hydrogen carrier key insights

- Ammonia contains more hydrogen per unit volume than liquid hydrogen itself., 120 kg H2/m3 $NH3_{liq}$ vs. 71 kg H2/m3 $H2_{liq}$
- Liquified hydrogen and ammonia are still competing as hydrogen transport alternatives
- Tankers for ammonia transport exist (LPG tankers), for liquified H2 transport they do not (first one in 2021, Suiso Frontier)
- Cost structures are different: Low transportation cost but high conversion and reconversion costs for ammonia vs low reconversion cost but high liquefaction and transport cost for liquified hydrogen.
- If Ammonia can be used directly avoiding reconversion to hydrogen, it becomes even more competitive compared to hydrogen.
- Maritime industry in Norway and power industry in Japan are driving development of direct use of ammonia as fuel.



Hydrogen transportation cost by ship to supply 2500 tons/day over 12000 km (Qatar to Germany) via 50 000 m3 ships
Source: IHS Markit 2021



Estimated costs for transport of hydrogen & ammonia-
Source: Royal Society 2020

IV. Ammonia as hydrogen carrier

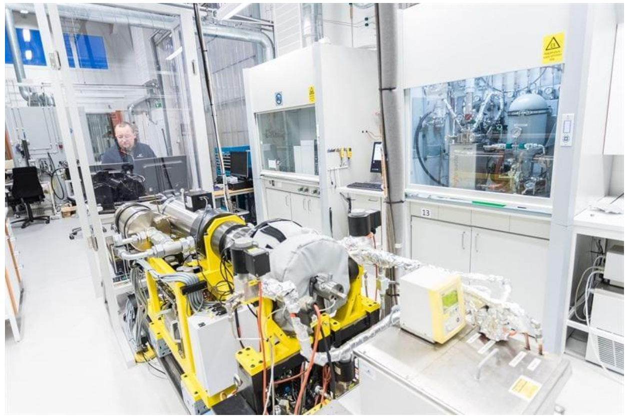
Hydrogen carrier key insights

- Hydrogen is a versatile energy vector that can find applications in all end-use sectors: residential and commercial, industry, power generation and transport
- Ammonia could eventually compete with hydrogen depending technology development in the coming decades
- Direct use of ammonia as final energy is technically possible. it is being tested at multi-MW scale and could quickly catch up with hydrogen
- The direct use of ammonia is possible both electro-chemically (fuel cells) and thermo-chemically (combustion: ICEs and GTs). SOFC is the most likely technology to be developed. NH3 or NH3/H2 or blends in GT's.

Process	Efficiency of ammonia or hydrogen production (renewable power from wind & solar)	Efficiency of application	Overall efficiency
Ammonia from electrolysis and Haber-Bosch, used with a **solid oxide fuel cell** to produce electricity	55 to 60%	50 to 65%	28 to 39%
Ammonia from electrolysis and Haber-Bosch burned in an **internal combustion engine**	55 to 60%	30 to 40%	17 to 24%
Hydrogen cracked from ammonia obtained by electrolysis and Haber-Bosch, and used in a **PEM fuel cell**	40 to 50%	40 to 50%	15 to 25%
Hydrogen from electrolysis and used in a **PEM fuel cell**	65 to 70%	40 to 50%	26 to 35%

Modelled efficiencies for energy provided from primary electricity - Source: Royal Society 2020

Mitsubishi Power's H-25 Series gas turbine - Source: powermag.com

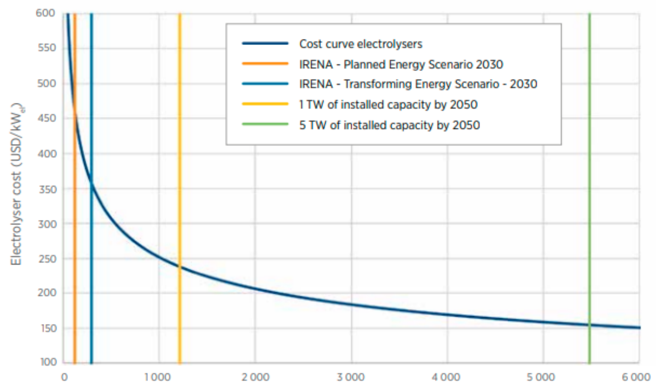


Wärtsilä ammonia SOFC tests - Source: gcaptain.com

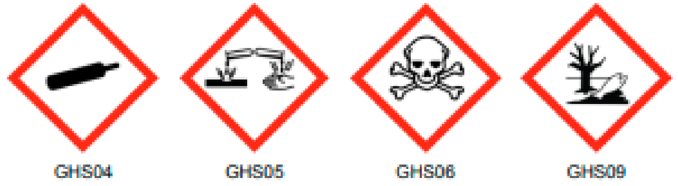
IV. Ammonia as hydrogen carrier

Challenges key insights

- Upfront investment costs and existing capacity of fossil-fuel based ammonia production could slow the implementation of green ammonia plants
- Market uncertainties as current predictions can in some cases vary between sources. Example predictions on use of ammonia as shipping fuel vary from 25% to 99% of the market.
- Electrolysis scale up and cost reduction: shared challenge with H2 market and other efuels. Many stakeholders pushing forward
- HB synthesis technologies development to scale down, face variability and contribute to cost reduction
- Ammonia cracking need to developed along with ammonia synthesis, goal to maximize efficiency
- Ammonia safety aspects of the use of ammonia as fuel: experience needs to be developed on new risk scenarios for this new application of the chemical to develop/update guidelines, protocols, procedures and thresholds of exposure as well as safety training.
- Regulatory framework likely must be developed and unified with existing standards and this both at national & international levels
- Erosion of revenue streams due to alternative efuels/hydrogen carriers such as methanol/DME/LOHCs



Potential cost decrease for electrolyzers- Source: Irena 2020



Ammonia hazard pictograms

PPE for Ammonia handling - Source: Fertilizer Canada code of practice 2022

V. Conclusions

- Ammonia offers an important potential to allow renewable energy storage as H_2 storage, representing a carbon free alternative to other chemical alternatives and with lower estimated transportation costs than liquefied hydrogen or other e-molecules.
- Interest in green ammonia as a hydrogen carrier boomed in 2020, especially for export-oriented investments. Following two key sectors announcements: maritime and power generation
- A rapid increase of NH_3 shipping demand alone will require additional annual production capacity and several NH_3 production plants going online every year up to 2050.
- Current HB with or without carbon capture to continue the transition towards green electrolysis-based HB in the 2020's and 2030's. Electrochemical synthesis of ammonia represents the final goal, but no commercial relevance before 2030/2040.
- In ARENHA project partners are involved in several technological developments all along the ammonia value chain to develop solutions for implementation of ammonia energy storage.

Expected impact when using ammonia for H2 storage

First Workshop ARENHA project, ENGIE Lab CRIGEN, 07-04-2022

Thank you for your attention

Website project: https://arenha.eu/

Contact: alvaro.ramirezsantos@engie.com