RESEARCH AND GUIDANCE FROM HSE

Use of ammonia in the maritime sector

Possible future developments, knowledge gaps in atmospheric dispersion, and summary of recent risk studies

Simon Gant and Mike Wardman

26th Annual George Mason University Conference on Atmospheric Transport and Dispersion Modeling, 26-28 July 2022

Research - HSE funded to provide evidence which underpins its policy and regulatory activities
Guidance - freely available to help people comply with health and safety law

Overview

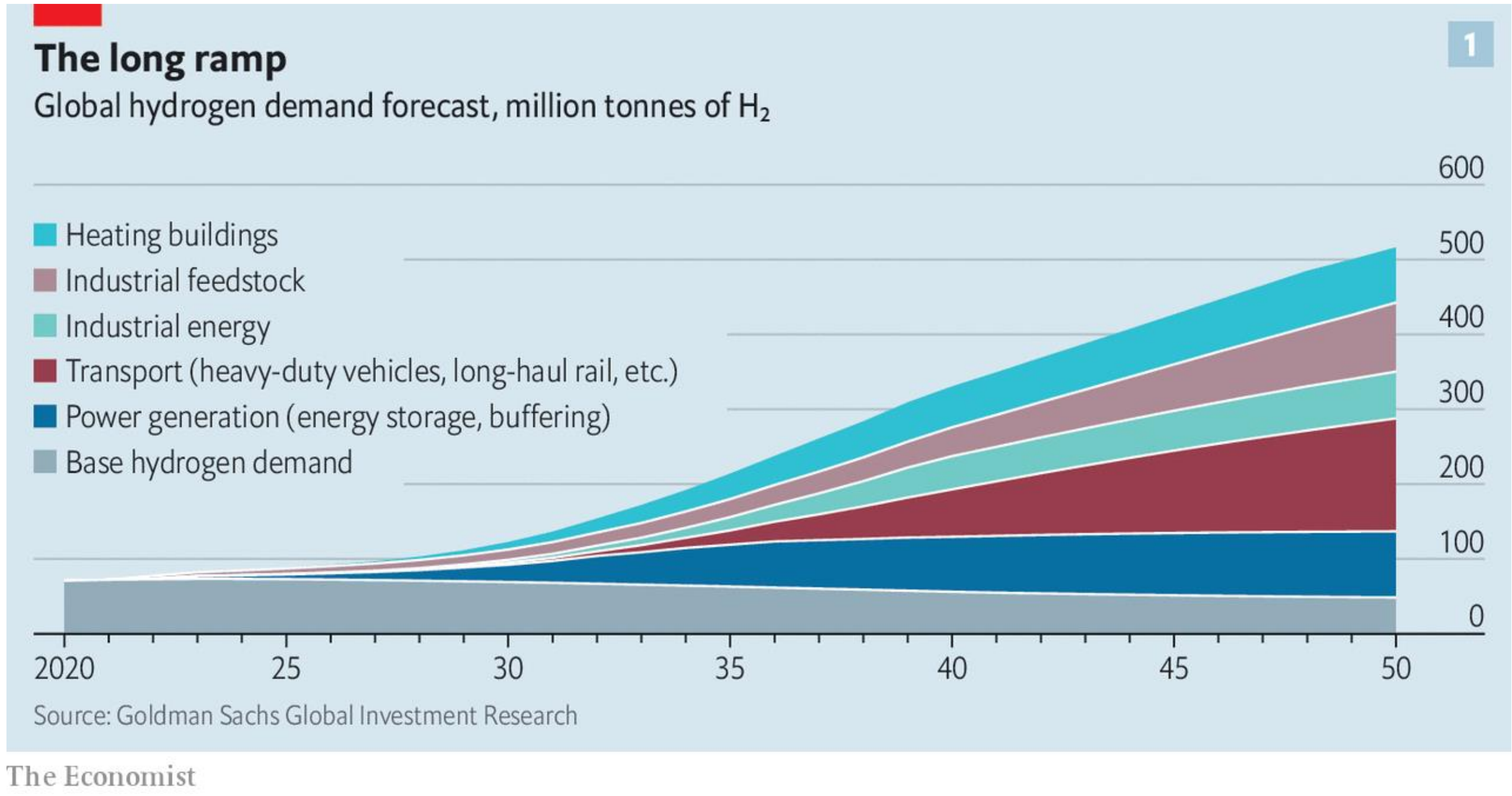
- Current international policy and industry drivers for the growth of ammonia in the maritime sector
  - Bulk transport of ammonia (energy vector, fertilizer, chemical feedstock, refrigerant etc.)
  - Ammonia as a shipping fuel

- Scientific knowledge gaps related to atmospheric dispersion of ammonia
  - In particular, related to ammonia spills on/into water

- Recent/ongoing safety and risk studies around the world on maritime transport of ammonia and its storage at ports

Hydrogen: Present and Future

- Net Zero carbon dioxide emissions by 2050 will likely require a significant increase in the use of hydrogen from clean energy sources in the coming years



https://www.economist.com/briefing/2021/10/09/creating-the-new-hydrogen-economy-is-a-massive-undertaking

- To transport this hydrogen, ammonia is emerging as a potential hydrogen vector

Hydrogen and ammonia supply chain

- For bulk transport by ship over large distances: reported to be cheaper to produce ammonia from hydrogen (NH_3 Haber-Bosch process) and transport liquefied ammonia than to transport liquid hydrogen[1]
  - Liquefied ammonia has higher volumetric energy density than liquefied hydrogen and fewer issues with boil-off
  - Cheaper to import green hydrogen from the Middle East as ammonia than produce green hydrogen in the UK?[2]
- Stored ammonia could potentially be cracked to hydrogen and fed into gas grid, or used in fuel cells to produce electricity, with waste nitrogen released to air[4] (cracking ammonia takes >13% of stored energy)[5]
- Ammonia could potentially also be used for balancing peak electrical demand when renewable energy sources cannot meet demand and for seasonal energy storage (like LNG peak shaving)[5]
- Ammonia currently produced/stored/shipped in large quantities (180 Mt produced, 18-20Mt shipped)[5]
  - Existing technologies, standards, procedures available for bulk handling of ammonia
- Ammonia seen as promising option for decarbonising shipping fuel (alternatives: methanol, hydrogen)
- Research ongoing for engines burning ammonia (however, potential issues with NOx and ammonia emissions; also requires change to IGC shipping fuel code[6])

For comparison, 30-40% of the energy content of hydrogen is required to liquefy it[2], although research on liquid hydrogen (LH_2) is ongoing on to prove the viability of shipping LH_2, e.g., Suiso Frontier first shipment of LH_2 from Australia to Japan in Feb 2022

	Hydrogen	Ammonia
Boiling point	-253°C	-33°C
Energy density[3] (cryogenic liquid)	9 MJ/litre	16 MJ/litre

1 https://doi.org/10.1039/D1SE00345C https://doi.org/10.1016/j.isci.2021.102903
2 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/880826/HS420_-_Ecuity_-_Ammonia_to_Green_Hydrogen.pdf
3 https://www.ammoniaenergy.org/articles/ammonia-for-power-a-literature-review/
4 https://www.gencellenergy.com/
5 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf
6 https://www.ics-shipping.org/wp-content/uploads/2021/07/MSC-104-15-9-Development-of-non-mandatory-guidelines-for-safety-of-ships-using-ammonia-as-fuel-Japan-Singapore-ICS-and....pdf

Hydrogen and ammonia supply chain

- Examples of media articles on shipping costs for ammonia and hydrogen
  - Research is ongoing to reduce cost of shipping hydrogen

'More than 85% of export-oriented low-carbon hydrogen projects plan to ship ammonia, not H2'

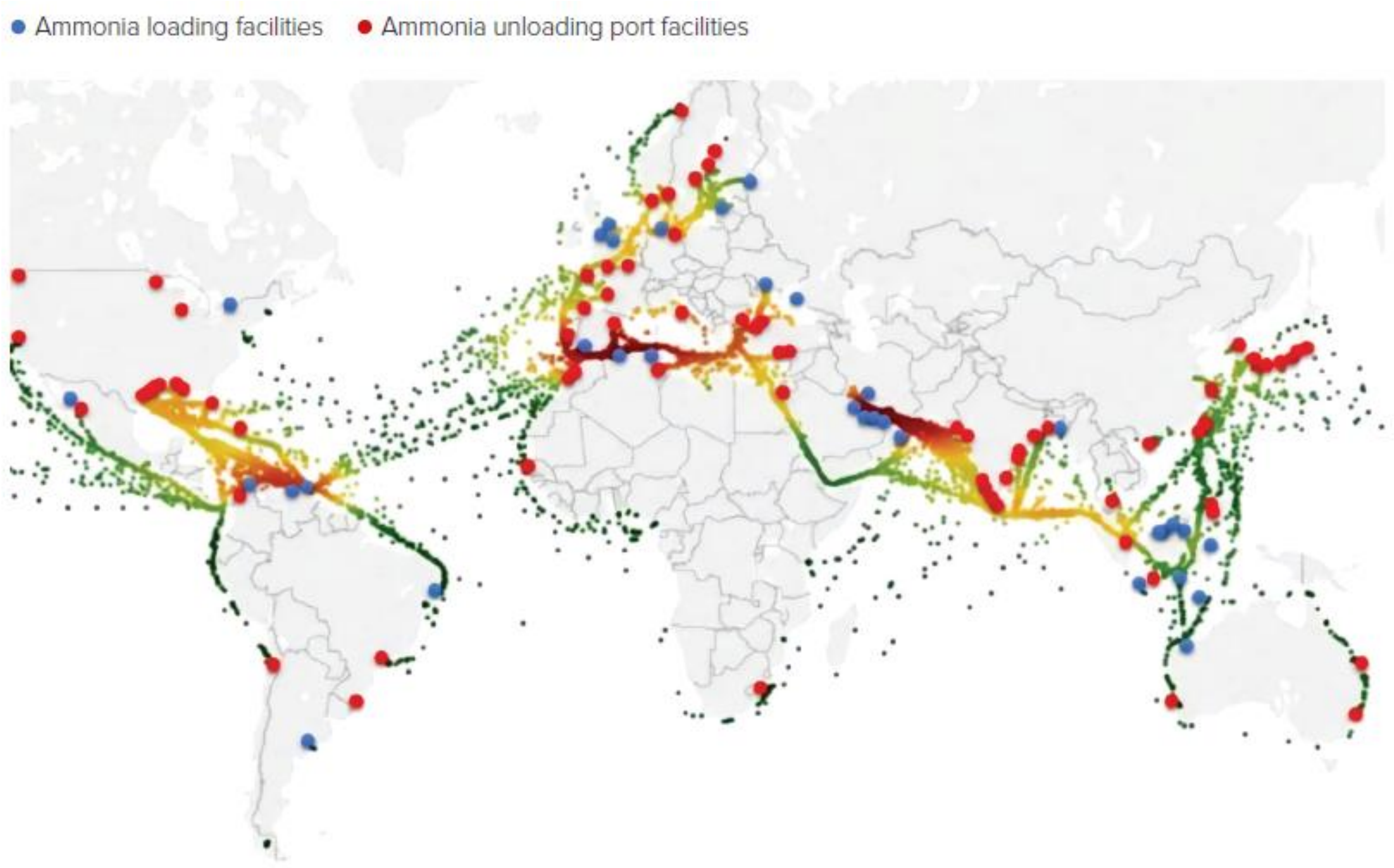
Green NH3 is emerging as the hydrogen carrier of choice, but it's not without its challenges, writes Noel Tomnay, global head of hydrogen consulting at energy analyst Wood Mackenzie

https://www.rechargenews.com

'Shipping green hydrogen to the EU will be too expensive, but importing green ammonia would be cheaper than producing it locally'

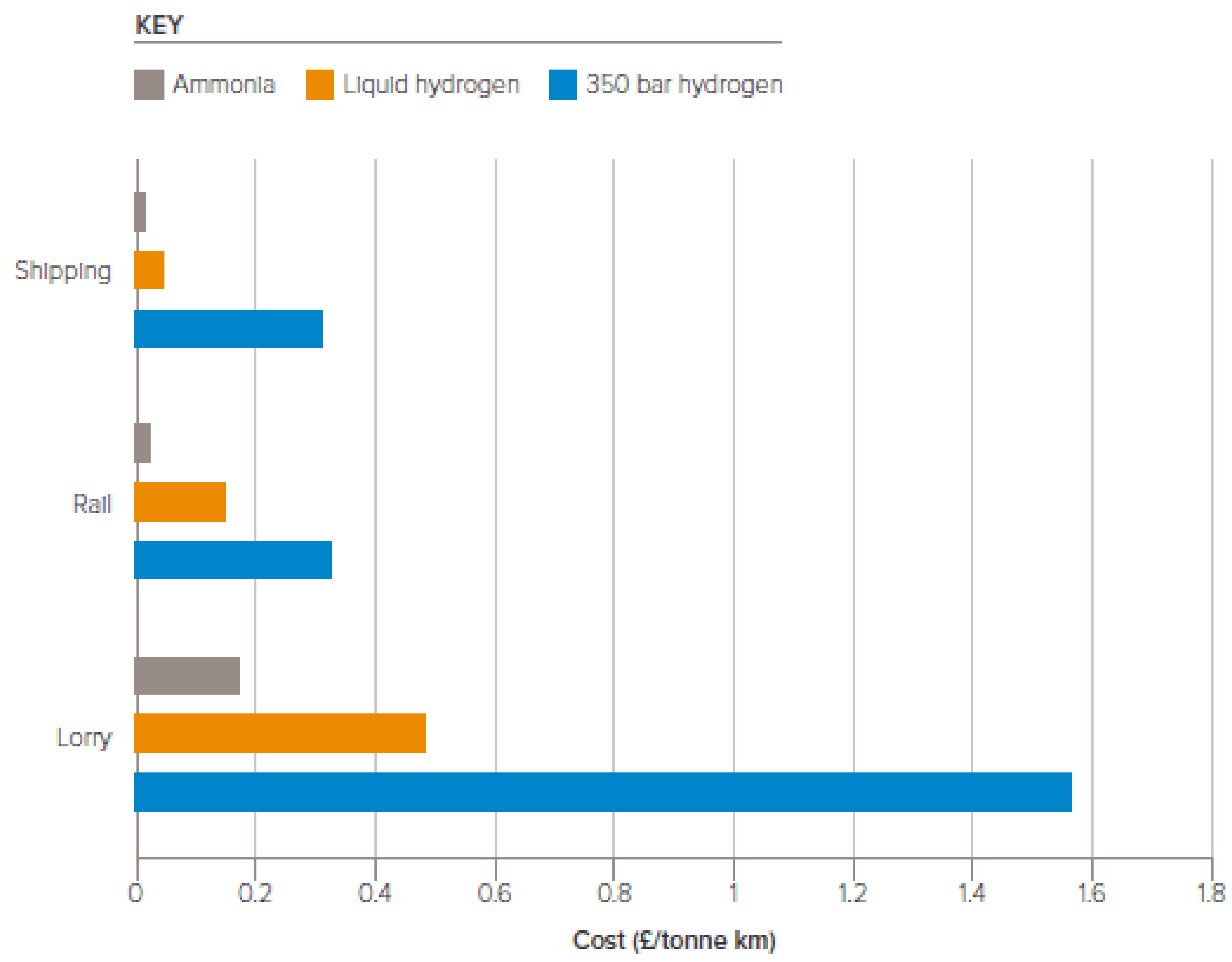
High shipping costs rule out importing low-cost H2 from places such as Chile and Australia, but the opposite is true for hydrogen derivatives, says think-tank report

Heat map of liquid ammonia carriers and existing ammonia port facilities (2017)



https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

Estimated costs for transport of hydrogen and ammonia by lorry, rail and ship[34].



34. ACIL Allen Consulting. 2018 Opportunities for Australia from Hydrogen Exports. See https://www.acilallen.com.au/projects/energy/opportunities-for-australia-from-hydrogen-exports (accessed 23 May 2019).

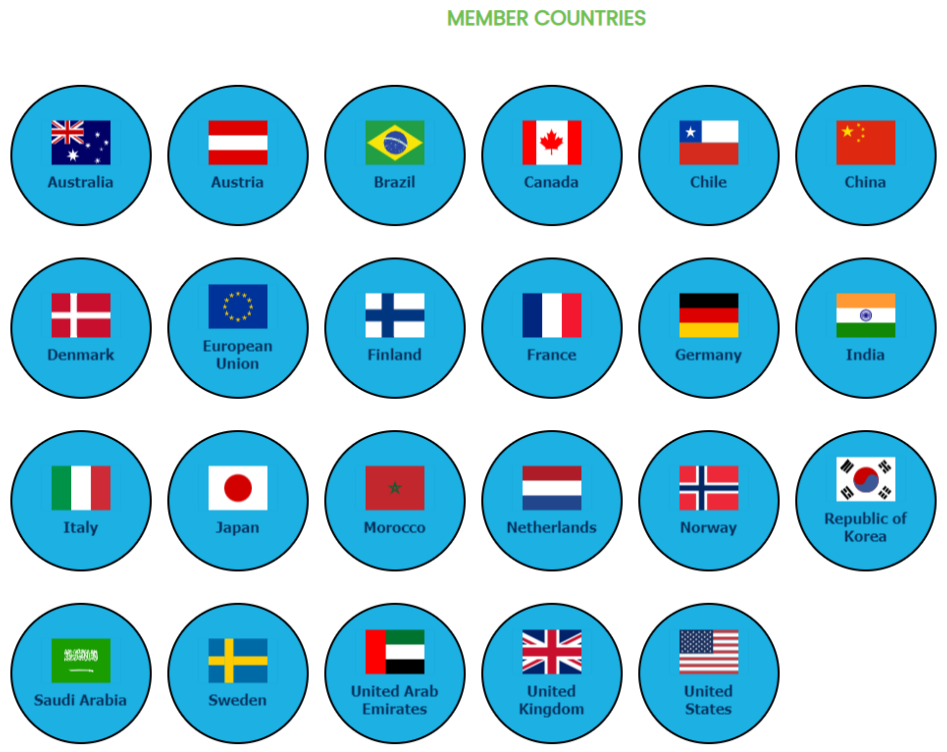
International Policy Drivers for Ammonia as Shipping Fuel

- Shipping industry responsible for 2-3% of the world's total CO_2 emissions[1]
  - And by 2050 these emissions are projected to increase by 90-130% from 2008 levels, assuming no new policies[4]
- International Maritime Organization (IMO) adopted in 2018 an initial greenhouse gas strategy[2]
  - Reduce CO_2 emissions by at least 40% by 2030 and 50% by 2050 compared to 2008 emissions
  - Dates when measures come into force will be defined in 2023
  - Recognition that global introduction of alternative fuels and/or energy sources will be necessary
- New legislation from European Commission[1] adopted in July 2021
  - Slow progress by IMO triggered the EU to take action on maritime transport
  - Emissions trading scheme extended to maritime transport and energy taxes revised
  - Max limit set on greenhouse gas content of energy used by ships calling at EU ports
  - Support for alternative fuel infrastructures at maritime and inland waterways, and supply of renewables
- COP26 Clydebank Declaration[3], November 2021
  - Aim for six zero-emission green maritime routes between international ports by mid-2020s
  - Signatory countries committed to support establishment of green shipping corridors
  - 24 signatories including: USA, UK, Australia, Netherlands, France, Italy, Denmark, Norway, Singapore

1 https://ec.europa.eu/clima/eu-actions-transport-emissions/reducing-emissions-shipping-sector_en
2 https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx
3 https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors
4 https://climateactiontracker.org/sectors/shipping/imo-policies-action/

Mission Innovation: Zero-Emission Shipping

MISSION INNOVATION
accelerating the clean energy revolution



Mission Innovation

- Global initiative of 22 countries and EU to catalyse action and investment in clean energy
- Launched alongside the Paris Agreement in 2015

Announcement of zero-emission shipping roadmap by Jennifer Granholm, US Secretary of Energy, June 2021

https://www.youtube.com/watch?v=hieC4eVqQZ0

ZERO-EMISSION SHIPPING MISSION

APRIL 2022
1ST EDITION

INDUSTRY ROADMAP FOR ZERO-EMISSION SHIPPING

MISSION INNOVATION BEYOND 2020

Challenges and opportunities

A paper by the MI Secretariat on the clean energy innovation landscape for input into discussions about the role and priorities of Mission Innovation beyond 2020

Shipping is likely to favour direct drop-in alternatives for existing engines, with hydrogen (e.g. stored in liquid organic hydrogen carriers) and ammonia likely to dominate in the long-term.[58]

The Zero-Emission Shipping Mission is an ambitious alliance between countries, the private sector, research institutes, and civil society to develop, demonstrate, and deploy zero-emission fuels, ships, and fuel infrastructure together by 2030 and make zero-emission ocean going shipping the natural choice for ship owners. This will lay the foundation for a zero-emission shipping future and accelerate progress towards net zero pathways.

In terms of ***Safety & operational risk management***, the analysis pinpoints the safety concerns and considerations to be prioritized for the respective fuels, including: mitigating concerns on the flammability; low activation and ignition energy of hydrogen; safety considerations associated with the bunkering and handling of ammonia; NO_x standards associated with biofuels; methane emissions standards;

http://mission-innovation.net/wp-content/uploads/2022/04/Zero-Emission-Shipping-Mission-Roadmap-1-1.pdf

NB. Concerns about ammonia as a “drop-in” fuel, due to toxic risks

http://mission-innovation.net/wp-content/uploads/2019/12/B2020-paper-publish-FINAL.pdf

UK Policy Drivers and DNV Forecast

By 2025 we expect that:

i. All vessels operating in UK waters are maximising the use of energy efficiency options. All new vessels being ordered for use in UK waters are being designed with zero emission propulsion capability.

ii. Zero emission commercial vessels are in operation in UK waters.

iii. The UK is building clean maritime clusters focused on innovation and infrastructure associated with zero emission propulsion technologies, including bunkering of low or zero emission fuel.

By 2035 we expect that:

iv. The UK has built a number of clean maritime clusters. These combine infrastructure and innovation for the use of zero emission propulsion technologies. Low or zero emission marine fuel bunkering options are readily available across the UK.

- Under the assumptions made in the research, ammonia is estimated to be more cost-effective than methanol or hydrogen for most ship types.

July 2019

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf

It is hard to identify clear winners among the many different fuel options across all scenarios, but ammonia (electro-based and 'blue') and bio-based methanol are the most promising carbon-neutral fuels in the long run.

https://eto.dnv.com/2021/maritime-forecast-2050/about

Climate Change Committee

CCC is an independent statutory body established under Climate Change Act 2008 that advises UK Government ministers

The Sixth Carbon Budget

Shipping

- **Options for reducing emissions**. Mitigation options considered include improvements in vessel efficiency (including electricity), and use of zero-carbon fuels (principally ammonia made from low-carbon hydrogen) to displace fossil marine fuels.

https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Shipping.pdf

Growth in Green Ammonia Production Projects

AIR PRODUCTS Gas Supply

05/26/2022 | LEHIGH VALLEY, PA; MUSCAT, OMAN; AND RIYADH, KINGDOM OF SAUDI ARABIA

Air Products, OQ and ACWA Power Sign Joint Development Agreement Toward World-Scale Green Hydrogen-Based Ammonia Production Facility in Oman

Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets

https://www.airproducts.com/news-center

"The world needs clean energy and hydrogen is a key to meeting this need. Green and blue ammonia is the critical enabler for storage and transport of hydrogen and thus has a major role to play. Our commitment to decarbonize the world's largest ammonia production network positions CF Industries at the forefront of clean ammonia and hydrogen supply."

—

Tony Will President and Chief Executive Officer CF Industries

https://www.cfindustries.com/who-we-are/clean-energy-economy-opportunity

Nutrien Announces Intention to Build World's Largest Clean Ammonia Production Facility

Evaluating existing Geismar, Louisiana site to produce 1.2 million tonnes of clean ammonia annually

SASKATOON, Saskatchewan--(BUSINESS WIRE)-- Nutrien Ltd. (TSX and NYSE: NTR) announced today that it is evaluating Geismar, LA as the site to build the world's largest clean ammonia facility. Building on the company's expertise in low-carbon ammonia production, clean ammonia will be manufactured using innovative technology to achieve at least a 90 percent reduction in CO_2 emissions. The project will proceed to the front-end engineering design (FEED) phase, with a final investment decision expected to follow in 2023. If approved, construction of the approximately US$2 billion facility would begin in 2024 with full production expected by 2027.

https://www.nutrien.com/investors/news-releases/2022-nutrien-announces-intention-build-worlds-largest-clean-ammonia

Queensland advances green hydrogen and ammonia project to be powered by renewables

Queensland's deputy premier Steven Miles said the project could create more than 550 jobs during a phased construction and about 140 ongoing jobs. Photograph: Darren England/AAP

The Queensland government has granted coordinated project status to a $4.7bn proposal to build a green hydrogen and ammonia plant in Gladstone, where climate transition plans are being pitched as saviour projects.

https://www.theguardian.com/australia-news/2022/apr/12/queensland-advances-green-hydrogen-and-ammonia-project-to-be-powered-by-renewables

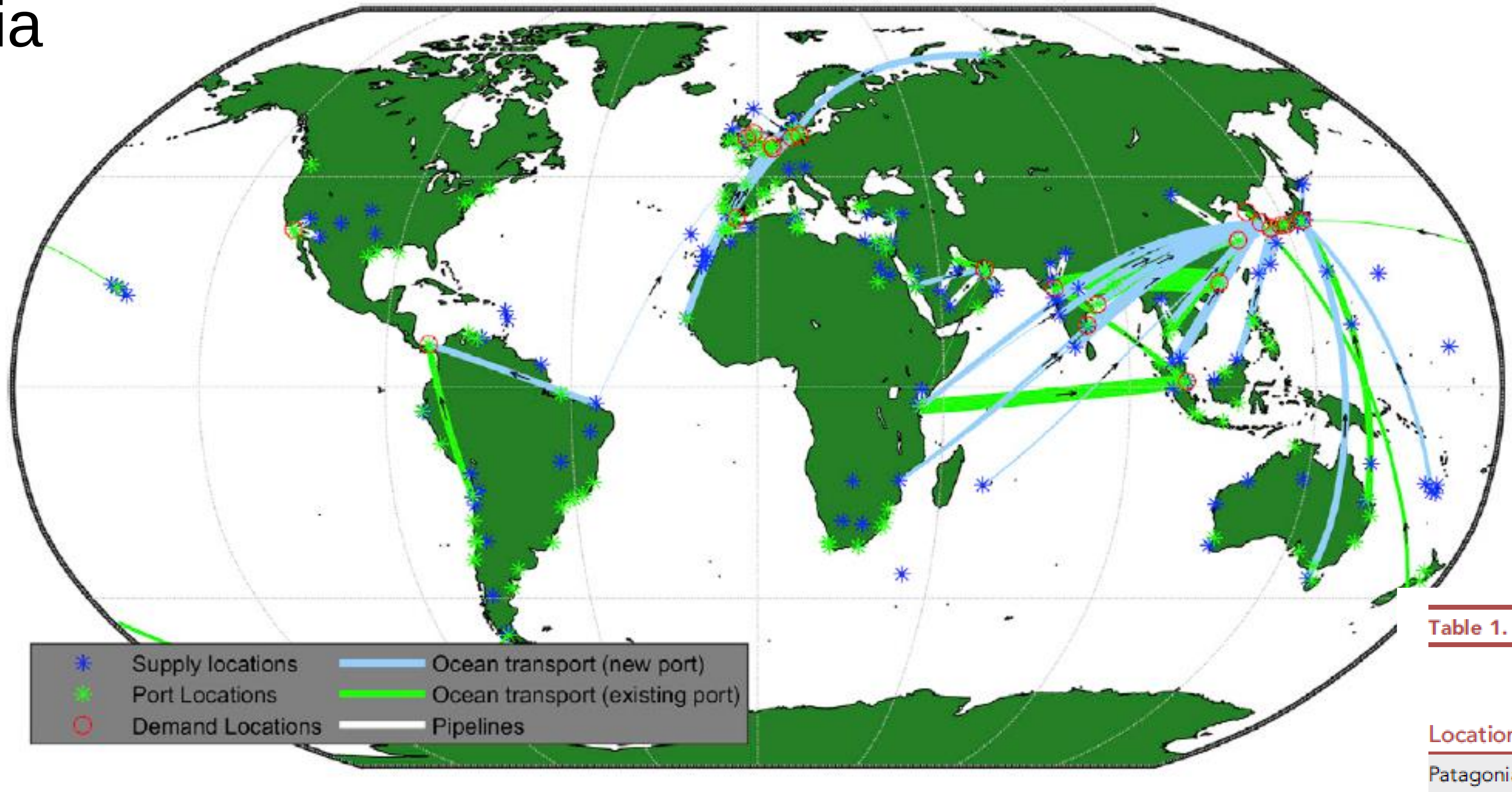
HEGRA YARA

With project HEGRA (Herøya Green Ammonia), Yara aims to electrify and decarbonize the ammonia plant in Porsgrunn, Norway. The project will reduce CO2-emissions by 800,000 tonnes annually.

https://www.yara.com/this-is-yara/yara-clean-ammonia

Growth in Green Ammonia Production Projects

- Possible green ammonia production locations:
  - Saudi Arabia
  - Oman
  - Australia
  - Chile
  - Argentina
  - Brazil
  - China
  - USA
  - Morocco
  - Norway



Green ammonia as a spatial energy vector: a review

Nicholas Salmon and René Bañares-Alcántara*

http://dx.doi.org/10.1039/d1se00345c

Article

Optimization of green ammonia distribution systems for intercontinental energy transport

Nicholas Salmon,[1] René Bañares-Alcántara,[1,2,*] and Richard Nayak-Luke[1]

https://doi.org/10.1016/j.isci.2021.102903

Table 1. Additional locations which are considered likely production sites of green ammonia

Location	Country	Latitude	Longitude	PLCOA (USD/t)	Rated wind fraction (%)	Full load hour equivalent per year	HB load factor	Electrolyzer rated power (MW)	NH3 synthesis (MW)
Patagonia (Argentina) (Armijo and Philibert, 2020)	Argentina	−44.5	−71	383	53	2850	67	930	67
Callide (CSIRO, 2020)	Australia	−24.5	150.5	375	20	2375	78	2,310	79
Eighty Mile Beach (Asian Renewable Energy Hub, 2020)	Australia	−20	120.5	551	12	1580	67	2,010	77
Port of Pecem (Bellini, 2021)	Brazil	−3.5	−39	329	0	2442	46	2,150	121
Calama Valley (Armijo and Philibert, 2020)	Chile	−22	−69	378	7	1684	63	2,450	90
Patagonia (Chile) (Armijo and Philibert, 2020)	Chile	−52.5	−71	298	84	4845	72	1,160	84
Taltal (Armijo and Philibert, 2020)	Chile	−25	−70	309	23	2370	76	2,220	80
Eqianqi (Keating, 2020)	China	41	109	352	0	2442	47	1,890	107
Ain Beni Mathar (Ennassiri et al., 2019)	Morocco	34	−2	350	0	2106	47	1,730	99
Boujdour (Ennassiri et al., 2019)	Morocco	26	−14	289	27	2788	79	1,500	67
Laayoune (Ennassiri et al., 2019)	Morocco	27	−13	273	41	3349	78	1,580	76
Ouarzazate (Ennassiri et al., 2019)	Morocco	31	−7	350	11	1946	69	1,920	78
Tarfaya (Ennassiri et al., 2019)	Morocco	28	−12.5	291	35	2935	75	1,620	76

Electrolyzer and ammonia power demands are shown for a plant size with an average energy supply of 1 GW. Citations provide details surrounding the existing proposals for the use of those sites.

- Trade-off between local production capacities and international production and transport costs

Growth in Ammonia for Shipping Fuel and Bunkering

Sembcorp Marine granted AiP for ammonia bunkering vessel

By Julian Atchison on January 20, 2022

A consortium led by Sembcorp Marine has been granted AiP by the American Bureau of Shipping for a new ammonia bunkering vessel design. Sembcorp and its subsidiary LMG Marin (who was recently engaged by Grieg Maritime and Wartsila to design the MS Green Ammonia) were responsible for the design phase, which passed a rigorous HAZID assessment with support from the American Bureau of Shipping. Consortium partners also include Mitsui O.S.K. Lines and Itochu, two organisations with growing ammonia interests in Singapore.

Click to learn more. Visualisation of the new ammonia bunkering vessel design. Source: Sembcorp.

The new announcement is one of a number of ammonia & ammonia-ready bunkering designs in progress:

- In March 2021 Korean Register granted AiP for an 8K ammonia bunkering vessel (dual-fuel with marine heavy oil).
- In June 2021 Oceania and Kanfer agreed to develop the world's first ammonia-ready bunkering vessel. It will initially run on & transport LNG, but be able to be modified to be powered by & carry ammonia as a bunker fuel.
- In September 2021 Azane Fuel Solutions received funding from the Norweigan government to build the world's first floating ammonia bunker terminal.
- And just last month, The Korean Green Ammonia Shipping/Bunkering Consortium won approval for two designs, including a 38,000 m^3-class ammonia transport/bunkering vessel.

https://www.ammoniaenergy.org/articles/sembcorp-marine-granted-aip-for-ammonia-bunkering-vessel/

MAN Energy Solutions is developing a fuel-flexible, two-stroke ammonia engine as a key technology in the maritime energy transition

Green ammonia is among several synthetic fuels key to establishing a greener shipping industry in the near future. MAN Energy Solutions aims to have a commercially available two-stroke ammonia engine by as early as 2024, followed by a retrofit package for the gradual rebuild of existing maritime vessels by 2025.

https://www.man-es.com/discover/two-stroke-ammonia-engine

World's first full scale ammonia engine test - an important step towards carbon free shipping

Wärtsilä Corporation, Trade press release, 30 June 2020 at 10:01 UTC+2

https://www.wartsila.com/

Ammonia flagged as green shipping fuel of the future

Marine operators are looking to clean up their act

Adaptive behaviour: the Viking Energy supply vessel which is planned to run on ammonia fuel cells

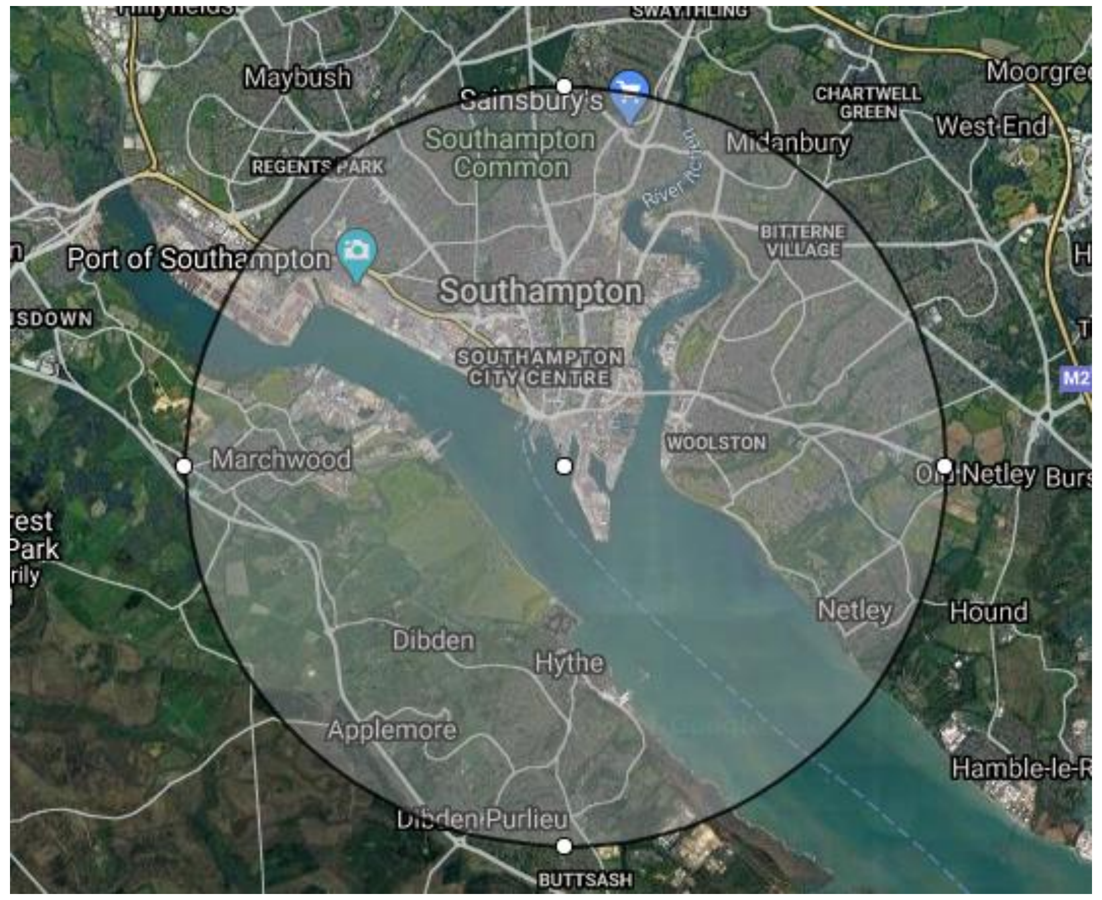
Charlotte Middlehurst MARCH 30 2020

11

https://www.ft.com/content/2014e53c-531f-11ea-a1ef-da1721a0541e

What are the important issues?

- Increased transport, storage and use of ammonia is highly likely in coming decade
  - New operators and emergency responders unfamiliar with ammonia safety
  - Change of risk profile
- Regulatory considerations for bulk ammonia storage at ports
  - Ports often located near populated areas
  - Onshore bunkering and/or floating barges?
  - Onshore/subsea pipeline connection to single mooring point?
  - Multiple stakeholders: Site operators, Health and Safety, Environment, Security, Port Authorities, Local Authorities, Coastguard, Emergency Services
- Risk assessment
  - Need to build confidence and trust in risk assessments for ammonia and ensure underlying models are validated and consistent
    - Includes source models, atmospheric transport and dispersion models, waterborne hazard models
- Emergency planning and response
  - Advice to emergency responders on cordon distances and protective actions



2.8 mile radius for ammonia railcar release

https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2020-08/ERG2020-WEB.pdf

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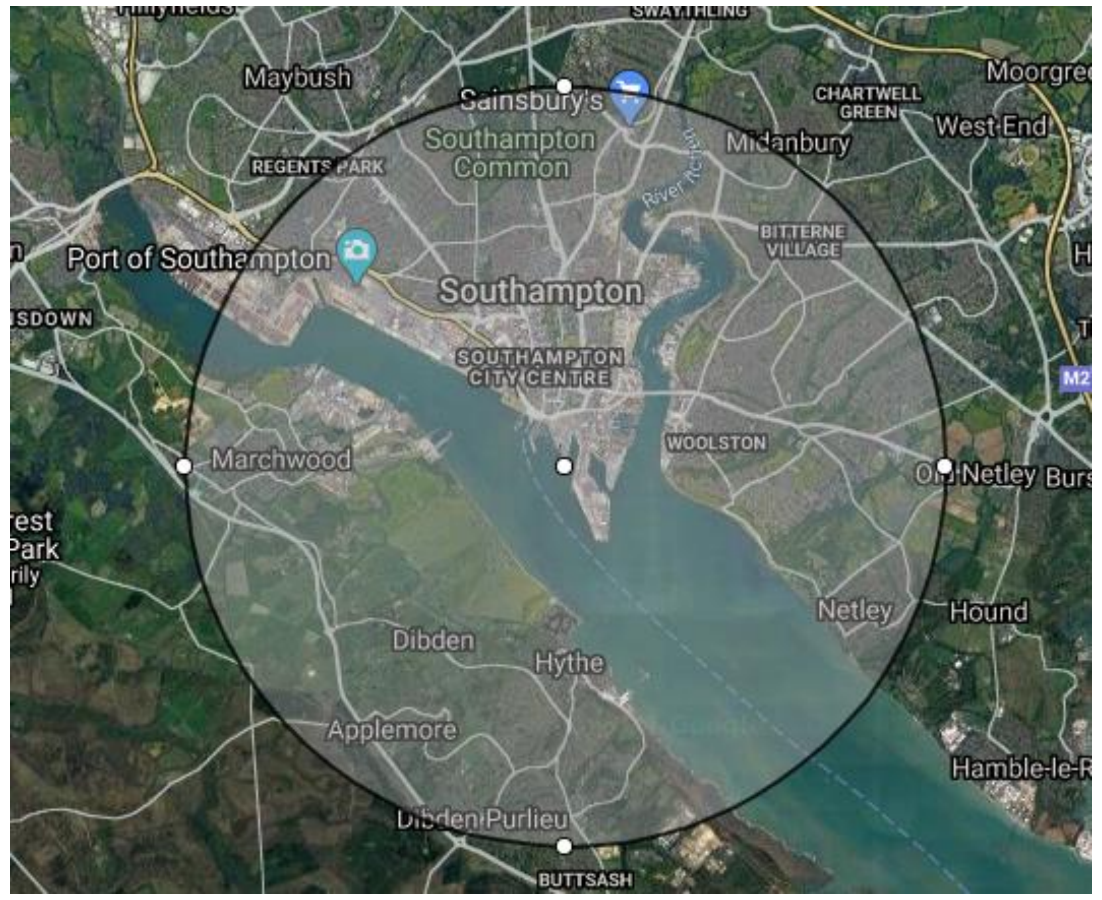


2.8 mile radius for ammonia railcar release

https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2020-08/ERG2020-WEB.pdf

Experimental Data for Liquid Ammonia Spills on/into Water

- Only one experimental waterborne ammonia spill dataset, by Raj *et al*. (1974)

PREDICTION OF HAZARDS OF SPILLS OF ANHYDROUS AMMONIA ON WATER

PREPARED FOR COAST GUARD

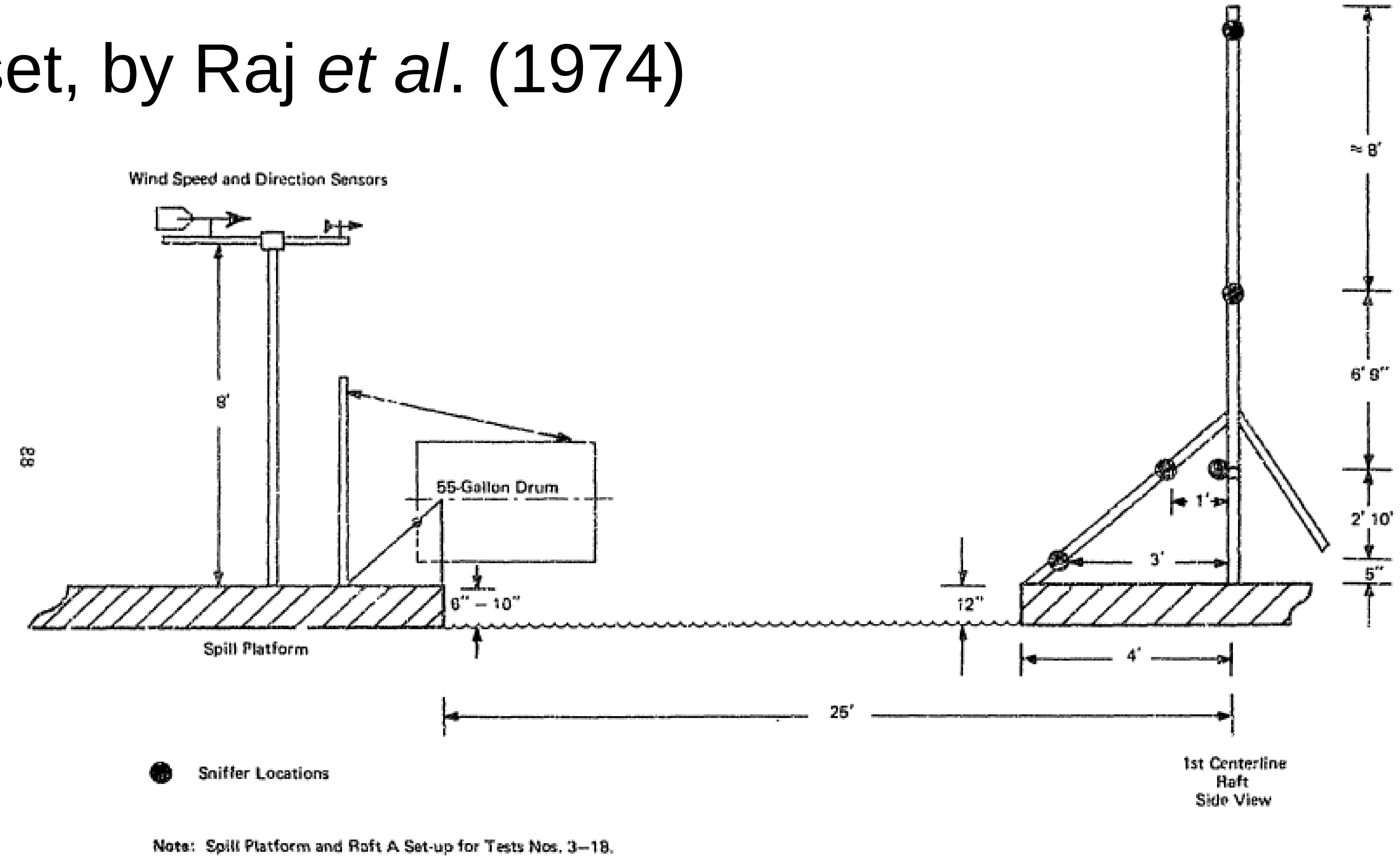
ARTHUR D. LITTLE, INCORPORATED

MARCH 1974

Raj, P.K., Hagopian, J., and Kalelkar, A.S.

The vapor puff formed is very buoyant and rises into the air as it travels downwind. The rate of rise depends on the wind velocity. Under low wind conditions the cloud forms a characteristic mushroom cloud before dispersing. The path of the cloud can be estimated with reasonable accuracy by existing plume theories. Because of the rapid rise in low wind, the toxic hazard at ground level is smaller for low wind than for high wind.

https://apps.dtic.mil/sti/pdfs/AD0779400.pdf



ɪURE 5–2 PARTIAL SIDE VIEW OF THE SPILL PLATFORM AND RAFTS

1.3.1 Laboratory Experiments
- 1.3.1.1 Surface Spills
- 1.3.1.2 Underwater Release

½ US gallon (2 litre)

1.3.2 Intermediate-Scale Experiments
- 1.3.2.1 Surface Spills
- 1.3.2.2 Underwater Release

5 US gallon (20 litre) in swimming pool

1.3.3 Large-Scale Experiments
- 1.3.3.1 Surface Spills
- 1.3.3.2 Underwater Release

50 US gallon (0.2 m^3) in lake

Ammonia ship capacities typically 30,000 – 80,000 m^3 (Source: http://www.liquefiedgascarrier.com)

Experimental Data for Liquid Ammonia Spills on/into Water

- HSE Report by Griffiths (1977) critical of conclusions drawn from Raj *et al*. (1974) tests
  - "… does not provide the information needed to perform hazard assessments of LNH_3 releases on water"
- Concluded that further experiments are needed

SRD SAFETY AND RELIABILITY DIRECTORATE

CRITICAL REVIEW OF THE USCG REPORT BY RAJ ET AL (1974) ON SPILLS OF LIQUID ANHYOROUS AMMONIA ON TO WATER, WITH AN ALTERNATIVE ASSESSMENT OF THE EXPERIMENTAL RESULTS

R. F. Griffiths

January 1977

SUMMARY

This report is principally devoted to a criticism of experiments performed by Raj et al (Reference 10) in which it was demonstrated that spills of LNH_3 (liquid anhydrous ammonia) on to water from refrigerated storage tanks result in releases of ammonia to the atmosphere. Raj et al concluded that such releases are adequately described in terms of a buoyant plume rise model, in which it is assumed that the ammonia is released as a pure undiluted vapour.

This conclusion is challenged on the grounds that it is incompatible with the experimental measurements. An alternative interpretation of the data is proposed which is shown to be consistent with the observed behaviour. In this scheme the ammonia is considered to be released as a plume containing both vapour and liquid droplet aerosol, by virtue of which it is rendered non-buoyant.

The difficulties inherent in providing a rigorous description of such a release are circumvented by use of a simplified model of the dispersion behaviour, which is used to calculate downwind ground level concentrations (GLC) of ammonia vapour. Comparison calculations are performed to demonstrate that the hazard ranges for a given consequence are significantly greater if the release is non-buoyant.

It is concluded that the study performed by Raj et al does not provide the information needed to perform hazard assessments for LNH_3 releases on to water, and that further experimental studies are required.

Haifa Ammonia Storage Tank Study, 2018

THE TIMES OF ISRAEL

HEZBOLLAH CHIEF LAST YEAR THREATENED TO TARGET FACILITY WITH MISSILES IN NEXT WAR

Hundreds of thousands of lives in danger from Haifa ammonia operation: report

12,000-ton storage container could 'fall apart tomorrow' or be attacked in a war, expert warns, creating a toxic suffocating cloud; managing company dismisses 'fear-mongering'

By STUART WINER

31 January 2017, 7:22 pm | 0

23 shares

Haifa's industrial zone. The ammonia tank is visible on the jetty jutting into the sea at the right. (Shay Levy/Flash90)

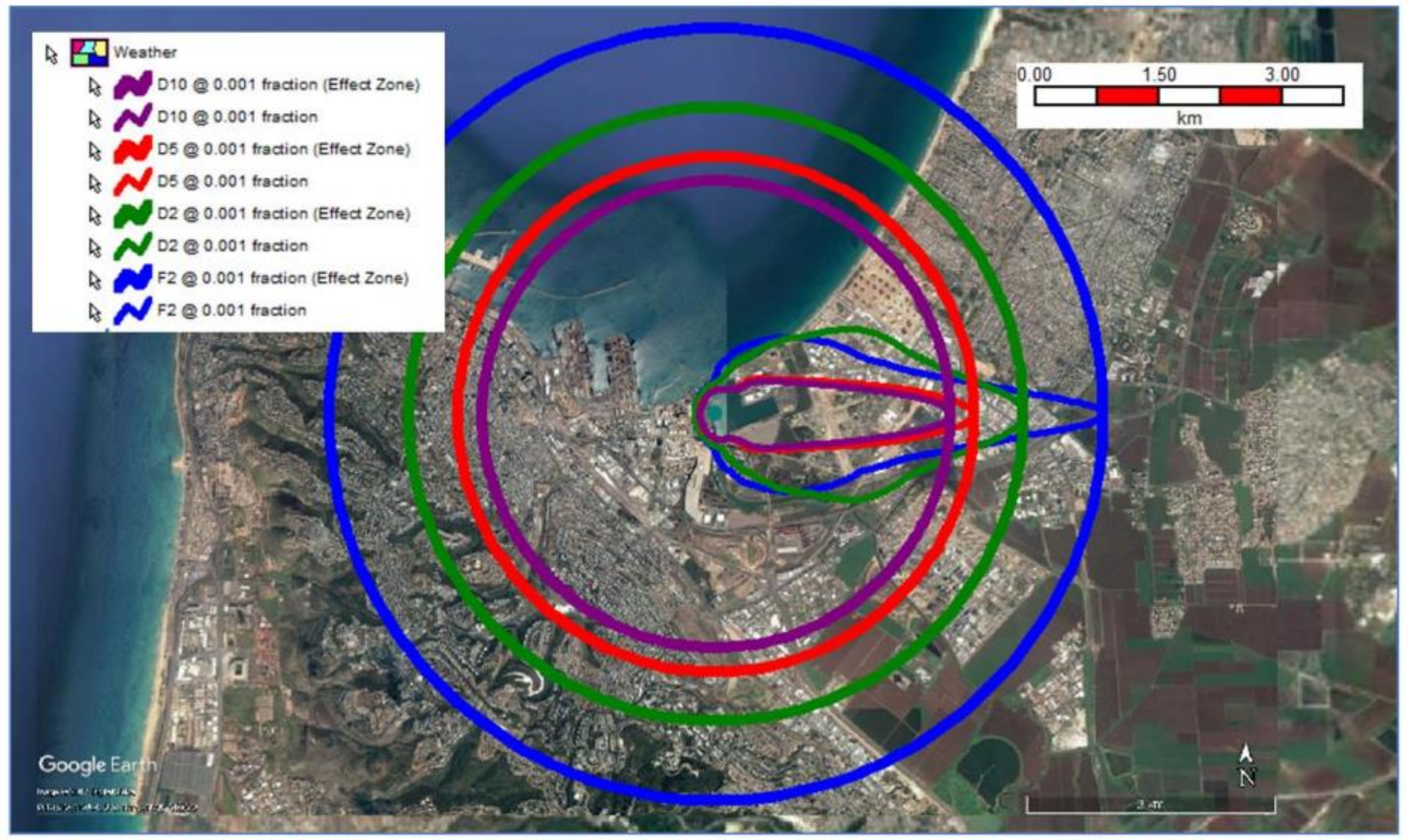
DNV·GL

AMMONIA DISPERSION STUDY

Initial Dispersion Analysis

Haifa Muncipality

Figure 5-13 0.1% Lethality Footprint and Effect Zone for Liquid Carrier (2500 te) Catastrophic Release (to the Sea)



https://www.davar1.co.il/wp-content/uploads/2018/03/DNV-Ammonia-Dispersion-Rev-3.1.18%D7%93%D7%95%D7%97-%D7%A1%D7%95%D7%A4%D7%99.pdf

Lloyds Register: ammonia and hydrogen risks, 2020

Lloyd's Register

Working together for a safer world

Hydrogen and Ammonia Infrastructure

Safety and Risk Information and Guidance

Report for:
Ocean Hyway Cluster

Arena Ocean Hyway Cluster

Table 5.1 – Coarse assessment of risk outside fence from simulated releases

Hazard distance	Fatality potential			Injury potential		
Scenario	Full bore	10%	1%	Full bore	10%	1%
Refrigerated NH_3	25m	25m	10m	280m	250m	220m
Compressed NH_3	~2,000m	270m	30m	>10,000m	~2,000m	200m
Liquid H_2	~300m	25m	N/A	~1,000m	300m	N/A
Compressed H_2	~30-40m	20m	N/A	~300m	200m	50m
LNG	>200m	35m	N/A	>200m	35m	N/A

Report no: PRJ11100256122r1 Rev: 00

Date: 7 May 2020

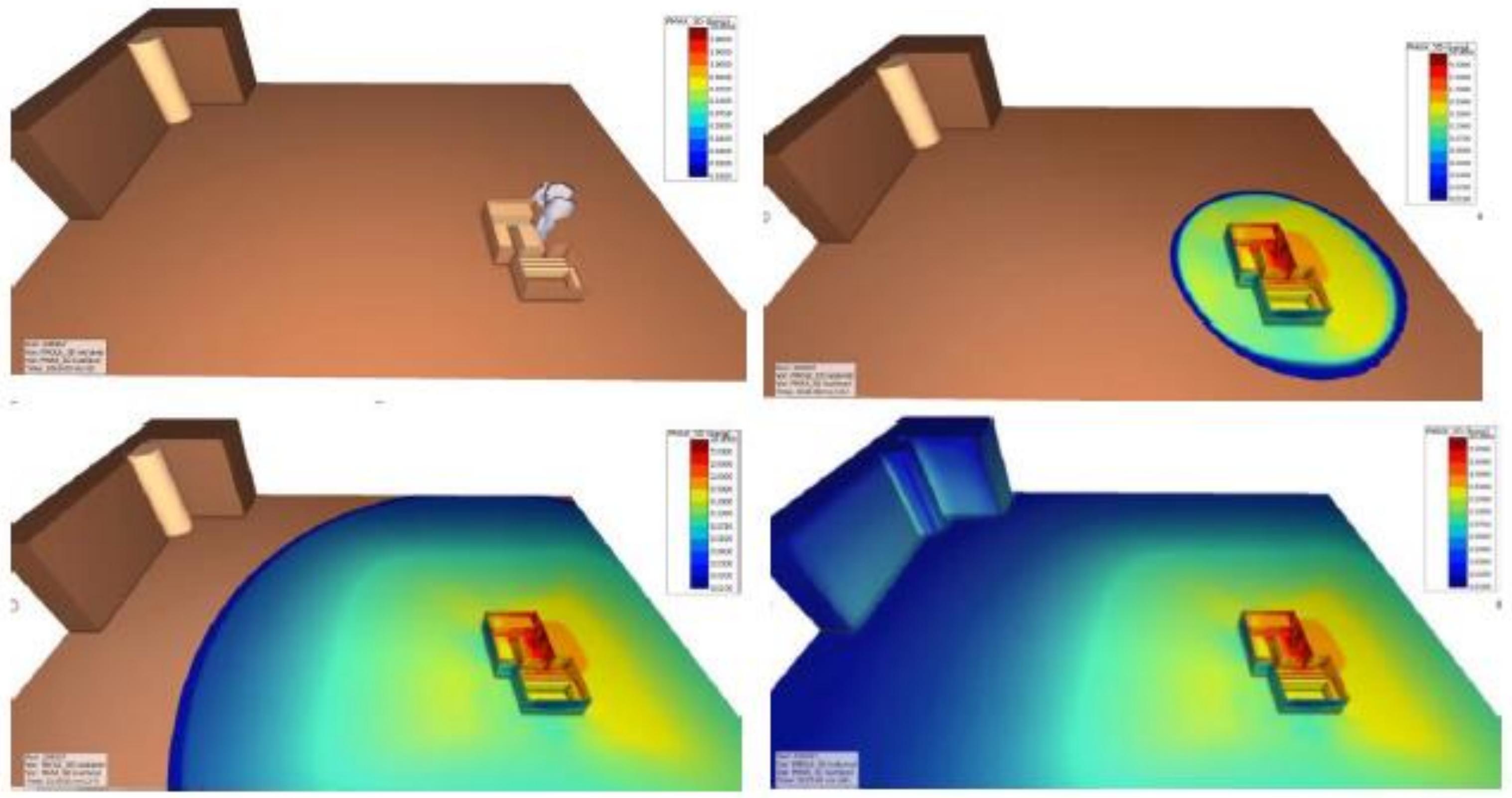
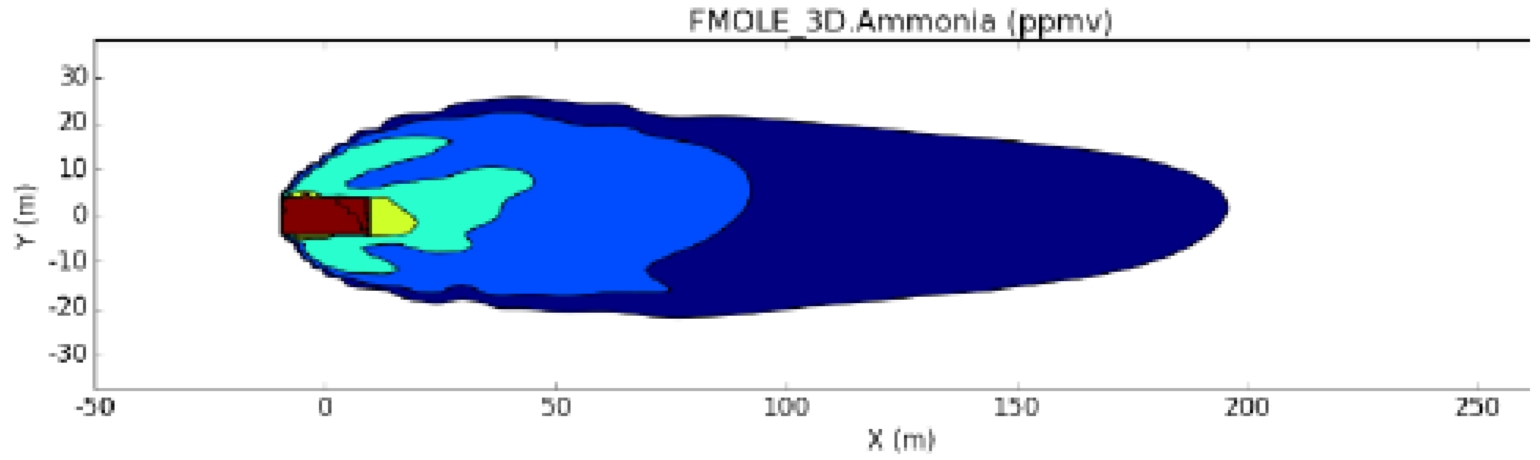


Figure 4-5– CFD-simulation of assumed hydrogen release and detonation [Hansen, 2019] in the Kjørbo accident, first frame shows predicted hydrogen cloud (>15%) at ignition, the other frames show maximum received blast pressures after 45ms, 130ms and 275ms.



Hazard range for ammonia extends further than for hydrogen or LNG (how was the refrigerated NH_3 spill modelled?)

https://static1.squarespace.com/static/5d1c6c223c9d400001e2f407/t/5eb553d755f94d75be877403/1588941832379/Report+D.3+Safety+and+regulations+Lloyds+Register.pdf

DNV Safety Study for Port of Amsterdam, 2021

External safety study - bunkering of alternative marine fuel for seagoing vessels

Port of Amsterdam

Report No.: 10288905-1, Rev. 0
Document No.: 11J5ON0R-1
Date: 2021-04-19

Recent study jointly developed by the Port of Amsterdam and DNV emphasises important spacial safety considerations when designing zero carbon fuel bunkering infrastructure at city ports

Focus areas

Focus areas are areas that visualise where without additional measures, people are insufficiently protected indoors against the consequences of accidents involving hazardous substances. In the new Environmental and Planning Act 2022, a distinction will be made between three types of focus areas:

- Fire focus area;
- Explosion focus area;
- Toxic cloud focus area.

Table 0-2: Maximum distance from bunker hose to focus area boundary

Fuel	Flow rate	Focus area distance (m)		
		Fire	Explosion	Toxic
LNG	400 m³/h (-146 °C)	249	274	- [1]
LNG	400 m³/h (-159 °C)	330	295	- [1]
Methanol	400 m³/h	102	- [1]	22
Ammonia (refrigerated)	400 m³/h	- [1]	- [1]	1446
Ammonia (pressurized)	400 m³/h	- [1]	- [1]	1478
Hydrogen (liquid)	400 m³/h	239	283	- [1]
Hydrogen (gaseous)	3 t/h	87	- [1]	- [1]
Hydrogen (gaseous)	700 bar (60 g/s)	55	- [1]	- [1]
Hydrogen (gaseous)	1000 bar (60 g/s)	55	- [1]	- [1]
LNG	1000 m³/h	448	229	- [1]
Methanol	1000 m³/h	154	- [1]	34
Ammonia (refrigerated)	1000 m³/h	- [1]	- [1]	2624
Ammonia (pressurized)	1000 m³/h	- [1]	- [1]	2060
Hydrogen (liquid)	1000 m³/h	324	338	- [1]

[1] The justification as to why no distances are calculated can be found under Table 7-3 in Section 7.2

https://sustainableworldports.org/wp-content/uploads/DNV-POA-Final-Report_External-safety-study-bunkering-of-alternative-marine-fuels-for-seagoing-vessels_Rev0_2021-04-19.pdf

Other Ongoing Safety Studies

- Ongoing ITOCHU Joint Study Framework on Ammonia as an Alternative Marine Fuel

https://www.trafigura.com/press-releases/trafigura-joins-cross-industry-study-into-the-adoption-of-green-ammonia-as-an-alternative-marine-fuel/

- Ongoing DNV-led study for Global Centre for Maritime Decarbonisation (Singapore)
  https://www.gcformd.org/press-release-ammonia-bunkering-safety-study-award

Other Ongoing Safety Studies

- Norwegian research institute, SINTEF, project MaritimeNH3

SINTEF

MaritimeNH3 – Enabling implementation of ammonia as a maritime fuel

Research Partners

- SINTEF Energy Research
- SINTEF Industry

Industry partners

- Yara International
- Amon Maritime
- ECONNECT Energy
- Ocean Hyway Cluster
- HYEX Safety
- Viridis Bulk Carriers

MaritmeNH3 focuses on developing improved models for safety assessments, methodologies for techno-economic analysis and GHG assessments of the whole NH_3 value chain, and technological advancements for end-use in NH_3-fuelled engines and fuel cells. It will address barriers related to the use of NH_3 as a maritime fuel including production, cost, safety, regulations, end-use technology and understanding of the value chain.

Project duration

2021 - 2024

Aims and objectives

MaritimeNH3's main objective is to develop and disseminate knowledge contributing to the necessary technology advancements in the ammonia (NH_3) value chain in order to enable a safe and cost-efficient implementation of NH_3 as a maritime fuel.

This will be achieved by:

- Improving risk mitigation for NH_3 bunkering installations in a Nordic climate by improving the modelling of NH_3 dispersion at ppm levels between rapidly lethal and detectable odour limits,
- Advancing the technological development of NH_3-fuelled combustion engines and high-temperature fuel cells by evaluating concepts for improving the combustion characteristics of NH_3 and determining the main degradation mechanisms that impact the lifetime of NH_3-fed fuel cells,
- Developing and applying a methodology for a techno-economic analysis and greenhouse gas (GHG) assessment of a Norwegian NH_3-based energy system for maritime transport, and comparing this to alternative H_2-based value chains, and
- Increasing the social acceptance of NH_3 as a maritime fuel, and promoting its uptake and further development.

https://www.sintef.no/en/projects/2021/maritimenh3-enabling-implementation-of-ammonia-as-a-maritime-fuel/aims-and-objectives

Summary

- Ammonia transport by ship and bunkering at ports is likely to increase significantly in coming years (IMO target: reduce maritime CO_2 emissions by at least 40% by 2030)
- Some of the issues that currently need considering:
  - Investigate potential safety issues associated with use of ammonia in the maritime industry, including intermediate storage and bunkering of ammonia at ports, and transfer operations
  - Anticipate safety barriers, investigate and implement appropriate risk reduction measures
  - Build confidence and trust in risk assessments for ammonia and ensure that underlying models are validated and consistent
    - Including analysis of source models, atmospheric transport and dispersion models, waterborne hazard models (new large-scale waterborne ammonia spill experiments are needed)
  - Work collaboratively with emergency responders to analyse potential hazards and risks so that this information can be integrated into their training and emergency management plans for dealing with potential accident scenarios

Acknowledgements

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- Contact points:
  - Simon Gant (simon.gant@hse.gov.uk)
  - Mike Wardman (mike.wardman@hse.gov.uk)

Thank you

Waterborne Ammonia Spill Experiments, 1974

Raj, P.K., Hagopian, J., and Kalelkar, A.S.

The vapor puff formed is very buoyant and rises into the air as it travels downwind. The rate of rise depends on the wind velocity. Under low wind conditions the cloud forms a characteristic mushroom cloud before dispersing. The path of the cloud can be estimated with reasonable accuracy by existing plume theories. Because of the rapid rise in low wind, the toxic hazard at ground level is smaller for low wind than for high wind.

R. F. Griffiths

This conclusion is challenged on the grounds that it is incompatible with the experimental measurements. An alternative interpretation of the data is proposed which is shown to be consistent with the observed behaviour. In this scheme the ammonia is considered to be released as a plume containing both vapour and liquid droplet aerosol, by virtue of which it is rendered non-buoyant.

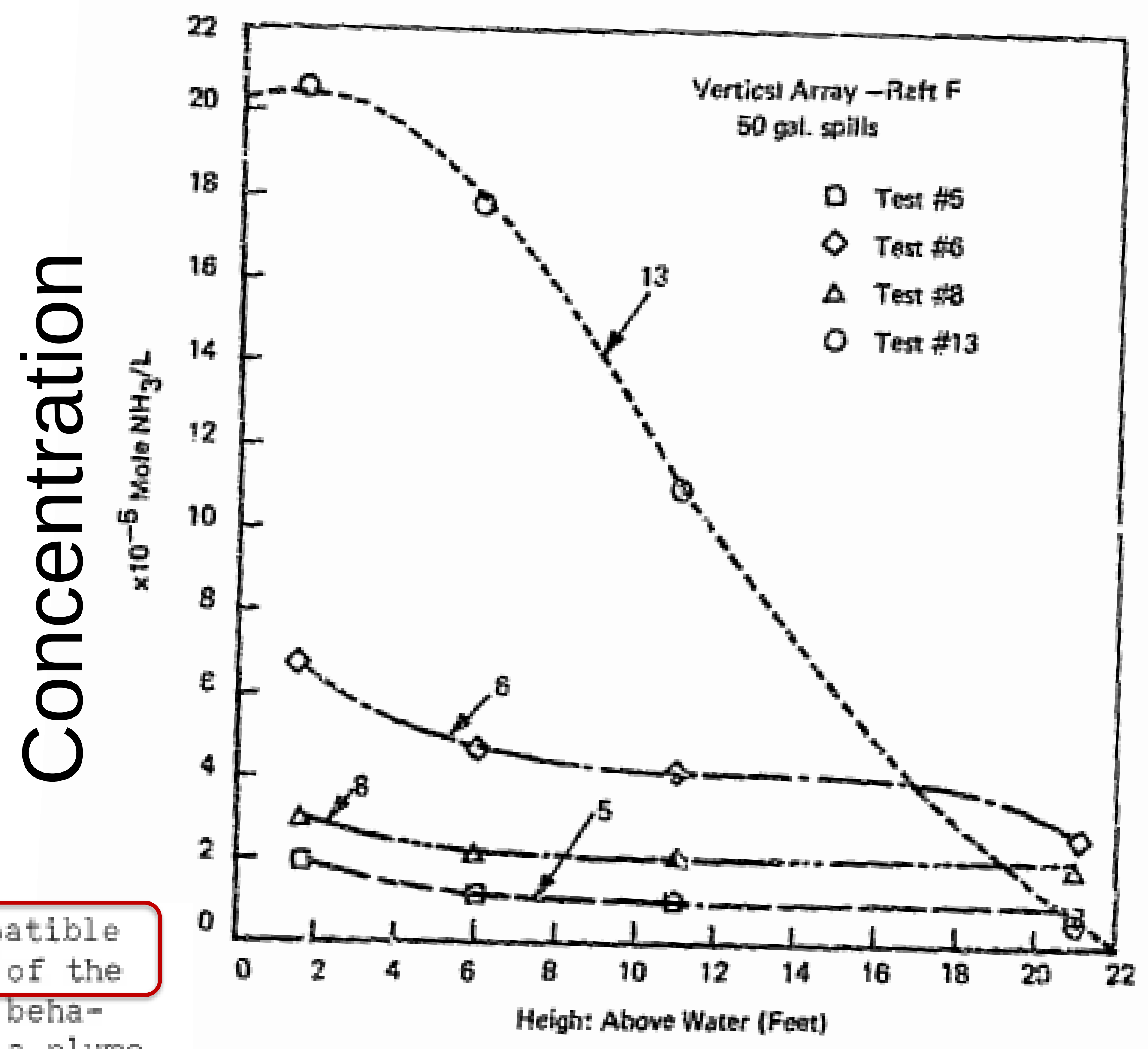

FIGURE 5–9b VERTICAL ARRAY IMPINGER DATA FOR SECOND ROW RAFT (C).

Height

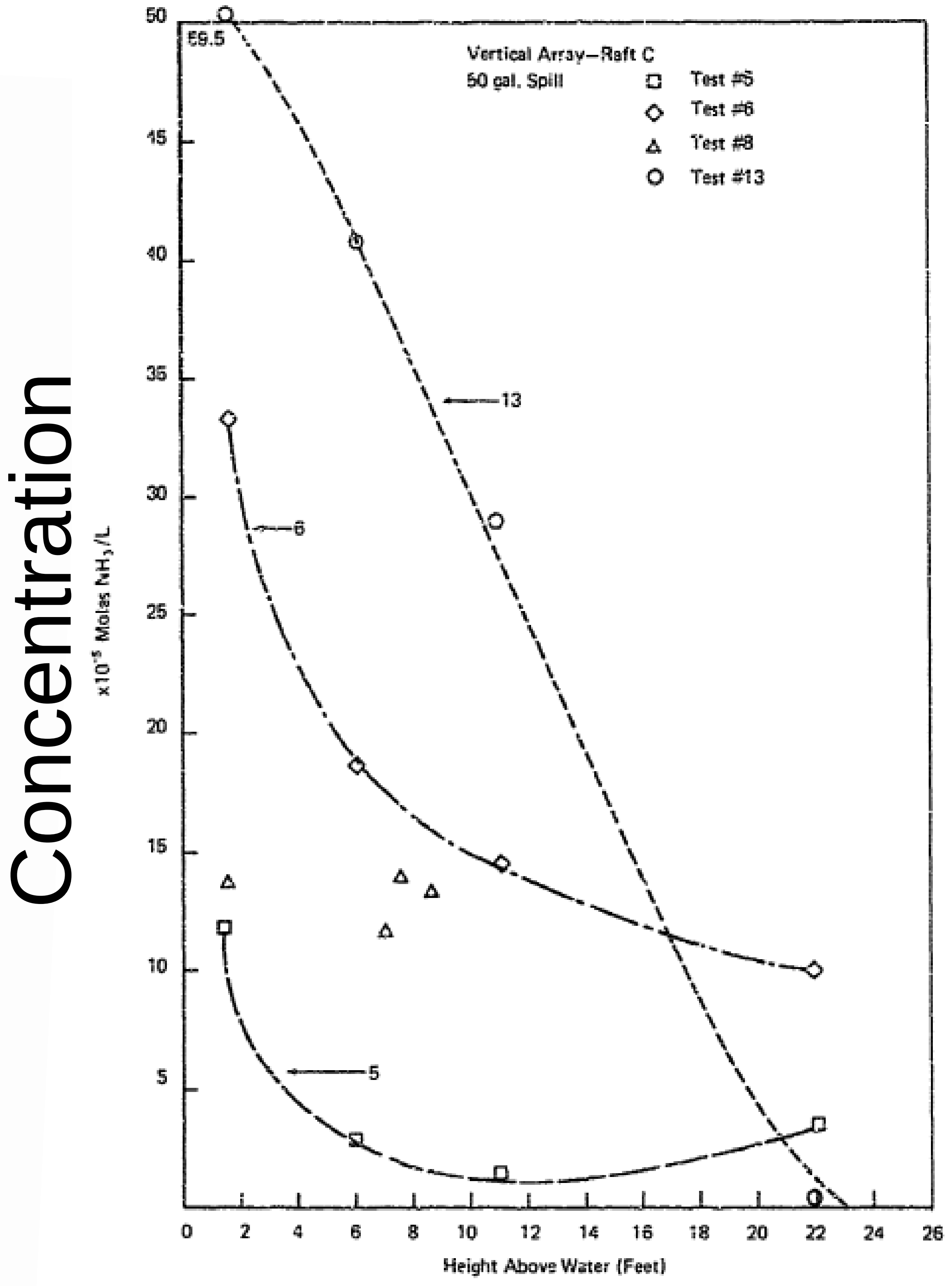

FIGURE 5–10b VERTICAL ARRAY IMPINGER DATA FOR THIRD ROW RAFT (F)

Height