RESEARCH AND GUIDANCE FROM HSE

Ammonia as a future clean energy vector and marine fuel: knowledge gaps and ongoing risk studies

Simon Gant

Health and Safety Executive (HSE)

Safety and Reliability Society evening talk, 31 January 2023

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

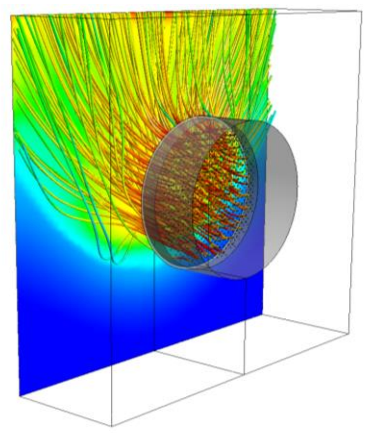
- Quick introduction to HSE
- UK support for Net Zero technologies
- Ammonia properties
- Previous incidents
- Recent safety and risk studies
- Scientific knowledge gaps

Introduction to HSE

- HSE is the UK regulator for workplace health and safety
  - Includes onshore/offshore pipelines, chemical/oil/gas infrastructure, offshore platforms etc.
  - Activities: evidence gathering, policy development, consultation, regulation, incident investigation, enforcement
  - HSE acts as an enabling regulator, supporting the introduction of new technologies
  - 2,400 total staff
  - £230M ($310M) budget: 60% from Government, 40% from external income



- HSE Science and Research Centre, Buxton, UK
  - 400 staff, 550 acre test site
  - Scientific support to HSE and other Government departments
  - “Shared research” or joint-industry projects co-funded by HSE
  - Bespoke consultancy on a commercial basis

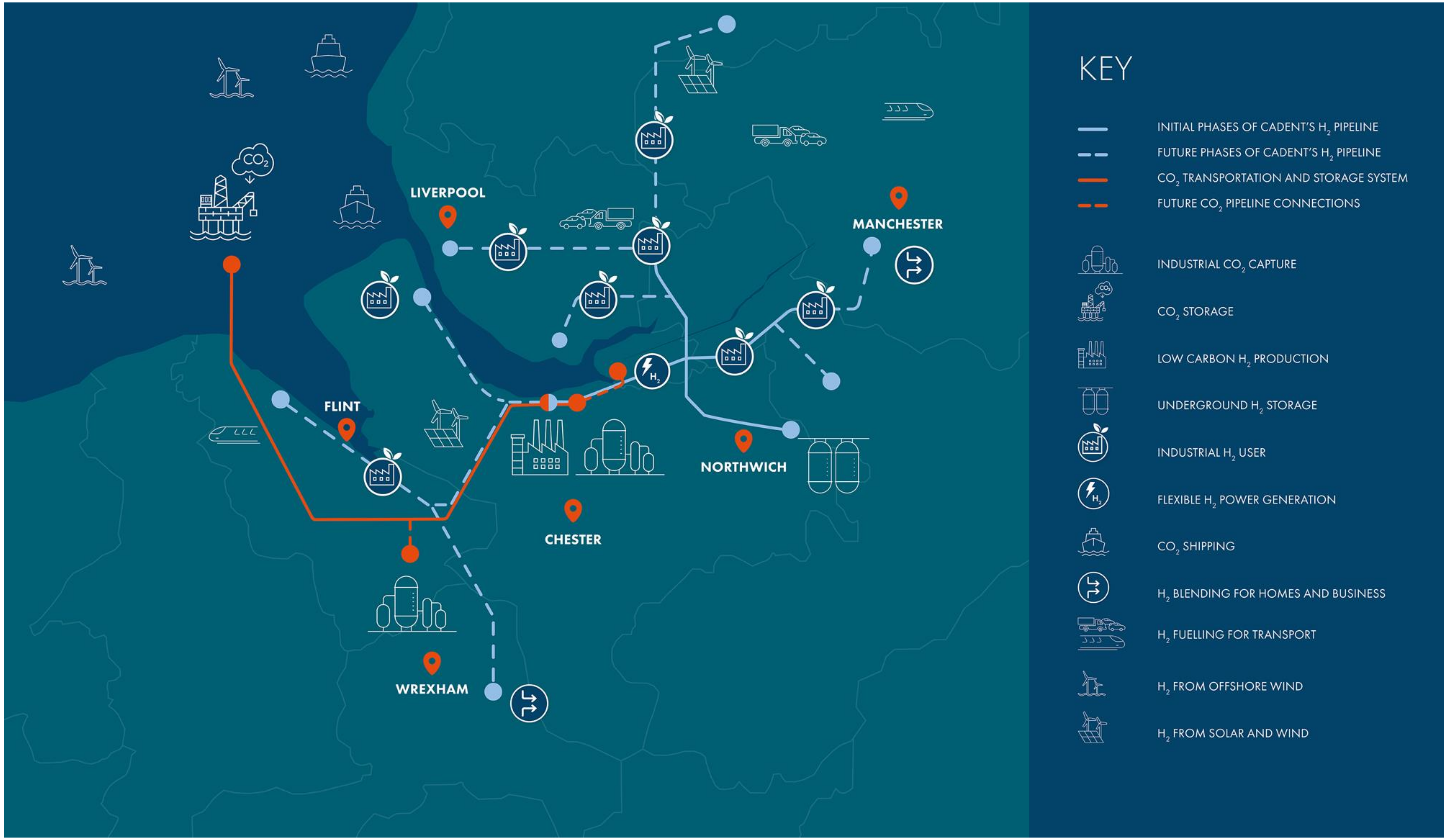
UK Government support for Net Zero

Map data: © 2022 Google

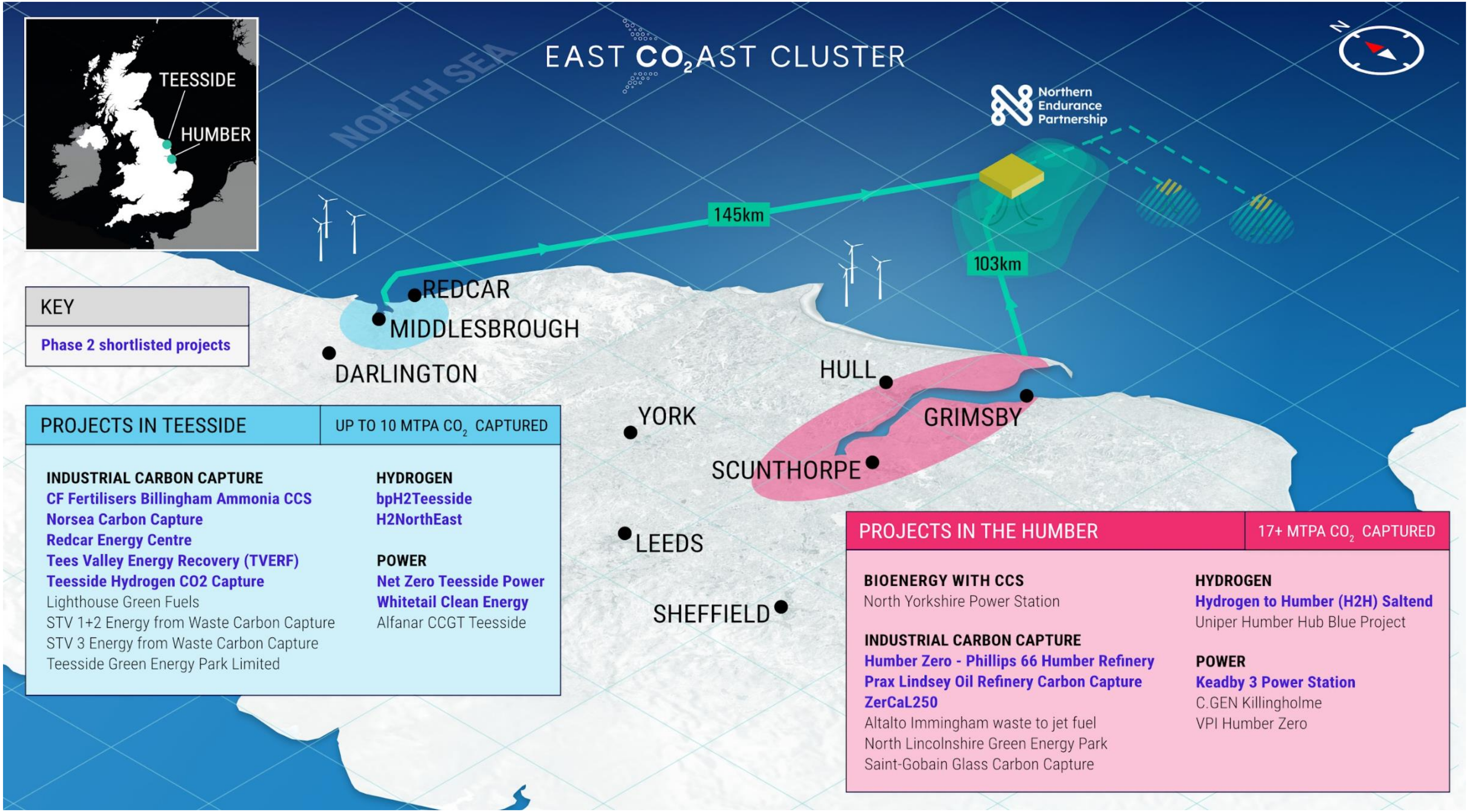
- Net Zero 2050
  - UK Government announced Ten Point plan[1] in November 2020
- Growth of low-carbon hydrogen and CCUS based around
  1. Regional hydrogen and CCUS industrial clusters
  2. Hydrogen for heating:
     - Government policy decision on hydrogen heating in 2026
     - 2023/4: Neighbourhood trial (300 properties, new PE distribution network, https://www.h100fife.co.uk/)
     - 2025/6: Village trial (1,000 – 2,000 properties, repurposed gas distribution network)
     - By 2030: Town pilot (start of roll-out)
  - Targets of 5 GW of low carbon hydrogen production and 10 Mt carbon capture by 2030
- Other Net Zero ambitions
  - Offshore wind, nuclear, zero-emission vehicles/planes/ships, greener buildings, protecting environment, green finance and innovation

[1] https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

HyNet North West



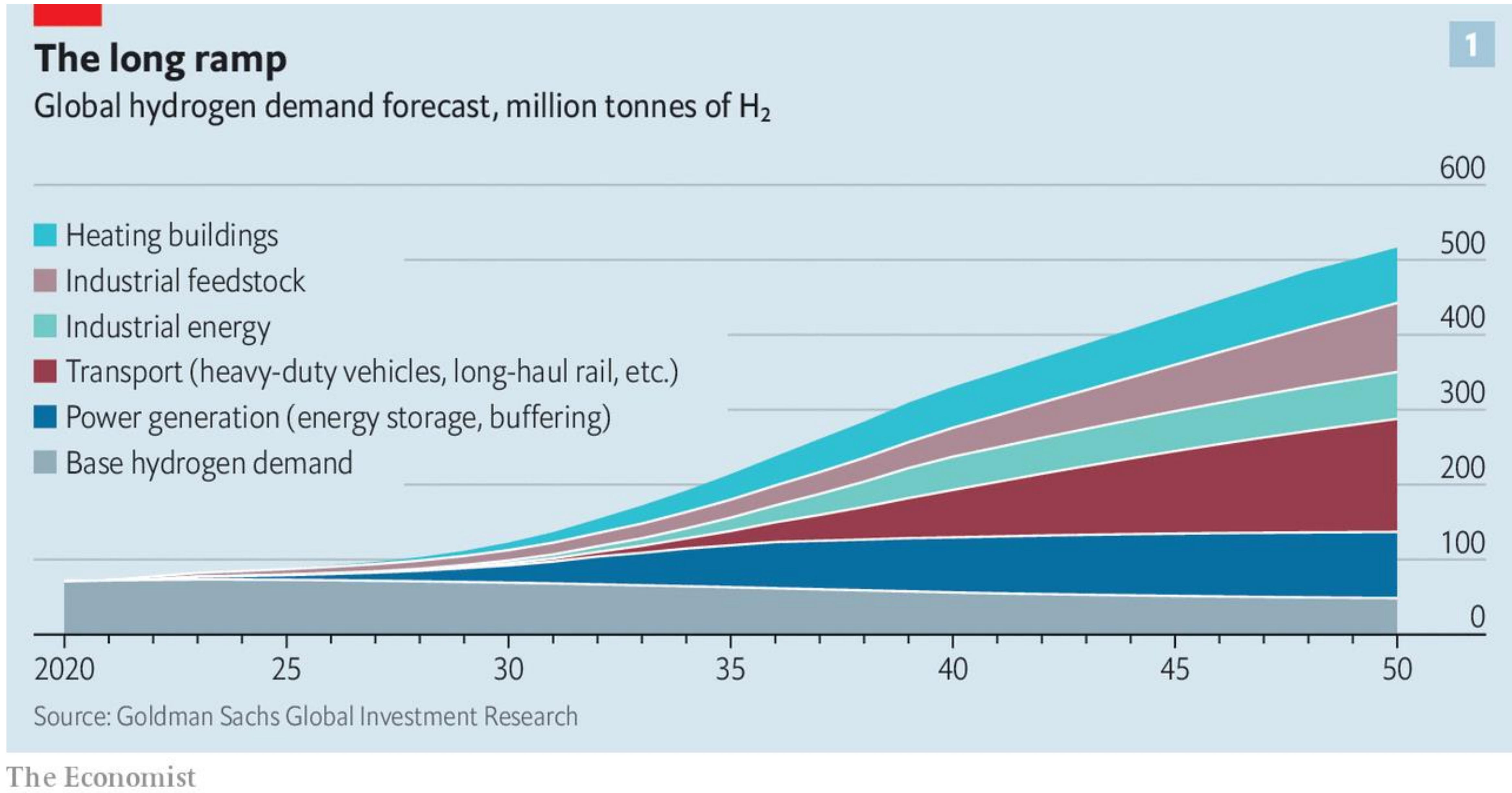
https://hynet.co.uk



https://eastcoastcluster.co.uk

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

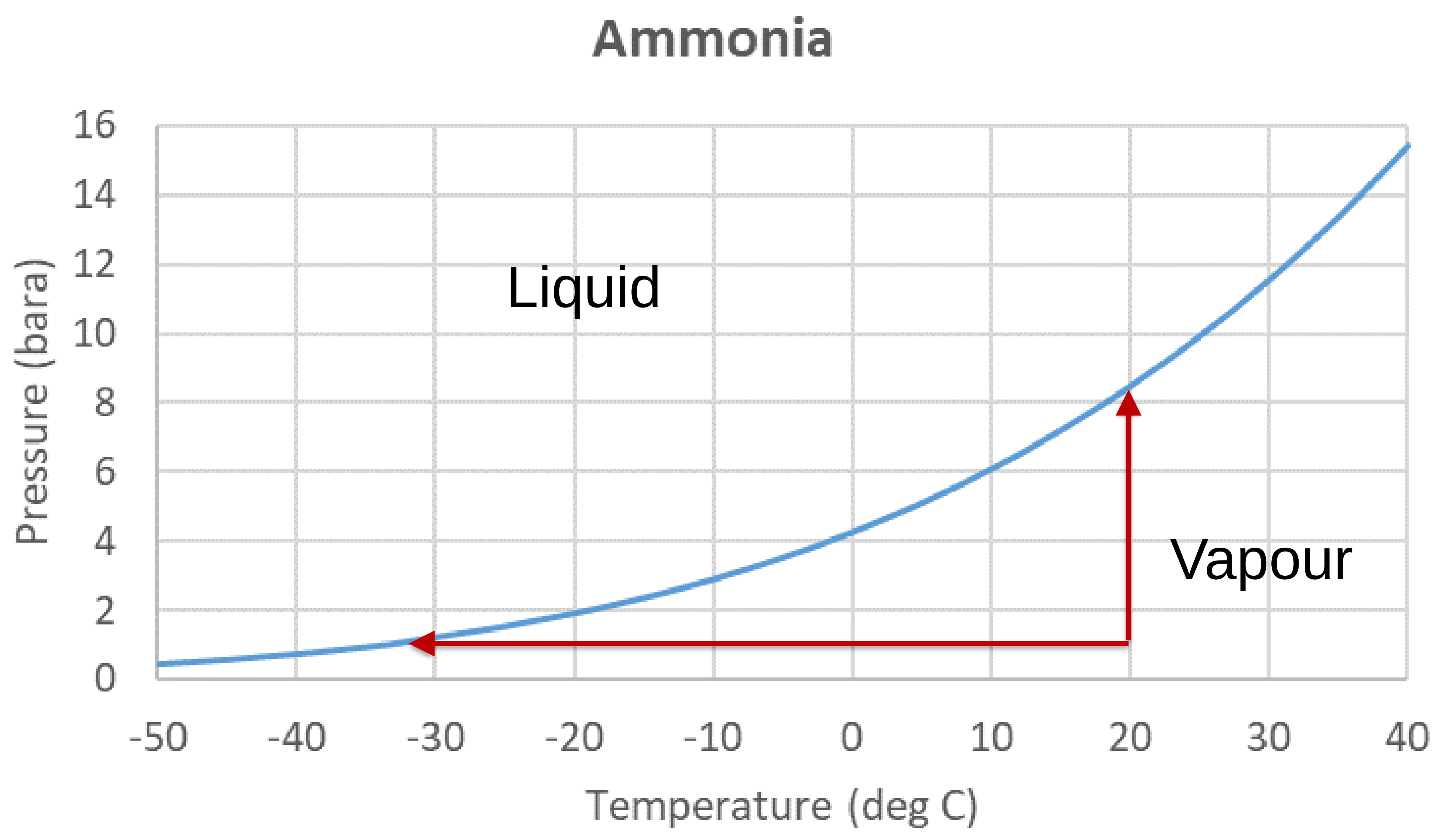
- To transport this hydrogen, ammonia is emerging as a potential hydrogen vector

Hydrogen and Ammonia Properties

- Compared to hydrogen, ammonia is:
  1. Easier to liquefy
  2. Higher volumetric energy density
  3. More difficult to burn
  4. Toxic

	Hydrogen (H_2)	**Ammonia (NH_3)**
Molecular weight[1]	2 g/mol	17 g/mol
Boiling point[1]	-253°C	-33°C
Energy density[2]	9 MJ/litre (liquid) 6 MJ/litre (gas 700bar)	16 MJ/litre (liquid)
Lower flammability limit	4 %v/v	15 %v/v
Upper flammability limit	75 %v/v	28 %v/v
Minimum ignition energy[2]	0.01 mJ	8 mJ
Laminar burning velocity[2]	3.5 m/s	0.07 m/s
Toxic AEGL-3 10 mins[3]	-	2,700 ppm

[1] https://encyclopedia.airliquide.com/
[2] https://www.ammoniaenergy.org/articles/ammonia-for-power-a-literature-review
[3] Life-threatening health effects or death https://www.epa.gov/aegl/ammonia-results-aegl-program



Pressure-liquefied above 8.5 bara (at 20°C)
Temperature-liquefied below -33°C (at atmos. pressure)

Ammonia as a Clean Energy Vector

- For bulk transport by ship over large distances: cheaper to produce ammonia from hydrogen (NH_3 Haber-Bosch process) and transport liquefied ammonia than to transport liquid hydrogen[1]
  - Cheaper to import green hydrogen from Middle East as ammonia than produce green hydrogen in the UK?[2]
- Stored ammonia could 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 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

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

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

Ammonia as a Clean Energy Vector

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

08/30/2022 | LEHIGH VALLEY, PA AND LONDON, THE UNITED KINGDOM

Large-Scale Green Hydrogen for the UK: Air Products and Associated British Ports partner on Renewable Hydrogen Production

Air Products (NYSE:APD) and Associated British Ports (ABP) announced today their intention to partner in bringing the first large scale, green hydrogen production facility to the UK.

The facility would import green ammonia from production locations operated by Air Products and its partners around the world. This would be used to produce green hydrogen, which would decarbonise hard-to-abate sectors such as transport and industry.

Immingham – the UK's leading port complex decarbonising energy

Air Products and ABP are working together to bring the new green hydrogen facility to the Port of Immingham. The location will provide the required maritime infrastructure and offers good proximity to markets and the required utilities. ABP will invest in new infrastructure with a new jetty to service the import and export handling of liquid bulk products. In addition to handling green ammonia, the jetty is being designed so that it can accommodate other cargoes connected to the energy transition, including the import of liquified carbon dioxide (CO2) from carbon capture and storage projects for sequestration in the North Sea – thereby playing a significant role in the UK's energy transition.

h2 green

HOME ABOUT HYDROGEN SOLUTIONS NEWS CONTACT US

- To deliver a third phase of hydrogen supply growth, H2 Green plans an ammonia importation facility. Ammonia is a medium for international hydrogen transport that can connect Shoreham to large-scale, low-cost, green energy projects worldwide.

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

Ammonia as a Clean Energy Vector

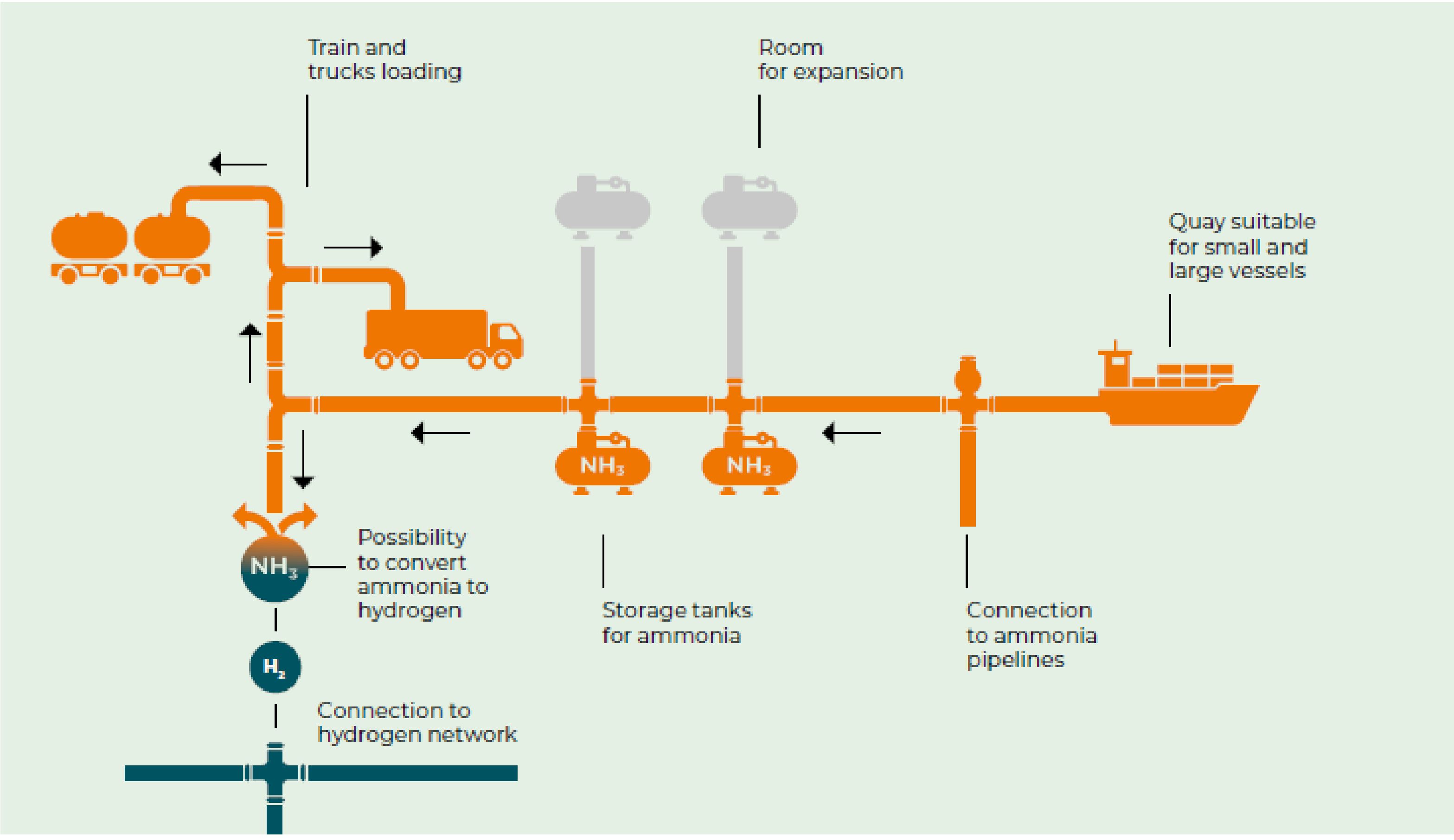
GAS FOR CLIMATE A path to 2050 Guidehouse

The European Commission recently published its REPowerEU plan which aims to rapidly reduce dependence on Russian fossil fuels and accelerate the green transition. Hydrogen plays a key role in this plan. A total of 20 Mt of hydrogen is targeted by 2030 – 10 Mt via domestic production and up to 10 Mt via imports. To meet the hydrogen import target, infrastructure, regulation, and support mechanisms must be fit for purpose. However, this is currently not the case. This paper provides insights on the existing challenges of imports and how they can be overcome.

Table 2: List of planned ammonia import terminals in Germany, Belgium and the Netherlands

Terminal	Start year	Ammonia imports capacity (Mt)	Imported hydrogen mass (Mt)[33]
RWE Ammonia Terminal Brunsbüttel, Germany[34]	2026	2	0.27
Uniper Wilhemlshaven, Germany[35]	2026	3	0.41
Fluxys Advario Antwerp Green Ammonia Termina, Belgium[36]	2027	1.2	0.16
Horisont Koole Ammonia Terminal, Rotterdam, Netherlands[37]	2026	1	0.14
Gasunie ACE Terminal, Rotterdam, Netherlands[38]	2026	1.2	0.16
Total		**8.4**	**1.14**

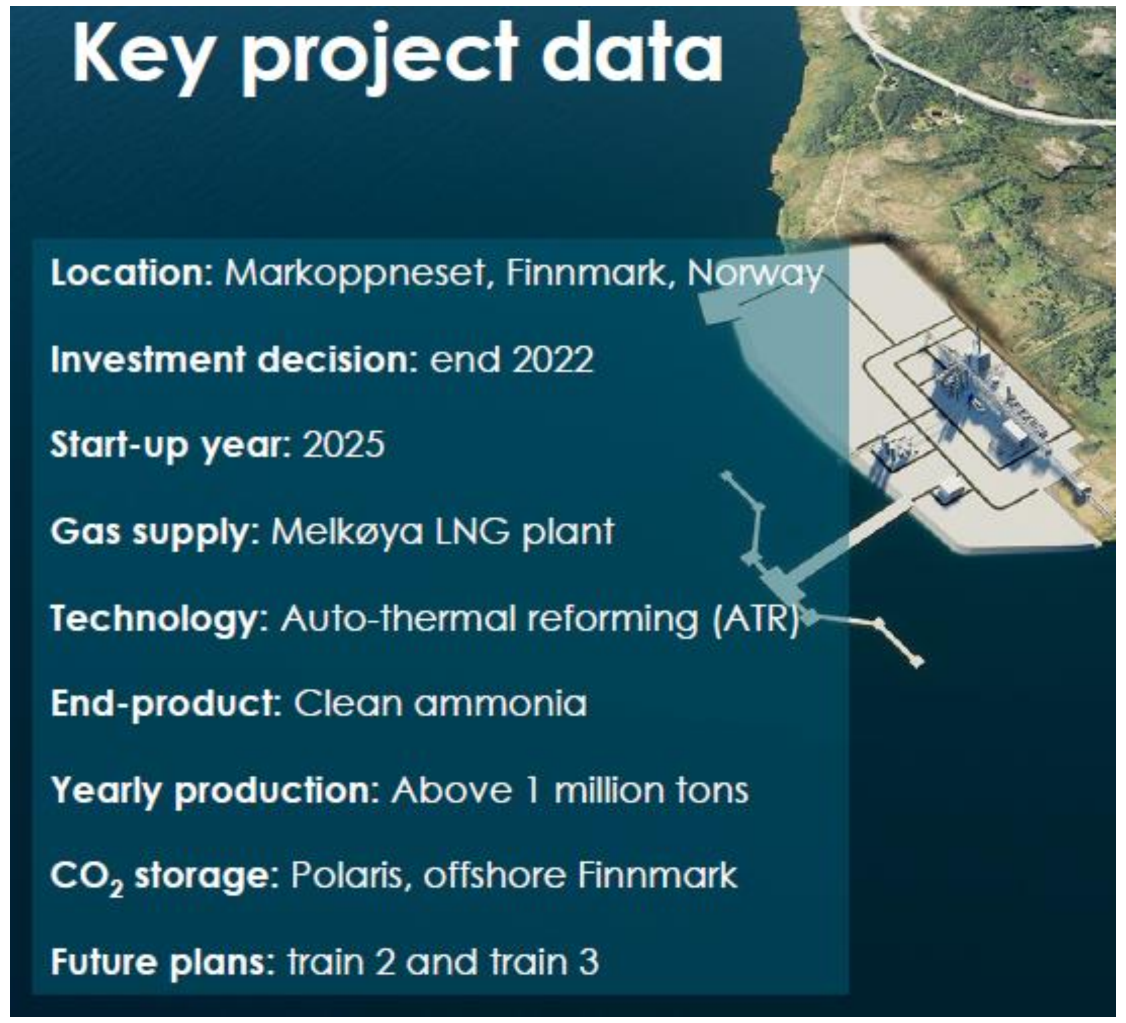
Figure 7: Ammonia terminal components[40]



https://gasforclimate2050.eu/wp-content/uploads/2022/10/2022_Facilitating_hydrogen_imports_from_non-EU_countries.pdf

Report discusses repurposing of existing LNG import terminals for ammonia

Growth in Green Ammonia Production Projects



https://www.horisontenergi.no/wp-content/uploads/2021/06/Barents-Blue-Project-Flyer-2021.pdf

"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

International Policy Drivers for Ammonia as Shipping Fuel

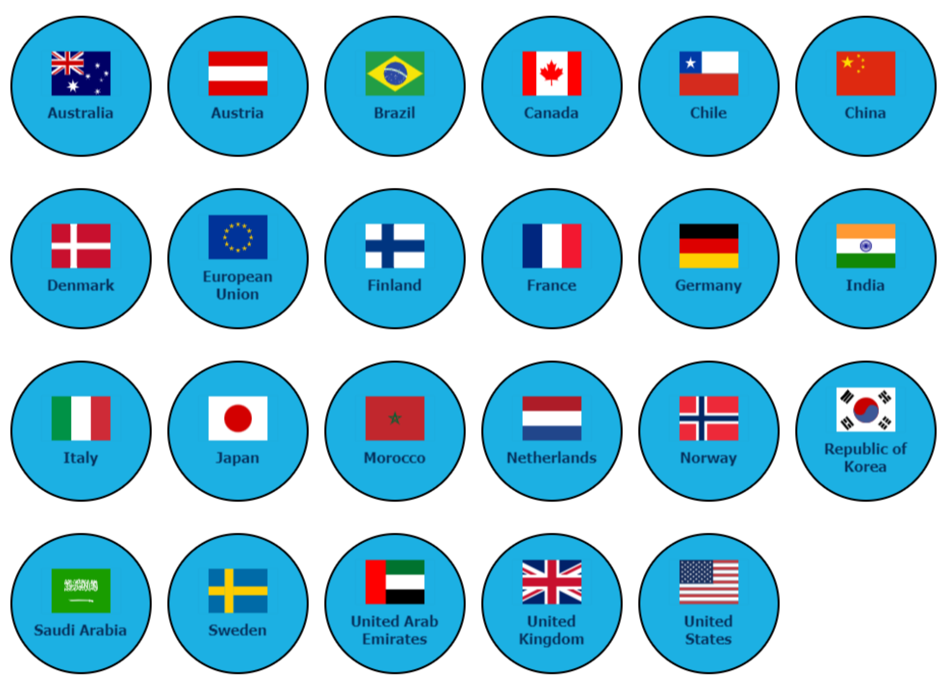
- Shipping industry responsible for 2-3% of the world's total CO_2 emissions[1]
  - And by 2050 these emissions are projected to increase by 90-130% from 2008 levels, assuming no new policies[4]
- International Maritime Organization (IMO) adopted in 2018 an initial greenhouse gas strategy[2]
  - Reduce 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

MEMBER COUNTRIES



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 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 m³-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/

FINANCIAL TIMES

Ammonia flagged as green shipping fuel of the future

Marine operators are looking to clean up their act

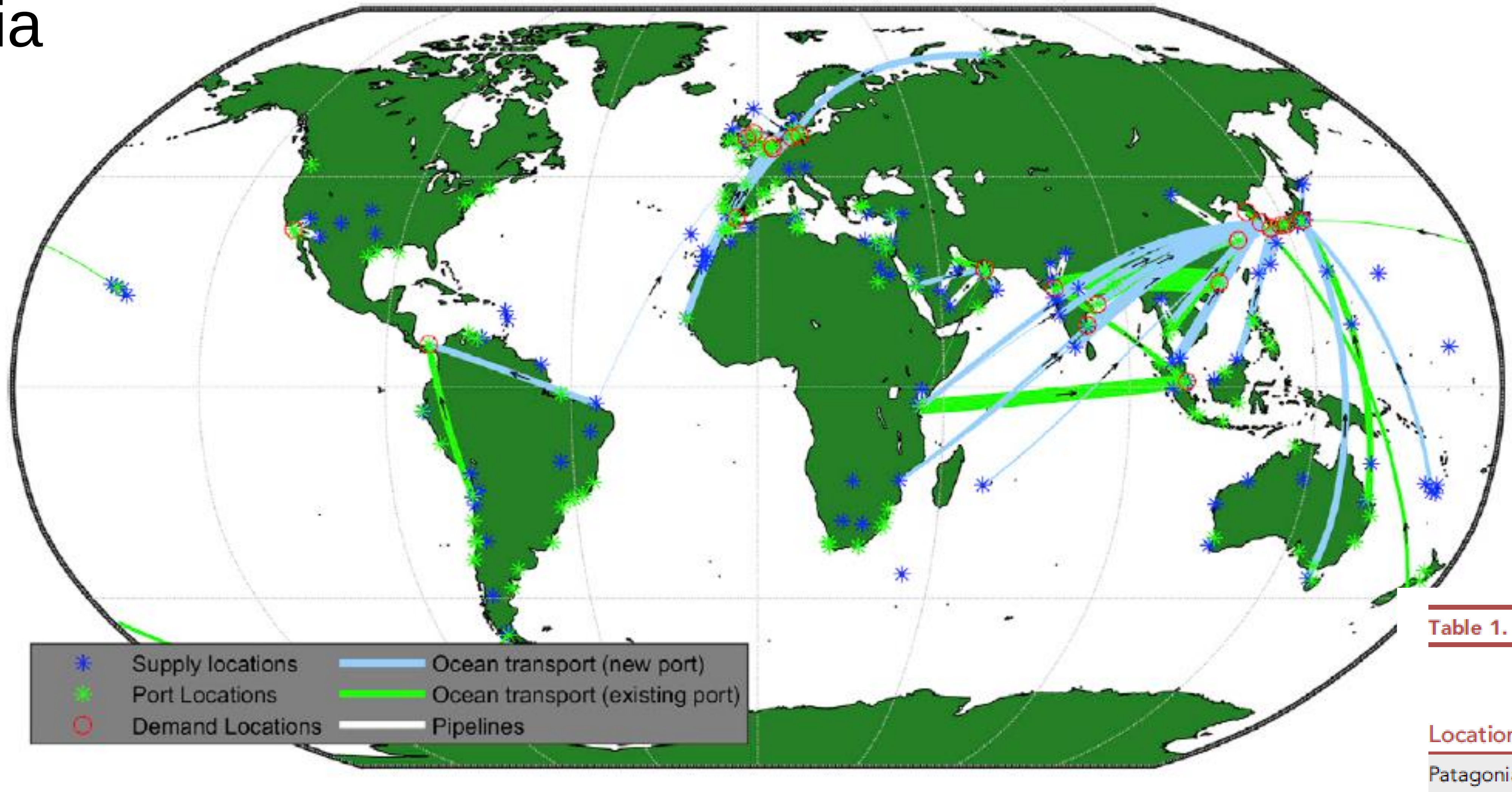
Adaptive behaviour: the Viking Energy supply vessel which is planned to run on ammonia fuel cells

Charlotte Middlehurst MARCH 30 2020

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

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

Recent Safety Studies

Lloyd's Register

Working together for a safer world

Hydrogen and Ammonia Infrastructure

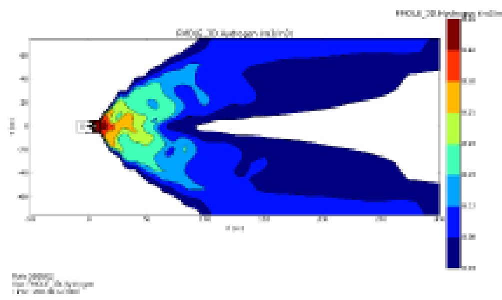
Safety and Risk Information and Guidance

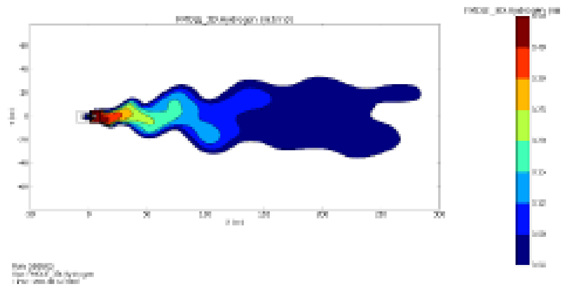
Report for:
Ocean Hyway Cluster

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





https://static1.squarespace.com/static/5d1c6c223c9d400001e2f407/t/5eb553d755f94d75be877403/158894183

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

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

Fuel	Flow rate	Focus area distance (m)		
		Fire	**Explosion**	**Toxic**
LNG	400 m^3/h (-146 °C)	249	274	- [1]
LNG	400 m^3/h (-159 °C)	330	295	- [1]
Methanol	400 m^3/h	102	- [1]	22
Ammonia (refrigerated)	400 m^3/h	- [1]	- [1]	1446
Ammonia (pressurized)	400 m^3/h	- [1]	- [1]	1478
Hydrogen (liquid)	400 m^3/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 m^3/h	448	229	- [1]
Methanol	1000 m^3/h	154	- [1]	34
Ammonia (refrigerated)	1000 m^3/h	- [1]	- [1]	2624
Ammonia (pressurized)	1000 m^3/h	- [1]	- [1]	2060
Hydrogen (liquid)	1000 m^3/h	324	338	- [1]

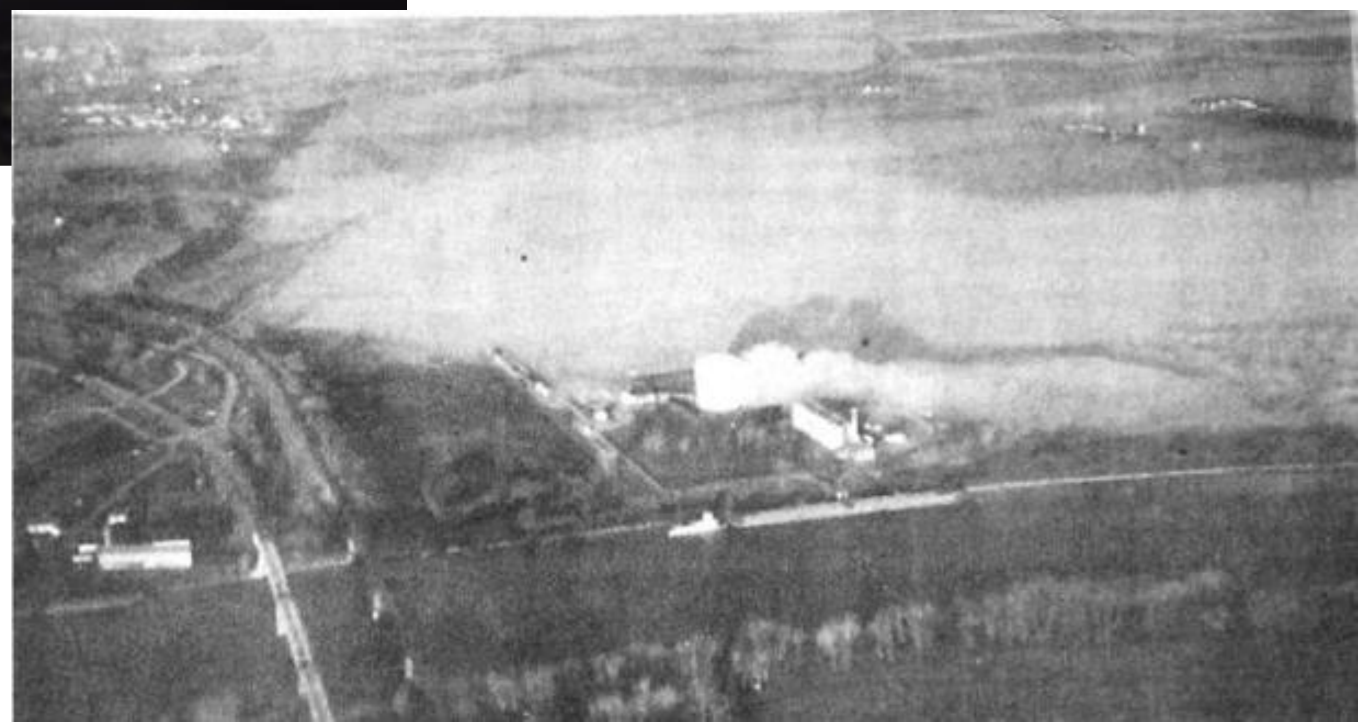
[1] The justification as to why no distances are calculated can be found under Table 7-3 in Section 7.2

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

Previous ammonia incidents

Pressure-liquefied ammonia truck release,
19 tonnes, Houston, Texas (1976)
6 dead, 78 hospitalised plus 100 injured

https://www.chron.com/news/houston-texas/houston/article/In-1976-an-ammonia-truck-disaster-claimed-the-12906732.php



Overflow from 40,000 tonne cryogenic liquid ammonia tank,
Blair, Nebraska (1970), no serious injuries
(© Washington County Enterprise,1970)

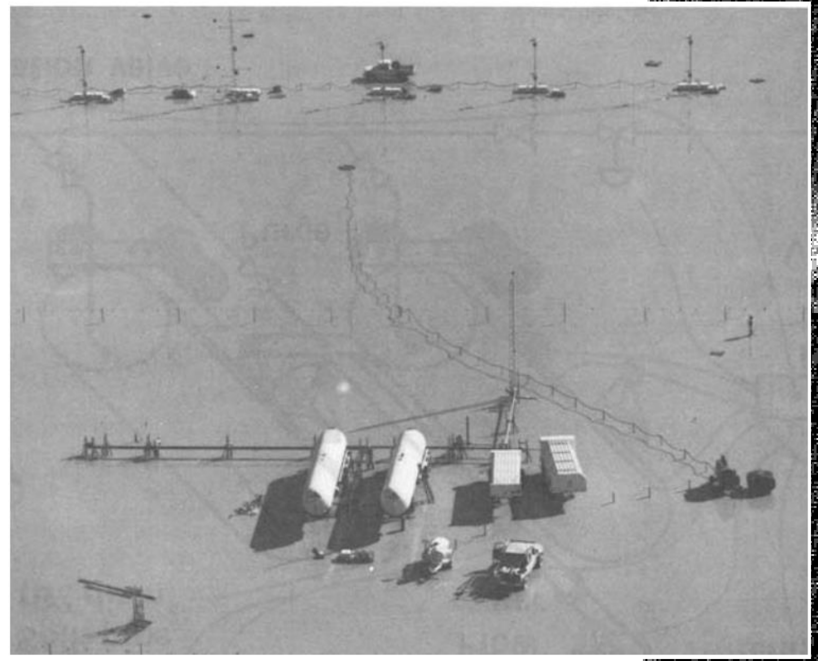
Previous Ammonia Incidents

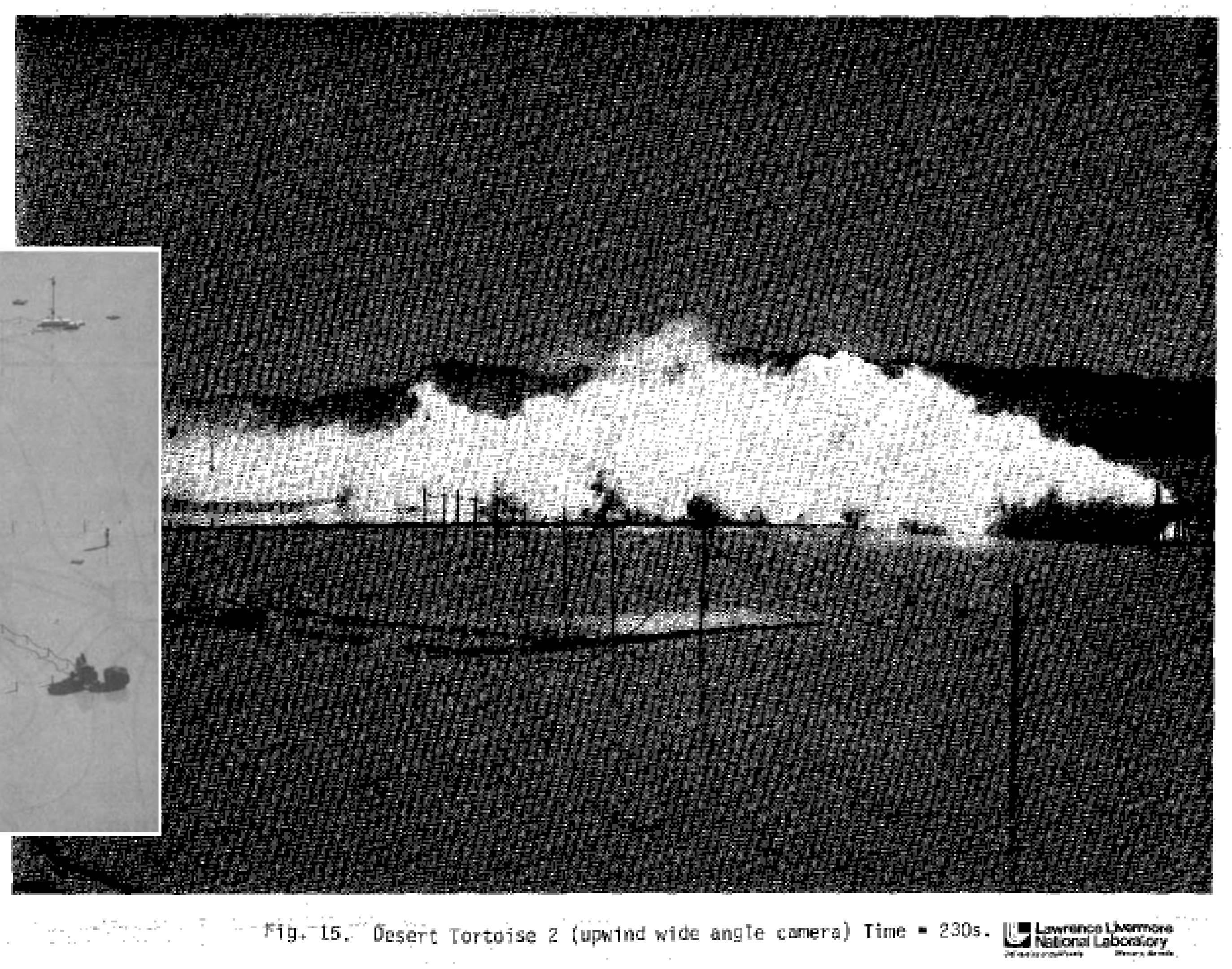
© Beach Park Fire Department, Illinois, 2019

https://www.chicagotribune.com/suburbs/lake-county-news-sun/ct-lns-ammonia-spill-no-charges-st-0626-20190625-ikztowsrhfhwhgym3lryjk4v2m-story.html

Pressure-Liquefied Ammonia Release Experiments

- **Desert Tortoise**
  - Tests conducted in 1983 at DOE Nevada Test Site
  - Release rates of 81 – 133 kg/s
  - 10 – 41 tonnes of ammonia released
  - Dispersion measurements at 100 m and 800 m
  - Largest tests to date on ammonia





Source: DesAutels & Schulman (2010)

- **FLADIS**
  - Tests conducted in 1993-4 at Landskrona, Sweden
  - Release rates of 0.25 – 0.55 kg/s
  - Dispersion measurements at 20 m, 70 m and 240 m (transition from dense to passive dispersion)

Photo © Kenneth Nyren, FOA
Source: Hall, Walker & Butler (1999)

Pressure-Liquefied Ammonia Release Experiments

- **INERIS, 1996-1997 (Bouet,1999)**
  - CEA/CESTA test site near Bordeaux, France
  - 15 ammonia releases of 2-3 tonnes, discharge rate 3-4 kg/s
  - Release orientations: horizontal, vertically-down, annular, with/without impingement
  - Six types of ammonia sensors on 150 masts at different heights on arcs from 20 m to 1700 m
  - Mitigation: effect of water sprays

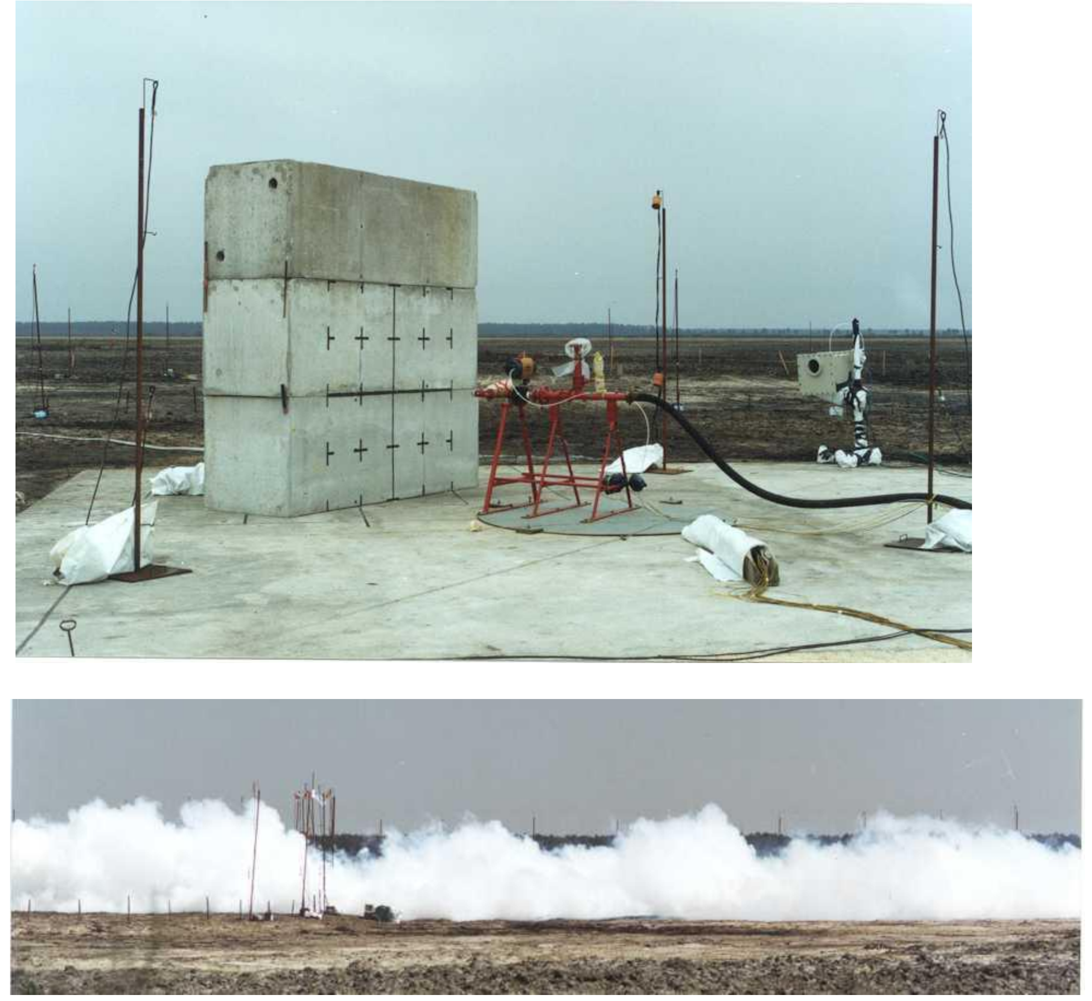


Image © INERIS. Source: Bouet (1999)

- **Jack Rabbit I, 2010**
  - Dugway Proving Ground, Utah, USA
  - Five 1 – 2 ton ammonia releases vertically downwards from 2 m AGL into 2 m deep, 50 m diameter depression
  - 62 ammonia sensors in rings from 50 m to 2,500 m
  - Some rainout and absorption of ammonia into desert playa
  - https://www.uvu.edu/es/jack-rabbit/

Image © CSAC, DHS. Source: Storwold *et al*. (2011)

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

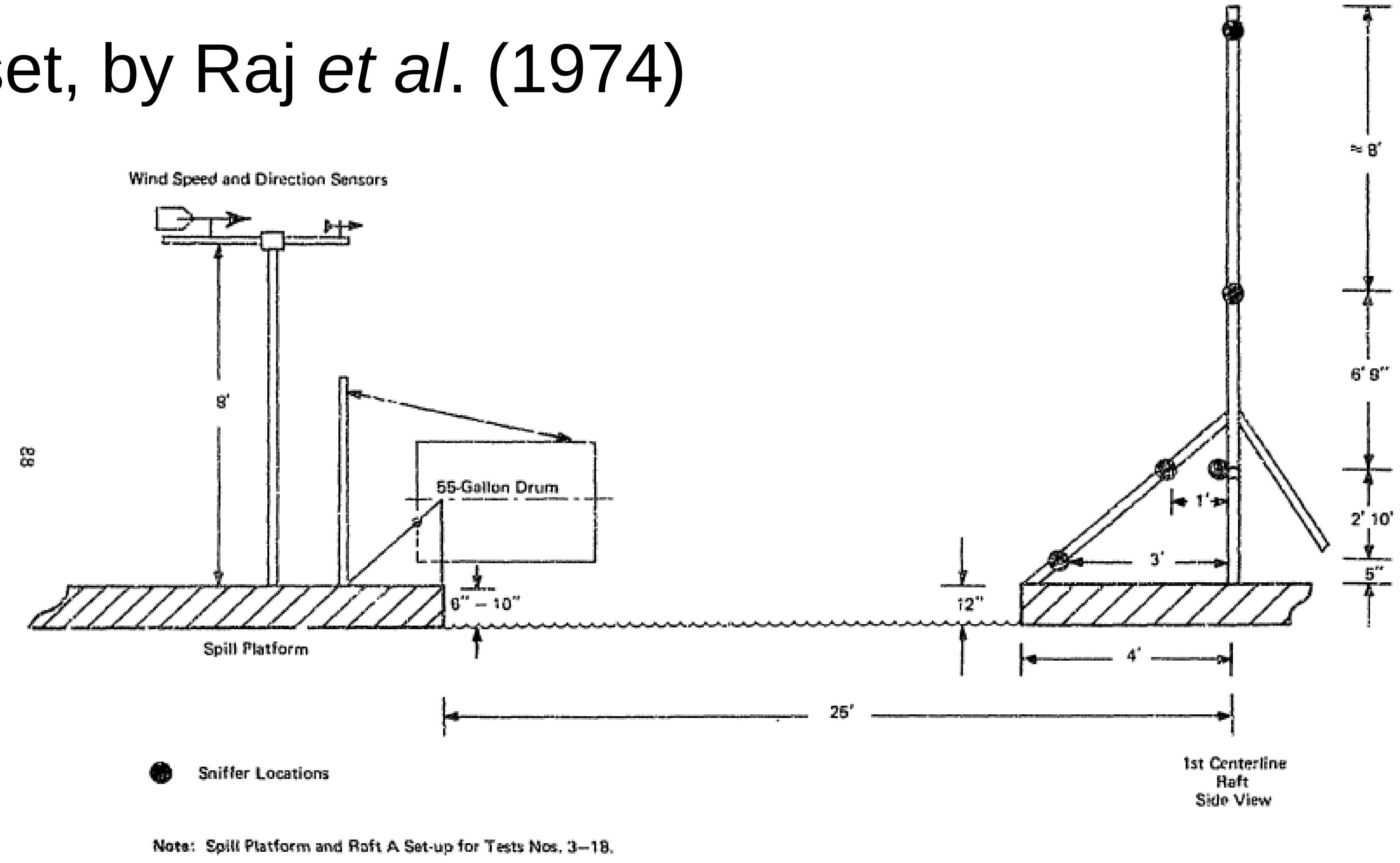
ARTHUR D. LITTLE, INCORPORATED

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



URE 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.

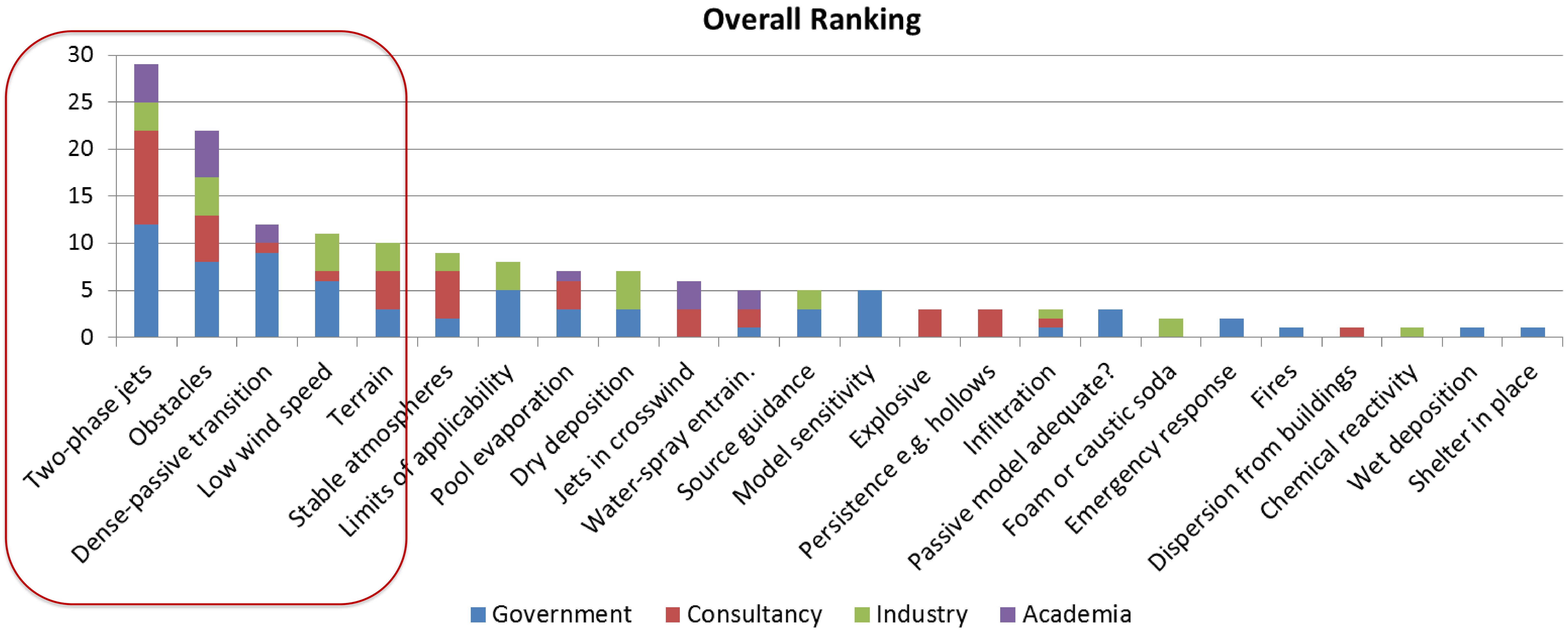
This conclusion is challenged on the grounds that it is incompatible with the experimental measurements. An alternative interpretation of the data is proposed which is shown to be consistent with the observed behaviour. In this scheme the ammonia is considered to be released as a plume containing both 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.

Scientific Knowledge Gaps

- HSE and DSTL coordinated a European expert elicitation exercise in 2020-2021
- Aim: to identify knowledge gaps that could be examined in future large-scale dispersion experiments
- Participants: Aria, BAM, BP, CEA, CERC, CNR, Demokritos, DNV, EDF, FFI, FMI, FOI, Gexcon, GT Science & Software, INERIS, Inovyn, JRC, Met Office, PHE, RIVM, Shell, Syngenta, TNO, VKI



Scientific Knowledge Gaps

- Knowledge gaps exercise run in parallel USA, coordinated by Steve Hanna
- Joint paper from USA-EU analysis published in 2021
- https://dx.doi.org/10.1002/prs.12289

Received: 19 March 2021 | Revised: 9 June 2021 | Accepted: 17 June 2021
DOI: 10.1002/prs.12289

ORIGINAL ARTICLE

PROCESS SAFETY PROGRESS

Gaps in toxic industrial chemical model systems: Improvements and changes over past 10 years

Steven Hanna[1] | Thomas Mazzola[2] | Joseph Chang[3] | Thomas Spicer[4] | Simon Gant[5] | Rachel Batt[5]

[1]Hanna Consultants, Kennebunkport, Maine, USA
[2]DTRA Reachback A&AS Support, SAIC, Lorton, Virginia, USA
[3]Engineering and Applied Sciences, RAND, Arlington, Virginia, USA
[4]Ralph E. Martin Department of Chemical Engineering, University of Arkansas, Fayetteville, Arkansas, USA
[5]Fluid Dynamics Team, Risk and Human Factors Group, HSE Science and Research Center, Health and Safety Executive, Buxton, UK

Correspondence
Steven Hanna, Hanna Consultants, 7 Crescent Ave., Kennebunkport, ME 04046, USA.
Email: stevenrogershanna@gmail.com

Funding information
Defense Threat Reduction Agency; Department of Homeland Security, Grant/Award Number: N/A; Health and Safety Executive

Abstract

To assess the hazards of the releases of toxic industrial chemicals (TICs) to the atmosphere, comprehensive model systems are often used, which begin with the scenario definition and end with an estimate of health risk. In 2008 and 2010, the US Department of Homeland Security and Defense Threat Reduction Agency sponsored reports that identified knowledge gaps in TIC modeling. The current paper discusses which of the knowledge gaps were satisfactorily resolved in the past 10 years by new theoretical and experimental research, such as the 2010 and 2015–2016 Jack Rabbit field experiments. For example, the linked source emissions and transport and dispersion (T&D) models have been shown, in comparisons with Jack Rabbit II observations, to not have large mean biases. Consequently, the T&D models are less likely to be the cause of model system overpredictions of casualties observed after large TIC accidental releases, such as the Festus, Macdona, and Graniteville chlorine railcar incidents. It may be that the deposition models and/or the health effects models still need improvement. In addition to comments on the knowledge gaps identified 10 years ago, a few new knowledge gaps are addressed, such as indoor T&D and deposition, and estimating the magnitude of the saturation deposition value for various substrates and chemicals.

KEYWORDS
anhydrous ammonia, chlorine, dense gas dispersion, hazards analysis, health risk, Jack Rabbit II field experiment, TIC

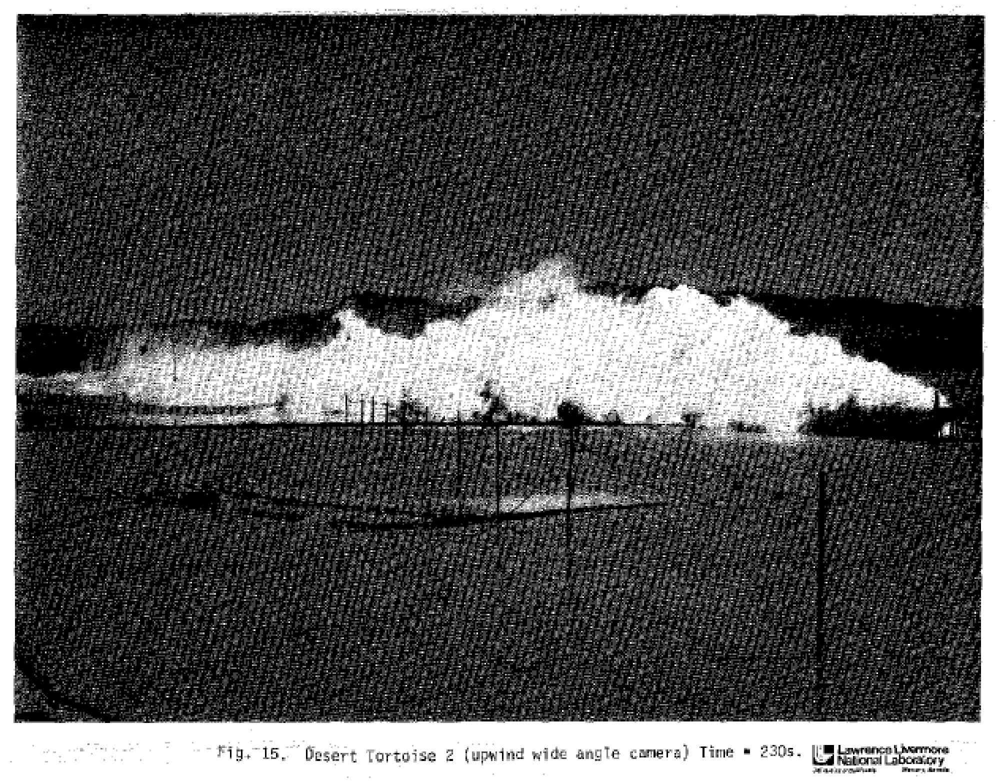
Jack Rabbit II (2015 – 2016)

Images © DHS S&T CSAC and Utah Valley University
https://www.uvu.edu/es/jack-rabbit/

Jack Rabbit III (2021 – ongoing)

JRIII Initial Modelling Exercise (2021-2022)

- Aims: run a model inter-comparison exercise to evaluate the performance of atmospheric dispersion models using data from previous ammonia release experiments
  - To understand the accuracy of models that may be used to design the Jack Rabbit III trials, e.g. to design the JRIII sensor array
  - To identify important model input parameters that we may need to carefully assess or measure in the trials



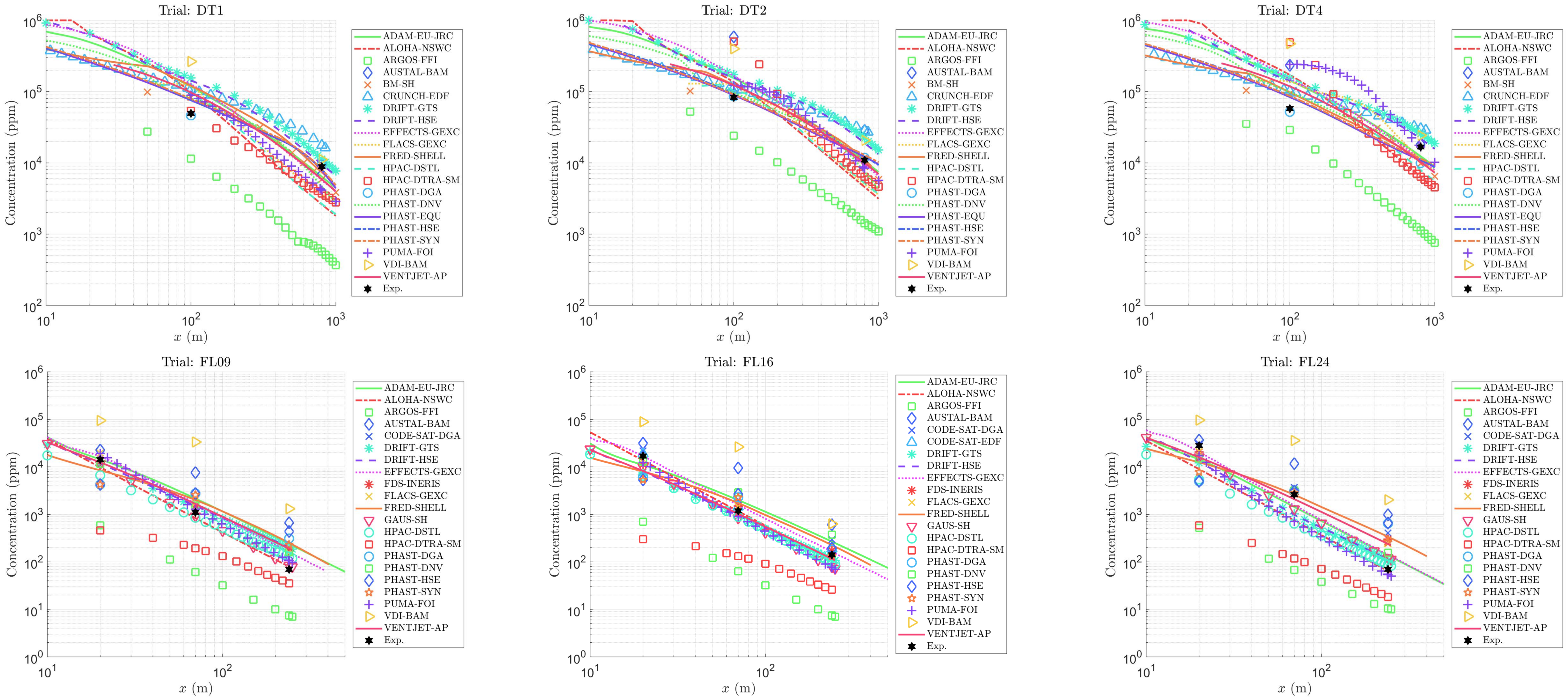
Desert Tortoise

FLADIS

Participants in the JRIII Initial Modeling Exercise

#	Organization	Model	Model Type				Desert Tortoise			FLADIS		
			Empirical nomogram/ Gaussian plume	Integral	Gaussian Puff/ Lagrangian	CFD	1	2	4	9	16	24
1	Air Products, USA	VentJet		■			■	■	■	■	■	■
2	BAM, Germany	AUSTAL			■		■	■	■	■	■	■
3		VDI	■				■	■	■	■	■	■
4	DGA, France	PHAST v8.6		■			■	■	■	■	■	■
5		Code-Saturne v6.0				■				■	■	■
6	DNV, UK	PHAST v8.61		■			■	■	■	■	■	■
7	DSTL, UK	HPAC v6.5			■		■	■	■	■	■	■
8	DTRA, ABQ, USA	HPAC v6.7			■		■	■	■	■	■	■
9	DTRA, Fort Belvoir, USA	HPAC			■		■	■	■	■	■	■
10	EDF/Ecole des Ponts, France	Code-Saturne v7.0				■					■	
11		Crunch v3.1		■			■	■	■			
12	Equinor, Norway	PHAST v8.6		■			■	■	■	■	■	■
13	FFI, Norway	ARGOS v9.10			■		■	■	■	■	■	■
14	FOI, Sweden	PUMA			■		■	■	■	■	■	■
15	Gexcon, Netherlands	EFFECTS v11.4		■			■	■	■	■	■	■
16	Gexcon, Norway	FLACS				■	■	■	■	■	■	■
17	GT Science & Software	DRIFT v3.7.19		■			■	■	■	■	■	■
18	Hanna Consultants, USA	Britter & McQuaid WB	■				■	■	■			
19		Gaussian plume model	■							■	■	■
20	HSE, UK	DRIFT v3.7.12		■			■	■	■	■	■	■
21		PHAST v8.4		■			■	■	■	■	■	■
22	INERIS, France	FDS v6.7				■				■	■	■
23	JRC, Italy	ADAM v3.0		■			■	■	■	■	■	■
24	NSWC, USA	RAILCAR-ALOHA		■			■	■	■	■	■	■
25	Shell, UK	FRED 2022		■			■	■	■	■	■	■
26	Syngenta, UK	PHAST v8.61		■			■	■	■	■	■	■

All Model Results



Future Jack Rabbit III Related Activities

- JRIII Working Groups
  - Source, instrumentation, health and human effects, modelling, emergency response, deposition and surface reactivity, data quality, waterborne

- JRIII model intercomparison exercise on an ammonia incident or JRI ammonia trials
  - Kick-off Spring/Summer 2023

- Dry deposition and surface reactivity of ammonia
  - ADMLC seminar at UKHSA, Harwell, UK in 2023?

- ADMLC webinar on "Dense gas dispersion modelling in complex terrain, with a focus on carbon dioxide pipelines", 7 March 2023
  - https://admlc.com/events/

Thank you

- Contact: simon.gant@hse.gov.uk
- The contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy