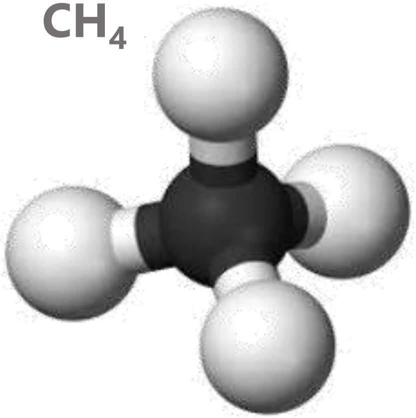
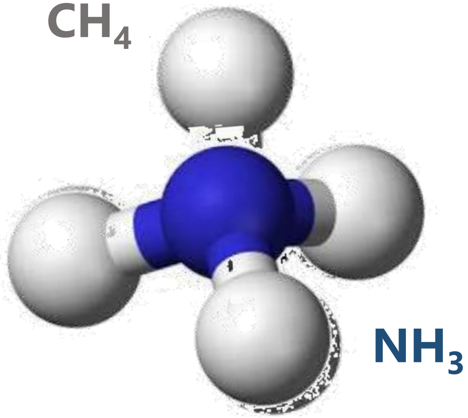
CH_4



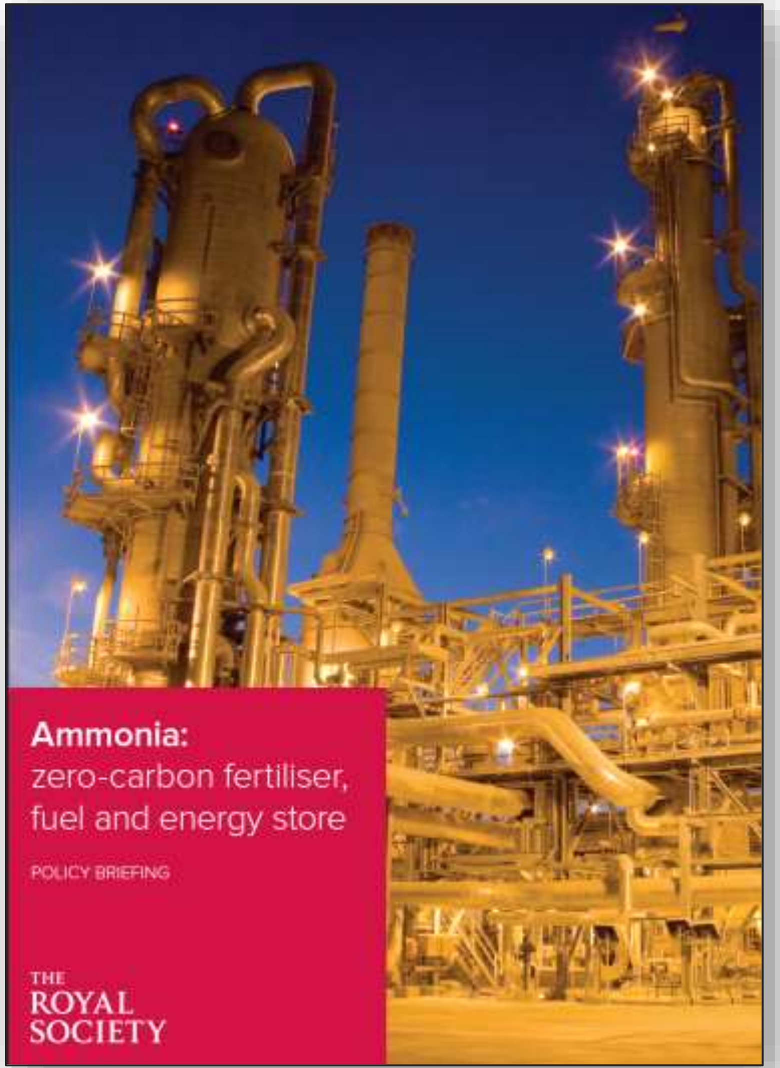


Clean Air Networks' Conference 2023

5-6 July 2023, University of Birmingham

ammonia as a green fuel:
real-zero carbon and real-zero nitrogen

BILL DAVID
PROFESSOR OF ORGANIC CHEMISTRY, INORGANIC CHEMISTRY LABORATORY, UNIVERSITY OF OXFORD, UK
STFC SENIOR FELLOW, RUTHERFORD APPLETON LABORATORY, HARWELL, OXFORDSHIRE, UK
CSO, SUNBORNE SYSTEMS LTD.



It is essential that new applications of ammonia prevent any additional emissions.

Ammonia: health and environmental considerations

In considering expanded roles for ammonia in energy storage, the health risks from ammonia exposure and the environmental risks arising from leaks must be closely scrutinised and all systems must be designed to minimise, and effectively eliminate, these risks. Ammonia is corrosive and potentially toxic. Its high vapour pressure under standard conditions enhances the risks associated with these hazards. However, ammonia is readily detectable by smell at concentrations substantially below levels that cause any lasting health consequences.

From an environmental perspective, ammonia represents a chronic hazard to terrestrial ecosystems as well as providing an increasing burden to air pollution. Human activity has greatly modified the very important biogeochemical global cycle. The global industrial synthesis of ammonia along with combustion sources of nitrogen compounds are similar in magnitude to the natural global fixation of atmospheric nitrogen by microbes in soils and in the oceans (Figure 7).

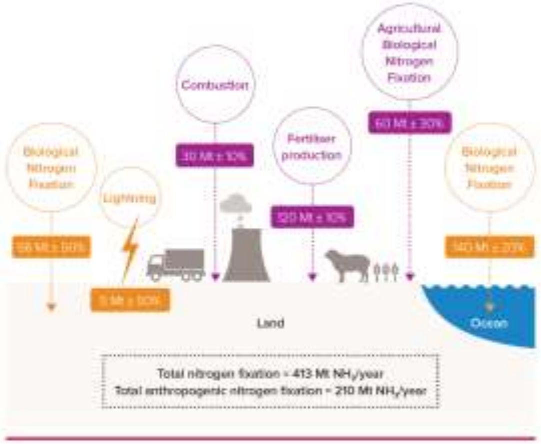
Agricultural fertilisers account for 80% of annual ammonia production but only 17% of that nitrogen is consumed by humans in crops, dairy and meat products[9]. The remainder leaches into the soil, air and water causing widespread biodiversity losses, eutrophication, and air quality issues from particulate matter, emissions of greenhouse gases and stratospheric ozone loss[10].

Once ammonia has been applied to soils either from fertilisers or deposited from the atmosphere, it is transformed, by microbes and depending on soil conditions, to a range of other compounds including nitric oxide, nitrous oxide, and molecular nitrogen.

Although ammonia is itself not a greenhouse gas, following deposition to soil it may be converted to nitrous oxide, an important contributor to radiative forcing of climate. It also has a substantial indirect impact on climate through its role in particulate matter. One of the most significant measures to improve the resulting air pollution in the UK, and more widely in Europe, is to minimise agricultural ammonia emissions, through decreasing deposition[11]. It is therefore important and essential that any new applications of ammonia include effective measures to prevent any additional emissions. In contrast to fertilisers, nitrogen release from energy storage applications of ammonia should be as nitrogen gas only. Stringent controls, which are already present at all ammonia storage and relevant industrial sites, must be in place for ensuring that the risks of ammonia release and NO_x formation are negligible.

FIGURE 7

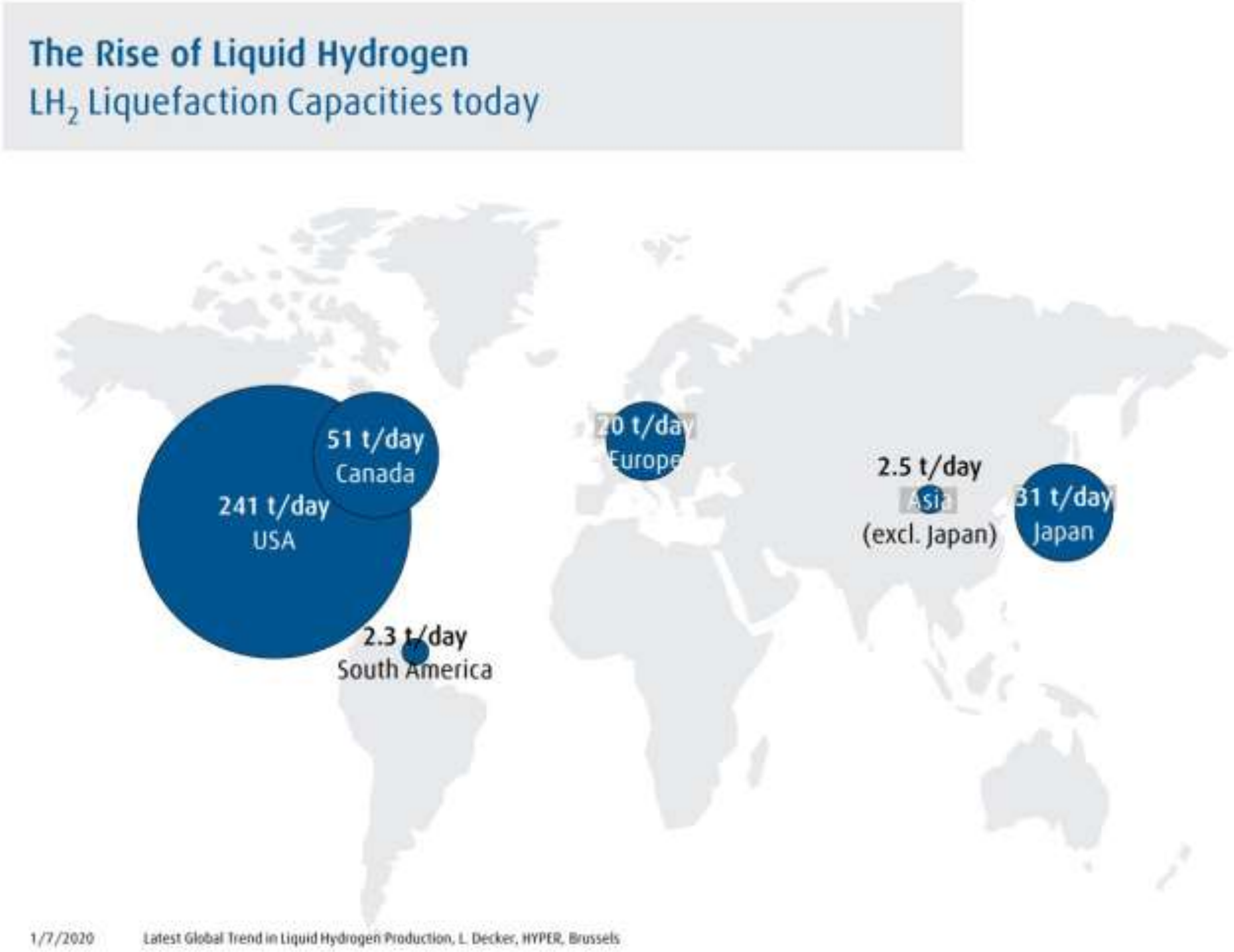
The global fixation of atmospheric nitrogen to reactive forms (ammonia, nitric oxide and nitrogen dioxide). The orange arrows represent natural processes, mainly Biological Nitrogen Fixation (BNF), the purple arrows represent anthropogenic sources[12].



’THE HYDROGEN
ECONOMY’
INFRASTRUCTURE

The term ‘Hydrogen Economy’ was coined by John Bockris during a talk he gave in 1970 at the GM Technical Centre.

World Power Consumption (TW) 18.9



350t/day ≅ 127,000t/yr

H_2 ΔH(LHV) = 33.3MWh/t

≅ **4.2TWh/yr**

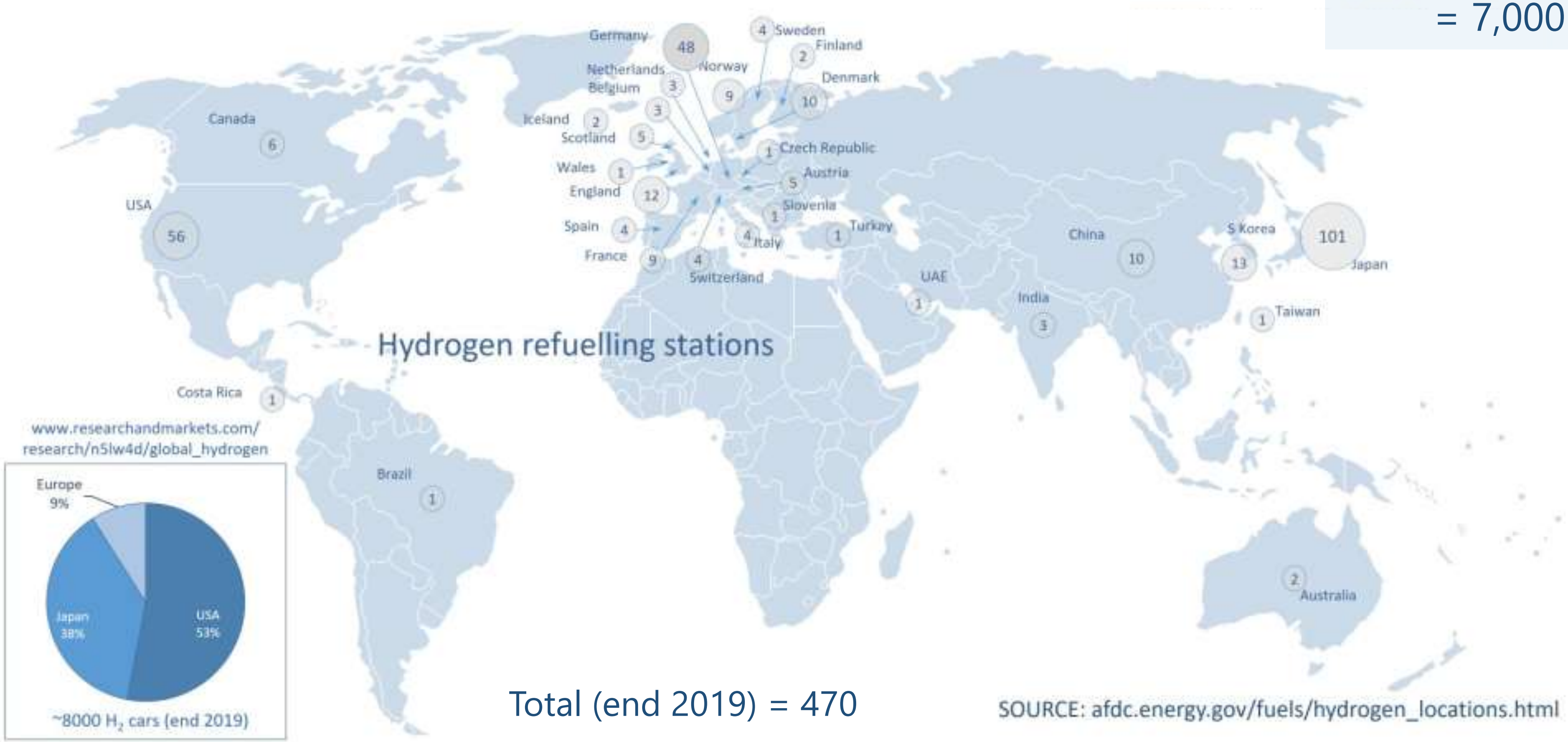
(4.2 × 60)/18.4 ≅ 14 mins

World Power Consumption (TW) 18.9

The hydrogen distribution infrastructure isn’t here yet.

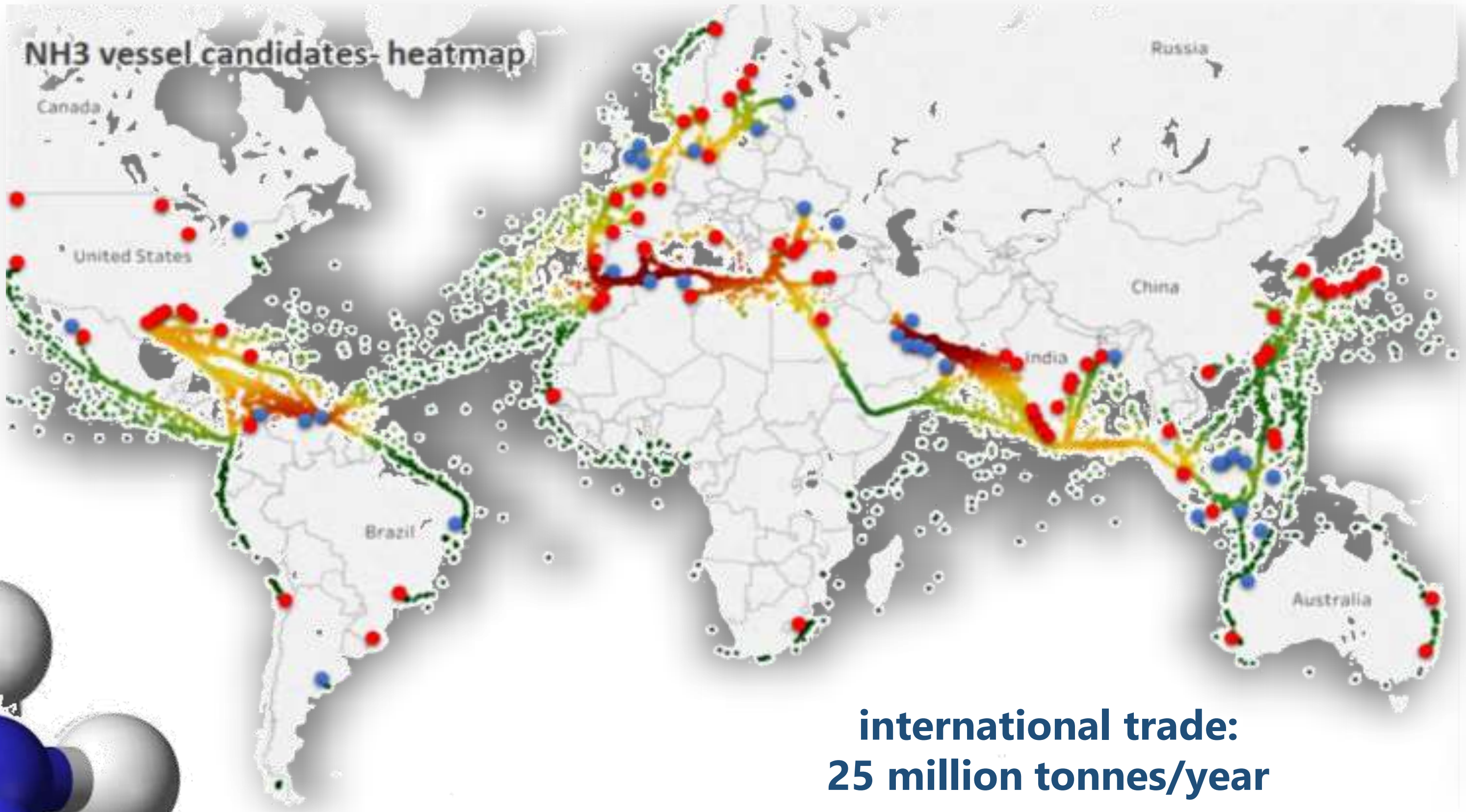
Global hydrogen refuelling infrastructure
100kg/day × 150 days × 470 stations
= 7,000 tonnes/year | 55,000 cars

7,000 tonnes/year
≅ **5.4GWh/year**
→ 10 seconds

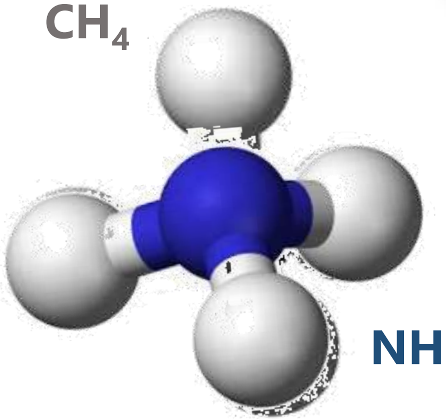


Total (end 2019) = 470

World Power Consumption (TW) 18.9



international trade:
25 million tonnes/year



2019 (global)

production: 182.2Mt/yr
capacity: 224.4Mt/yr

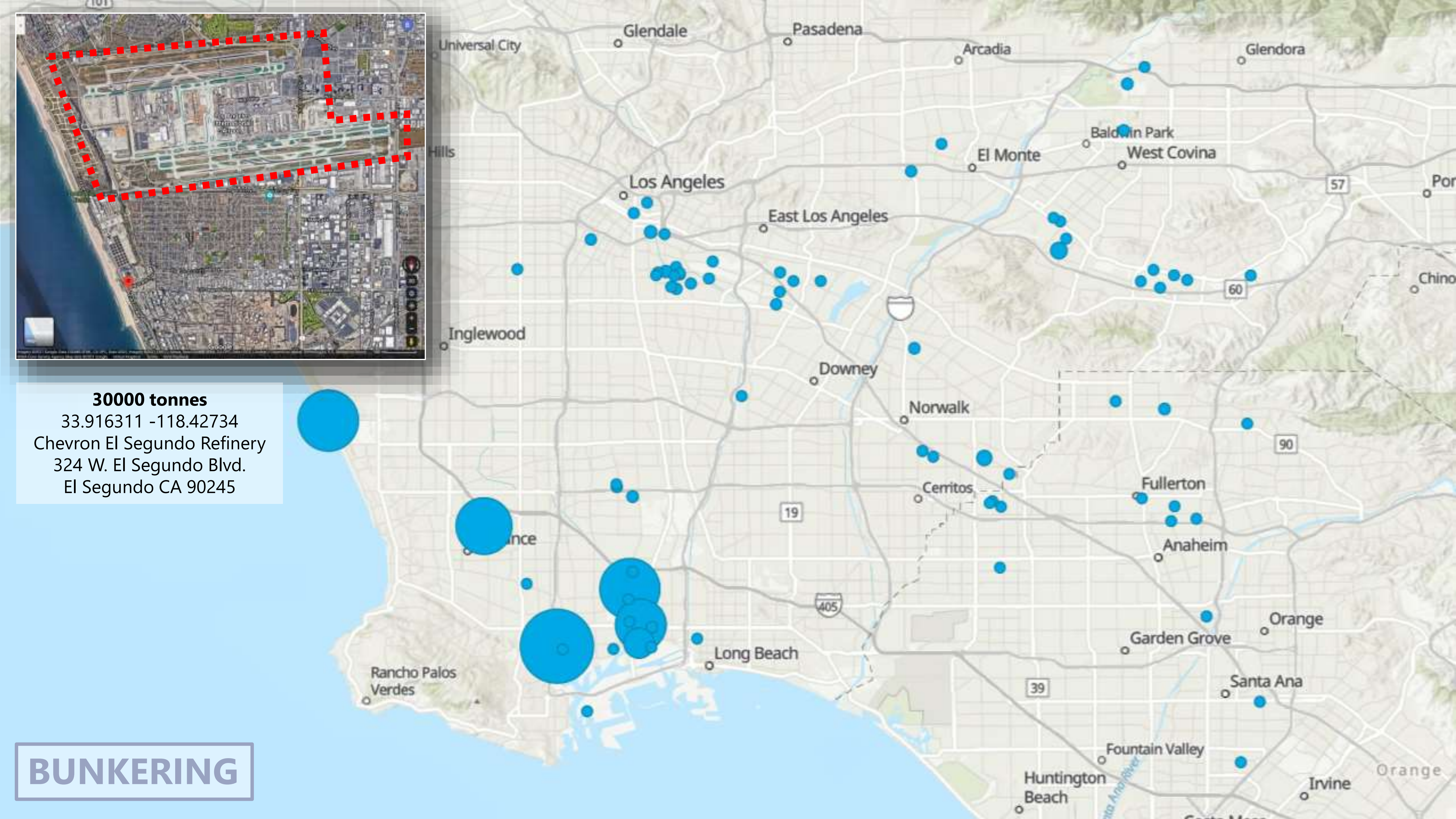
NH_3 (ΔH_{LHV}-ΔH_{vap}) = 3.9MWh/t

= 3.9TWh/Mt

production: **710TWh/yr**
capacity: **875TWh/yr**

production: (710/18.87)h
capacity: (875/18.87)h

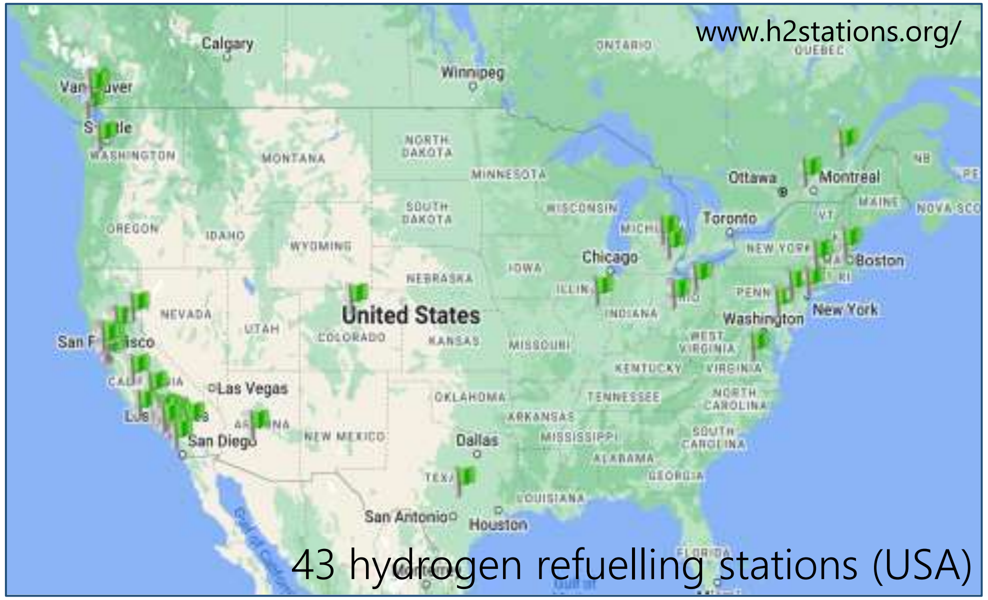
production: 37h
capacity: 46h



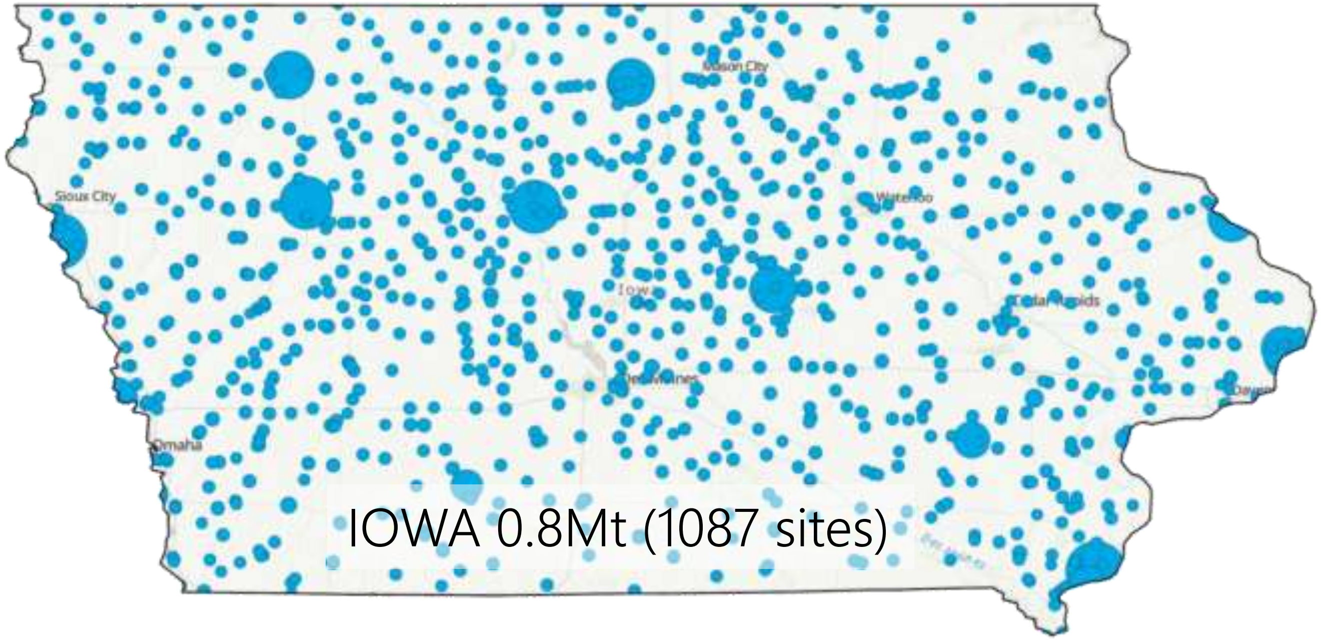
30000 tonnes
33.916311 -118.42734
Chevron El Segundo Refinery
324 W. El Segundo Blvd.
El Segundo CA 90245

BUNKERING

DISPATCHED AND DISTRIBUTED FUEL STORAGE: US STATUS



43 hydrogen refuelling stations (USA)

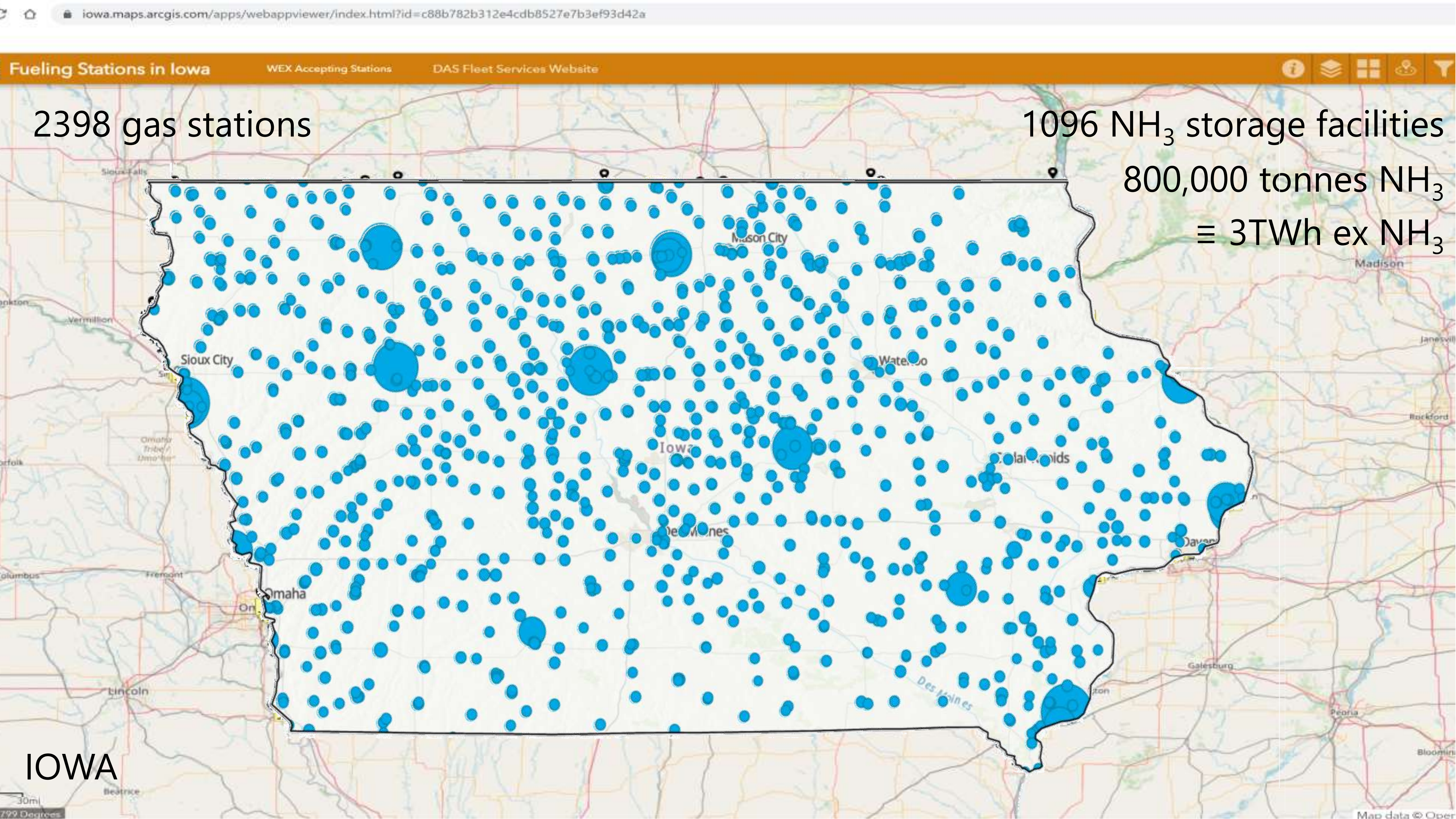


IOWA 0.8Mt (1087 sites)

US NH_3 storage facilities: 10,636
US capacity: 24.2Mt NH_3/year
US production: 22.2Mt NH_3/year

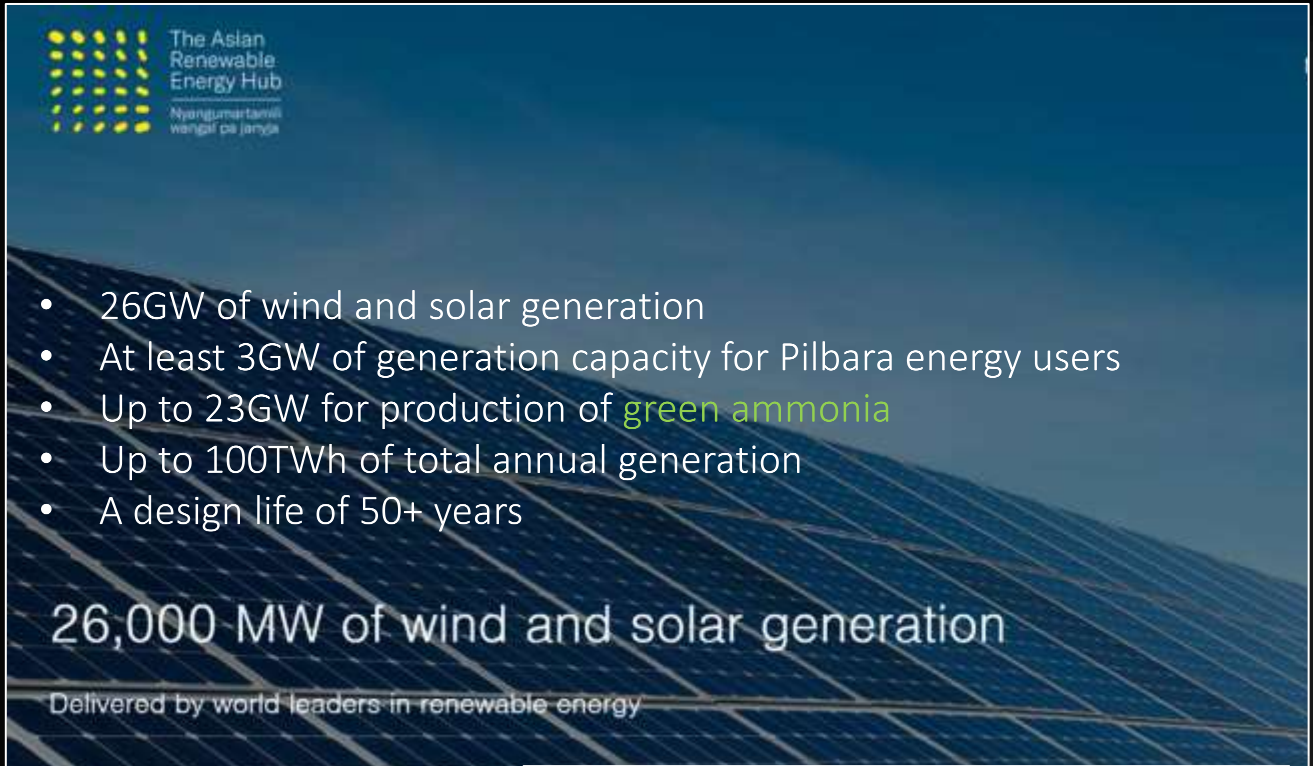
43× 100kg/day × 250 days/year
→ 1075 tonnes H_2/year → 36GWh/year

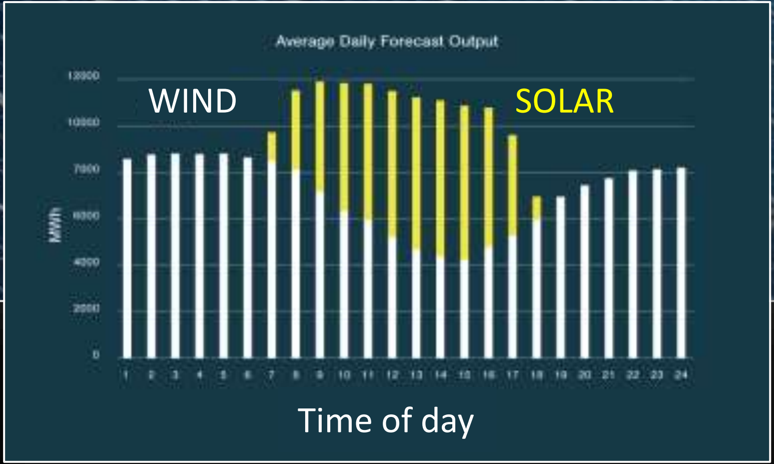
24.2Mt NH_3/year → 122TWh/year = 122,000GWh/year
×3400

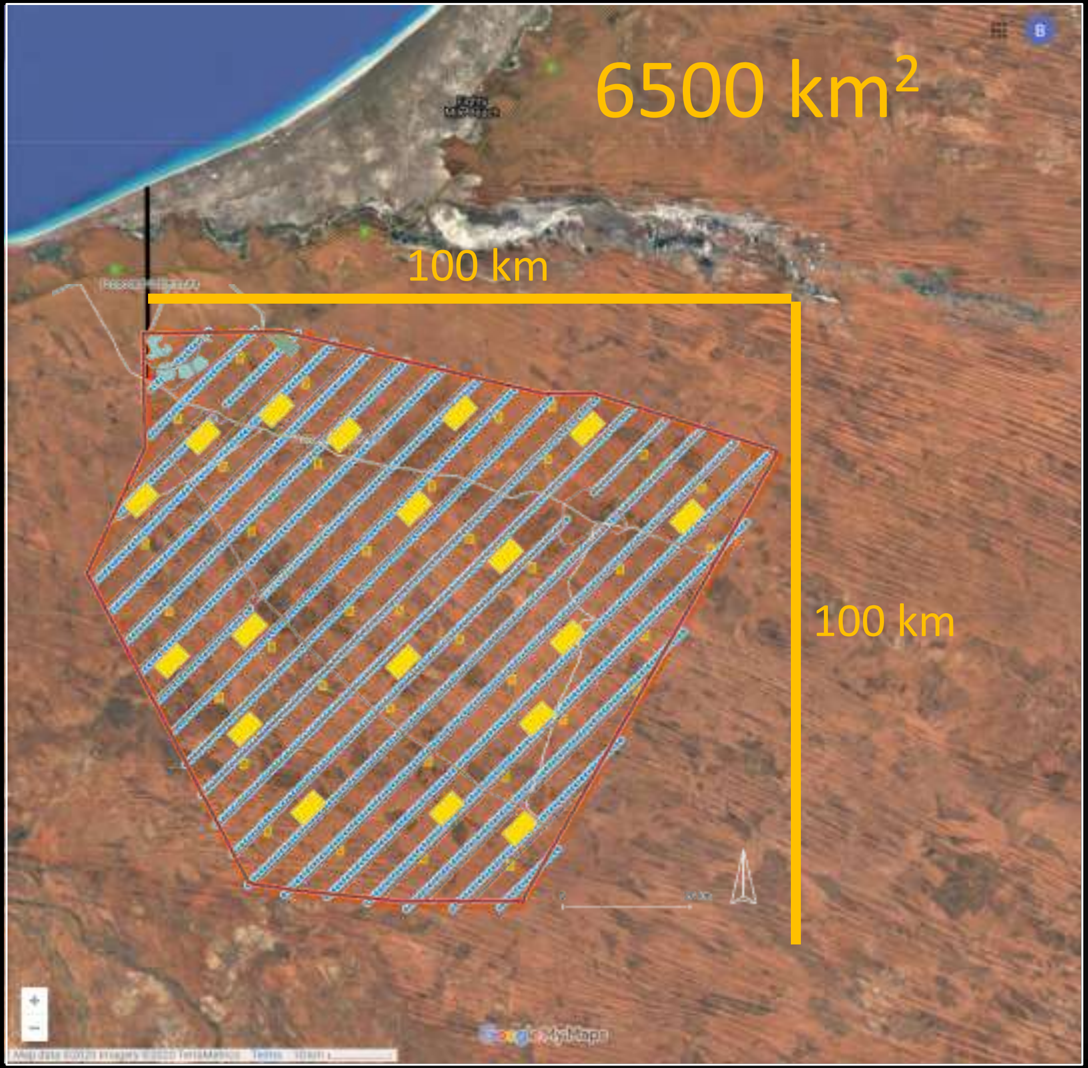


iowa.maps.arcgis.com/apps/webappviewer/index.html?id=c88b782b312e4cdb8527e7b3ef93d42a
Fueling Stations in Iowa
WEX Accepting Stations
DAS Fleet Services Website
2398 gas stations
1096 NH_3 storage facilities
800,000 tonnes NH_3
≡ 3TWh ex NH_3
Sioux City
Mason City
Waterloo
Iowa
Omaha
Madison
Lincoln
IOWA

- 26GW of wind and solar generation
- At least 3GW of generation capacity for Pilbara energy users
- Up to 23GW for production of green ammonia
- Up to 100TWh of total annual generation
- A design life of 50+ years







Low-Carbon Ammonia Plants Project List - April 2022.xlsx [Read-Only] - Excel

Low carbon ammonia plant list

ID	Project name	Location	Country	Continent	Company	Status	Year	Capacity (t/y)	Capacity (kt/	Capacity (Mt,	Project type	Hydrogen production techno	Hydrogen licensor	Plant Type
WGEH_1	WGEH	Western Australia	Australia	Oceania	Intercontental Energy, CWP Global	Announced		20000000	20000.00	20.00	Newbuild	Electrolysis		Renewable
FFIArgent_3		Patagonia	Argentina	Latin America	Fortescue Future Industries	Announced	2030	12359551	12359.55	12.36	Newbuild	Electrolysis		Renewable
Papua_1			Papua New Guinea	Oceania	Fortescue Future Industries, Papua Ne	Announced		11500000	11500.00	11.50	Newbuild	Electrolysis		Renewable
AMAN_1	AMAN		Mauritania	Africa	CWP Global	Announced		11425000	11425.00	11.43	Newbuild	Electrolysis		Renewable

Company	Status	Year	Capacity (t/y)	Capacity (kt/	Capacity (Mt,	Project type	Hydrogen production techno	Hydrogen licensor	Plant Type
Intercontental Energy, CWP Global	Announced		20000000	20000.00	20.00	Newbuild	Electrolysis		Renewable
Fortescue Future Industries	Announced	2030	12359551	12359.55	12.36	Newbuild	Electrolysis		Renewable
Fortescue Future Industries, Papua Ne	Announced		11500000	11500.00	11.50	Newbuild	Electrolysis		Renewable
CWP Global	Announced		11425000	11425.00	11.43	Newbuild	Electrolysis		Renewable
OQ, Intercontinental Energy, EnerTech	Announced	2038	10450000	10450.00	10.45	Newbuild	Alkaline or PEM electrolysis		Renewable
Saudi Aramco, Intercontinental Energy,	Announced		10000000	10000.00	10.00	Newbuild	Electrolysis		Renewable
Intercontinental Energy	Announced	2035	9900000	9900.00	9.90	Newbuild	Alkaline electrolysis		Renewable
Total Eren	Announced	2027	4400000	4400.00	4.40	Newbuild	Electrolysis		Renewable
Intercontinental Energy	Announced	2030	3000000	3000.00	3.00	Newbuild	Alkaline electrolysis		Renewable
Horisont Energi	Announced		3000000	3000.00	3.00	Newbuild	Autothermal reforming		Fossil
Woodside Energy	Announced		2949438	2949.44	2.95	Newbuild	Alkaline or PEM electrolysis		Renewable
Hyphen Hydrogen Energy	Announced	2030	2592000	2592.00	2.59	Newbuild	Electrolysis		Renewable
Proton Ventures, Trammo, Global Ener	Announced		2500000	2500.00	2.50	Newbuild	Electrolysis		Renewable
Province Resources, Total-Eren	Announced	2030	2400000	2400.00	2.40	Newbuild	Electrolysis		Renewable
Woodside Energy	Announced	2023	2359551	2359.55	2.36	Newbuild	Natural gas reforming		Fossil
MRHP, Copenhagen Infrastructure Part	Announced	2028	1900000	1900.00	1.90	Newbuild	PEM electrolysis		Renewable

ID	Project name	Location	Country	Continent	Company	Status	Year	Capacity (t/y)	Capacity (kt/	Capacity (Mt,	Project type	Hydrogen production techno	Hydrogen licensor	Plant Type
Freeport_1		Freeport	United States	North America	Yara, BASF	Operational	2018	750000	750.00	0.75	Newbuild	Ethane cracking		Fossil
HyEx_2	HyEx	Antofagasta	Chile	Latin America	Enaex, ENGIE	Announced	2030	700000	700.00	0.70	Newbuild	Electrolysis		Renewable
Iowa_2		Iowa	United States	North America	OCI Nitrogen	Announced		700000	700.00	0.70	Revamp	Natural gas reforming		Fossil
PAU_1	PT Panca Amara Utama ammonia plant	Central Sulawesi	Indonesia	Asia	PAU joint-venture	Announced	2026	660000	660.00	0.66	Revamp	Natural gas reforming		Fossil
Esbjerg_1		Esbjerg	Denmark	Europe	Copenhagen Infrastructure Partners, N	Announced	2026	650000	650.00	0.65	Newbuild	Electrolysis		Renewable
PLNL_1		Point Lisas	Trinidad & Tobago	North America	Point Lisas Nitrogen Ltd.	Operational	1998	648000	648.00	0.65	Newbuild	Natural gas reforming		Fossil
PortBonython_1	Port Bonython blue hydrogen	Port Bonython	Australia	Oceania		Announced		625500	625.50	0.63	Newbuild			Fossil
H2Perth_1	H2Perth	Perth	Australia	Oceania	Woodside Energy	Announced	2023	589888	589.89	0.59	Newbuild	Alkaline or PEM electrolysis		Renewable
Billingham_1		Billingham	United Kingdom	Europe	CF Industries	Announced		540000	540.00	0.54	Revamp	Natural gas reforming		Fossil
GreenWolv_1	Green Wolverine	Lulea-Boden	Sweden	Europe	Fertiberia	Announced	2026	520000	520.00	0.52	Newbuild	Electrolysis		Renewable
HYPORT_2	HYPORT*	Duqm	Oman	Middle East	DEME Concessions, OQ	Announced		520000	520.00	0.52	Newbuild	Electrolysis		Renewable
Bolivia_1		Oruro	Bolivia	Latin America	H2 Bolivia, Government of Oruro	Announced	2024	500000	500.00	0.50	Newbuild	Electrolysis		Renewable
Porsgrunn_2		Porsgrunn	Norway	Europe	Yara, Statkraft, Aker Horizons	Announced	2026	500000	500.00	0.50	Revamp	Electrolysis		Renewable
TarafertG_1	Tarafert-2	La Laguna	Mexico	North America	Tarafert	Announced	2026	500000	500.00	0.50	Newbuild	Electrolysis		Renewable
Joffre_1		Joffre	Canada	North America	Nutrien	Operational	1987	490000	490.00	0.49	Newbuild	Ethane cracking		Fossil
Aghada_1		Aghada	Ireland	Europe	EI-H2, Zenith	Announced	2028	488764	488.76	0.49	Newbuild	Electrolysis		Renewable
YURI_3	YURI	Pilbara	Australia	Oceania	Yara, ENGIE	Announced	2028	480000	480.00	0.48	Revamp and Newbuild	Alkaline or PEM electrolysis		Hybrid
Origin_1	Origin Energy Bell Bay Green Hydrogen and Ammoni	Bell Bay	Australia	Oceania	Origin	Announced	2025	420000	420.00	0.42	Newbuild	Electrolysis		Renewable
Coffeyville_1	Coffeyville fertilizer plant	Coffeyville	United States	North America	CVR Energy, Chaparral Energy, Blue Sou	Operational	2013	375000	375.00	0.38	Revamp	Gasification		Fossil

Plant list

announced low-carbon ammonia plants project list (courtesy Ammonia Energy Association) https://airqualitynews.com/news/fuels-news/green-ammonia-plant-receives-funds-to-move-from-concept-to-reality/

The air quality news and information site
airqualitynews.com
Part of the PSN Network

Fuels , Headlines

Green ammonia plant receives funds to move from concept to reality

Paul Day
April 14th 2023

In May last year, the Science and Technology Facilities Council (STFC) announced that they, along with partners Frazer-Nash Consultancy had won £284,000 in early-stage funding to design a green ammonia plant.

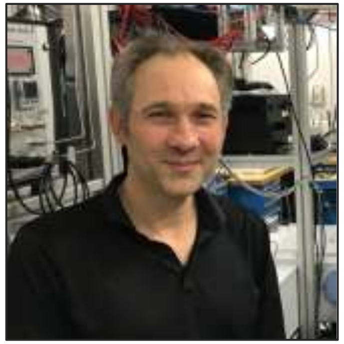
The funding was awarded by the Department for Business, Energy and Industrial Strategy (BEIS) through its Net Zero Innovation Portfolio Low Carbon Hydrogen Supply 2 competition after the team put forward their plans to create a complete and ready-made design for industry.

The project, which was titled the Ammonia Synthesis Plant from Intermittent Renewable Energy (ASPIRE) initiative has now been awarded another £4.28 million by the Department for Energy Security and Net Zero to develop a small demonstration plant at the STFC Rutherford Appleton Laboratory in Oxfordshire.

While ammonia has long been made in chemical plants (grey ammonia) for use in fertiliser, the global CO2 footprint of the industry is equivalent to the total output of South Africa's energy industry. What's more, its potential as a 'superfuel' means demand for ammonia will increase rather than decrease, so a more environmentally friendly method of producing it was needed.

As Dr Tristan Davenne, Senior Research Engineer in STFC's Energy Research Unit said last year: 'Although ammonia-based technology looks set to be a major player in a carbon-free future, currently its production creates a significant amount of greenhouse gas.

'To make ammonia fuel truly green and sustainable, we need to think about making the production process carbon free as well. Our aim is to design a flexible scalable plant which is optimised to generate green ammonia from intermittent renewable power sources such as wind and solar.'

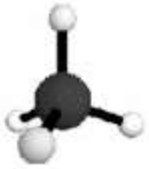


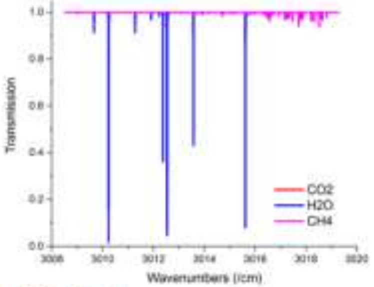
Damien Weidmann

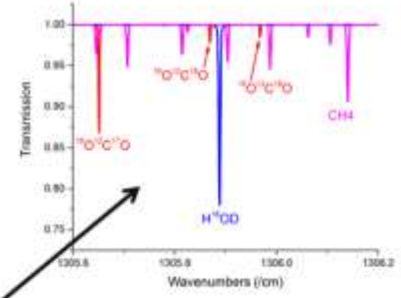
Principles of Molecular Sensing

High spectral resolution for fingerprinting

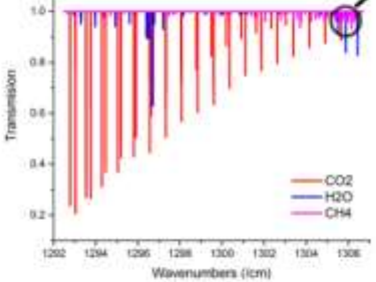
Stretching - Vibration mode ν3 - 3157 cm^{-1}







Bending - Vibration mode ν4 - 1367 cm^{-1}



- Narrow window sufficient
- Sounding optimization
- Information from a resolved line
  - Altitudinal information
  - Non LTE effects
  - Velocity
  - EM field information
  - Isotopologue discrimination

RAL Space

MIRICO Transformational Gas Measurement

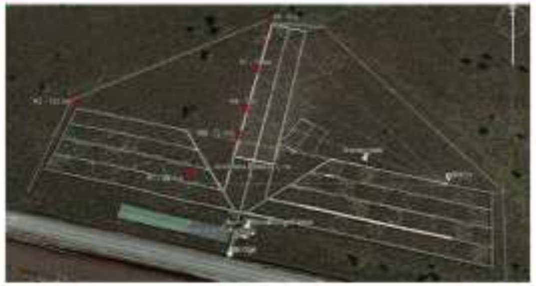
UK Centre for Ecology & Hydrology

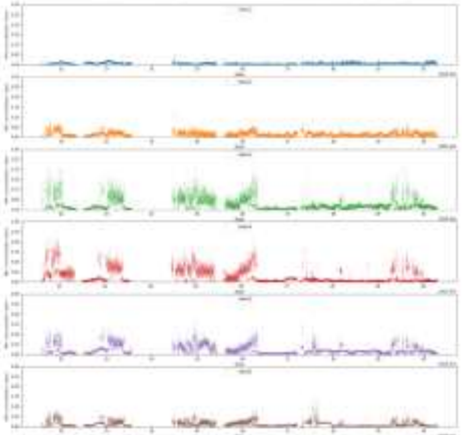
UKRI Science and Technology Facilities Council RAL Space

ORION: A new open-path ammonia sensor

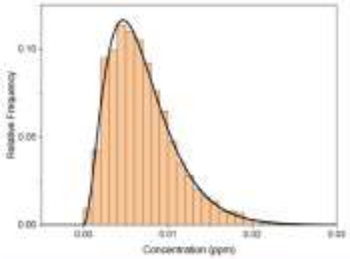
Richard Kovacich[1*], Catlin Gunn[1], Sophie Purser[1],
Marsailidh Twigg[2], Matthew Jones[2], Duncan Harvey[2], and Damien Weidmann[1,3]
[1] Mirico, Unit 6, Zephyr Building, Eighth Street, Harwell Campus, Didcot OX11 0RL, UK
[2] UK Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, UK
[3] STFC RAL Space, Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK
* richard.kovacich@mirico.co.uk

- Open-path laser dispersion spectrometer
- Autonomous system, continuous measurements
- Can measure over many paths to give spatial and temporal information
- Operates in a wide range of weather conditions
- 360° horizontal coverage, ±10° vertical





- 10-day field trial at the Whim Bog Facility
- Measured controlled releases of ammonia over ~1 km^2 using 6 retro-reflectors
- ORION operated in several periods of heavy rain with no deterioration in performance



- Immediate response to ammonia release
- No tailing at the end of a release
- Measurement limit 1 ppm·m over 1 sec (10 ppb over 100 m)
- Long-term statistics over 6 days give a background of 6.9 ppb ± 4 ppb.

- Improvements have been identified that will allow a dynamic range of 0.1 ppb → 4 ppm.
- Measurements were carried out in partnership with the UK Centre for Ecology and Hydrology

SUNBORNE SYSTEMS

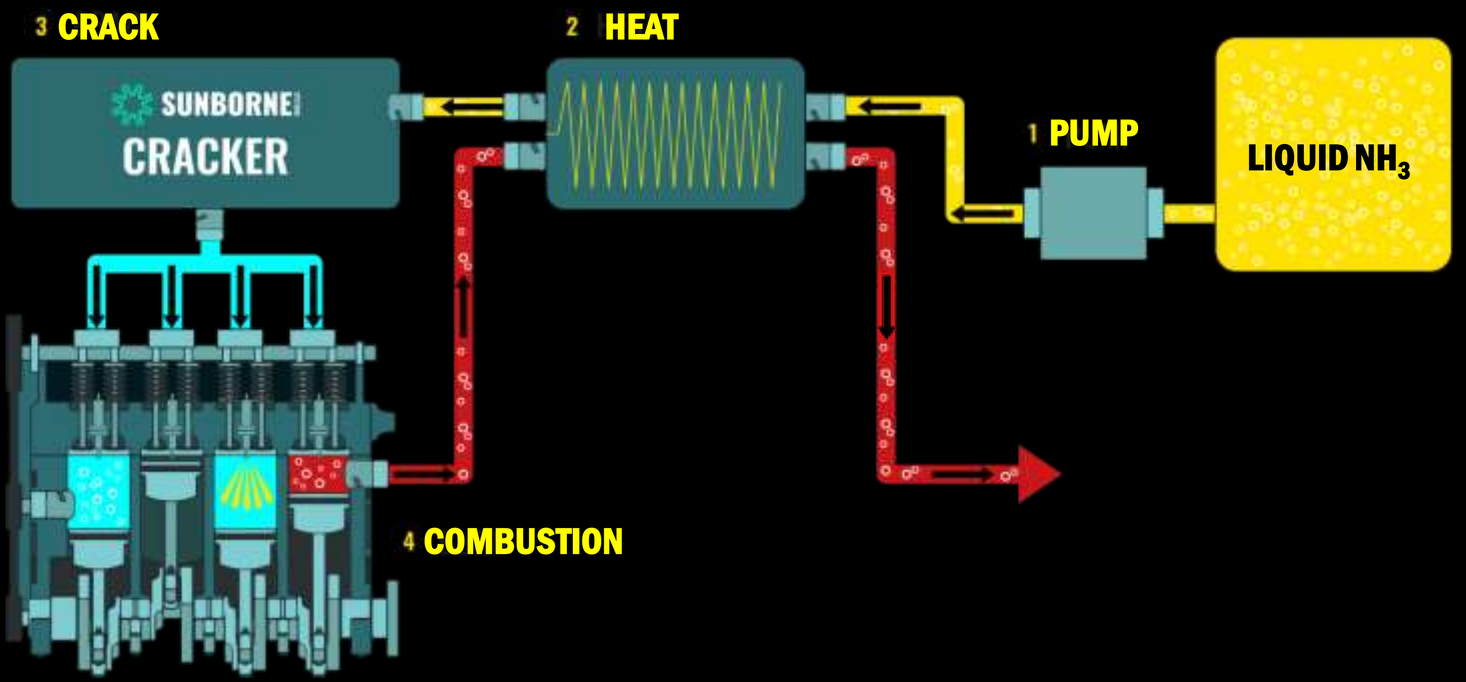
WELCOME TO THE AMMONIA AGE

www.sunbornesystems.com

THE FUEL REVOLUTION IS HERE

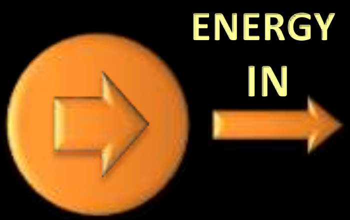
SUNBORNE SYSTEMS

ZERO CO_2 ZERO NO_x



- allows existing engine architectures to convert to NH_3
- in-line cracking turns waste heat into power
- unique heat exchanger and catalyst technology means lower-temperature waste heat can be used.
- NH_3/H_2 blends create a self-piloting mixture that addresses combustion instabilities and minimise NO_x emissions
- overall system efficiency increases

GOAL: TO DE-DEMONISE THE INTERNAL COMBUSTION ENGINE



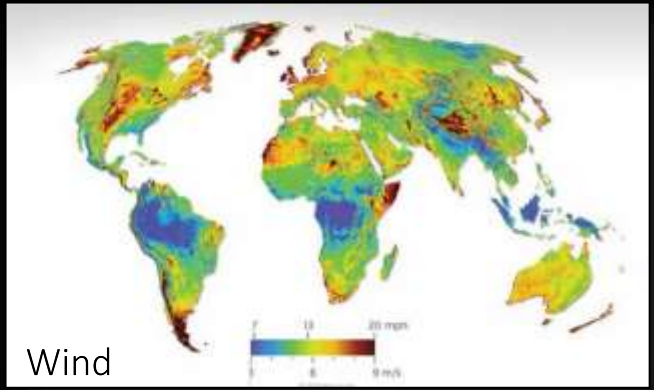
Solar

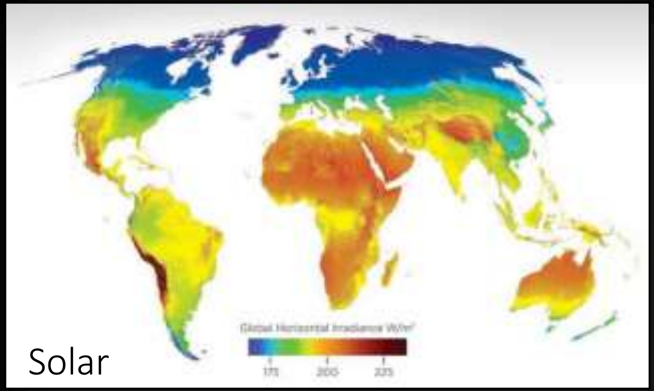
Wind

Nuclear

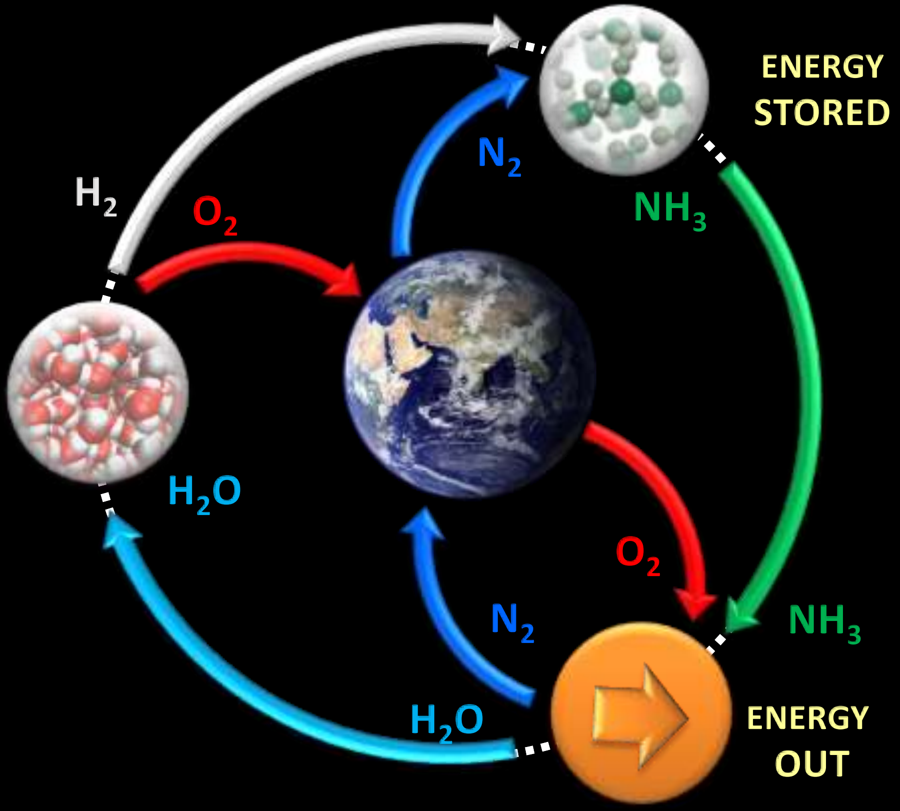
THE WATER-AMMONIA CYCLE $6H_2O + 2N_2 \longleftrightarrow 4H_3N + 3O_2$

H_3N (air hydride 1) $\longleftrightarrow$ H_2O (air hydride 2)





DEMOCRATISING ENERGY



THE ULTIMATE VIRTUOUS CIRCLE