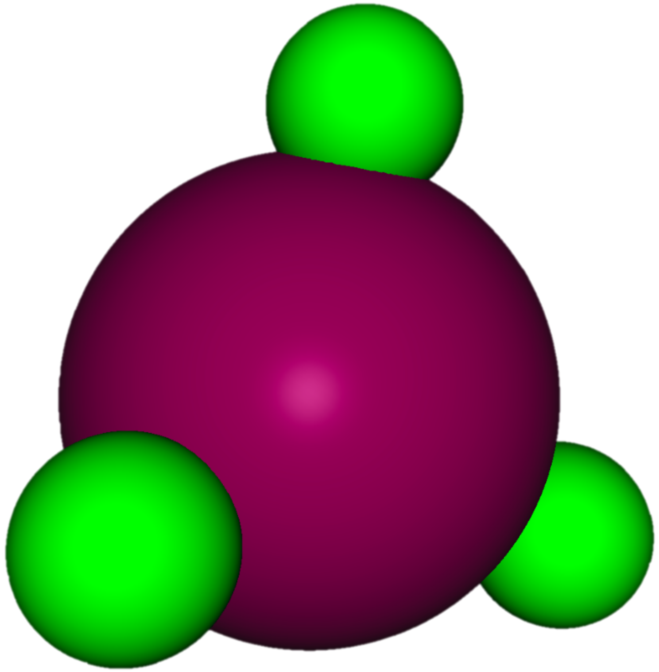
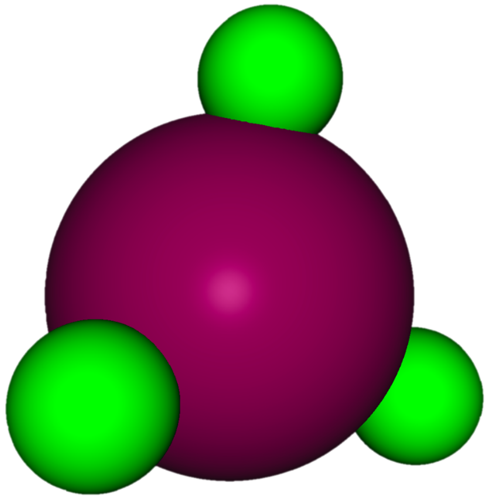
Green Ammonia

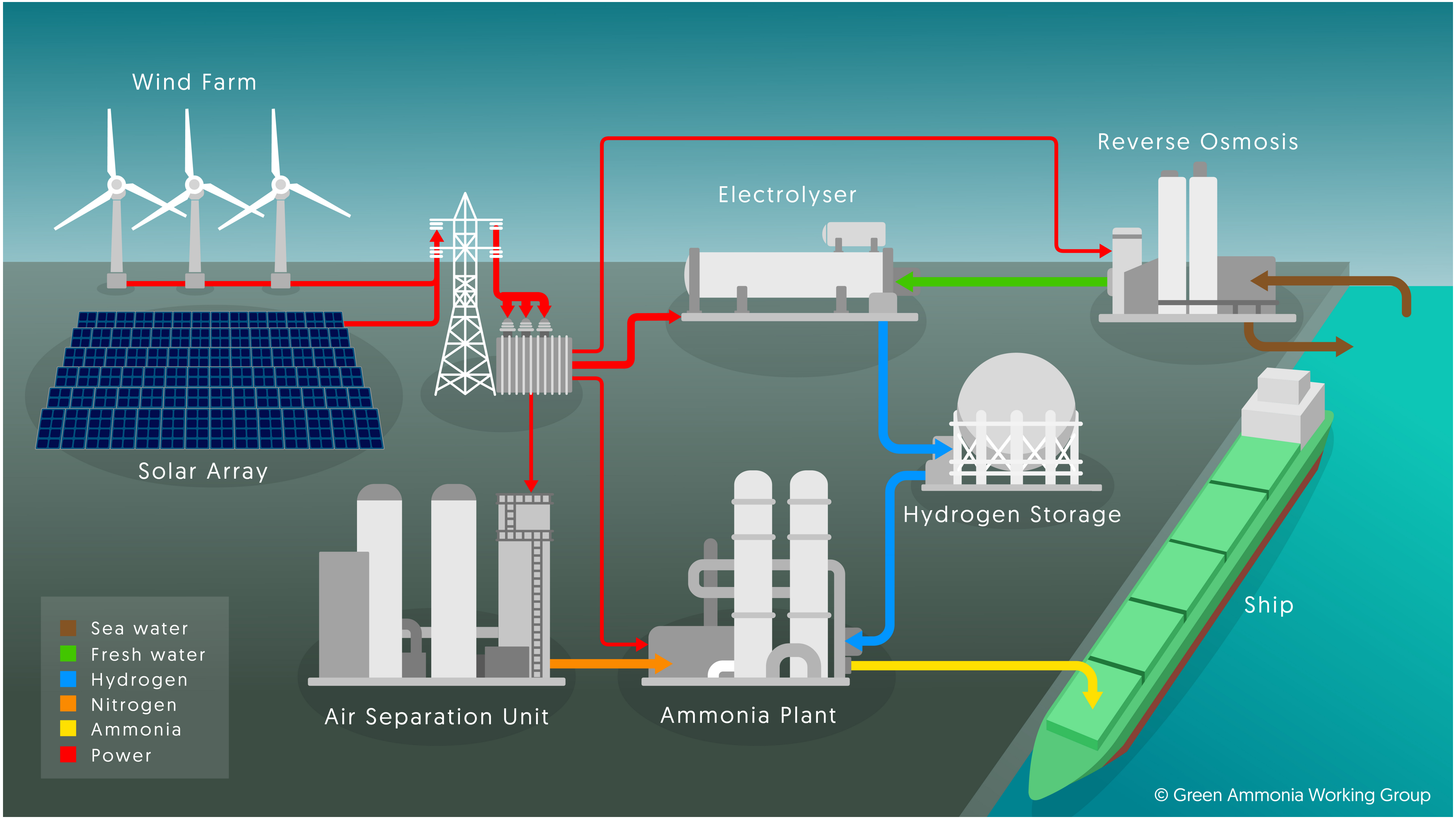
A potential global reserve fuel for a decarbonised world

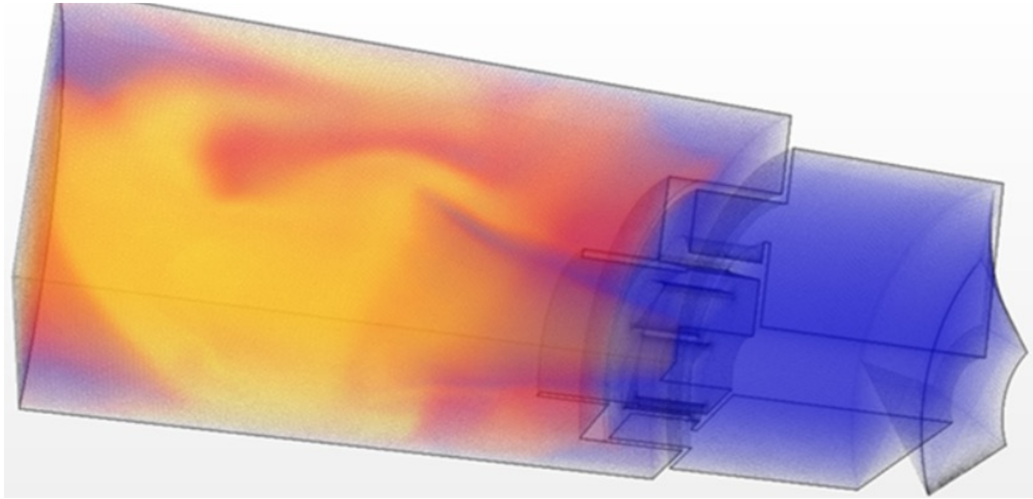
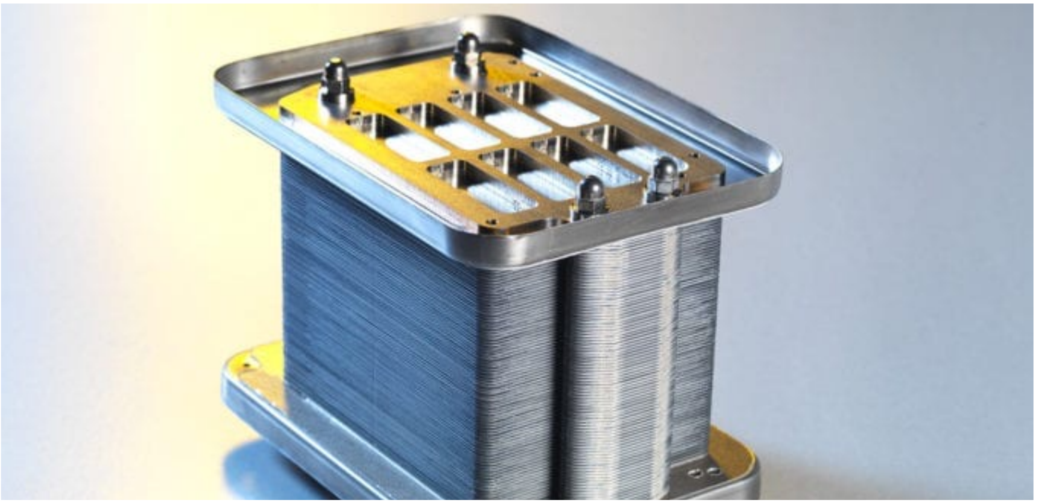
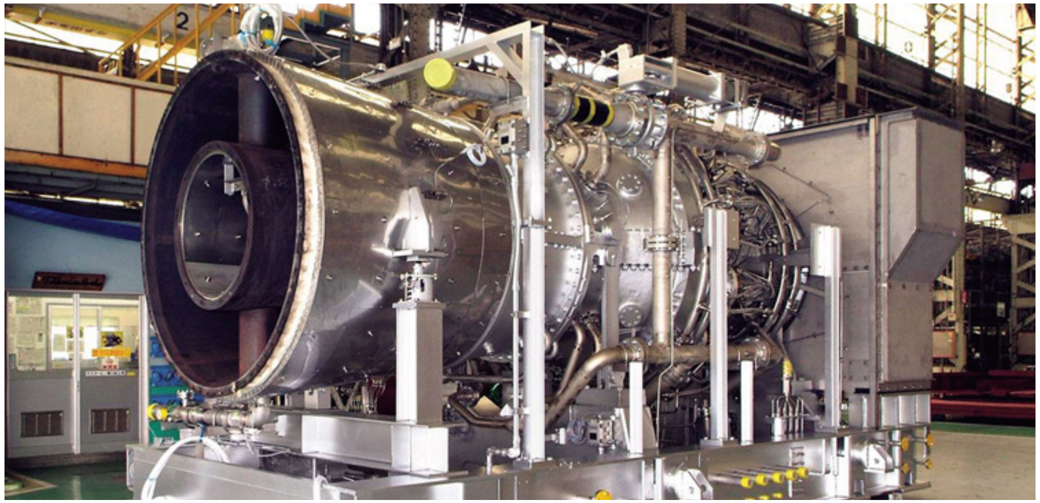


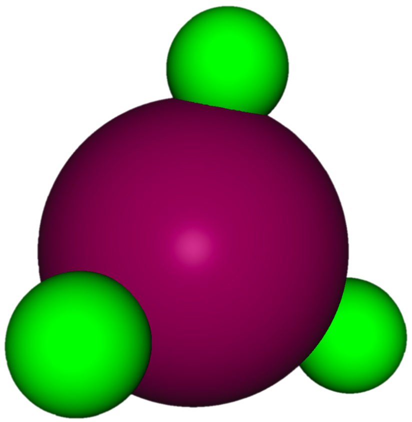
Some Background

- Nitrogen atom with 3 Hydrogens attached
- Input energy from electricity - splitting water to make hydrogen
- Oxidises to form H2O and N2, in the process releasing energy
- Can be burned direct, converted to Hydrogen and burned, or used in a fuel cell




Wind Farm
Solar Array
Electrolyser
Reverse Osmosis
Hydrogen Storage
Air Separation Unit
Ammonia Plant
Ship
Sea water
Fresh water
Hydrogen
Nitrogen
Ammonia
Power
© Green Ammonia Working Group

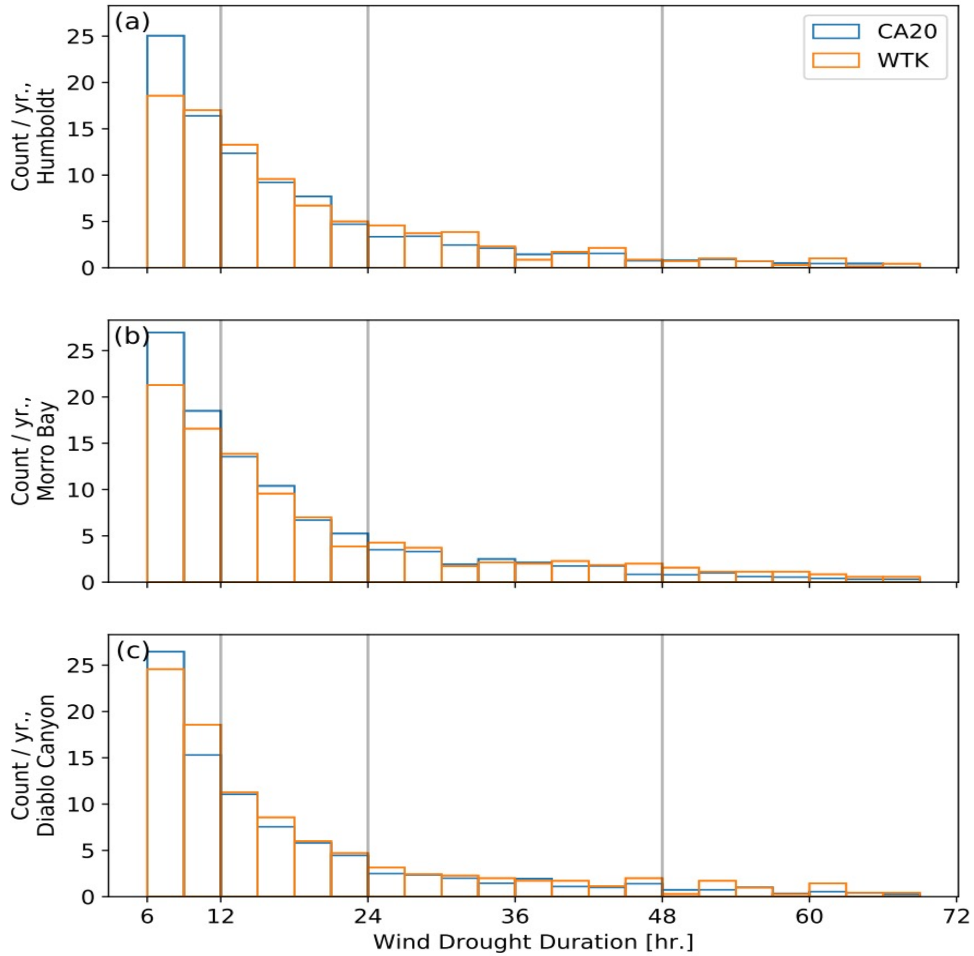







Problems of Time and Place

The Problem - Supporting Grids

- Coal and gas power are low capital cost and high operating cost, and fuel is easy to store
- Renewables have near 0% operating cost and near 100% capital cost. **No fuel to store!**
- Grids need 100% availability
- Over-building renewables does no good if the wind isn't blowing



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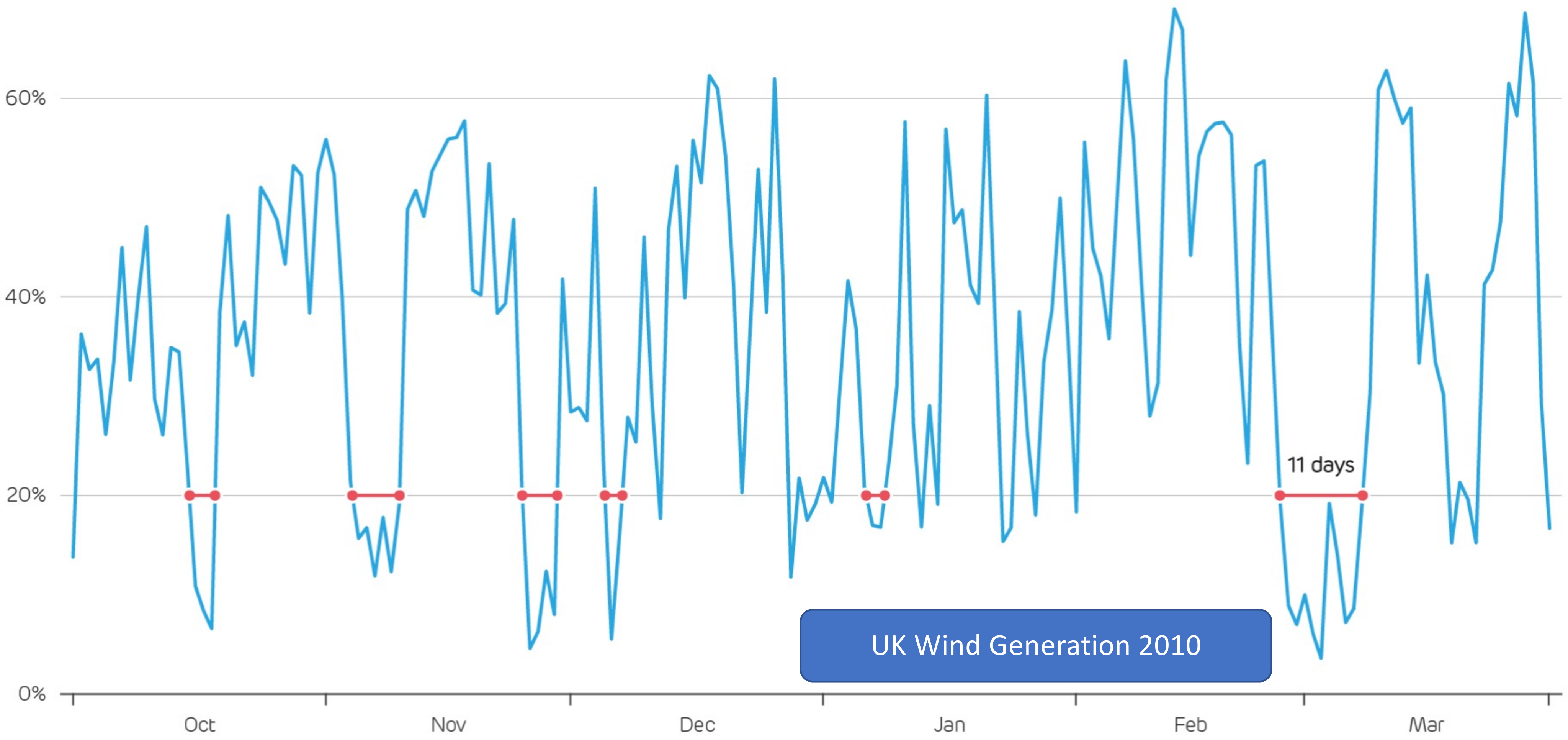

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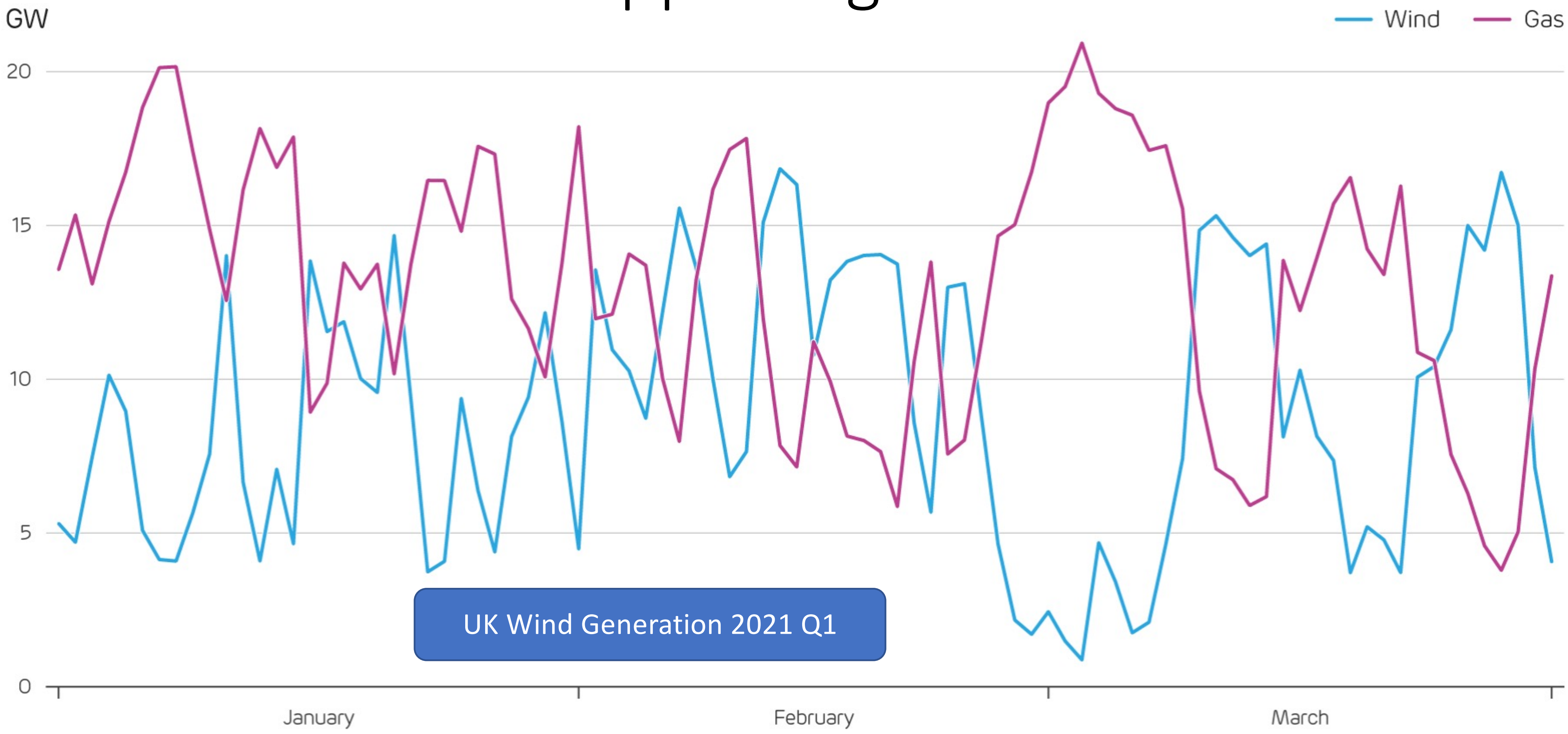
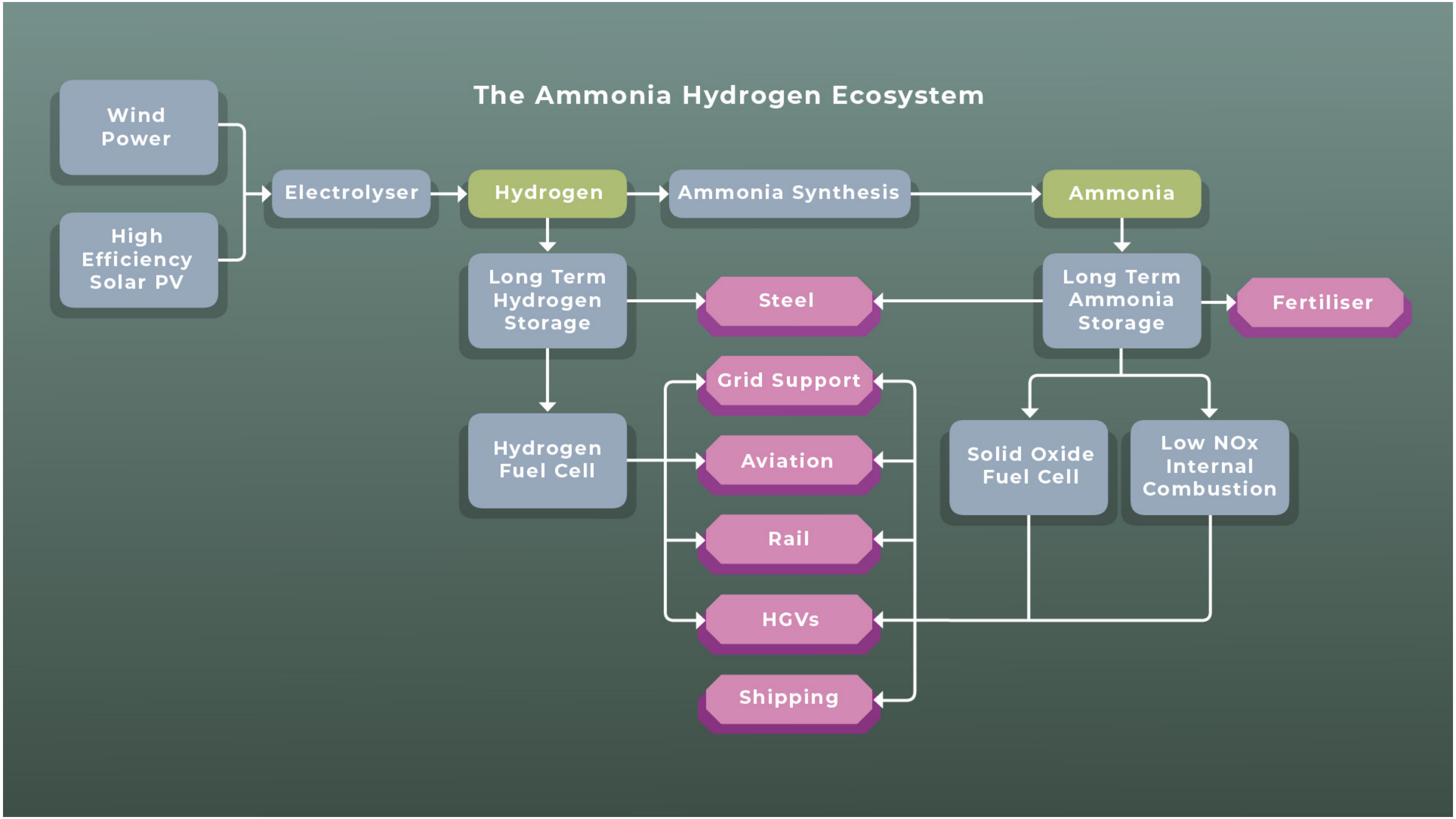


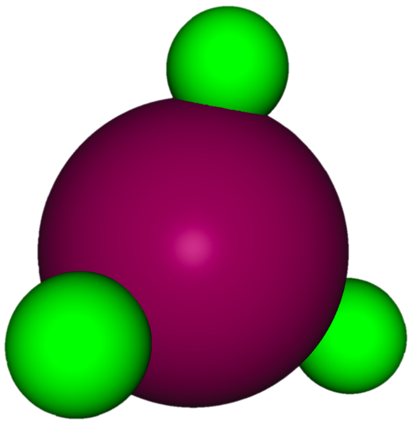
Winter of 1963

Not a time to run out of power!

Not just electricity!

Ammonia can tackle some of the difficult to decarbonize sectors


The Ammonia Hydrogen Ecosystem
Wind Power
High Efficiency Solar PV
Electrolyser
Hydrogen
Ammonia Synthesis
Ammonia
Long Term Hydrogen Storage
Steel
Long Term Ammonia Storage
Fertiliser
Grid Support
Hydrogen Fuel Cell
Aviation
Solid Oxide Fuel Cell
Low NOx Internal Combustion
Rail
HGVs
Shipping

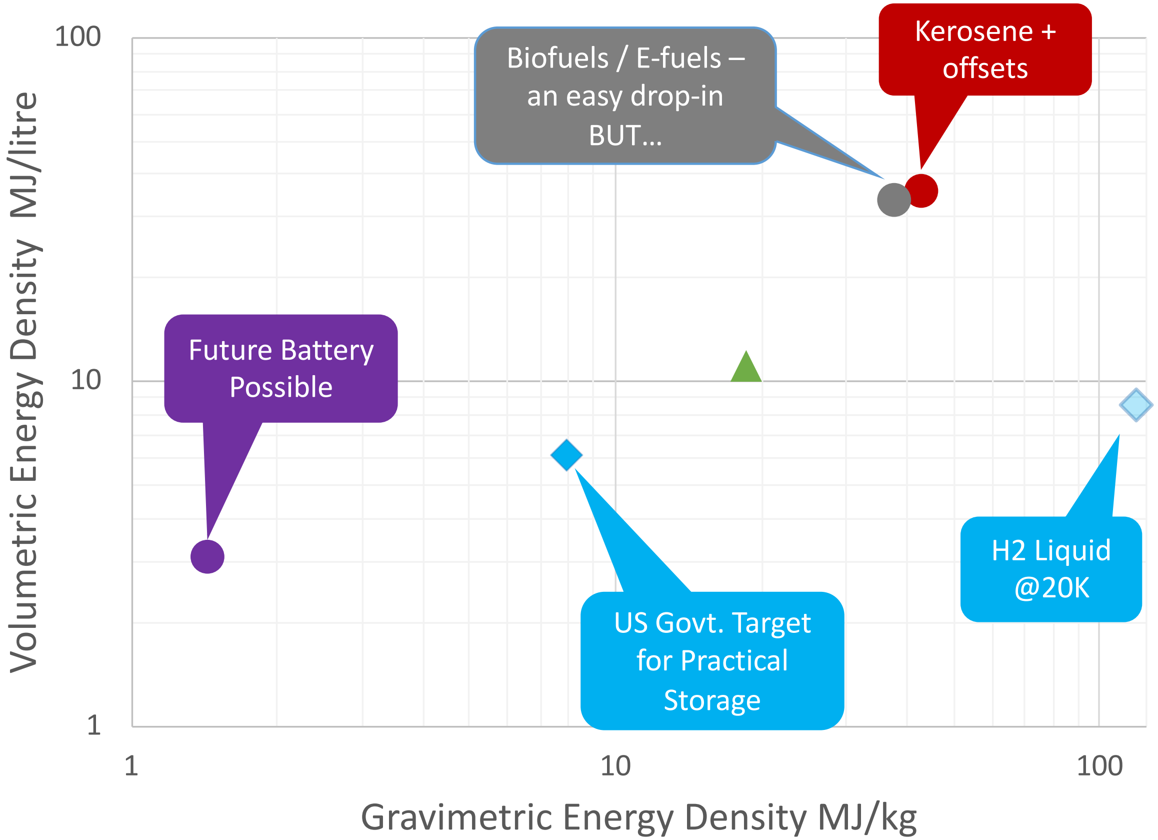


Why Ammonia?

Some Alternative Energy Vectors

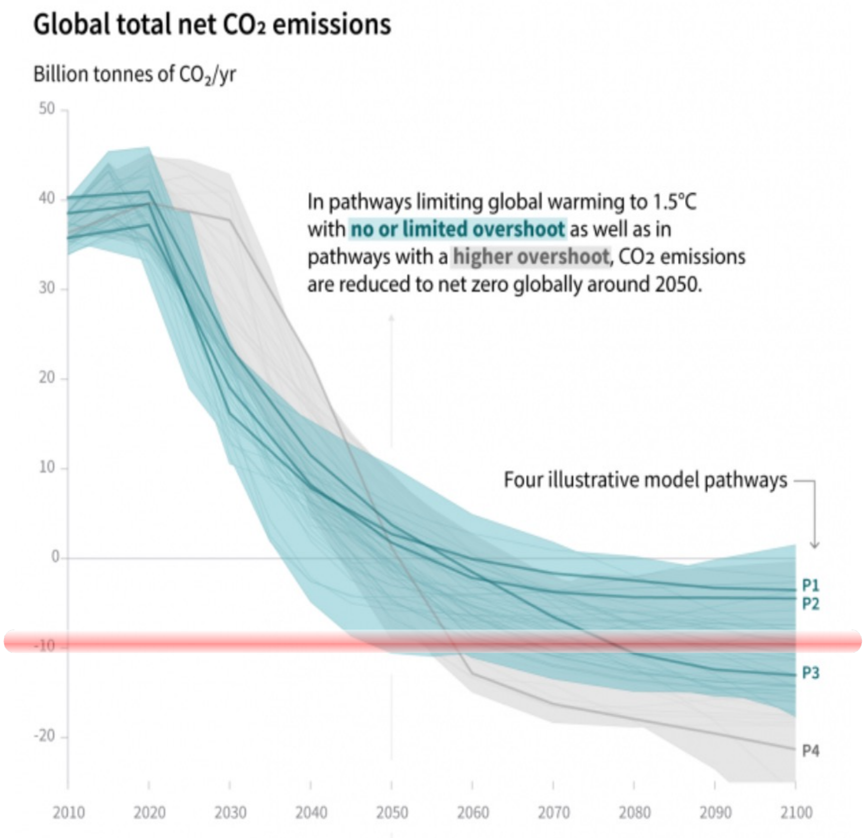
Storing and Moving Energy – Some Alternatives

- Batteries – low energy density unless major breakthrough and very expensive for long term storage
- Hydrogen – clean, green, energy dense, but storage is a real problem
- Biofuels and e-fuels
  - Yes but…



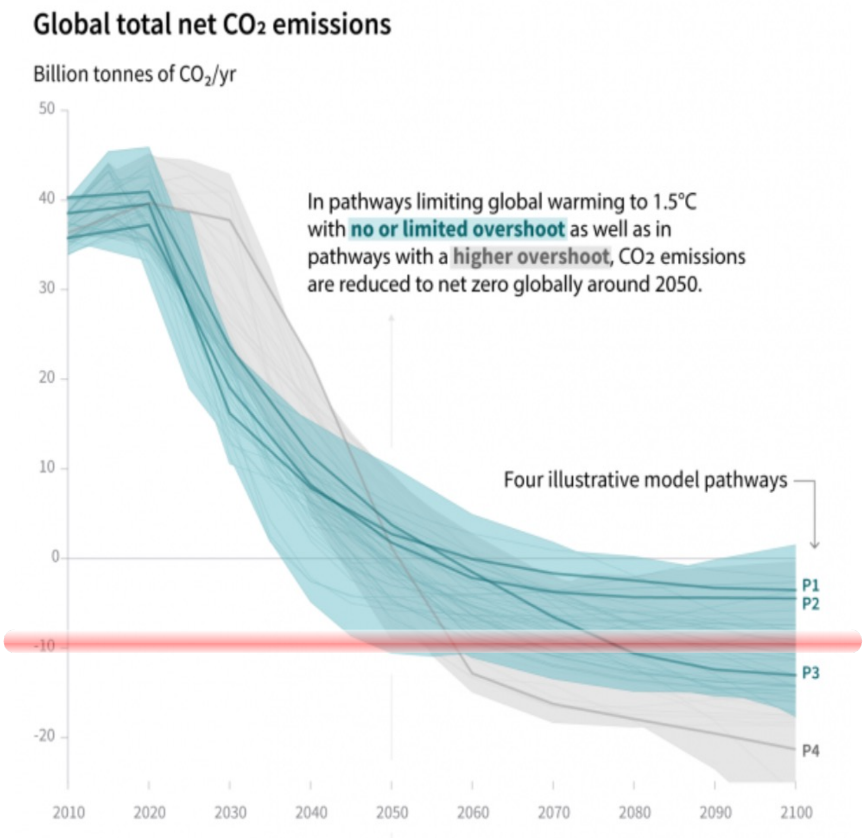
Biofuels, e-Fuels or Fossil fuel with Offsets?

- At 1.2°C over pre-industrial temperatures we already have major fires, storms floods
- We are bound to overshoot any plausible 1.5°C pathway
- The world will need Negative Carbon not 'reduced carbon' by about 2050
  - Possibly need to capture and sequester 10 GT/year CO_2
  - 2x the scale of global oil industry in reverse!
- Will need to treat **30 million tonnes per minute** air to remove CO_2 for >100 years



Biofuels, e-Fuels or Fossil fuel with Offsets?

- Each tonne of carbon-based fuel emits 3 tonnes of CO_2
- Where does the carbon come from?
  - By 2050 there will be no convenient point sources of CO_2 left
  - Direct air capture @ 400ppm(v) expensive
  - Expanding agriculture will simply drive deforestation. Agriculture has to shrink – not grow



Carbon Opportunity Costs of Biofuels

- Expanding biofuels into forests or crops is a disaster
- 1 t palm oil ≅ 1 t biofuel
- 1t biofuel ≅ 11 t CO_2 emission
- Plus massive biodiversity loss

RESEARCH LETTER

Table 1 | COCs and global PEMs of major crop and livestock products

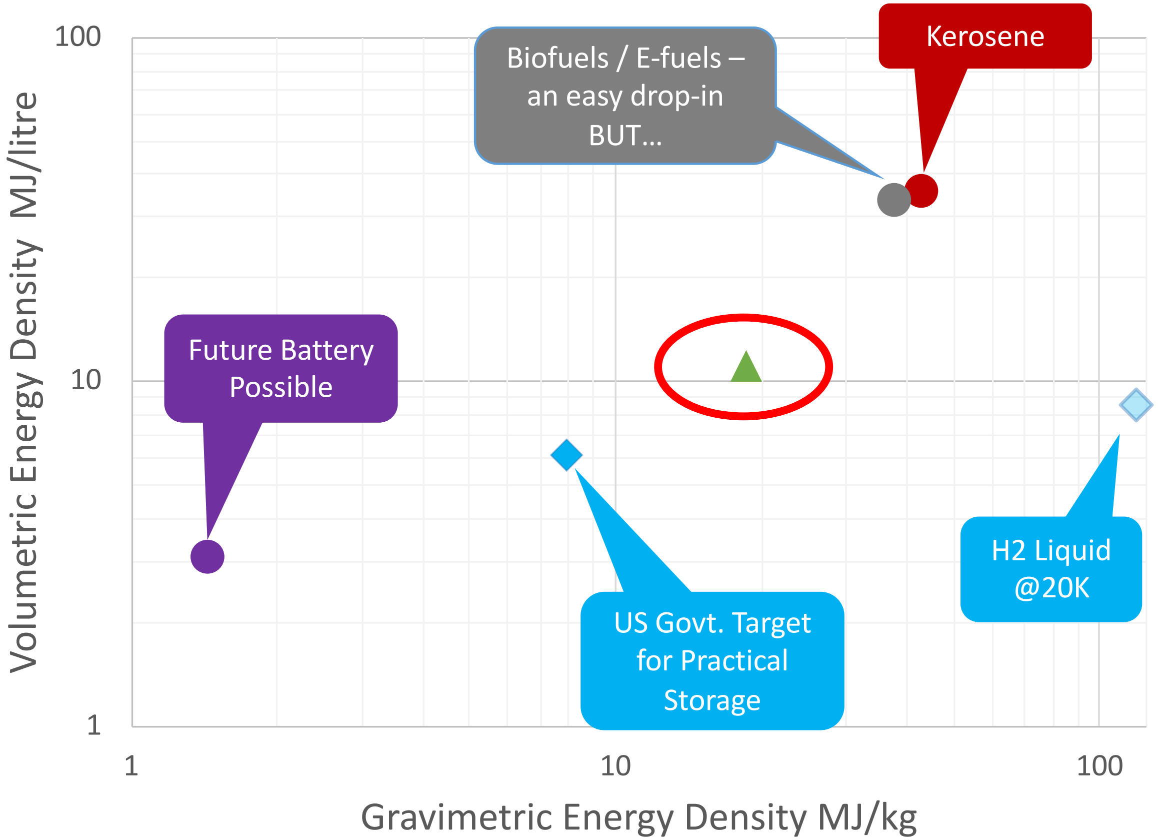
	COC[a] (kg CO_2 per kg fresh weight)	PEMs (kg CO_2e per kg fresh weight)	Total (kg CO_2e per kg fresh weight)	Total (g CO_2e per kcal[c])	Total (kg CO_2e per kg protein)
Maize	2.1	0.46	2.6	0.82	29
Rice (rough)	2.6	2.17	4.8	2.0	69
Wheat	1.9	0.69	2.6	0.9	23
Cassava	1.7	0.04	1.7	1.6	160
Potato	0.6	0.09	0.7	1.1	38
Soybeans	5.9	0.26	6.1	1.5	17
Pulses	10.5	0.55	11	3.1	47
Vegetable oils	9.7	1.3	$\boxed{11}$	1.2	Not applicable
Beef[b]	144	44	188	102	1,250
Cow milk	6.2	2.3	8.4	13.1	260
Pork	14	5.5	20	9.4	150
Poultry meat	11	3.7	14	8.4	110

Values are calculated using the carbon loss method and 4% time discounting.
[a]Includes peatland emissions.
[b]Average, including meat from dairy animals.
[c]1 kcal = 4,184 J.

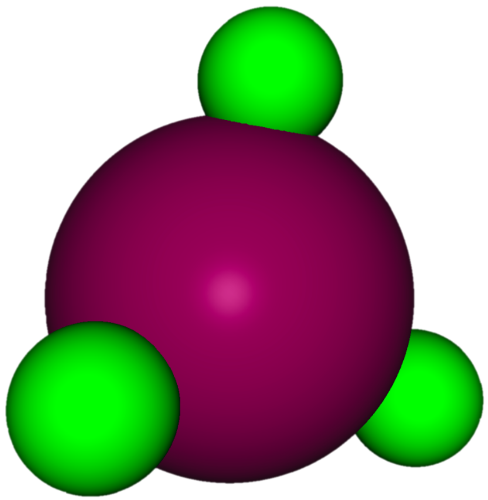
Searchinger, Timothy D., Stefan Wirsenius, Tim Beringer, and Patrice Dumas. 2018. "Assessing the Efficiency of Changes in Land Use for Mitigating Climate Change." *Nature* 564 (7735): 249–53.

Possible Energy Vectors - Ammonia

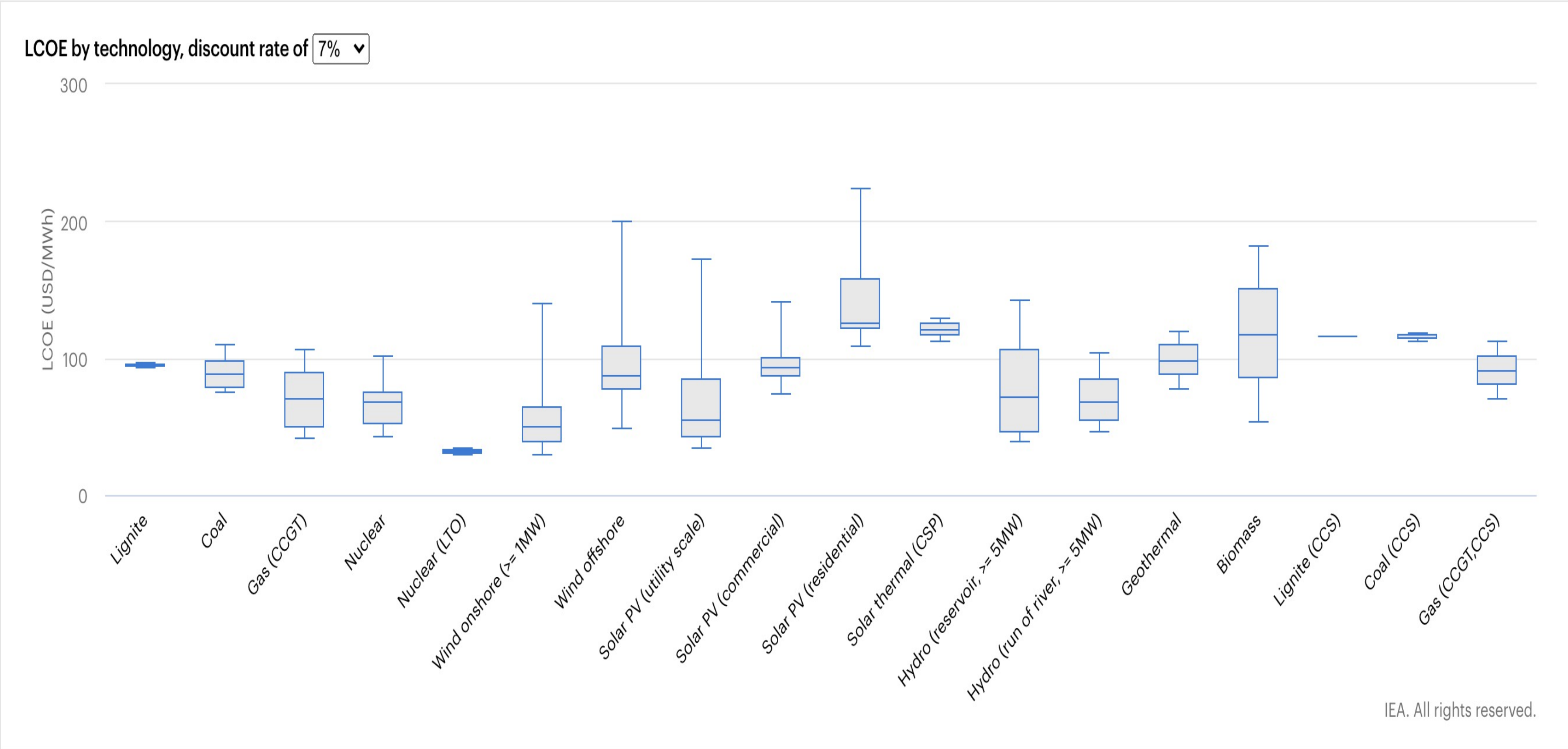
- Easily liquified at 10 bar or -33C compared to hydrogen at -253C
- Freezes at -77C
- Flexible, can be burned or used in fuel cells
- Not as good as oil – but could it be ‘good enough’?



What would it cost?



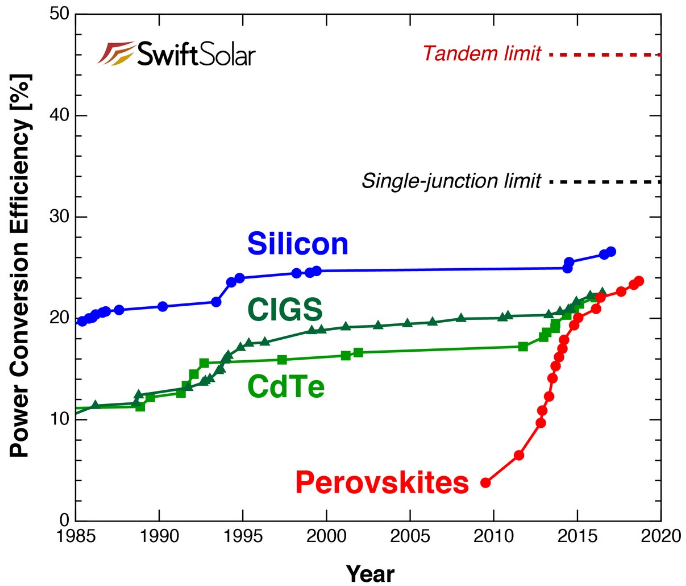
IEA Electricity Costs – 2020 Estimates



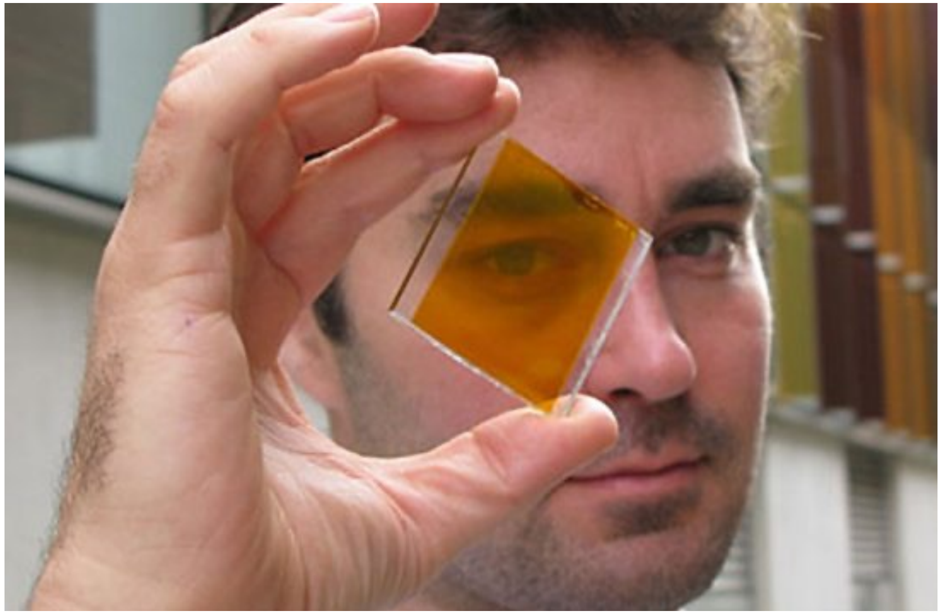
Portuguese government confirms world record solar price of $0.01316/kWh

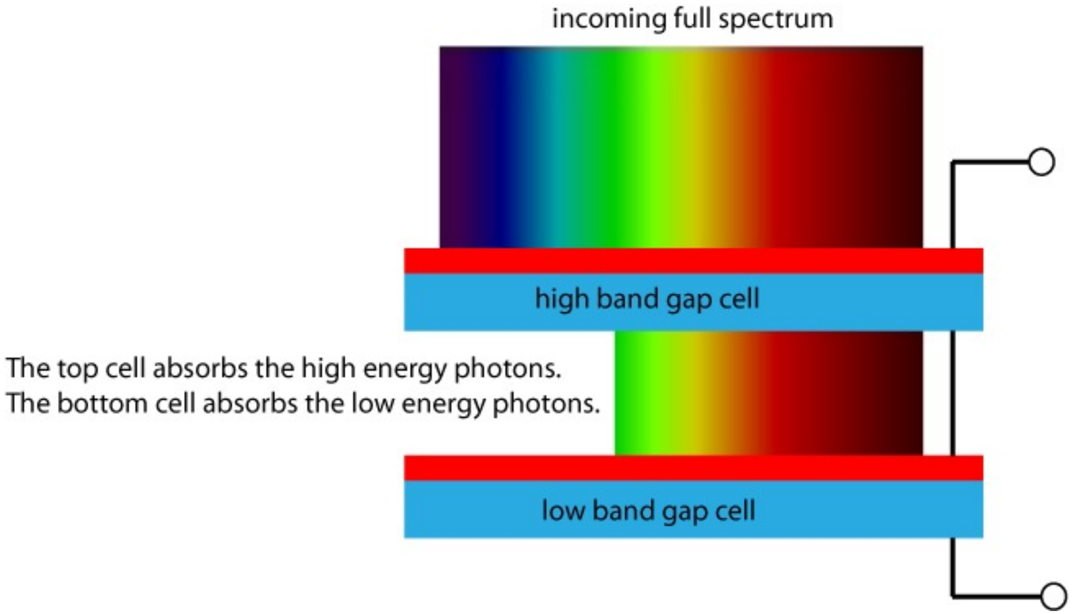
The Portuguese government has revealed some of the preliminary results of the national solar auction which closed on Tuesday. Antonio Delgado Rigal, chief executive of energy forecasting service Aleasoft, said that the 15-year contracts awarded in the auction were the key to understanding the reason of such a low price. This, combined with the rights for land and grid connection guaranteed by the auction, makes attractive bidding at low prices.

AUGUST 27, 2020 EMILIANO BELLINI



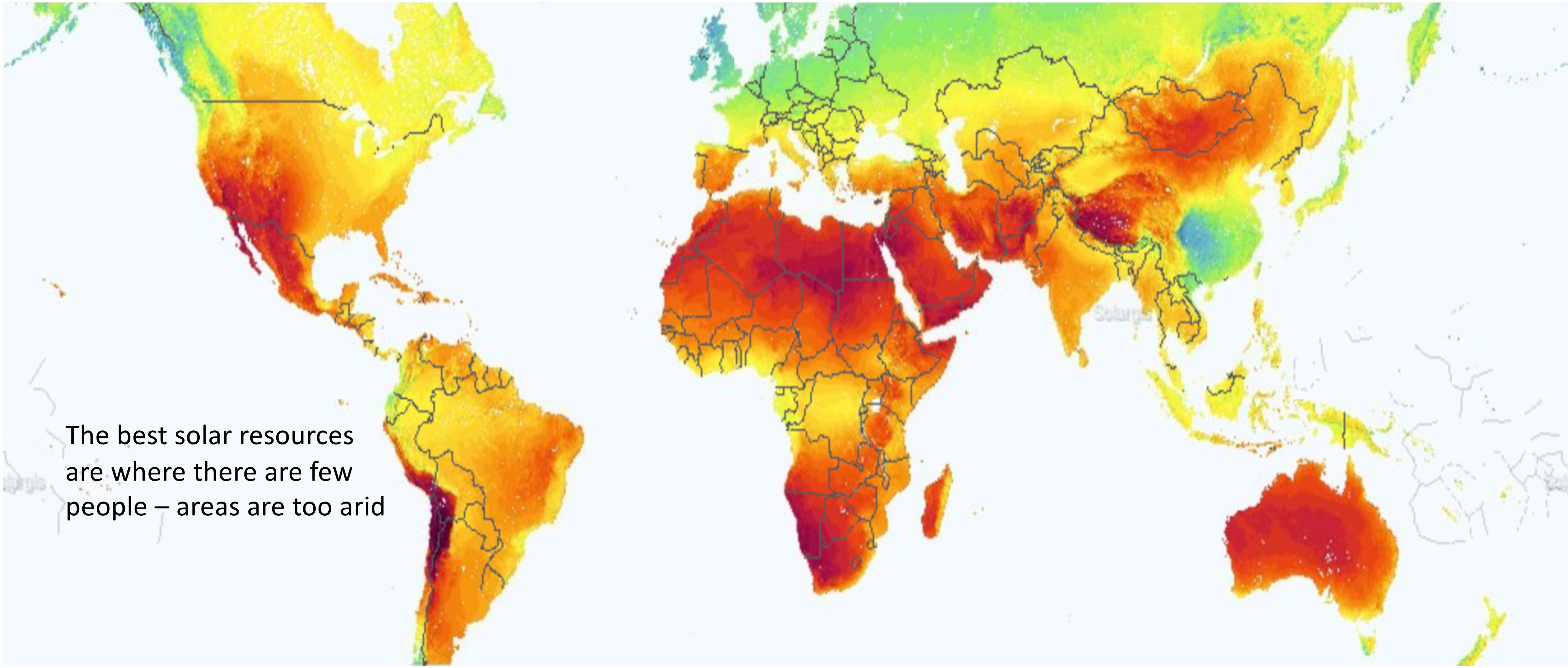
SwiftSolar
Tandem limit
Single-junction limit
Silicon
CIGS
CdTe
Perovskites
Power Conversion Efficiency [%]
Year
0
10
20
30
40
50
1985
1990
1995
2000
2005
2010
2015
2020





incoming full spectrum
high band gap cell
The top cell absorbs the high energy photons.
The bottom cell absorbs the low energy photons.
low band gap cell

Where is the resource?



The best solar resources are where there are few people – areas are too arid

Transporting Energy Across Time and Place

WIRE

- Politically fraught
- Technically fraught
- Vulnerable
- Imperfect solution

Best at scale of large country to reduce but not eliminate problems

HYDROGEN

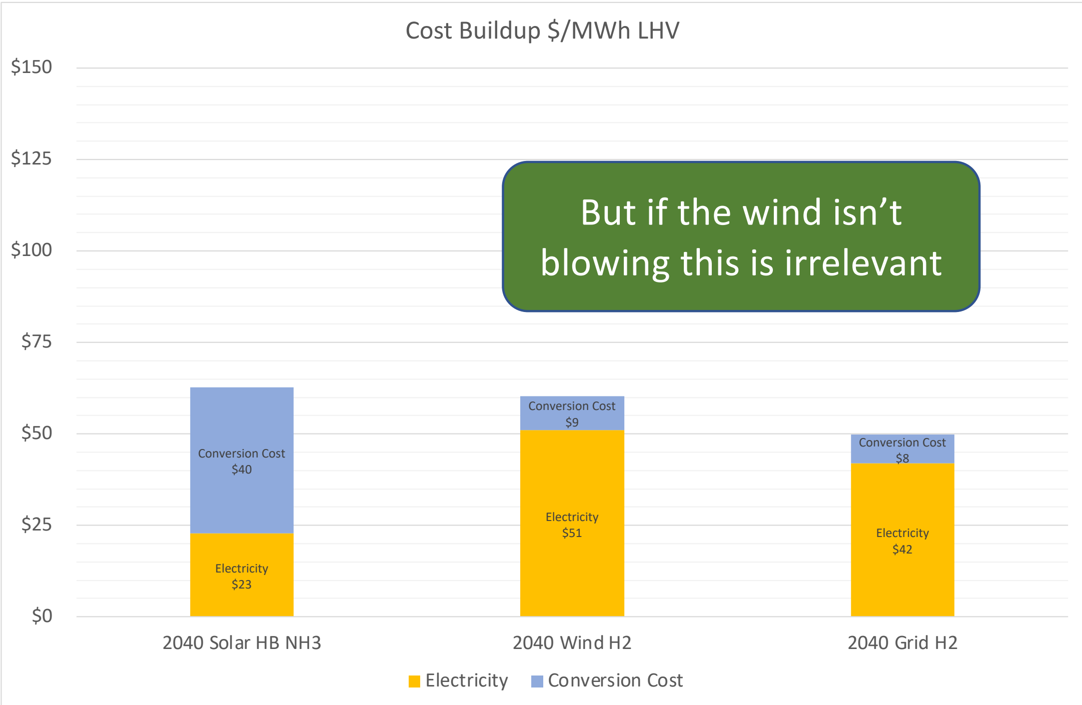
- Hard to liquify
- Hard to store
- Hard to transport
- Leaky (GWP 4)

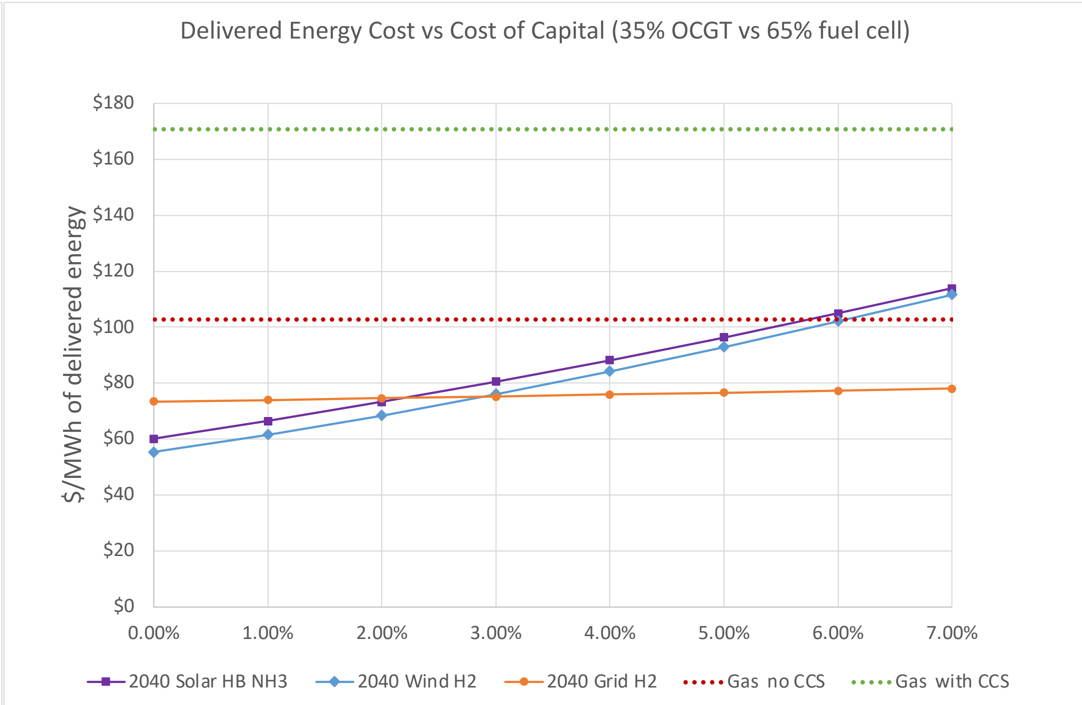
Best if you have salt caverns (for storage) close to both energy source and demand

AMMONIA

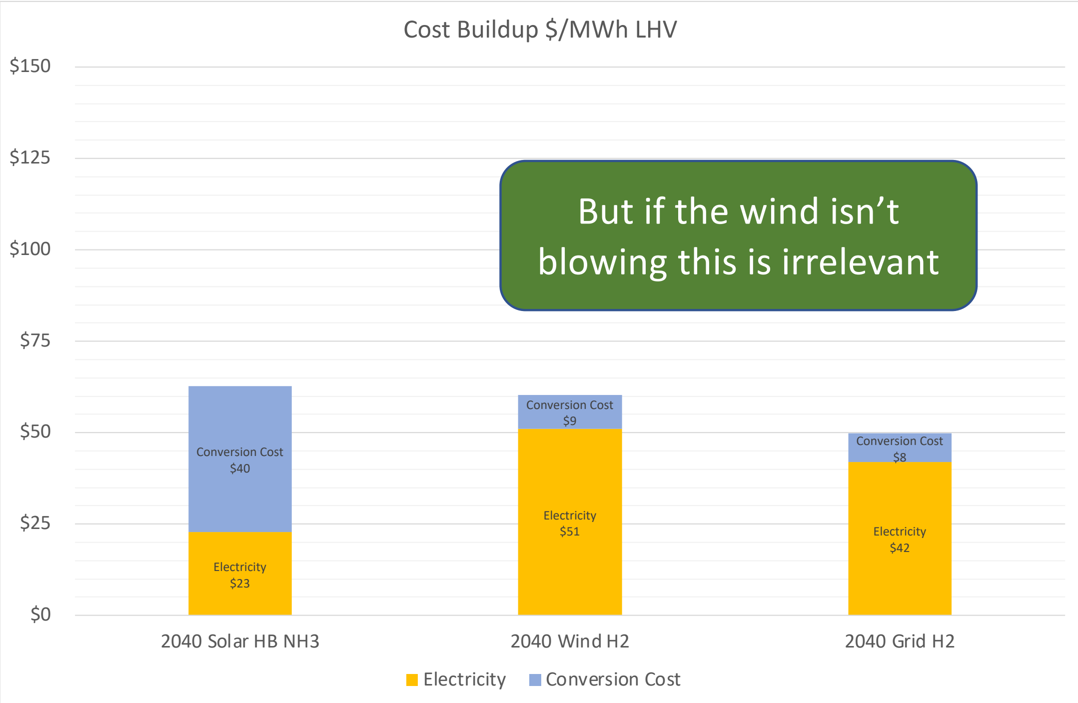
- Easy to Liquify
- Easy to store
- Easy to transport
- More expensive than H2 at same site – but…
- Make it where energy is cheapest

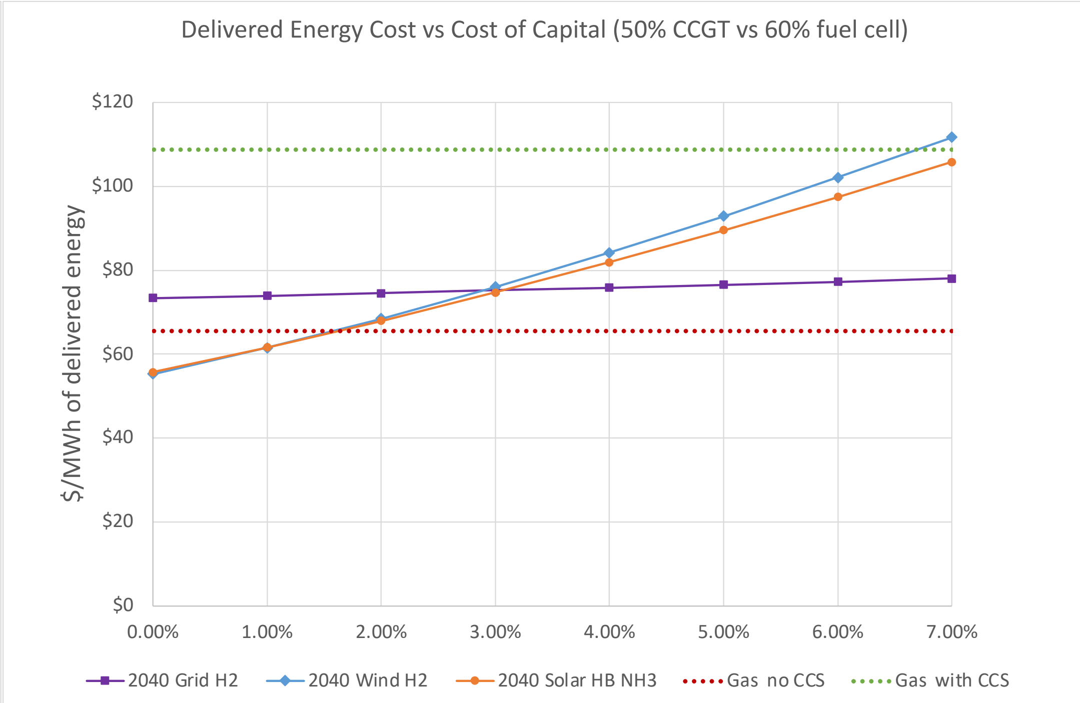
Intermittent Electricity - What Will It Cost?





Firm Dispatchable Electricity - What Will It Cost?





Marine is Already Moving

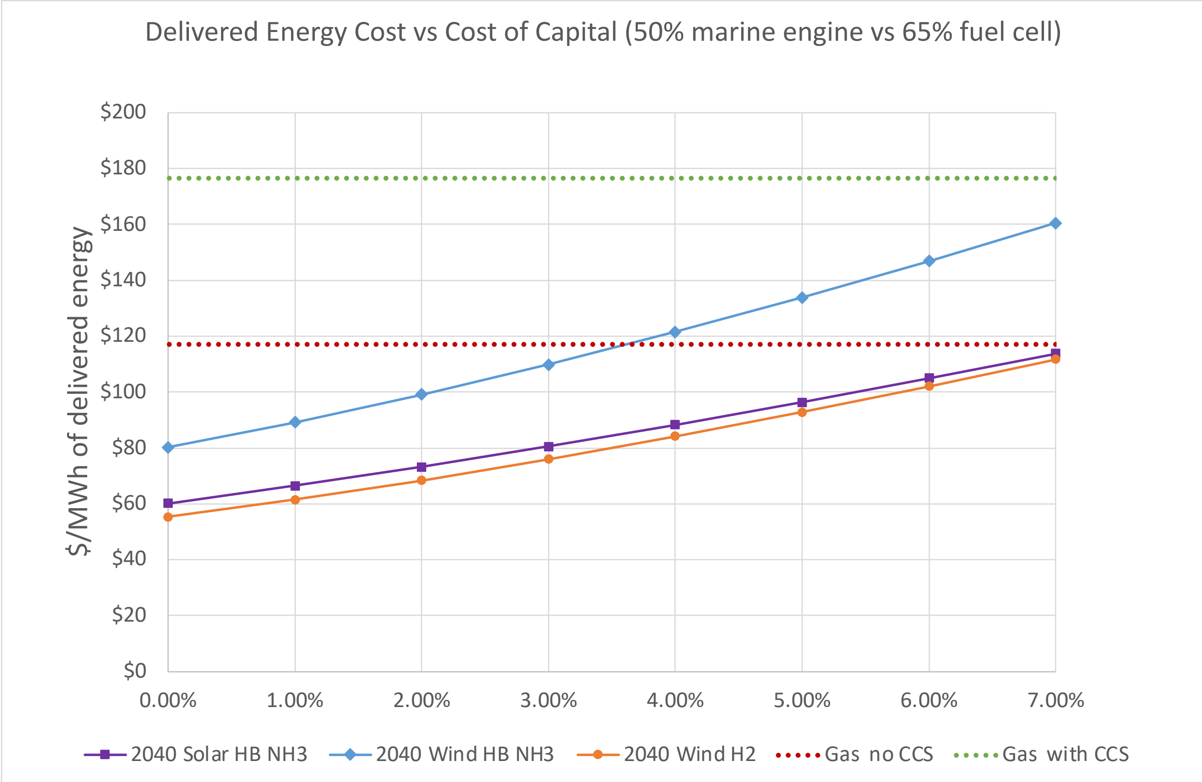
MARINE

Fortescue aims to launch world's first ammonia-powered ship in 2022

By Loz Blain
November 11, 2021

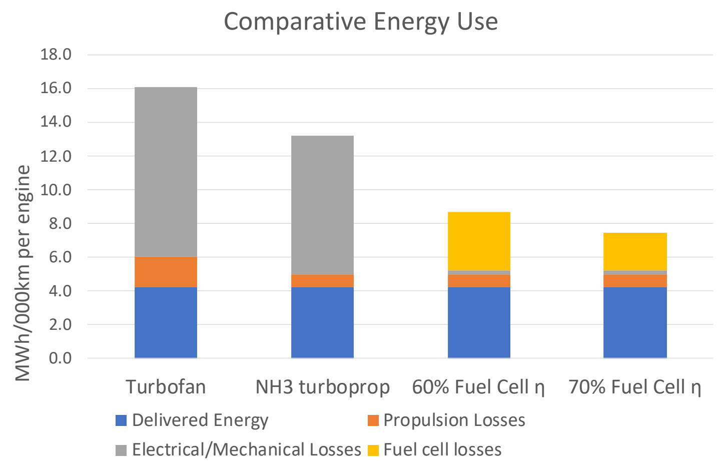
Listen To This Article

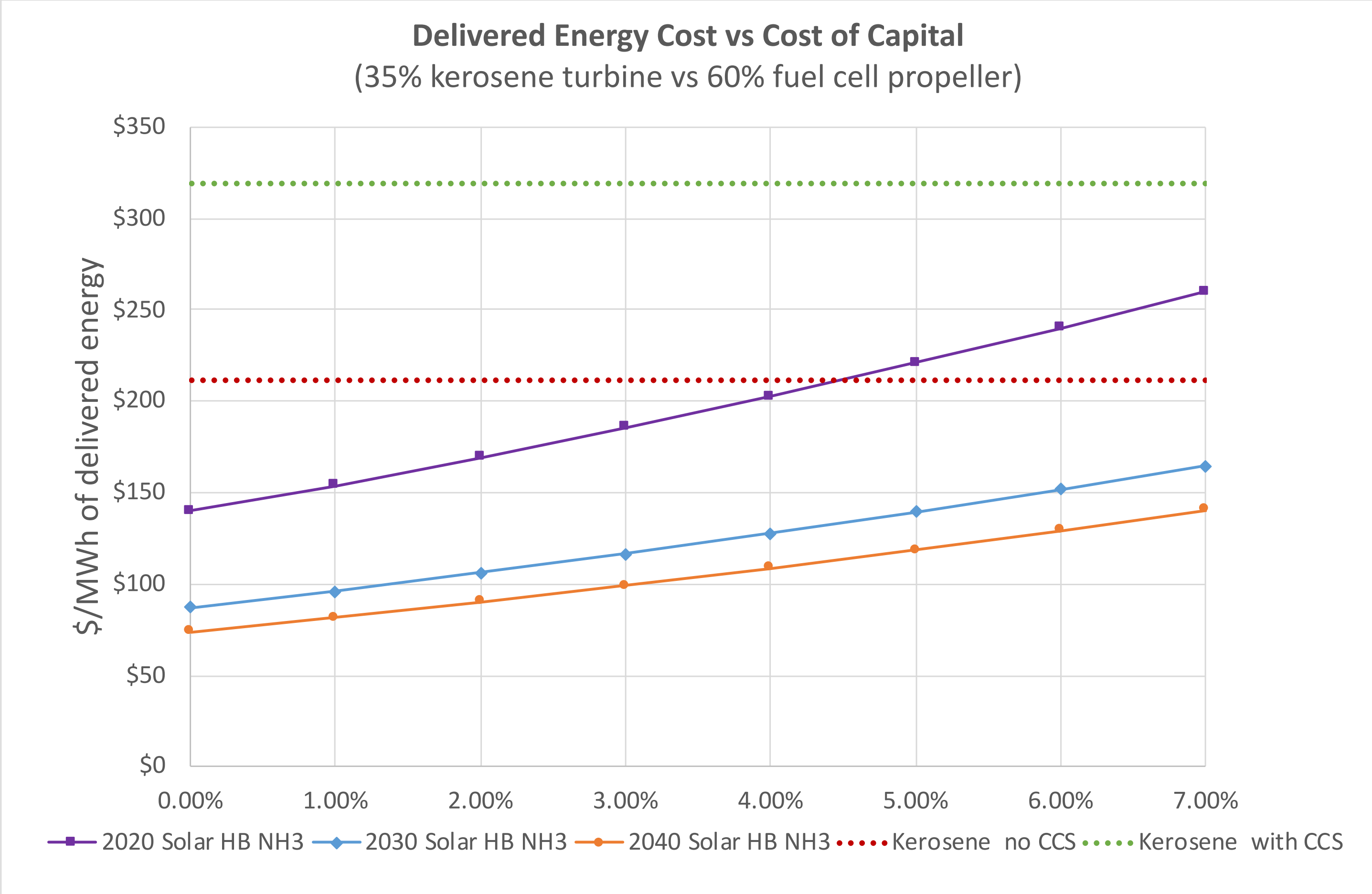
The MMA Leveque will be converted by Fortescue to run nearly entirely on ammonia, with the aim of being the world's first ammonia ship in 2022 MMA Offshore



Aviation Cost – for Electric Prop vs Jet

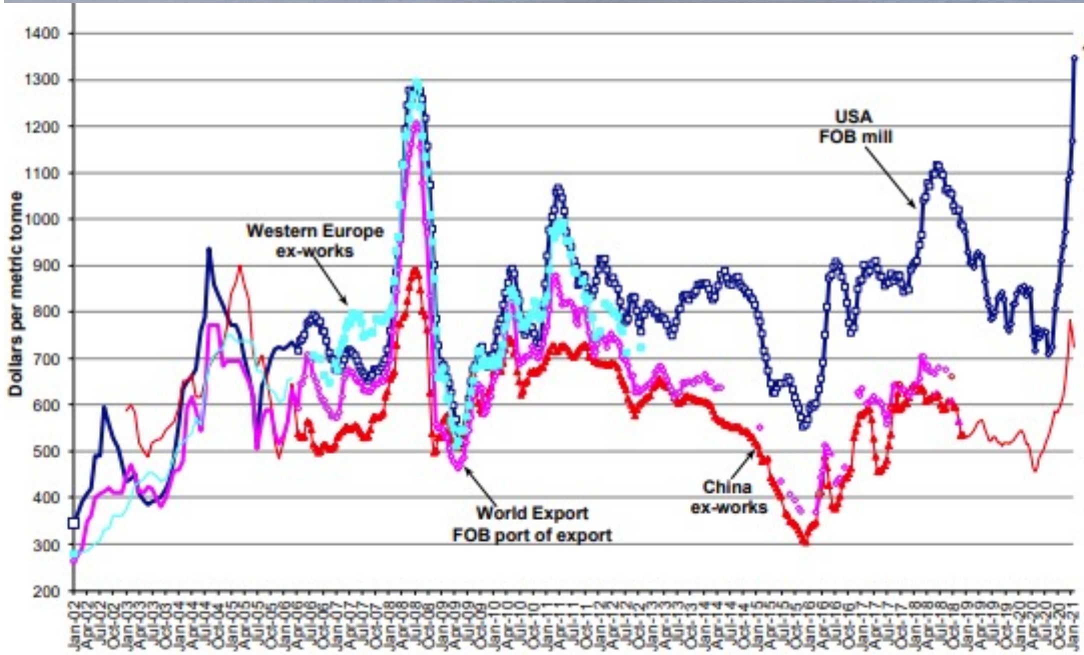
By 2030 green NH_3 is cheaper than 2020 kerosene even without CO_2 charge, assuming 60% η fuel cells





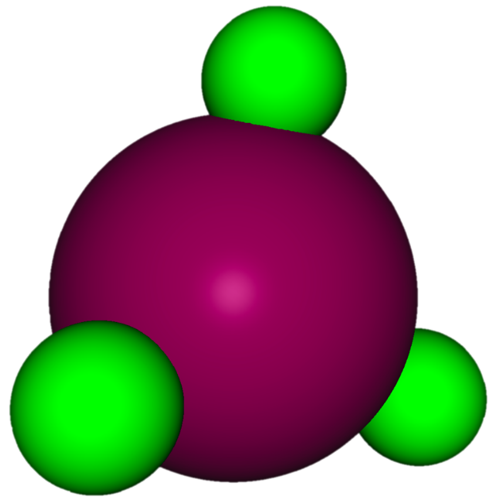
Steel Cost

- Ammonia can be reduced to hydrogen or possibly used directly
- Cost about the same as hydrogen – depending on location and availability
- Adds 8%-12% to cost of steel
    - Much less than the natural price variability



Is it Safe?

The key Issue



Fire Safety of NH_3

- **NH_3 is almost non-flammable.**
- *"Although ammonia is designated as a non-flammable gas for shipping purposes by the United Nations and the U.S. Department of Transportation, it is flammable in air within a certain range of concentrations. Because these concentrations are quite high, it would be extremely difficult to reach those conditions in an outdoor shipping situation. The fact that ammonia gas is lighter than air and that it diffuses readily in air makes it difficult to create a flammable situation outdoors."*
- *From IIAR Handbook of Ammonia*

Toxicity

- Vapour is lethally toxic to humans at concentrations >3500mg/m^3
- Survivable for up to 30 minutes at concentrations between 1750 and 3000 mg/m^3.

Public Health England

Ammonia

Toxicological Overview

Table 1: Summary of toxic effects following acute exposure to ammonia by inhalation

Exposure		Signs and symptoms
mg/m^3	ppm	
35	50	Irritation to eyes, nose and throat (2 hours' exposure)
70	100	Rapid eye and respiratory tract irritation
174	250	Tolerable by most people (30–60 minutes' exposure)
488	700	Immediately irritating to eyes and throat
>1,045	>1,500	Pulmonary oedema, coughing, laryngospasm
1,740–3,134	2,500–4,500	Fatal (30 minutes' exposure)
3,480–6,965	5,000–10,000	Rapidly fatal due to airway obstruction, may also cause skin damage

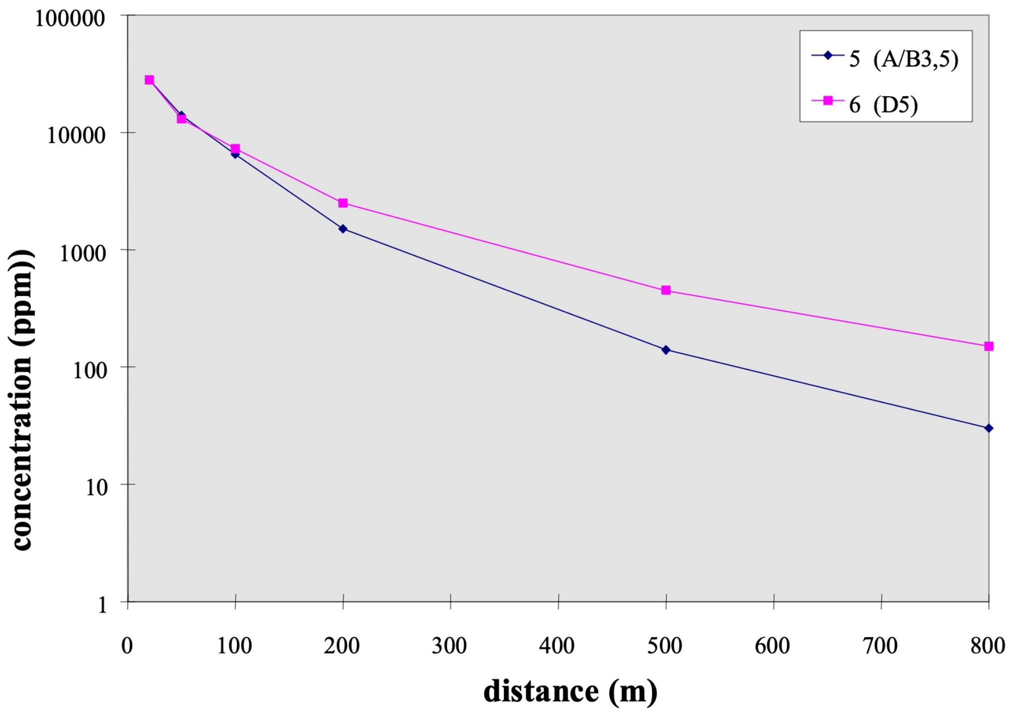
Values in mg/m^3 are approximate calculations from ppm, where mg/m^3 = ppm x gram molecular weight/24.45 (molar volume of air at standard temperature and pressure)

References

[2, 14]

Test Data – Warm Pressurised Releases

- All known dispersion tests have involved pressurised releases of ambient ammonia
- Plumes form – but concentrations drop very rapidly over 200-300m range downwind
- **No known data exists for tests of cold unpressurised ammonia liquid or solids**



Ineris. 2005. Ammonia large-scale atmospheric dispersion tests.

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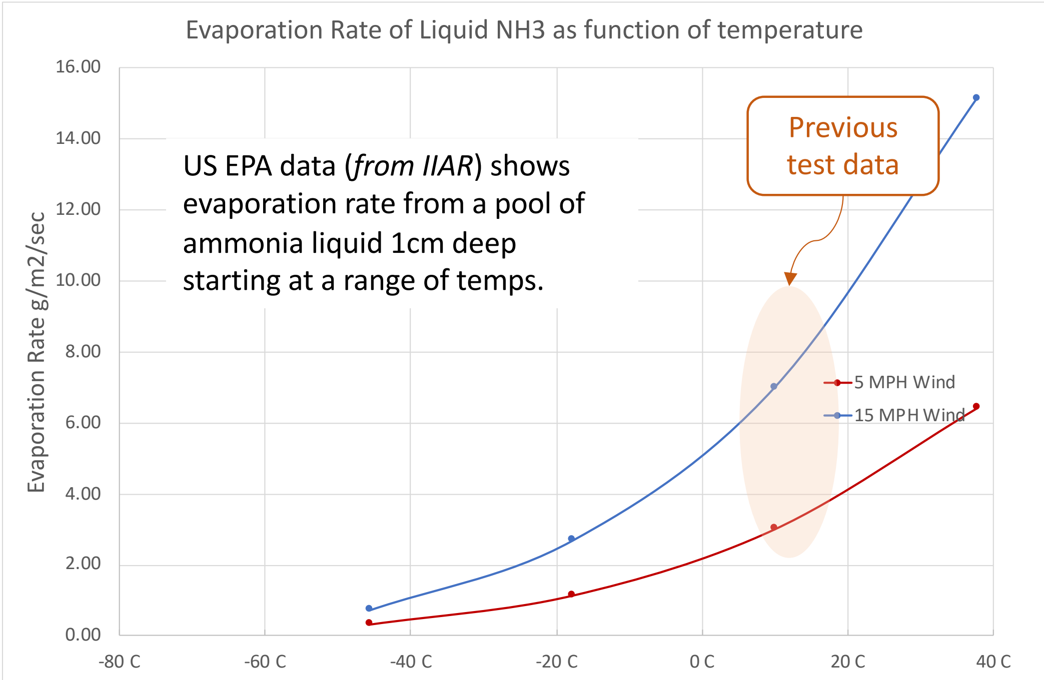
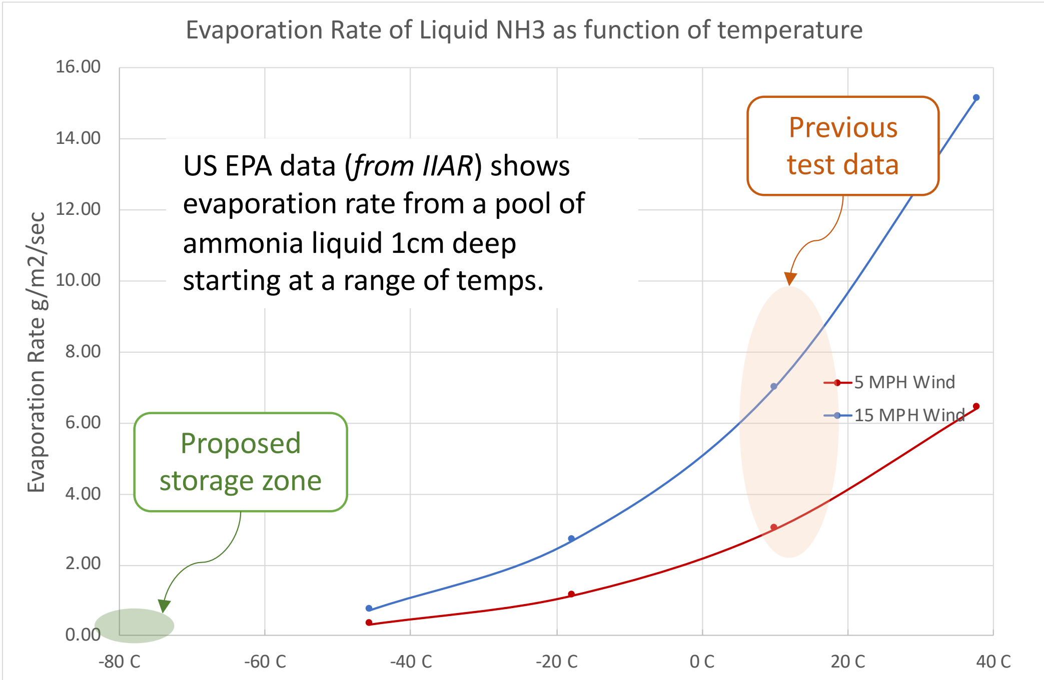


Toxic Plume Development – Cold Spill

- Liquid ammonia has high specific heat and high latent heat of vaporisation
- EPA data suggests at -77°C (freezing point) evaporation rate is <0.2g/s/m^2)
- If crash site is 200m x 50m and fuel spilled evenly,(*extreme worst case*) evaporation rate in 15mph (6.7m/s) wind for -77°C fuel would be <2 kg/s
- Time to evaporate 1 tonne would be > 500 seconds.
- Assume no diffusion, no mixing, no turbulence, 2.5 m deep x 100m wide, concentration would be <1,200mg/m^3. This would be painful but not fatal.
- **Creation of a potentially fatal toxic plume from a simple spill of cold liquid ammonia is difficult**

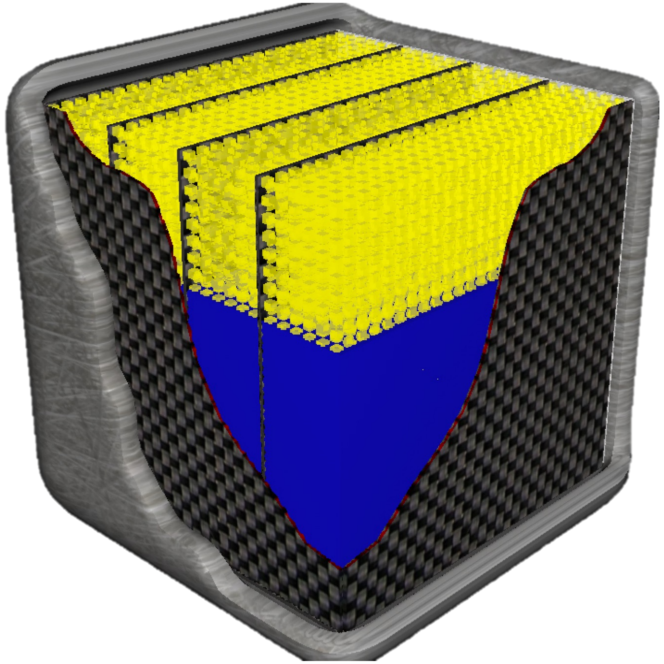


Mitigating the Risks – 3 Different Routes

- Foam-filled tanks with multiple compartments to reduce mist volume. Widely used in military aircraft to prevent fire and explosion
- Blanket the tanks with a fibre layer (fibreglass) to trap and coalesce droplets and prevent misting

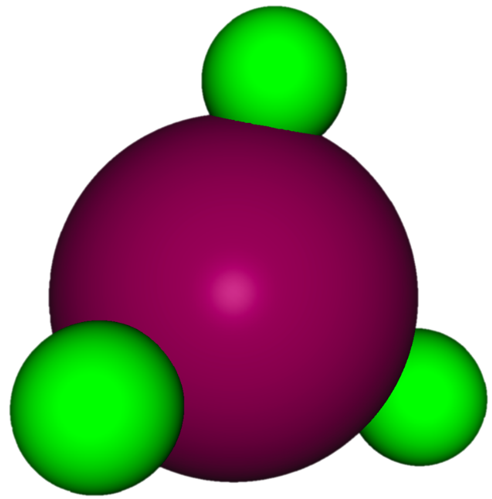
- Pump NH_3 in as ice slush, then freeze with liquid N_2. Ice doesn't form mists.
- Use loose fibre matrix in frozen ammonia tank to hold particles together
- Use liquid NH_3 and waste heat to scavenge solid NH_3

- Use rheology modifiers for liquid ammonia to make honey-like consistency



The Ammonia Advantages

Range of uses, Diversity, Transport and Storage



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Dealing with Rare Events

- Rare events are difficult to manage with solar, and wind – and even nuclear
  - Huge capital cost for rarely used assets
  - The rarer the event the more expensive it becomes to deal with
- Systems with high fuel costs but low capital costs are ideal
  - Fuel cost is irrelevant – very little is used
  - Reliability of supply is crucial

Diversity Gains for NH_3 compared to H_2

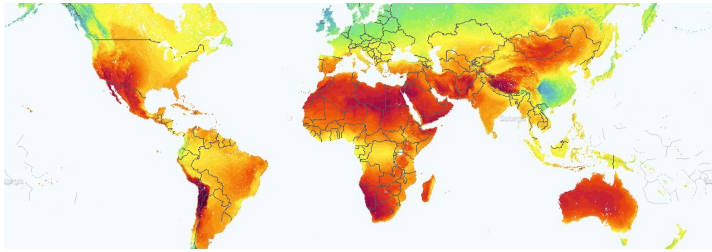
- Countries will have varying and unpredictable needs for long term storage to guarantee energy supply security
- This means either locally stored $H_{2,}$ or NH_3 stored where it is made and imported as needed
- Many countries have uncorrelated, or even negatively correlated patterns of demand and storage
- Locally stored hydrogen means that global total storage = sum of each individual country needs
- **Shared Ammonia storage means the total amount of energy stored may be very considerably less than the sum of every individual need**

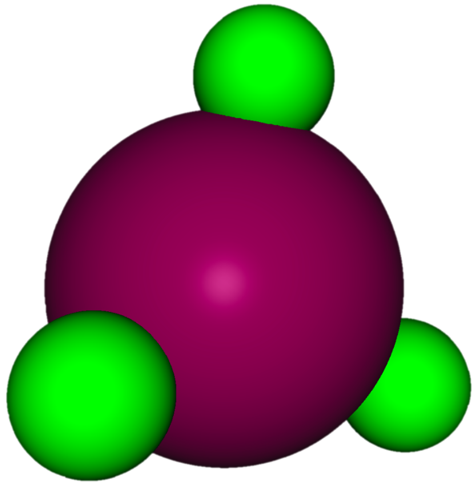
NH_3 as the Global Reserve Fuel

- NH_3 made and stored in sunny places is cheap to make and store
- Existing fertiliser markets and new shipping and transport markets will increase daily throughput massively
  - Annual production already c 200million tonnes/year ≅ 3TWh/day
  - Global energy demand ≅ 500TWh/day
  - NH_3 fertiliser market can bear short term interruptions
- This provides a base for energy reserves akin to global strategic oil reserves without the geopolitical risks
  - Everyone can make NH_3 – only question is cost

In Summary

- NH3 fills crucial gaps in the renewables energy system
  - It allows very cheap energy to be moved in time and space
  - It can compete with fossil fuels with low or no carbon pricing
  - It competes with hydrogen and is often more convenient
  - It can meet the needs of difficult to decarbonise sectors
- It can be made almost anywhere - so democratises energy and improves energy security (*Russian gas? Saudi oil?*)
- It can be safe – but work is needed





Thank You

For more information please visit the Green Ammonia Working Group website at http://gawg.info

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