Ammonia for Maritime Shipping Decarbonization

TEMASEK

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13 December 2023
Temasek Sustainable Solutions

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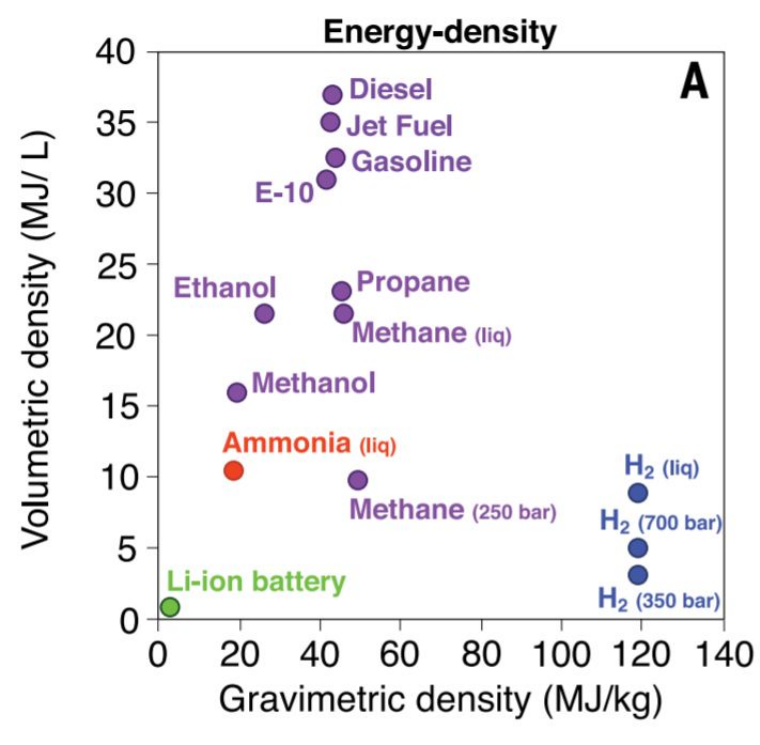
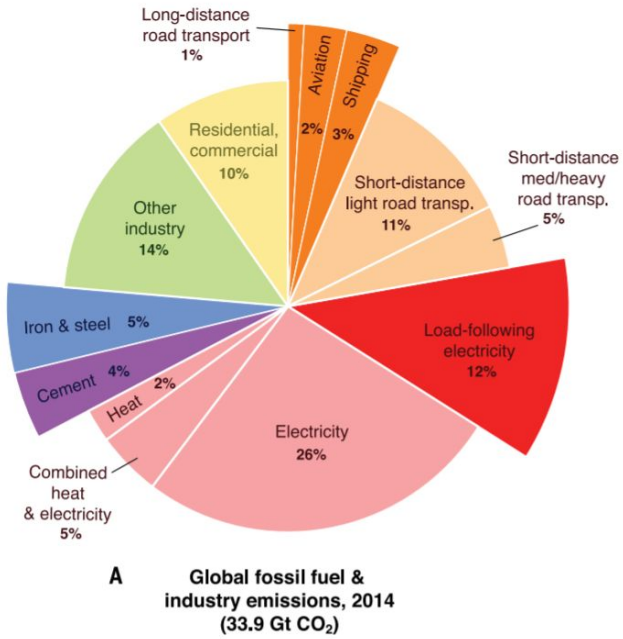
cheap net-zero

Maritime Decarb Needs Fuels*



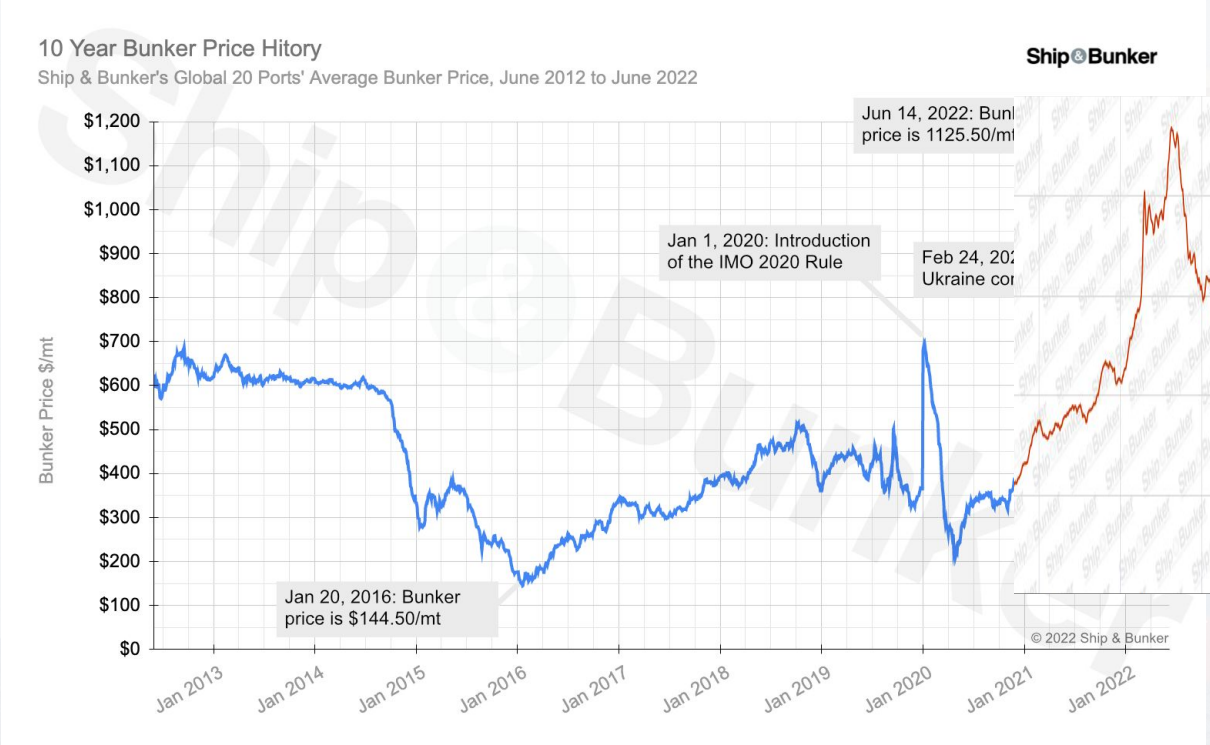


A **Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)**

Science **2018**, *360*, eaas9793.
doi:10.1126/science.aas9793

* *q.v.* Endnote 1

Maritime Decarb Needs cheap net-zero Fuels*



https://shipandbunker.com/prices/av/global/av-glb-global-average-bunker

* *q.v.* Endnote 1

Maritime Decarb Needs cheap net-zero Fuels*

Fuel	Energy Density		Cost		Notes
	wt% H	*LHV (MJ / kg)*	*$ / tonne*	*¢ / kWh*	
Heavy Fuel Oil (HFO)	~10%	39.0	$625	5.77¢	@ 2.689 USD / gal
Liquified Natural Gas (LNG)	25.0%	45	$325	2.60¢	@ 6.57 USD / 1000 ft^3
Ammonia	17.6%	18.8	$790	15.1¢	anhydrous, from SMR/H-B (not green)
Methanol	12.5%	20.1	$575	10.3¢	from SMR (not green)
Hydrogen	100%	120	$8000	24.0¢	@ 8 USD / kg (green)

* *q.v.* Endnote 1

cheap net-zero

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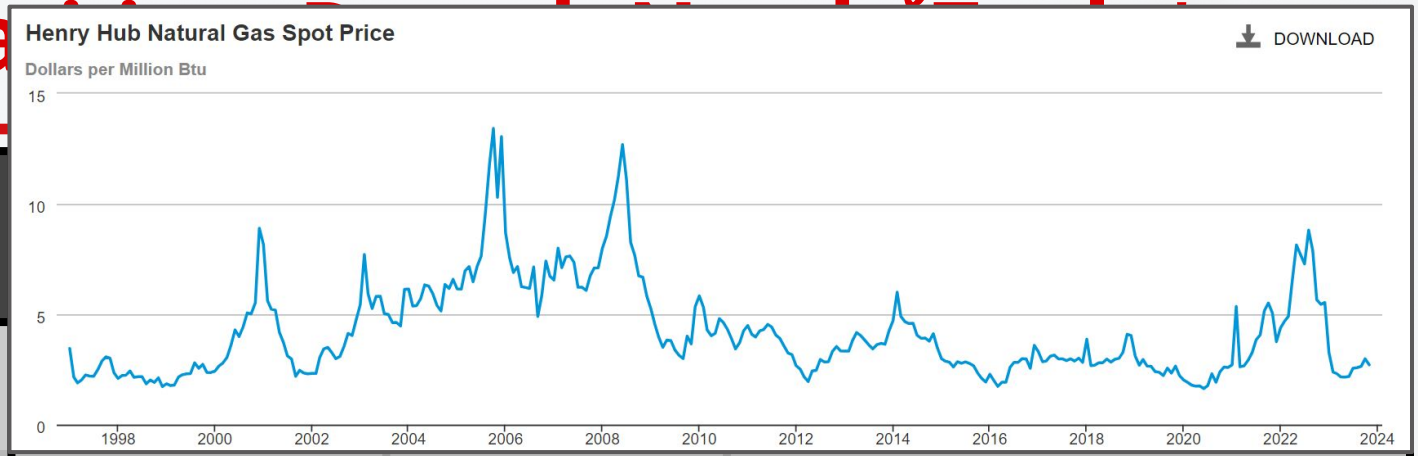

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Atmosphere **2023**, *14*(3), 584. doi:10.3390/atmos14030584

* *q.v.* Endnote 1

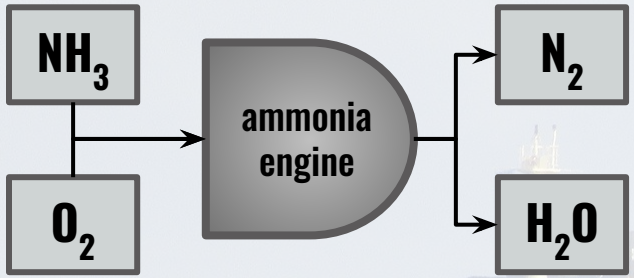
Maritime Ammonia: Pros and Cons

+ tractable to store
  - 7.5 bar *or* -33 °C
  - comparable to LNG
+ tap into global fertilizer industry
  - 180 MMt/yr
+ use directly or as a hydrogen carrier
  - 17.6 wt% H

– extant challenges:
  - engine design
  - ammonia bunkering
  - NO_x emissions
– toxicity
  - regulatory burden
– requires green NH_3
  - Haber-Bosch is hard to beat! †

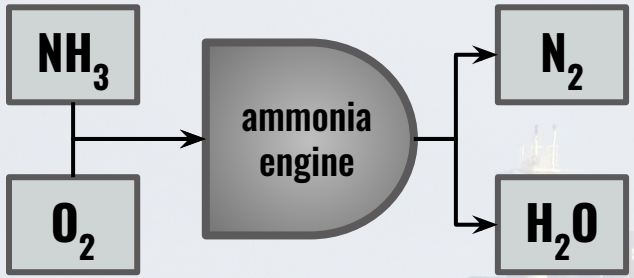
† *q.v.* Endnote 2

Two Classes of Ammonia-Fueled Ships



Direct Combustion:

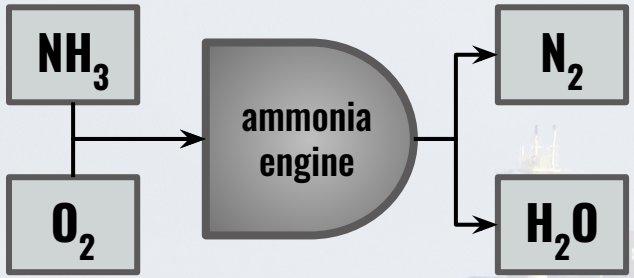
Two Classes of Ammonia-Fueled Ships



Direct Combustion:

\+ Easier ICE retrofit

Two Classes of Ammonia-Fueled Ships



Direct Combustion:

+ Easier ICE retrofit
+ Fairly mature tech

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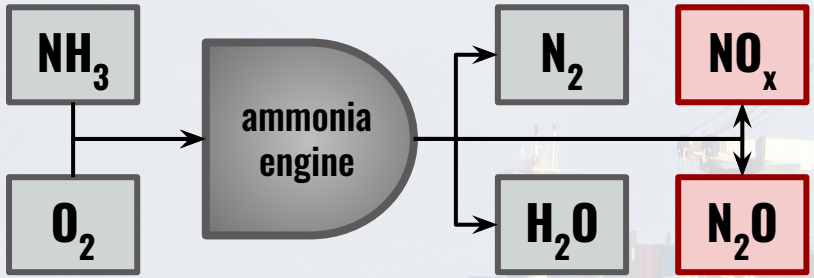

Direct Combustion:

+ Easier ICE retrofit
+ Fairly mature tech
− Nonzero emissions

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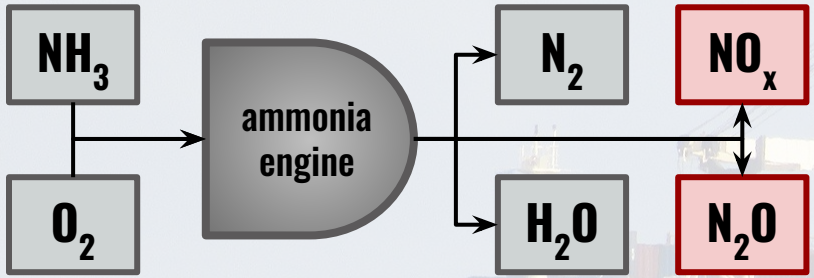

Direct Combustion:

+ Easier ICE retrofit
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− Nonzero emissions
− Less efficient

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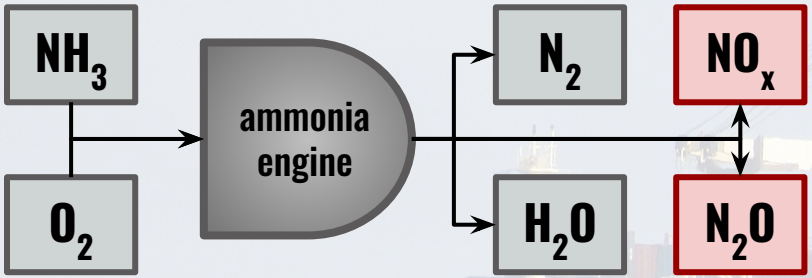

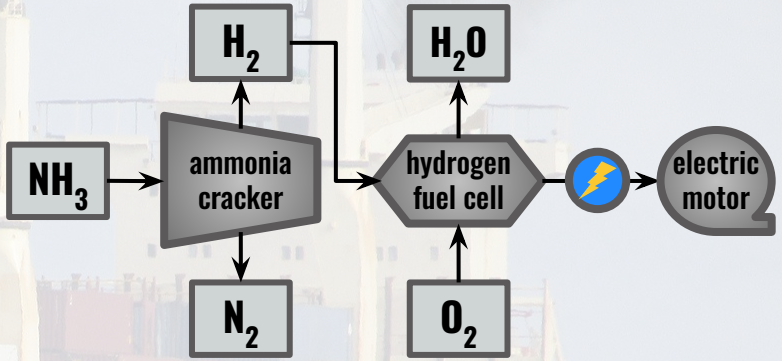

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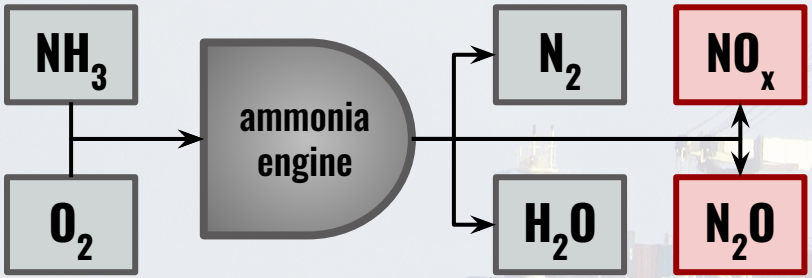
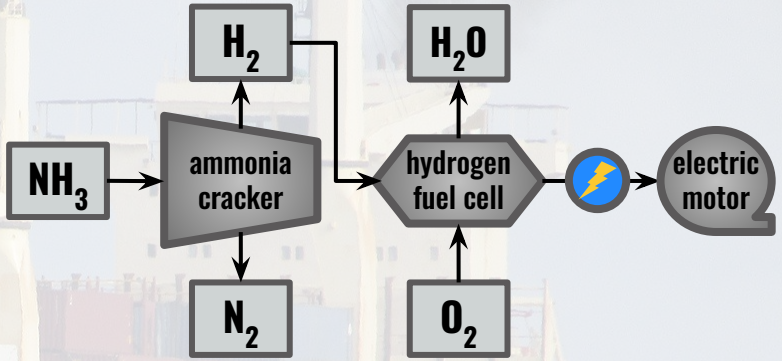
Hydrogen Fuel Cell:

Two Classes of Ammonia-Fueled Ships





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Hydrogen Fuel Cell:

+ Efficient motors

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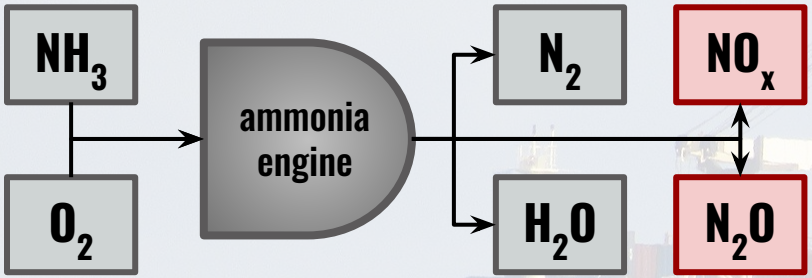

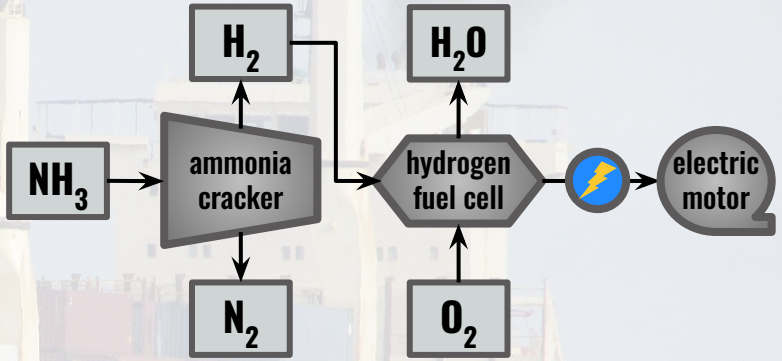

Direct Combustion:

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− Nonzero emissions
− Less efficient

Hydrogen Fuel Cell:

+ Efficient motors
+ Completely clean

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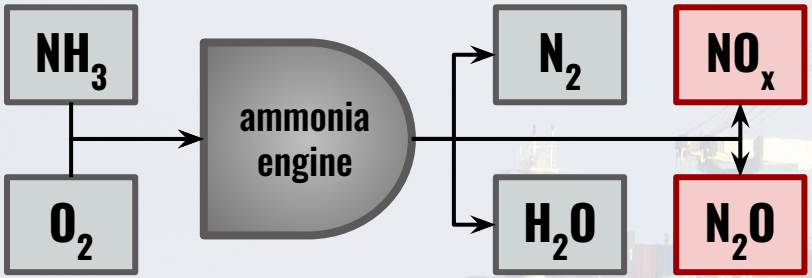

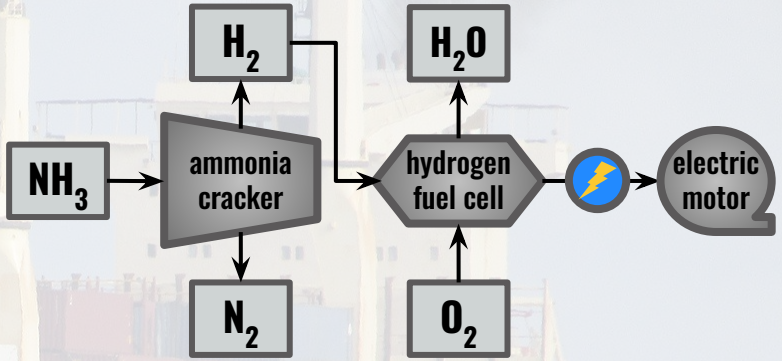

Direct Combustion:

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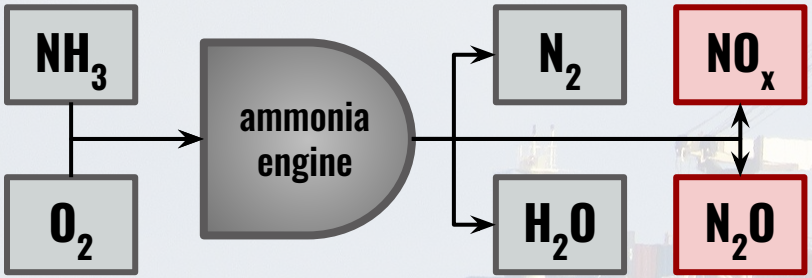
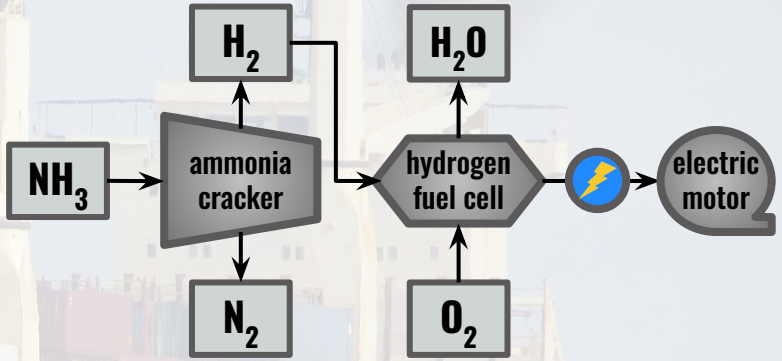




Direct Combustion:

+ Easier ICE retrofit
+ Fairly mature tech
− Nonzero emissions
− Less efficient

Hydrogen Fuel Cell:

+ Efficient motors
+ Completely clean
− Less mature tech
− New builds only

Ammonia Tech Development Areas

Ammonia Tech Development Areas

- Ammonia engines

Wärtsilä continues to set the pace for marine decarbonisation with launch of world-first 4-stroke engine-based ammonia solution

Wärtsilä Corporation, Press release 15 November 2023 at 11:00 UTC+2

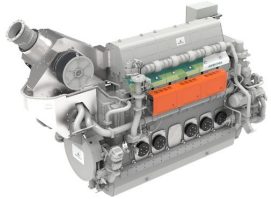
WÄRTSILÄ

MAN Energy Solutions

Thursday, July 13, 2023

Groundbreaking First Ammonia Engine Test Completed

Successful ammonia combustion in MAN B&W two-stroke engine marks 'historic' step for company and maritime sector



[1] https://wartsila.com/media/news/15-11-2023-wartsila-continues-to-set-the-pace-for-marine-decarbonisation-with-launch-of-world-first-4-stroke-engine-based-ammonia-solution-3357985

[2] https://man-es.com/discover/two-stroke-ammonia-engine

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- NH_3 fuel blending

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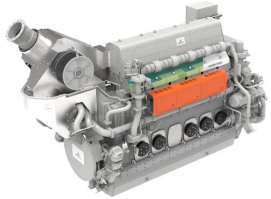

Carbon-free combustion of ammonia/hydrogen fuel

Achieving an efficient combustion performance in existing applications with the on-site and on-demand generation of ammonia/hydrogen fuel

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[2] https://man-es.com/discover/two-stroke-ammonia-engine

[3] https://blazeenergytech.com/

Ammonia Tech Development Areas

- Ammonia engines
- NH_3 fuel blending
- NH_3 cracking

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[2] https://man-es.com/discover/two-stroke-ammonia-engine
[3] https://blazeenergytech.com/
[4] https://ammoniaenergy.org/articles/amogys-ammonia-powered-tug-to-hit-the-water-in-late-2023/

Ammonia Tech Development Areas

- Ammonia engines
- NH_3 fuel blending
- NH_3 cracking
- Green NH_3 synth ‡

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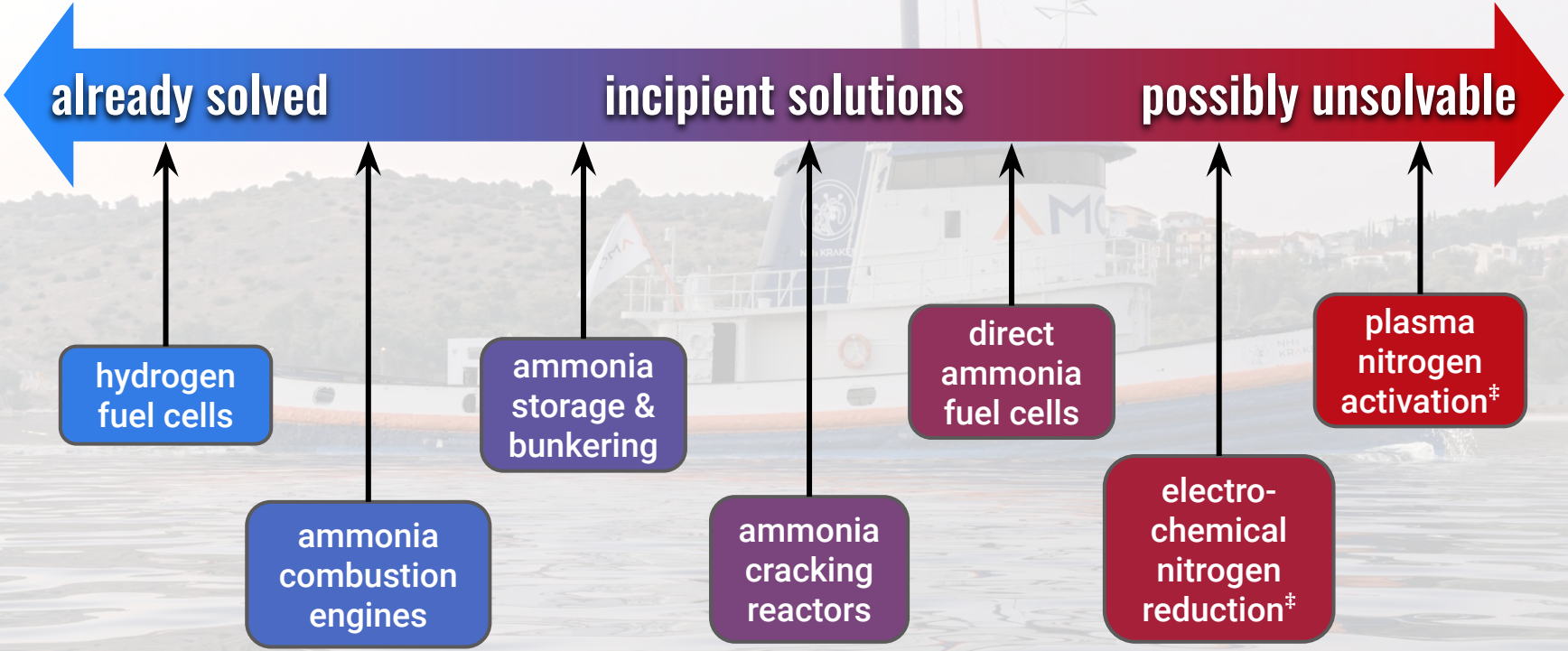
[4] https://ammoniaenergy.org/articles/amogys-ammonia-powered-tug-to-hit-the-water-in-late-2023/

‡ *q.v.* Endnote 3

A Subjective NH_3 Technology Ranking



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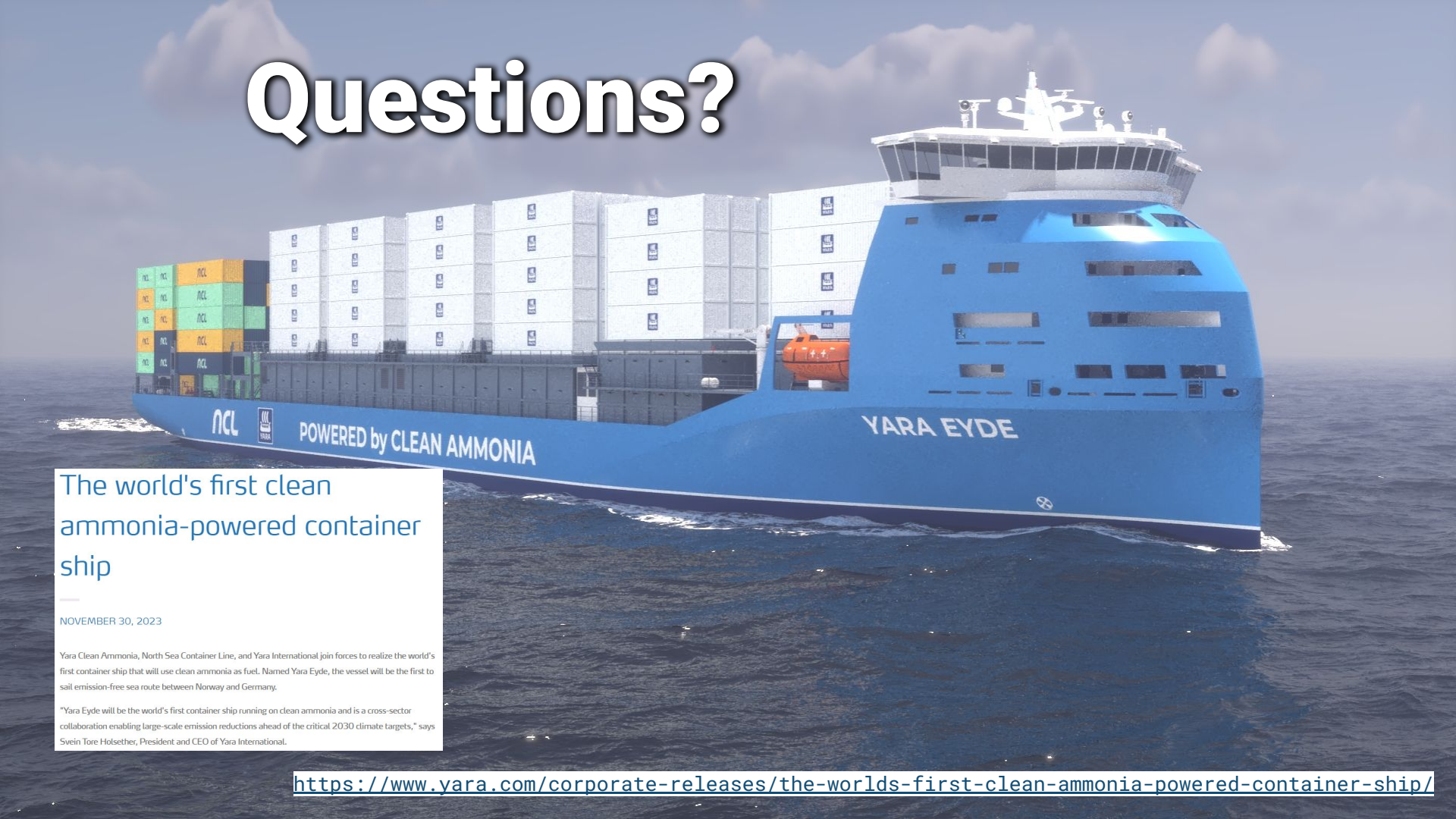
Questions?



The world's first clean ammonia-powered container ship

NOVEMBER 30, 2023

Yara Clean Ammonia, North Sea Container Line, and Yara International join forces to realize the world's first container ship that will use clean ammonia as fuel. Named Yara Eyde, the vessel will be the first to sail emission-free sea route between Norway and Germany.

"Yara Eyde will be the world's first container ship running on clean ammonia and is a cross-sector collaboration enabling large-scale emission reductions ahead of the critical 2030 climate targets," says Svein Tore Holsether, President and CEO of Yara International.

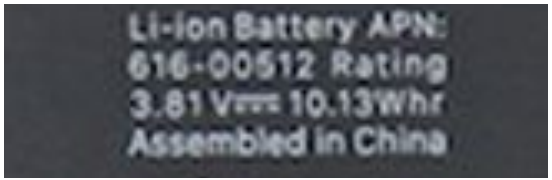
https://www.yara.com/corporate-releases/the-worlds-first-clean-ammonia-powered-container-ship/

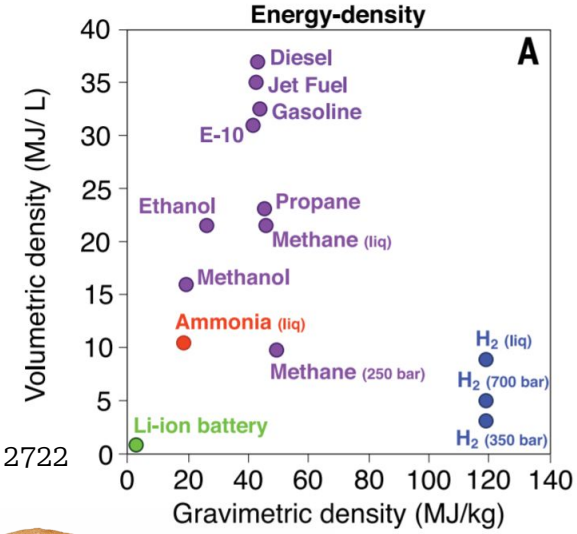
*Endnote 1: Batteries Can't Beat Fuels

(146.7 × 71.5 × 7.4) mm^3 = 78 mL

2659 mA*h × 3.81 V = 10.13 W*h = 36.4 kJ

(phone battery charge) (phone battery voltage) (phone battery energy capacity)





Car Battery:

63 A*h × 12 V = 756 W*h = 2722 kJ

<

Footlong Sub Sandwich:

750 kcal × 4.184 kJ/kcal = 3138 kJ

36.4 kJ ÷ (34.2 MJ/L) = 1.07 mL

(phone battery energy capacity) (volumetric energy density of gasoline) (volume of gas tank it would take to replace your phone battery)

Nutr. Rev. **2010**, *68*, 439.
Appl. Energy **2013**, *103*, 256.
INL/EXT-13-31768, **2013**.

†Endnote 2: The Haber-Bosch Process

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

T = 300 °C

P = 300 bar

K:Fe_3O_4 catalyst

†Endnote 2: The Haber-Bosch Process

$N_2 + 3\ H_2 \rightarrow 2\ NH_3$ ← Haber-Bosch Process (H-B)

$CH_4 + H_2O \rightarrow CO + 3\ H_2$ ← Steam Methane Reforming (SMR)

$2\ CH_4 + O_2 + CO_2 \rightarrow 3\ H_2 + 3\ CO + H_2O$ ← Autothermal Reforming (ATR)

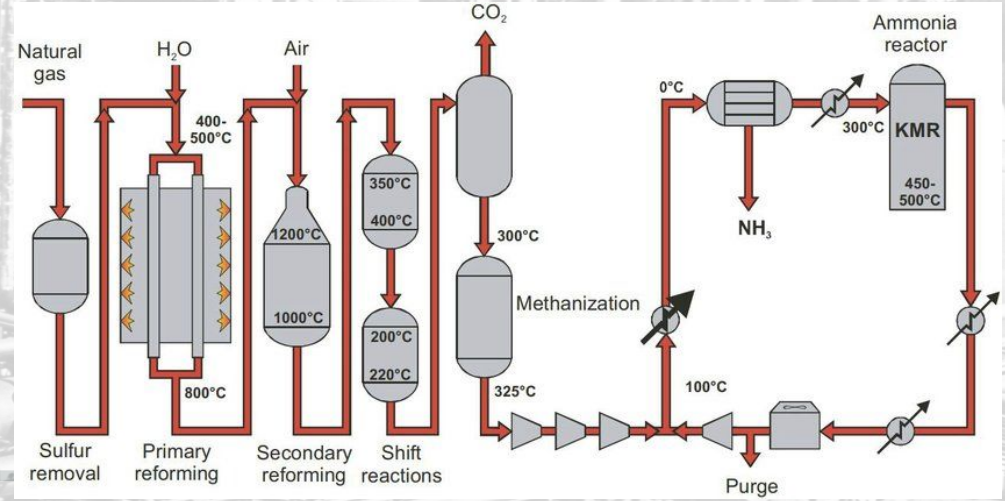
$CO + H_2O \rightarrow CO_2 + H_2$ ← Water-Gas Shift (WGS)

$6\ N_2 + 5\ CH_4 + O_2 + 8\ H_2O \rightarrow 5\ CO_2 + 12\ NH_3$

↑

actual integrated H-B + SMR + ATR + WGS net reaction

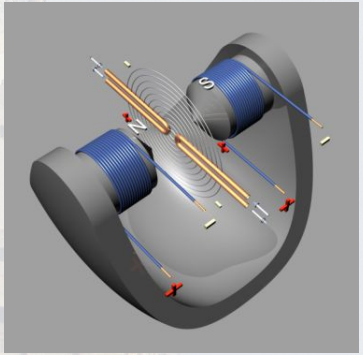
green hydrogen is not a drop-in decarbonization solution for Haber-Bosch!

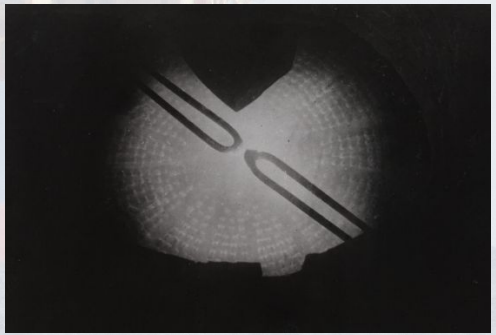


Green Chem. **2020**, *22*, 6258. doi:10.1039/D0GC02058C
Melville, J. F. PhD Thesis, MIT, Cambridge, Massachusetts, **2021**. hdl:1721.1/139141

‡Endnote 3: Making Green Ammonia

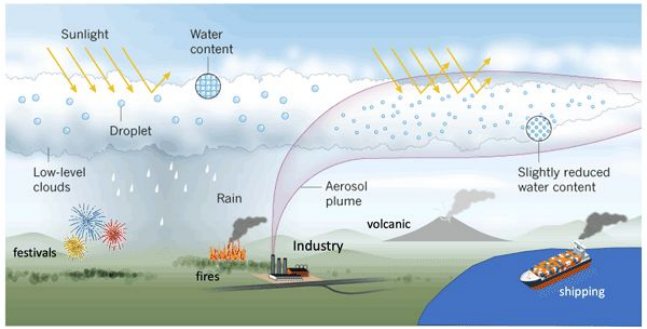
- Green H_2 + H-B *(not drop-in!)*
- Electrochemical NRR (eNRR)
  - N_2 + H_2 (electrochemical H-B)
  - N_2 + H_2O (built-in water splitting)
  - NO_x + H_2O (reverse Ostwald)
- Plasma-catalysed
  - MHCDs / MIMs
  - Birkeland-Eyde Process (BEP)





Melville, J. F. PhD Thesis, MIT, Cambridge, Massachusetts, **2021**. hdl:1721.1/139141

§Endnote 4: Accidental Maritime Geoengineering



New regulations from the International Maritime Organization (IMO) limiting sulfur emissions from the shipping industry are expected to have large benefits in terms of public health but may come with an undesired side effect: acceleration of global warming as the climate-cooling effects of ship pollution on marine clouds are diminished. Previous work has found a substantial decrease in the detection of ship tracks in clouds after the IMO 2020 regulations went into effect [...] we confidently detect a reduction in the magnitude of cloud droplet effective radius decreases within the shipping corridor and find evidence for a reduction in the magnitude of cloud brightening as well.

Atmos. Chem. Phys. **2023**, *23*, 8259.
doi:10.5194/acp-23-8259-2023