Innovations in Ammonia

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US DOE, Hydrogen & Fuel Cell Technical Advisory Committee

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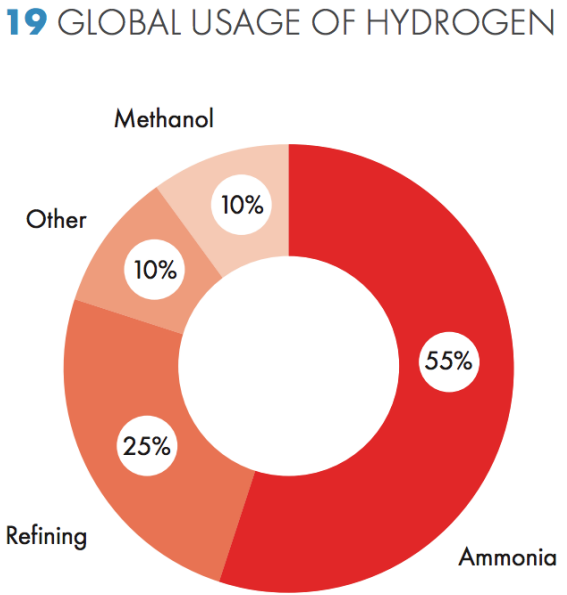
Ammonia: Hydrogen at Scale

2017 Production (metric tons)	Ammonia	Hydrogen (17.8 %wt NH_3)
USA	12.8 million	2.3 million
World	183 million	32.6 million



Hydrogen is captive:

- SMR / POX process; gas, coal, etc feedstock

Ammonia is mostly captive:

- Urea, nitric acid, AN, UAN, etc

Mature markets:

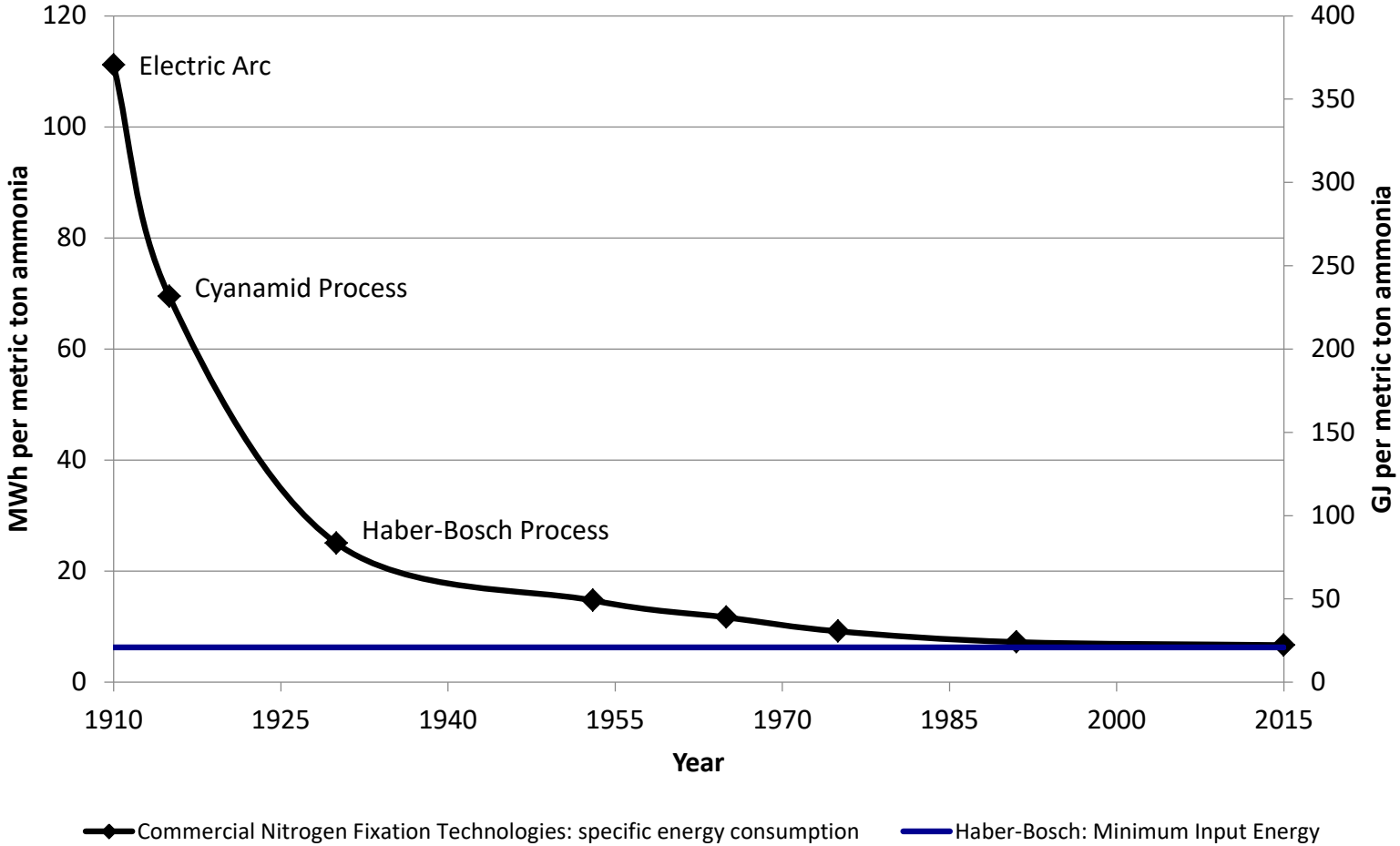
- 80% fertilizer, ~2% CAGR, <10% traded (16-17 million merchant tons)

Innovations in Ammonia

1) History of Innovation: **Energy Efficiency**
2) Future of Innovation: **Carbon Efficiency**
3) Low-carbon Ammonia: **Available Today**
4) Carbon-free Ammonia: **Electrolysis + Haber-Bosch Pilot Plants**
5) Green Ammonia Markets: **Hydrogen Carrier Technologies**

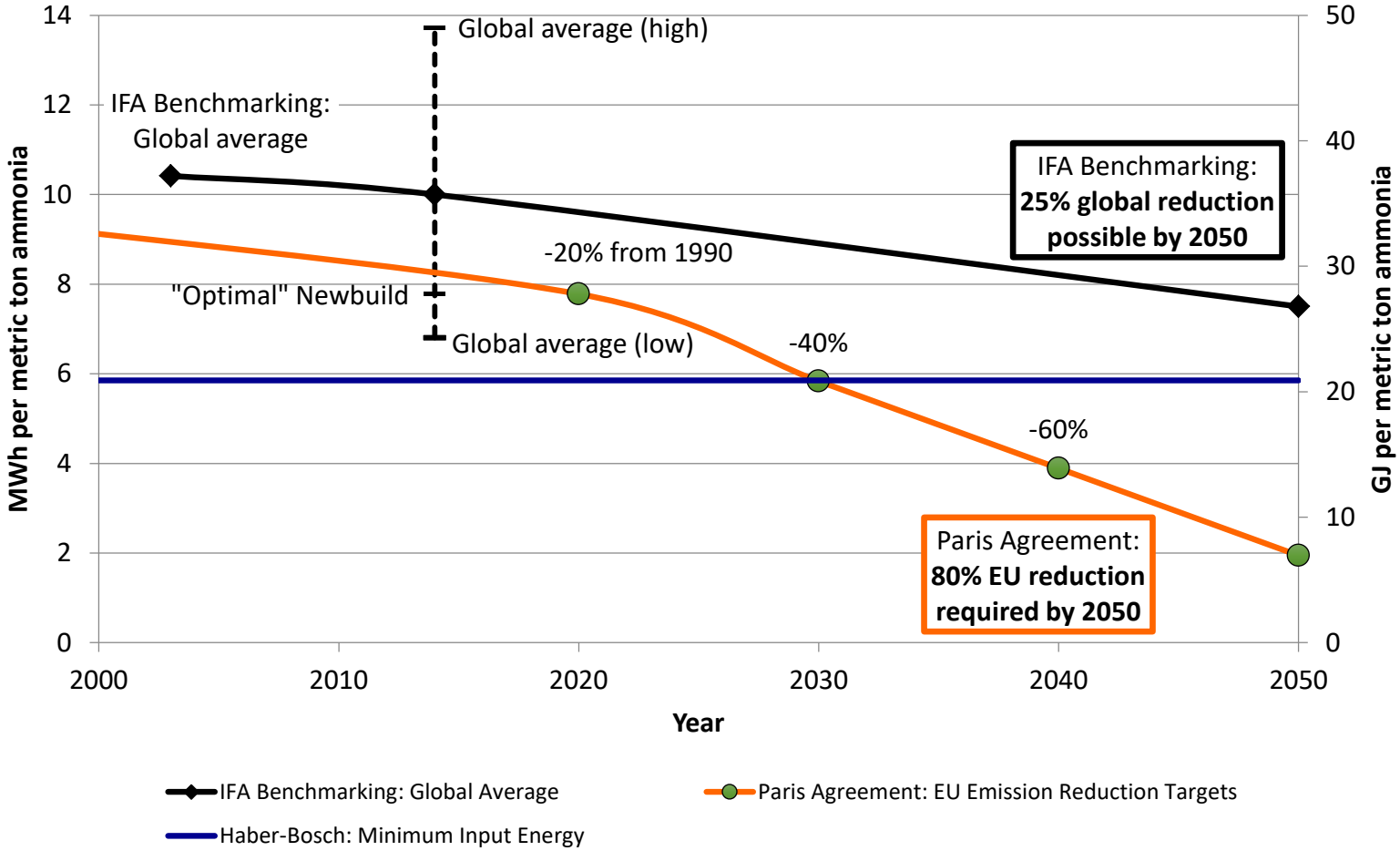
Ammonia Synthesis (Nitrogen Fixation): Energy Efficiency, 1910-2015

Various sources / AmmoniaIndustry.com, November 2018



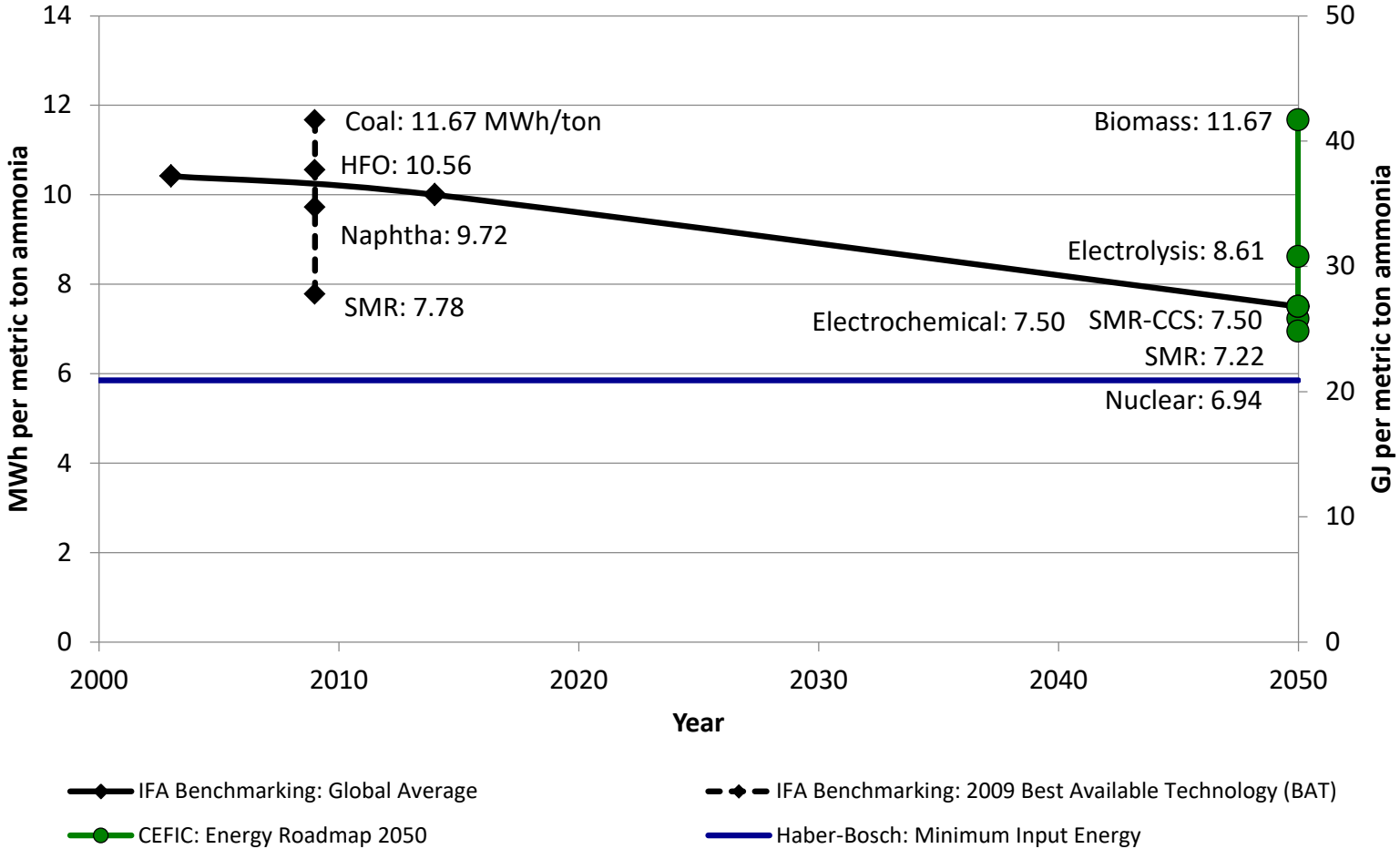
Ammonia Synthesis: Energy Efficiency, 2000-2050

IFA Benchmarks / AmmoniaIndustry.com, November 2018



Ammonia Synthesis: Best Available Technologies, 2000-2050

IFA Benchmarks / CEFIC / AmmoniaIndustry.com, November 2018



Ammonia Synthesis: Carbon Efficiency, 2000-2050

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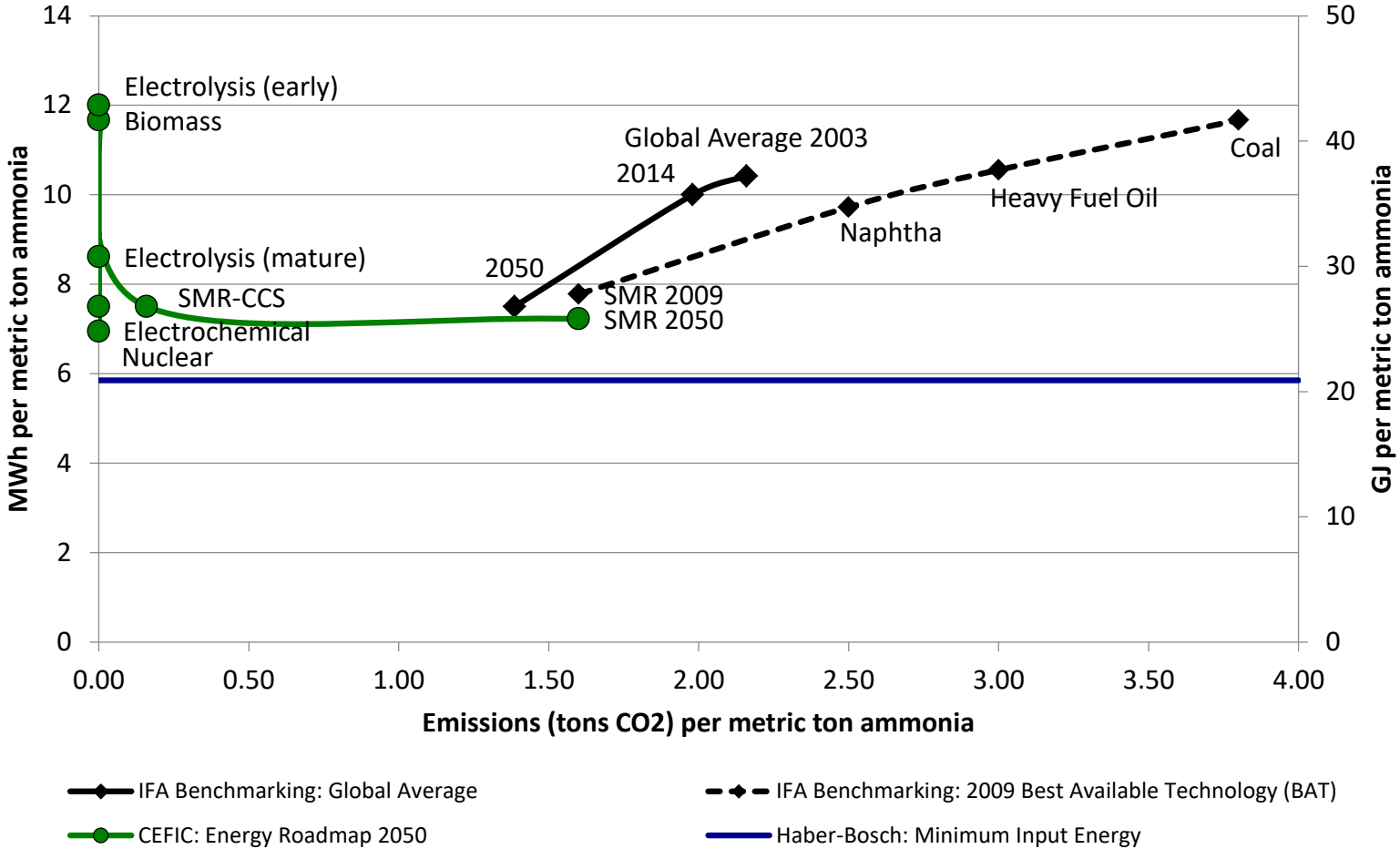


Low-carbon Haber-Bosch: Available Today

Showa Denko (Kawasaki, Japan)

- Plastic gasification since 2003
- Ammonia capacity 175 tons per day
- 65% hydrogen feedstock from recycled plastic

Premium for low-carbon technology in Japan

- Ecoann™ ammonia sold as deNOx product

"Approved and rated high as 'eco-friendly goods for procurement' by major electric power companies."

Low-carbon Haber-Bosch: Available Today

Nutrien (Joffre, Canada)

- Byproduct hydrogen feedstock since 1987
- Ammonia capacity 1,350 tons per day
- 25% reduction in carbon footprint v SMR

Premium for low-carbon technology in Canada

- Alberta carbon tax hits both fuel and feedstock

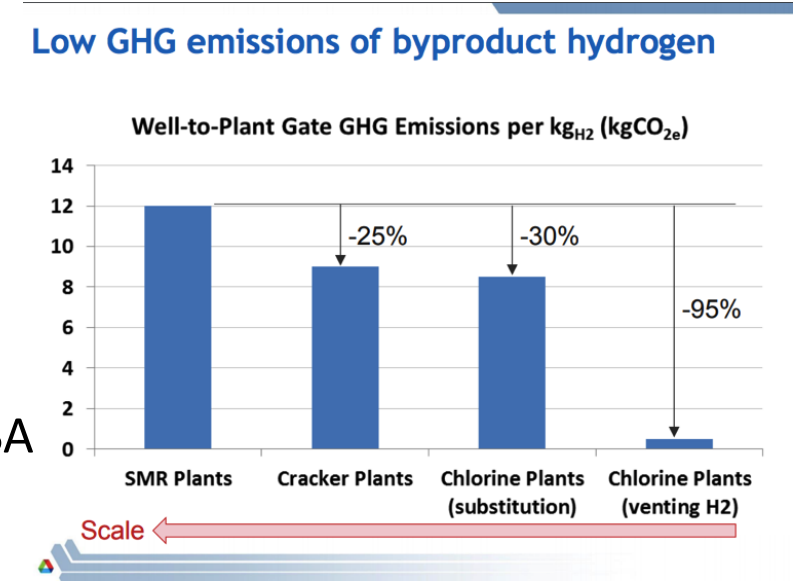
Joffre plant generates carbon credits that offset emission cost of other plants in Nutrien's fleet

Low-carbon Haber-Bosch: Available Today

Yara / BASF, Freeport, TX

- Byproduct hydrogen feedstock since 2018
- Ammonia capacity 2,200 tons per day
- 25% reduction in carbon footprint v SMR

No premium for low-carbon technology in USA



Green Ammonia: Back to the future

Yara (Norsk Hydro), Glomfjord, Norway

- Hydropower ammonia, 1953 – 1991
- The world's biggest electrolyzers:
  2 x 135 MW units; 30,000 Nm^3 per hour
- 100% carbon free

Closed because no market advantage,
not competitive v SMR.

But now, in 2018 …
electrolyzer costs down, efficiency up; and
renewable power input prices dropping

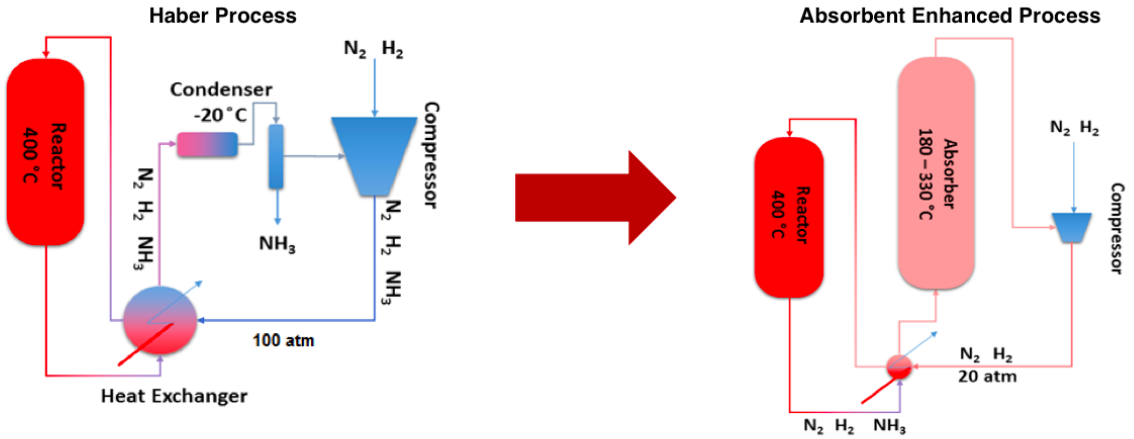
Green Ammonia: Electrolyzer Pilot Plants

- **University of Minnesota**: Morris, MN, US
- Operational since 2013
- R&D innovation:
  Scaling down Haber-Bosch to match wind

Green Ammonia: Electrolyzer Pilot Plants

Lowering Capital Cost: Absorbent Enhanced Synthesis

- Absorption instead of condensation[1]
- Lower pressure and less heat exchange (temperature difference)
- Lower capital cost than conventional process, especially at small scale[2]



[1] Malmali et al, *Ind. Eng. Chem. Res.*, 2016, 55, 33, 8922-8932.
[2] Palys et al, *Processes*, 2018, 6, 7, 91.

Green Ammonia: Electrolyzer Pilot Plants

- **FREA**: Fukushima, Japan
- Operational since April 2018
- R&D innovation:
  Catalyst development optimized for low-pressure electrolytic hydrogen

Green Ammonia: Electrolyzer Pilot Plants

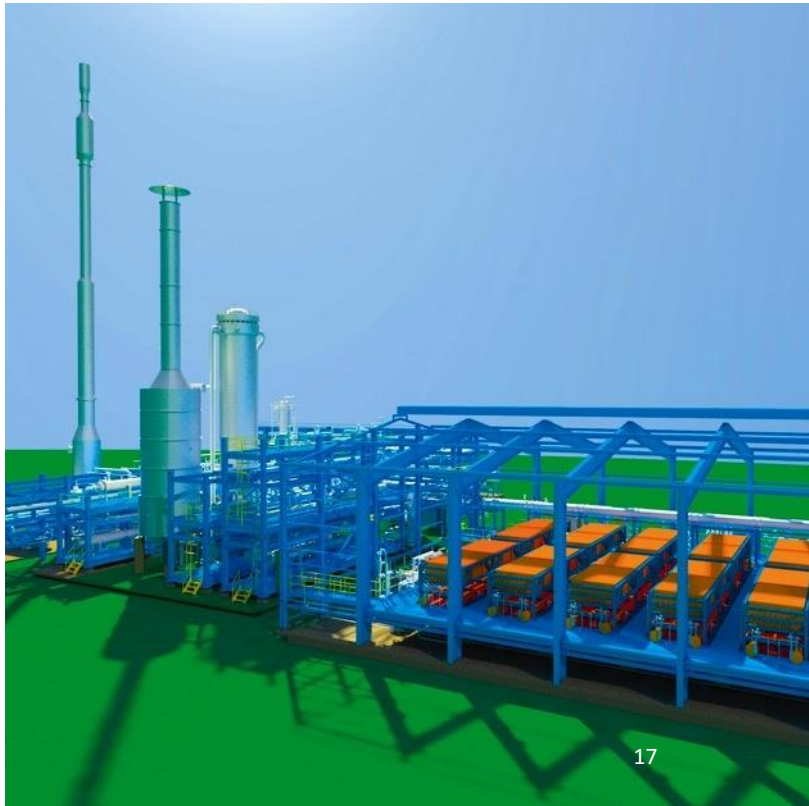
- **Siemens**: Oxford, UK
- Operational since June 2018
- R&D innovation:
  Business Models: ancillary grid services (DSM), energy storage, electrofuel production

Green Ammonia: Electrolyzer Pilot Plants

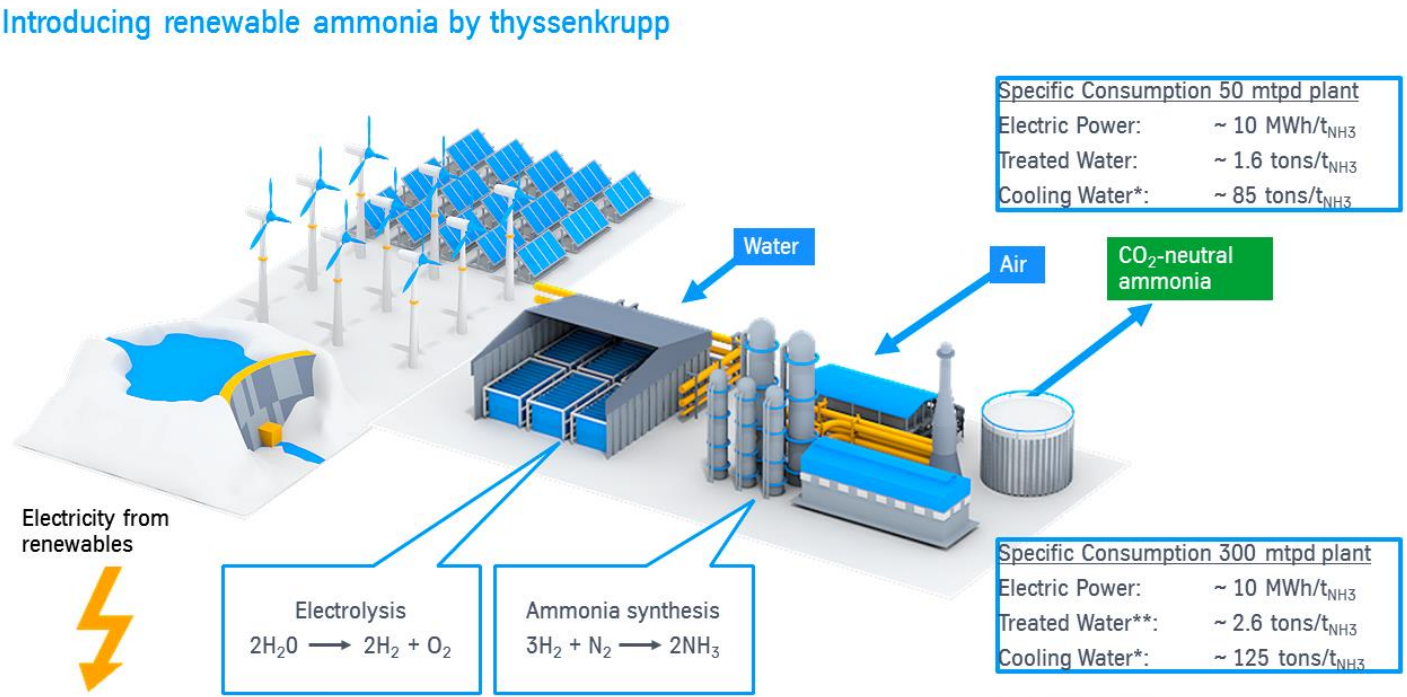
Image not available for publishing

Green Ammonia: Electrolyzer Pilot Plants

- **ThyssenKrupp**: Port Lincoln, Australia
- Announced 2018 for 2020 start
- R&D innovation:
  Market development for ammonia exports as renewable energy commodity



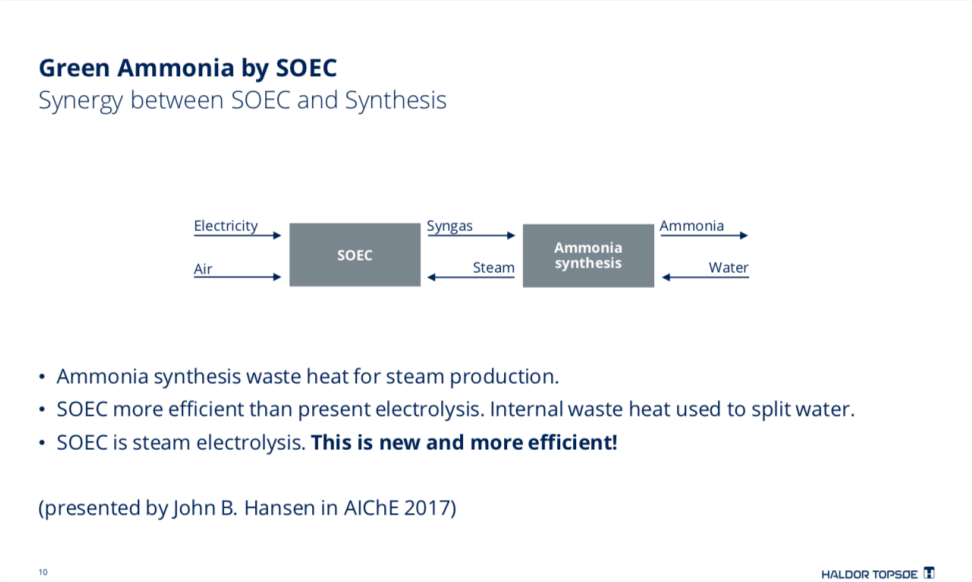
Green Ammonia: Electrolyzer Pilot Plants



Green Ammonia: Electrolyzer Pilot Plants

Green Ammonia: Electrolyzer Pilot Plants

- **Haldor Topsoe**: Denmark
- Announced 2018 for 2025 start
- R&D innovations:
  Solid oxide electrolyzer,
  SMR-ammonia plant revamp



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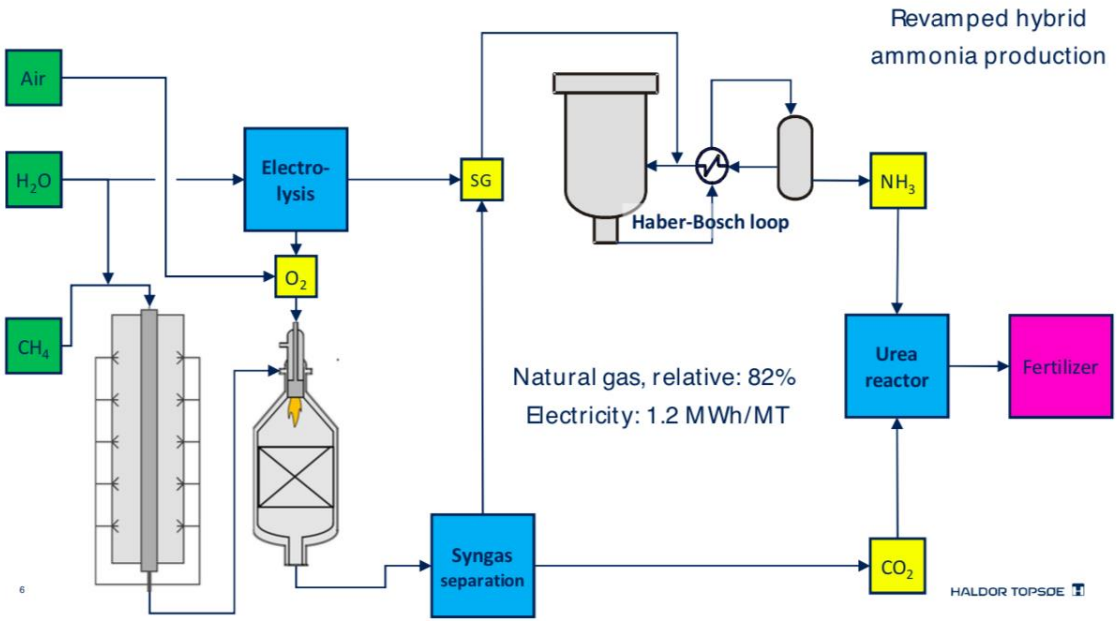

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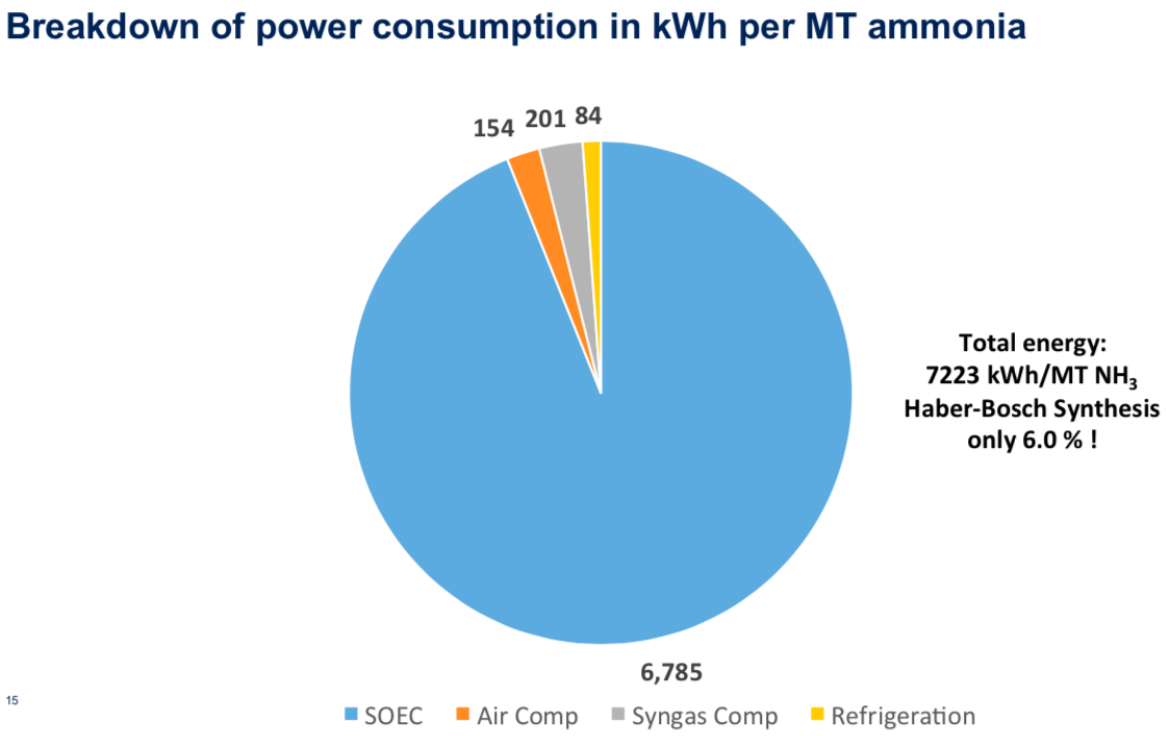
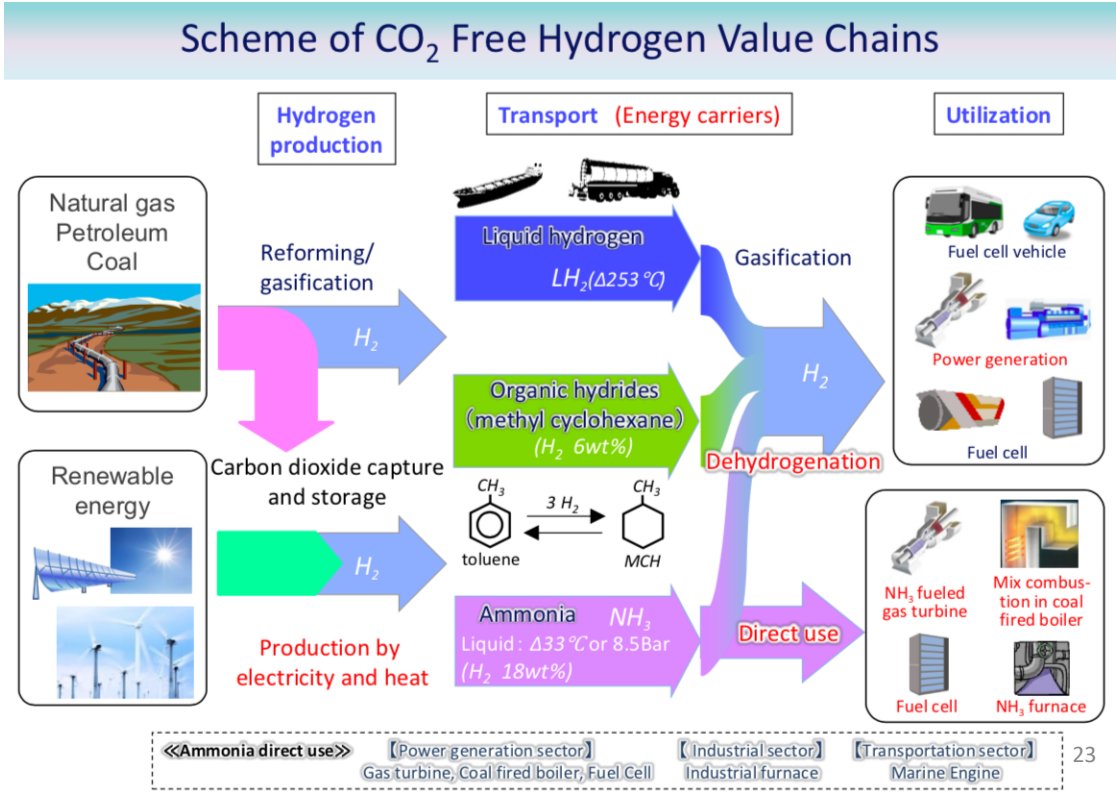


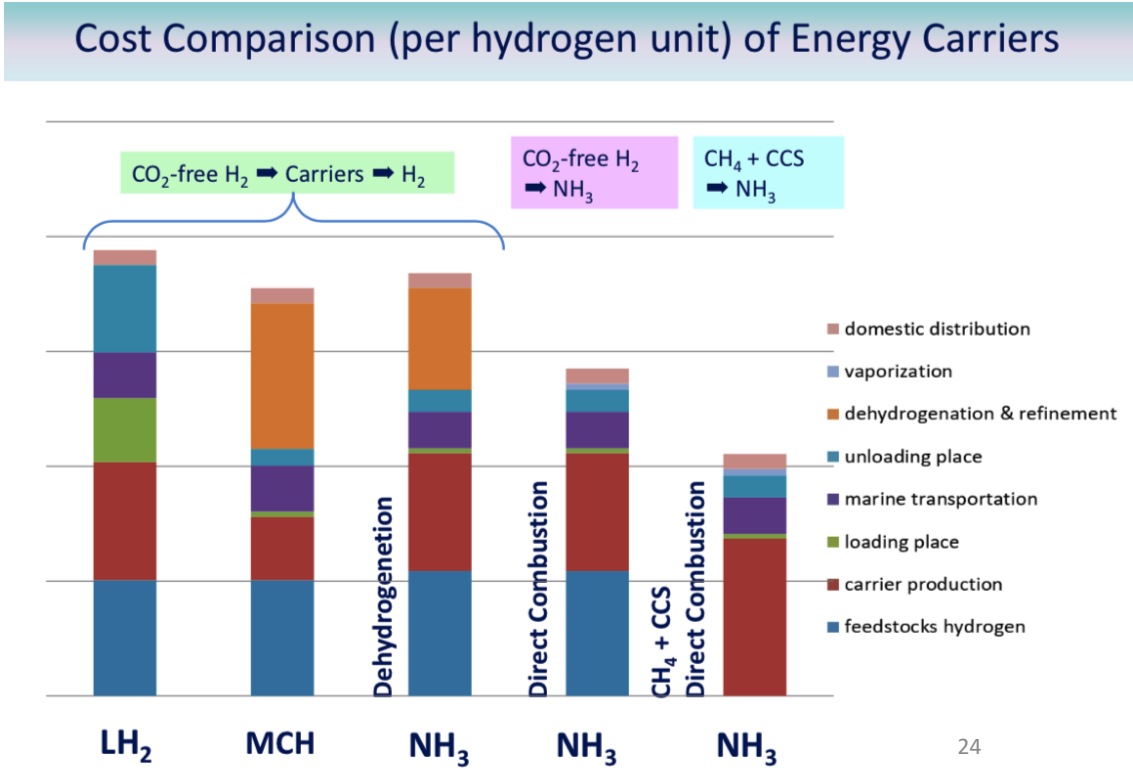
Japan: SIP "Energy Carriers"

- Gov't-Industry-Academia R&D, launched 2015
- Ammonia demonstrations:
  - Green ammonia synthesis
  - Ammonia SOFC
  - Ammonia turbine
  - Ammonia furnace
  - Ammonia co-combustion (coal power, cement)
  - Ammonia cracking / purification on-site, for hydrogen stations (PEM FC)
  - Ammonia safety, regulations, & public acceptance issues



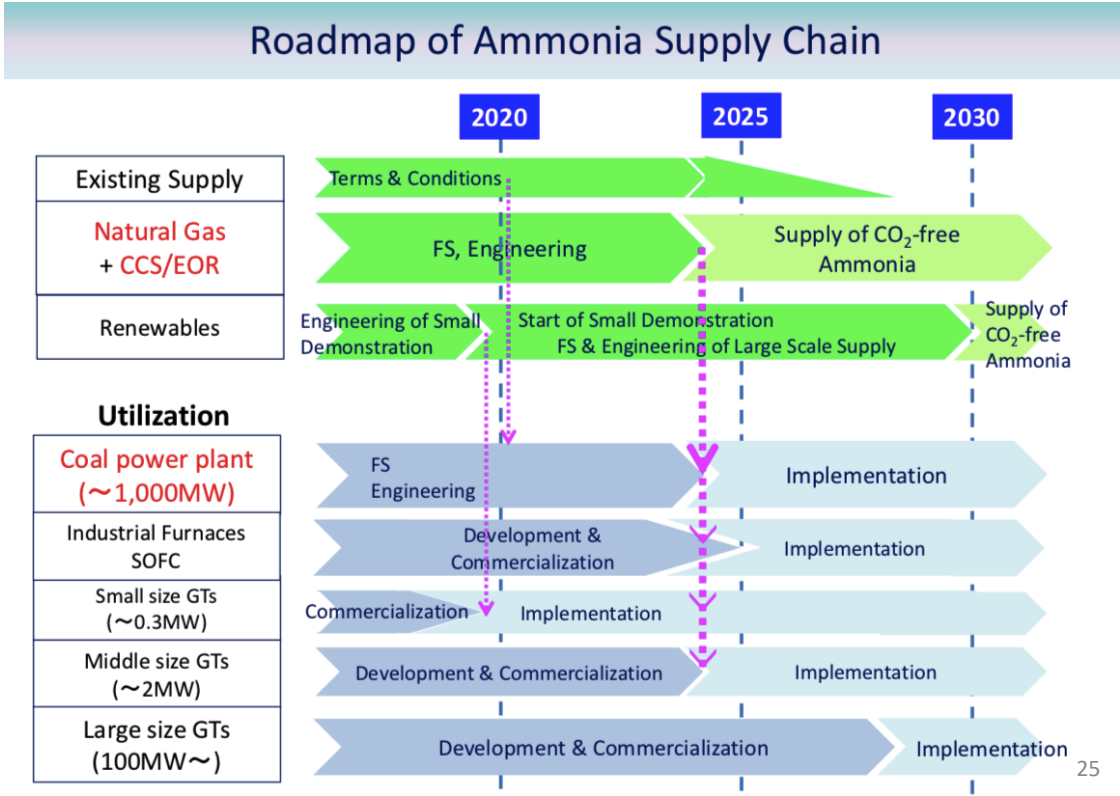
Japan: SIP “Energy Carriers”

- Cheaper to import and dehydrogenate ammonia than to import hydrogen
- Economics improve if using ammonia as direct fuel
- Economics improve using conventional process with sequestration (CH4+CCS) as bridge technology



Japan: SIP “Energy Carriers”

- Demonstration projects already operational
- Imports of CO2-free ammonia planned to begin in 2024 (CH4+CCS)
- Imports of CO2-free ammonia planned to begin in 2030 (renewables)
- Signed into law by PM Abe, Hydrogen Basic Strategy, December 2017



Green Ammonia: Market Transformations

- Nitrogen Commodity → Hydrogen Commodity
- Homogenous Commodity → Heterogeneous Commodity

  Price Premium = Local Function[Carbon Footprint]
- Green Ammonia (Energy Markets) → Green Ammonia (Ag Markets)

  Low-Carbon Leakage: supply creates demand

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Questions?
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