Ammonia combustion emissions

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Ammonia Energy Association

- The Ammonia Energy Association (AEA) is a global industry association that promotes the responsible use of ammonia in a sustainable energy economy

- **Supply**: decarbonize ammonia production
- **Demand**: adopt ammonia in energy markets

- **Members**: global and cross-sectoral

MEMBER LIST — May 2022

PLATINUM: bp, CF Industries*, CWP Global, Denbury Inc., The Hydrogen Utility*, InterContinental Energy*, KBR*, LSB Industries, Mitsui & Co., Monolith Materials, Nutrien*, OCI*, Starfire Energy*, Yara*. **GOLD**: AFC Energy, Airgas, Aker Clean Hydrogen, Asian Renewable Energy Hub, Casale*, Enaex, Engie, Equinor, Fortescue Future Industries, FuelPositive, Haldor Topsøe*, Hamilton Locke, Marnco, Mitsubishi Heavy Industries, Origin Energy*, Proton Ventures*, S&P Global Platts, Syzygy Plasmonics, thyssenkrupp Industrial Solutions*, Trammo, Trigon, Tri-State Generation & Transmission. **SILVER**: AES Gener, Air Products, Ammonigy, AmmPower, Amogy, Argus Media, BASF, Black & Veatch, Bureau Veritas, Burns & McDonnell, Casa dos Ventos, Consorcio Eólico, CRU Group, CS Combustion Solutions, Copenhagen Atomics, Cummins, EIFER, Enterprize Energy, Fertiberia, GenCell Energy, GTI Energy, Gunvor Group*, H2Site, Heraeus, Horisont Energi, HyFuels Holdings, IHI Americas, Inherent Solutions Consult, inodú, Intecsa Industrial, Johnson Matthey, Koch Fertilizer, Linde, Lotte Fine Chemical, Mabanaft, Maersk*, Mercuria, MineARC Systems, Mitsui OSK Lines, Nel Hydrogen*, Pacific Green Technologies, SagaPure*, Schoeller-Bleckmann Nitec, Shell, Skeiron, Sperre Industri, Stamicarbon, Talos Energy, Thorium Energy Alliance*, TotalEnergies*, Tsubame BHB, Universal H2, Wonik Materials, Woodside Energy. **MEMBERS**: AB Achema, Advanced Ionics, Advanced Thermal Devices, AHMON, Air Liquide, Airthium, Apex Clean Energy, Arizona Public Service, Ark Energy, Arranged, AustriaEnergy, Avaada Energy, Axetris, BLG, Brittany Ferries, C-Job Naval Architects, Carbon-Neutral Consulting*, CHZ Technology, ControlRooms, Cozairo, Cura IT, Danaos Shipping, Duiker Combustion Engineers, El-H2, Energy Estate, Eneus Energy, ESNA, Evergy, Exmar, George Propane, GESCA, Greenfield Nitrogen, GTT North America, Idemitsu Kosan, Incitec Pivot, Ingenostrum, IT Power Australia, JGC Holding Corporation, John Cockerill, Jupiter Ionics, Keppel Infrastructure, Koole, Mainspring Energy, MAN Energy Solutions, MicroEra Power*, Moda, Nebraska Public Power District, Neology, Netsco, New Energy Technology, NGLStrategy, Nordex, Northern Nitrogen, NovoHy, NYK Energy Transport (USA), Oceanic Vessels, Oiltanking, Osaka Gas USA, Renewable Hydrogen Corporation Canada, SAFCell, SBM Schiedam, Shrieve Chemical Company, Syntex, Terrestrial Energy, Tokyo Gas, Unconventional Gas Solutions, UPC\AC Renewables, Vahterus, Varo Energy, Vopak.

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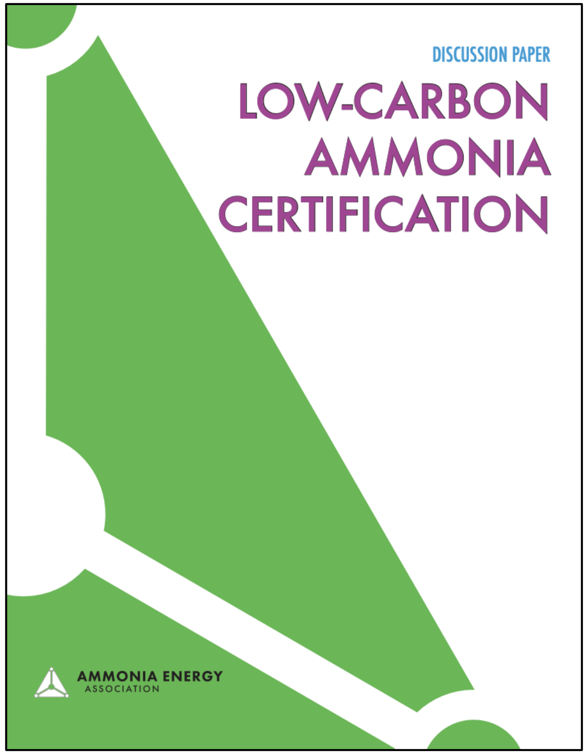
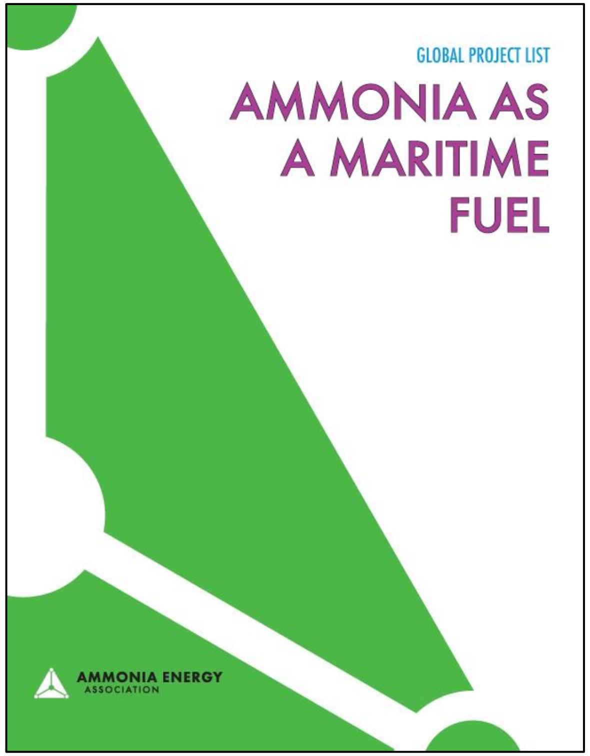
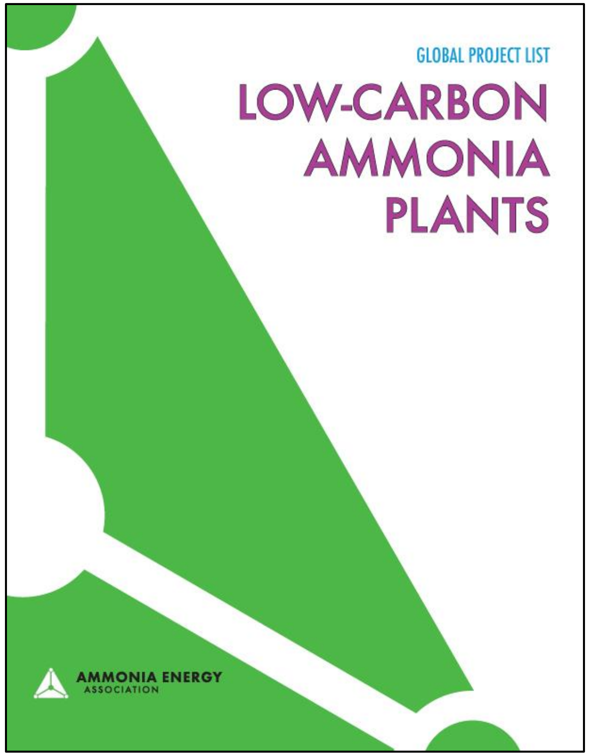


Develop certification scheme for low carbon ammonia

Innovation Outlook: Renewable Ammonia. (collaboration with IRENA)

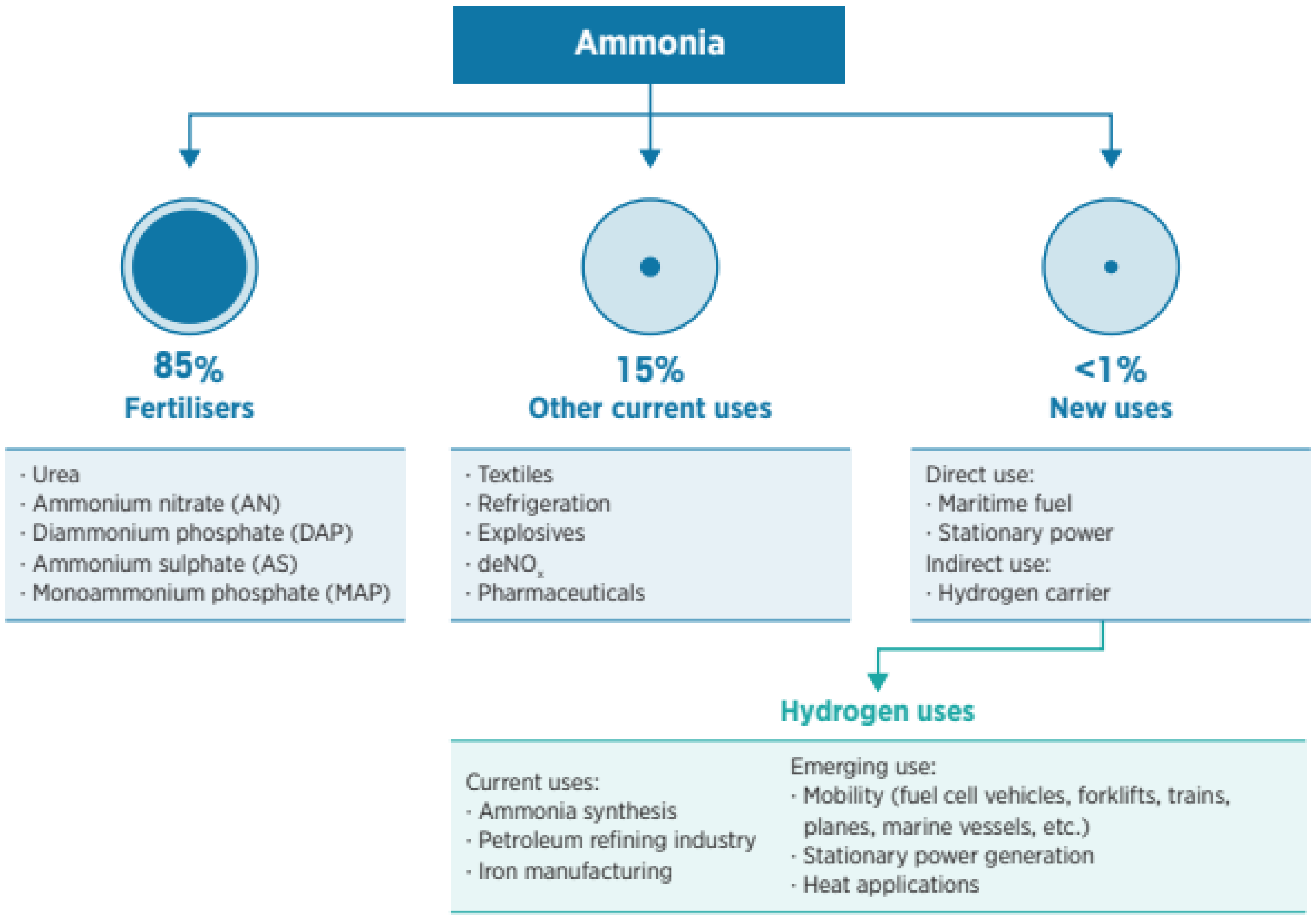


Mapping maritime ammonia projects (+ webinars)



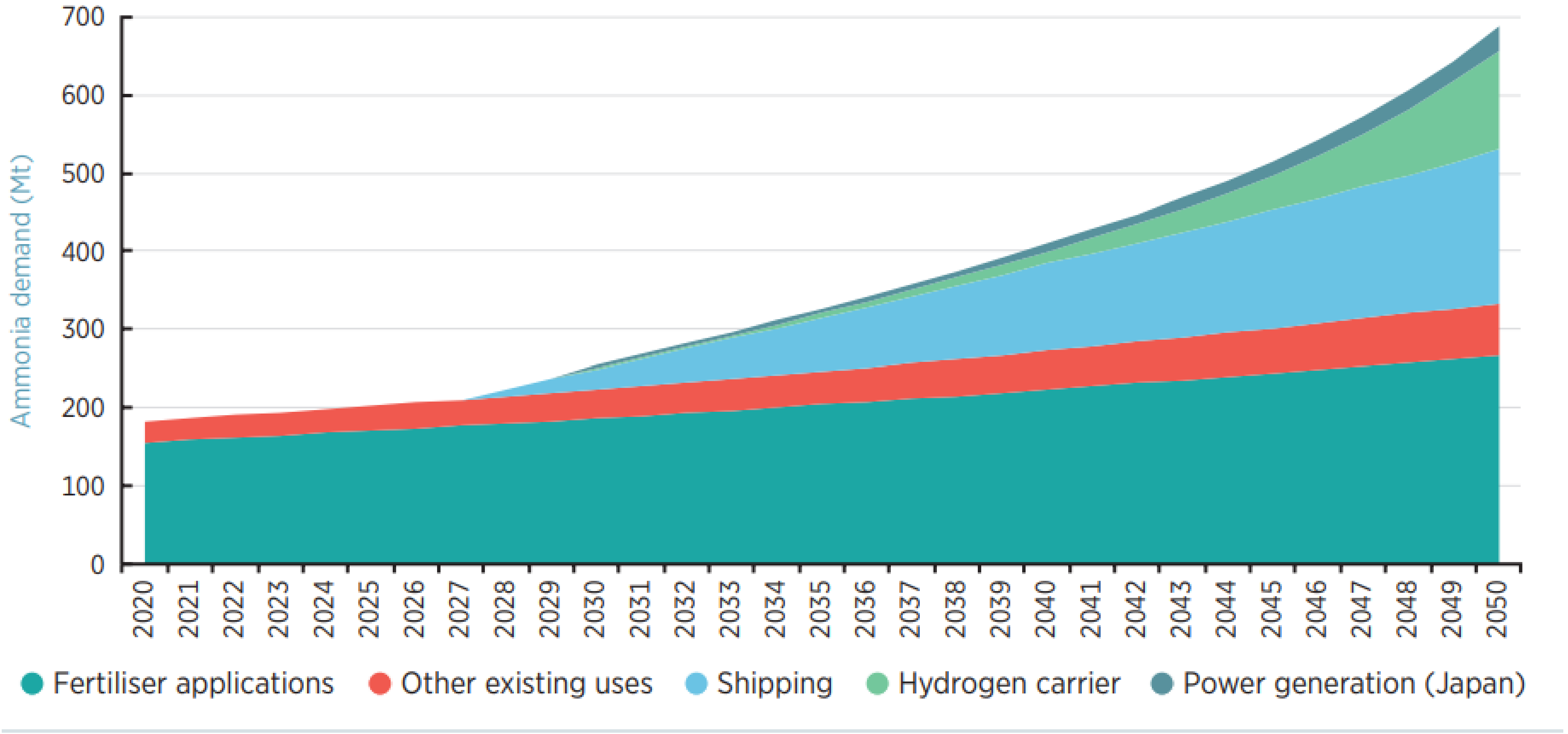
Mapping low carbon ammonia plants (+ webinars)

Ammonia demand



Link: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

Ammonia demand



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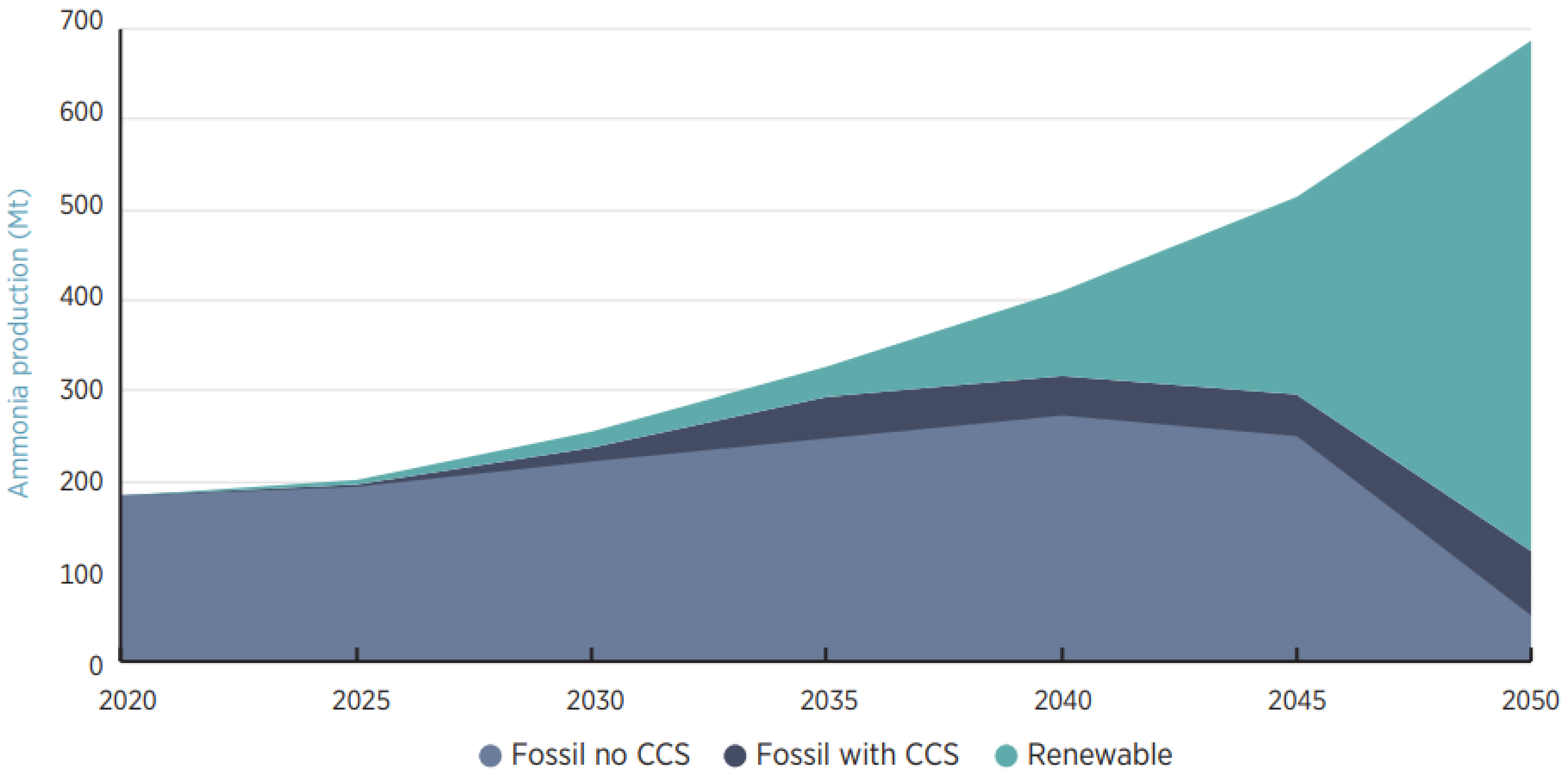
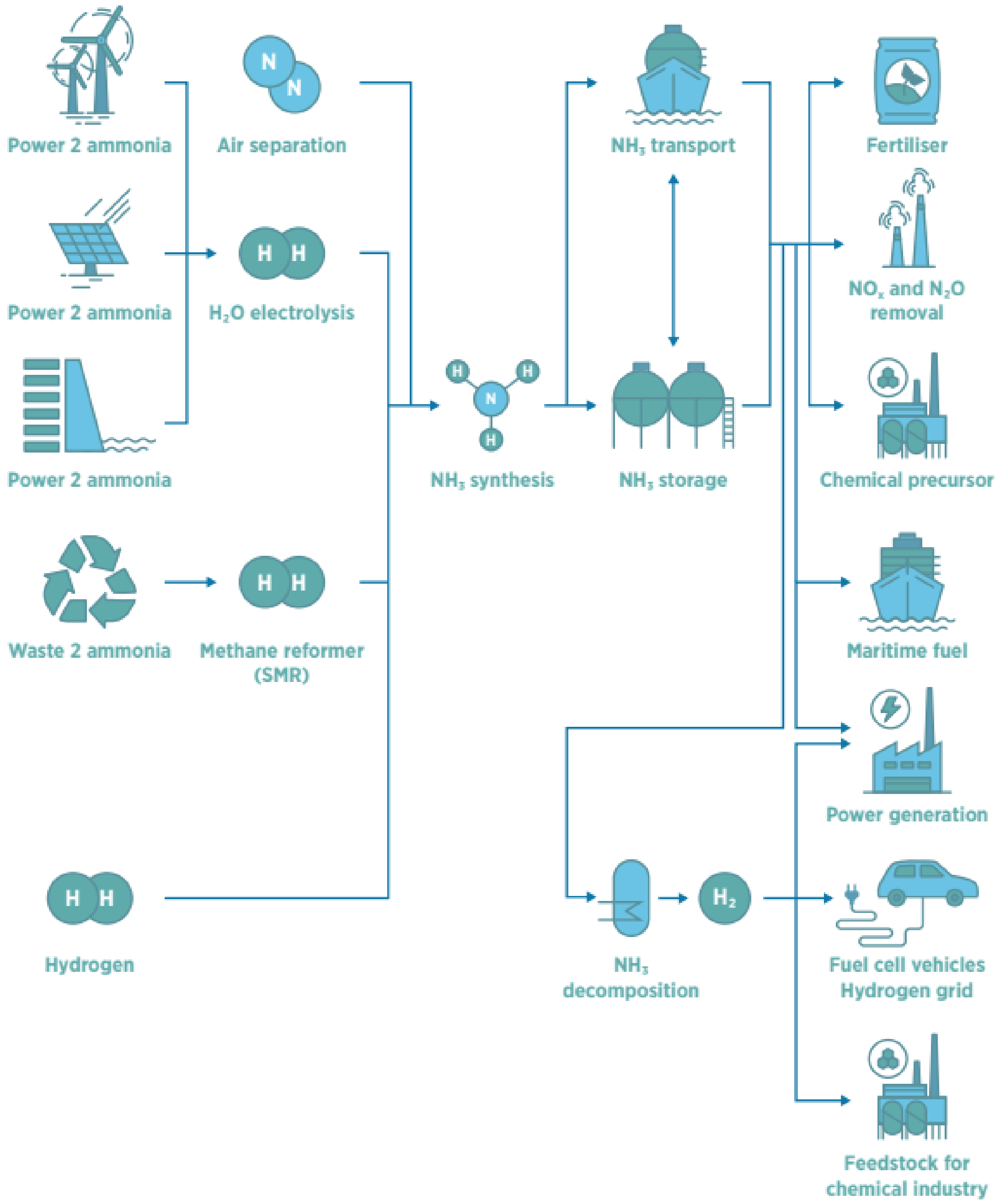
Production pathways



Link: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

Emissions

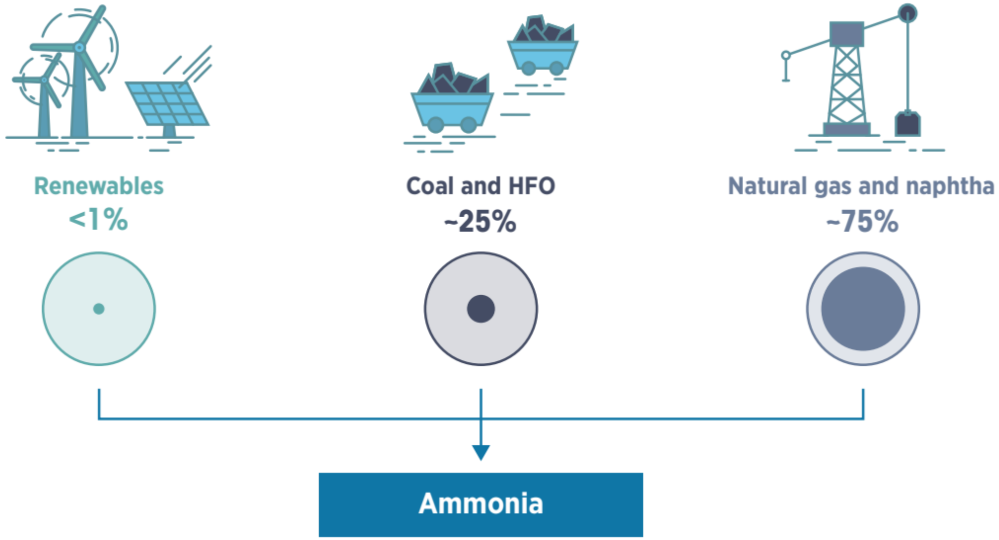
- Upstream ammonia emissions (cradle-to-ammonia product)
- Direct / indirect ammonia conversion emissions



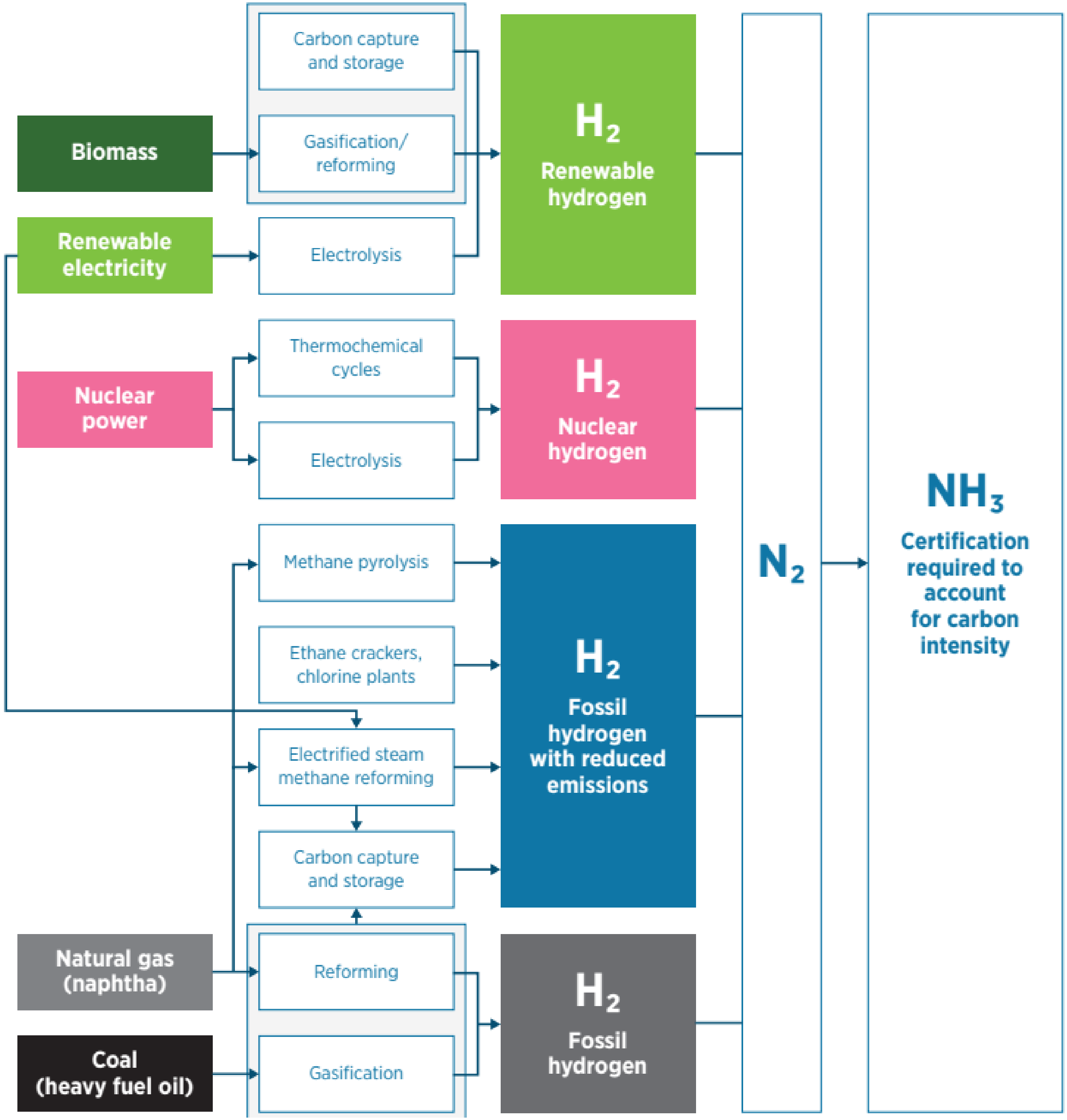
Link: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

Production pathways

Current production (**185 Mt**) exclusively fossil:



- About **90% of the energy input** for H_2 production, so determines CO_2 footprint!
- Colours of ammonia ≠ carbon footprint, as depends on Scope 1-3 emissions

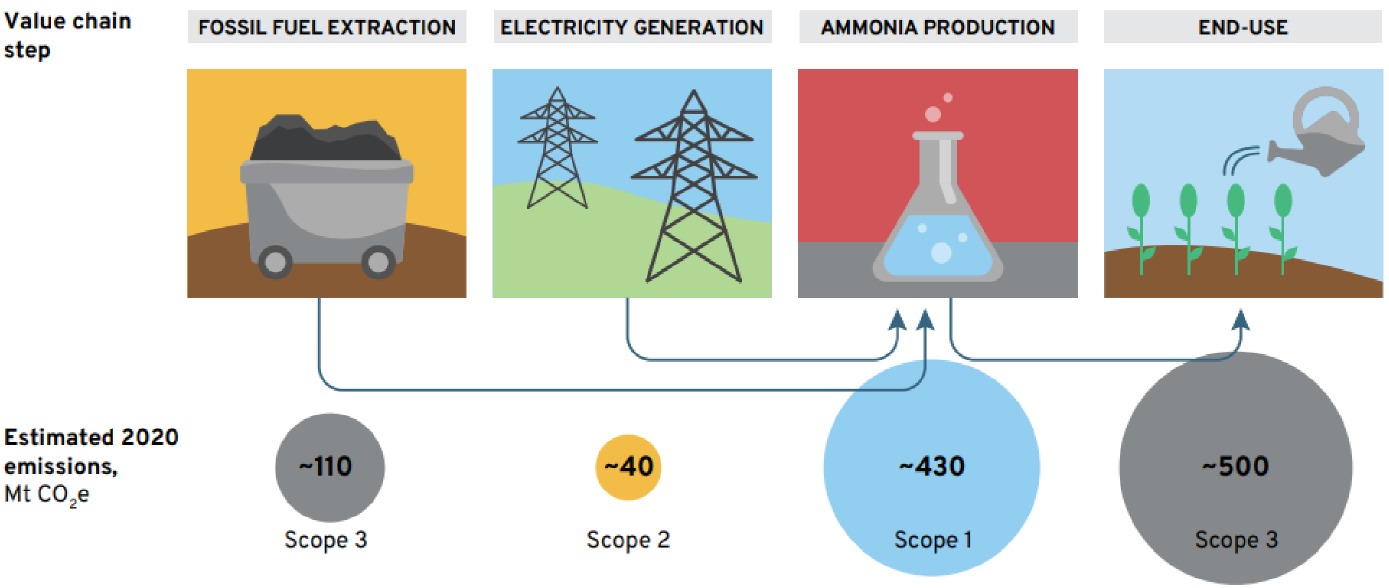


Upstream ammonia emissions

- **From cradle to ammonia product**: ~3.1 t-$CO_{2,eq}$/t-NH_3 on average in 2020

EXHIBIT 1.3

GHG emissions along the ammonia supply chain by scope in 2020



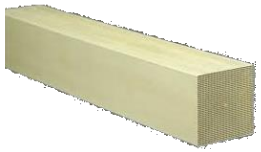
Note: Due to their nature, upstream and downstream Scope 3 emissions are highly uncertain with many different estimates from different sources. These emissions have been calculated using estimated emissions factors for each region.

Source: MPP analysis; IEA; IPCC[7]

Link: https://missionpossiblepartnership.org/wp-content/uploads/2022/09/Making-1.5-Aligned-Ammonia-possible.pdf

Case study: SCR for Nitric acid production

- EU integrated pollution prevention and control (IPPC) directive effective from October 2007. EU ETS covers N_2O
- Uses ammonia, aqueous ammonia, or urea
- $2\ NO + 2\ NH_3 + 1/2\ O_2 \rightarrow 2\ N_2 + 3\ H_2O$
- In Europe, N_2O emissions from nitric acid have been abated successfully



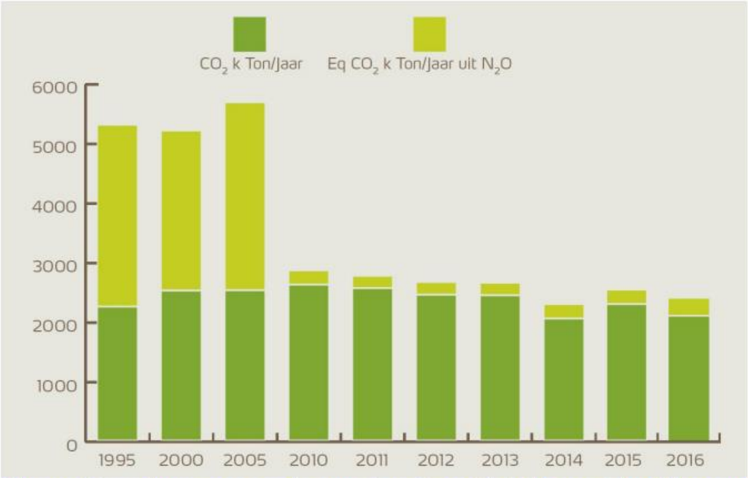
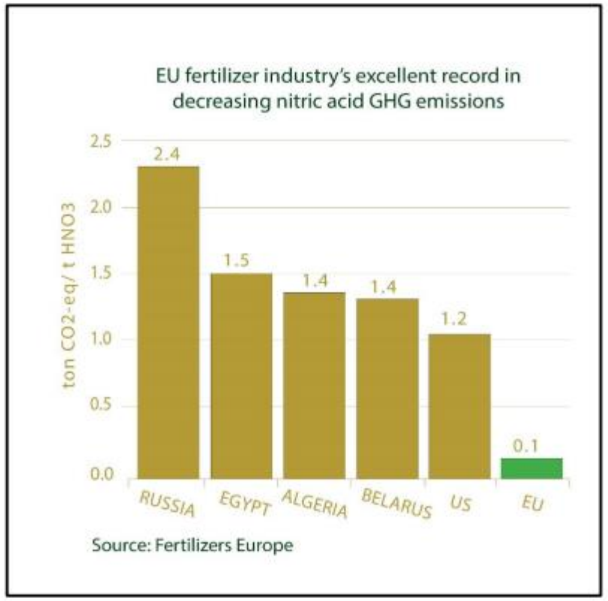


Figure 4 Greenhouse gas emissions from Yara Sluiskil's sustainability report (Yara Sluiskil B.V., 2017)



Link: https://www.ammoniaenergy.org/articles/renewable-fertilizers-in-europe/

Fundamentals of ammonia conversion

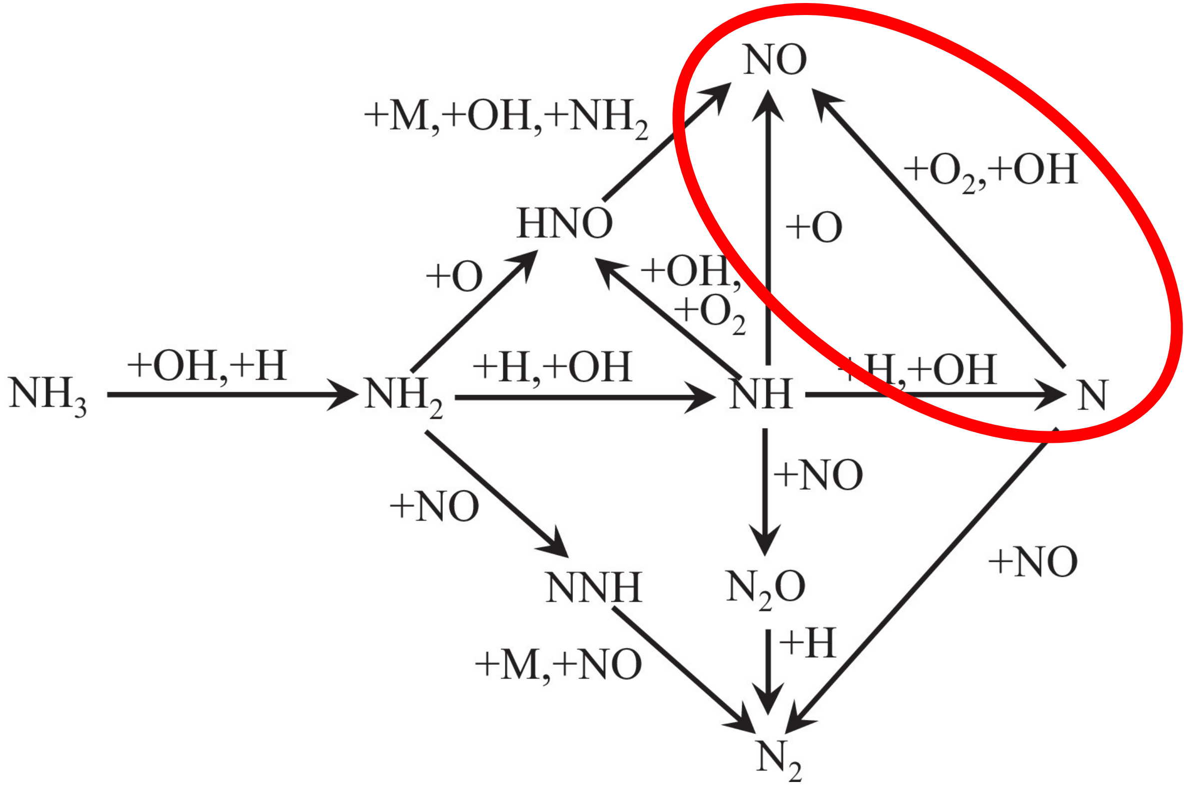
Ammonia combustion:

1. Pure NH_3 combustion
2. Partially cracked NH_3 combustion (mixture $H_2/NH_3/N_2$)

- **Ideal NH_3 combustion**: $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$
  $\Delta H = -1130$ kJ mol^{-1}
- **Ideal H_2 combustion**: $2H_2 + O_2 \rightarrow 2H_2O$
  $\Delta H = -572$ kJ mol^{-1}

Fundamentals ammonia conversion emissions

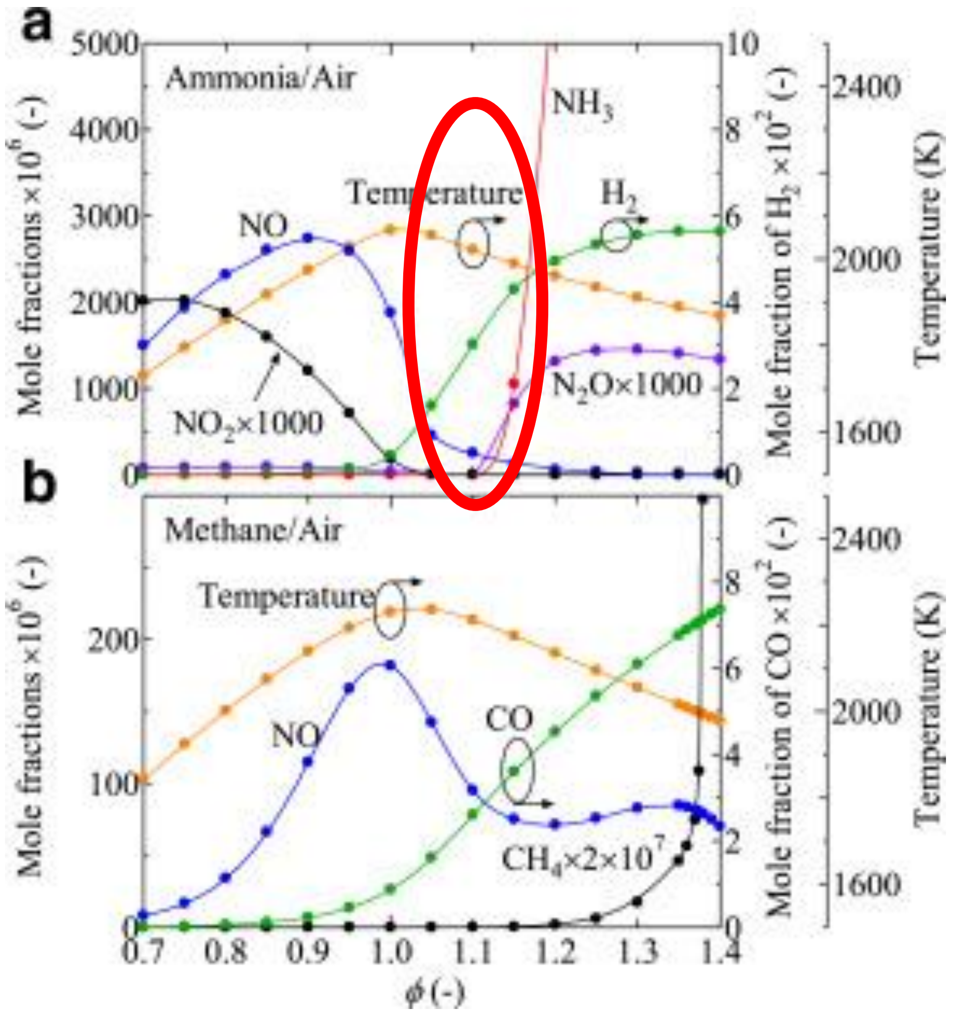
- **Ideal**: $4NH_3+3O_2 \rightarrow 2N_2+6H_2O$
  $\Delta H=-1130\ kJ\ mol^{-1}$
- **NH_3 slip**: some ammonia may not have converted
- **Thermal NO formation (Zeldovich)**: At high temperatures (>1200°C), N, O radicals are formed, and molecules vibrationally activated, resulting in NO formation
- **NO formation from feedstock**: Ammonia may convert to NO



Link: https://www.sciencedirect.com/science/article/pii/S1540748918306345

Strategies to minimize ammonia combustion emissions

1. Optimize performance & minimize emissions
2. Perform after treatment for NO_X, N_2O & NH_3 slip mitigation



Link: https://www.sciencedirect.com/science/article/pii/S1540748918306345

Initial conclusion: Applications

- The following applications are relevant for ammonia conversion:

Application	Size	Commercial development (fleshed out in case studies)	Emissions expected (unmitigated)
Transportation fuel with engines (shipping)	Medium	Under development / demonstration	NH_3 slip, NO_X, N_2O
Transportation fuel with engines (locomotives)	Medium	Under development	NH_3 slip, NO_X, N_2O
Transportation fuel with turbines (aviation)	Medium/large	Under development	NH_3 slip, NO_X, N_2O
Power generation (gas turbines)	Medium/large	Under development / demonstration	NH_3 slip, NO_X, N_2O
Power generation (boilers / coal power plants)	Large	Under development / demonstration	NH_3 slip, NO_X, N_2O (PM and SO_X from co-fuel)
Power generation / transportation (SOFCs)	Small/Medium	Under development / demonstration	NH_3 slip
Hydrogen production (ammonia cracker & H_2 purification)	Small to Large	Commercially available (on paper), but not yet operated	NH_3 slip, NO_X, N_2O
Nitric acid fertilizer production	Large	Industrially applied	NO_X, N_2O

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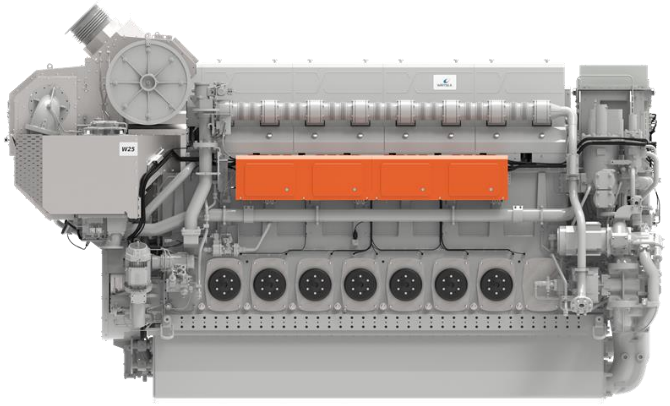
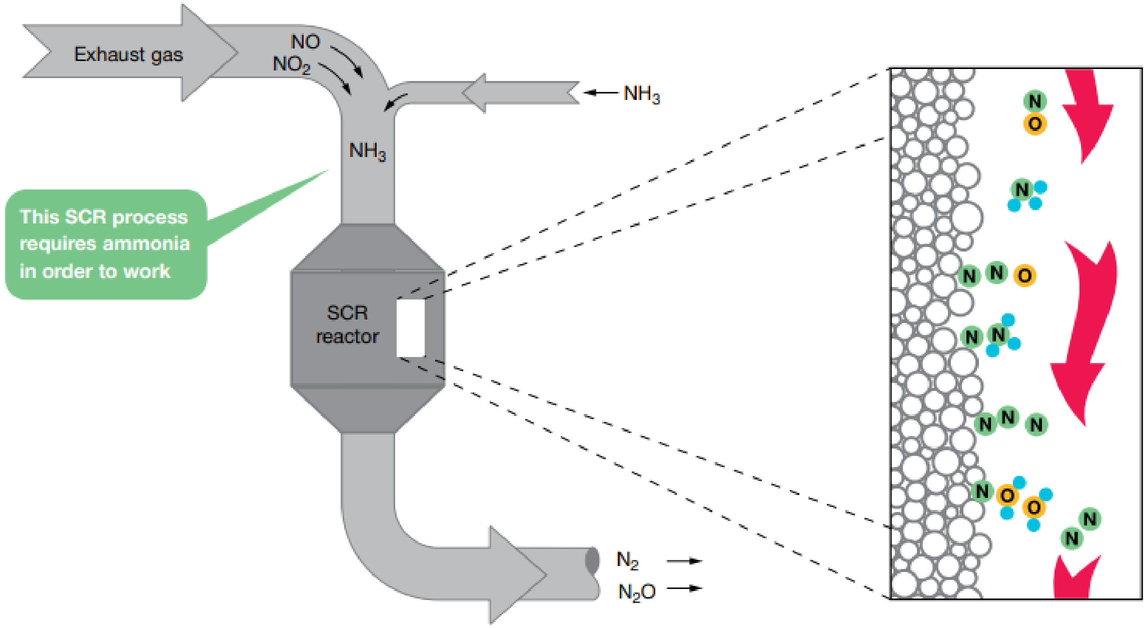
Example: Shipping

- Two-stroke engines & four-stroke engines can be operated with NH_3 as fuel, to be commercially available by 2023-2024
- NO_X emissions, NH_3 slip may be an issue

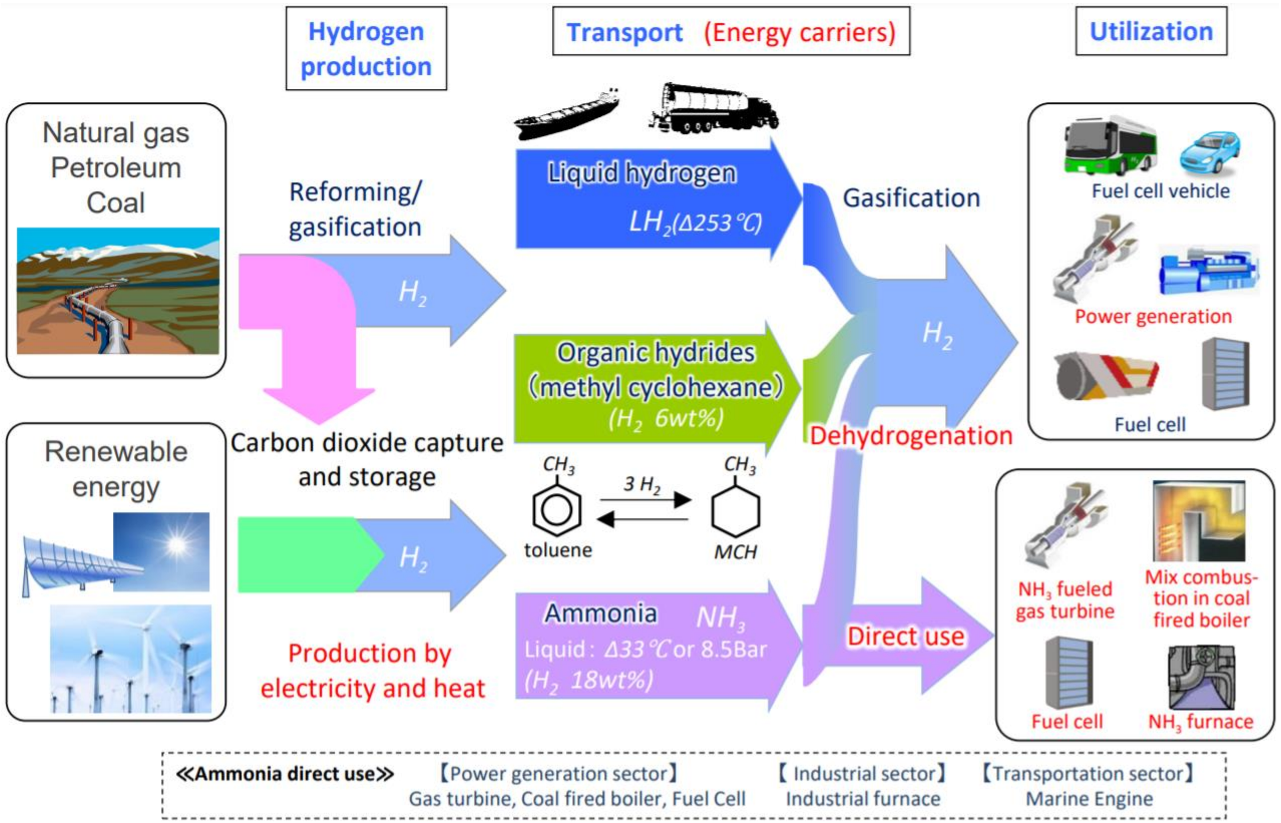
- NO_X emissions can be mitigated with NH_3 in an **SCR system**
- Exhaust Gas Recirculation (**EGR**) can reduce NO_X emissions further
- **Observation**: NH_3 slip mitigation (**AMOX**) is similar to preventing CH_4 slip from LNG engines





Low carbon ammonia utilization: Power

- **Japan**: Imports LNG for energy, SIP energy carriers to decarbonize energy sector [1]
    - Current high LNG prices spur decarbonization



[1] https://www.ammoniaenergy.org/wp-content/uploads/2021/02/AEA-Imp-Con-01Nov18-Shigeru-Muraki-Keynote-Address.pdf

Low carbon ammonia utilization: Power

- **Co-firing ammonia** in existing coal plants (20% in 2025 [1]), and gas turbines
  - Gradual increase to fully ammonia-fired power plants by 2040s
  - **2025**: **40 MW 100% ammonia-fed gas turbine** [2]
- **30 Mt** ammonia demand for power by 2050, according to Japanese government [3]
- **Supply of ammonia**: Australia, Chile, Middle-East, United States
- Similar scenario for **South Korea** [4] (possibly Northern Europe)

- Retrofit existing infrastructure, rather than stranded assets

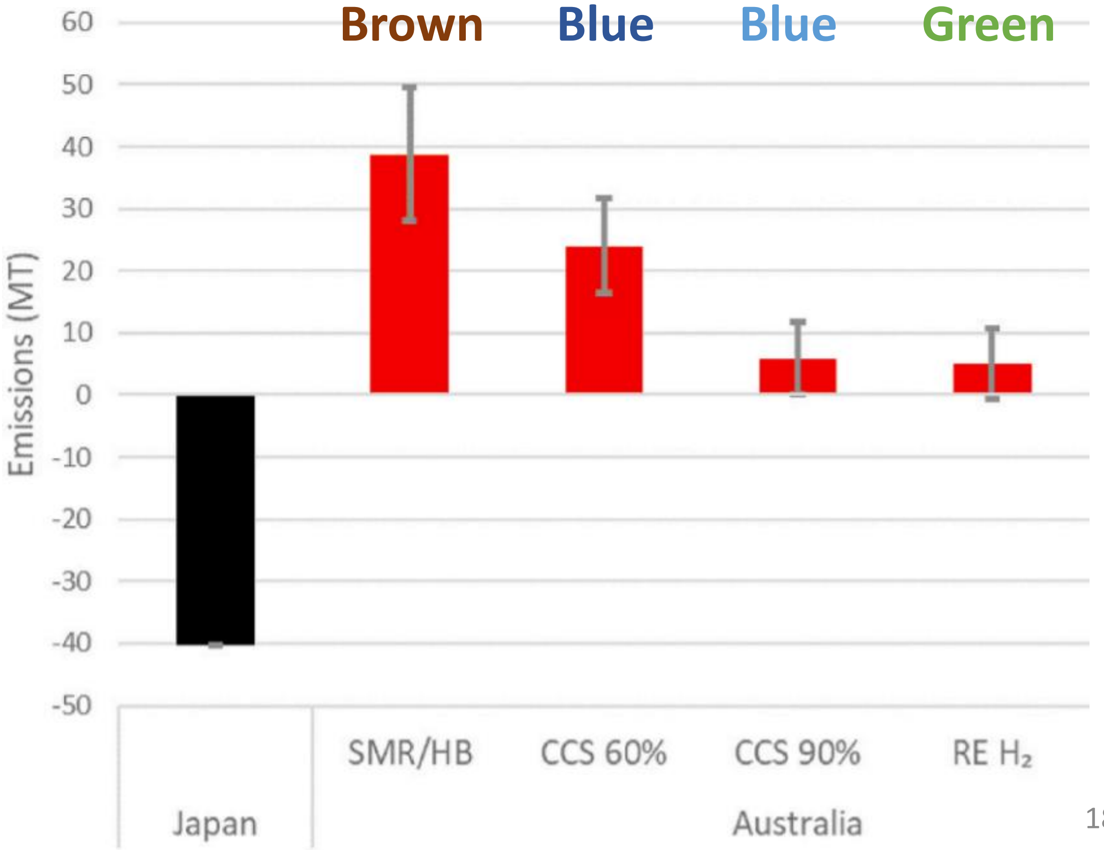
[1] https://www.yara.com/corporate-releases/yara-and-jera-plan-to-collaborate-on-clean-ammonia-to-decarbonize-power-production-in-japan/
[2] https://www.powermag.com/mitsubishi-power-developing-100-ammonia-capable-gas-turbine/
[3] https://www.argusmedia.com/en/news/2184741-japan-targets-3mn-tyr-of-ammonia-fuel-use-by-2030
[4] https://www.cell.com/iscience/fulltext/S2589-0042(21)00871-3

Low carbon ammonia utilization: Power

- **Australia-Japan case**: <u>need low carbon ammonia</u> for decarbonization versus fossil fuels
    - 20% co-firing of ammonia in all coal-fired power plants in Japan

$$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O$$

Ammonia



[1] https://www.sciencedirect.com/science/article/abs/pii/S095965262104258X

Initial conclusion: Emission mitigation technologies & strategies (page 1)

Cracker type	Commercial development	Pathway to commercialization for ammonia combustion (fleshed out in case studies)
Selective Catalytic Reduction (SCR)	• Commercially applied for deNOx in nitric acid production • Commercially applied for deNOx in natural gas-fired turbines & coal-fired power plants, engines in vehicles	Application of SCR to commercial ammonia-fired gas turbines & coal power plants, demonstrate low NOx emissions
Selective Non-Catalytic Reduction (SNCR)	• Commercially applied for deNOx for coal-fired power plants	Application of SNCR for commercial ammonia-fired coal power plants, demonstrate low NOx emissions
Ammonia Oxidation (AMOX)	• Commercially available to prevent ammonia slip down to below 10-20 ppmv	Demonstrate ammonia slip mitigation for commercial ammonia energy application
SCONOX / Lean NO_X trap (LNT)	• Commercially available for deNOx of engines in vehicles	Demonstrate SCONOX/LNT for NOx mitigation for commercial ammonia energy application

Initial conclusion: Emission mitigation technologies & strategies (page 2)

Cracker type	Commercial development	Pathway to commercialization for ammonia combustion (fleshed out in case studies)
Exhaust Gas Recirculation (EGR)	• Already applied to limit temperature (and thermal NOx formation) in engines	Apply EGR to ammonia-fueled engines to prevent thermal NOx formation
Low NOx burners (DNL or ULN)	• Swirl burners are developed to enhance ammonia combustion in research institutes	Demonstrate low NOx burners at commercial pilot scale, with subsequent scale-up to commercial scale
Water & Steam injection	• Already applied in some gas turbines, needs development for ammonia combustion applications	Demonstrate NOx reduction upon water/steam injection to ammonia combustor at a relevant scale
Secondary air injection	• Proposed for ammonia combustion applications	Demonstrate practical NOx & NH_3 emission reduction in experimental set-up, thereafter in demonstrator unit

Key conclusions

- Ammonia emissions require a value chain approach, also including ammonia emissions during ammonia production
- Downstream emissions from ammonia as zero-carbon fuel and hydrogen carrier should be essentially zero, as opposed to ammonia and derivatives for fertilizers
- Technologies for ammonia conversion emission mitigation are commercially applied, albeit under different conditions

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Thank you for your attention!