Electrification and decarbonization of chemical manufacturing

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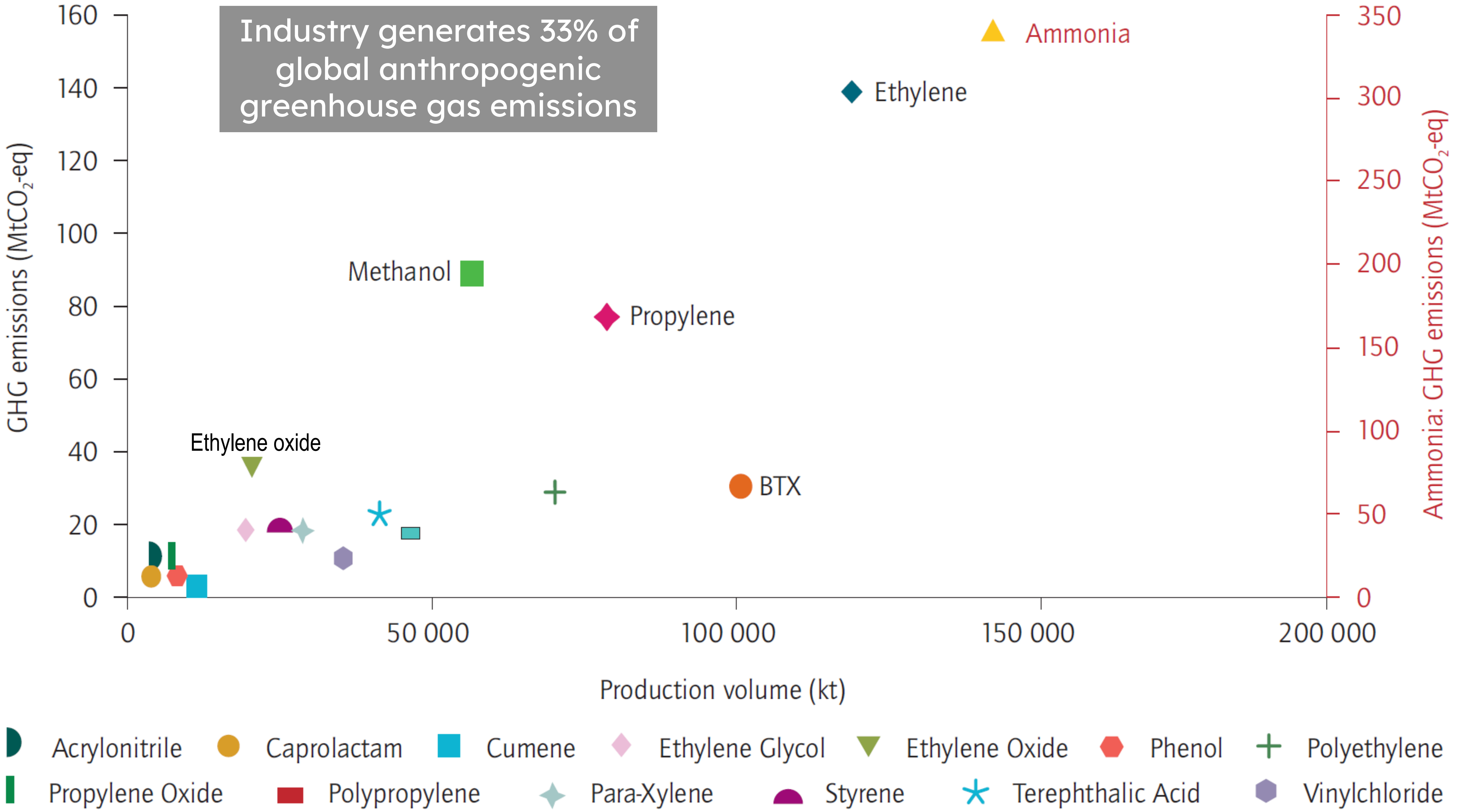
Image: Wikipedia



Source: DECHEMA




Images: Wikipedia, Harvard, Home & Heavens, Seattle Fabrics

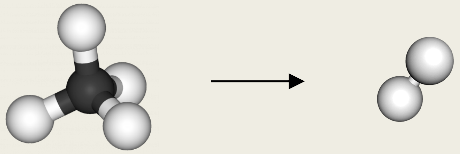
How we make ammonia (NH_3) today

$$CH_4 + H_2O \xrightarrow[>700\ ^oC]{} 3H_2 \quad (+\ CO_2)$$

$$3H_2 \xrightarrow[400\text{-}500\ ^oC,\ 150\text{-}250\ bar]{N_2} 2NH_3$$

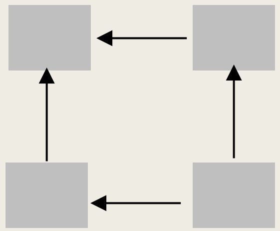
Large carbon footprint and harsh conditions that require centralization

Image: BASF

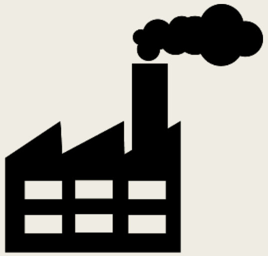


Feedstock associated emissions require process changes

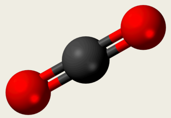
Burning fossil fuels for heat



Industrial processes are highly integrated



Facilities have long lifetimes



Commodity products for which externalities are not valued

Electrification of chemical manufacturing

CO_2 & N_2

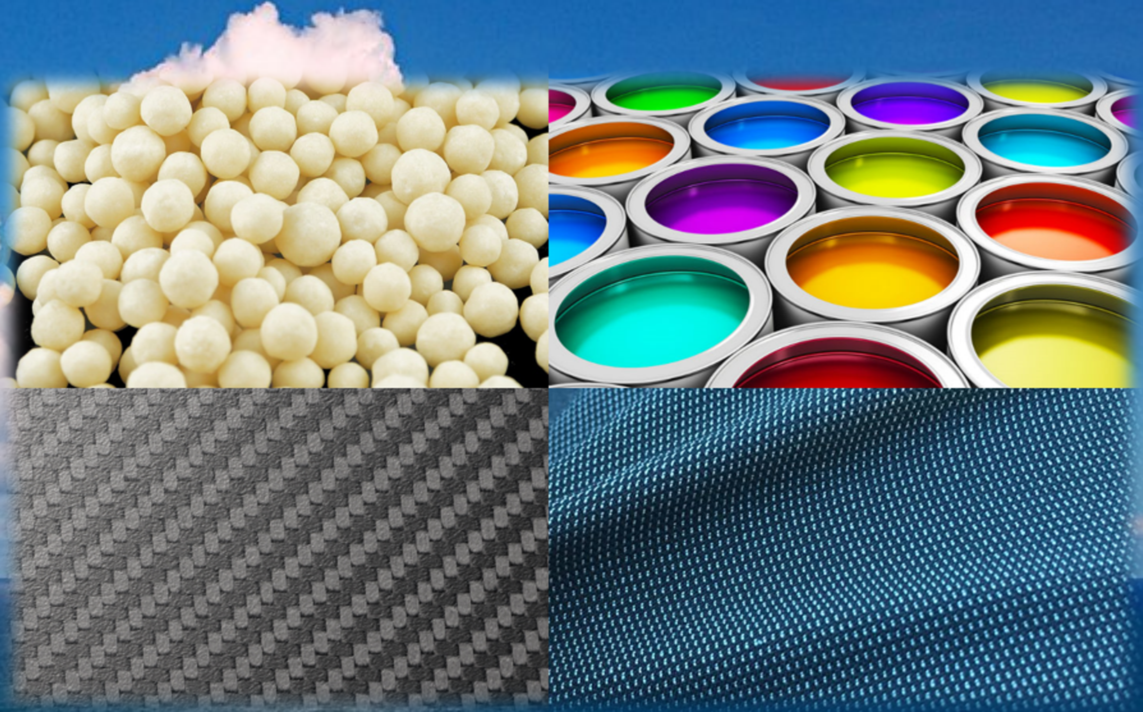
(air & exhaust gas)

Renewable power

25 °C

1 bar

H_2O



Making diverse chemicals from CO_2, N_2, and H_2O

Image: Wikipedia, ThyssenKrupp, HDFreefoto, Protech Composites, Textile School

Ammonia from air and water

$$N_2 + 3\,H_2O \xrightarrow[\text{1 bar, Renewable power}]{25\ ^oC} 2\,\mathbf{NH_3} + {}^3/_2\,O_2$$

25 °C
1 bar
Renewable power

Eliminate carbon footprint and operate at ambient conditions, enabling distributed synthesis

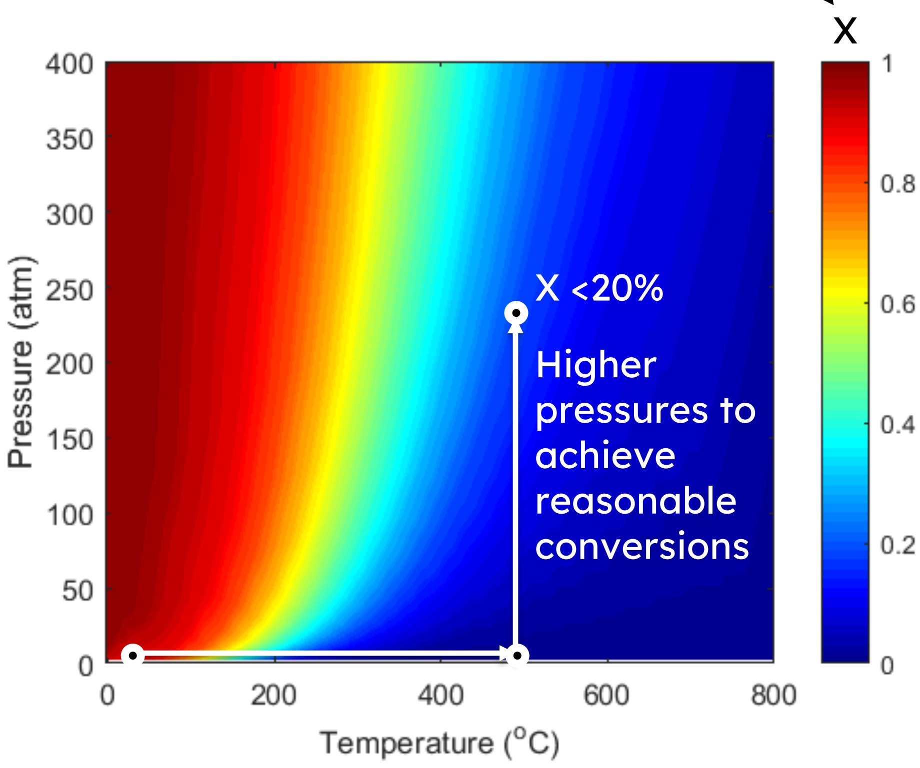
Image: Steve Proehl

$^{1}/_{2}\ N_2 + {}^{3}/_{2}\ H_2 \rightarrow NH_3$

Zachary Schiffer

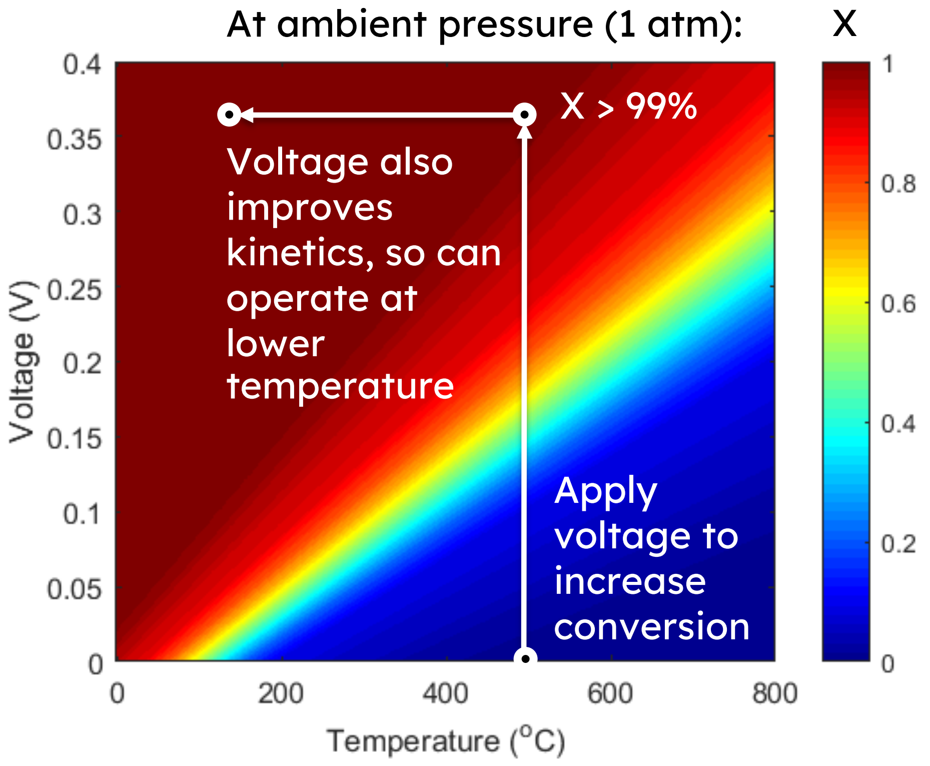
Thermochemical

Conversion



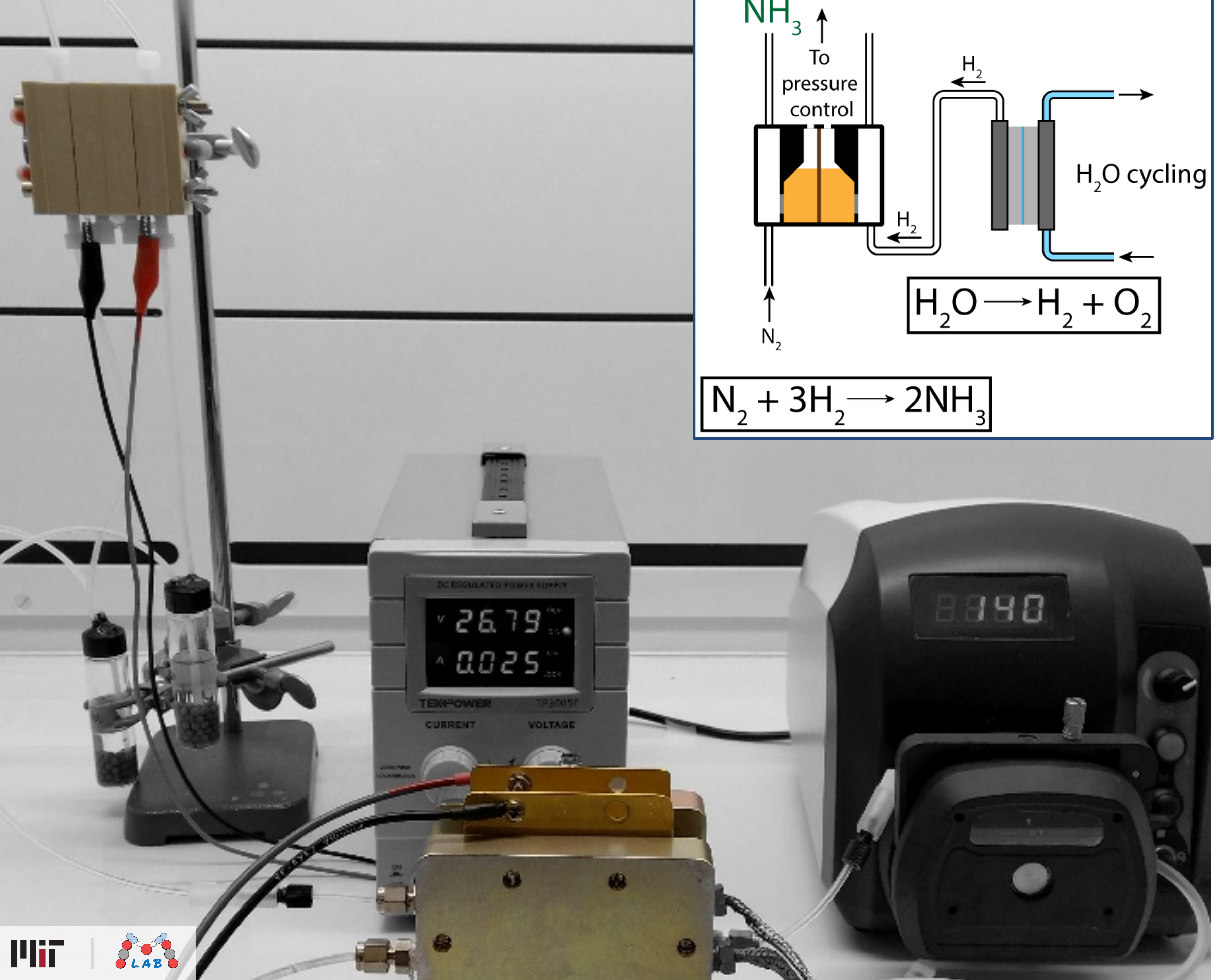
Higher temperatures to achieve reasonable rates

Electrochemical



Need for high temperatures and pressures can be replaced with voltage for appropriate reactions

Z. J. Schiffer and K. Manthiram *Joule* 1 10-14 (2017).



Nikifar Lazouski

$$N_2 + 3\ H_2O \rightarrow 2\ \mathbf{NH_3} + {}^3/_2\ O_2$$

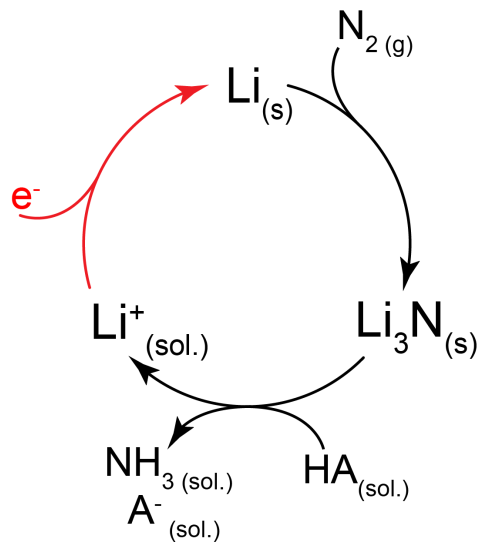
25 °C
1 bar
Electricity

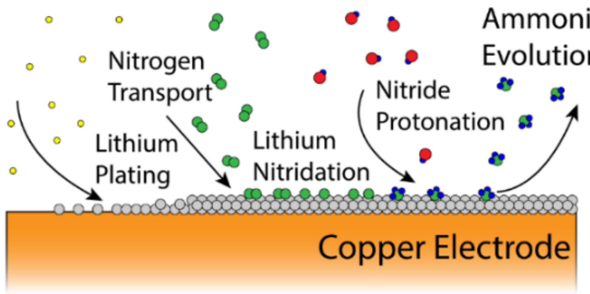
Lab-scale prototype of a fully electrified process for converting air and water into ammonia

Source: N. Lazouski, M. Chung, K. Williams, M. Gala, and K. Manthiram, *Nature Catalysis* **3** (2020).

Synthesis of ammonia at ambient conditions

Ammonia synthesis at ambient conditions

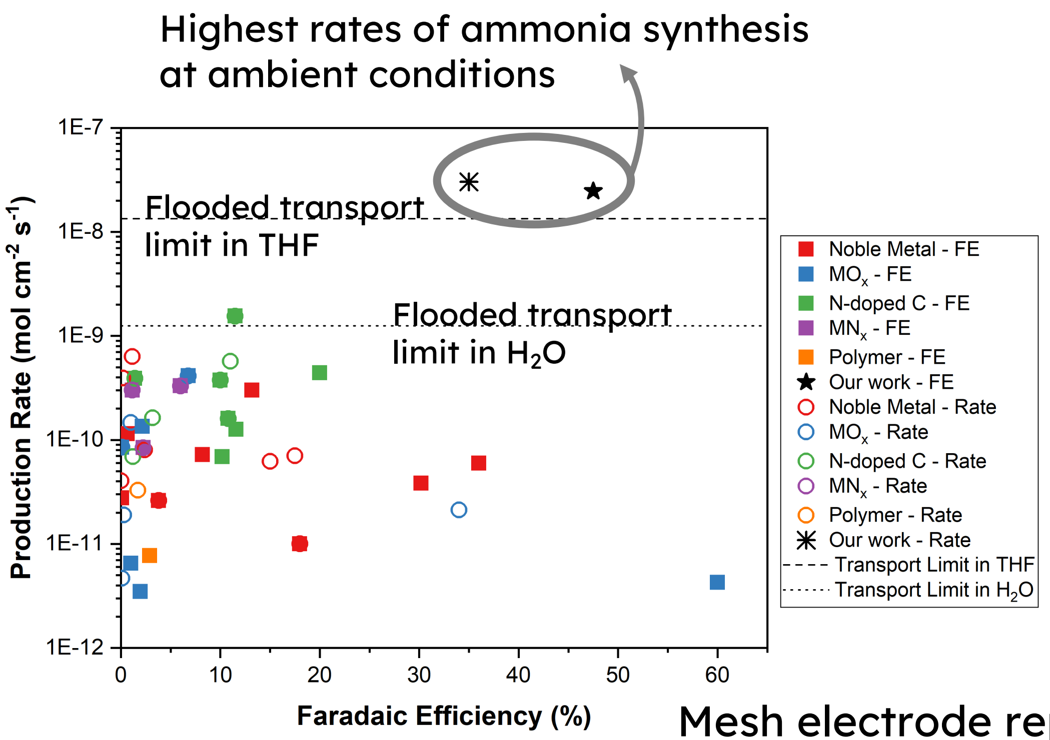


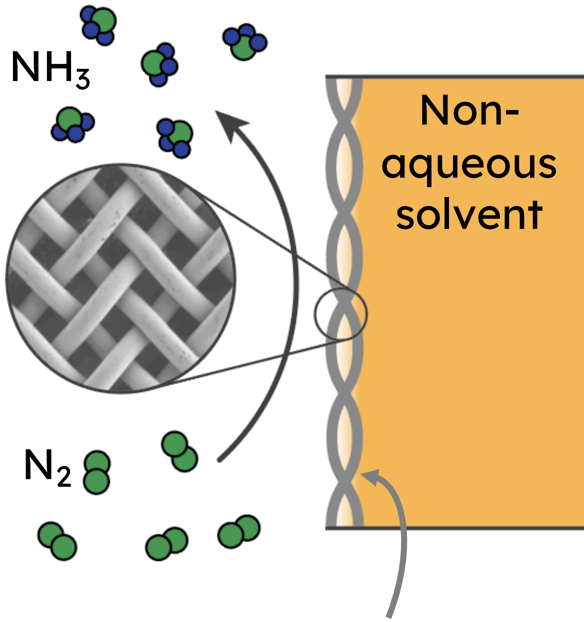


Ambient conditions and no CO_2 footprint

Lazouski et al. *Nature Catalysis* **3** (2020)
Lazouski et al., *Joule* **3** (2019)
Lazouski et al., *Trends in Chem.* **1** (2019)
Schiffer et al., *J. Phys. Chem. C* **123** (2019)
Schiffer et al., *Joule* **1** (2017)

New architecture for fast gas transport in non-aqueous medium

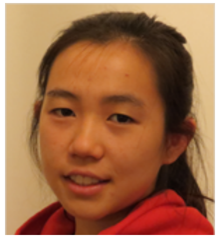




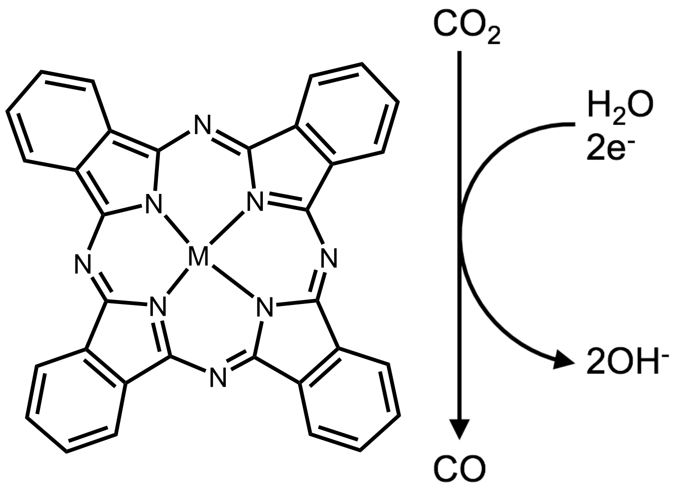
Mesh electrode repels flooding of non-aqueous solvent by exploiting Laplace pressure

Impact: Highest rates of continuous ammonia synthesis at ambient conditions enabled through new architecture which facilitates transport of sparingly soluble reagents in non-aqueous solvents

CO_2 REDUCTION



Joy Zeng

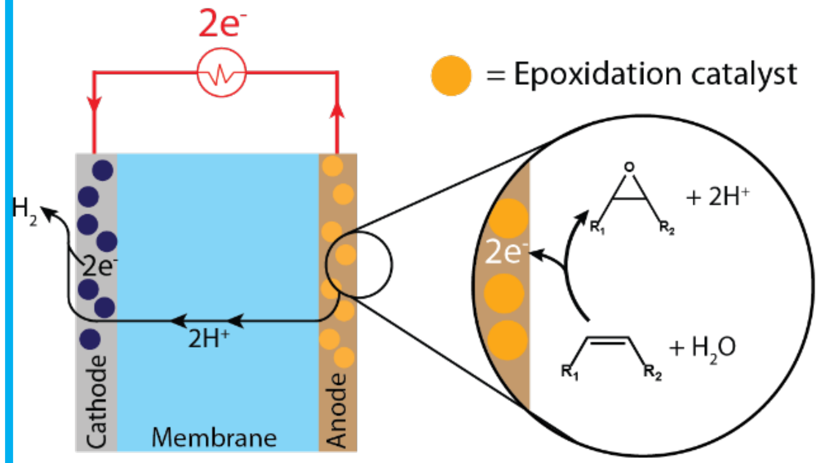


Directing carbon dioxide to syngas

J. S. Zeng, N. Corbin, K. Williams, and K. Manthiram
ACS Catalysis **10**, 4326 (2020).

EPOXIDATION

Kyoungsuk Jin



Sustainable oxygen-atom transfers from water to hydrocarbons

K. Jin, J. H. Maalouf, N. Lazouski, N. Corbin, D. Yang, and K. Manthiram, *J. Am. Chem. Soc.* 141, 6413-6418 (2019).

GHG emissions (MtCO$_2$-eq)

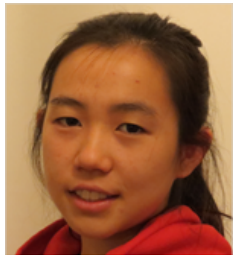
Production volume (kt)

Acrylonitrile Caprolactam Cumene Ethylene Glycol Ethylene Oxide Phenol Polyethylene
Propylene Oxide Polypropylene Para-Xylene Styrene Terephthalic Acid Vinylchloride

Source: DECHEMA

Acknowledgements

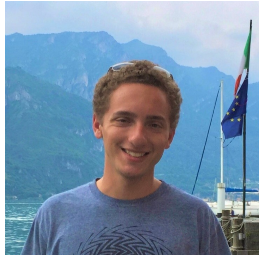
Aditya Limaye



Joy Zeng

Katie Steinberg

Nikifar Lazouski

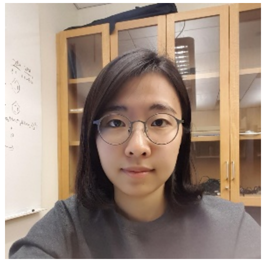


Trent Weiss

Zachary Schiffer

Kindle Williams

Nathan Corbin



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