Electrification of Ammonia Synthesis

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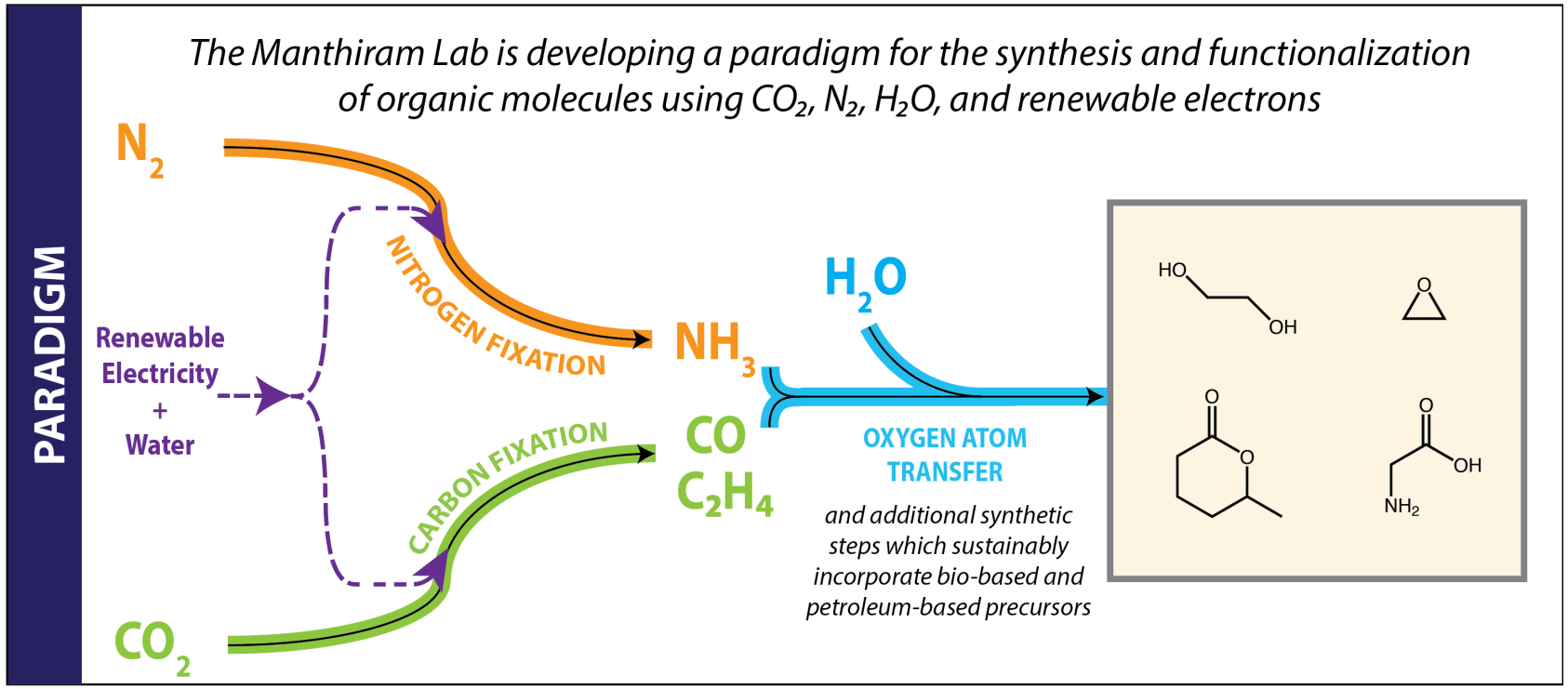
Manthiram Lab: Electrifying and decarbonizing chemical transformations



Air, water, and renewable electrons are distributed, sustainable resources

Electrical potential enables mild conditions of operation, replacing temperature and pressure

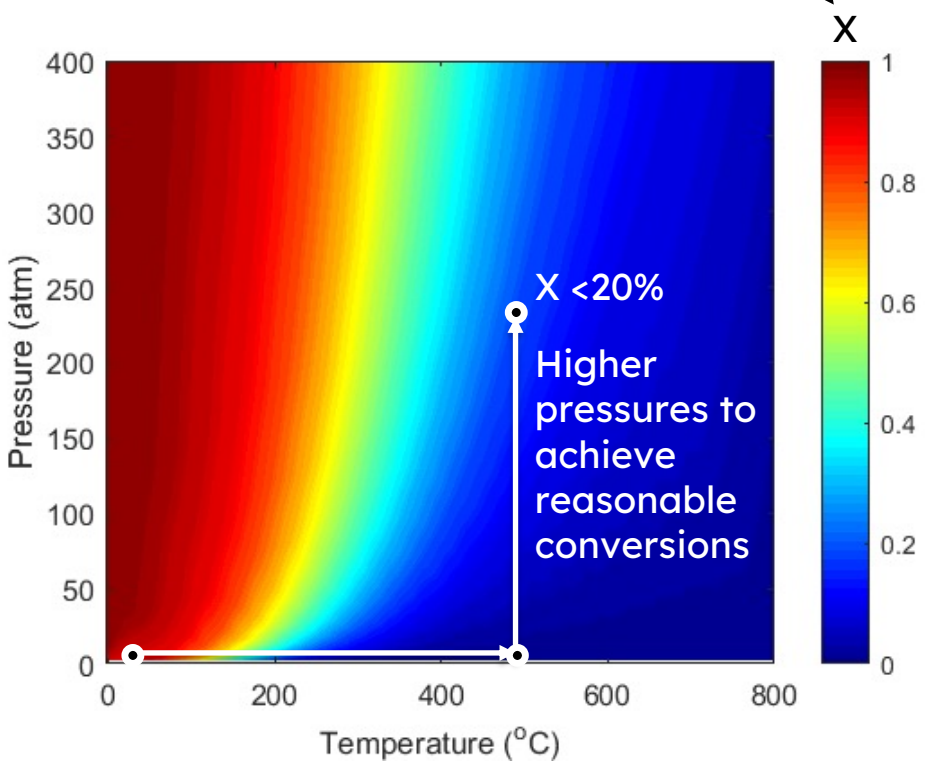
Our lab has developed new catalysts and integrated processes for electrically-driven ammonia synthesis, carbon dioxide fixation, and plastic production

Replacing pressure with voltage

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

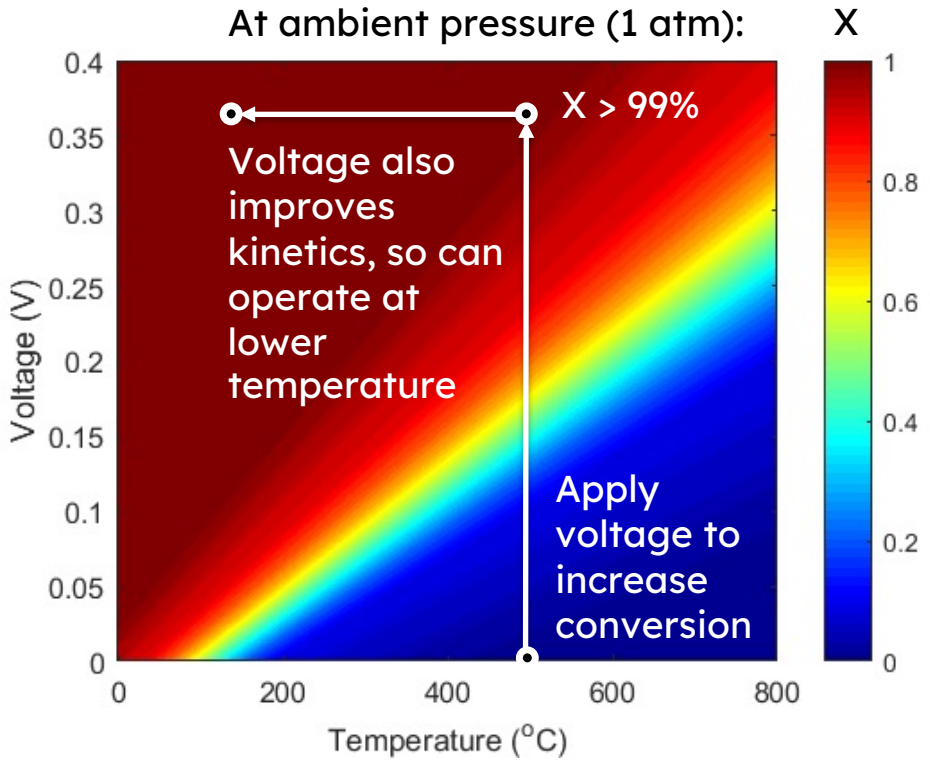
Zachary Schiffer

Thermochemical

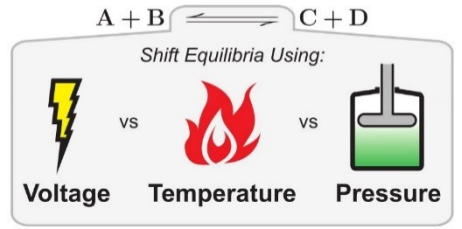


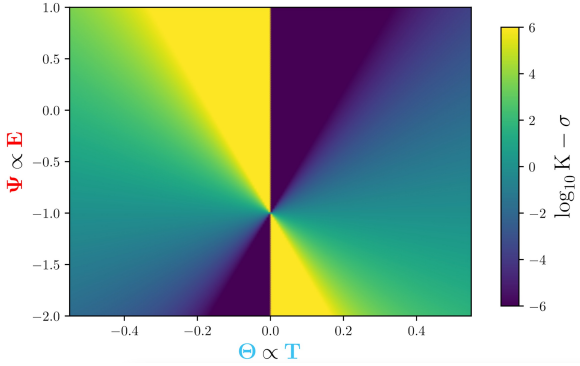
Higher temperatures to achieve reasonable rates

Electrochemical



Should temperature, pressure, or voltage be used to drive a given chemical reaction?



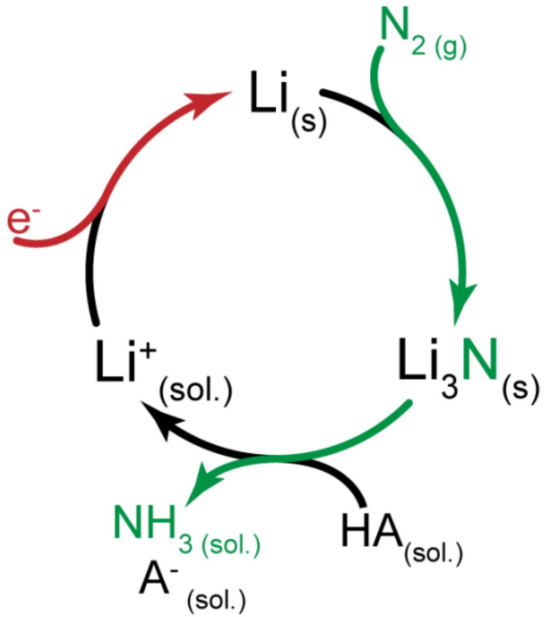


Z. J Schiffer, A. Limaye, and K. Manthiram, *Joule* **5**, 135-148 (2021).

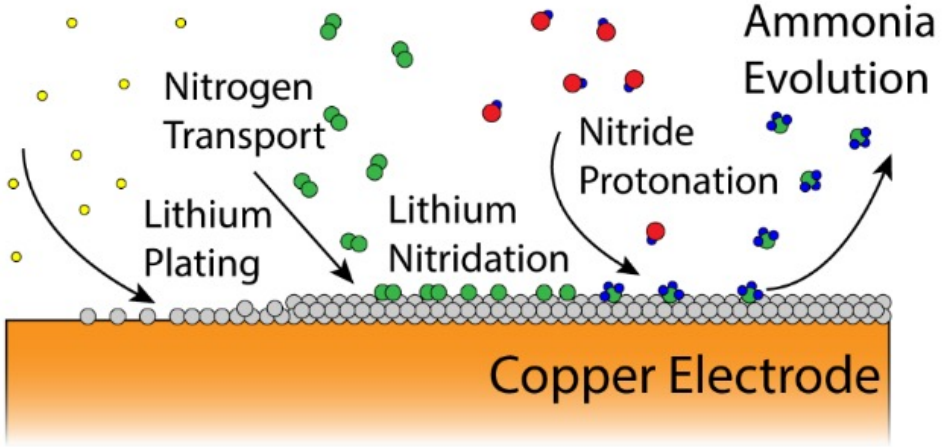
Z. J. Schiffer and K. Manthiram *Joule* **1**, 10-14 (2017).

Lithium mediated ammonia synthesis

Nikifar Lazouski



Cycle involving electrochemical and thermochemical steps

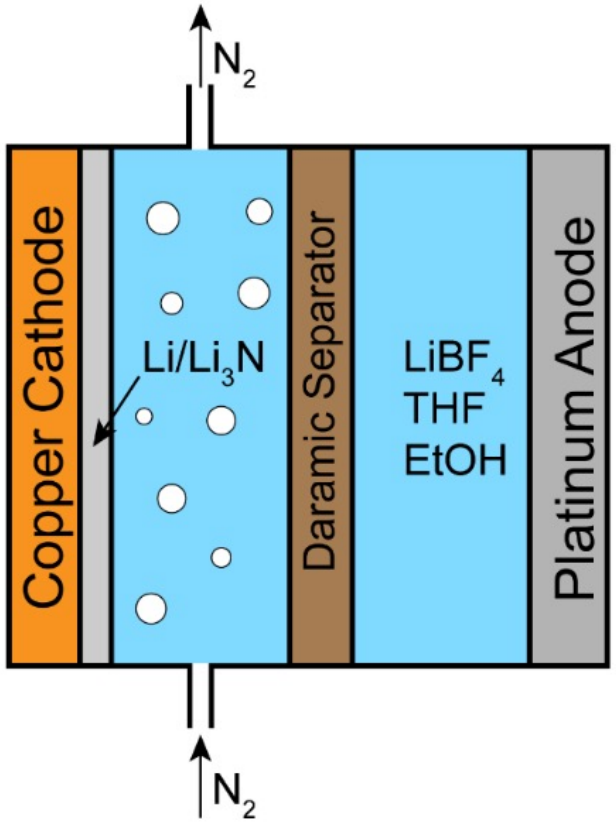


Reactions occur continuously at electrode surface

Fichter, P. G. F, Erlenmeyer, H. *Helv. Chim. Acta* (1930)
Tsuneto, A. J. *Electroanal. Chem.* (1994)
N. Lazouski, Z. J Schiffer, K. Williams, and K. Manthiram, *Joule* 3, 1127-1139 (2019).

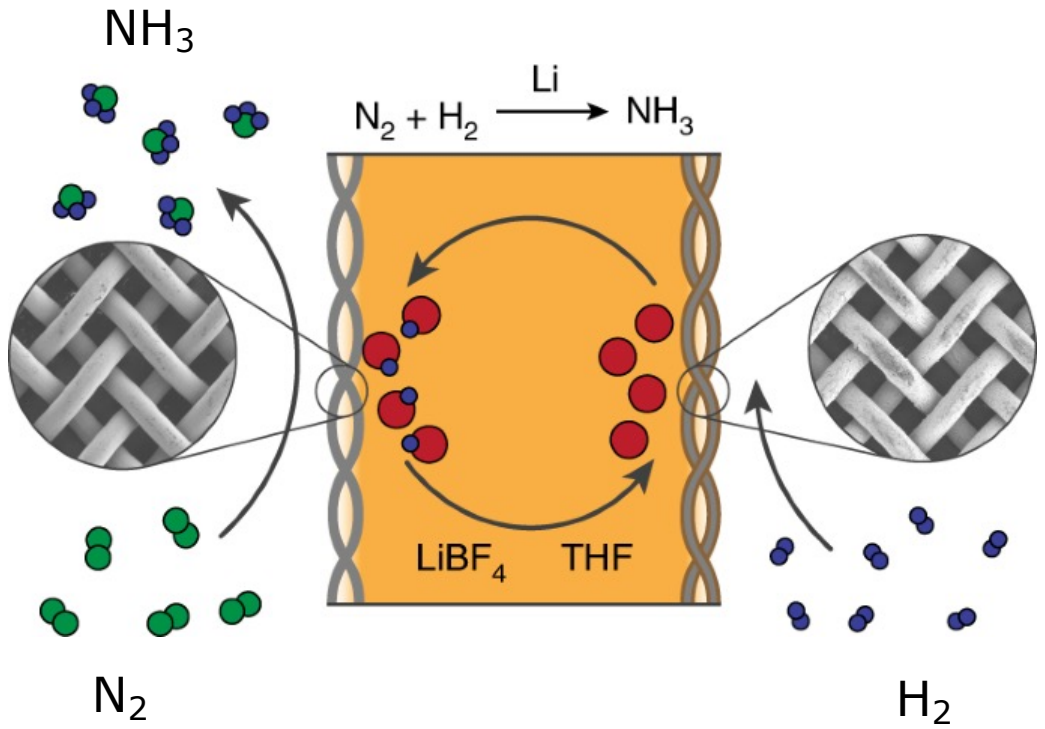
Overcoming transport limitations and undesired overall reaction

Flooded



Rates limited by transport, undesirable proton source, and low energy efficiency

Non-aqueous gas diffusion electrodes

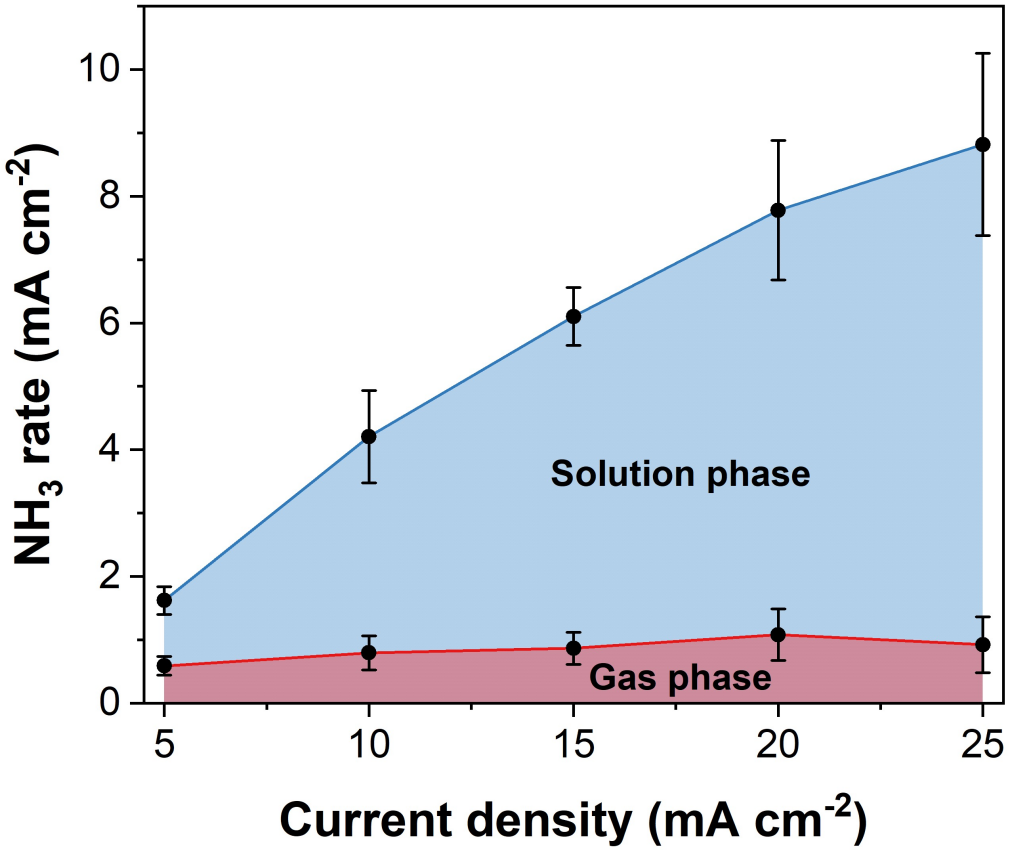


Metal cloth-based gas diffusion electrodes to enable

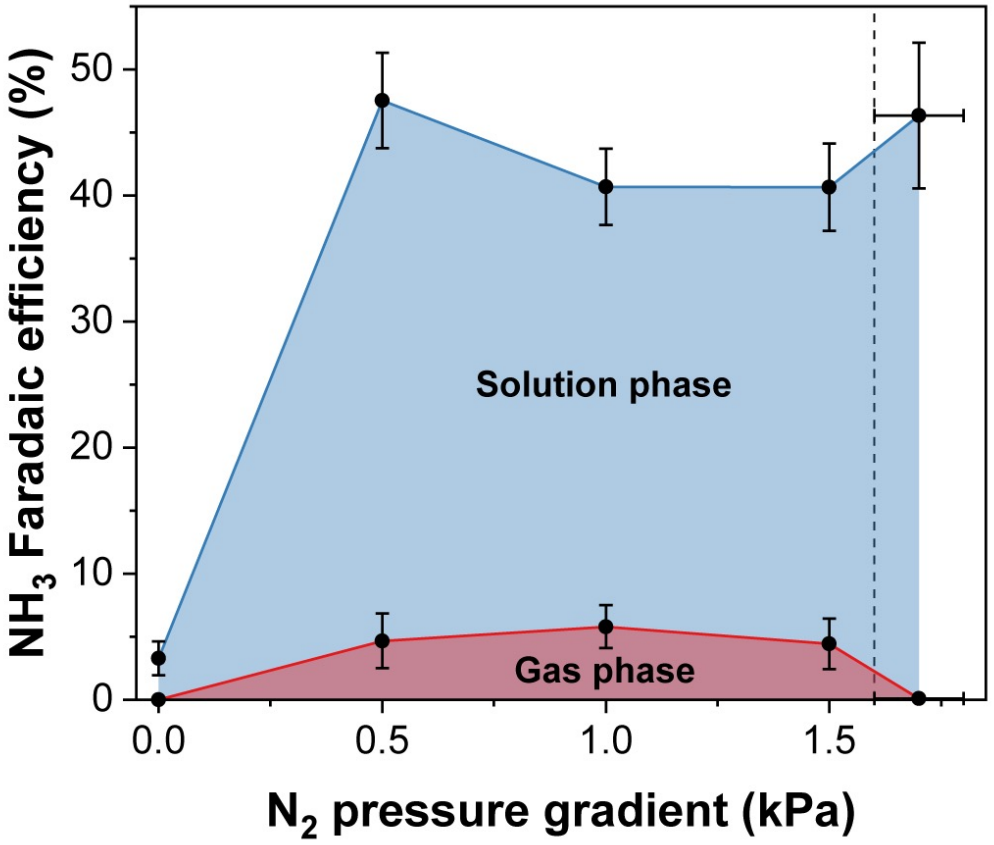
$N_2 + 3H_2 \rightarrow 2NH_3$

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

Rates of ammonia synthesis above the flooded transport limit



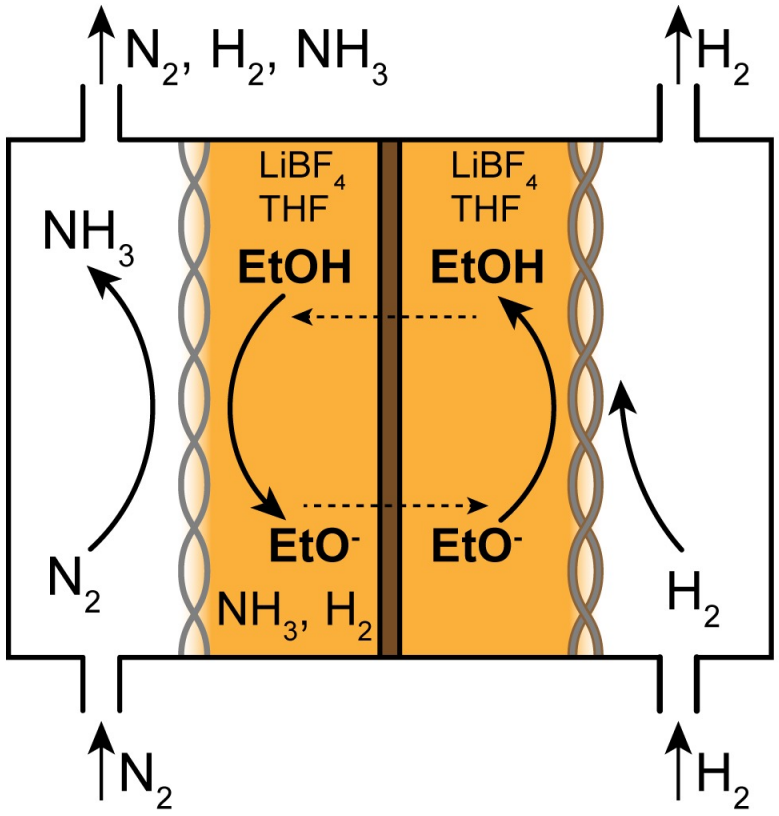
The rate of nitrogen reduction is increased significantly, with some produced ammonia found in the gas phase

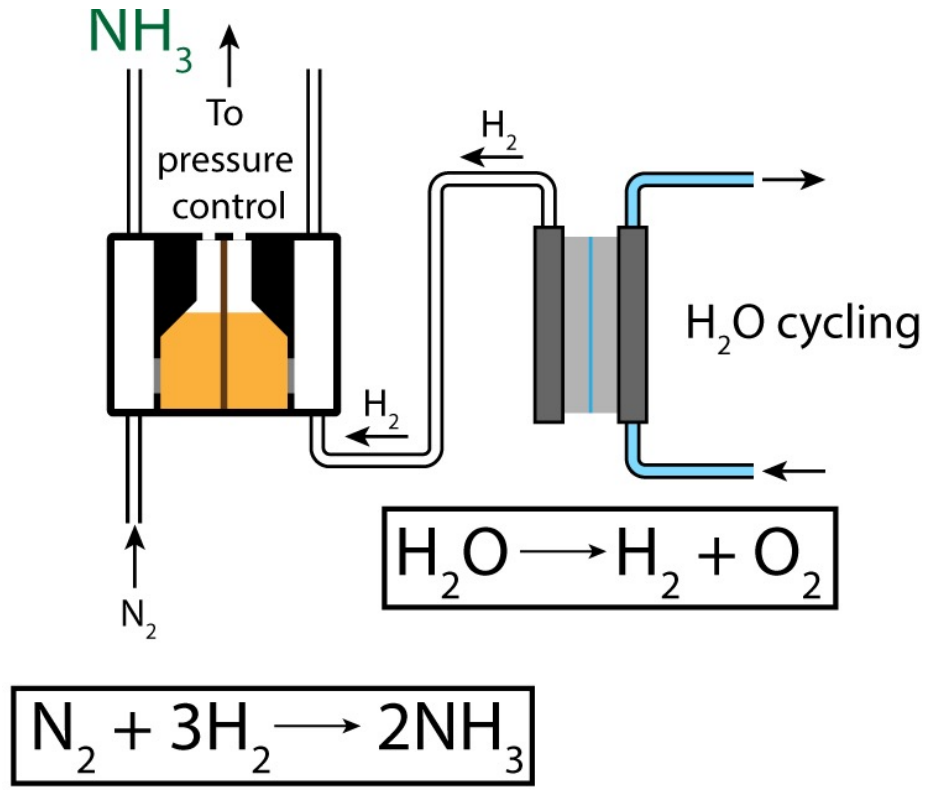


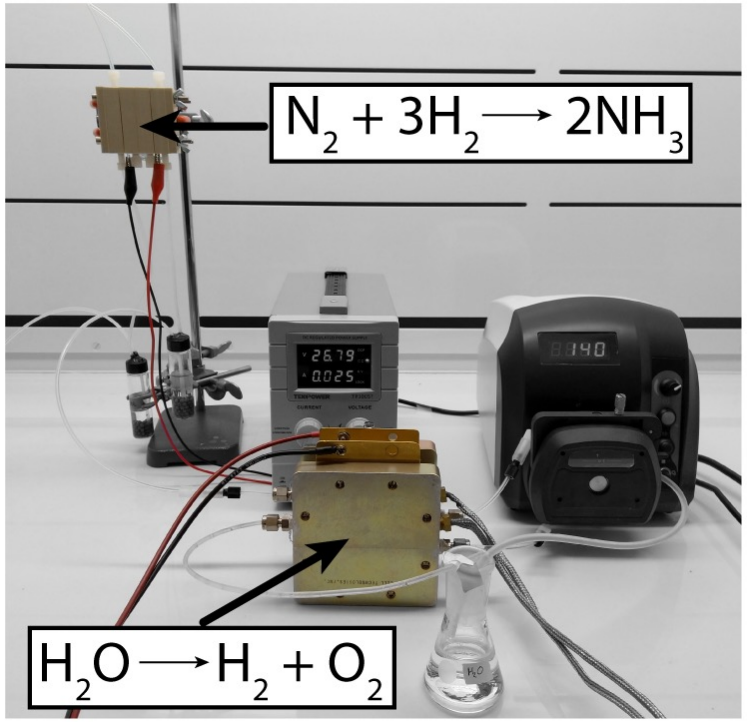
High FEs can be obtained at 15 mA cm^{-2} at non-zero pressure gradients across the GDE

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

Coupling to water splitting







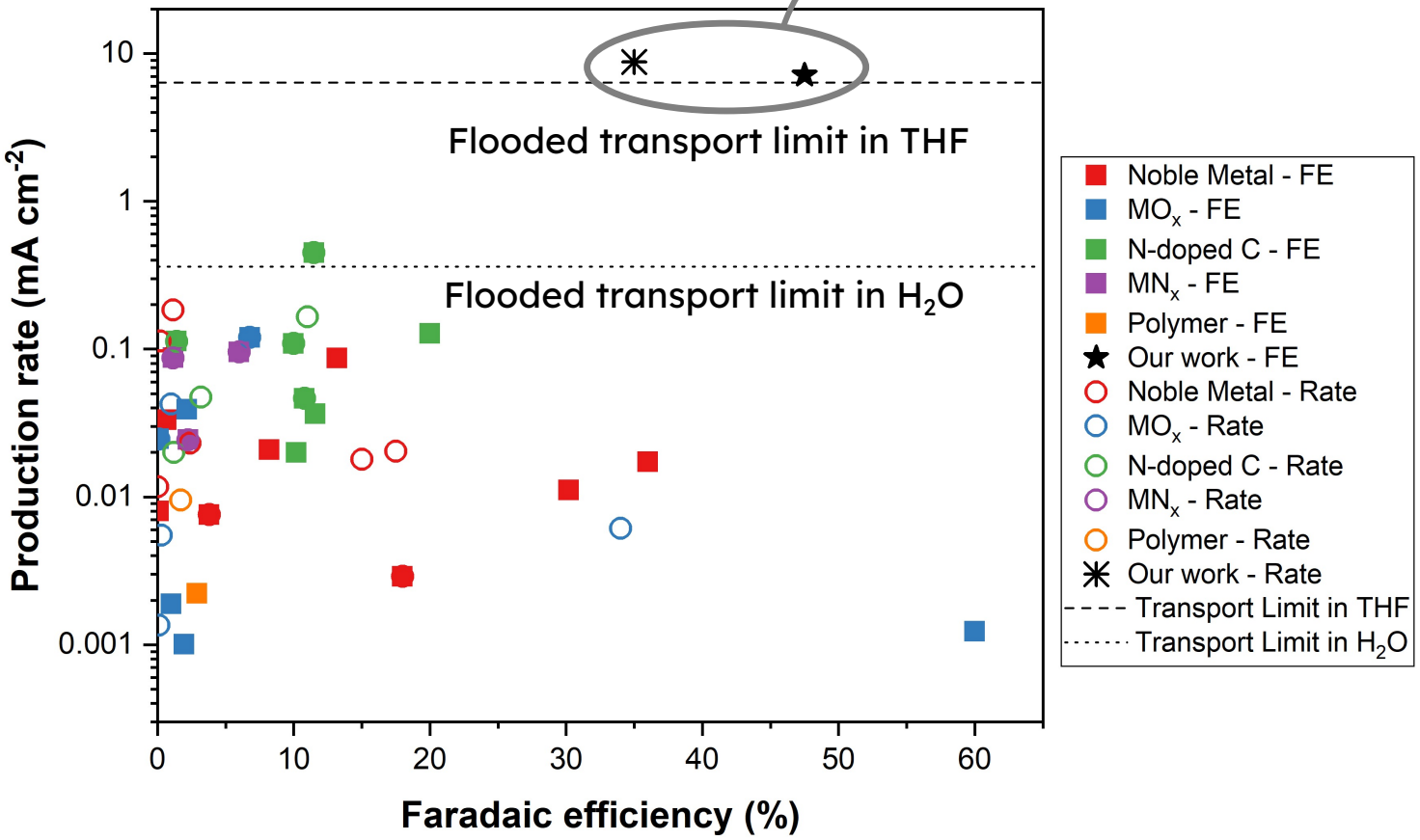
Hydrogen oxidation at the anode can replenish protons in the electrolyte

Water splitting-derived hydrogen can be used at the anode to have overall ammonia production from N_2 and H_2O

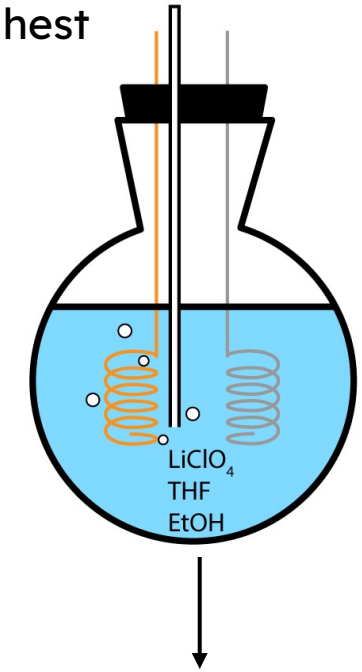
N. Lazouski, M. Chung, K. Williams, M. Gala, and K. Manthiram, *Nature Catalysis* 3 (2020)

Comparing our system to reported catalysts

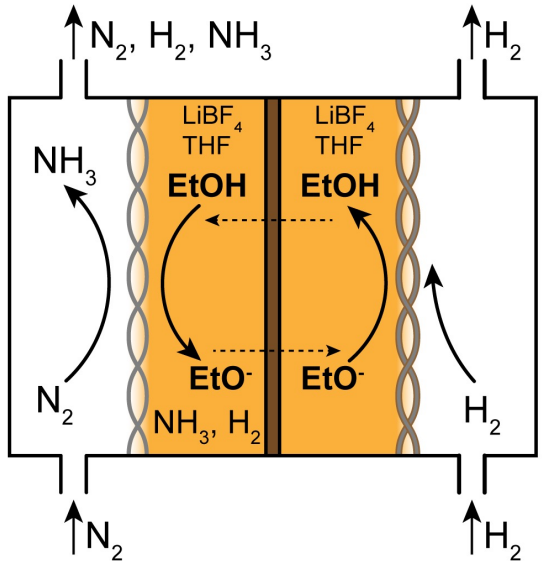
Our approach achieves the highest rates for a semi-batch process



Energy efficiency of 2% - critical barrier to overcome



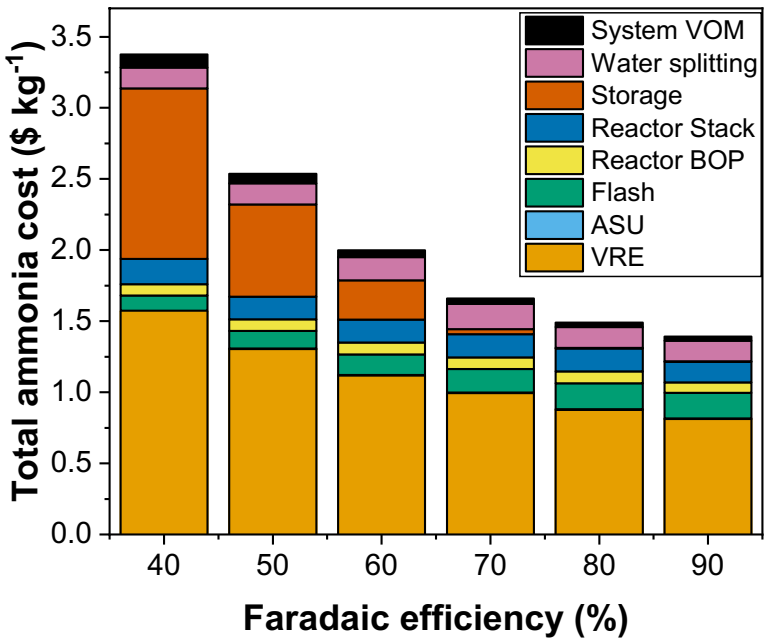
Tsuneto (1994)
8.4% FE
0.16 mA cm^{-2}

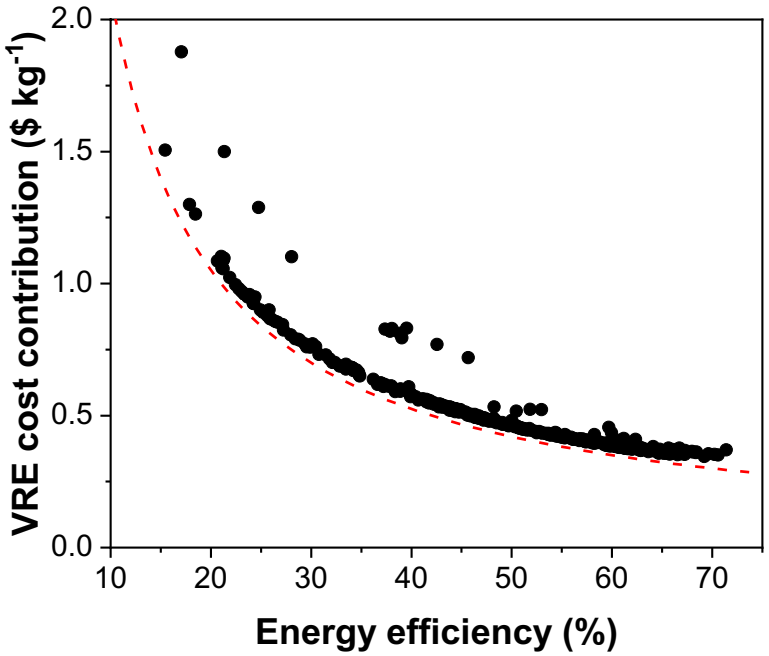


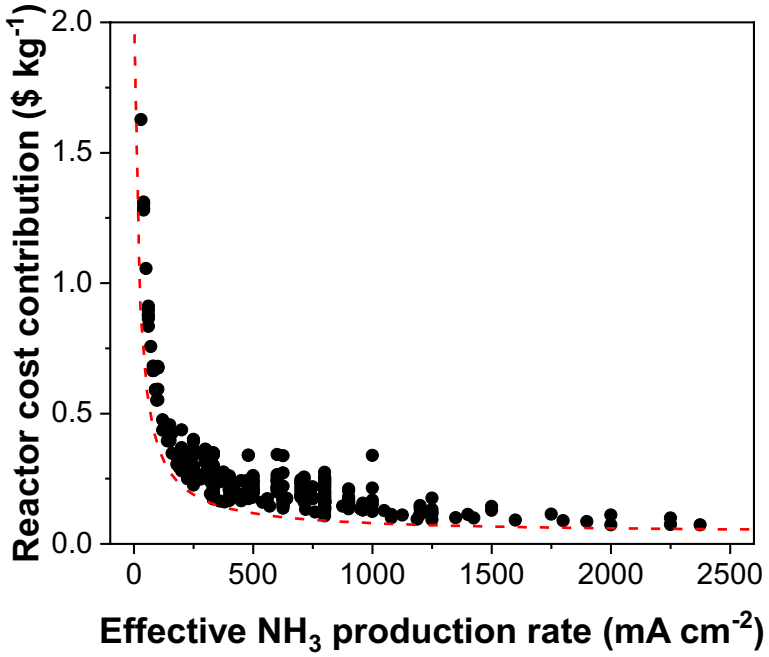
Our work (2020)
47% FE
8.7 mA cm^{-2}

Further improvements in rate and energy efficiency are necessary

(with D. Mallapragada, MIT Energy Initiative)







Detailed technoeconomic analysis of large-scale process can determine optimal NH_3 cost given process characteristics

Energy efficiency of NH_3 reactor predicts VRE (and storage) costs well; ~40% efficiency is necessary

Capital cost of reactor can be predicted by production rate of ammonia; ~400 mA cm^{-2} partial current is necessary

250 tons/day
VOM: Variable Operating and Maintenance Costs
ASU: Air Separation Unit
BOP: Balance of Plant
VRE: Variable Renewable Energy

Acknowledgements

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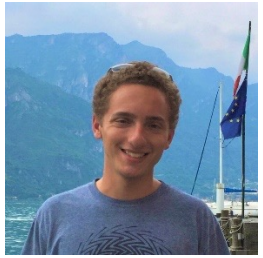
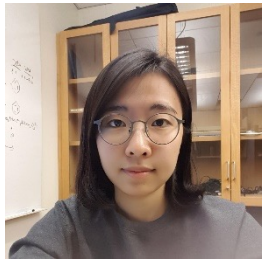


Trent Weiss

Zachary Schiffer

Kindle Williams

Nathan Corbin



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