Electrification and decarbonization of chemical manufacturing

Karthish Manthiram
Assistant Professor
Massachusetts Institute of Technology
Industry generates 33% of global anthropogenic greenhouse gas emissions.
How we make ammonia (NH$_3$) today

CH$_4$ + H$_2$O $\rightarrow$ CO$_2$ + 3H$_2$

N$_2$ $\rightarrow$ 2NH$_3$

400-500 °C, 150-250 bar

Large carbon footprint and harsh conditions that require centralization
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

Making diverse chemicals from CO$_2$, N$_2$, and H$_2$O
Ammonia from air and water

\[ \text{N}_2 + 3 \text{H}_2\text{O} \rightarrow 2 \text{NH}_3 + \frac{3}{2} \text{O}_2 \]

25 °C

1 bar

Renewable power

Eliminate carbon footprint and operate at ambient conditions, enabling distributed synthesis.
Higher pressures to achieve reasonable conversions

\[ \frac{1}{2} \text{N}_2 + \frac{3}{2} \text{H}_2 \rightarrow \text{NH}_3 \]

Higher temperatures to achieve reasonable rates

Electrochemical
At ambient pressure (1 atm):

Voltage also improves kinetics, so can operate at lower temperature

Apply voltage to increase conversion

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

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

\[ \text{N}_2 + 3 \text{H}_2 \text{O} \rightarrow 2 \text{NH}_3 + \frac{3}{2} \text{O}_2 \]

25 °C
1 bar
Electricity

Synthesis of ammonia at ambient conditions

Ammonia synthesis at ambient conditions

New architecture for fast gas transport in non-aqueous medium

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

Lazouski et al. *Nature Catalysis* 3 (2020)
Lazouski et al., *Joule* 3 (2019)
Schiffer et al., *Joule* 1 (2017)
CO₂ REDUCTION

Directing carbon dioxide to syngas

J. S. Zeng, N. Corbin, K. Williams, and K. Manthiram

Sustainable oxygen-atom transfers from water to hydrocarbons
