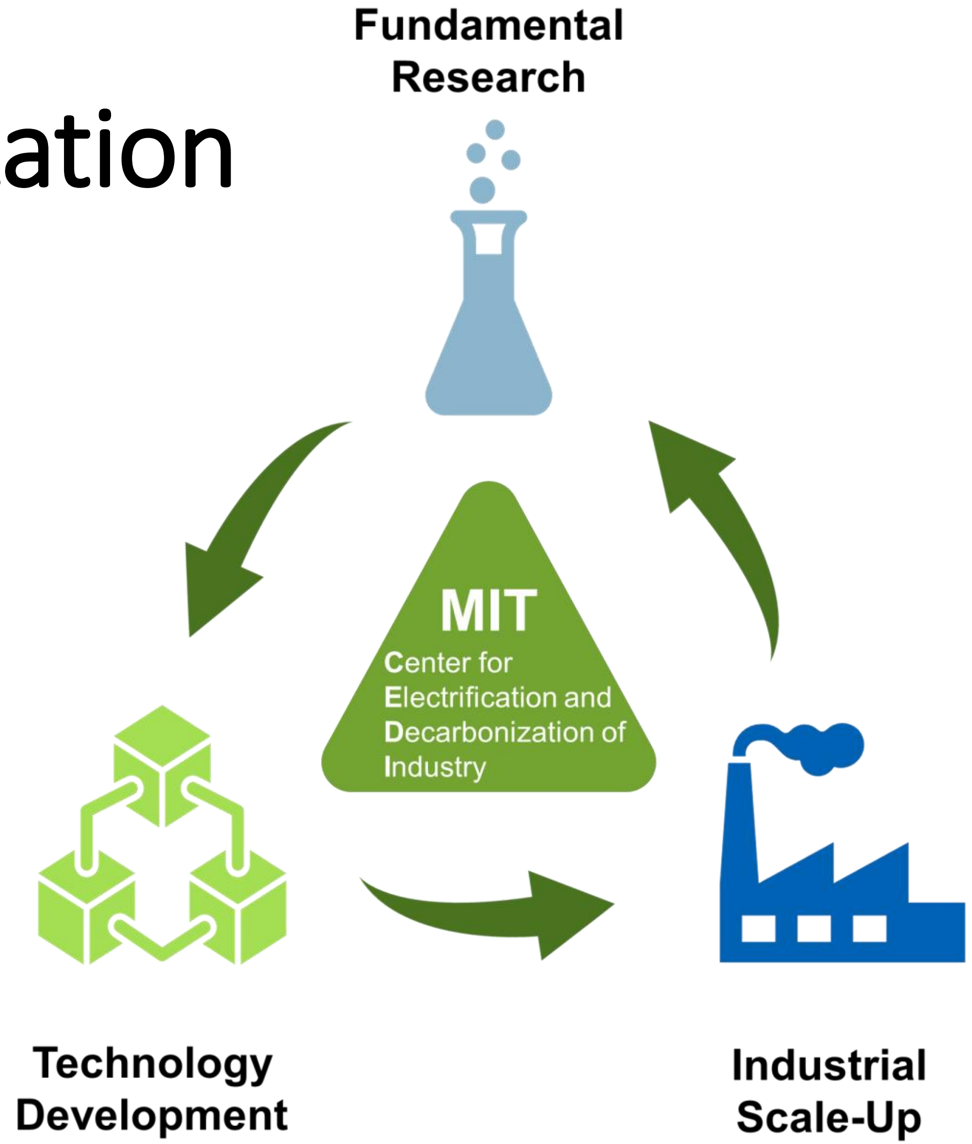
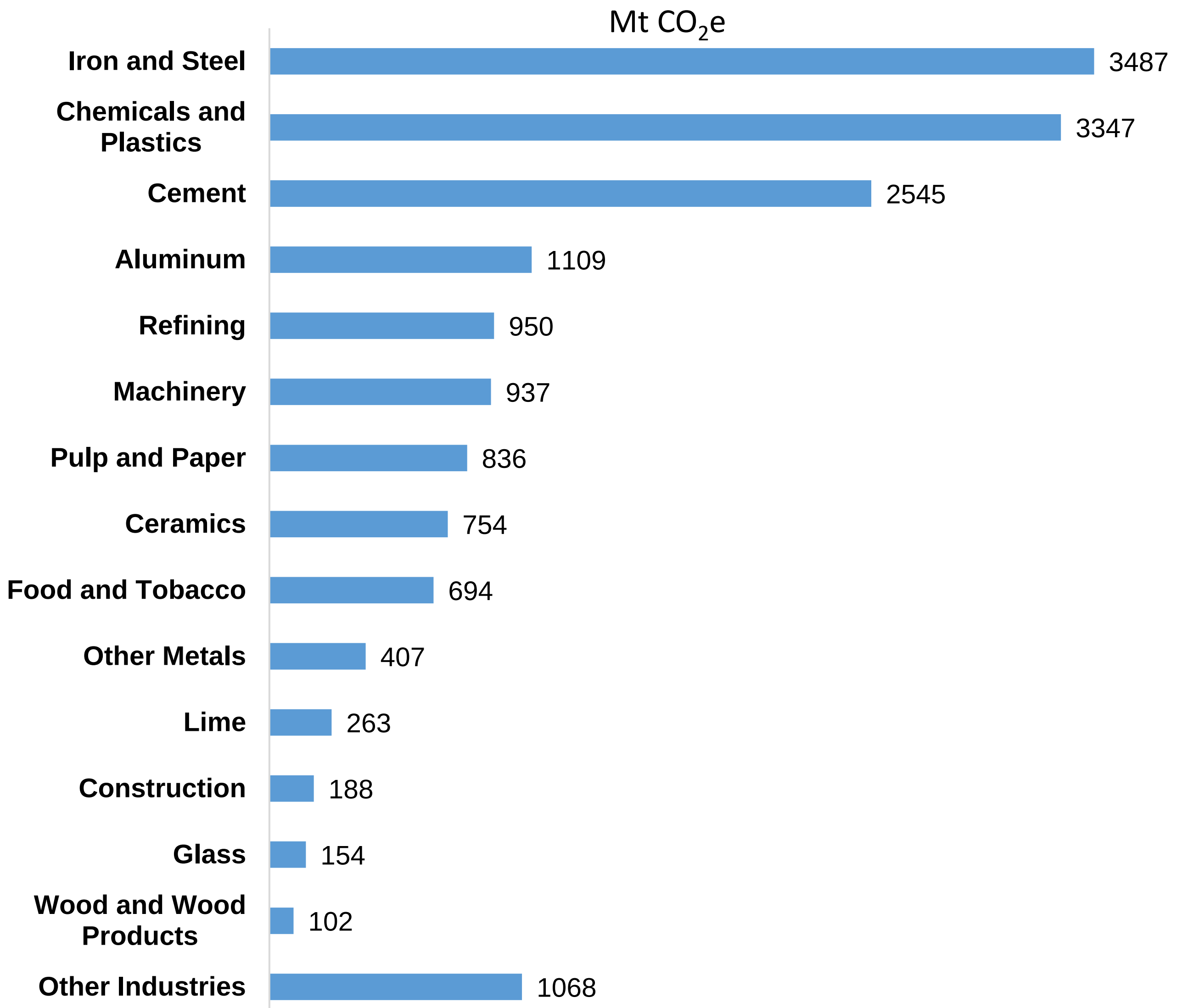
Electrification and Decarbonization of Industry

Now: 33% of CO_2 emissions.
Goal: net-zero.

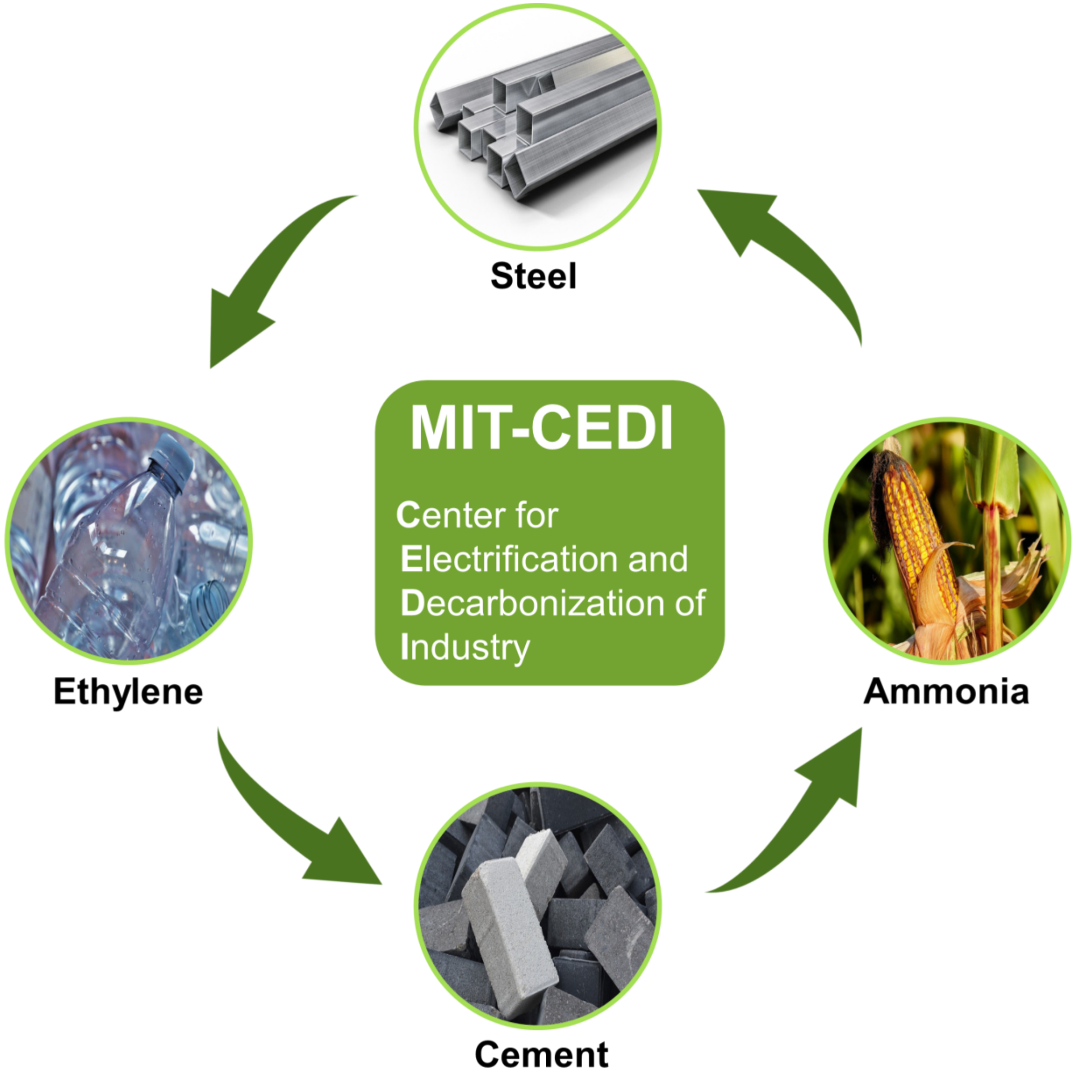


Co-Leads: Yet-Ming Chiang, Bilge Yildiz
Massachusetts Institute of Technology

Industrial pillars of society, ammonia, cement, ethylene and steel responsible for 45% of industrial CO_2 emissions and 15% of global emissions



Rissman et al. *Applied Energy* **266** (2020)



Electrifying and Decarbonizing Industry

Need to master the ability to make and break chemical bonds using electricity - electrochemistry - to decarbonize manufacturing of
ammonia, ethylene, cement, and steel

Cement produces 8% of global CO_2
and has had the least innovation of any emissions category

4 billion tons
cement /year

1 ton = 1 ton
Portland cement = of CO_2

$CaCO_3$ + fossil-fueled heat → $CaO + CO_2$

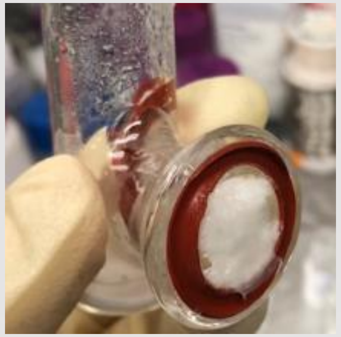
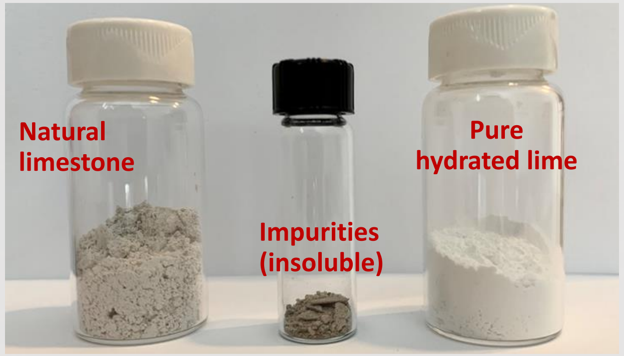
Limestone	1,000°C	Lime
Lime + silica	1,500°C	Cement

50% of cement's CO_2 is from fossil fuel.

The other 50% is from limestone.

Electrolytic decarbonation of limestone to lime



L. D. Ellis, et al., Y-C. Chiang, PNAS, 201821673 (2019).

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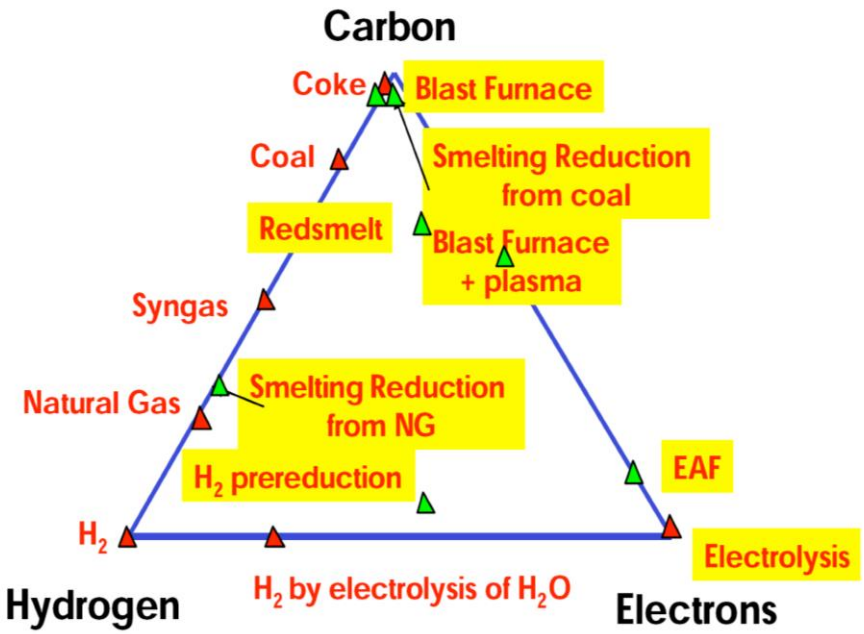
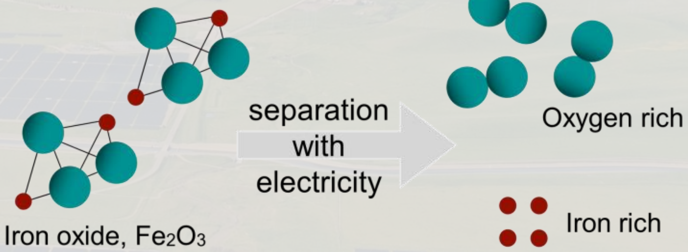
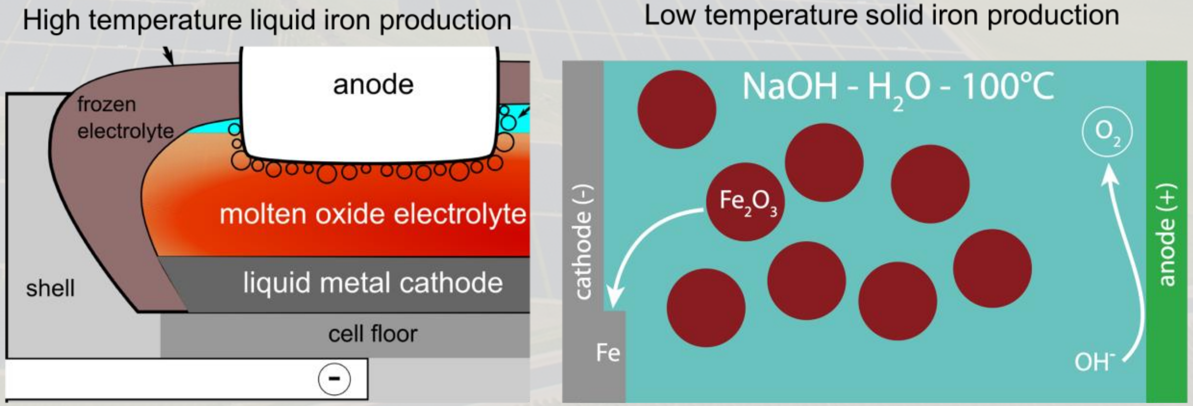
Steel: CO_2-source at iron ore reduction
2 tonnes of CO_2 / tonne of steel



Electrolytic CO_2-free steel



Electrochemical reduction and separation of iron oxide



A. Allanore, MIT.

Electrification and Decarbonization of Industry

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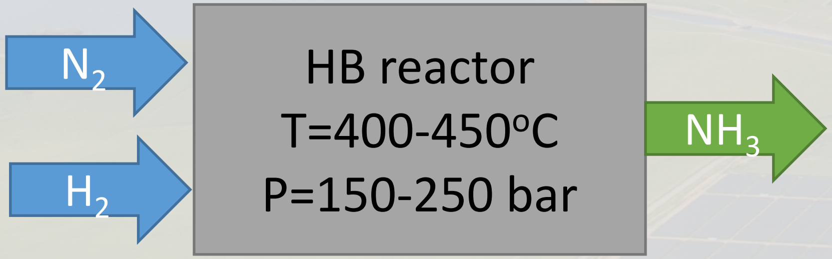
Ammonia: CO_2 source, thermal input to H_2 and Haber-Bosch (HB)



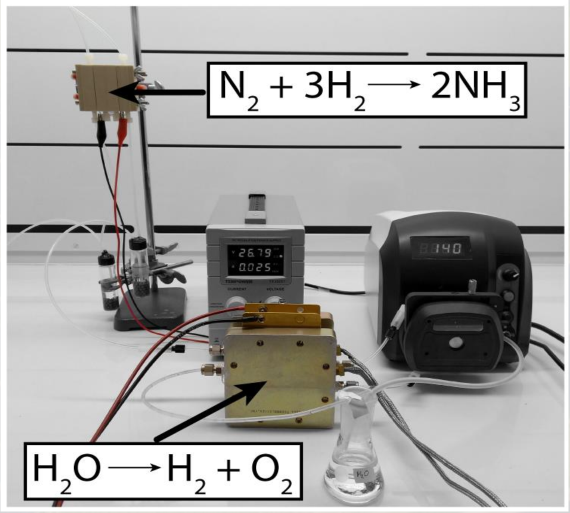
1.5 $t_{CO2\text{-}eq}/t_{NH3}$

- ☒ Energy intensive due to elevated temperature and high pressure operation
- ☒ H_2 from steam-methane-reforming (SMR): the most energy intensive and carbon emitting part of the HB

Electrolytic CO_2-free ammonia

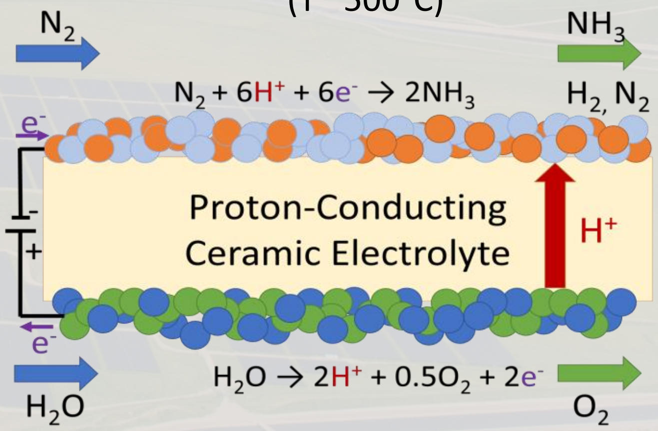
Fully electrified process for converting nitrogen and water into ammonia

Liquid electrochemistry (RT)



N. Lazouski, et al., and K. Manthiram, *Nature Catalysis* **3** (2020).

Solid, ceramic electrochemical cell (T ~500°C)



Higher current densities

Higher energy efficiency

Y. Shao-Horn, A. Ghoniem, J. Li, R. Gomez-Bombarelli, Y. Surendranath, B. Yildiz, MIT

Electrification and Decarbonization of Industry

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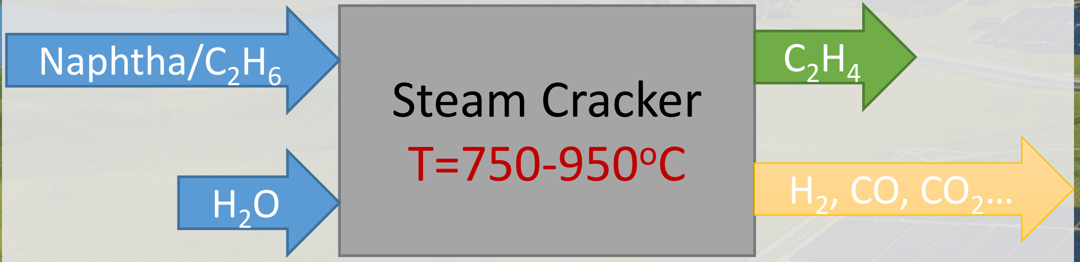
Ethylene: CO_2 source, thermal energy input, conversion selectivity

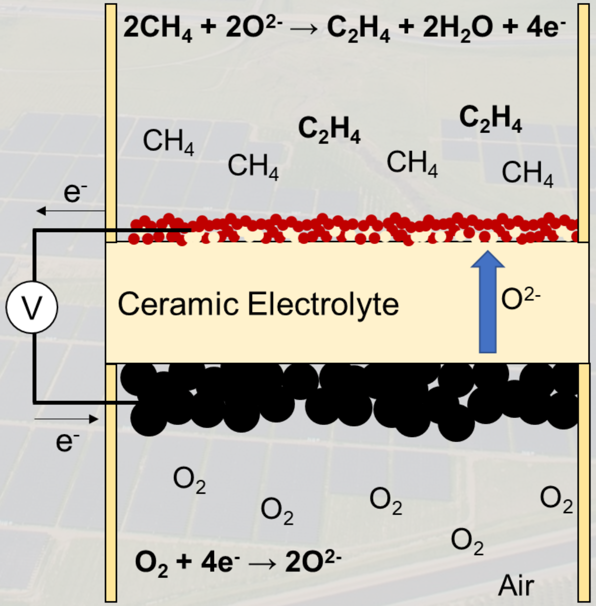


Naphtha → 2.9 $t_{CO2\text{-}eq}/t_{C2H4}$
Ethane→1.5 $t_{CO2\text{-}eq}/t_{C2H4}$

- ☒ Highly endothermic reaction (at 750-950°C)
- ☒ Hydrocarbon combustion for cracking

Electrolytic CO_2-free ethylene

Electrochemical oxidative coupling of methane (E-OCM); air and methane to ethylene



Lower operating T (600-800°C)

No extra cost for O_2 separation

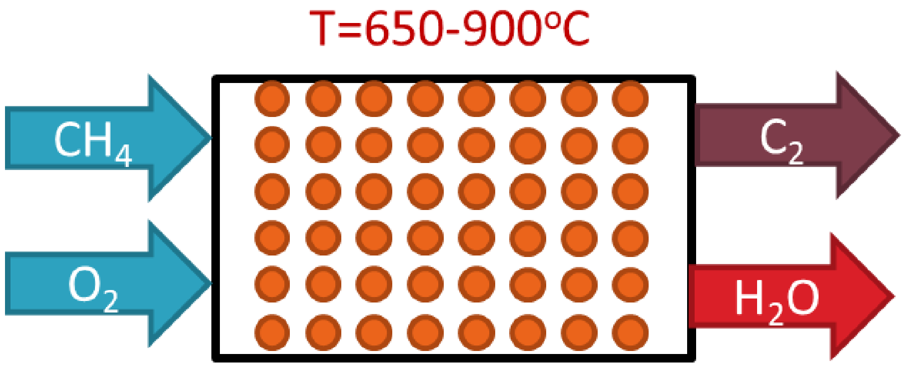
More selective C_2H_4 production wit high yield.

C_2H_4 + electricity (SOFC) / C_2H_4 + chemical (SOEC)

B. Yildiz, H. Tuller, B. Green, A. Ghoniem, T. Swager, MIT

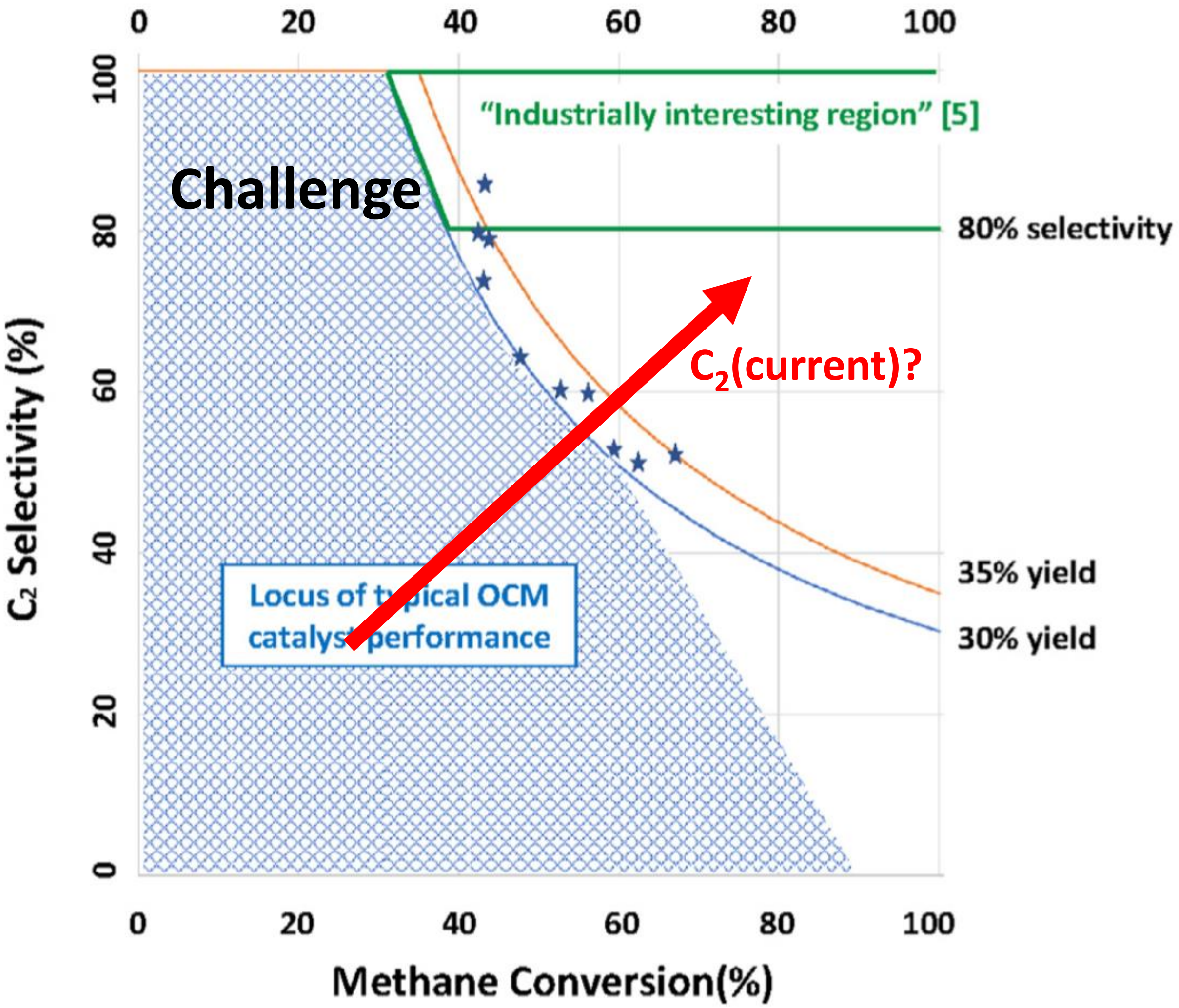
Can we beat the *selectivity – conversion* competition using electrochemistry?

Thermochemical OCM



$$2CH_4 + \frac{1}{2}O_2 \xrightarrow{\text{Cat}} C_2H_6 + H_2O,\ \Delta H^o_{298K} = -176.9\,\text{kJ/mol}\ C_2H_6$$

$$2CH_4 + O_2 \xrightarrow{\text{Cat}} C_2H_4 + 2H_2O,\ \Delta H^o_{298K} = -281.8\,\text{kJ/mol}\ C_2H_4$$



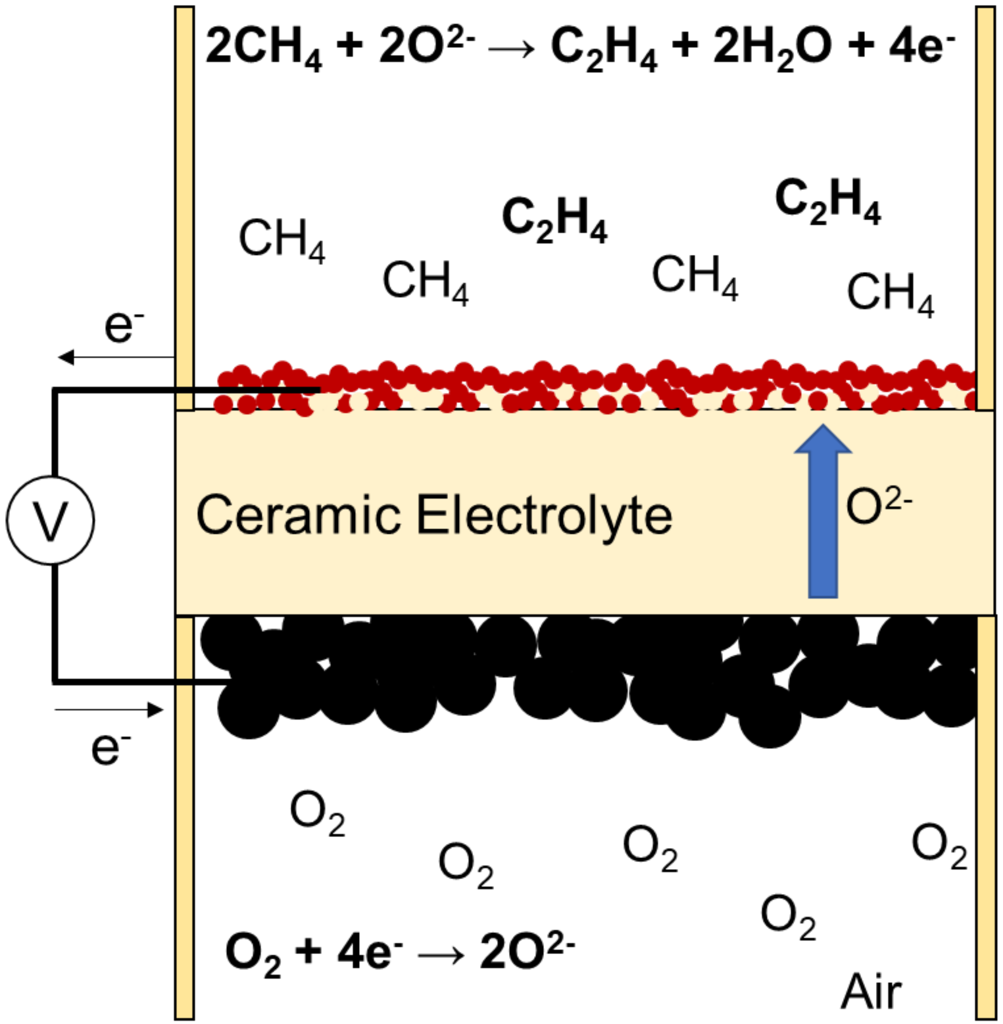
- ✓ Reaction exothermicity reduces temperature
- ✓ Natural gas from shale cheap and available
- ✓ Steam in the products easy to separate

☒ "Deep oxidation" of CH_4 to CO/CO_2 limits selectivity to C_2 (C_2H_6 and C_2H_4), and yield.

G. Dimitrakopoulos, B. Yildiz, and A. Ghoniem, *Sustainable Fuels*, 2021

M.A. Barteau, *Journal of Catalysis* 408 (2022) 173–178

Electrochemical oxidative coupling of methane (E-OCM); air and methane to ethylene



Use electrochemistry to drive high rate

@Lower operating T (600-800^{o}C)

→ Higher selectivity to C_2

No extra cost for O_2 separation

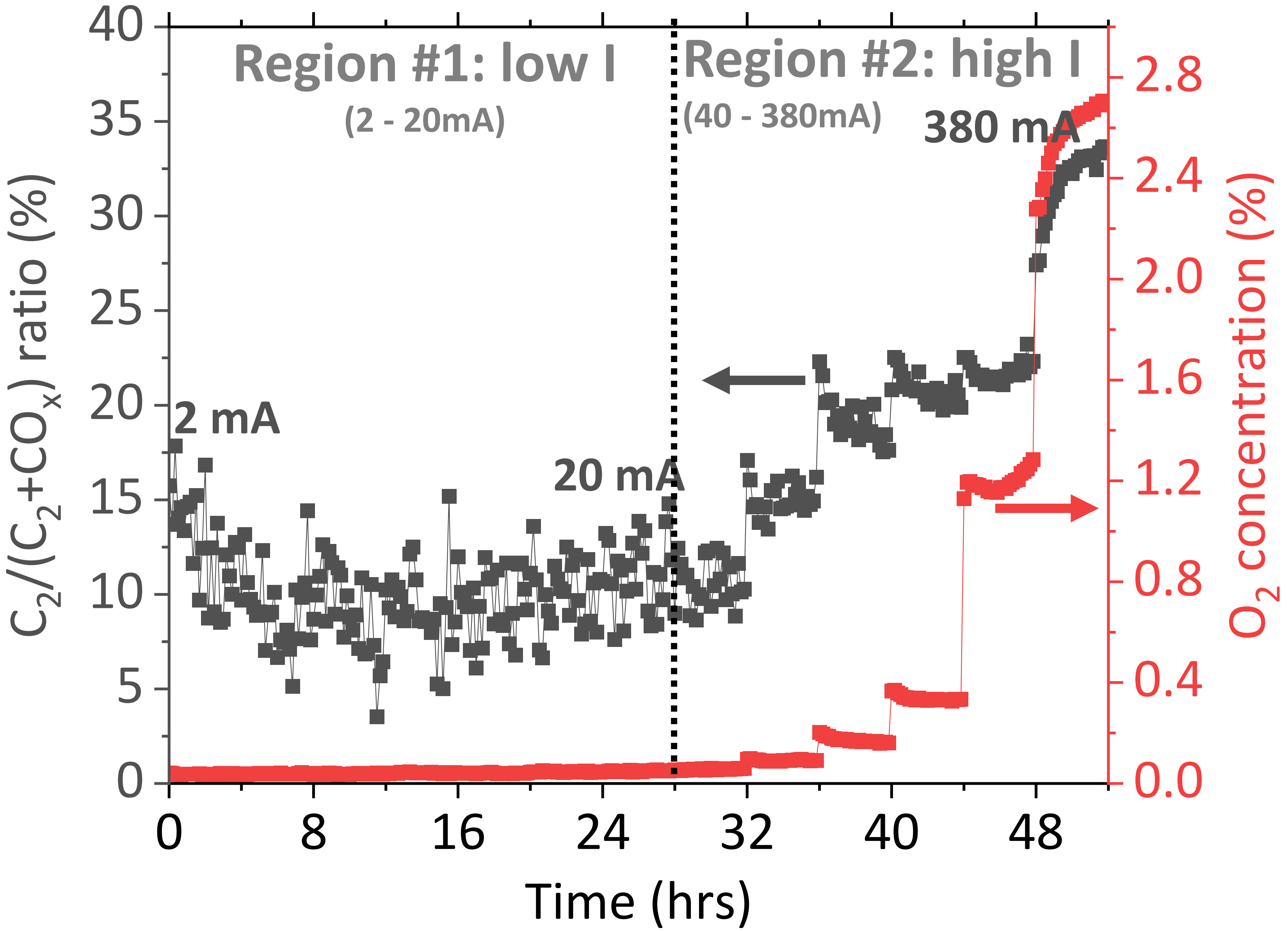
C_2H_4 + electricity (SOFC)

C_2H_4 + H_2, CO (SOEC)

Bloom Energy

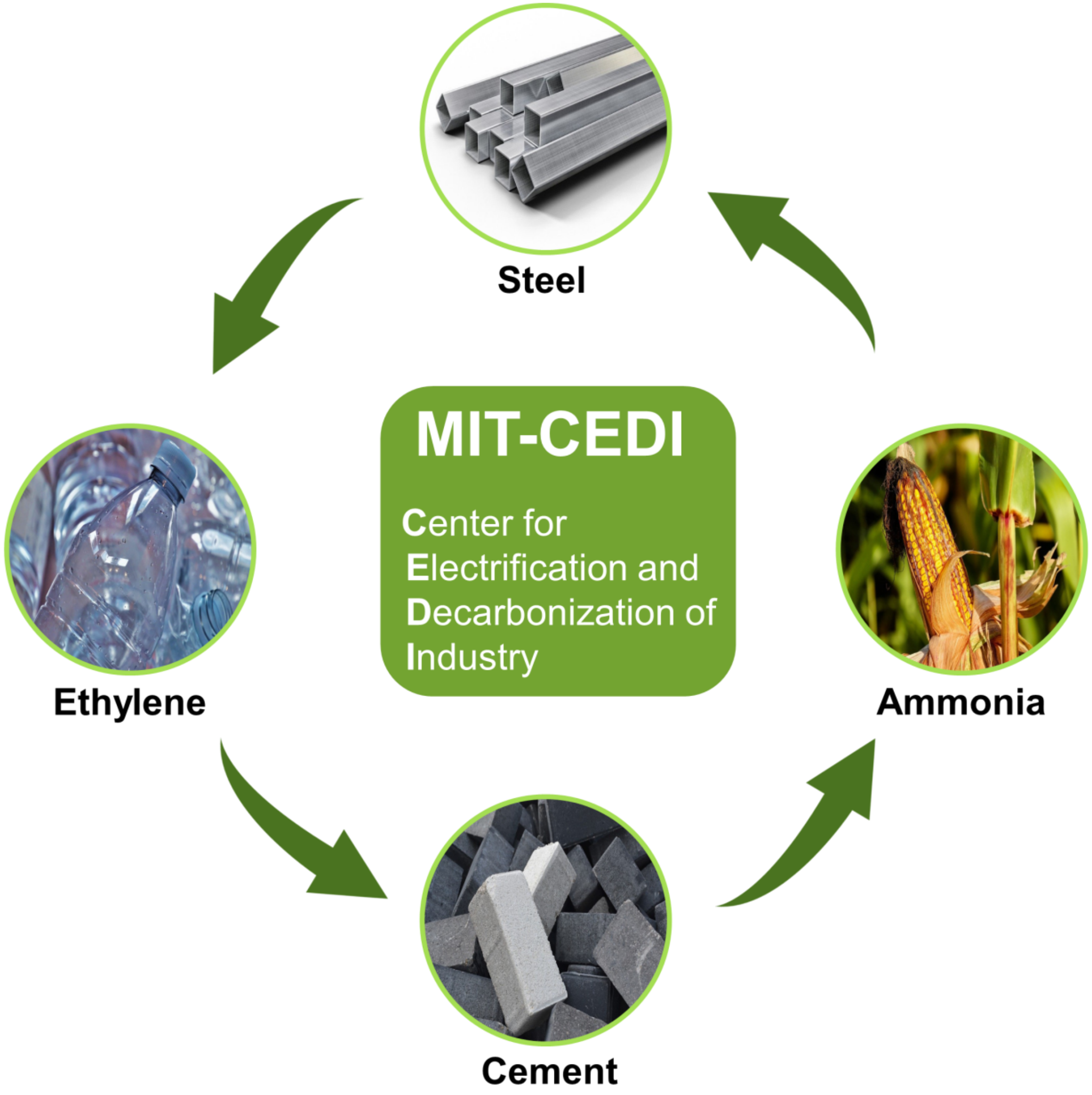
SOFC technology exists, but anode for E-OCM does not…

EOCM – C_2 selectivity goes up with increasing current density!



- Selective oxidative coupling needs O^-, O_2^- or O_2^{2-}.
- Onset of significant O_2 concentration increase
  - Correlates with selectivity increase!
- Hypothesis: O_2 evolution produces species selective for C_2's

Integrative approach



Connecting input and output streams to create a self-contained supply chain that minimizes overall emissions: *waste streams as feedstocks*

- CO_2 from $CaCO_3$ as supply to ethylene synthesis
- H_2 from electrochemical ethylene to extract iron from iron ore, or to feed to ammonia synthesis
- H_2 as waste in many electrochemical processes for electricity generation.
- Colocation versus pipelines