Electrochemical ammonia synthesis using proton-conducting ceramics

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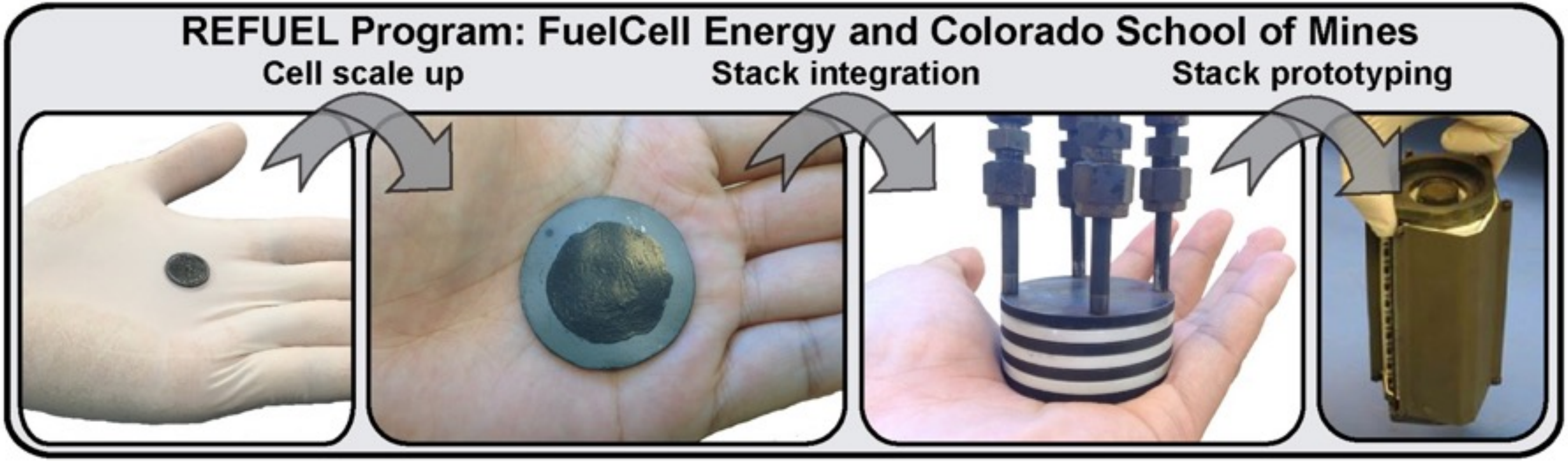
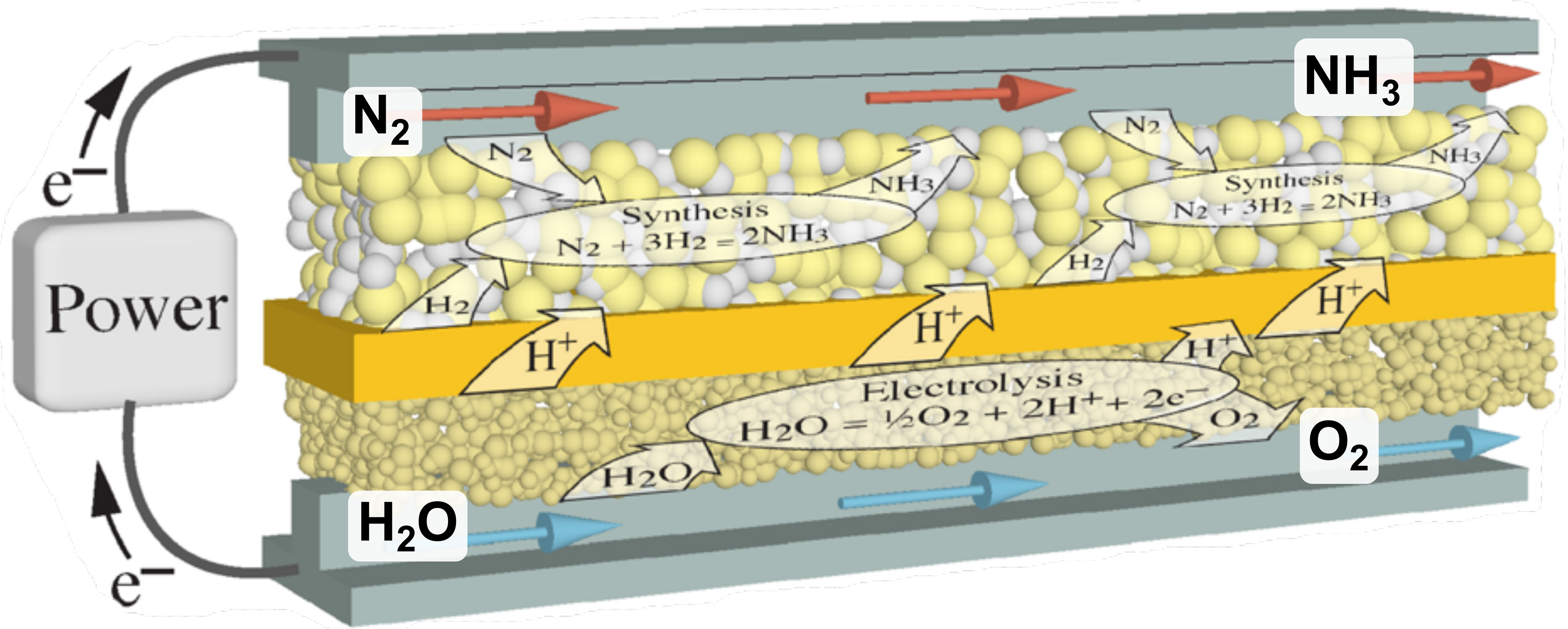
U.S. DoE, NASA, FuelCell Energy, and Colorado School of Mines have invested in proton-conducting ceramics

- ARPA-E REBELS: Proton-conducting ceramic fuel cells (5 years)
- ARPA-E REFUEL: NH_3 synthesis with protonic ceramics (3.5 yrs)
- EERE HTWS: Proton-conducting ceramic electrolyzers (2 yrs)
- FE NETL: CO_2-to-fuels through electrochemical catalysis (2 yrs)
- NASA NSTRF: Making fuel on Mars with protonic ceramics (2 yrs)



Proton-conducting ceramics are an emerging material with broad energy applications

Protonic-ceramic electrochemical cell for "green" ammonia synthesis



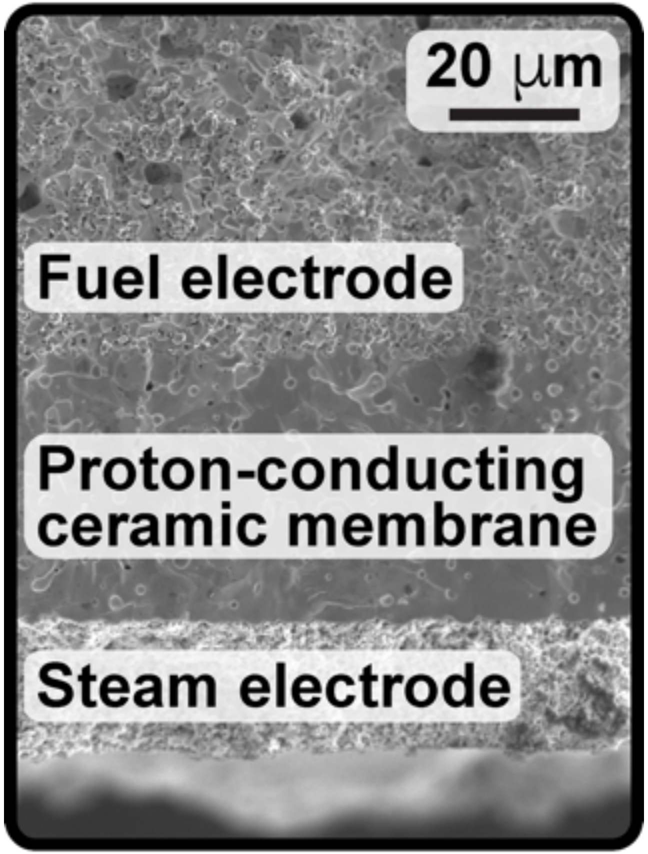
The CSM FuelCell Energy team explores electrochemical NH_3 synthesis from many perspectives

- Experimental efforts on electrochemical ammonia synthesis
  - Neal P. Sullivan, Liangzhu Zhu, Chuancheng Duan, Ryan O'Hayre, Max Pisciotta, Long Le, Carolina Herradon Hernandez, Michelle Butler, Colorado School of Mines
- Catalyst characterization
  - Chris Cadigan, Canan Karakaya, Robert J. Kee, Colorado School of Mines
- Techno-economic analysis of electrochemical ammonia synthesis
  - Fred Jahnke and Hossein Ghezel-Ayagh, FuelCell Energy

CFCC Colorado Fuel Cell Center   arpa·e   fuelcellenergy

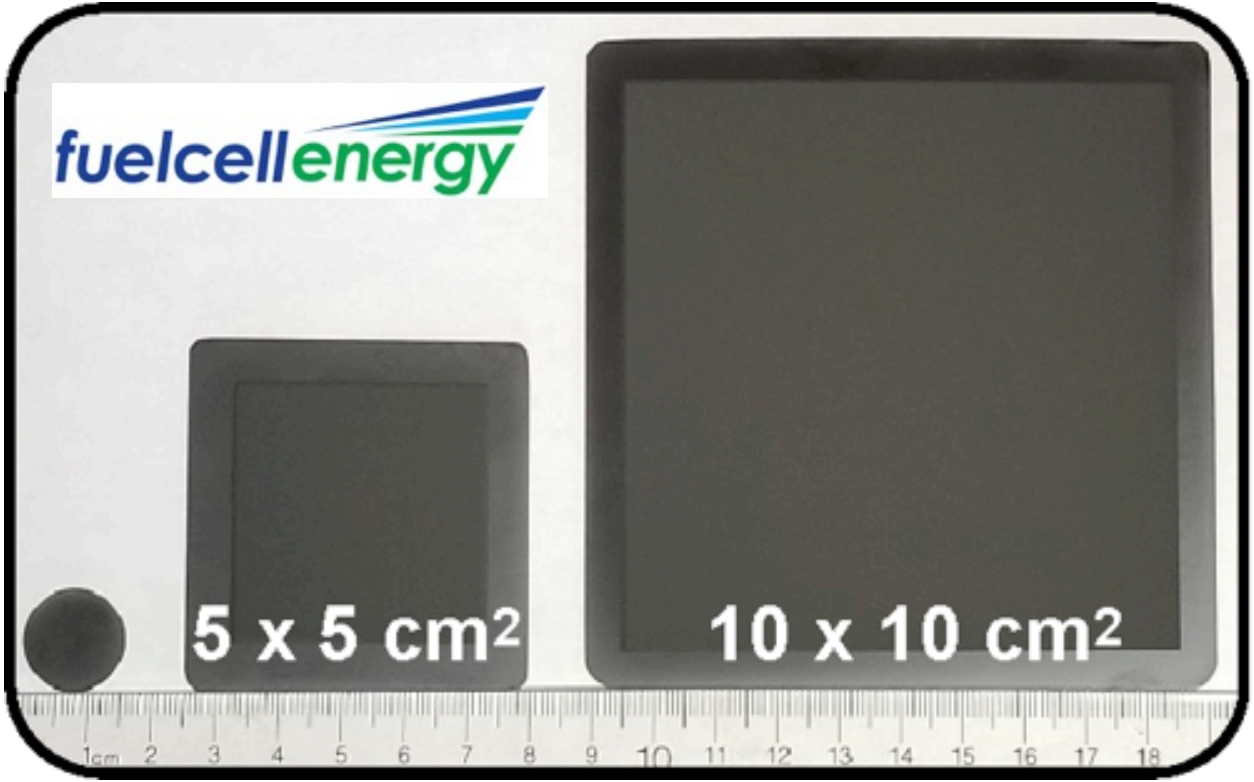
The proton-conducting ceramic electrochemical cell is the heart of our ammonia-synthesis approach

- Perovskite ceramic membrane
  - $BaCe_{0.4}Zr_{0.4}Y_{0.1}Yb_{0.1}O_{3-d}$ (BCZYYb)
- Composite metal – ceramic fuel electrode
  - Porous Ni - BCZYYb
  - Forms mechanical support for MEA
- Porous steam electrode
  - $BaCo_{0.4}Fe_{0.4}Zr_{0.2}O_{3-\delta}$ (BCFZY)
  - Triple-conducting electrode (H^+, O^{2-}, *e'*)
  - Splits H_2O into H^+ and O_2
- Operating conditions
  - ~ 600 ºC at atmospheric pressure
  - Need to increase pressure and lower temperature for NH_3 synthesis



FuelCell Energy has successfully scaled up proton-conducting ceramics, targeting 1-kW_e stack

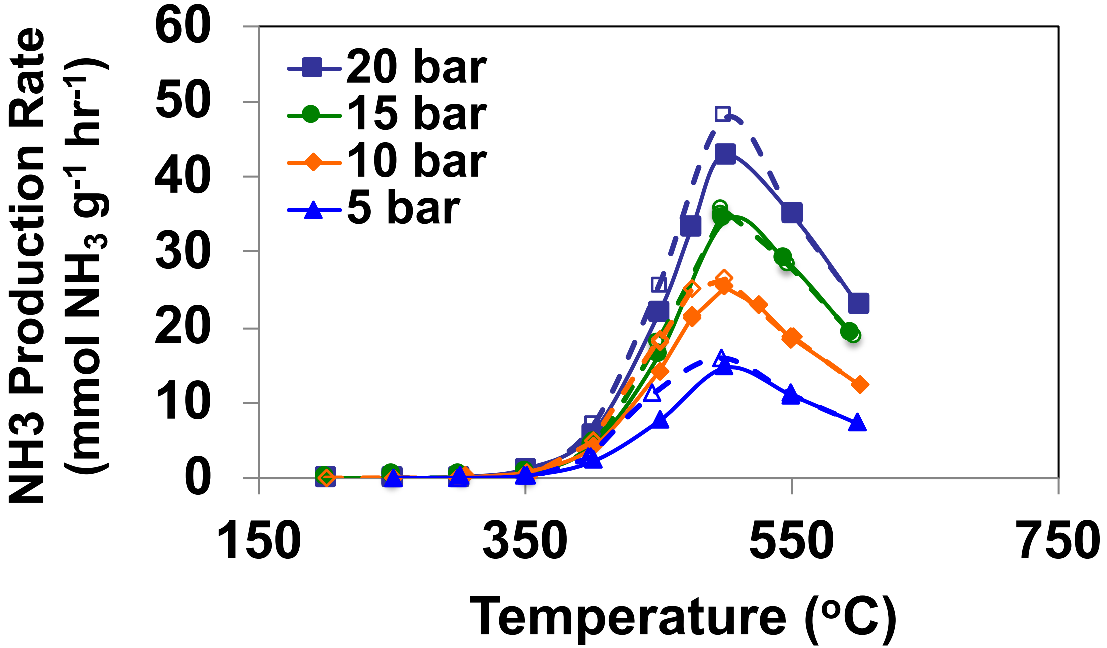
World's largest proton-conducting ceramic cells



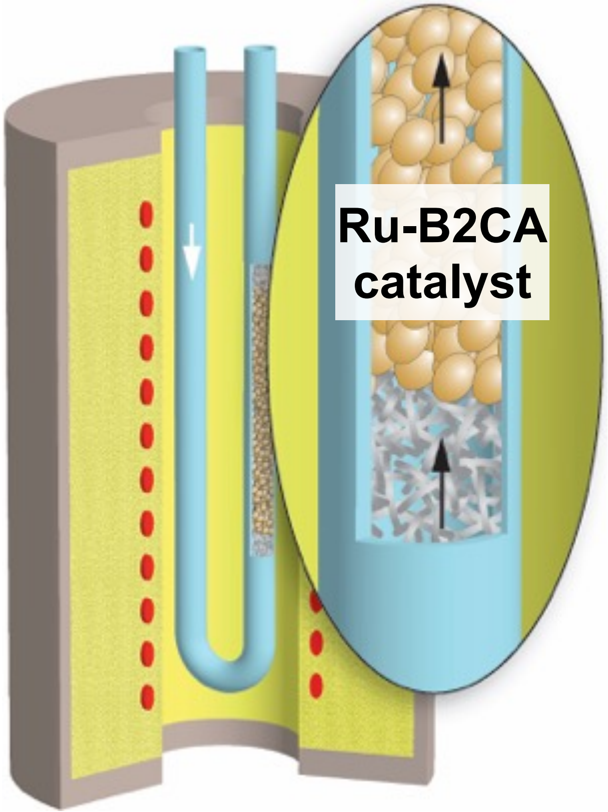
Target stack

A patent-pending catalyst developed by StarFire Energy reacts N_2, H_2 and H^+ to form NH_3

- "Ru-B2CA" catalyst
  - Ruthenium catalyst
  - $Ba_2CaAl_2O_6$ support

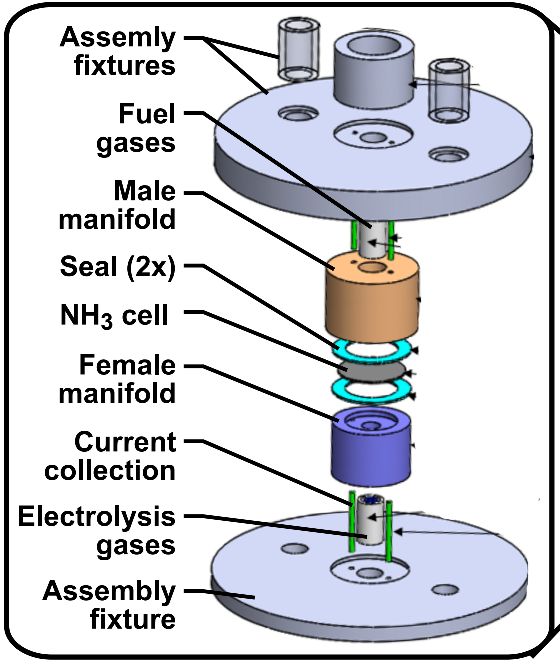


Packed-bed reactor

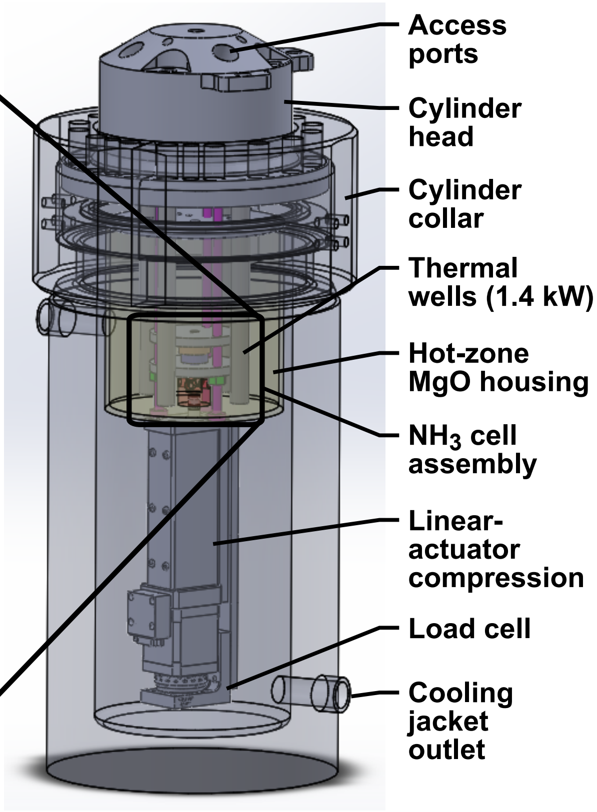


Colorado School of Mines has invested in a pressurized electrochemical test stand

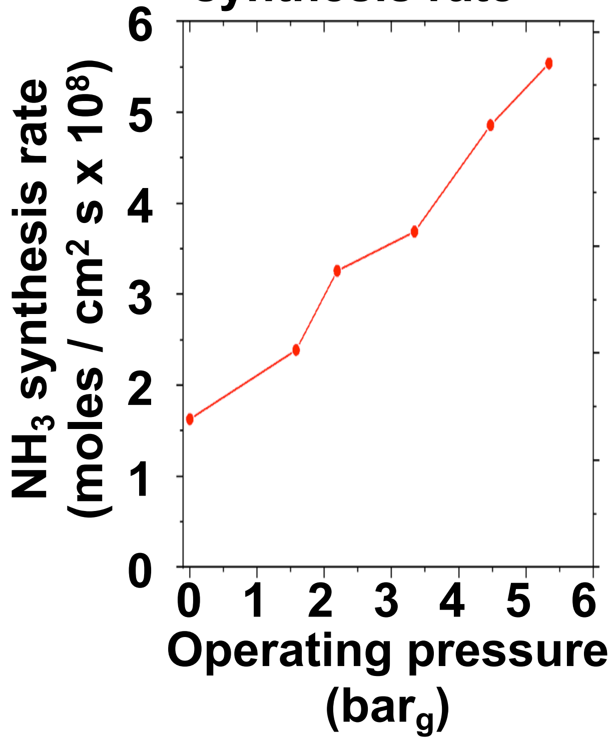
Cell packaging



Pressure vessel



Effect of pressure on electrochemical NH_3-synthesis rate

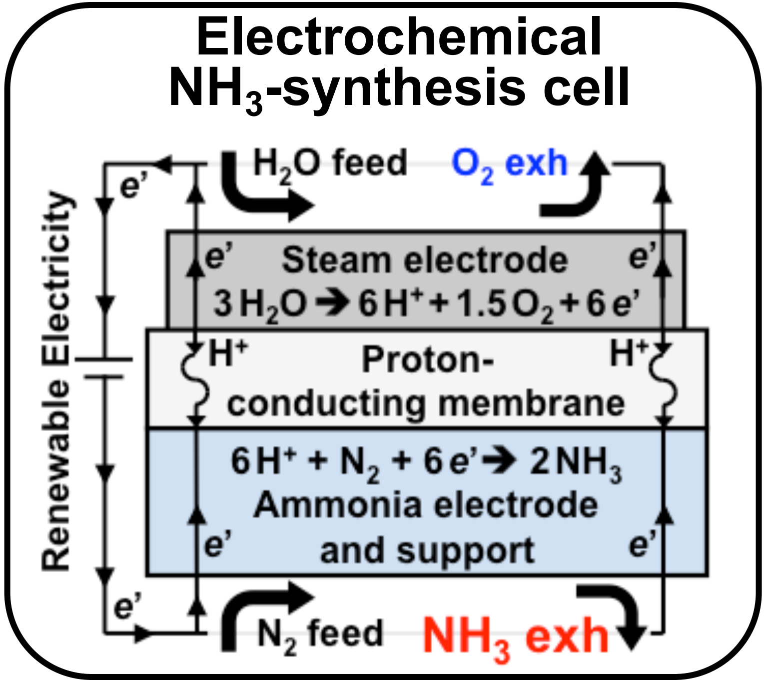


We have had the most success when decoupling the hydrogen production from the ammonia catalysis

Coupled approach

Electrolysis and catalysis at 600 ºC

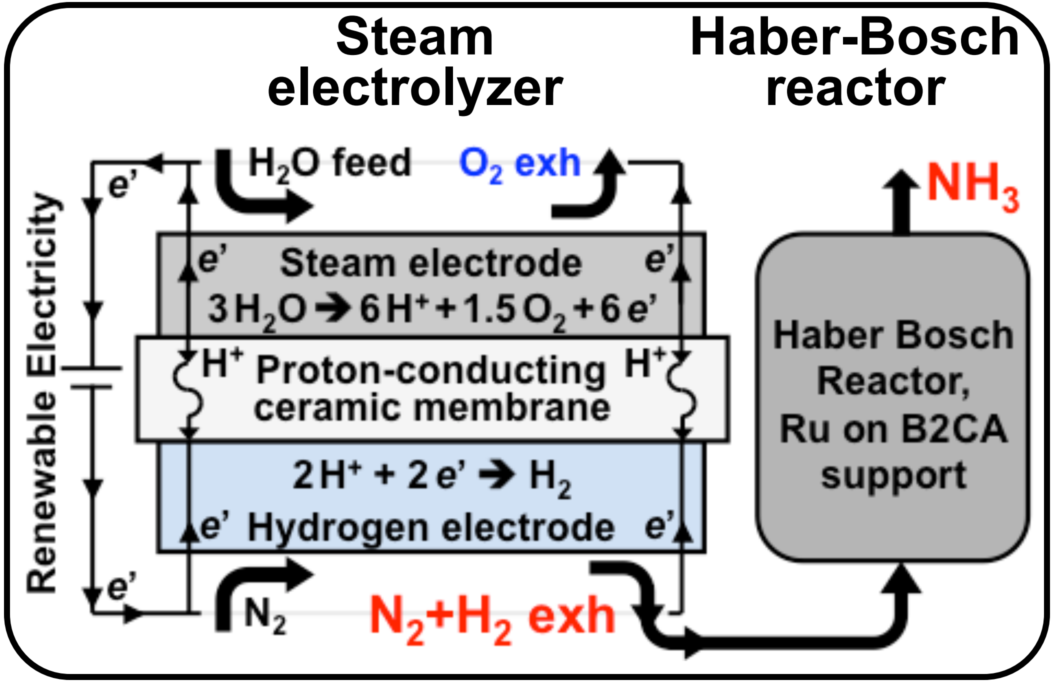
A bit hot for NH_3 synthesis



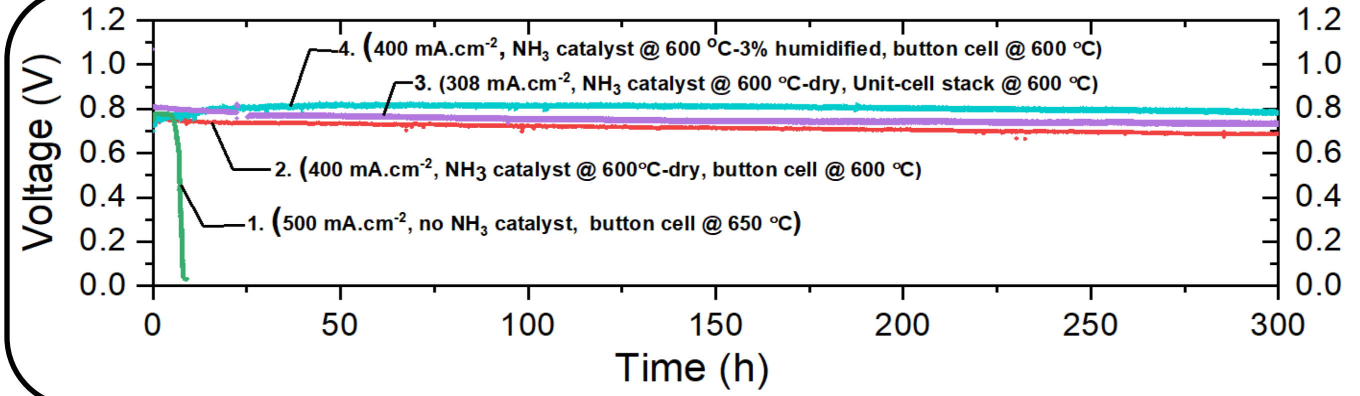
Decoupled approach

Electrolysis at 600 ºC

NH_3 catalysis at ~ 450 ºC



The protonic-ceramic / B2CA combination shows encouraging longer-term, "reversible" operation

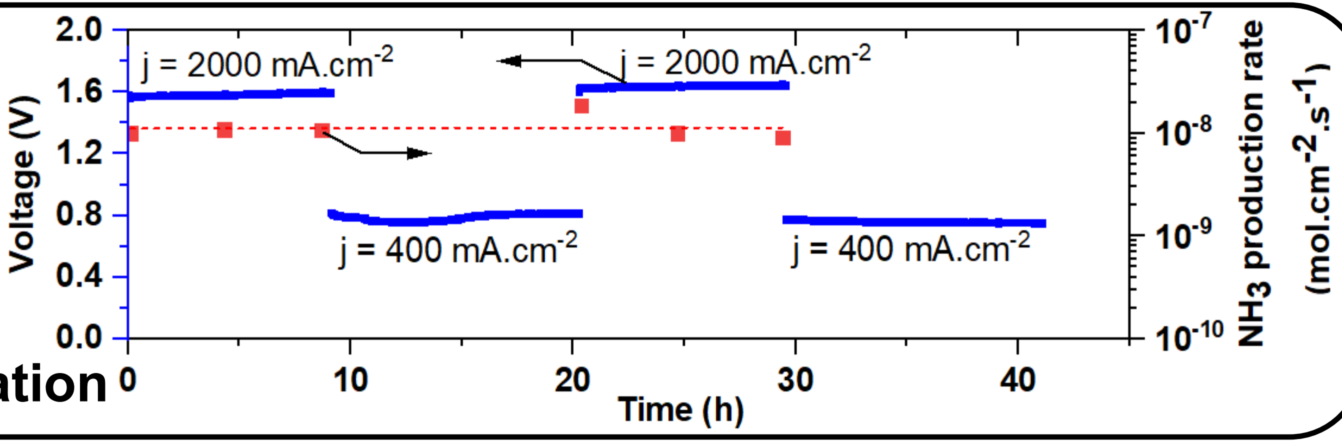


NH_3-fueled protonic-ceramic **fuel cell** for electricity generation

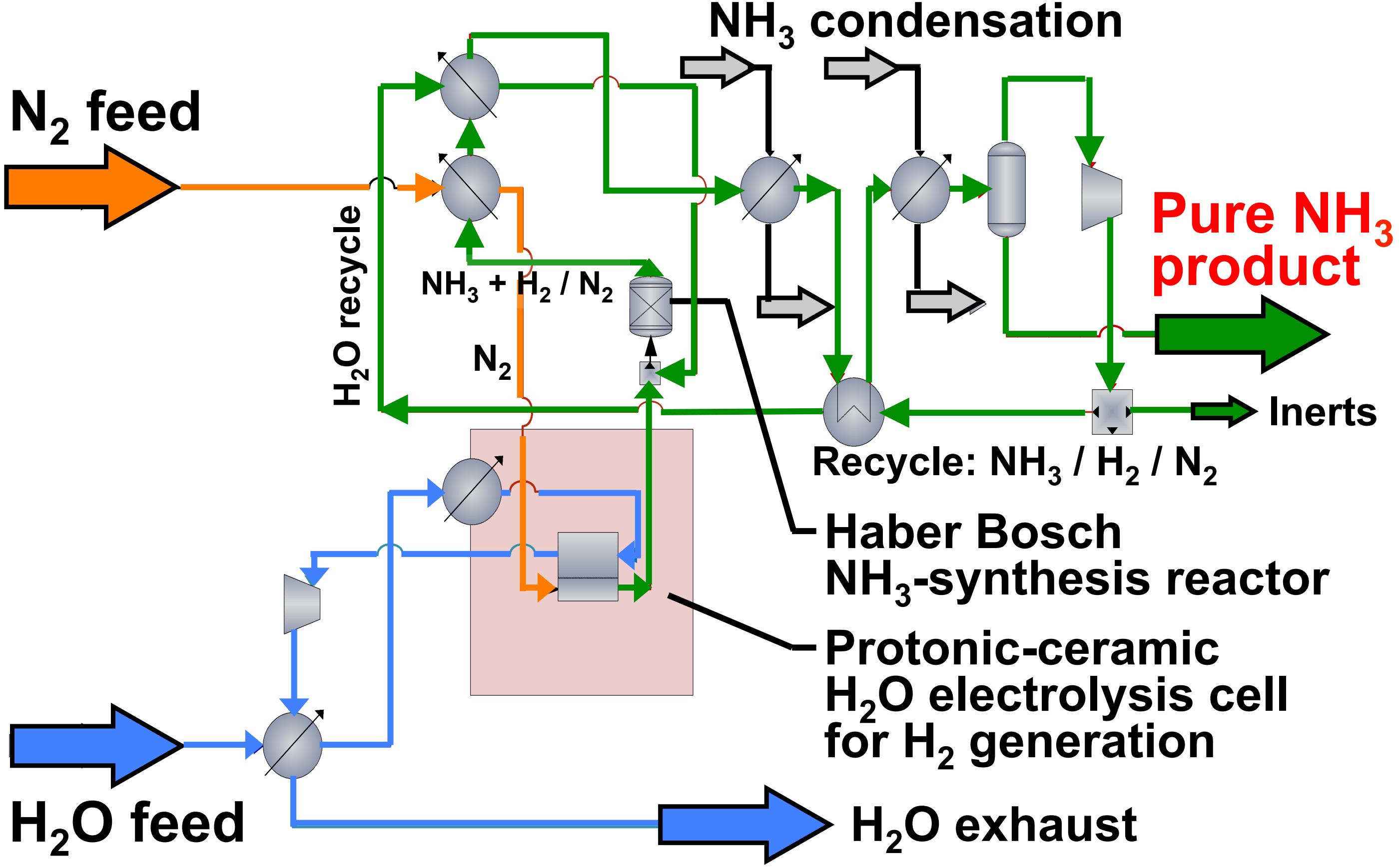
Reversible cell:

NH_3-synthesis = energy storage;

NH_3 fuel cell = electricity generation

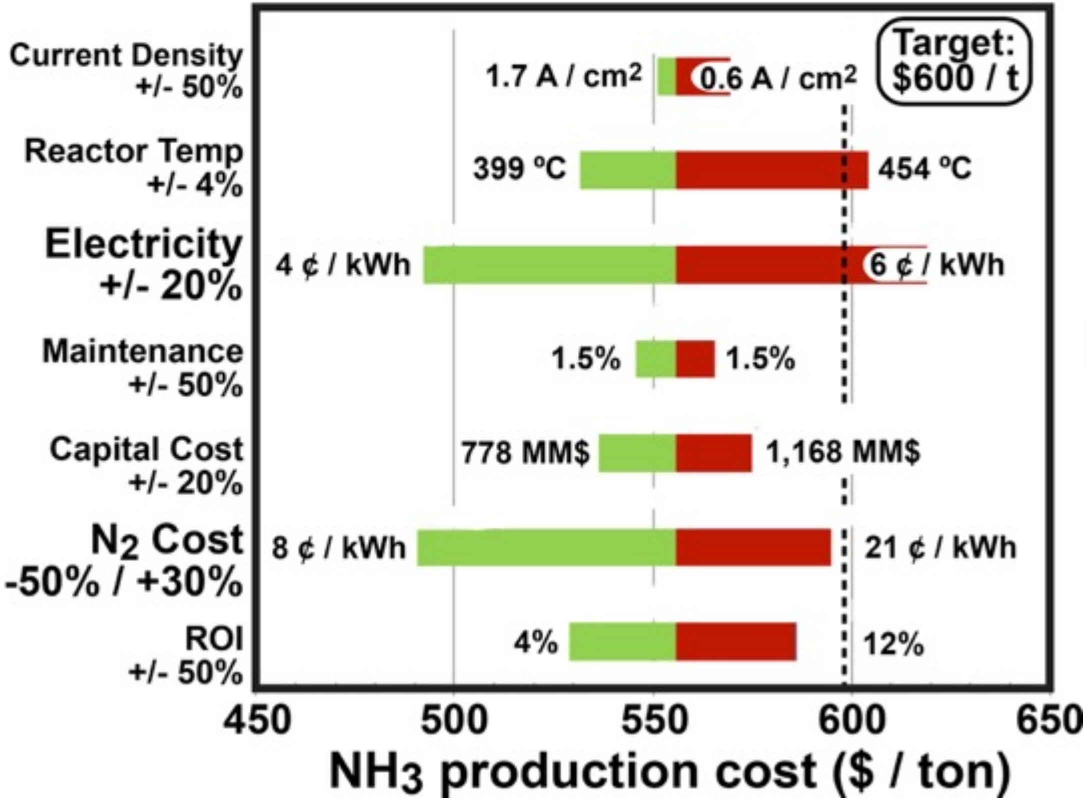


Techno-economic analysis at FuelCell Energy finds pressures need to reach 60 bar to be cost-competitive

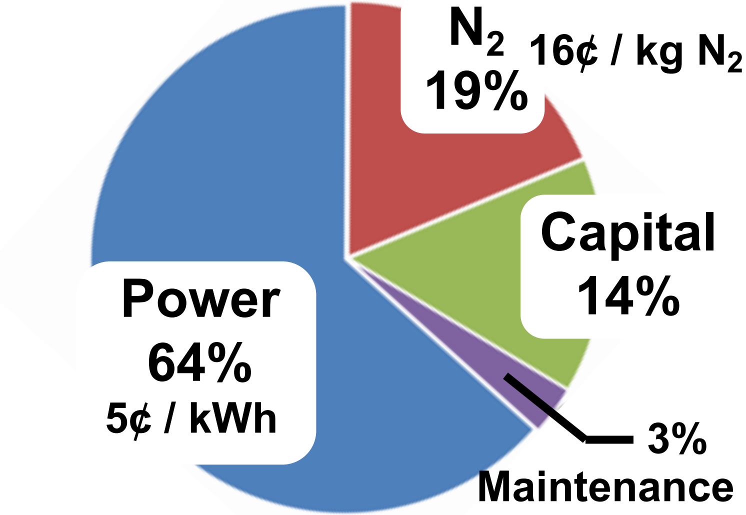


Cost drivers are electric power to drive water splitting, and pure nitrogen feedstock

Sensitivity analysis at 60 bar operation

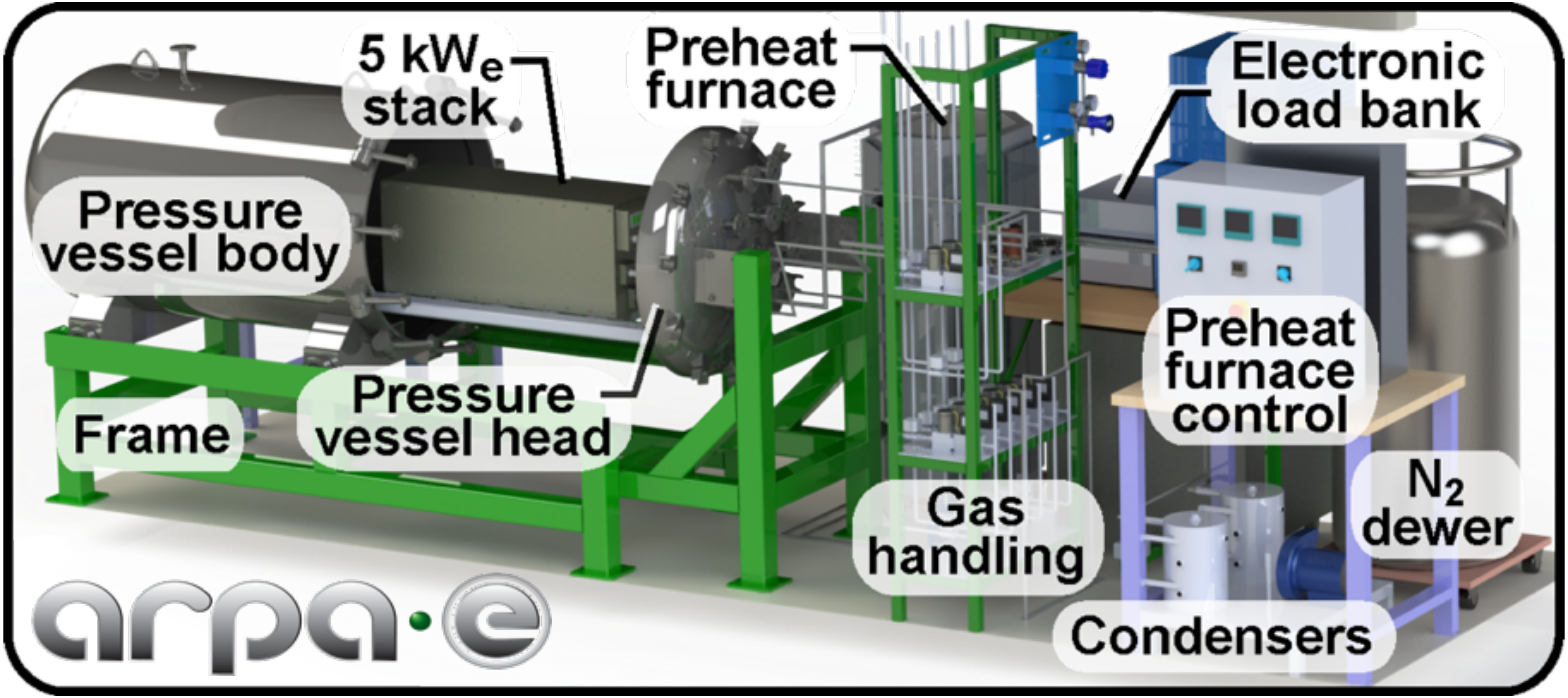


Pie chart of projected costs



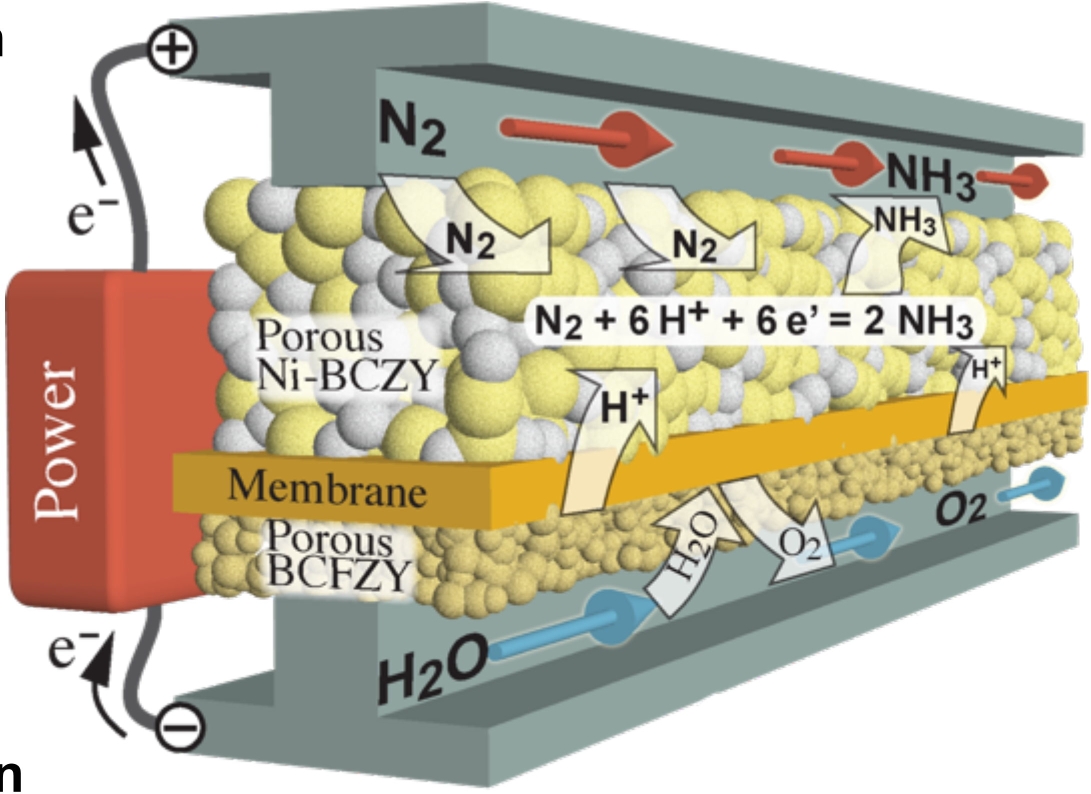
Projected production costs = \$557 / ton NH_3

We have built a kW-capacity pressurized test stand to explore stack performance at elevated pressure



The CSM-FCE team is making encouraging progress towards cost-competitive green ammonia production

- Proton-conducting ceramics
  - Efficient H_2 production
  - Scalable devices
- Ru – B2CA catalyst
  - Good performance at modest pressures
- Techno-economic analysis
  - Encouraging cost projections
- Going forward
  - Drive H_2O-electrolysis temperature down to NH_3-catalysis condition



Acknowledgements

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