# Protonic Ceramics for Energy Storage and Electricity Generation with Ammonia

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## Project goals:

Develop reversible proton-conducting ceramic cells that **synthesize ammonia** for energy storage, and also, **convert ammonia into electricity** for power generation.

## Technology development path:

1. Integrate ruthenium based catalyst within proton-conducting cells for ammonia production (energy storage mode) and decomposition (power production mode).

2. Develop reversible proton-conducting ceramic cells that convert ammonia into electricity for power generation, or synthesize ammonia for energy storage.

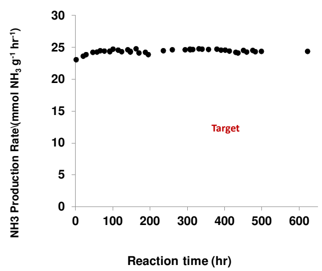
3. Develop fabrication processes for cost-effective manufacturing of scaled-up protonic ceramic cells.

4. Demonstrate operation of a proton-conducting stack prototype manufactured using commercially relevant processes.

5. Complete detailed techno-economic analyses that maximize the value proposition of the reversible ammonia system.

6. Pathways for proton-conducting ceramic technology applications for ammonia synthesis.

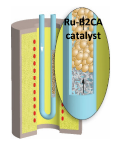
## 1. Ru- catalyst shows excellent stability over 600 hours of continuous operation




1wt%Ru supported catalyst developed by CSM

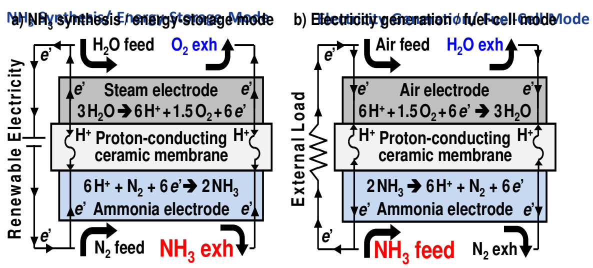
Catalytic tests: 30 psi, $3H_2$:$1N_2$

0.2 g catalyst diluted with 0.4 g $Al_2O_3$

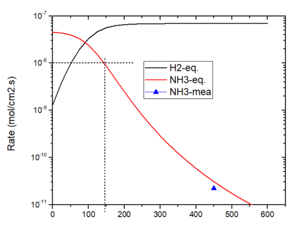



Packed-bed reactor

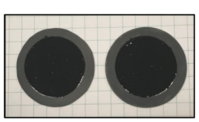
## 2. Cell Configurations: reversible operation




## 2.1 Ammonia-production cell with integrated catalyst in $NH_3$ electrode



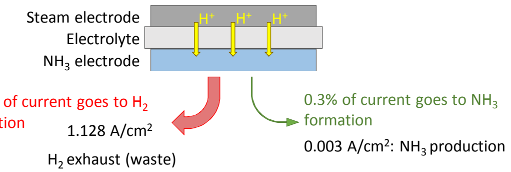

Proton-Conducting Cell



## 2.2 Original design: efficiency and production are limited by low equilibrium conversion

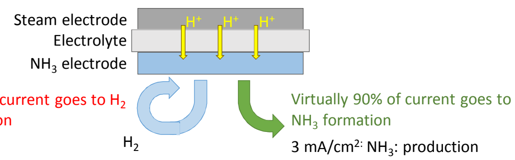
Our target of 1 x 10$^{-8}$ mol $NH_3$ / cm$^2$·s

- Most $H^+$ flux goes to $H_2$ due to low equilibrium-conversion rate.
- $H_2$ is swept out with exhaust gas.




## 2.3 Efficiency is greatly improved by $H_2$ recirculation

- Run high current at startup to generate excess $H_2$, then recirculate.
- At steady state, provide only enough current to replenish consumed $H_2$.




## 2.4 Comparisons of results with references reflect CSM's record-high $NH_3$-production rates

Table. Summary of ammonia production rate from literature studies and the recent CSM work

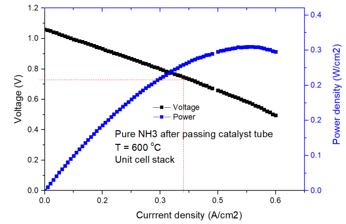
| Materials Set: Steam Electrode \| Electrolyte \| $NH_3$ Electrode | $NH_3$ production rate (mol·S$^{-1}$·cm$^{-2}$) | Conversion efficiency (%) | Temp. (°C) |
|---|---|---|---|
| Pd \| $SrCe_{0.95}Yb_{0.05}O_{3-\delta}$ \| Ru [1] | 9.10 x 10$^{-14}$ | ~0.00015 | 650 |
| LaCsFeNi \| (Li,Na,K)$CO_3$-GDC \| LaCsFeNi [2] | 1.20 x 10$^{-10}$ | 0.06 | 400 |
| Pt \| BZY \| Pt [3] | < 1 x 10$^{-12}$ | < ~0.006 | 550 |
| LSCF \| BZY \| LSCF [3] | 8.50 x 10$^{-11}$ | 0.33 | 550 |
| CSM Electrolyte supported \| electrolysis | 3.29 x 10$^{-11}$ | 0.06 | 600 |
| CSM Anode supported \| electrolysis | 8.74 x 10$^{-9}$ | TBC* | 600 |
| CSM Anode supported \| electrolysis \| cylinder gas | 4.06 x 10$^{-8}$ | TBC | 600 |
| CSM Reactor: cylinder gas only | 9.65 x 10$^{-7}$ | TBC | 500 |

[1] A. Skodra, M. Stoukides, *Solid State Ionics* 180 (2009) (23) 1332.
[2] R. Lan, K.A. Alkhazmi, I.A. Amar, S. Tao, *Electrochimica Acta* 123 (2014) 582.
[3] D.S. Yun, J.H. Joo, J.H. Yu, H.C. Yoon, J.-N. Kim, C.-Y. Yoo, *Journal of Power Sources* 284 (2015) 245.

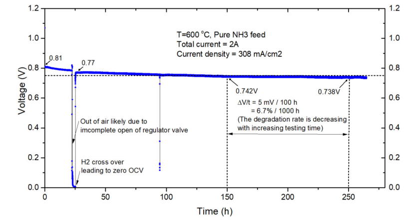
* TBC: to be calculated

## 2.5 Excellent performance from an $NH_3$-fueled unit-cell stack

$NH_3$ passes through Ru catalyst
400 mA / cm$^2$ at 0.75 V, 600°C




Only stack-level $NH_3$-fueled PCFC result ever reported.
Electrolysis Performance: > 250h steady state



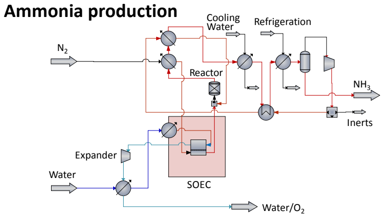

## 3. & 4. Established success in scale-up, manufacturing & commercialization of fuel-cell and allied electrochemical systems

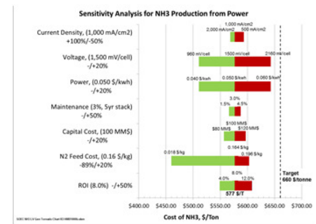



- Pilot manufacturing of solid oxide fuel cell (SOFC) and stacks.
- Tape casting/screen printing/co-firing fabrication process has been scaled up to 1000 cm$^2$.
- Production volumes of 500 kW annually.

## 5. Techno-economic analyses: FCE evaluates value proposition of reversible $NH_3$ cells

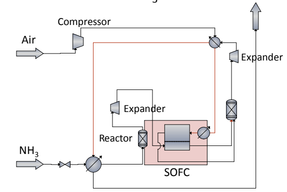
### Ammonia production

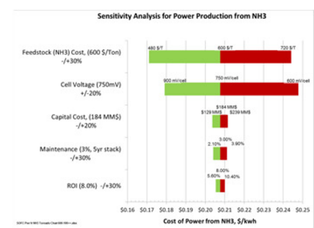


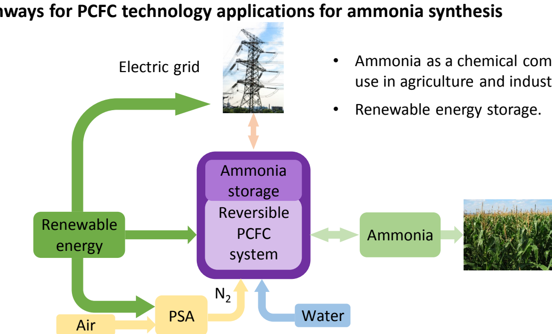

### Power Production

Economic $NH_3$ with Low Cost Power




## 6. Pathways for PCFC technology applications for ammonia synthesis




- Ammonia as a chemical commodity for use in agriculture and industry.
- Renewable energy storage.