Protonic Ceramics for Energy Storage and Electricity Generation Using Ammonia

Hossein Ghezel-Ayagh

May 7, 2021

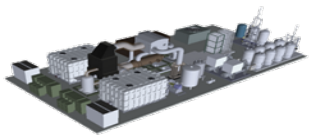
FuelCell Energy: A Global Leader in Fuel Cell Technology - Established in 1969

Company Overview

- FuelCell Energy (FCE) delivers clean and affordable fuel cell solutions for the supply, recovery and storage of energy
- Turn-key solutions from design and installation of a project to long-term operation and maintenance of fuel cell system

Products

Distributed Generation | **Distributed Hydrogen** | **Hydrogen & Energy Storage** | **Carbon Capture**

fuelcellenergy + ExxonMobil

- Advanced technologies include carbonate fuel cell-based CO_2 capture systems, and solid oxide systems for power generation, electrolysis, and hydrogen-based energy storage

Global Customers

Pfizer, ExxonMobil, Toyota, City of Tulare, Port of Long Beach, LIPA, City of Riverside, Federal Ministry of Education and Research, American Electric Power, Pepperidge Farm, Radisson Blu, Hartford Hospital – Connect to healthier., Yale, Friatec, AVANGRID, Pacific Gas and Electric Company, ICOSPO, Southern California Edison, e.on, cmeec, Clearway Energy

Over 250 MW Operating on 3 Continents

Grid Support with CHP

- 20 MW site built in 2018
- Power sold to grid
- Heat sold to district heating

Resiliency for Pharmaceutical

- 5.6 MW w/steam for company use
- Reliable power solving local grid instability

Grid Support / Urban Upgrade

- 15 MW on 1 ½ acres
- Power sold to grid
- 12 mo. Installation

Fuel Cell / Solar Integration

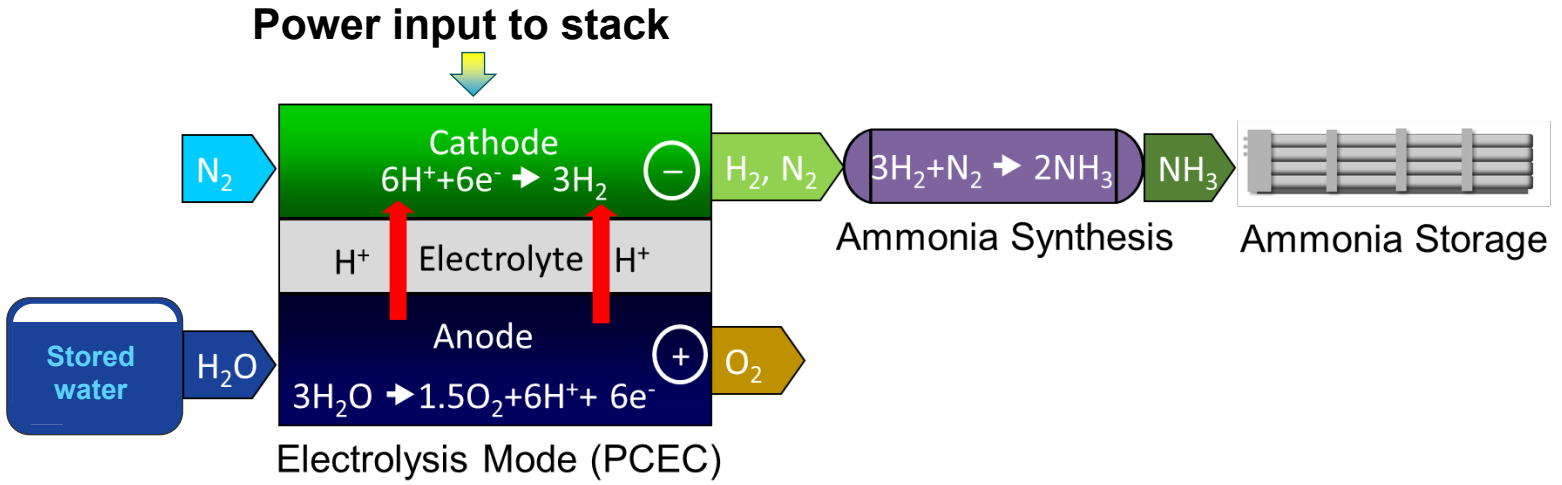
- 2.8 MW fuel cell on ¼ acre
  - *~23,000 MWh annually*
- 2.2 MW solar on ~9 acres
  - *~3,000 MWh annually*

Enable The World To Live A Life Empowered By Clean Energy

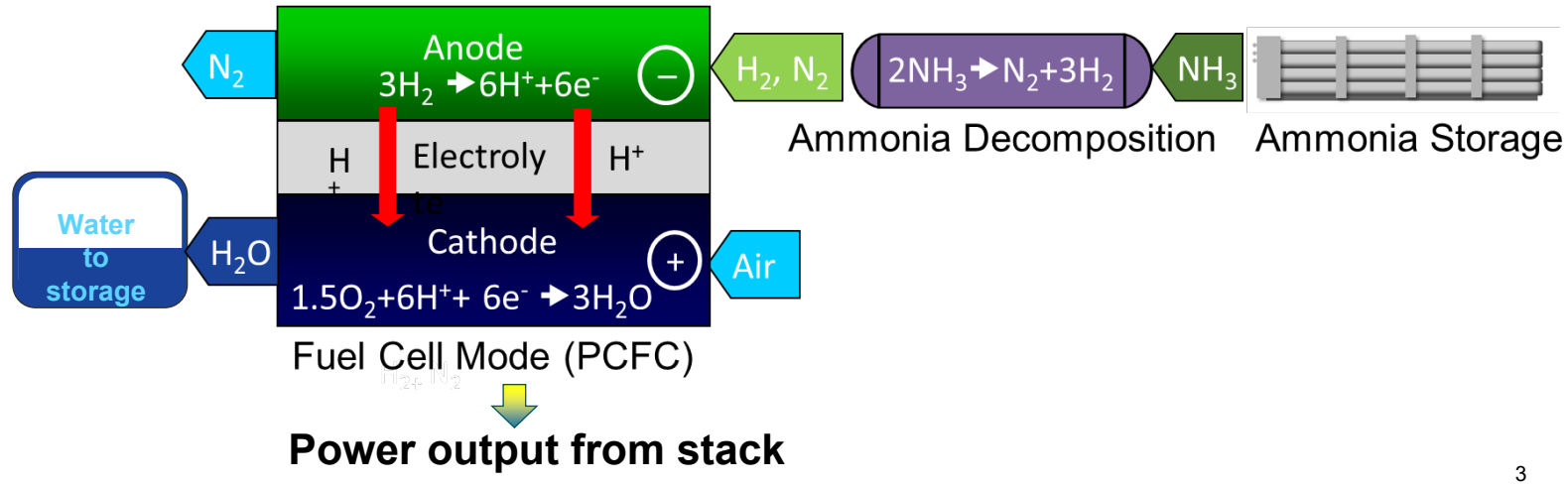
Ammonia Based Energy Storage Using Proton Conducting Ceramic Cells

- Protonic ceramic cells have demonstrated capability to run in **electrolysis mode (PCEC)** and **fuel cell mode (PCFC)**, and the ability to switch in between the two
- Protonic ceramic cells run more efficiently than conventional low temperature electrolysis, and operate with high efficiency in power generation
- Protonic ceramic stacks with ammonia and water storage are an advanced energy storage approach:
  - High round-trip system efficiency
  - Long duration achieved by adding low-cost ammonia and water storage capacity, without the need to add more stacks

Charging in electrolysis mode:

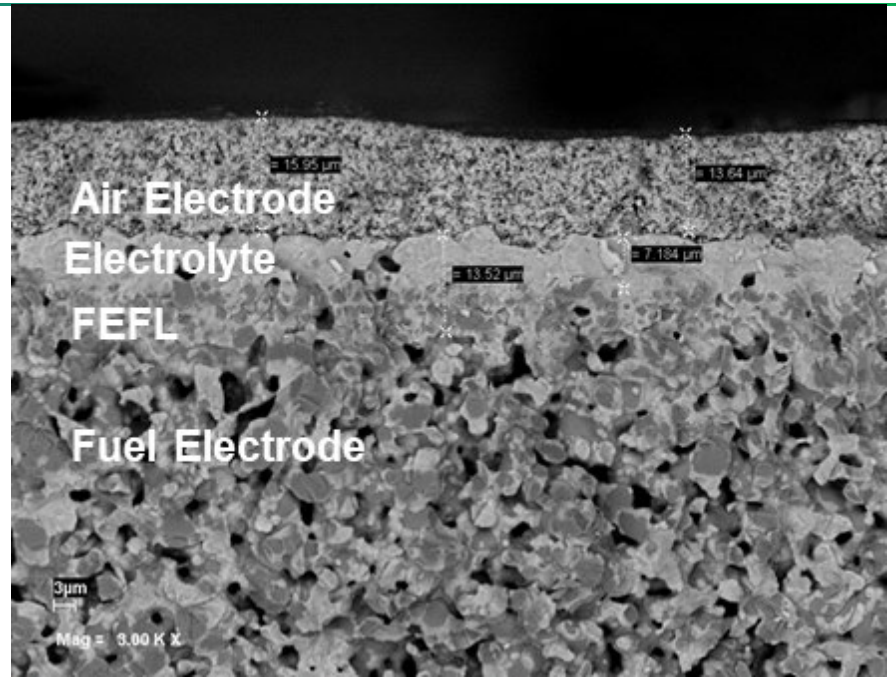


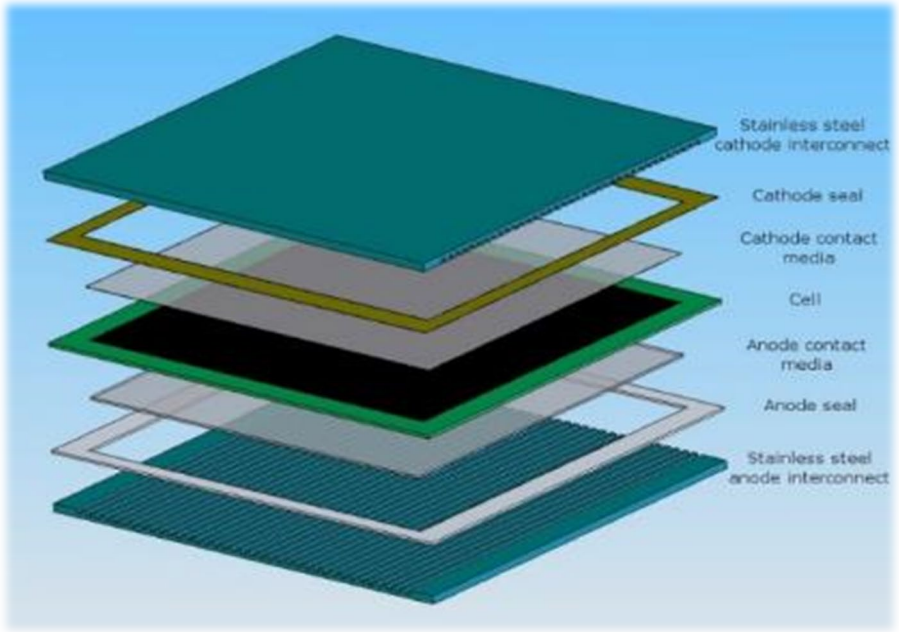
Discharging in fuel cell mode:



Proton Conducting Ceramic Cell Technology

- Fuel electrode-supported cell
- 0.5 to 1.5 mm fuel/H_2 electrode:
  BCZYYb4411 ($BaCe_{0.4}Zr_{0.4}Y_{0.1}Yb_{0.1}O_{3-\delta}$) / Ni
- ~15 micron fuel electrode functional layer (BCZYYb4411 / Ni)
- ~10 micron electrolyte (BCZYYb4411)
- 10 - 50 micron air/steam electrode:
  - BCFZY ($BaCo_{0.4}Fe_{0.4}Zr_{0.1}Yb_{0.1}O_{3-\delta}$) / BCZYYb-4411
- 16 to 81 cm^2 active area





- Development of Proton conducting cell technology is conducted in collaboration with Colorado School of Mine (CSM)

SCHOOL OF MINES 1874 COLORADO

CFCC Colorado Fuel Cell Center

Solid Oxide Manufacturing and Testing Capabilities

- Cell fabrication processes are flexible & scalable to high volume and low-cost production

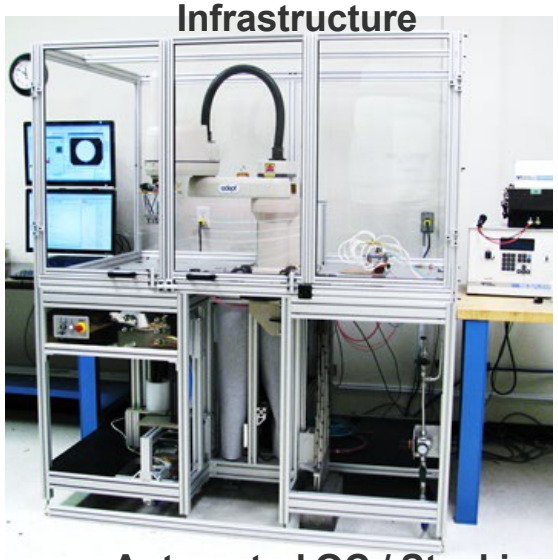
Tape Casting

Automated Screen Printing

Conditioning & Test Infrastructure

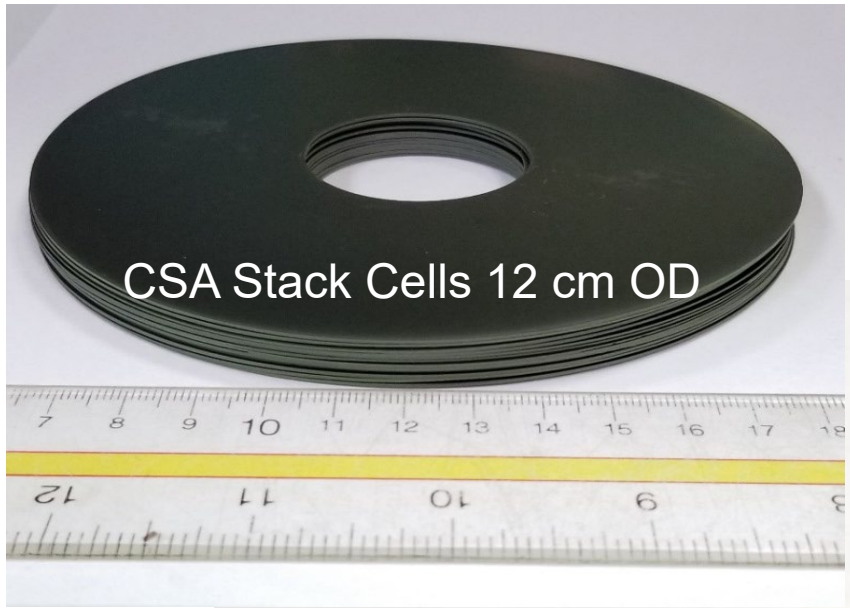
3000 m^2 facility with pilot cell / stack production, R&D and extensive 33 test stand capability (Calgary, AB)

Sintering

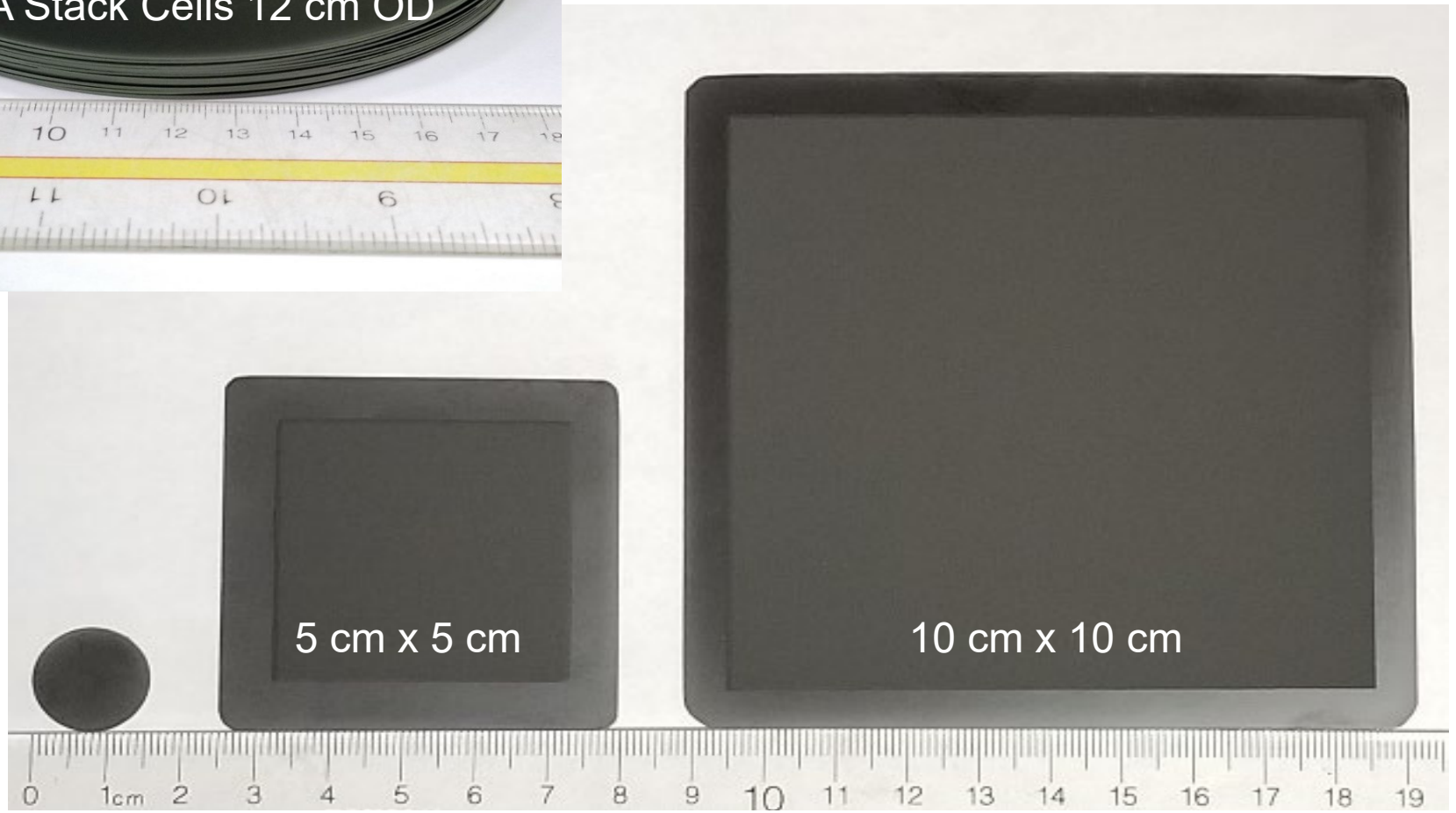


Automated QC / Stacking

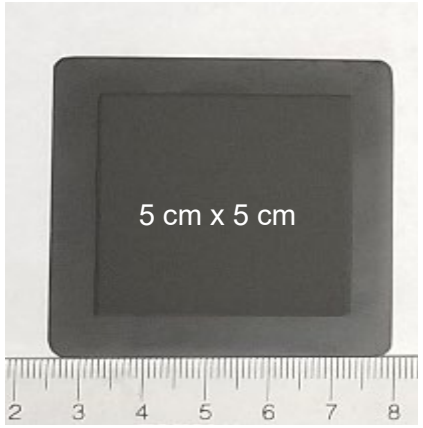
Proton-Conducting Cell Scale-Up



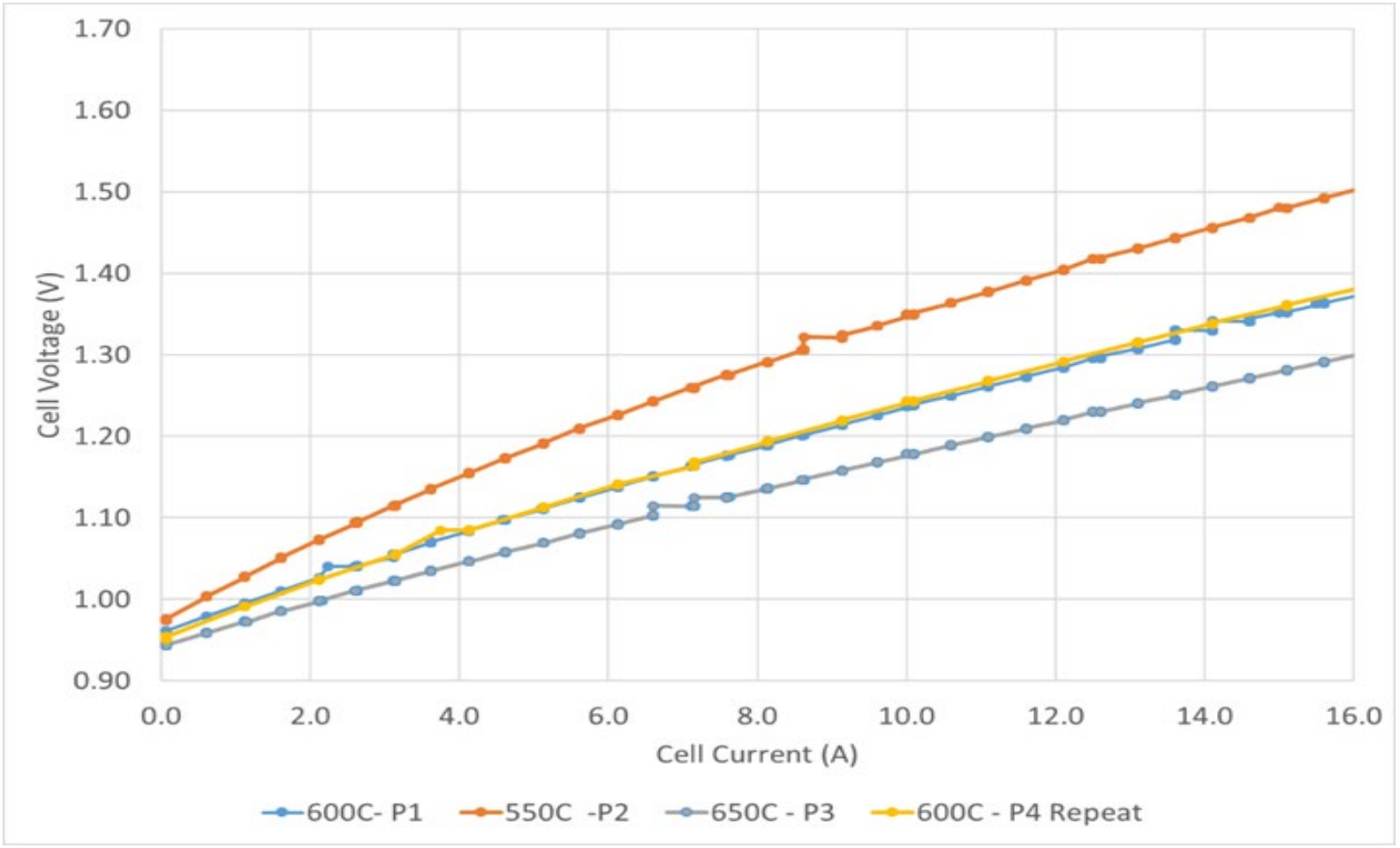
- Cells have been successfully scaled up to 10 cm x 10 cm single-cell and stack cells have been prepared for demonstration purposes



Performance Test of 5cmx5cm BCZYYb-4411 Cell in Electrolysis Mode

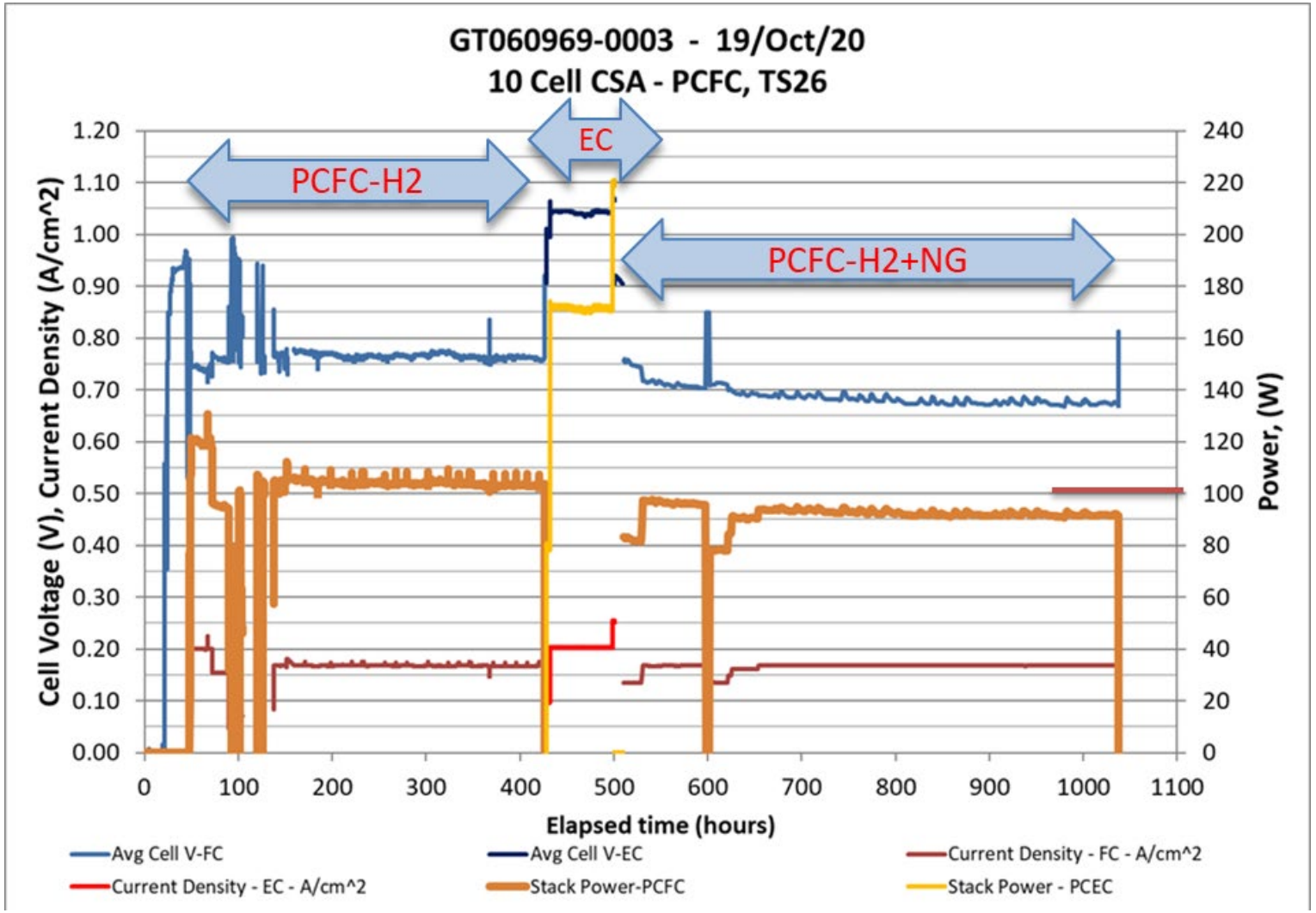


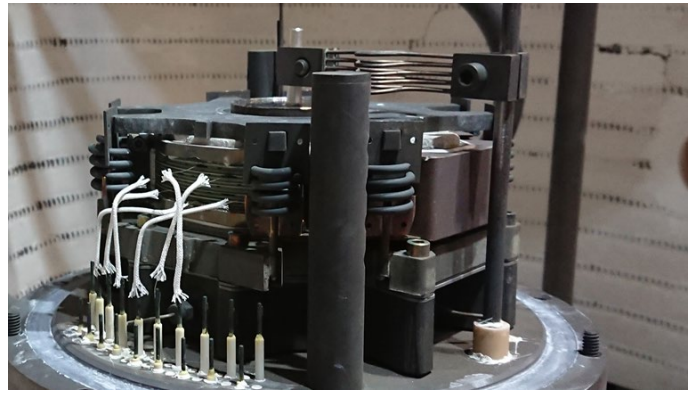
Active Area 16 cm^2



- **Cell performance using composite steam electrode:**
  - 80 wt-% BCFZY ($BaCo_{0.4}Fe_{0.4}Zr_{0.1}Y_{0.1}O_{3-\delta}$)
  - 20 wt-% BCZYYb-4411 ($BaCe_{0.4}Zr_{0.4}Y_{0.1}Yb_{0.1}O_{3-\delta}$)

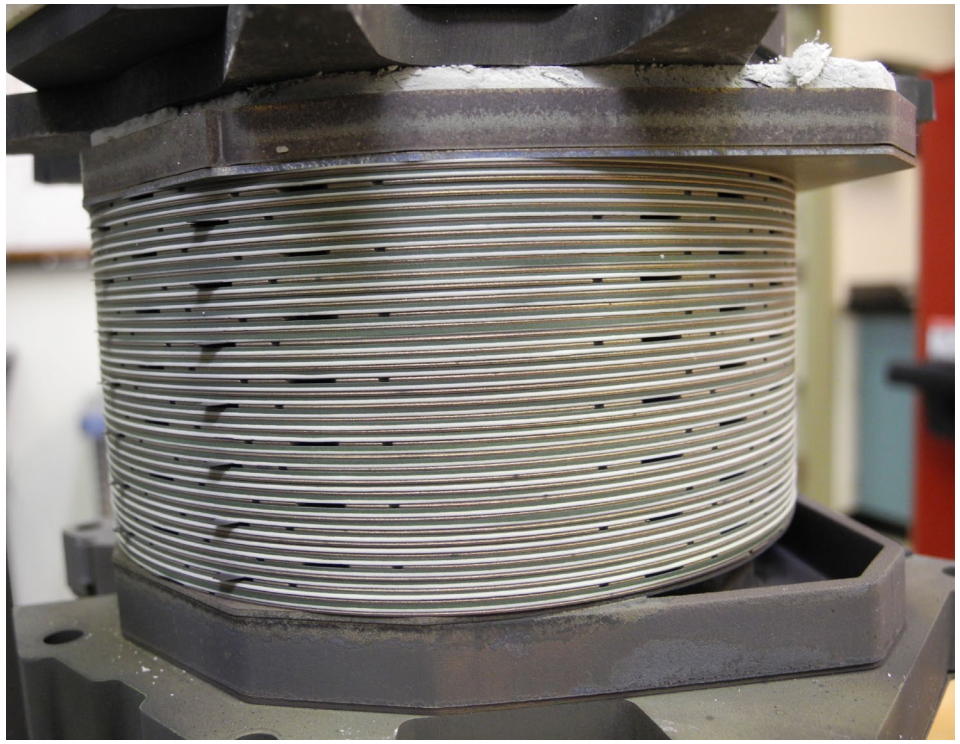
10-cell CSA PCFC Test Overview

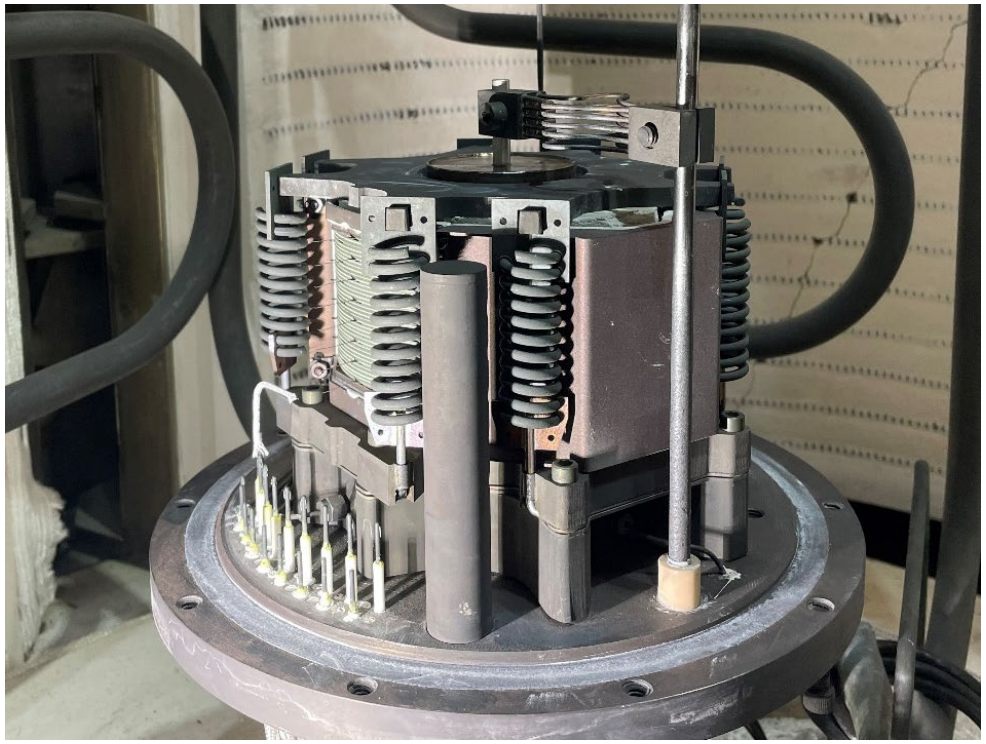




Completed > 1000 hours of testing, both in Fuel Cell as well as Electrolysis modes

35-cell Proton Conducting Stack



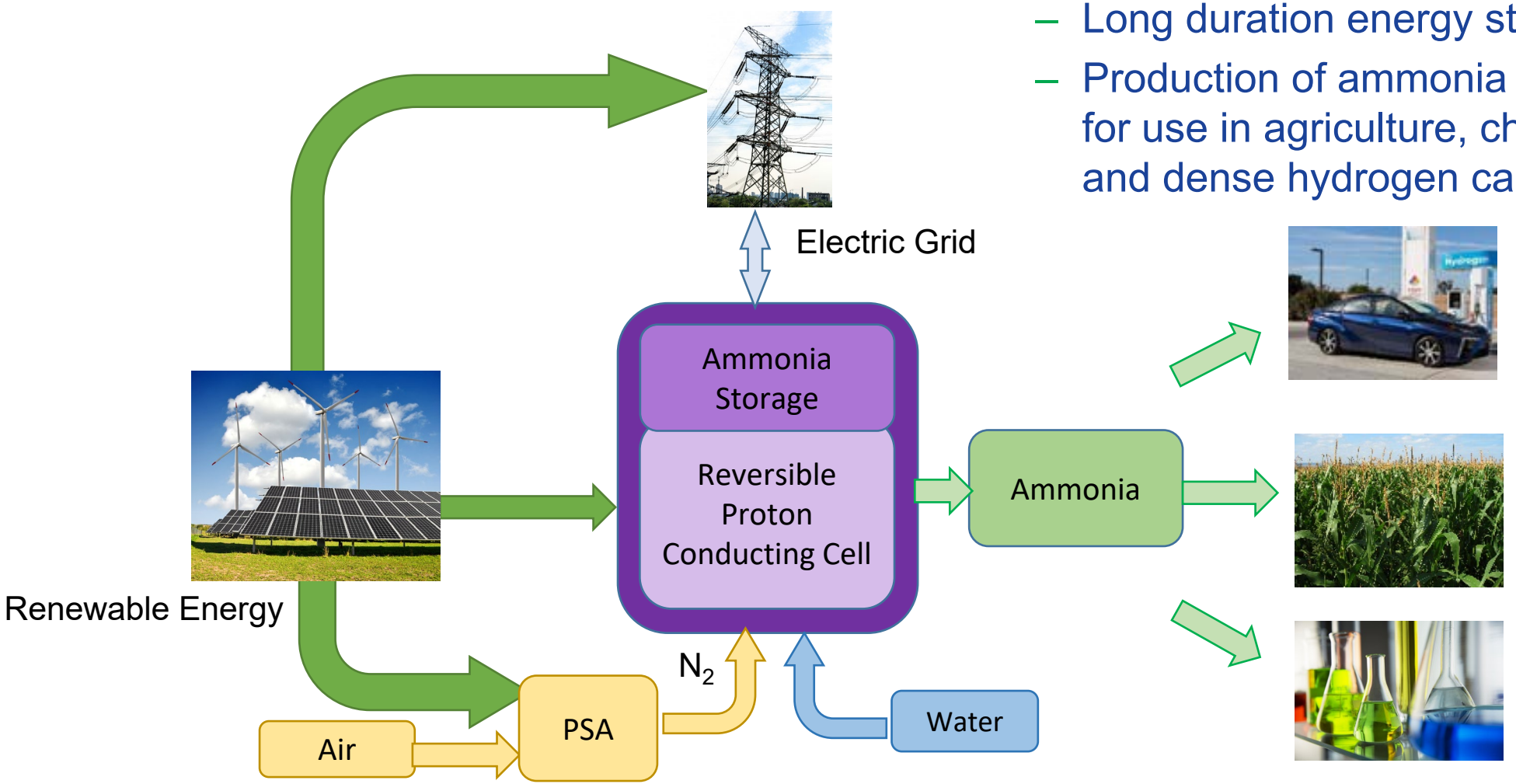


35-cell PCEC Stack – Core (Left) and Stack in Test Stand (Right)

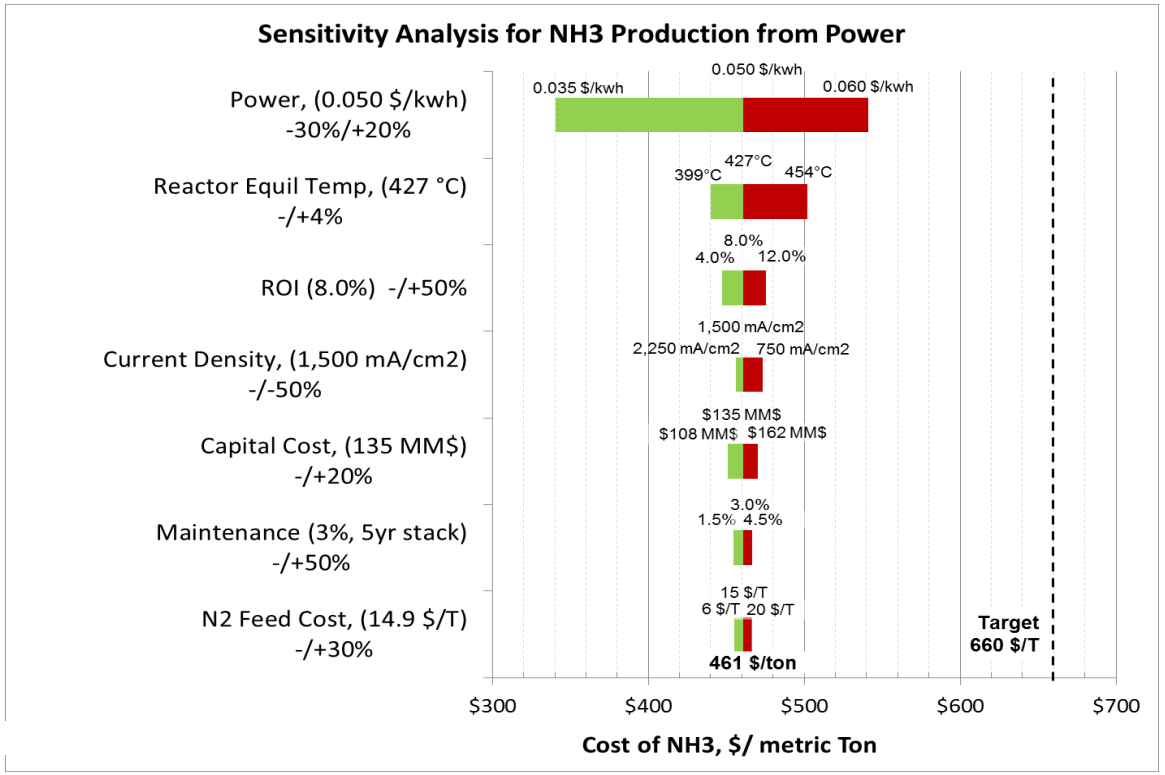
CSA Cell Count	Current Density	Stack Current	H2 Production	H2 Production @ 95% FE
[#]	[A/cm^2]	[A]	g H2/day	g H2/day
35	1	81	2,559	2,431

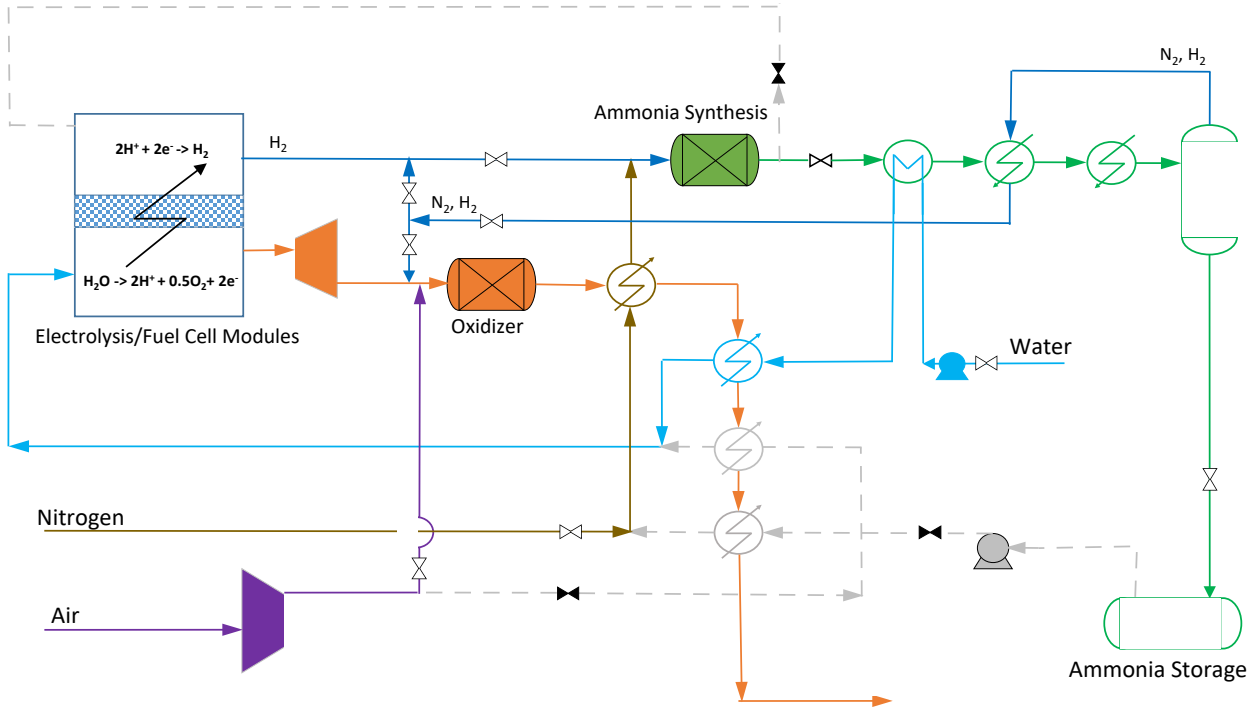
Market Strategies for Carbon Neural Ammonia

- Pathways for PCEC/PCFC technology applications in ammonia synthesis/use:
  - Long duration energy storage
  - Production of ammonia as a commodity for use in agriculture, chemical industry, and dense hydrogen carrier (H2@Scale)



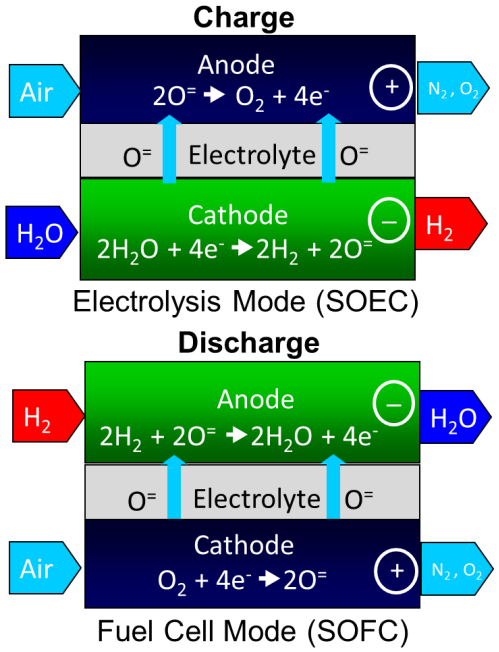
Ammonia Production Cost Analysis (1000 ton/day Capacity)





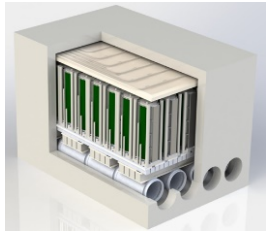
- System cost estimation resulted in ammonia production at $460 per metric ton, well below the $660 per ton (equivalent to 13 cents/kWhr) ARPA-E target

Solid Oxide Applications



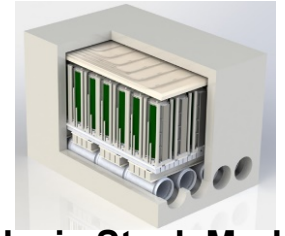
Compact SOFC Architecture (CSA) Stack

CSA is FCE's trade name for solid oxide stacks used for power generation, electrolysis, and energy storage applications

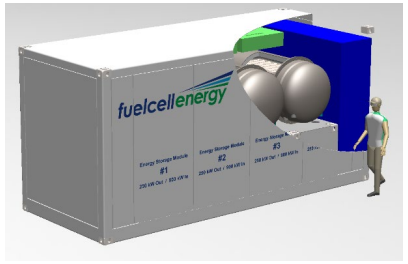


Power Generation Stack Module – Only runs in power generation mode on natural gas fuel

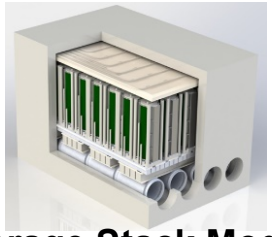
Power Generation System



Electrolysis Stack Module – Produces hydrogen from steam with power input



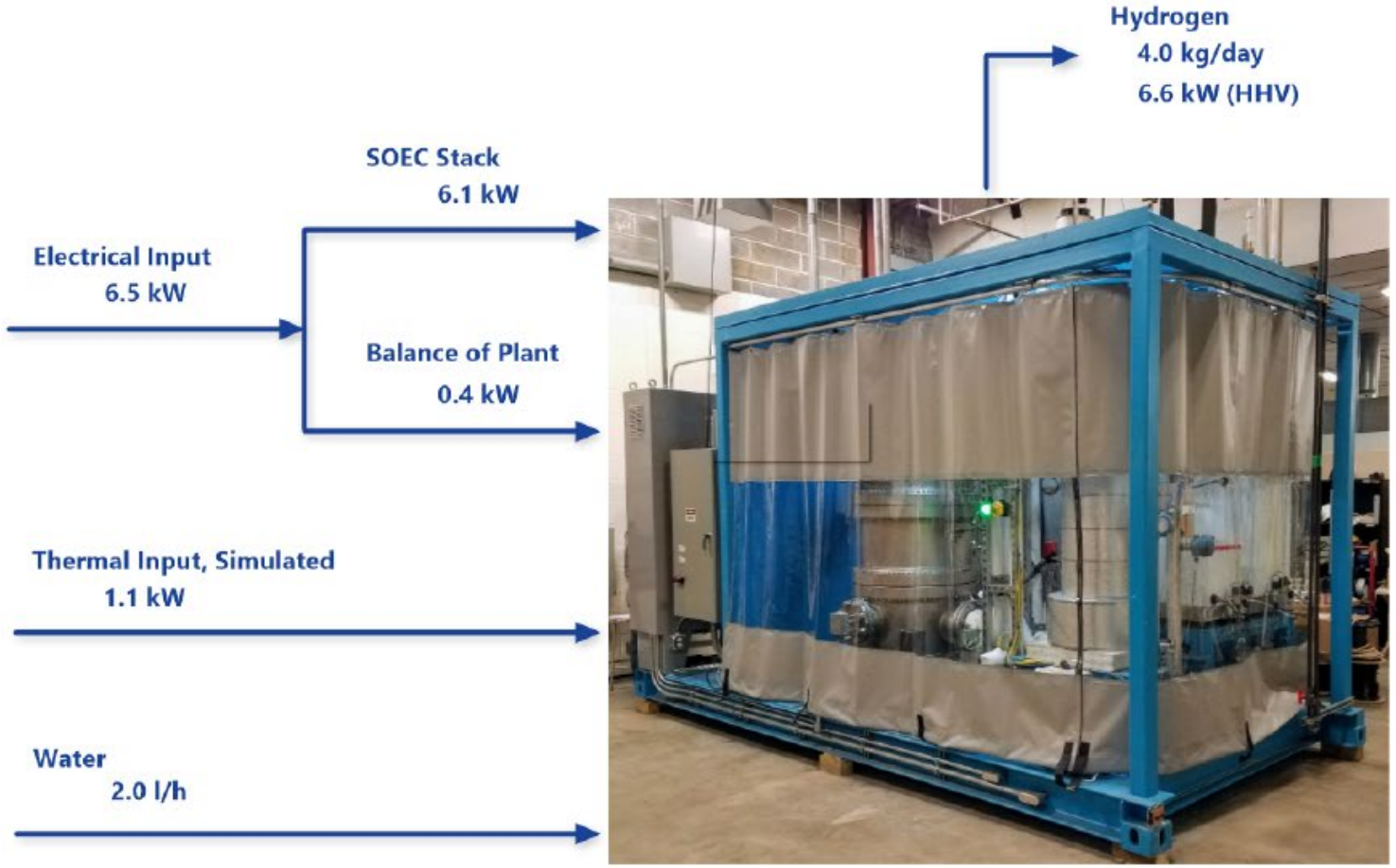
Electrolysis



Energy Storage Stack Module – Alternates between power generation on hydrogen fuel and electrolysis producing hydrogen from water

Energy Storage System

4kg H_2/day Solid Oxide Electrolysis Pilot System Performance



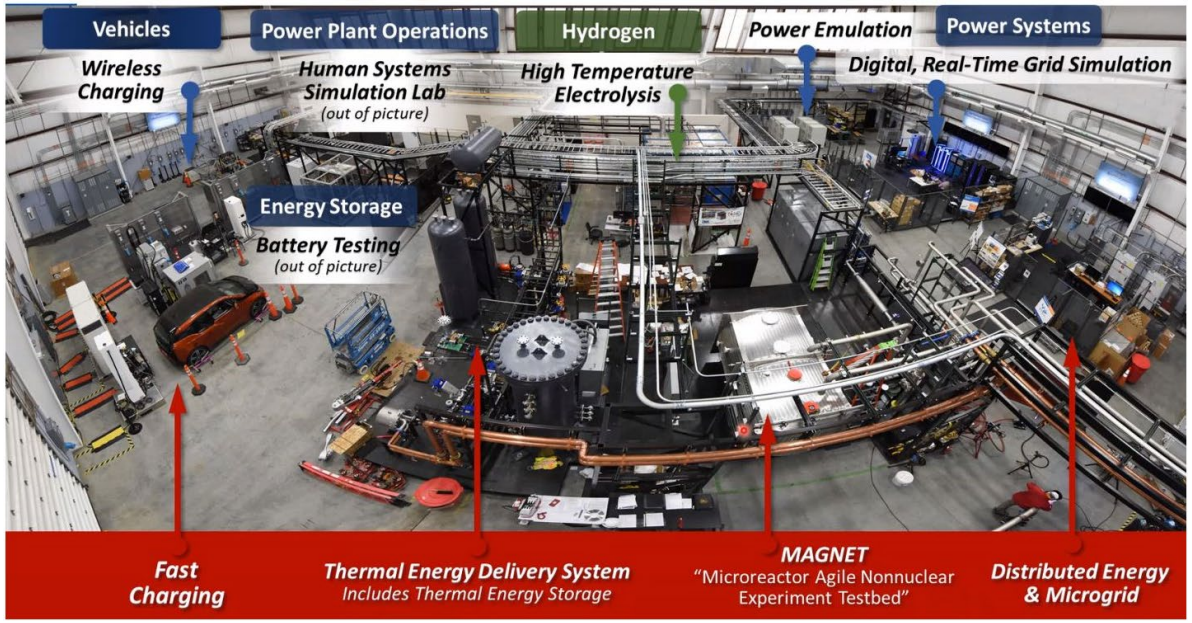
System Performance Parameter	Value
Stack Electrical Efficiency (HHV)	110.2 %
System Electrical Efficiency (HHV)	100.7 %
System Total Efficiency (HHV)	86.4 %
Electricity Consumption	39.2 kWh/kg
Thermal Consumption, Simulated	6.5 kWh/kg
Total Energy Consumption	45.6 kWh/kg

- ***Achieved system electrical efficiency of ~ 100% (HHV Hydrogen) in the pilot scale system tests***

250kW Solid Oxide Electrolysis Demonstration System

- Demonstration of high efficiency prototype system at Idaho National Laboratory (INL) at nuclear plant operating modes, including thermal energy support for ultra high efficiency electrolysis
- 150 kg/day Hydrogen production from 270kW (or 250kW with thermal input)
- Will demonstrate high efficiency without thermal input, and up to 100% efficiency with thermal input

- ***Packaged prototype of module repeated in larger systems***



Idaho National Laboratory Test Facility

Stack Operating Pressure	5 Bara (60 psig)
Product Hydrogen Pressure	22 Bara (300 psig)
Product Composition	99.95% H_2, 0.05%H_2O
System Efficiency	78% LHV, 92% HHV
System Electrical Consumption	42.7 kWh/kg

Thank You

Contact:
Hossein Ghezel-Ayagh
Email: hghezel@fce.com

fuelcellenergy

A Leader in **Sustainability and Environmental Stewardship** using advanced technology platform solutions