Solid Oxide Electrolysis System Demonstration

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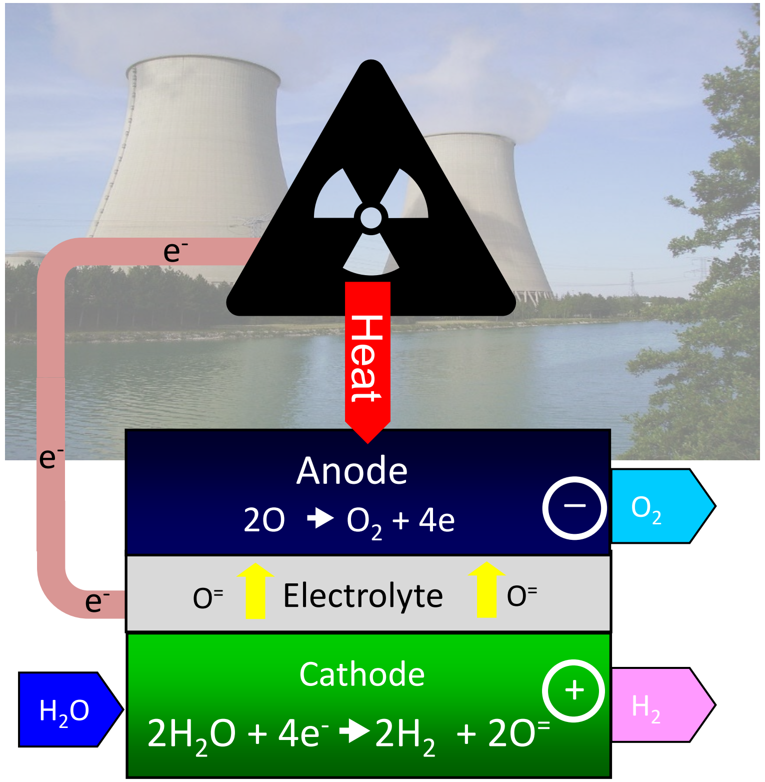
DOE Hydrogen Program
2021 Annual Merit Review and Peer Evaluation Meeting

Project ID# TA039

Project Goal

- The goal of this project is to validate that the integration of high temperature solid oxide electrolysis technology with nuclear plants will result in high efficiency and low-cost alternative for production of hydrogen utilizing electricity and waste heat from the power plant



Solid Oxide Electrolysis Cell (SOEC)

Overview

Timeline and Budget

- Project Start Date: 10/1/2020
- Project End Date: 9/30/2021
- Total Project Budget: $10,500,000
  - Total Recipient Share: $2,500,000
  - Total Federal Share: $8,000,000
  - Total DOE Funds Spent*: $0
  - Total Cost Share Funds Spent*: $0

* As of 3/31/2021 the project is a conditional award pending successful negotiations between FCE and DOE

Barrier

- Key barriers addressed in the project are:
  - F. Capital Cost
  - G. System Efficiency and Electricity Cost
  - L. Operations and Maintenance

Partner

- FuelCell Energy (FCE) – Project Lead
- Versa Power Systems (VPS)
- Idaho National Laboratory (INL)

Relevance and Impact Potential

Project objectives relate to the hydrogen production subprogram of HFTO by addressing the technology validation at a pilot scale and operational verification of the solid oxide electrolysis integrated with a nuclear plant

Project Objectives:

- Validate SOEC technology performance and reliability for steam electrolysis and hydrogen production
- Develop and verify nuclear industry specific system operational and control strategies in a packaged electrolysis system
- Demonstrate key features of the SOEC electrolysis systems, i.e. high electric efficiency and waste heat utilization, in a 250kW class unit prototypical of larger scale systems suitable for integration with nuclear plants
- Provide the data necessary to valorize the integration of SOEC systems in the LWR (Light Water Reactor) facilities for increasing their operational flexibility and profitability by switching between electricity production and hydrogen generation

Relevance

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Technology Development Approach

Technical approach includes design, build and test a 250kW (input) steam electrolysis system using hardware-in-the-loop simulation of nuclear plant operation

Design

- Develop process, mechanical and electrical designs of a 250kW steam electrolysis protype unit
- Develop balance of plant equipment design for the 250kW system including heat exchangers, steam generator, and rectifier for ac-to-dc conversion
- Complete design of SOEC stack module hardware for housing > 12 electrolysis stacks
- Prepare 3-D CAD and fabrication drawings for construction of the >250kW steam electrolysis demonstration unit

Build

- Fabricate the electrolysis stack module consisting of pressure vessel, thermal insulation, electric power take-offs, instrumentation, support structure, and gas distribution conduits
- Fabricate the balance-of-plant process equipment and electrical/control system hardware
- Develop control strategies and software for the 250kW electrolyzer include HMI (Humane Machine Interface), data-base of test results and sensors data, safety alarm tags and limits, and control loop algorithms

Test

- Perform system factory tests and commissioning
- Perform operational tests of the 250 kW demonstration unit at Idaho National Laboratory (INL) using controller hardware-in-the-loop (CHIL) combined with High-Level front-end Controller (HLC) simulating communications from a nuclear plant and electric grid

T2M

- Conduct Techno-economic Assessment (TEA) of large-scale electrolysis systems of up to 500MW based on the cost/performance of the 250kW SOEC demonstration unit and operation data acquired from the tests at INL

Approach

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Budget Period 1 (BP1) Milestones

Milestone Type (Milestone, Go/No-Go Decision Point, End of Project Goal)	Milestone Number* (Go/No-Go Decision Point Number)	Milestone Description (Go/No-Go Decision Criteria)	Anticipated Date (Months from Start of the Project)	Anticipated Quarter (Quarters from Start of the Project)	Status
Milestone	M 1.1.1	Acquisition of major raw materials to initiate cell fabrication completed	M2	Q1	
Milestone	M 1.1.2	≥ 50% of Cell subcomponents fabrication for use in stacks completed	M4	Q2	
Milestone	M 1.1.3	Electrochemical cell fabrication for integration in stacks completed	M6	Q2	
Milestone	M1.2.1	Fabrication of the stacks to be included in the 250kW system completed	M7	Q3	
Milestone	M2.1.1	Final 3-D CAD stack module design completed	M2	Q1	
Milestone	M2.1.2	Module assembly fabrication drawing completed	M3	Q1	
Milestone	M2.2.1	Final Process Flow Diagram (PFD) prepared	M2	Q1	
Milestone	M2.2.2	250kW system process design including equipment specification completed	M2	Q1	
Milestone	M2.2.3	250 kW system packaged mechanical layout including detailed component assemblies, instrumentation, and skid completed	M4	Q2	
Milestone	M2.2.4	250 kW system electrical design including detailed wiring diagrams and equipment specifications completed	M6	Q2	
Milestone	M2.3.1	INL's facility design modifications to accommodate installation of the 250 kW electrolysis system completed	M8	Q3	

Approach

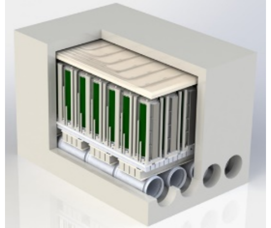
Budget Period 1 (BP1) Milestones (Continued)

Milestone Type (Milestone, Go/No-Go Decision Point, End of Project Goal)	Milestone Number* (Go/No-Go Decision Point Number)	Milestone Description (Go/No-Go Decision Criteria)	Anticipated Date (Months from Start of the Project)	Anticipated Quarter (Quarters from Start of the Project)	Status
Milestone	M3.1.1	Electrolysis stack module fabrication completed ready for installation of SOEC stacks	M6	Q2	
Milestone	M3.2.1	Balance of Plant components fabrication completed ready for installation of SOEC stacks	M6	Q2	
Milestone	M4.1.1	Control philosophy and the associated control software completed	M8	Q3	
Milestone	M4.2.1	Stack Module assembly including installation of SOEC stacks and instrumentation completed	M7	Q3	
Milestone	M4.2.2	250kW electrolysis system assembly including integration of BoP components and stack module completed	M8	Q3	
Milestone	M4.3.1	250kW electrolysis system commissioning and factory acceptance tests completed	M10	Q4	
Go/No-Go Decision Point	G-n-G 1	System design completed and the main components and stacks ready for system and module assembly	M10	Q4	

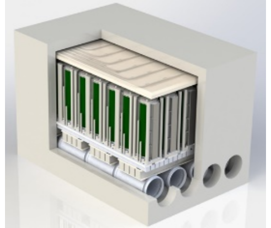
Approach

Unified Solid Oxide Cell Stack Technology

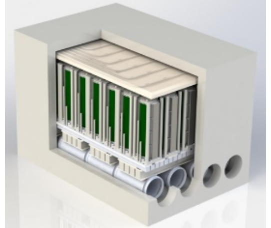
SOFC Stack



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

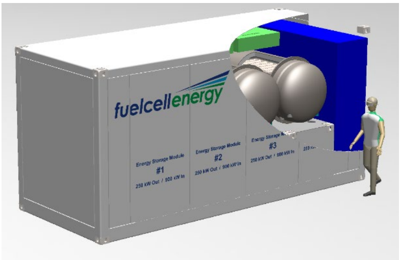


Electrolysis Stack Module – Produces hydrogen from steam with power input



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

Power Generation System

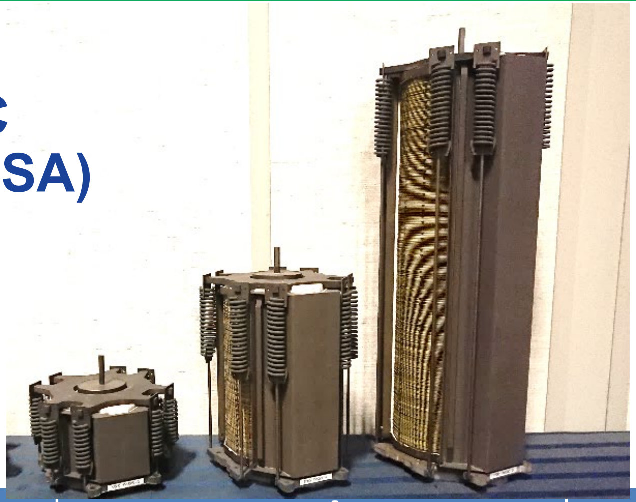


Electrolysis
4,000 kg/day H2 from 7.3MW

Energy Storage System
1MW, 8MWh

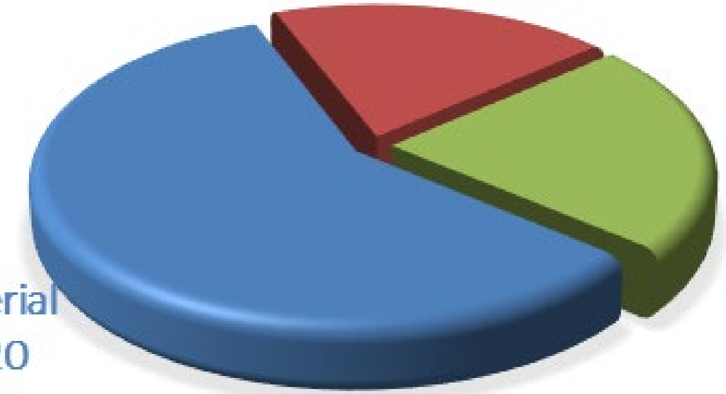
Background: Electrolysis Stack Technology

- **Compact SOEC Architecture (CSA) Platform**



Property	Scale			Comments
		Mid		
Cell count				
Stack voltage, V		193	450	At 1.285 V/cell
Stack Power, kW	4.7	15.6	36.4	At -1 A/cm^2
Hydrogen Production, kg/day				
Height, mm (in)	91 (3.6)	211 (8.3)	440 (17.3)	

Estimated CSA stack cost ~ $900 @ 140,000 stacks/year



SOEC Cost @ 1.0 A/cm^2 = $25/$kWe_{in}$

Full height CSA stack can produce >25kg H_2/day with estimated cost of $25/kW at high volume production

Background: Pilot System Demonstration

- FCE has built and operated a brass-board >4 kgH_2/day SOEC system under a DOE/EERE project (DE-EE0007646)
- The pilot unit has the key balance-of-plant equipment similar to a commercial plant and is utilized to study the performance of SOEC stacks

Parameter	Value
Cell Voltage	1.285 V/cell
Current Density	~1 A/cm^2
Operating Temperature	700-750°C
Operating Pressure	5 Bara (60 PSIG)
Flush Gas Inlet	Air
Flush Exhaust Composition	60% N2, 40% O2
Inlet Composition	50% H2, 50% Steam
Steam Utilization, stack	60%
Steam Utilization, system	88%

Nominal system operating conditions selected to achieve project objectives for efficiency with acceptable stack life

System Parameter	Performance
Stack Electrical Eff (LHV)[1]	97.5%
System Electrical Eff (LHV)[1]	90.9%
System Total Eff (LHV)[1]	78.0%
Electricity Consumption [2]	36.8 kWh/kg
Thermal Consumption (kWh/kg)	5.9 kWh/kg
Total Energy Consumption[1]	42.7 kWh/kg

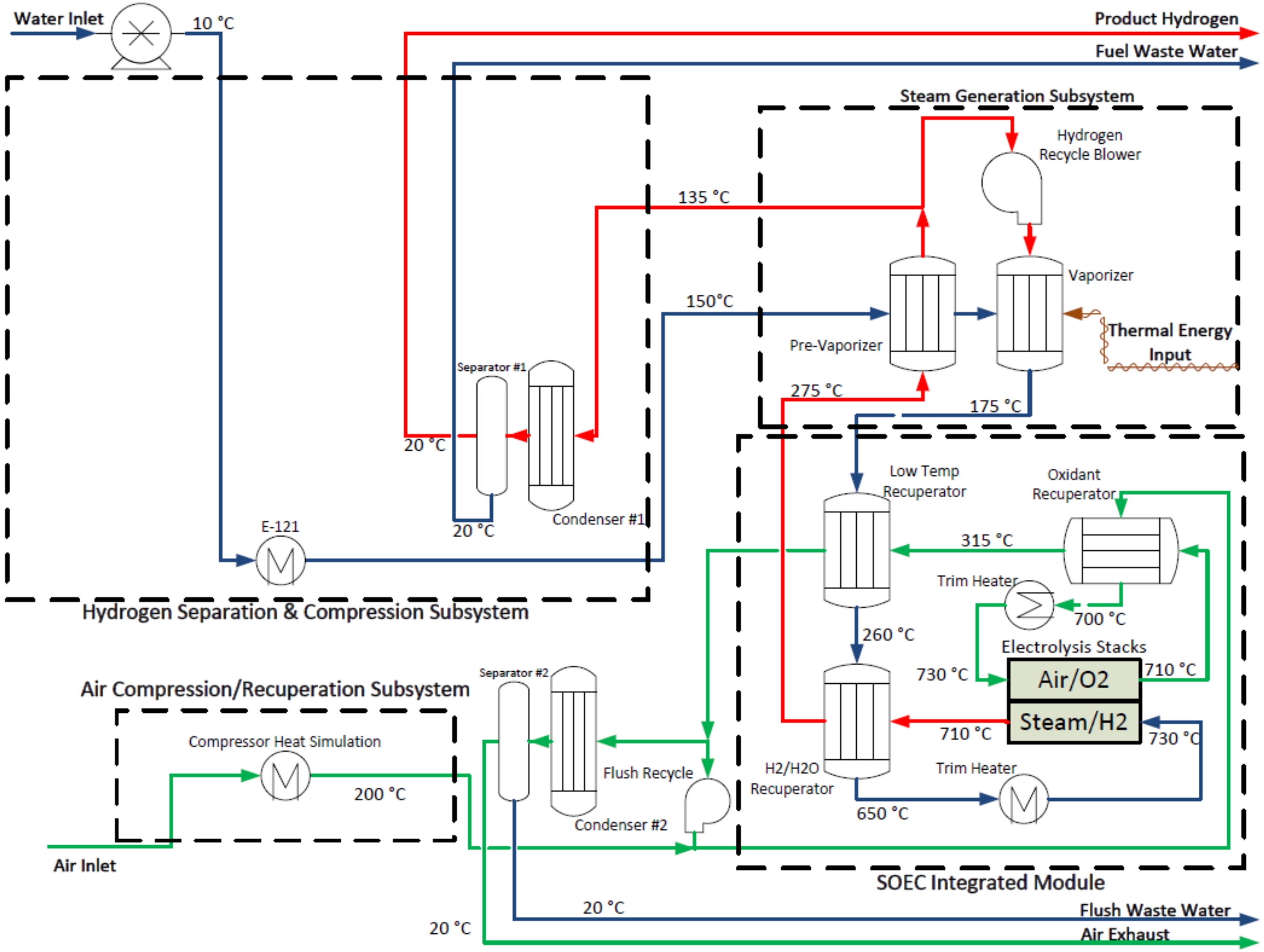
[1] Based on 98% rectifier efficiency, other BoP efficiency also included (motor efficiency, etc)
[2] Total electrical consumption includes stack, BoP, and high temperature thermal input

Background: Pilot System Design

System Characteristics:

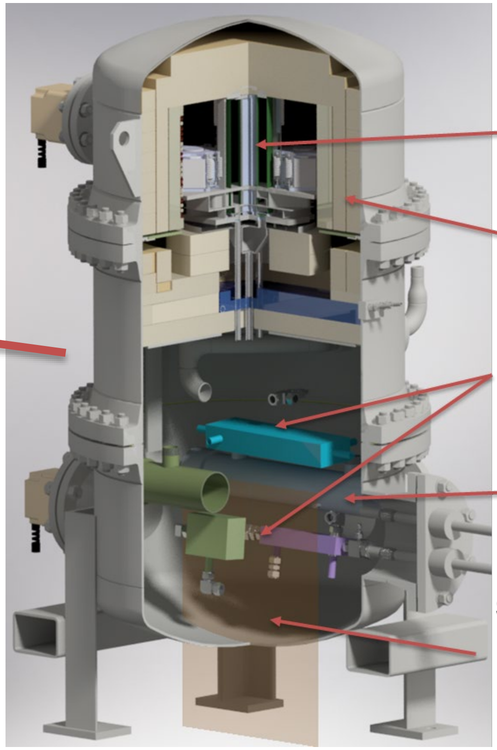
- Nominal 4 kg/day (flexible to achieve up to 20 kg/day)
- 7-32 kWe input
- Water balance measurement
- 1-5 Bara operation
- 1 stack module (flexibility for 1x 145-cell stack or 4x 45-cell stacks)
- Air compressor simulated by compressed house air and electric preheat
- Thermal input simulated by electric vaporizer system

Electrolysis Demonstration System Process Flow Sheet

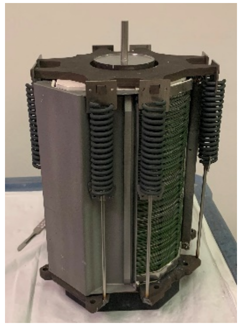


Background: Steam Electrolysis Pilot System

SOEC Electrolyzer System



SOEC Electrolyzer Module



Mid Size CSA Stack

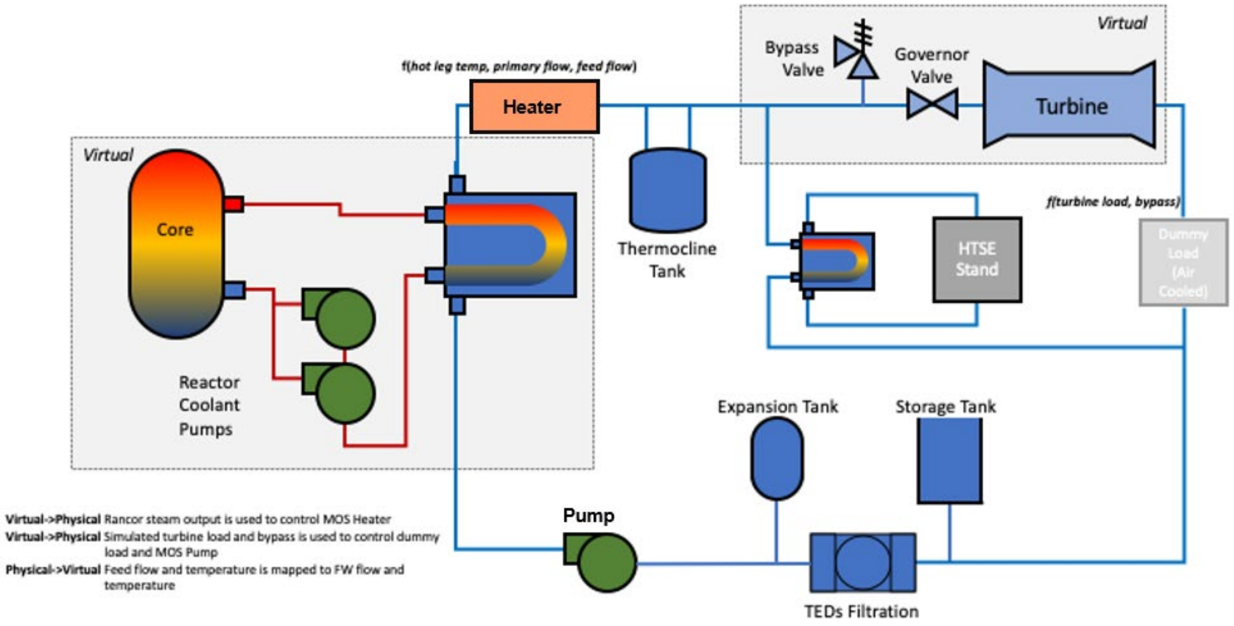
Stack Module Assembled

Stack Module:

- 125 psig (8.6 barg) design pressure
- Accommodates 1x150-cell stack or 4x45-cell stacks with adapter
- **Three thermal zones:**
  - Hot zone for the electrolyzer stack
  - Mid-temp zone for BOP components such as electric heaters and heat exchangers
  - Cool zone for Instrument termination points
- Vessel is designed in accordance with ASME B&PV Code Section VIII Div. II, with internal insulation to allow a touch-safe vessel wall temperature

Background: Human-in-the-Loop and Hardware-in-the-Loop

- Configure nuclear power emulator to behave as a nuclear power plant
- Use mock procedures to test starting and stopping SOEC plant
- Engage plant operators acting as humans-in-the-loop



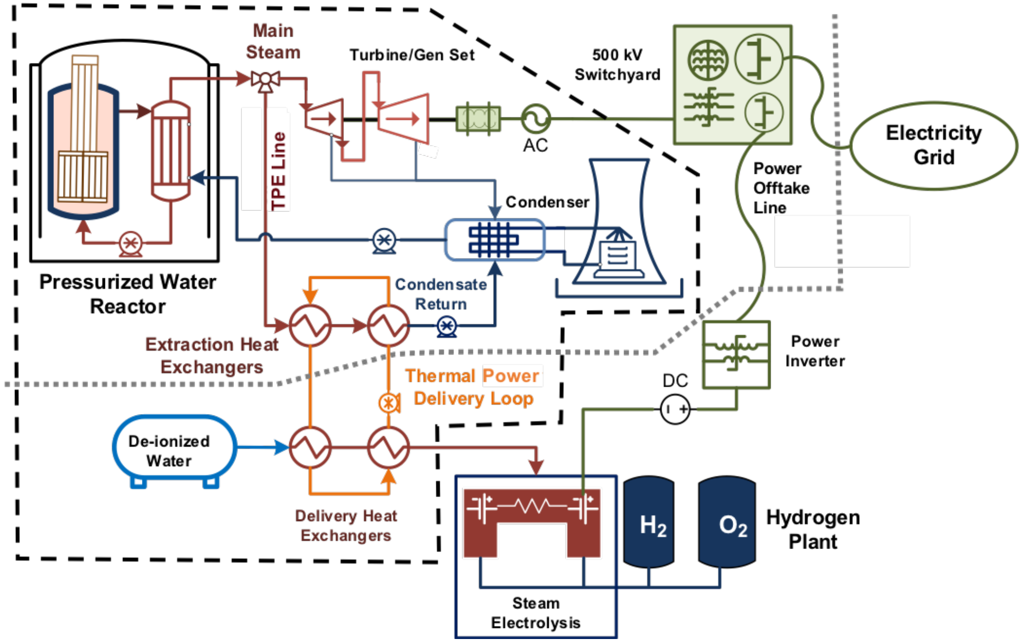


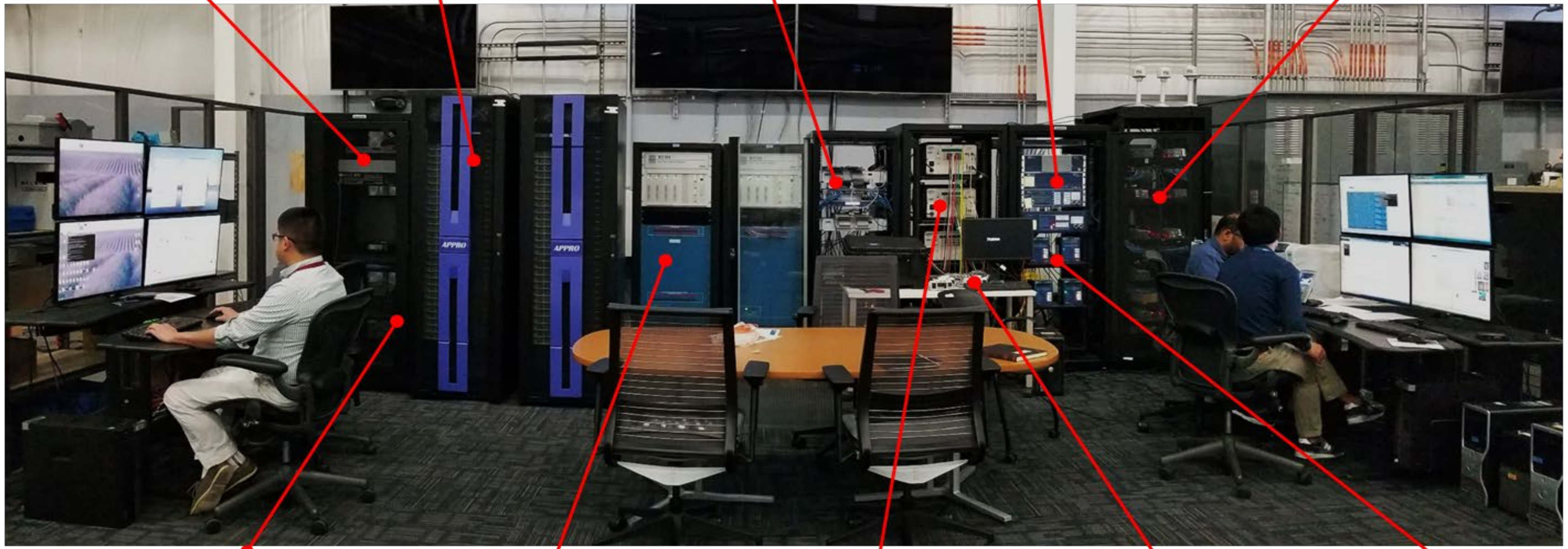
Illustration of nuclear power emulator coupled to Thermal Energy Distribution System (TEDS) and 250 kW SOEC system

Technical Accomplishments and Progress

Background: Planned 250kW Steam Electrolysis System Tests

INL Power and Energy Real Time Laboratory

- Connect real-time digital simulation to 250 kW SOEC system
- Controller Hardware-in-the-Loop (CHiL) tests to implement control strategies while simulating power grid characteristics



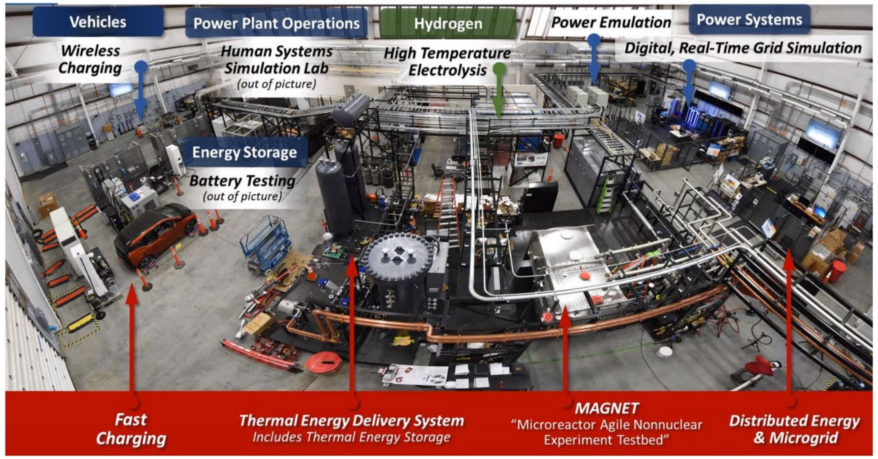
Responses to Previous Year Reviewers' Comments

- This project was not reviewed last year.

Collaborations

- **Idaho National Laboratory (INL)**
  - INL's Energy System Integration Laboratory will be utilized for demonstration of the 250kW SOEC system
    - 16,000 square-feet
    - 600kW AC available power
  - INL expertise in Techno-Economic Analysis (TEA) of steam electrolyzers integrated with nuclear plants will be employed

INL's Energy Systems Integration Laboratory



Idaho National Laboratory

- **Versa Power Systems (VPS), Operating as FuelCell Energy**
  - VPS, a wholly owned subsidiary of FCE, will be providing the following expertise in the project:
    - Cell materials & testing
    - Stack design & testing
    - Cell/stack pilot manufacturing and QC

Cell Pilot Manufacturing Processes at VPS: (Tape Casting, Screen Printing, and Co-sintering)

Collaboration and Coordination

Remaining Challenges and Barriers

- Design of an autonomous 250kW SOEC packaged system capable of producing 150 kg H_2/ day
- Fabrication of a truck-transportable steam electrolyzer
- Durability of electrolysis stacks under system operation
- Operation of the system integrated with INL's CHiL to simulate dynamic behavior of a nuclear power plant

Future Work

- With this project to be starting soon, the following major work remains to be completed:
  - Design of the 250kW system including stack module and balance-of-plant components
  - Fabrication of system components and stack module
  - Fabrication of solid oxide electrolysis cell and >12 stacks
  - Development of control hardware and software for autonomous operation
  - System assembly and commissioning
  - Operation of the 250kW system at INL's Energy Systems Integration Laboratory for more than 2000 hours
  - Techno-economic Analysis
    - SOEC product configuration
    - Stack and system cost at high volume production
    - Operating and maintenance costs

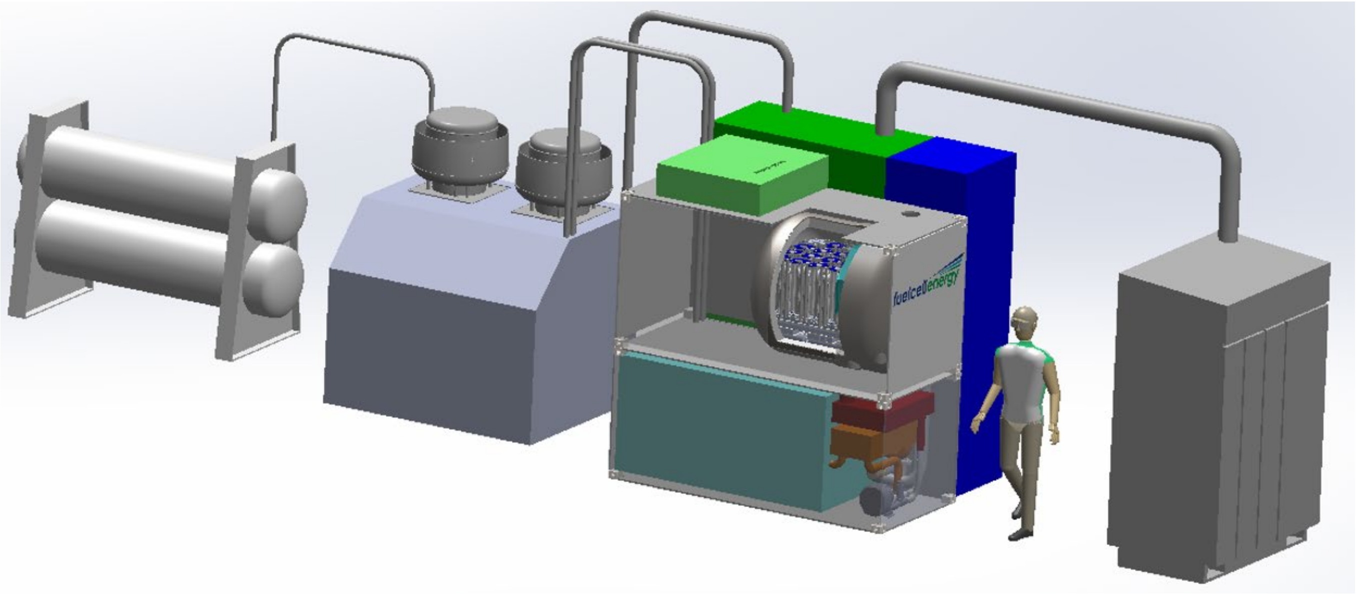
Any proposed future work is subject to change based on funding levels

Proposes Future Work

Summary

- FuelCell Energy Inc. (FCE) in partnership with Idaho National Laboratory (INL) will develop, verify and validate a 250 kW solid oxide electrolysis cell (SOEC) system integrated into a nuclear plant environment.

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



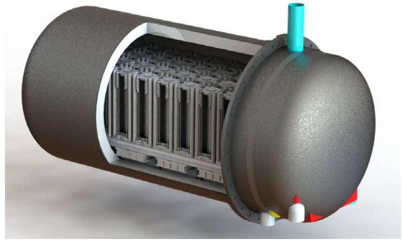
Technical Backup and Additional Information

Technology Transfer Activities

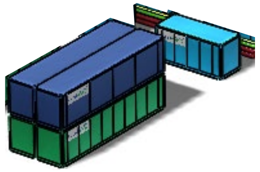
FCE is exploring SOEC systems market opportunities in a variety of applications including a recent study under a Cooperative Research and Development Agreement (CRADA) with participants consisling of: Exelon, Idaho National Laboratory, Sandia National Laboratory, Argonne National Laboratory, and National Renewable Energy Laboratory.

- Forecourt Refueling – Small Commercial
  - Small, single module system
- 50 MW Block – Mid Industrial/Central
  - 32 MT H_2/day
  - Process Integration (Ammonia, steel, etc)
- 1000 MW Block – Large Industrial/Nuclear
  - 640 MT H_2/day
  - Thermal Integration – coupled with industry

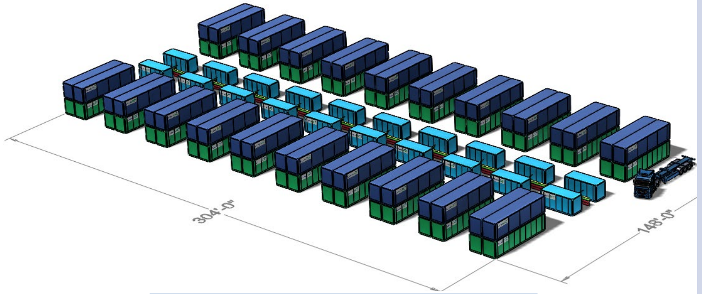
System Parameter	Performance
Stack Electrical Eff (LHV)	97.5%
System Electrical Eff (LHV)	90. 9%
System Total Eff (LHV)	78.0%
Electricity Consumption	36.8 kWh/kg
Thermal Consumption (kWh/kg)	5.9 kWh/kg
Total Energy Consumption	42.7 kWh/kg



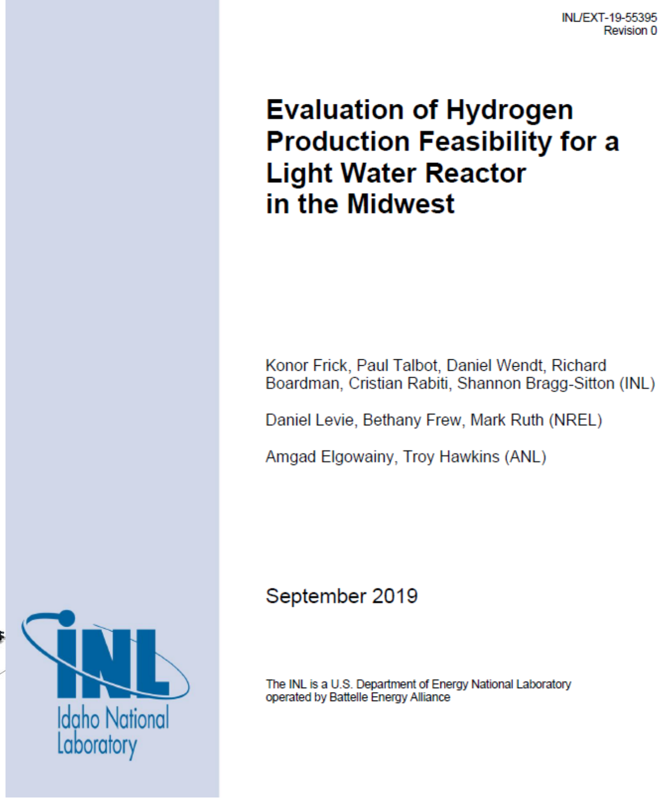
Single Module	
# of Stacks	40
Production Rate	1 MT/day
Gross Power	1.43 MWe
Physical Size	4’x4’x8’



50 MW Block	
# of Stacks	1280
Production Rate	32 MT/day
Gross Power	50 MWe
Physical Size	20’x80’x16’



1000 MW System	
# of Stacks	25600
Production Rate	640 MT/day
Gross Power	1000 MWe
Physical Size	~ 1 Acre



INL/EXT-19-55395
Revision 0

Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest

Konor Frick, Paul Talbot, Daniel Wendt, Richard Boardman, Cristian Rabiti, Shannon Bragg-Sitton (INL)

Daniel Levie, Bethany Frew, Mark Ruth (NREL)

Amgad Elgowainy, Troy Hawkins (ANL)

September 2019

INL Idaho National Laboratory

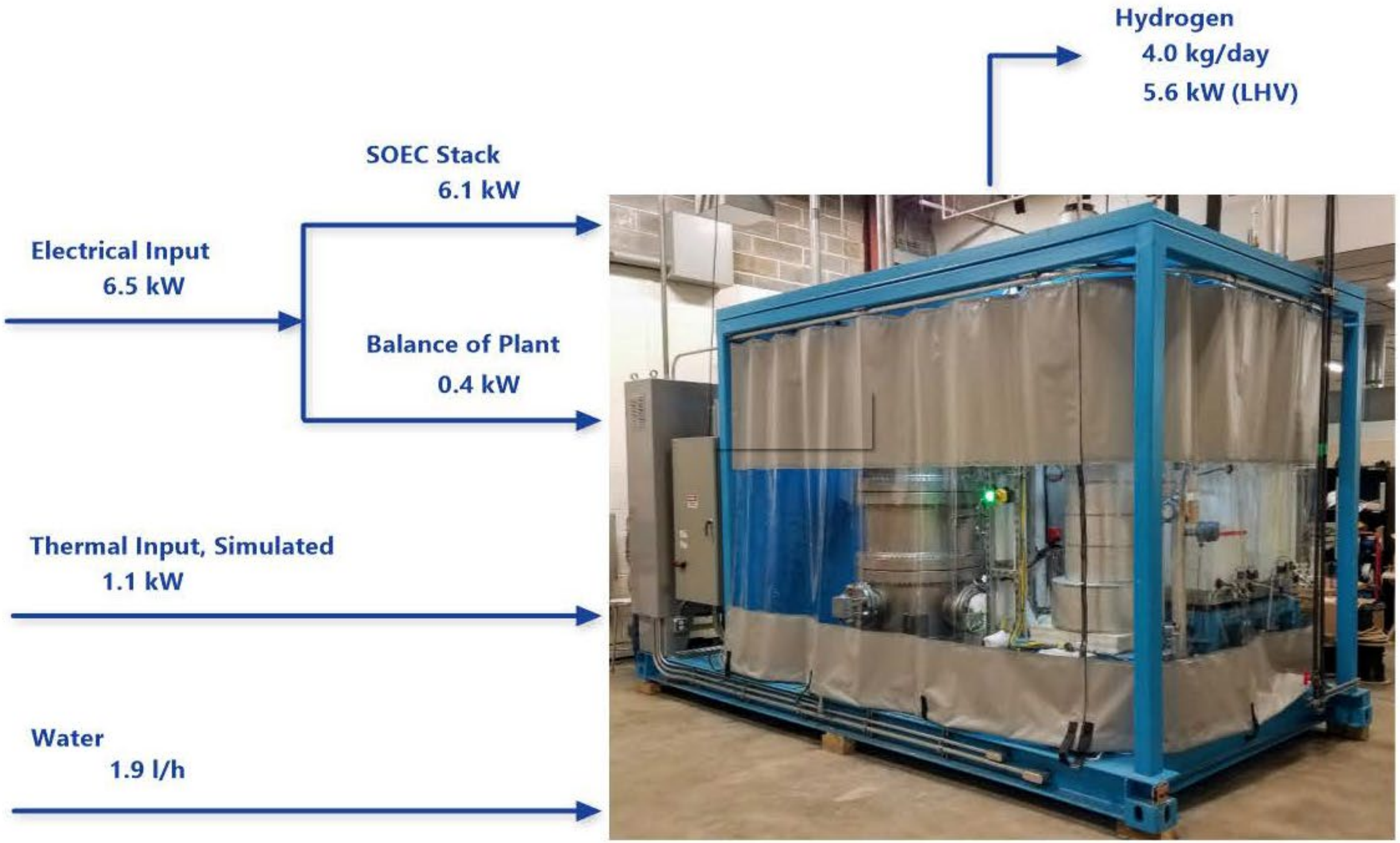
The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

Progress toward DOE Targets

This project will contribute to the development of a stack module pilot scale (250 - 500 kW) electrolysis system suitable for renewable and grid electricity integration as outlined in Advanced Electrolysis Technologies' task descriptions within the Hydrogen Production subprogram of Hydrogen Fuel Cell Technology Office (HFTO) Multi Year R&D and Demonstration (MYRDD) Plan

- Verify the BOP's ability to meet the 2020 system efficiency targets. (Q1, 2018)
- Create modularized designs for optimized central electrolysis systems projected to meeting 2020 capital and hydrogen production cost targets. (Q3, 2018)
- Verify the stack and system efficiencies against the 2020 targets. (Q1, 2020)
- Build an integrated renewable energy source and electrolysis pilot system for target verification and durability testing. (Q4, 2020)

4kg H2/day Pilot System Performance



System Performance Parameter	Value
Stack Electrical Efficiency (LHV)	93.1 %
System Electrical Efficiency (LHV)	85.1 %
System Total Efficiency (LHV)	73.0 %
Electricity Consumption	39.2 kWh/kg
Thermal Consumption, Simulated	6.5 kWh/kg
Total Energy Consumption	45.7 kWh/kg

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