Overview

Timeline

- **Project Start:** Oct. 1, 2016
- **Program Novation:** Apr.-Dec., 2017
- **Project End:** June 30, 2020
- **Percent Complete:** 40%

Budget

- **Total Project Budget:** $3.52MM
  - **Total Federal Share:** $2.81MM
  - **Total Recipient Share:** $0.71MM
  - **Total DOE Funds Spent**: $1.36 MM

  * As of 12/31/2018

Technical Barriers (Advanced Compression)

B. Reliability and Costs of Gaseous Hydrogen Compression

Technical Targets: Small Compressors: Fueling Sites (~100 kg H₂/hr)\(^1\)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2015 Status</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>%</td>
<td>70-90</td>
<td>85</td>
</tr>
<tr>
<td>Compressor Specific Energy</td>
<td>kWh/kg</td>
<td>1.60(^2)</td>
<td>1.60(^2)</td>
</tr>
<tr>
<td>Uninstalled Cap. Cost(^2)</td>
<td>$</td>
<td>275k</td>
<td>170k</td>
</tr>
<tr>
<td>Annual Maintenance % of Capital Cost</td>
<td></td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Years</td>
<td>--</td>
<td>10</td>
</tr>
<tr>
<td>Outlet Pressure Capability</td>
<td>bar</td>
<td>950</td>
<td>950</td>
</tr>
</tbody>
</table>

\(^1\) FCTO Multi-Year Research, Development, and Demonstration Plan (2015). \(^2\) 100-bar delivery/Commercial mechanical compressors are >6-8 kWh/kg (at 7-bar delivery).

Partners

- National Renewable Energy Laboratory (National Lab) – Membrane/System Validation
- Rensselaer Polytechnic Institute (Academic) – Membrane Development
- Gaia Energy Research Institute (Private) – Techno-Economic Analysis
- Giner, Inc. (R&D/Private) – System Development & Assy

Collaborations

- TÜV SÜD America – Codes/Stack Certification
- Intertek – Codes/System Certification
Relevance

Overall Project Objectives

- Develop/demonstrate electrochemical hydrogen compressor (EHC) to address critical needs of lower-cost, higher efficiency, and improved durability

FY 19 Objectives

- Engineer stack & cell components for 12,688 psi (875 bar) operation
- Scale-up membranes, MEA, Stack hardware
  - Assemble EHC Stack and verify EHC stack operation at a pressure of 875 bar.
- Initiate design of EHC prototype unit
- Optimize stack hardware and demonstrate cell performance \( \leq 0.250 \text{ V/cell at current densities } \geq 1,000 \text{ mA/cm}^2 \)

Impact

- Low cost, reliable, high pressure hydrogen to support FCEV penetration
  - Compressor reliability is a major concern for enhanced use of high pressure hydrogen systems and threatens the deployment of a hydrogen infrastructure
EHC Background

EHC: Benefits & Uses
- Solid State, No moving parts
  - Improves downtime
- No membrane degradation (no O₂)
  - Enables use of low-cost Aromatic membranes
- Cross-cutting technology
  - Fuel Cells, Electrolyzers
- Alternative applications:
  - Home/Roadside-Refuelers
  - Hydrogen Purification/Separation (eg. Storage/Natural Gas appl.)
  - Hydrogen Circulation (Refrigeration)
  - H₂ Sensor Applications
  - Power Generation (Reversible)

Efficient, stable, high pressure, & high current EHC operation requires:

- **Water Management**
  - Difficult under varying operating parameters (P_i, P_o, T_i, Current, H₂O_d)
    - Leads to catalyst flooding or membrane dehydration
  - High electro-osmotic drag (EOD) in conventional membranes; 6X higher than can be supplied by humidification

- **Thermal Management**
  - Limits to operating current density
  - Individual cell cooling required

- **Mechanical Strength**
  - Stack hardware, membranes, sealing

Advanced EHC Cell Design
Approach: Program Overview

Membrane

- Aromatic membranes: Synthesize membranes with:
  - Low Electroosmotic Drag & gas permeation
  - Compatible support structures
  - Improve cell voltage performance
  - Demonstrate 0.25V/cell @ 1A/cm², 5000+ psi

- Water management membrane (WaMM):
  - Provides passive water management

Stack

- Design high pressure stack & cell components
- Engineered flow distributor plates
  - Provides heat removal of each individual cell
  - Enables variable H₂ Feed (1-100 bar)
  - Enables dead-ended feed
- Scale-up active area of stack (& membranes)
- Build/Demonstrate 875+ bar stack operation

System

- Build 0.5 kg-H₂/hr prototype system
- Lab-scale demonstration of the technology
- Increase TRL level from 3 to 5
## Approach: YR1 Tasks & Milestone Progress

<table>
<thead>
<tr>
<th>Task No.</th>
<th>Task Title</th>
<th>Milestone</th>
<th>Milestone Description (Go/No-Go Decision Criteria)</th>
<th>Progress Notes</th>
<th>Percent Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Test Hardware Development</td>
<td>M1.1</td>
<td>Fabricate 50cm² test hardware for evaluation of HC and WaMM membranes</td>
<td>Designed &amp; fabricated test hardware to accommodate distributor plate and WaMM</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 sets of hardware delivered to NREL for testing &amp; validation of membrane samples</td>
<td></td>
</tr>
</tbody>
</table>
| 2        | Hydrocarbon Membrane        | M1.2      | Synthesis Aromatic membranes with IECs in the range of 1.8–2.6 mmol/g, protonic conductivity >0.1 S/cm, and electro-osmotic requirement <50-80% than conventional PFSA PEMs | Partially fluorinated Aromatic membranes synthesized (on-going):  
  ▪ Conductivity: 0.106 S/cm ✓  
  ▪ EOD: 50% of PFSA ✓  
  ▪ IEC: 1.4 / 2.0 mmol/g demonstrated ✓  
  ▪ Optimize/reduce back diffusion (on-going)  
  WaMM synthesized:  
  ▪ Water flux: ≥0.1 g/min-cm² ✓  
  ▪ Through-plane conductivity: > 1.0 S/cm ✓  | 100% But continue investigation at 900 bar |
|          | Fabrication, WaMM Fabrication |           | Synthesize WaMM with water flux of ≥0.039 g/min-cm² and conductivity ≥ 1.0 S/cm membrane |                                                                                  |                  |
| 3        | Evaluate Cell Performance   | M1.3      | Voltage performance 250 mV @ ≥ 1,000 mA/cm² (combined Task 1, 2, & 3)                   | EHC cell voltage performance @ 1,000 mA/cm² (300 psig):  
  ▪ 170 mV/cell (PFSA)  
  ▪ 105 mV/cell (Aromatic), | 100% |
| 4        | Preliminary Stack Design    | M1.4      | Complete preliminary design of scaled-up stack (300 cm²) for 875 bar operation          | Complete (May require fine tuning based on results from 50 cm² testing at 875 bar) | 100%             |
|          | Desktop Review of EHC System| M1.5      | Complete Desktop Review of EHC system                                                   | Intertek 1st review round complete. Report submitted                           | 100%             |

**Go/No-Go Decision Y1**

Demonstrate EHC voltage performance of ≤ 250 mV/cell @ ≥ 1000 mA/cm² in a 50 cm² stack platform utilizing advanced ‘Aromatic’ membranes

Successfully operated EHC at 350 Bar ≤ 0.250V @ ≥ 1,000 mA/cm²

Demonstrated Aromatic membrane operation at 0.217V @ 1000 mA/cm², 350 bar
## Approach: YR2 Tasks & Milestone Progress

<table>
<thead>
<tr>
<th>Task No.</th>
<th>Task Title</th>
<th>Milestone</th>
<th>Milestone Description (Go/No-Go Decision Criteria)</th>
<th>Progress Notes</th>
<th>Percent Complete</th>
</tr>
</thead>
</table>
| 5        | Cell Components Scale-up Stack / Cell Components | M2.1 | Scale-up HC membrane in Task 1 to 300 cm² | Developed new membrane architecture and sealing technique  
- 20,000 psi (1,400 bar) seal demonstrated  
- Sealing under high clamping loads (not effected by thermal or pressure cycling)  
- Demonstrated scale-up to 300 cm²  
  - Complete, but additional optimization on HC membranes required  
- Bubble-tight seal for 875 bar stack developed & demonstrated | 50% |
|          |            | M2.2 | Fabricate scaled-up stack hardware including internal components (flow distributor plates). Stack will be designed to accommodate 300 cm² hydrocarbon membranes and WaMM. | Demonstrated method to scale-up unitized cell architecture  
- Issues with stack component delivery times | 10% |
|          | Preliminary Stack Design | M2.3 | Assemble EHC Stack and verify EHC stack operation at a pressure of 875 bar | Fabricated components for a 50 cm² high pressure (875 bar) stack that will be used to fine tune the design of the 300 cm²  
- Modification in distributor plate required. New parts received. On test. 1st run at 875 bar ✓ | 20% |
| 6        | Prototype System Design | M2.4 | Complete preliminary design of lab-scale prototype unit. This includes delivery of P&ID and PFD diagrams | Initiated. P&ID, PFD, Layout, Component Selection, and HazOp Study under review by Intertek | 65% |

**Go/No-Go Decision Y1**  
Scale-up stack, membranes, and distributor plates to an active area of 300 cm. Demonstrate EHC operation at 875 bar and EHC cell voltage performance of ≤ 250 mV/cell @ ≥ 1000 mA/cm²  
---  
---
Progress- Aromatic Membrane/MEA Development

- **Hydrocarbon Membranes (BPSH)**
  - Inexpensive starting materials
  - Reduces gas permeation by 1 order of magnitude
  - Reduction in electro-osmotic drag transport

- **Biphenyl Series Membranes (BP-ArF4, BP-ArSA, BP-SA)**
  - Similar benefits as BPSH, but include:
    - Higher protonic conductivity at lower IEC with lower swelling in water
    - Improved mechanical stability
  - Membrane support structures added for increased mechanical stability

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**Polymer Synthesis**

- BPSH-50 IEC = 2.0
- Biphenyl-Based Polymers
  - BP-ArF4
    - IEC = 1.4
  - BP-ArSA
    - IEC = 2.0
  - BP-SA
    - IEC = 2.6

**MEA Fabrication**

- MEA Fabrication & Catalyst Deposition at NREL
- External Support

**Supports**

- Addition of Internal Membrane Supports
Progress-Latest MEA Developments

Development of High-Pressure Seals

- Membrane supports required for superior creep resistance; when operating pressure >2000 psi
- Difficult to maintain seal above 7000 psi with ‘Traditional’ membrane supports
  - High operating pressures require large clamping loads and a ‘Solid’ membrane surface to seal against
- Developed & demonstrated NEW membrane sealing technology for 875-bar EHC operation
  - Thermoplastic extension of membrane
  - Demonstrated sealing to 20,000 psi (1,400 bar)
  - NREL support in characterization and optimization of new support

![Diagram of membrane sealing pressures](image)

- **20,000 psi** (1,400 bar)
- **7,000 psi** (480 bar)
- **2,000 psi** (140 bar)

Non-Supported Membrane

Traditional Dimensionally Supported Membrane (DSM)

‘Solid’ Supported Membrane (SSM)
Progress - Latest MEA developments

Scale-up of EHC Membrane

- SSM bonds directly to polymer membranes (while in the acid form). Demonstrated:
  - Sealing under high clamping loads
  - Resistance to pressure and thermal cycling
  - Dry assemblies (with Dry membranes)
  - Unitized Cell structures (1 piece/cell). Ease of assembly/cost reduction
- Non-contaminating
- Process applicable to PFSA & Aromatic membranes
- **Demonstrated scale-up of MEA and SSM to 300 cm²**
Progress - EHC MEA Performance & Optimization

Catalyst Optimization

Distributor Optimization

WaMM Optimization

Membrane Optimization

Back-Diffusion Optimization

Operating Conditions:
Outlet H₂ Pressure: 280 psi (~20 bar)
Inlet H₂ Pressure: 30 psig (~2 bar), dry/dead-ended flow

Operating Conditions:
Outlet H₂ Pressure: 280 psi (~20 bar)
Inlet H₂ Pressure: 30 psig (~2 bar), dry/dead-ended flow
Progress - EHC MEA Performance & Optimization

Catalyst Optimization

Best Catalyst

Distributor Optimization

Best Distributor

WaMM Optimization

Membrane Optimization

Best WaMM

Back-Diffusion Optimization

Best Membranes

3X Voltage Improvement!

Catalyst optimization provided highest voltage improvements
Progress - EHC MEA Performance & Optimization

Catalyst Optimization

Distributor Optimization

WaMM Optimization

Membrane Optimization

Back-Diffusion Optimization

4.5X Voltage Improvement!

Improved Gas Distribution
Progress - EHC MEA Performance & Optimization

Catalyst Optimization

Distributor Optimization

WaMM Optimization

Membrane Optimization

Back-Diffusion Optimization

4.6X Voltage Improvement!

Slight voltage improvement, maintains membrane hydration, stabilizes cell voltage
Progress - EHC MEA Performance & Optimization

Catalyst Optimization

- Use of Aromatic membranes with high water content
- Largest Improvements related to Catalyst & Membrane Optimization

Best Catalyst

Distributor Optimization

Best Catalyst

WaMM Optimization

Best Distributor

Membrane Optimization

Best WaMM

Back-Diffusion Optimization

Best Membranes

7.7X Voltage Improvement!

PFSA Baseline
PFSA (Mod A)
PFSA (Mod B)
BP-ArF4 (Mod A)
BP-ArF4 (Mod B)
Progress - EHC MEA Performance & Optimization

- **Catalyst Optimization**
  - PFSA improving
  - Best Catalyst: PFSA

- **Distributor Optimization**
  - PFSA
  - Best Distributor: PFSA

- **WaMM Optimization**
  - PFSA
  - Best Distributor: PFSA

- **Membrane Optimization**
  - PFSA
  - Best WaMM

- **Back-Diffusion Optimization**
  - PFSA Baseline
  - PFSA (Mod A)
  - PFSA (Mod B)
  - BP-ArF4 (Mod A)
  - BP-ArF4 (Mod B)

- **7.6X Improvement**
  - Voltage improvement!
  - No further voltage improvement, but diffusion reduced.
  - PFSA (Mod): 50%
  - BP-ArF4 (Mod): 32%
DEMONSTRATED CAPABILITIES OF EHC

- Dead-ended H₂ Inlet feed
  - Simplifies system: no H₂ flow thru, No external humidification, and No H₂ recovery required
- Dry H₂ Inlet feed (humidified H₂ ok, will not improve performance)
- Variable inlet feed pressure up to 1,500 psi (100 bar), & Stable Cell Voltage at each inlet pressure
- High Voltage Efficiency to 2 kWh/kg-H₂!

**Voltage Efficiency:**
- 4.2 kWhₑ/kg-H₂
  - 1 A/cm² (0.159V/cell)
- 2.0 kWhₑ/kg-H₂
  - 0.5 A/cm² (0.078V/cell)
MEA Performance (5,000 psig) as a function of Inlet pressure

6 mV/Cell

71 mV/cell

Improvement

at 1,500 psi (100 bar) inlet

Reduced voltage gain with increasing inlet pressure

Voltage Efficiency:

4.2 kWh_e/kg-H_2

1 A/cm^2 (0.159V/cell)

2.0 kWh_e/kg-H_2

0.5 A/cm^2 (0.078V/cell)
Progress – Modeling EHC Performance

- Combined effect of iR-losses, Nernstian Penalty, Catalytic Activity, Ionic conductivity, and Back diffusion
- Increased power consumption at high operating pressure (back diffusion)
- Max efficiency at ~500 mA/cm²

Where are we?

- Outlet Pressure: 1,450 psi (100 bar)
- 5,000 psi (350 bar)
- 12,688 psi (875 bar) H70 Refueling
- 6,250 psi (430 bar) H35 Refueling

50°C. 100 bar Feed. Assumes optimal water management

<table>
<thead>
<tr>
<th>PFSA Membrane Thickness (mils)</th>
<th>2</th>
<th>5</th>
<th>7</th>
<th>10</th>
<th>12</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (kWh_e/kg-H₂)</td>
<td>3.1</td>
<td>3.7</td>
<td>5.3</td>
<td>2.7</td>
<td>3.7</td>
<td></td>
</tr>
</tbody>
</table>

0.5 A/cm² 1 A/cm²
Progress – Modeling EHC Performance

- Combined effect of iR-losses, Nernstian Penalty, Catalytic Activity, Ionic conductivity, and Back diffusion
- Increased power consumption at high operating pressure (back diffusion)
- Max efficiency at ~500 mA/cm²

Where are we?

Outlet Pressure:
- 1,450 psi (100 bar)
- 6,250 psi (430 bar) H35 Refueling
- 12,688 psi (875 bar) H70 Refueling

Current Density (mA/cm²)

Electrical Usage (kWh/kg)

Outlet: 5,000 psi (350 bar)
Inlet: 1,500 (100 bar Inlet)

50°C. 100 bar Feed. Assumes optimal water management

Efficiency (kWhₑ/kg-H₂), 350 bar
0.5 A/cm²
1 A/cm²

- PFSA 2.0 4.2
- BP-ArF4 2.7 → 1.7est. 3.7 → 2.7est.
Progress - EHC Stack Design & Fabrication

**875 bar Stack Novel Design Features**
- Proof pressure design: 20,000 psi (1,400 bar)
  - Scale-up active area to 300 cm²
  - Utilizing low cost materials: SS
  - Design incorporates use of integrated distributor plate and WaMM, reduced part count
  - Enhanced bipolar plate design for 20 ksi capability

**Proof-Pressure Testing**
- Hydraulic pressure assembly rated to 50,000 psi
- Test enclosure assembled - Measures deflection of endplate
- Stack successfully pressure tested to **20,000 psi** (1,400 bar) with new ‘SSM’ MEA

Evaluation of high pressure components, Flow distributors & internal cell components, membrane strength/rupture testing

Catalyst, Membrane & Cell-Component, Testing & Validation
Progress- 875 bar EHC Operation

875 bar Operation!

- Stack designed with SS internal components
- Operates at inlet pressures ranging from 1 to 100 bar
  - Single stage compression to 875 bar
  - Can be operated above 875 bar based on proof pressure ratings
- Optimization of 875 bar hardware followed by scale-up
Progress - System Design

- Initiated procurement of system components/System assembly
- Design Specs:
  - H₂ Flux Rate: 0.5 kg/hr
  - H₂ Inlet Pressure: 1-100 bar
  - H₂ Outlet pressure: 875 bar
  - Dimensions: 4’x4’x1’
- System reviewed by Intertek. Over 20 standards* apply. Influences how system is designed

Program objective:
Increase TRL from 3 to 5

Goal: Certification & commercialization of the technology
### Projected Compression Cost

<table>
<thead>
<tr>
<th>H₂ Compression Cost Contribution</th>
<th>Current Status ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs¹</td>
<td>0.175</td>
</tr>
<tr>
<td>Feedstock Costs²</td>
<td>0.239 (1000 mA/cm²)</td>
</tr>
<tr>
<td></td>
<td>0.114 (500 mA/cm²)</td>
</tr>
<tr>
<td>Fixed O&amp;M</td>
<td>0.004</td>
</tr>
<tr>
<td>Variable Costs</td>
<td>0.001</td>
</tr>
<tr>
<td>Total Cost ($/kg)³</td>
<td>0.419</td>
</tr>
</tbody>
</table>

¹10 year lifetime, ²Based on electrical cost of $0.057/kWh kWhₑ/kg, ³Design Capacity: 100 kg-H₂/hr, 1,000mA/cm² EHC Operation. Assumes large scale production. ⁴Compared to previous year: CapEX & OpEx previously 0.196 & 0.305 $/kg, respectively.

- **Economics:** determined using PEM-based system cost models
  - Feed Stock, based on Efficiency Range @ 350 bar:
    - 2.0 to 4.2 kWhₑ/kg-H₂
    - Projected Operating Lifetime: designed to operate for a term of 10 years or more (> 20 years expected)
    - Use of SS components vs. Ti
  - 10 year lifetime: Membranes are not expected to degrade due to lack of O₂ in system
## Collaborations/Acknowledgements

<table>
<thead>
<tr>
<th>Company/Institution</th>
<th>Sector</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Giner ELX, Inc.</strong></td>
<td>Industry</td>
<td>Stack and system engineering, development, and operation. Fabrication and optimization of catalyst and membrane electrode assemblies. WaMM development and optimization. Testing &amp; validation</td>
</tr>
<tr>
<td><strong>National Renewable Energy Laboratory (NREL)</strong></td>
<td>National Lab</td>
<td>Membrane and cell component validation. Coordinate stack testing and optimization studies of membranes, cell components &amp; materials. Testing of high-pressure EHC stack and system</td>
</tr>
<tr>
<td><strong>Rensselaer Polytechnic Institute (RPI)</strong></td>
<td>Academia</td>
<td>Development of mechanically-stable Aromatic PEMs which serve as a key material in this project.</td>
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<tr>
<td><strong>Gaia Energy Research Institute LLC (Gaia)</strong></td>
<td>Small Business</td>
<td>EHC stack cost analysis and system-level analysis. Developing EHC cost estimates, techno-economic analysis (TEA), and life cycle assessment (LCA)</td>
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<tr>
<td><strong>Intertek/TUV</strong></td>
<td>Nationally Recognized Testing Laboratory</td>
<td>Certification for System &amp; Stack</td>
</tr>
<tr>
<td><strong>Giner, Inc.</strong></td>
<td>R&amp;D</td>
<td>System assembly, sub-component fabrication, PLC controls. Includes documentation for certification process</td>
</tr>
</tbody>
</table>

**Department of Energy, DOE Fuel Cell Technologies Office (FCTO),**
Ms. Neha Rustagi, Dr. Dave Peterson, Dr. Eric Miller
Dr. Sunita Satyapal
Summary

- **Demonstrated EHC operation to a pressure of 875 bar**
  - Demonstrated compression ratio of 875:1, single stage

- **Membrane Development:**
  - Designed MEA with new sealing properties;
    - Enables bubble-tight seal to 20,000 psi (1,400 bar) & Stack operation to 12,688 psi (875 bar)
      - Resistant to thermal & pressure cycling
    - Demonstrated scalability of MEA & seal to 300 cm², unitized cells, & dry build
  - Reduced membrane back diffusion by > 50% in PFSA, 32%; Aromatic membranes
  - Optimization: Demonstrated further improvements in cell voltage:
    - 0.159V/cell (100 bar inlet); Stack efficiencies to 2.0 kWh/kg-H₂ at 5,000 psi (350 bar)
    - Highest Efficiency for EHC operating at 5,000 psi (350 bar)
      - Further improvements expected in next round of aromatic membrane tests

- **Stack Development:**
  - Successfully designed, assembled, and operated a 875 bar EHC stack (50 cm² platform)
  - Demonstrate proof pressure of 20,000 psi (1,400 bar)
    - Operates at an inlet pressure range of 1-100 bar, dead-ended feed, & dry H₂
  - Reduced Stack Cost
    - Unitization of cell components (reduced part count/cell)
      - Combined Flow-Distributor and WaMM compartment into single component
      - Use of SS cell components

- **System Development:**
  - Initiated procurement and assembly of 875 EHC system
Future Plans & Challenges (FY2019-20)

Future Plans*

- **Membrane**: Fabricate aromatic membranes using SSM seal, integrate into 875 bar stack and evaluate
- **Stack**: Optimize internal cell components to replicate performance achieved in 350 bar stack, Scale up to 300 cm²
- **System**: Complete assembly of prototype system design
  - Initiate operation and system studies

Future Challenges

- Increase stack active-area to 300 cm²
  - Scale-up for aromatic membranes
- Further reduce stack costs
  - Endplate thickness & cost
    - Investigate techniques to reduce cell component fabrication costs
      - Possibility of stamping components
- Investigate embrittlement of cell components
- Determine effect of H₂ impurities
  - Giner ELX will conduct additional studies with impure H₂ sources
    - e.g. Removal, and compression, of hydrogen from NG source containing 5% H₂

*Any proposed future work is subject to change based on funding levels*
Technical Back-Up Slides
Progress – 875 bar Stack Design – Endplate Scale-up

900 bar stack endplate (50 cm²)
Large End-Plate due to Nuts/Bolts

<table>
<thead>
<tr>
<th>Stack Active Area</th>
<th>Endplate</th>
<th>Thickness (in.)</th>
<th>Dia. (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 cm²</td>
<td></td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>300 cm²</td>
<td></td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>1,000 cm²</td>
<td></td>
<td>12</td>
<td>-</td>
</tr>
</tbody>
</table>

Program Target

Minimize Endplate thickness with Bolt pattern

50 cm²  300 cm²  >1000 cm²
Dual-bolt circle design