INCREASE YOUR H2IQ

The #H2IQ Hour

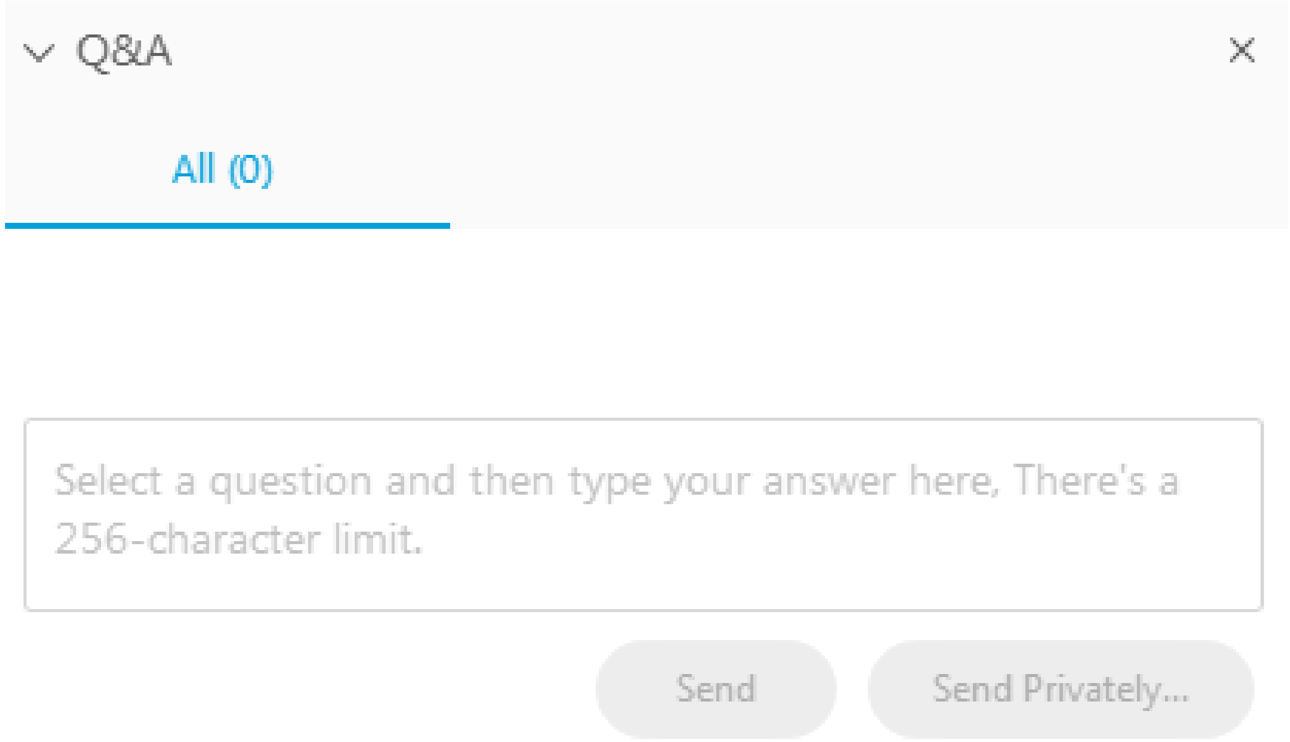
Today's Topic:

How advanced manufacturing is helping to address needs in hydrogen and fuel cells

This presentation is part of the monthly H2IQ hour to highlight research and development activities funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

How advanced manufacturing is helping to address needs in hydrogen and fuel cells

G. Jeremy Leong, Bob Gemmer, Chad Schell, Brian Valentine, Nick Lalena and Kathryn Peretti Technology Managers, Advanced Manufacturing Office

Valri Lightner, Deputy Director, *Advanced Manufacturing Office*

Presentation for H2IQ

manufacturing.energy.gov

EERE's Advanced Manufacturing Office (AMO)

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Advanced Manufacturing Office

BUDGET

$395M
FY20

WHAT WE DO

Partner with industry, academia, states, and National Laboratories **to catalyze R&D and the adoption of advanced manufacturing technologies and practices**

R&D Projects
FY20 = $151M

R&D Consortia
FY20 = $199M

Technical Assistance
FY20 = $45M

AMO Guiding Principles

AMO works to **increase energy and material efficiency in manufacturing** to drive energy productivity and economic growth.

MANUFACTURING

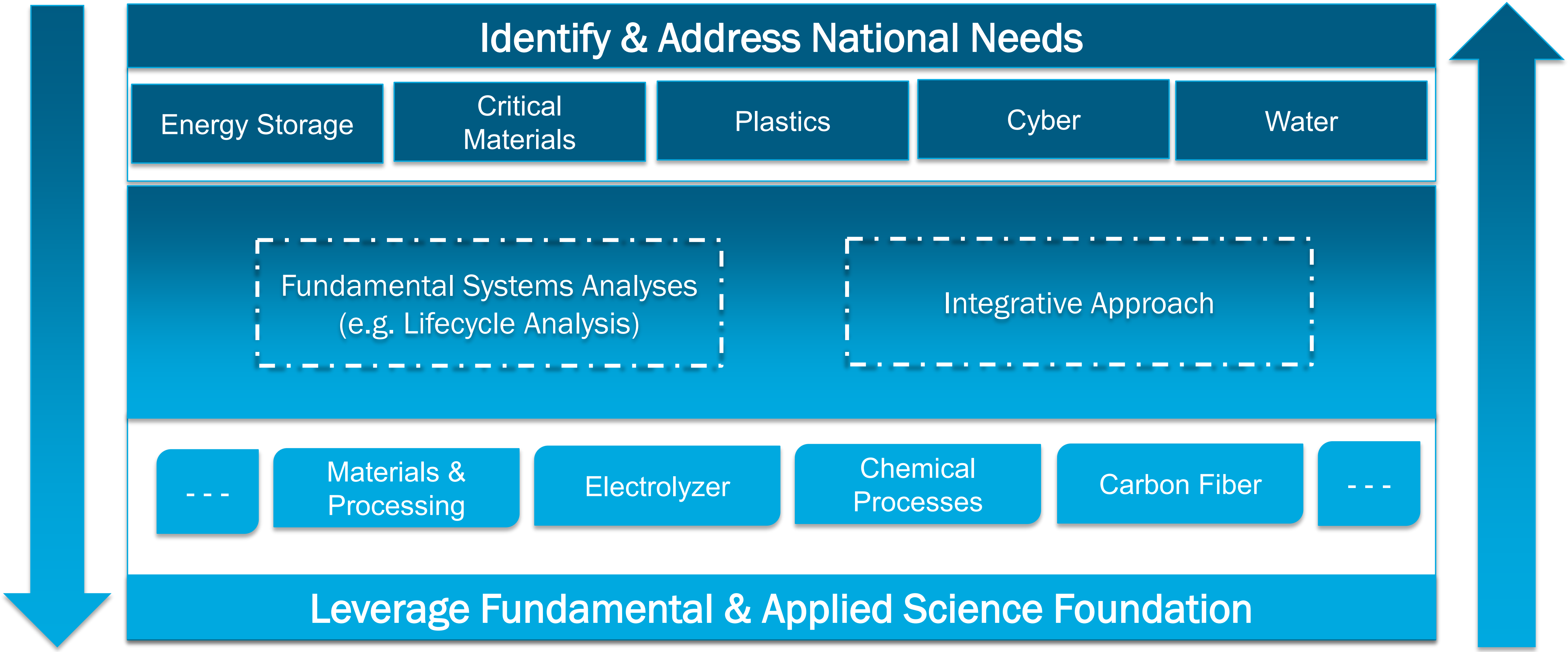
- Uses roughly 25% of the nation's primary energy
- Represents nearly 80% of energy use in energy-intensive sectors
- Generates 11% of the U.S. GDP and 12 million jobs
- Incurs $150 billion in energy costs annually

AMO GOALS

- Improve the **productivity, competitiveness, energy efficiency, and security** of U.S. manufacturing
- Reduce the **life cycle energy and resource impacts** of manufactured goods
- Leverage diverse **domestic energy resources and materials** in U.S. manufacturing, while strengthening environmental stewardship
- Transition DOE-supported innovative technologies and practices into **U.S. manufacturing capabilities**
- Strengthen and advance the **U.S. manufacturing workforce**

Framework to Shape AMO's Portfolio

A holistic top-down and bottom-up systems approach to
shape the AMO portfolio with the highest potential for impact.



Anticipated Workshops

Ongoing input from
INDUSTRY
& ACADEMIA
to understand current and emerging challenges and opportunities

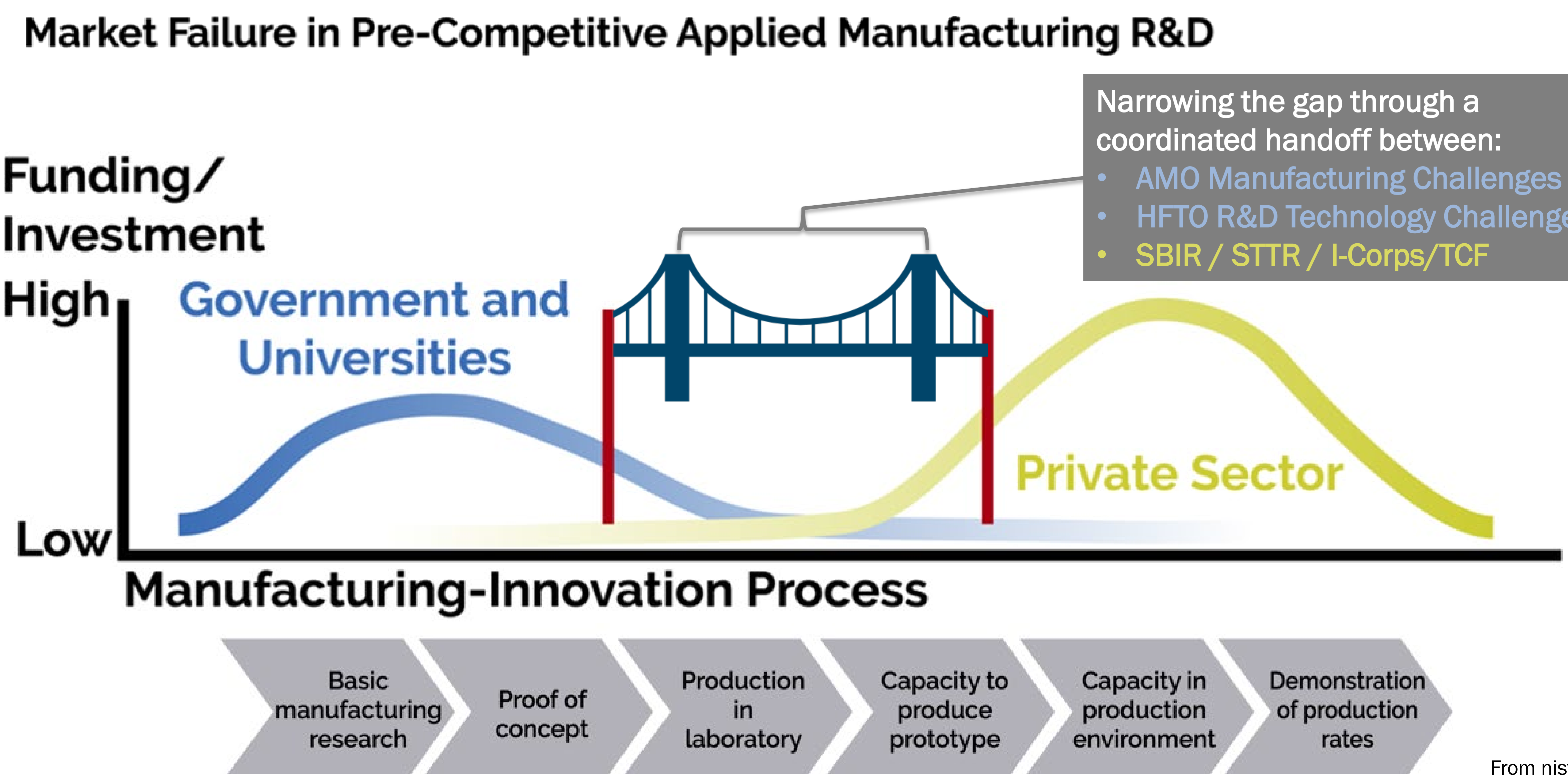
VIRTUAL WORKSHOPS
anticipated in FY21 to build on technical white papers

ADDITIONAL STAKEHOLDER ENGAGEMENT
roundtables in FY21 on sustainable chemistry, electrochemistry - manufacturing

SAMPLE TOPICS

- Materials for Harsh Service Conditions
- Innovation in Water Infrastructure
- Next Generation of U.S. Manufacturing
- Workforce Development
- Semiconductor Manufacturing
- Critical Materials Analysis
- Thermal Process Intensification
- Combined Heat and Power in the Flexible Manufacturing Enterprise

Inter-office collaborations narrows the “gap” though de-risking technologies



Narrowing the gap through a coordinated handoff between:

- AMO Manufacturing Challenges
- HFTO R&D Technology Challenges
- SBIR / STTR / I-Corps/TCF

From nist.gov

Collaborative Funding Opportunities (FY20)

AMO MULTI-TOPIC FOA: ≤ $67M

- Next-generation manufacturing processes that improve energy efficiency in energy-intensive and energy-dependent industries, including steel manufacturing
- Modular, hybrid, or catalytic processes to improve energy efficiency in chemical manufacturing
- Connected, flexible, and efficient manufacturing facilities, products, and energy systems

WATER SECURITY

Water Resource Recovery Prize: ≤ $1M

- Two-phased competition for novel, systems-based solutions for resource recovery at small-to-medium-sized water resource recovery facilities

Water security-specific FOA: ≤ $20M

CRITICAL MATERIALS FOA: ≤ $30M

R&D for:

- Field validation and demonstration
- Next-generation extraction, separation, and processing technologies

BATTERY MANUFACTURING LAB CALL ≤ $12M*

- Collaborate with industry on battery technology scale-up

*Joint with the Vehicle Technologies Office

BOTTLE FOA: ≤ $25M*

- Highly recyclable or biodegradable plastics
- Novel methods for deconstructing and upcycling existing plastics
- BOTTLE Consortium collaborations

*Joint with the Bioenergy Technologies Office

TRANSPORTATION FOAs

- **≤ $15M*:** Polymer Composites for Vehicle Applications
  - *Joint with the Vehicle Technologies Office)
- **≤ $15M**:** Electrolyzer Manufacturing R&D
  ≤ $15M:** Advanced Carbon Fiber for Compressed Gas Storage Tanks
  - **Joint with the Hydrogen and Fuel Cell Technologies Office

Summary on Joint HFTO/AMO Awards

Selectee Name	Location (city, state)	Project Title	Federal Share
TOPIC 1: ELECTROLYZER MANUFACTURING R&D			
3M Company	Saint Paul, MN	Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzer Oxygen Evolution Reaction Catalysts and Electrodes	$4,854,808
Giner ELX, Inc.	Newton, MA	Integrated Membrane Anode Assembly & Scale-up	$4,592,664
Proton Energy Systems, Inc.	Wallingford, CT	Enabling Low Cost PEM Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces	$4,400,000
TOPIC 2: ADVANCED CARBON FIBER FOR COMPRESSED HYDROGEN AND NATURAL GAS STORAGE TANKS			
Collaborative Composite Solutions Corporation	Oak Ridge, TN	Melt Spun PAN Precursor for Cost-Effective Carbon Fiber in High Pressure Compressed Gas Tankage	$2,700,540
Hexagon R & D LLC	Lincoln, NE	Carbon Composite Optimization Reducing Tank Cost	$2,599,945
University of Kentucky	Lexington, KY	Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks	$2,415,576
University of Virginia	Charlottesville, VA	Low-Cost, High-Performance Carbon Fiber for Compressed Natural Gas Storage Tanks	$2,701,552

https://www.energy.gov/sites/prod/files/2020/07/f76/hfto-h2-at-scale-new-markets-foa-selections-for-release.pdf

AMO Technical Areas Relevant to the Hydrogen and Fuel Cell Communities

- **Electrolyzers: Bob Gemmer (AMO)**
- Advanced Composite Materials: Chad Schell (AMO)
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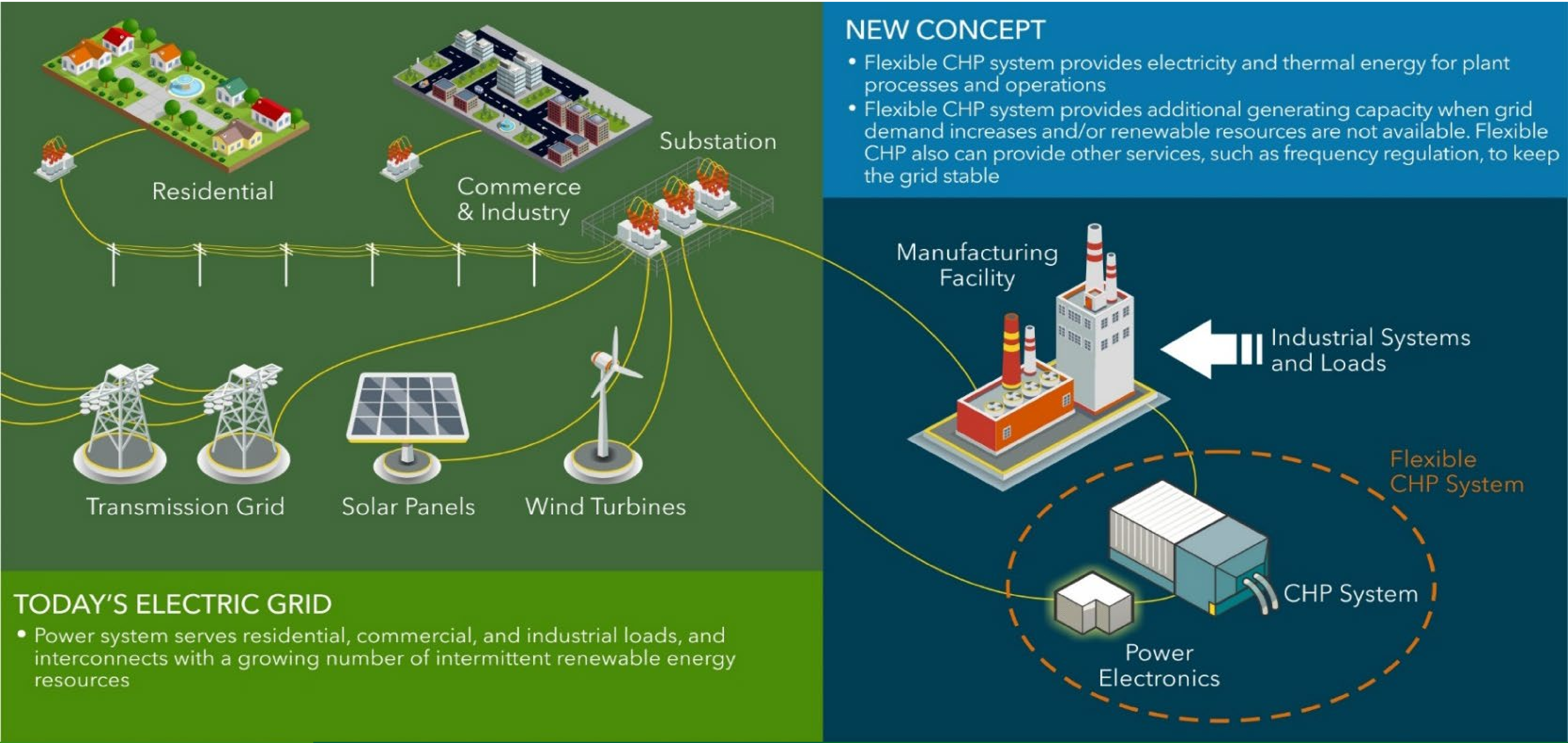
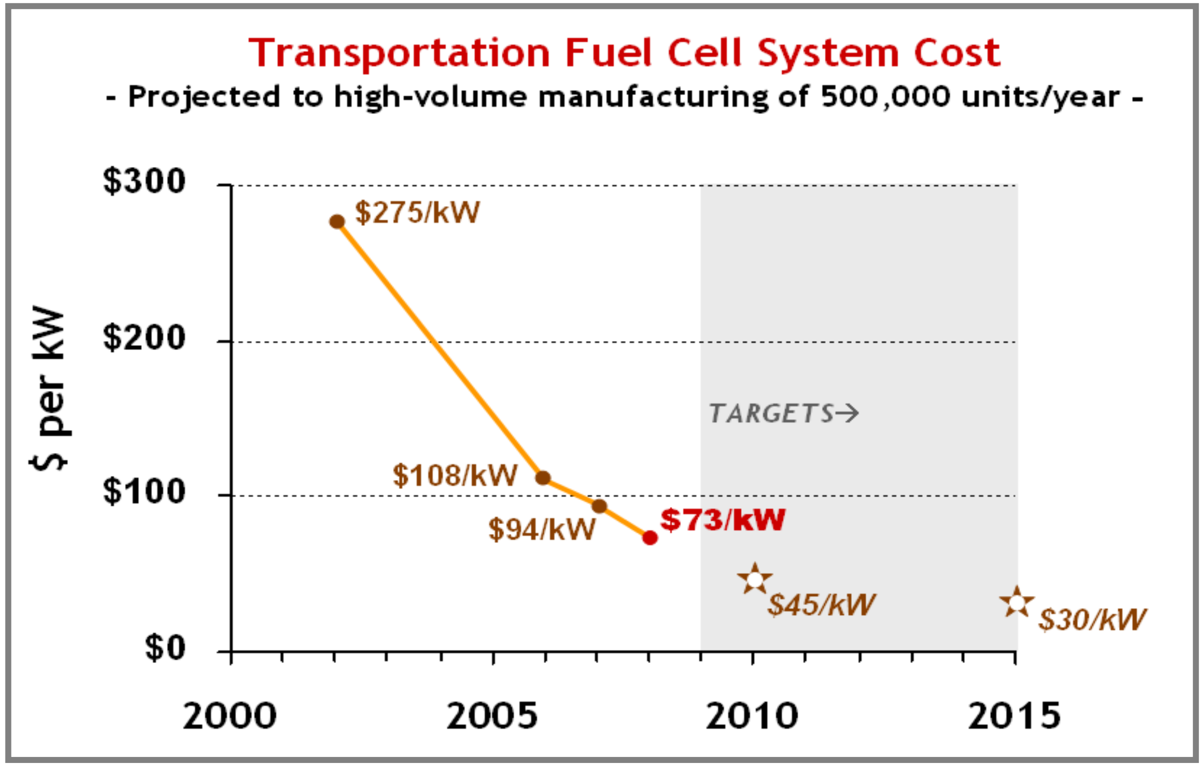
Flexible Combined Heat and Power Systems



Manufacturing R&D throughout the Years



Source: 2009 AMR, S. Satyapal

Consistent ~30% annual growth since 2010

Global Market Potential in 10- 20 years*

$14B – $31B/yr for stationary power
$11B /yr for portable power
$18B – $97B/yr for transportation

*Fuel Cell Economic Development Plan, Connecticut Center for Advanced Technology, Inc. January 2008

Fuel Cell Electric Vehicles Are Here

Auto Shows

Source: 2016 AMR, S. Satyapal

Manufacturing Cost Analysis for PEM Water Electrolyzers

The main cost drivers for PEM electrolyzers are cost of electricity and capital cost of electrolyzer stacks

Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers

Ahmad Mayyas, Mark Ruth, Bryan Pivovar, Guido Bender, and Keith Wipke

National Renewable Energy Laboratory

August 2019, Funded by LDRD

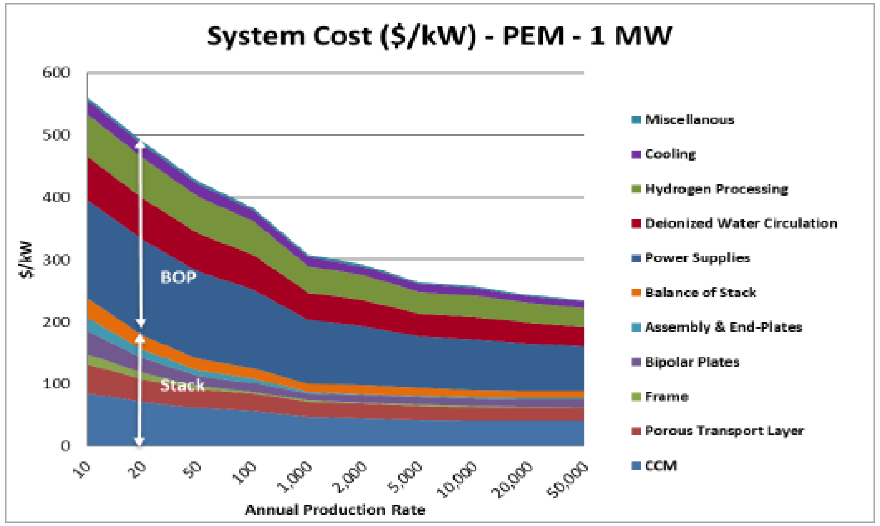


Figure ES-1. 1-MW PEM electrolyzer system cost at different annual production rates

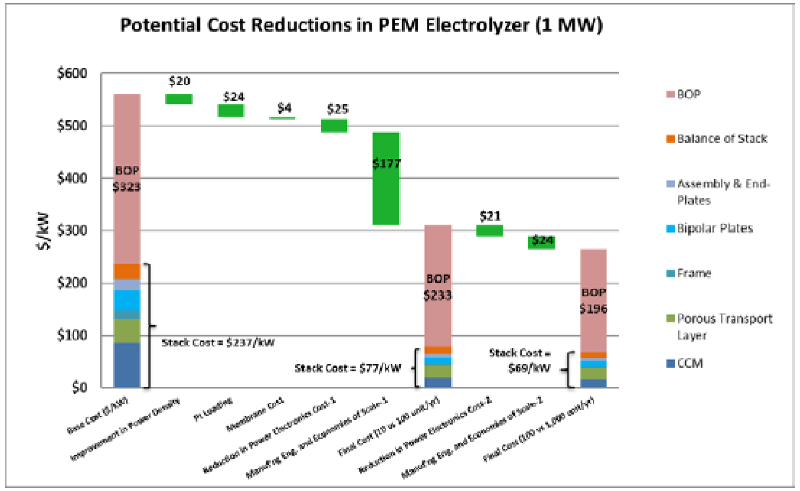


Figure ES-2. Waterfall charts showing areas where R&D can play a role in reducing the cost of the 1-MW electrolysis system

Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzer Oxygen Evolution Reaction Catalysts and Electrodes | Andy Steinbach / 3M Company

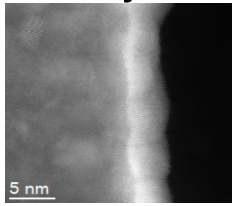
Advanced manufacturing technology development will enable fabrication of state-of-the-art catalysts and electrodes at rates sufficient for 3.75 gigawatts of PEM water electrolyzers per year.

The state-of-the-art catalysts and electrodes will reduce H_2 costs and reduce Ir usage relative to commercial and competitive technologies, due to the unique nm-scale thin film catalyst morphology.

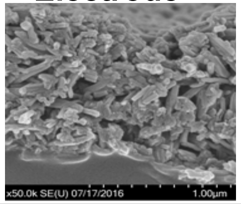
When integrated into advanced megawatt-scale stacks, the components will produce high power with high durability, and will be compatible with high renewable content electricity grids.

Advanced Components

Catalyst



Electrode



GW-Scale Manufacturing

MW-Scalable Electrolyzers

Courtesy of Giner ELX

Key Personnel

NREL: Michael Ulsh, Scott Mauger, Peter Rupnowski
ORNL: Dave Cullen.
Giner, Inc.: Hui Xu. Plug Power: Cortney Mittelsteadt

Program Summary

Period of performance: 36 months

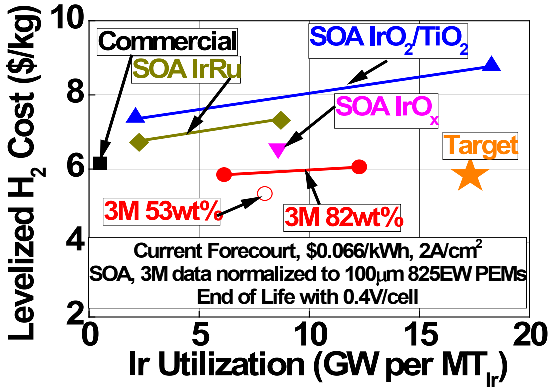
Federal funds: $4.855MM
Cost-share: $1.213MM
Total budget: $6.068MM

	Key Milestones & Deliverables
Year 1	• GW-scale process feasibility demonstrated. • Materials meet performance, durability targets.
Year 2	• 2 GW/year fabrication rate achieved. • Durable, high power density, sub-scale stack.
Year 3	• 3.75GW/year fabrication rate achieved. • Durable, high power density, 230kW stack

Technology Impact

Key barriers to gigawatt-scale water electrolysis will be reduced through advanced process and materials technologies.

1. Lower H_2 cost
2. Reduced Ir usage.
3. GW manufacturing.



Advanced processes and materials for GW-scale water electrolysis

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Reducing the Cost and Energy Intensity of Advanced Composite Materials for Lightweighting and Compressed Gas Storage

AMO focuses on improving cost and energy efficiency of fiber reinforced, polymer matrix composites materials and final parts

Objective in this area is to advance material production technologies that:

- Reduce embodied energy and emissions
- Reduce cost of composites to be competitive with current materials and manufacturing methods to enable widespread use of composite materials in energy-related applications

Current portfolio:

- **Institute for Advance Composites Manufacturing Innovation (IACMI)**
  Collaborative Composites Solutions
- **Innovative High-feed Rate Additive Manufacturing Using Nano- Micro- Cellulose-Reinforced Thermoplastic Composites**, Oak Ridge National Lab & University of Maine
- **Manufacturing Demonstration Facility**, Oak Ridge National Lab
- **Carbon Fiber Technology Facility**, Oak Ridge National Lab
- Compressed gas storage and vehicle parts joint topics with HFTO and VTO

AMO Composites Key Concepts/Thrusts

Target	2015 Baseline	Progress to Date
7.1: Reduce production cost of finished carbon fiber composite components for targeted energy-consuming applications by 50% compared to 2015 state-of-the-art technology.	Auto: \$55-\$78 per kg Wind: \$16 per kg Pressure Vessel: \$28 per kg	Auto: \$32 per kg (42% improved) Wind: \$12 per kg (25% improved) Pressure Vessel: Research ongoing
7.2: Develop composite molding manufacturing process with <1.5-minute part-to-part cycle time for a structural component with surface area >0.5m^2.	3.5 - 9.0 minutes depending on component and process	Automobile seat back compression molded approximately 2 min cycle Fender with 40% carbon fiber reinforcement injection molded in approximately 60 second cycles
7.3: Develop manufacturing technologies that reduce the embodied energy and production-associated GHG emissions of carbon fiber reinforced polymer (CFRP) by 75% compared to 2015 typical technology.	Auto: 1409 MJ/kg (carbon fiber) Wind: 131 MJ/kg Pressure Vessel: 2247 MJ/kg	Auto: 1004 MJ/kg (20% improved) Wind: 717 MJ/kg (23% improved) Pressure Vessel: Research ongoing
7.4: Develop technologies that recycle or reuse >95% of fiber reinforced polymer composites into useful components with projected cost and quality competitive with virgin materials.	30% raw material scrap typical continuous fiber composites	Carbon fiber recovered successfully from scrap materials. Research in progress to incorporate into materials for compression and injection molding.
7.5: Develop fiber reinforced polymer composites with projected cost and embodied energy parity with 2015 typical glass fiber composites and with performance of carbon fiber composites.	Cost: \$25/kg (representative automotive part – injection overmolded) Embodied Energy: 94 MJ/kg (representative automotive part – injection overmolded)	Cost: Carbon fiber cost reduced to \$21.56/kg (31% Improved) for large tow carbon fiber produced by CFTF Embodied Energy: Research ongoing

Carbon Fibers and Composite Materials

The Carbon Fiber Technology Facility CFTF

- Only **Open Access** State-of-the-Art Facility in the U.S
- 42,000 ft^2 facility with production capacity of 25 tons/year of fiber from multiple precursors in various forms

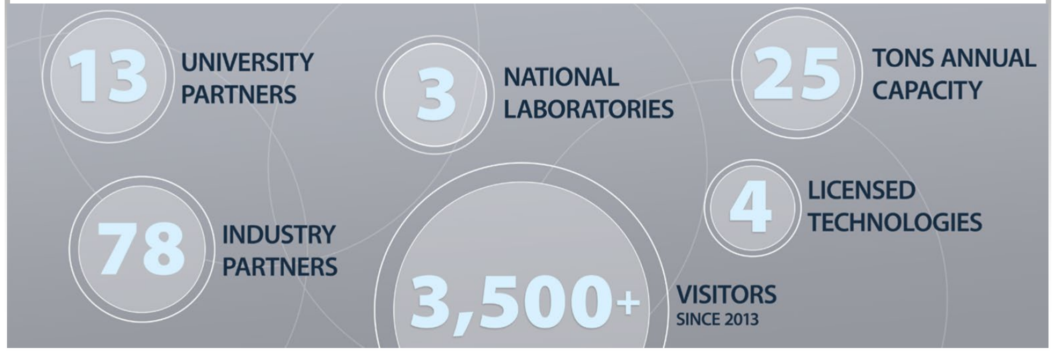
The Carbon Fiber Technology Facility (CFTF) serves as a national resource to assist industry in overcoming the barriers of carbon fiber cost, technology scaling, and product and market development. CFTF is intended to be the bridge from R&D to deployment and commercialization of low-cost carbon fiber

- Demonstrate carbon fiber production using lower-cost precursors and reduced energy
- Enable development of domestic commercial sources for production of low-cost fiber or high-volume composites applications
- Formulate a Workforce Development program for carbon fiber and advance composites workforce

Key Thrusts

- Establish and perform collaborative R&D projects to reduce technical uncertainties of CF manufacturing process
- Investigate potential alternative carbon fiber precursors
- Investigate CF intermediate forms and technical challenges in composite applications
- Establish artificial intelligence-based framework and correlate process data to product characteristics
- Investigate and develop process measurement, sensing, and control methods

Up to **70% reduction** in carbon fiber manufacturing process **embodied energy**



Carbon Fiber Technology Facility – N95 Filter Production

ADVANCED EQUIPMENT AND EXPERTISE

- AMO's investment in the CFTF created conditions for the team to react nimbly to develop new, scalable methods to meet demand for N95 filter material.
- Experts de-risked a specific and reproducible set of parameters, making them adoptable by the manufacturing industry.

AGILE RESPONSE TO N95 DEMAND

- Work with N95 inventor Dr. Peter Tsai to tackle real-time challenges with conversion
- Partner with engine, filtration, and power generation manufacturer Cummins to convert their commercial melt blowing lines to potentially produce millions of pounds of N95 material
- Open source the process parameters for industry, enabling textile and filter manufacturers with melt blown machines to start making N95 filters

CAPABILITY SUCCESS

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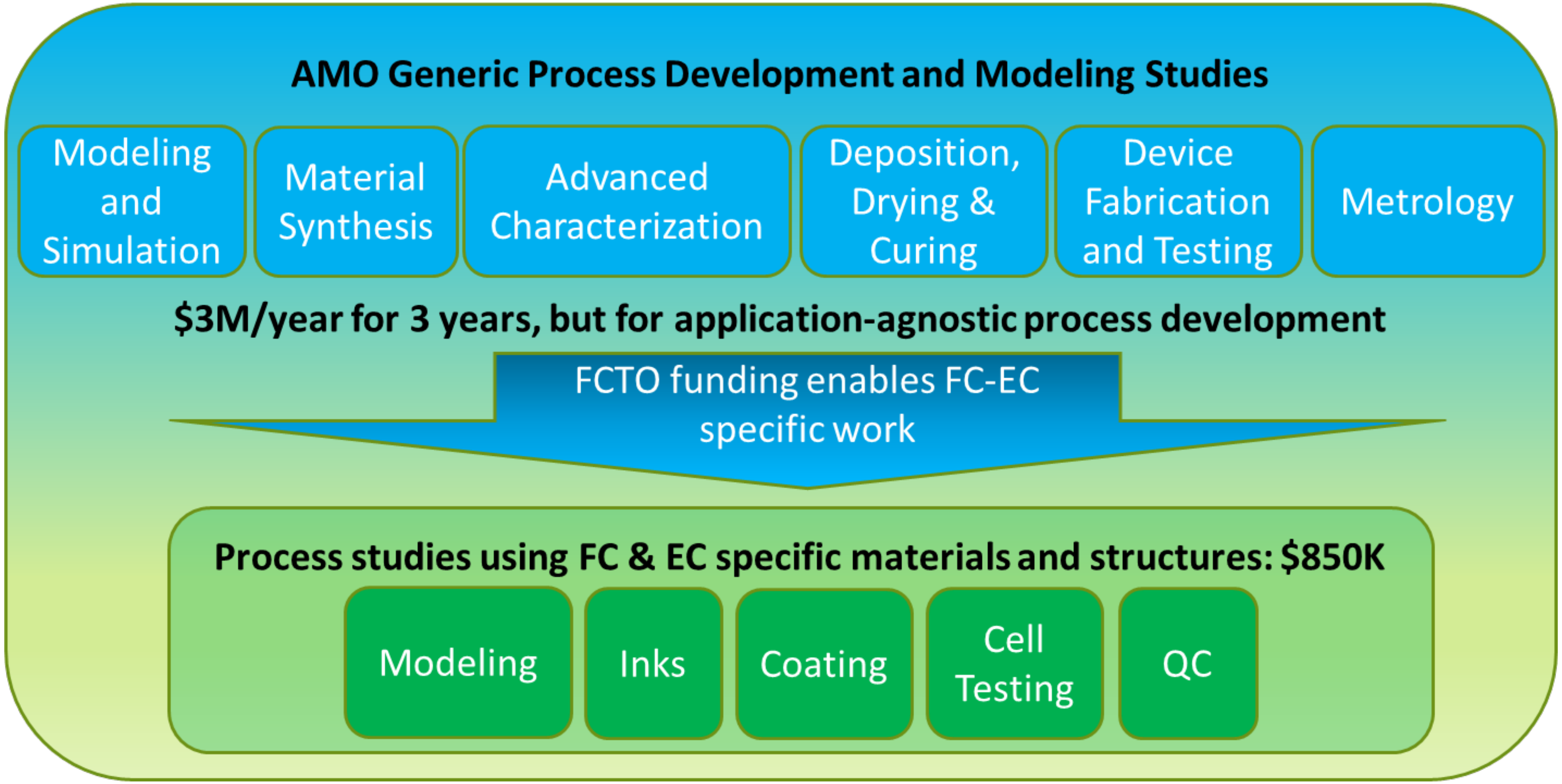
Concept: Leveraging AMO Generic Process Development to Address HFTO Manufacturing Barriers

- Barriers: Lack of high-volume MEA processes, Low levels of quality control
- Goal: Develop roll to roll manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) from the 2008 value of $38/kW to $20/kW by 2025.



R2R Manufacturing Collaborations

AMO DE-FOA-0001980 Topic 1.2 battery manufacturing FY20 awards (co-supported by VTO)

HFTO DE-FOA-0002229 Topic 1 Electrolyzer Manufacturing R&D (co-supported by AMO)

AMO R2R Advanced Materials Manufacturing (AMM) Collaboration

nel

GM

PLUG POWER

Argonne NATIONAL LABORATORY

- Novel deposition via electrospinning
- In-situ characterization via x-ray scattering
- Advanced testing capabilities

OAK RIDGE National Laboratory

Kodak

SAINT-GOBAIN

- Colloidal chemistry & surfactant research
- Slurry processing & coating scale-up
- Deposition parameters, drying, and curing

SOLAR WINDOW TECHNOLOGIES, INC.

nel

FISKER

NAVITAS SYSTEMS

NREL NATIONAL RENEWABLE ENERGY LABORATORY

- Physics & methods for coatings / deposition
- Fabrication / In-situ testing
- Novel NDE, QC, and metrology

INDUSTRY

BERKELEY LAB

- Macroscopic mathematical modeling of colloids
- Coating parameter measurement & quantification
- X-ray tomography of dried coatings

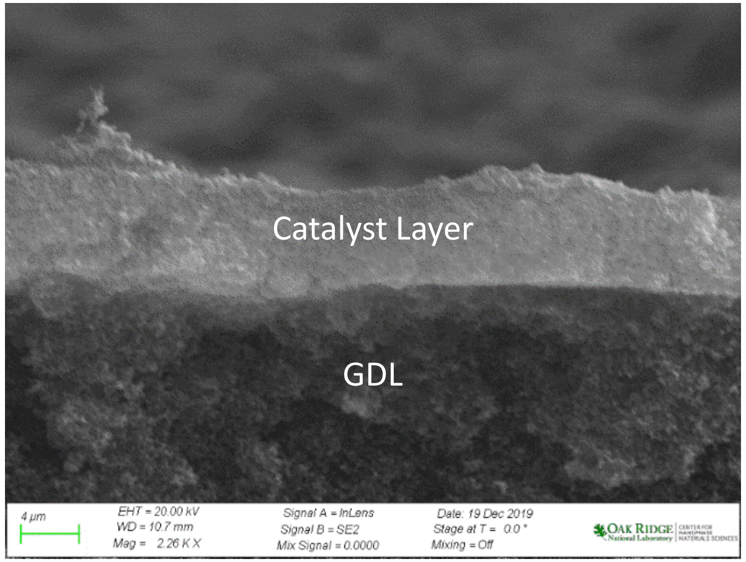
Sandia National Laboratories

- Validation of continuum-scale models
- Acceleration of coating designs & scale-up processes
- Prediction of optimum coating / deposition windows

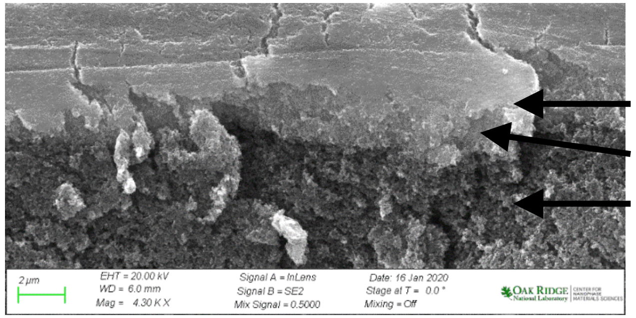
Achieved Target 0.1 mg/cm² Pt Loading of Fuel Cell Inks with Single and Dual Slot-Die Coating

Line Speed (ft/min.)	Ink Extrusion Rate (mL/min.)	Catalyst Layer Thickness (µm)	Pt Loading (mg/cm^2)
4.0	4.6	TBD	0.098
4.0	5.7	7	0.08
5.0	4.6	TBD	0.107
5.0	5.7	2	0.16

4 ft/min.
5.7 mL/min.



First Dual-Layer Slot-Die Coating Completed

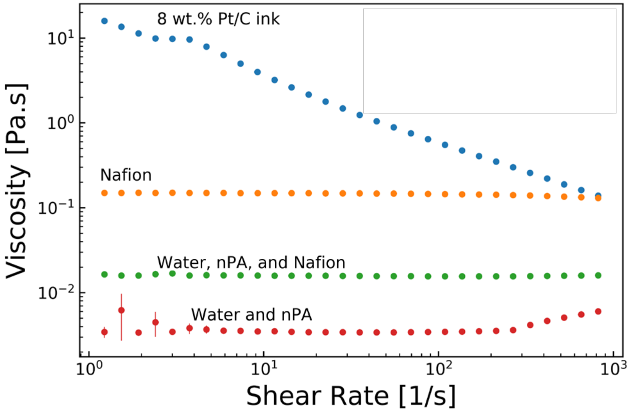


Ionomer Overlayer
Catalyst Layer
GDL

R2R Slot Die Coating of Fuel Cell Catalyst Layers

Slurry Prep

Component	Wt. %
Pt/C	8.00
Water	56.25
Nafion D2020	19.16
n-Propanol	16.59
Total	100.00
Solid Content	**12.02**



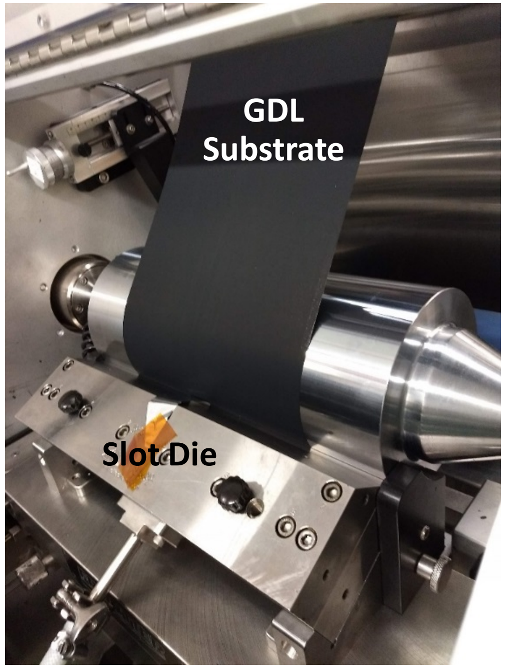
Solids increase viscosity. Pt/C makes ink shear thinning.

Shear mixing

at 10,000 rpm for 1 h

Coating

on a Dynacoat line



FY20-21 HFTO Project Overall Multi-year Workplan

1. **Modeling**
   a. Inks: interparticle interactions and macro properties as a function of constituent properties
   b. Coating
   c. Drying/consolidation

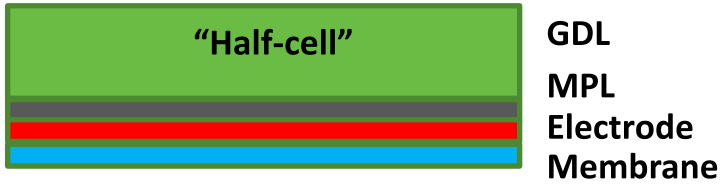
2. **Inks & Colloids**
   a. Ink formulation and substrate interactions
   b. Dispersion methods and scalability
   c. Advanced characterization: agglomeration and interactions

3. **Coating & Drying**
   a. Parametric studies of 1L and ML coated structures related to different cell build methods (CCM vs. GDE)
   b. Drying of 1L and ML coatings
   c. Advanced characterization: nano- and micro-morphology
   d. Correlation of ink structure with consolidated coating structure

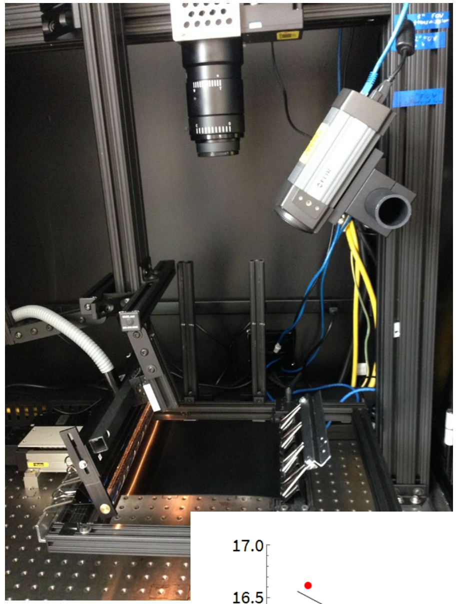
4. **QC**
   a. QA measurements for inks prior to and during coating
   b. In-line QC for active layers, ML

5. **MEA fabrication and testing**
   a. Fuel cell (FC)
   b. Electrolysis (LTE)
   c. Correlation of ink structure, coating architecture, and MEA performance

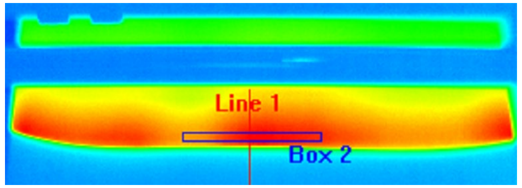
Progress: GM



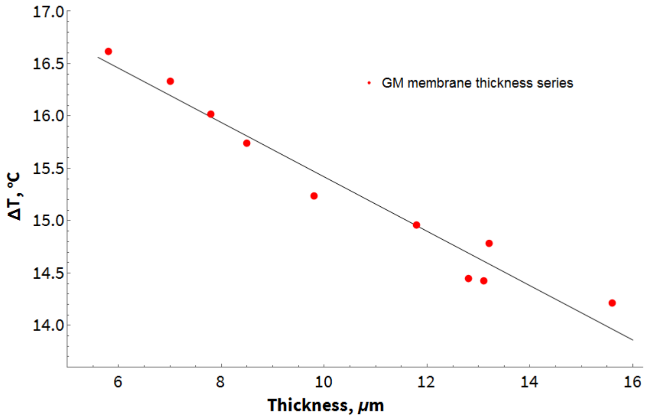
- GM: Continue existing effort with NREL for in-line PEM “half-cell” QC method
- Measure membrane thickness in multilayer structure
  - Connection with Collaboration phase II goals
- “Thermal scanning” technique
  - Protected by joint NREL-ORNL patent (VTO/AMO effort)



Benchtop testbed



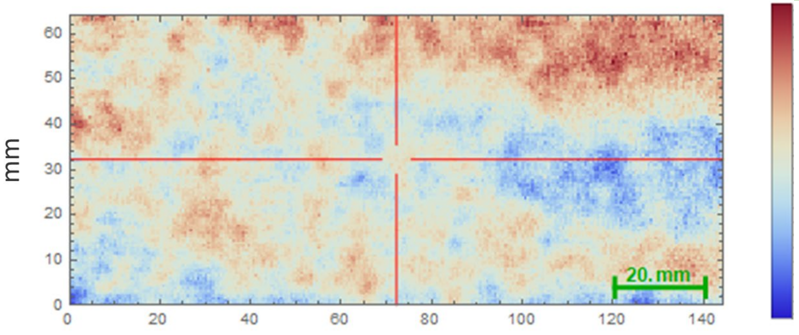
Example thermal image of sample moving under energy source



Previously established temperature-thickness correlation

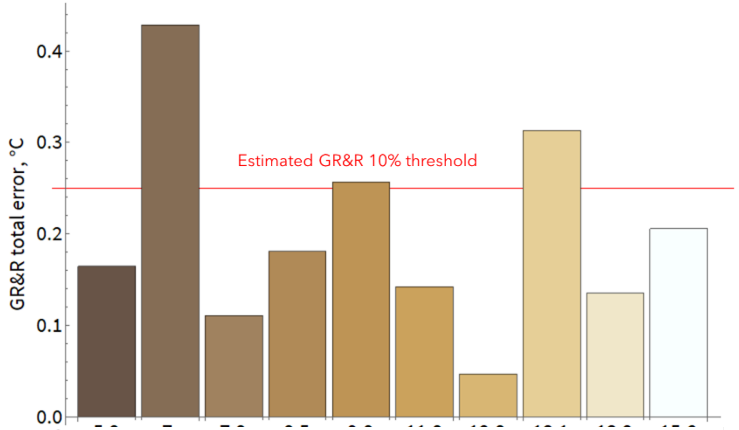
Progress: GM

- **Current work**
  - Verify acceptable error
  - Understand mapping capability
- **Using existing thermal imaging data, perform Gauge R&R analysis**
  - Error close to GR&R standard 10% threshold
  - Error less than GM stated 30% of thickness target
  - Spatial analysis increases error, but perhaps acceptably

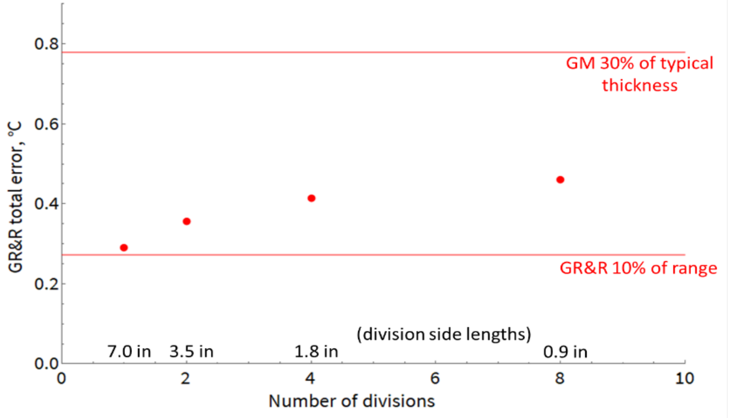


Prior result: Membrane thickness map

What is the error?



GR&R error for each GM sample



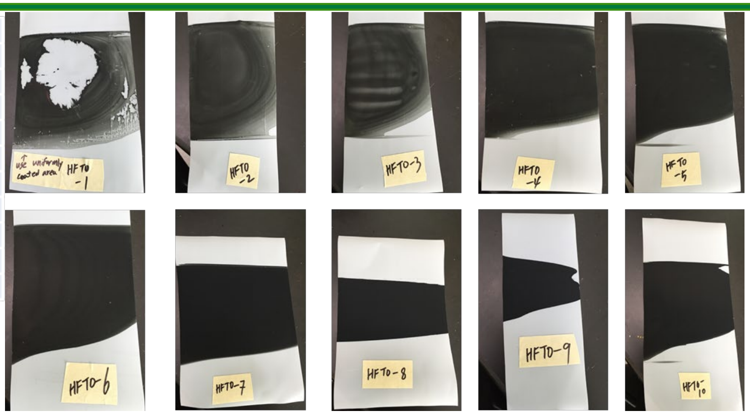
Error analysis as a function of spatial segregation

Progress: NeI

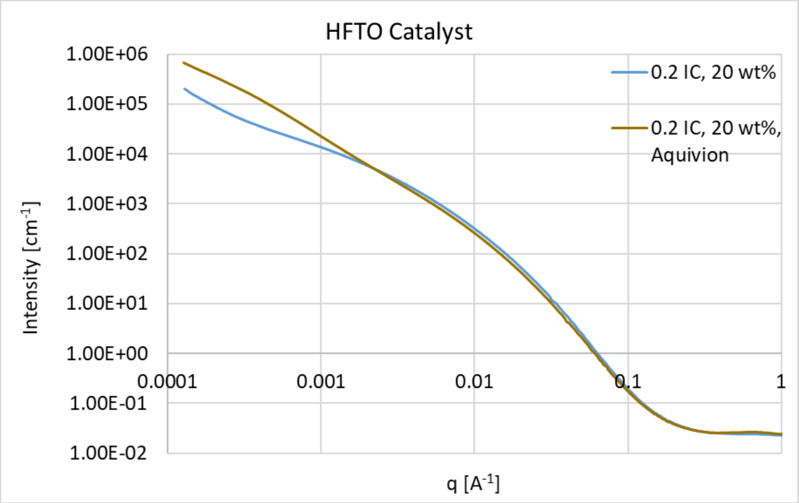
- **Anode (IrOx) inks fabricated with different:**
  - Ionomer to catalyst ratio
  - Total solids
  - Ionomer type
- **Catalyst layers rod-coated onto decal (PTFE)**
  - Using inks above
  - Different wet thickness/loading
- **Inks and CLs sent to ANL**
  - USAXS performed at the APS
  - Data analysis ongoing

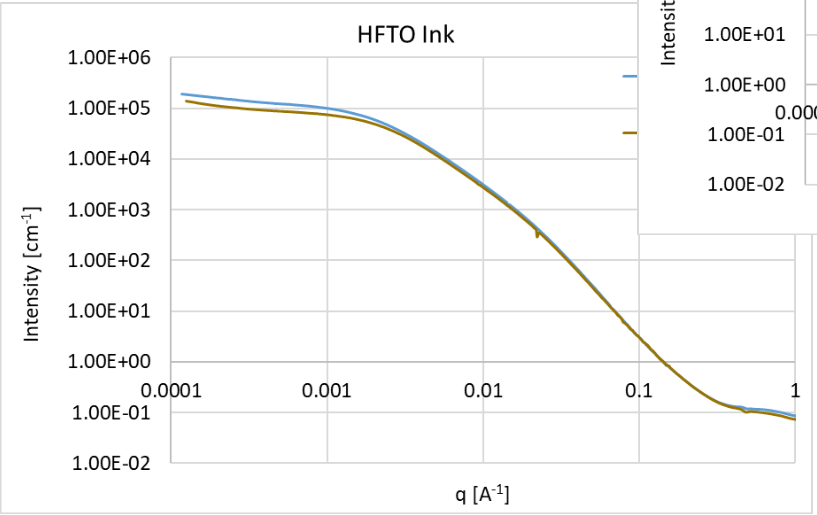
Ink and rod coating matrix, rod-coated decals

Sample ID	I:C	wt.%	Ionomer types	Blade coating gap (um)
HFTO-1	0.1	10	Nafion	90
HFTO-2	0.2	10	Nafion	90
HFTO-3	0.3	10	Nafion	90
HFTO-4	0.1	20	Nafion	45
HFTO-5	0.2	20	Nafion	45
HFTO-6	0.3	20	Nafion	45
HFTO-7	0.1	30	Nafion	30
HFTO-8	0.2	30	Nafion	30
HFTO-9	0.3	30	Nafion	30
HFTO-10	0.2	20	Aquivion	45



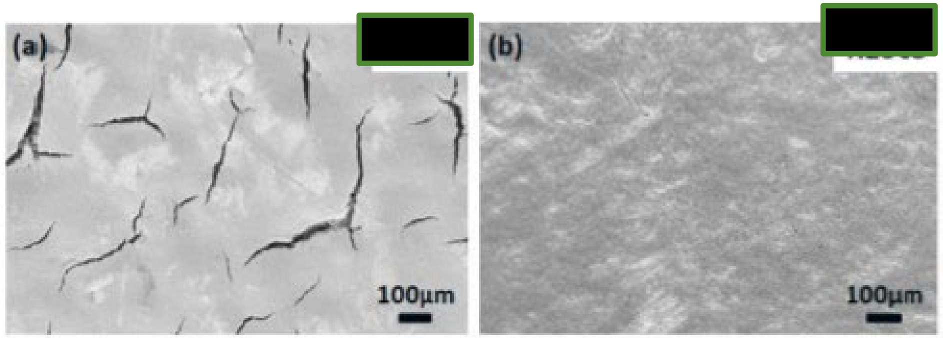
Preliminary USAXS data for ink (below) and coating (right)

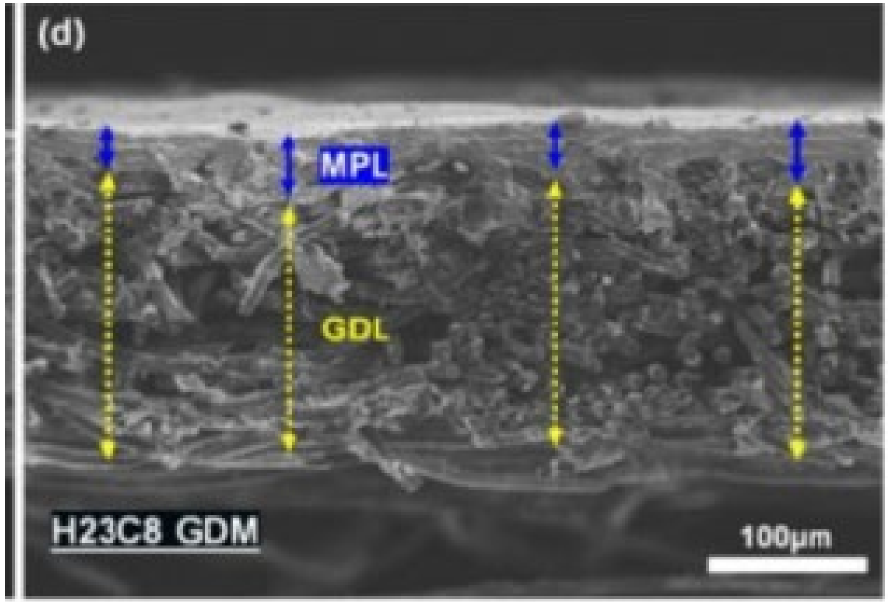




Progress: Plug Power

- Plug wants to qualify Gas Diffusion Media from US-based manufacturers
  - Three most used GDM are foreign manufactured
  - Plug will provide sheet samples of GDM from at least four US manufacturers
  - Labs will assess coatability for making electrodes, performance of GDEs, and suitability of media for R2R processing
    - GDE coating
    - Advanced characterization
    - Device fabrication and testing





Example GDM images

AMO Technical Areas Relevant to the Hydrogen and Fuel Cell Communities

- Electrolyzers: Bob Gemmer (AMO)
- Advanced Composite Materials: Chad Schell (AMO)
- Roll-to-Roll: Brian Valentine (AMO)
- **Hydrogen in Iron Refining and Steel Manufacturing: Nick Lalena (AMO)**
- Electrochemical Technologies: G. Jeremy Leong and Kathryn Peretti (AMO)

Utilizing Hydrogen in Iron Refining and Steel Manufacturing

- Since 1970, the very energy-intensive configuration of a Blast Furnace (which produces “pig iron”) feeding into a Basic Oxygen Furnace (BOF) has been the dominant process for primary steelmaking from iron ores. In the Blast Furnace, coke is used as the fuel to generate heat. On burning, it produces CO, which is used as the reducing agent for the iron oxide. In the BOF, oxygen is blown through the molten pig iron, lowering the carbon content and producing low-carbon steel.

- In competition with this process, the Electric Arc Furnace (EAF) can make steel at much lower energy requirements from 100% scrap metal feedstock, although the heavy and dynamic electric load requirements can, if unmitigated, result in electric grid instability.

- “Sponge iron” produced from the solid-state reduction of iron ore using syngas (a mixture of CO and H2) inside a Direct Reduced Iron (DRI) furnace can be added to the scrap EAF feedstock to increase its purity.

https://www.ussteel.com/products-solutions/knowledge-base/photo-gallery-6

https://www.asminternational.org/web/hts/news/newswire/-/journal_content/56/10180/35899880/NEW

http://www.worldsteelnews.com/world-largest-dr-ironmaking-plant/

Energy Use by Process

Process	Energy Use (GJ/t steel)
Blast Furnace	10.4 – 10.9
	12.7 – 18.6
	16.7
BOF	0.06 – 0.5
	0.7 – 1
EAF	3.4 – 5.5
	4 – 6.5
DRI	10.9 – 16.9
	10.4 – 12.4

LBNL Report: Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry (2010)
CO2 abatement in the iron and steel industry, IEA Clean Coal Centre (2012)
H2@Scale Workshop Presentation, Berry Metal Company, Aug 01, 2018

Utilizing Hydrogen in Iron Refining and Steel Manufacturing

- The reduction of iron ore with hydrogen as a solo reductant has greater gas utilization and a greater thermodynamic driving force at high temperatures than does reduction with CO. However, while reduction with CO is mildly exothermic, H2 reduction is endothermic meaning that **heat must be supplied to the system in order to maintain a constant reduction temperature**.

- The biggest challenges are in the kinetics of iron oxide reduction, which is affected by many process parameters (temperature, pressure, and reducing gas composition) as well as material properties (grain size, morphology, and porosity), each having a major influence on the reduction performance. Although hydrogen is generally a better reducing agent compared with carbon monoxide in these respects, **the parameters need investigation and optimization**.

- Another problem that must be solved for commercial viability of pure H2 reduction is the availability of the required amount of hydrogen. It is not possible to produce all the needed hydrogen via low carbon or renewable energies so bridging H2 production technologies are necessary. Additionally, the flue gas contain a large fraction of hydrogen that must be separated from hydrogen/steam stream and recycled. The hydrogen demand of pure H2 reduction technologies may cause an increase in energy consumption. The motivation is lies in the **lowered CO_2 emissions**.

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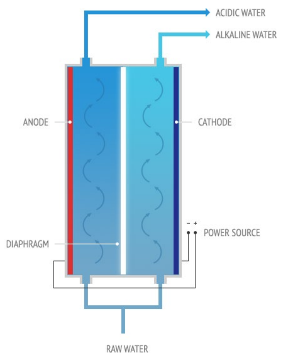
Leveraging Electrochemistry Advances in Manufacturing

- **Electrochemical systems could provide numerous benefits to manufacturing:**
  - Energy and Resource Efficiency
    - High product selectivity leads to lower waste and simplified processes.
    - Energy reduction through intensified manufacturing processes and lower thermal budgets.
    - Distributed nature allows manufacturing industry to be nimble and can benefit from the variable/dynamic nature of operation based on grid loads.
  - Emissions Reduction
    - Leverage renewable resources through electrification of manufacturing processes
    - Enables chemical transformations (like CO_2 to fuels) that would otherwise be inaccessible

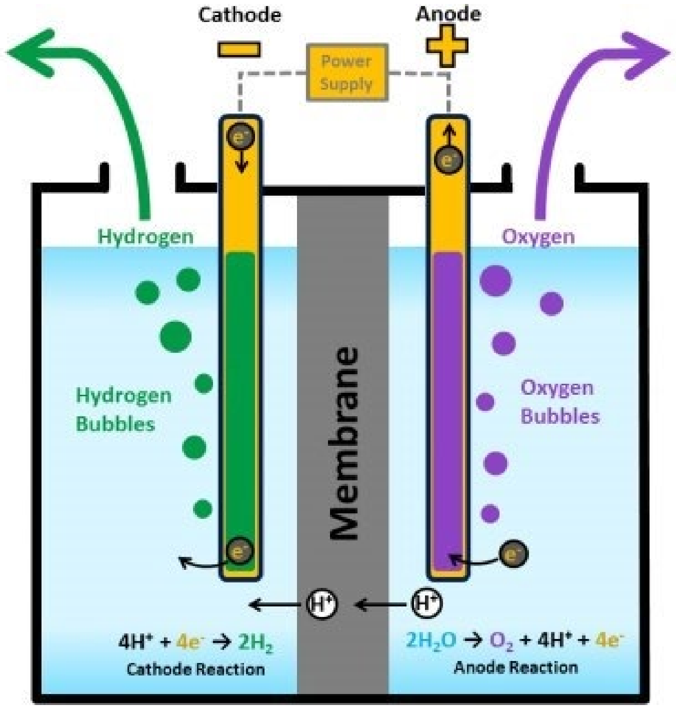


Problem: Despite extensive research and recent advances in technology, scale up and commercialization of electrochemical systems in manufacturing has been slow.

Images taken from Envirolyte website, EFS 2018 presentation, and OE progress report

Leveraging Opportunities and Addressing Challenges

- **Opportunities:**
  – Cost of electricity, a major cost of electrochemical operations, is coming down.
  – Technical advances using electrochemistry for chemical synthesis, including ammonia, methanol, ethylene, epoxides, nitriles and other specialty chemicals.
  – Increased use of electrochemistry to manufacture chemicals such as methanol and ammonia could save up to 200MTCO_2eq by 2050.



- **Challenges:**
  – Durability of the electrode, catalyst and membrane
  – Poor understanding of how to optimize activity, selectivity, and durability through operational parameters
  – Multidisciplinary nature of devices; lack of familiarity of electrochemical principles
  – Manufacturability has not been a major focus of cell development

2013 IEA technology roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes

Connection to AMO and DOE Initiatives

- Electrochemistry touches several key AMO and DOE initiatives:
  - Industrial sector electrification
  - CO_2 utilization
  - Scalable H_2 production
  - Efficient water purification
  - Process Intensification
  - Energy storage

- Accelerating commercial deployment of electrochemical systems in a variety of applications, including basic chemical synthesis would:
  - Improve energy efficiency of U.S. manufacturing by simplifying industrial processes and enabling lower temp. transformations with lower energy consumption.
  - Reduce the life cycle energy and resource impacts of manufactured goods by electrifying industry and reducing energy and solvent use through elimination or simplification of separation processes.
  - Leverage renewable electricity in U.S. manufacturing, while strengthening environmental stewardship
  - Accelerate the transition of DOE-supported innovative technologies and practices into U.S. manufacturing capabilities by taking a multidisciplinary approach and considering manufacturing in module design and development.

Looking Forward: Manufacturing Challenges with Electrochemical Technologies

AMO is coordinating with other DOE offices to seek input from stakeholders and experts in the area to inform future work.

Potential topics could include:

- Common pinch-points in the development and deployment of electrochemical devices across application spaces
- Challenges/opportunities of integrating electrochemistry into manufacturing processes
- An analysis of how each component contributes to the economics of electrochemical devices and identify where R&D could have the most impact

To learn more and subscribe for updates on workshops, solicitations, and more, visit [manufacturing.energy.gov.](manufacturing.energy.gov)

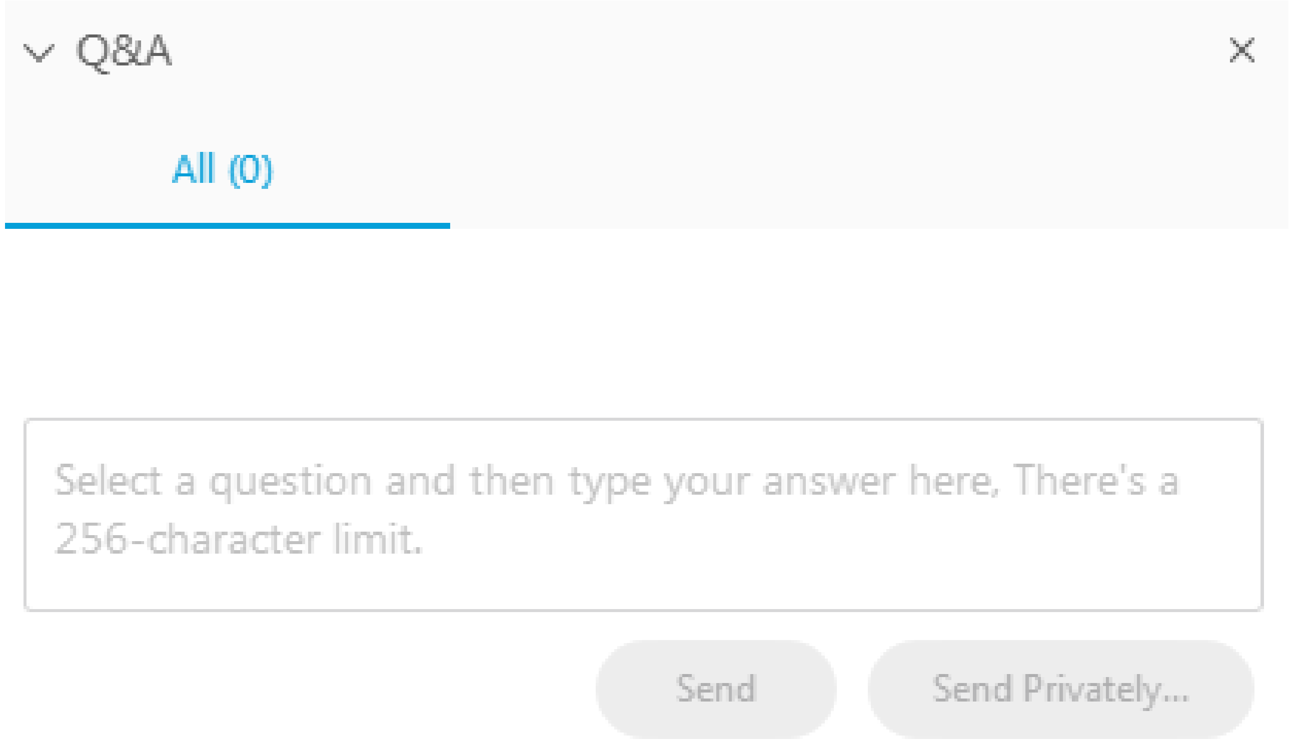
Thank You

For additional information
and to subscribe for updates:

manufacturing.energy.gov

The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



INCREASE YOUR H_2IQ

The #H2IQ Hour

Thank you for your participation!

Learn more:

energy.gov/fuelcells
hydrogen.energy.gov

Backup Slides

Lab-Embedded Entrepreneurship Programs

GOAL

Empower innovators to mature their ideas from concept to first product, positioning them to align with the most suitable commercial path to bring their technology to scale.

1. **Recruit** the best energy technology innovators
2. **Leverage** expert mentorship and world-class facilities at the national labs on a win-win basis
3. **Position** people and technology for market

Spin the nation's top innovators "in" to the National Labs

Technical Assistance

C A P A B I L I T Y

Public-private partnerships help manufacturers and industrial organizations set and achieve long-term energy intensity reduction goals through:

- Technical assistance and in-plant training
- Access to National Laboratory resources, software, and instrumentation
- Networking opportunities
- National recognition through awards, case studies, and success profiles

S U C C E S S

230+ partners

3,200+ plants

54 energy & water goal achievers

>$6B cumulative energy cost savings

>1 quadrillion TBtu saved

Better Plants® U.S. DEPARTMENT OF ENERGY

Manufacturing's Role in Energy Storage Grand Challenge

GOAL

U.S. global leadership in energy storage utilization and exports with a **secure domestic manufacturing supply chain independent of foreign sources of critical materials**

DOE FOCUS

Accelerate scale-up of **emerging manufacturing processes**

Improve **critical materials supply chain** resilience

Address **technical barriers** in production and manufacturing

Technologies and Supply Chains

Meeting the Energy Storage Grand Challenge goal will require a combination of research and technology development across the manufacturing supply chain.

Raw materials → Refined materials → Component manufacturing → Energy storage system manufacturing → End user → Recycling/ Reuse/ Disposal

R&D AREAS

- Manufacturing process intensification
- Critical materials use & sourcing
- Roll-to-roll manufacturing capabilities
- Membrane manufacturing processes
- New materials & manufacturing processes for harsh service environments
- Water desalination & purification
- Combined Heat & Power systems

POTENTIAL TECHNOLOGIES

- Flow batteries
- Thermal energy storage
- Lithium-based batteries
- Non-lithium-based solid state batteries
- Hydrogen generation & storage
- Compressed air energy storage
- Pumped hydro
- Synthetic fuels (e.g. synbiogas)
- And others