

PAJARITO POWDER, LLC

Comprehensive Catalyst Products for
Fuel Cells & Electrolyzers

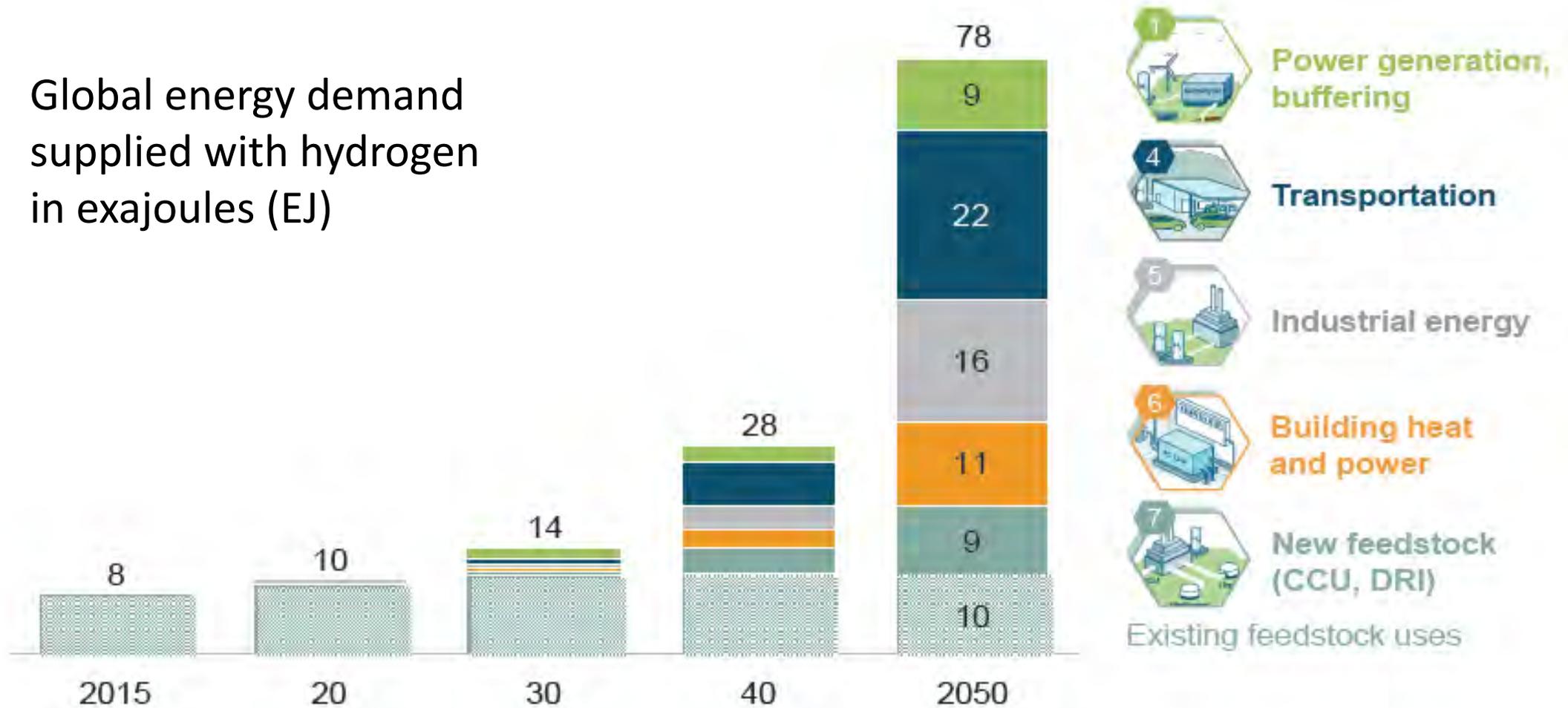
December 2020



PAJARITO
POWDER
FUEL CELL CATALYSTS

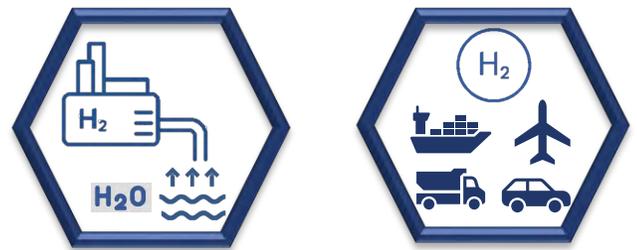
Hydrogen demand could increase 10-fold by 2050

Global energy demand supplied with hydrogen in exajoules (EJ)



SOURCE: Hydrogen Council

Potential Niobium Use for Hydrogen Mobility



	Class	Power Used or Produced per Device	Annual H ₂ Produced or Used per Device	NbOx Required per Device	2030 Total NbOx Demand
  	Small Electrolyzer	1 MW	160 Tons	500g	180 T
  	Passenger Car	90 kW	160Kg	~50g	239T
  	Light Truck	150 kW	240Kg	~82.5g	
   	Heavy Truck/Bus	250 kW	6.7 Tons	~137.5g	

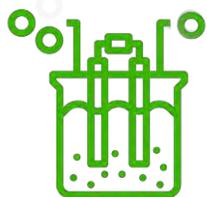
3.6M Cars + Light Trucks in 2030
 186,000 Heavy Trucks + Buses in 2030

361 GW of Electrolyzers in 2030
 58 Million Tons of H₂ Produced in 2030

H₂ Production

H₂ Delivery

H₂ Consumption



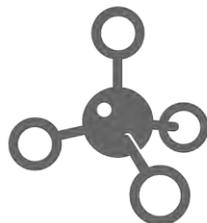
Electrolysis

Green

Expected Demand in 2030:
49 Million Tons H₂ =
180 Tons of NbOx
225 Tons of FeNb

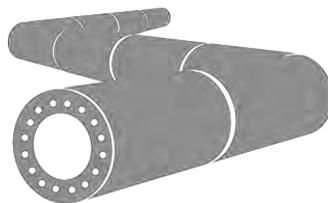


Steam Methane Reforming
with Carbon Capture
Blue



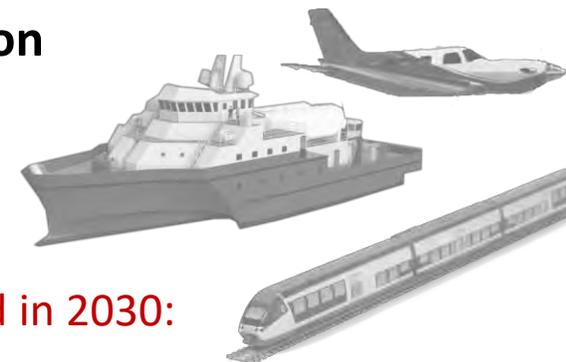
Steam Methane Reforming
No Carbon Capture
Grey

**Maximum potential demand
for FeNb equivalent in 2030
1.400 Mt**



Expected Demand in 2030:
1.700 KM of H₂ Pipeline
= 880 Tons of FeNb

Transportation



Expected Demand in 2030:
435 GW of Power
= 239 Tons of NbOx / 300 Tons FeNb

Ammonia Production



Steel Production

Burn for Heat



Expected Demand in 2030:
1.9 GW of Power
= 1-2 Tons of NbOx / 2,5 Tons FeNb

Combined Heat & Power



Backup Power



Pajarito Powder Overview

8

8-year old startup with established customers



Electrocatalyst products for Fuel Cell & Electrolyzer



Electrocatalyst products for PEM & Alkaline



Intellectual Property (IP) portfolio > 40 patents



Proprietary, patented manufacturing platform



Product roadmap for electrocatalyst products



World-class technical team & advisory boards

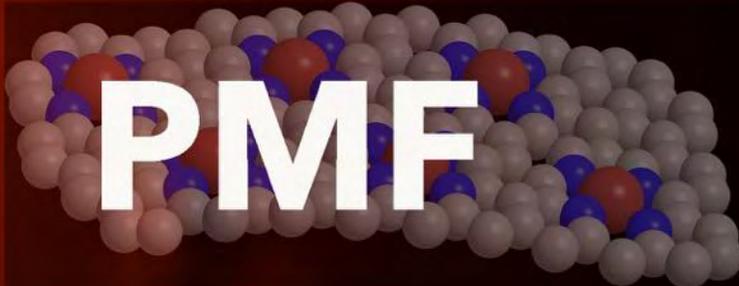


Sales to major automotive OEMs and suppliers

VariPore™



ECS



PMF

**Electrolyzer
Catalysts**



Pajarito Powder Products



Fuel Cell Catalysts and Supports

- Engineered Catalyst Supports™ (ECS)
 - For improved platinum utilization, improved durability and enhanced catalyst performance
- Precious Metal/ECS Catalysts
 - Full customer solution
 - Materials solution tailored to customer system design

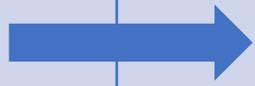
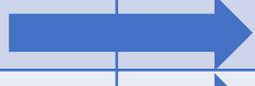
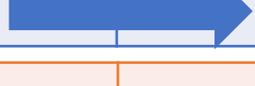
Electrolyzer Catalysts

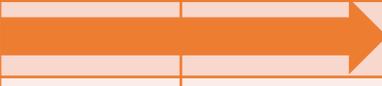
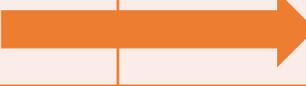
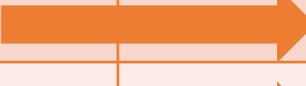
- Engineered Electrolyzer Catalysts (EEC)
 - For PEM, AEM, & Alkaline



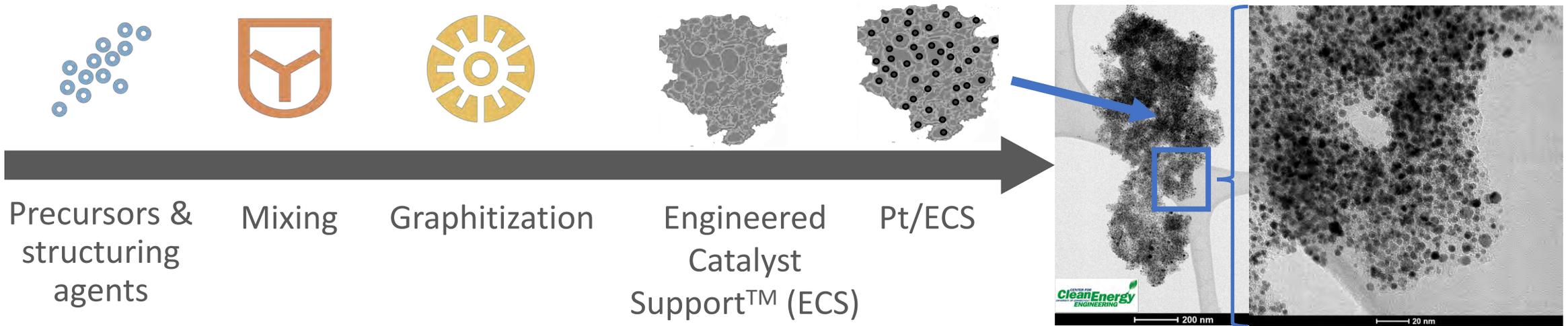
PEM Fuel Cell Product Roadmap

Pajarito Powder is developing and manufacturing high-performance PEM fuel cell catalysts featuring Niobium: Carbon supports that are Niobium-doped or coated, PtNb intermetallic alloy catalysts, and Nb-based carbon-free supports in development.

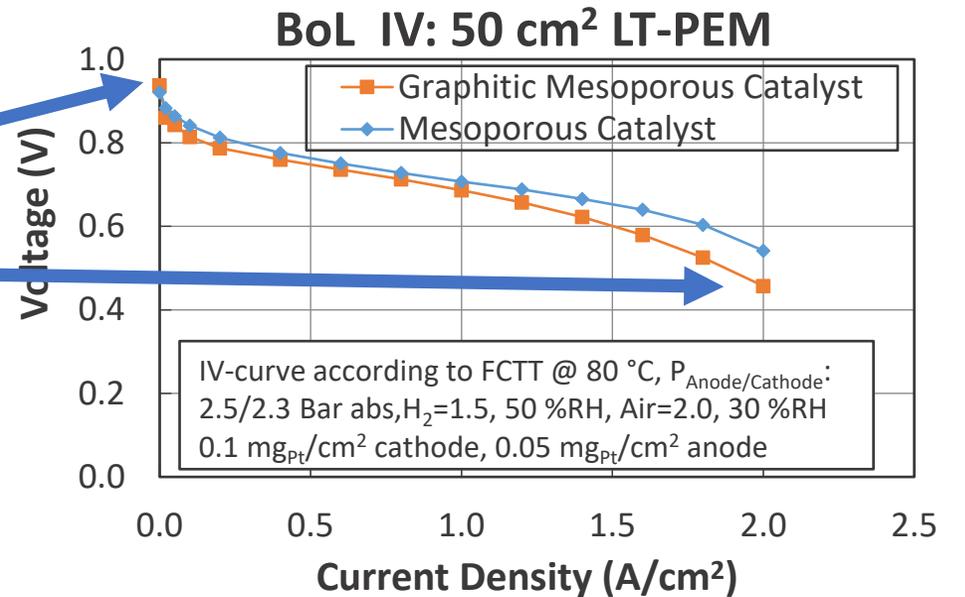
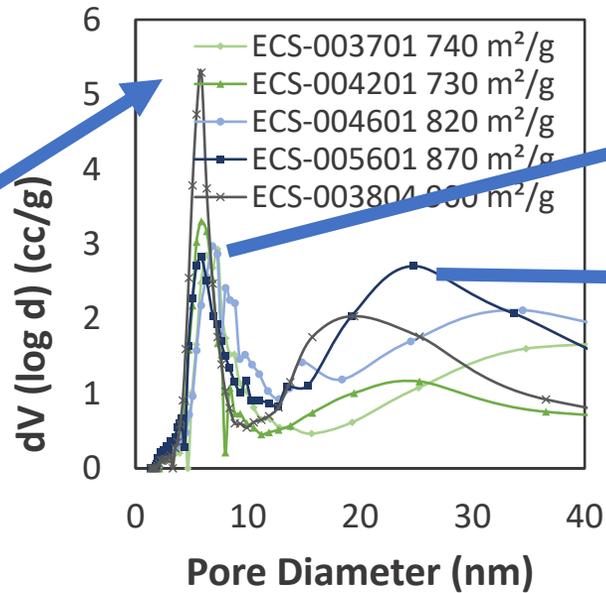
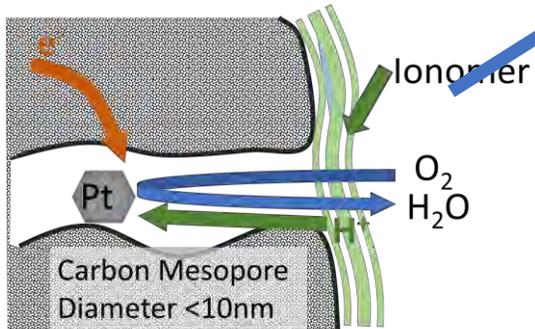
Cathode Materials (ORR)	Product	2017	2019	2022	2026
Precious Metal in Niobium based coated support (Nb-C-O oxycarbide layer or cluster on carbon support)	• Pt / ECS Nb _{ML}				
Platinum Niobium Intermetallic Alloy in Engineered Catalyst Support incorporating Nb	• PtNb _{IM} / ECS _{Nb}				
Pt in Niobium based support	• Pt / NbX				
Pt Niobium alloy in Niobium-alloy based support	• PtNb / NbX				

Anode Materials (HOR)	Product	2017	2019	2022	2026
Pt in Niobium alloy support	• Pt / NbX				
Precious Metal in Niobium based coated support (Nb-C-O oxycarbide layer or cluster on carbon support)	• Pt / ECS Nb _{ML}				
Pt Niobium alloy on Niobium alloy support	• PtNb / NbX				
Unsupported Pt/PtNb alloy Black	• Pt Black • PtNb Black				

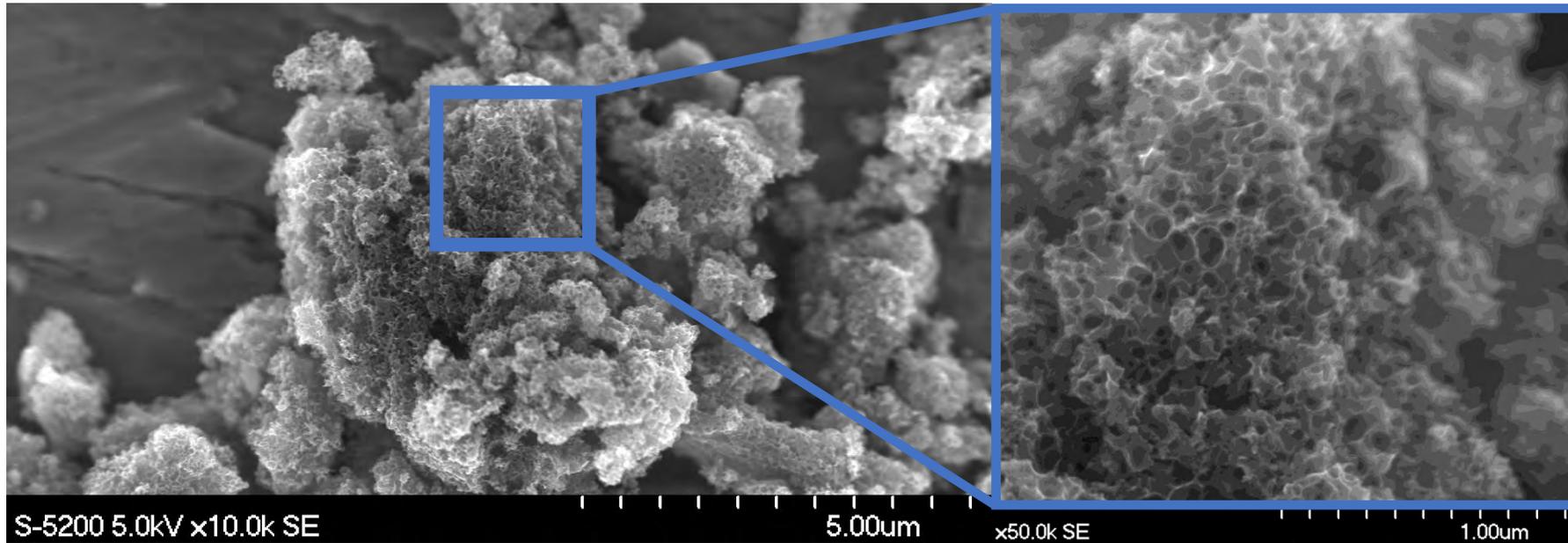
Fuel Cell Catalyst Products



- Mesoporous effect**
- Improve Pt effectiveness
 - Allow high current densities
 - Improves stability



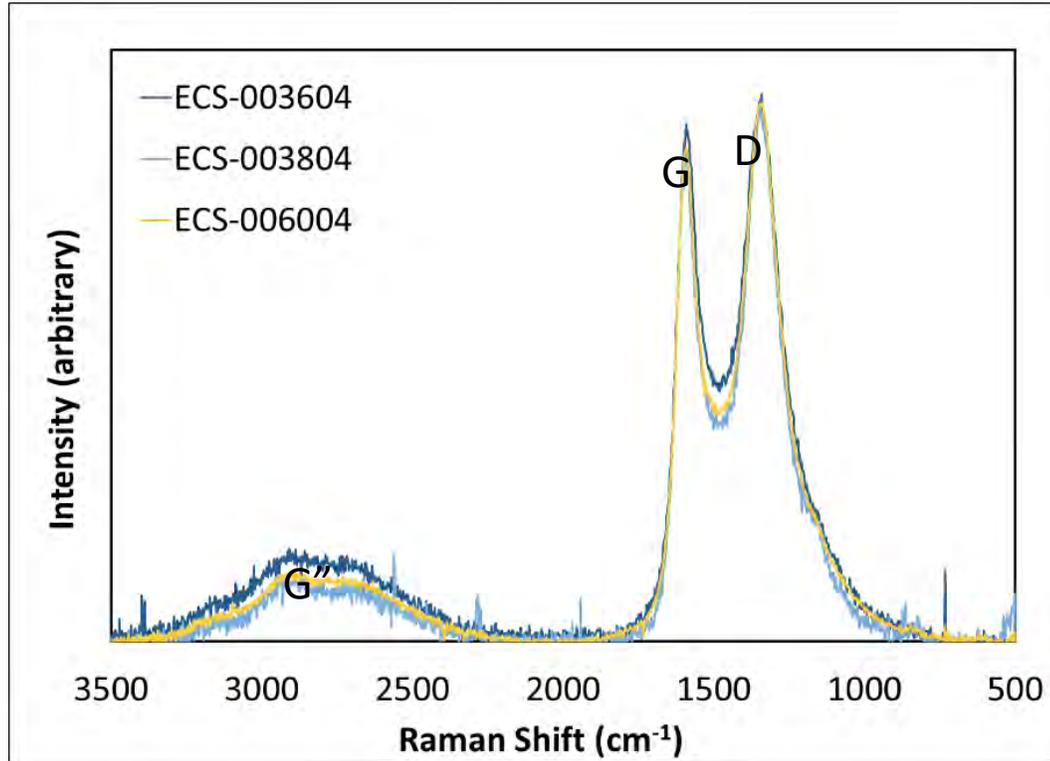
Engineered Catalyst Supports Overview



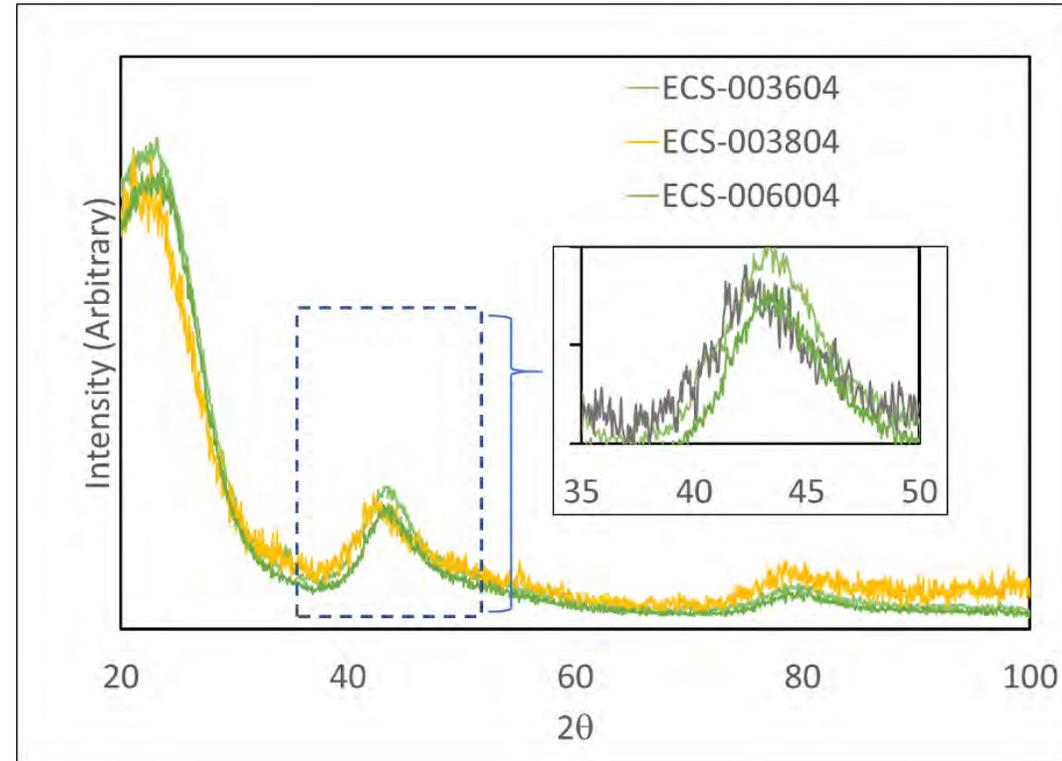
Specification:	Value/Range
Surface area, BET	400 – 900 m ² /g
Pore size	5 nm – 50+ nm
Particle size, DLS	0.4 - 1.0 μm
Available dopants	Nitrogen and others
Other properties	G/D ~0.8 - 1.2, pore volume ~0.5 – 2.5 cc/gr

Nb-Doped Support Structure

Raman Spectroscopy



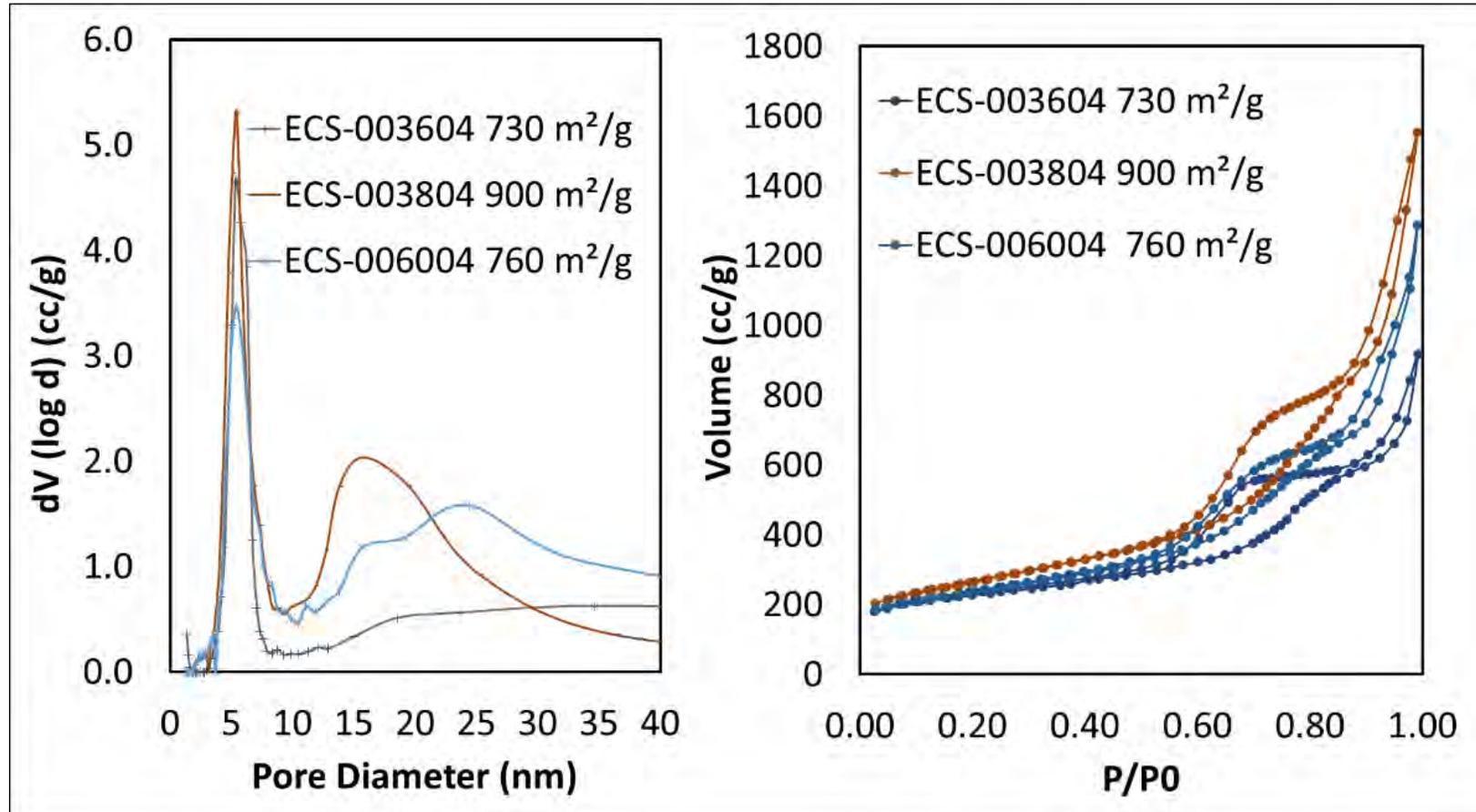
X-Ray Diffraction



Nb doping of carbon supports does not change overall chemical and crystalline structure.

ECS_{NB} Mesoporous Supports Porosimetry

N₂ Physisorption and Pore Analysis



Nb-dope ECS Materials made with a range of 700-900+ m²/gr surface areas and pore sizes with 5-8 nm and 15-40 nm mesopores

Pajarito Powder Products



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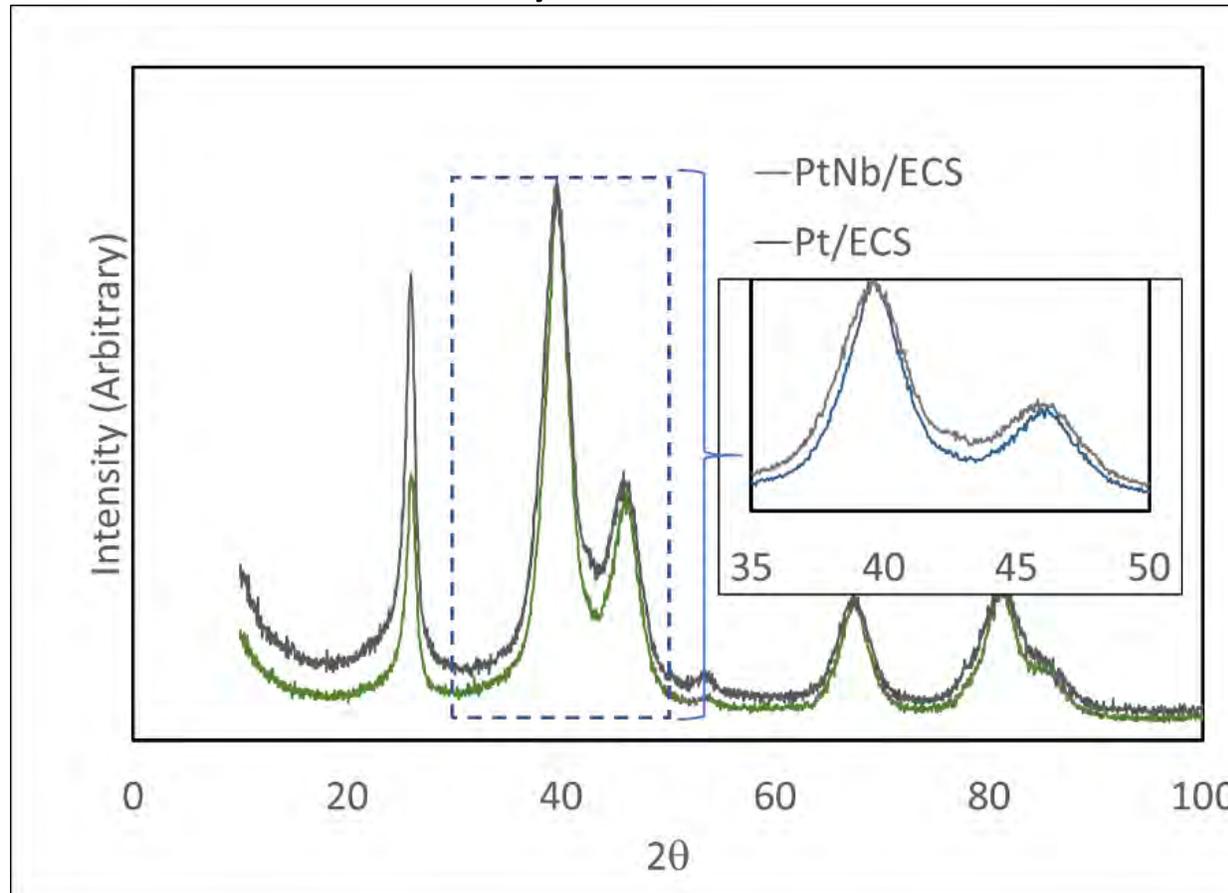
Electrolyzer Catalysts

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 - For PEM, AEM, & Alkaline



ECS Platinization Capability and Examples

X-Ray Diffraction

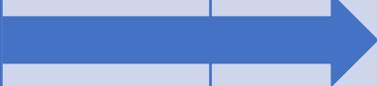
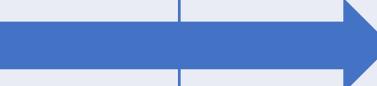


30 wt% Pt₉Nb and 30 wt% Pt supported showing both materials are a Pt crystal structure, and with 2.5-3.1 nm crystallite sizes.

- Program 1: US DOE Hydrogen Fuel Technologies Office (HFTO) program for development of medium- and heavy-duty electrodes awarded to General Motors under [M²FCT program](#)
 - Team: 3M, Pajarito Powder, Colorado School of Mines, and Cornell University
 - Pajarito Powder providing and developing full catalysts, both pure Pt and advanced alloy catalysts, for Heavy-Duty application
 - www.hydrogen.energy.gov/pdfs/review20/fc323_ramaswamy_2020_p.pdf
- Program 2: NSF Fuel cell catalyst scale-up and manufacturing
 - Team: Colorado School of Mines, University of Connecticut, Forge Nano, NREL, Fraunhofer Institute (DE) and Pajarito Powder.
 - Pajarito providing Fuel cell catalysts for scale-up and manufacturing analysis

PEM Electrolyzer Product Roadmap

Pajarito Powder offers an existing line of high-performing PEM electrocatalyst in quantities up to 1 Kg/monthly. Development of high-performing Niobium containing electrocatalysts initiated in 2019 shows promise.

Anode Materials (OER)	Product	2017	2019	2022	2026
Precious Metal	<ul style="list-style-type: none"> PtIrNb IrO₂Nb IrRuO₂Nb 				
Precious Metal on Nb Support	<ul style="list-style-type: none"> PtIr / Nb IrO₂ / Nb IrRuO₂ / Nb 				
Precious Metal/Carbon-free	<ul style="list-style-type: none"> IrRuO₂ / NbO_x 				

Cathode Materials (HER)	Product	2017	2019	2022	2026
Precious Metal on ECS	<ul style="list-style-type: none"> Pt / ECS_{Nb} PtNb / ECS_{Nb} PtNi / ECS 				
Precious Metal	<ul style="list-style-type: none"> Pt Black PtNb Black 				

Pajarito Powder Products



Fuel Cell Catalysts and Supports

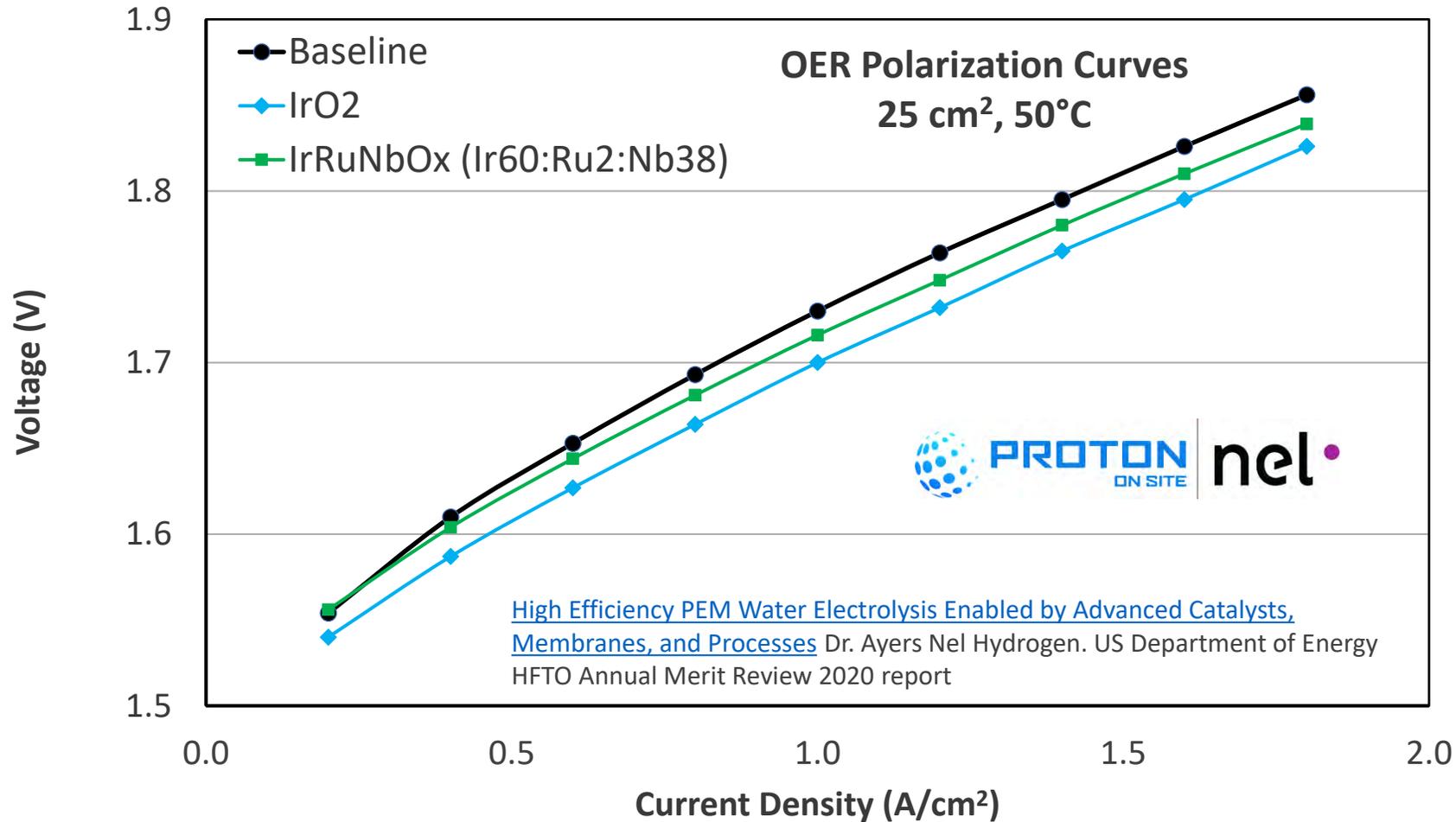
- Engineered Catalyst Supports™ (ECS)
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Electrolyzer Catalysts

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 - For PEM, AEM, & Alkaline

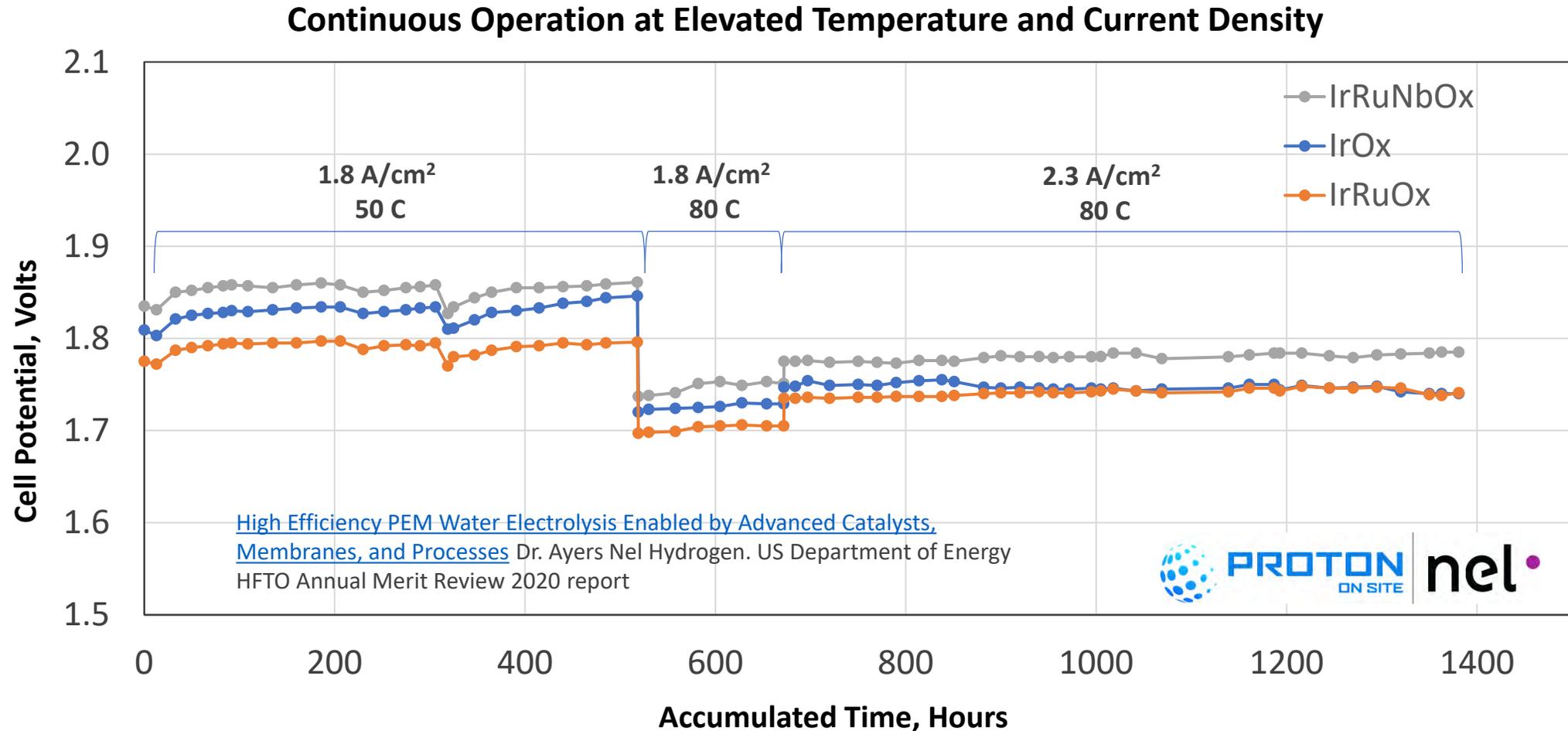


EEC Demonstrative Performance - Anode



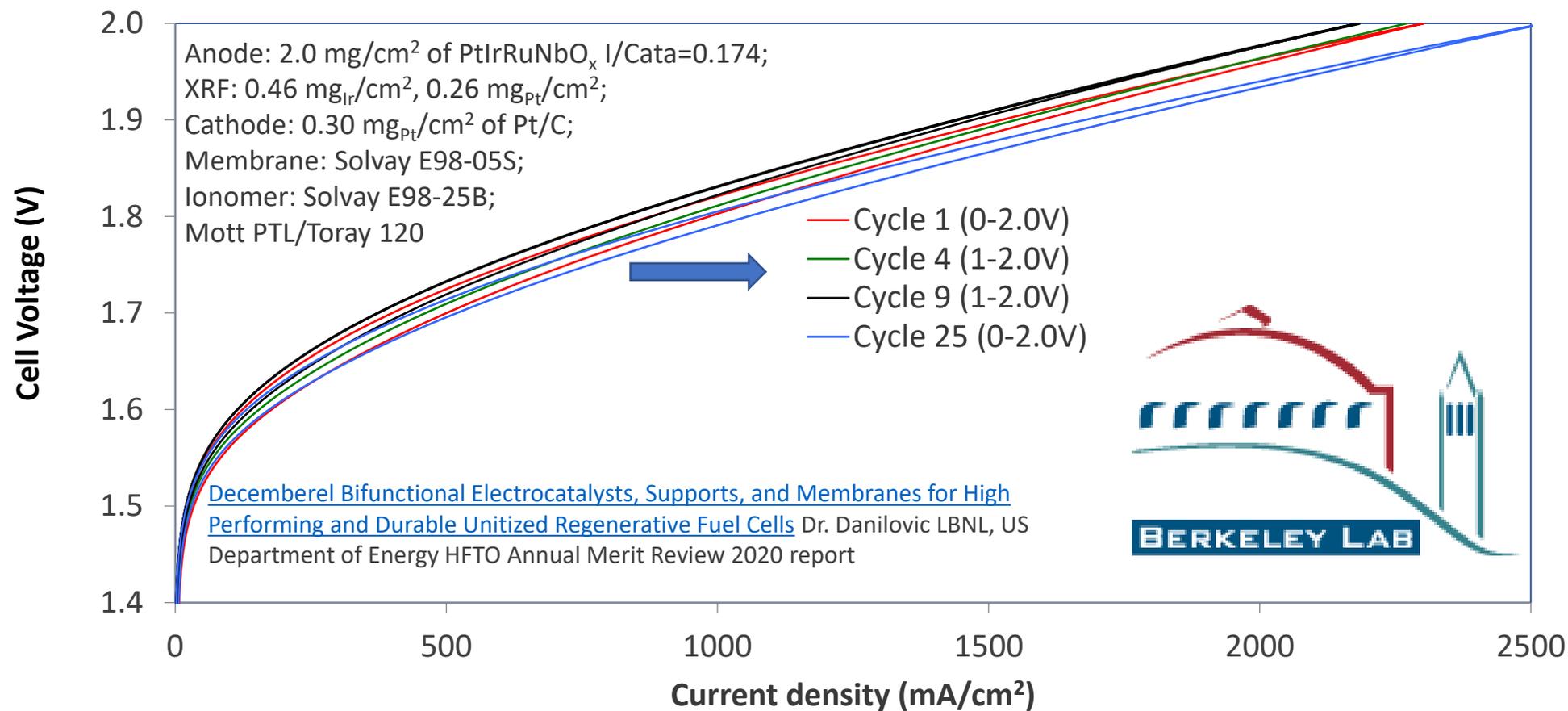
High surface area IrO_x and IrRuO_x/NbO_x showing excellent performance compare to baseline IrO_x under polarization

EEC Demonstrative Performance - Stability



High surface area IrO_x, IrRuO_x, and IrRuO_x/NbO_x all showing stability over 1400 hrs of testing.
First proof of long-term use of Nb in PEM Electrolysis

Supported Pt/Ir for Fuel Cell/Electrolyzer



High surface area Pt/IrRuO_x/NbO_x showing excellent anode performance under repeated polarization testing for Reversible Fuel Cell Electrolyzer Operation – **Energy Storage Potential!**

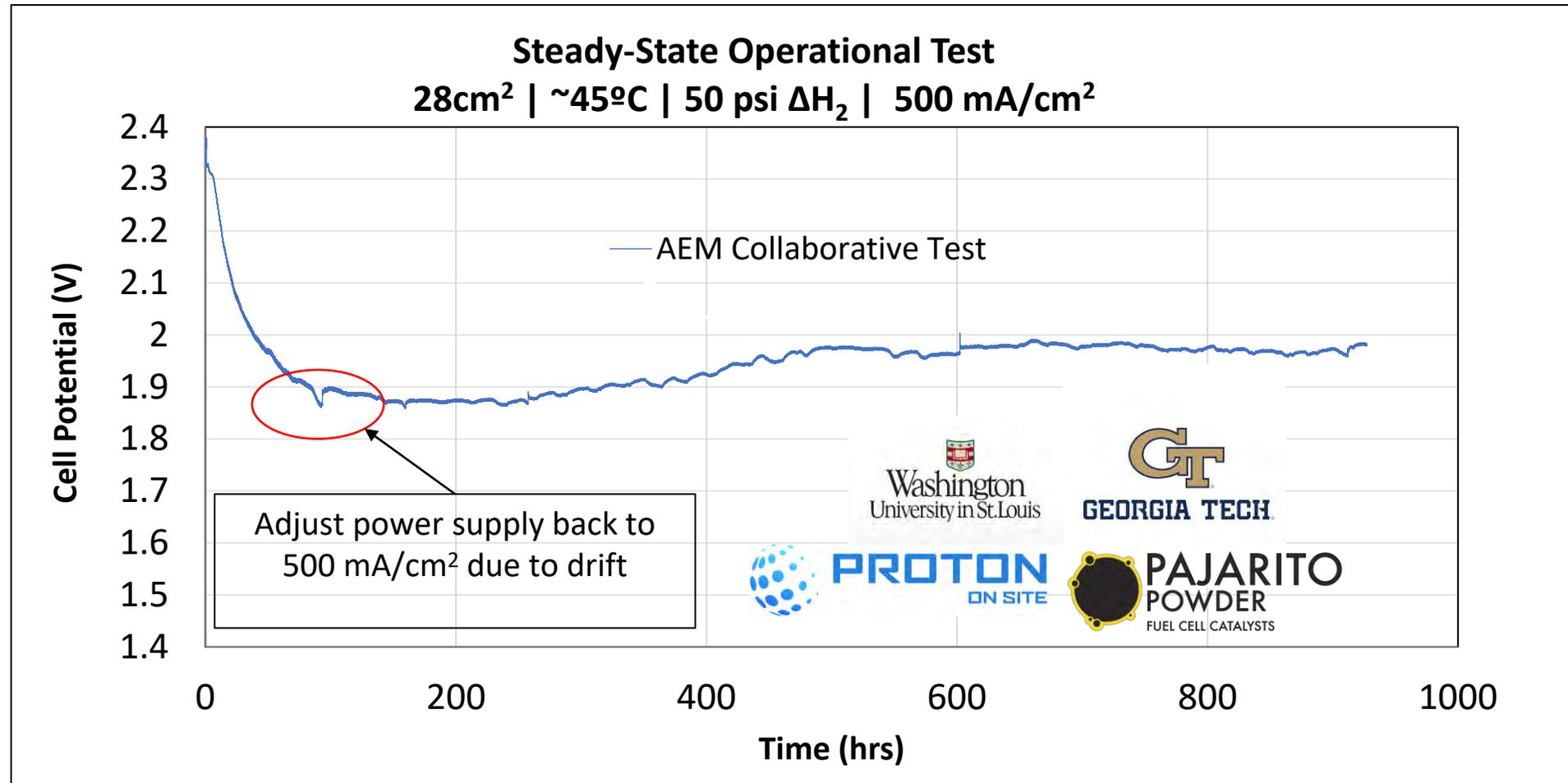
AEM & Alkaline Electrolyzer Product Roadmap

Pajarito Powder is developing and manufacturing high-performance, low cost, PGM-free and low-PGM electrolyzer catalysts explicitly designed for AEM and alkaline systems, based upon experienced developed through several on-going government-funded projects.

Anode Materials (OER)	Product	2017	2019	2022	2026
Precious Metal	<ul style="list-style-type: none"> PbRuO_x IrRuO₂ 	→			
PGM-free	<ul style="list-style-type: none"> Perovskites Perovskite/NbO_x 		→		
Precious Metal / Carbon-free	<ul style="list-style-type: none"> Supported IrO₂ IrRuO₂ / NbO_x 	→			

Cathode Materials (HER)	Product	2017	2019	2022	2026
Precious Metal on ECS	<ul style="list-style-type: none"> PtAlloys / ECS_{Nb} Pt / ECS_{Nb} 	→			
Precious Metal-free	<ul style="list-style-type: none"> Ni Alloys, supported and unsupported NiMo Niobium Sulfide 		→		

AEM PGM-OER Catalyst Stability



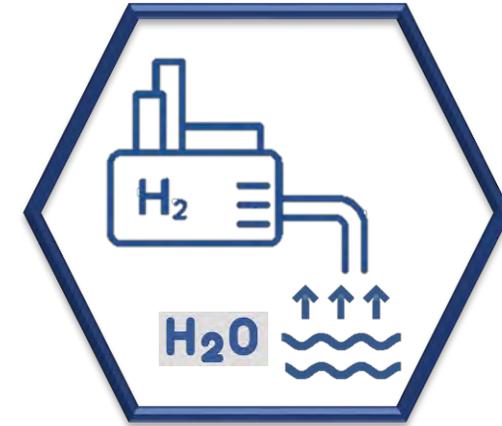
Near 1000 hr stability at 0.5 A/cm² using Georgia Tech AEM (PES SBIR)

Development and deployment of catalysts for AEM and PEM electrolyzers and energy storage www.h2awsm.org

- Program 1 – Georgia Institute of Technology
Objective: Develop catalysts for AEM
- Program 2 – Los Alamos National Laboratory (LANL)
Objective: Improved AEM electrodes and PGM-free catalysts
- Program 3 – Lawrence Berkeley National Laboratory (LBNL)
Objective: Improved and supported catalysts for PEM Unitized Regenerative Fuel Cell
- Program 4 – Lawrence Berkeley National Laboratory (LBNL)
Objective: Low PGM catalysts for PEM OER

Example Customer: Hydrogen Production

- **Major Electrolyzer manufacturer**
 - Based in Europe and the U.S.
- **Selling Engineered Electrolyzer Catalysts (EEC)**
 - Both anode and cathode catalysts
- **Multiple levels of product qualification**
 - Pajarito Powder formulating catalyst as “drop-in” replacement
 - Customer qualifying catalyst for next generation
 - Completion originally targeted for 2020; now early 2021 (COVID delay)
 - This is a Nb-based product*
 - Future solutions will include further material modifications (Nb+others)
- **Working with company since 2016**
 - Began relationship with shared grant activity



Example Customer: Mobility

- **Major Asian Automotive OEM**
 - Have fuel cell vehicles on the road today
- **Selling primarily Engineered Catalyst Support (ECS)**
 - Some interest in full catalyst solution
- **Currently in qualification for inclusion in next generation vehicle**
 - Company tried multiple variations of ECS materials
 - Current qualification is refined version of standard product
 - Target roll-out in 2023
 - Future solutions could include material modifications (Nb + others)
- **First contact in 2016**
 - First product shipment in 2017



PajaritoPowder.com

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December 2020



Questions?

Thank you