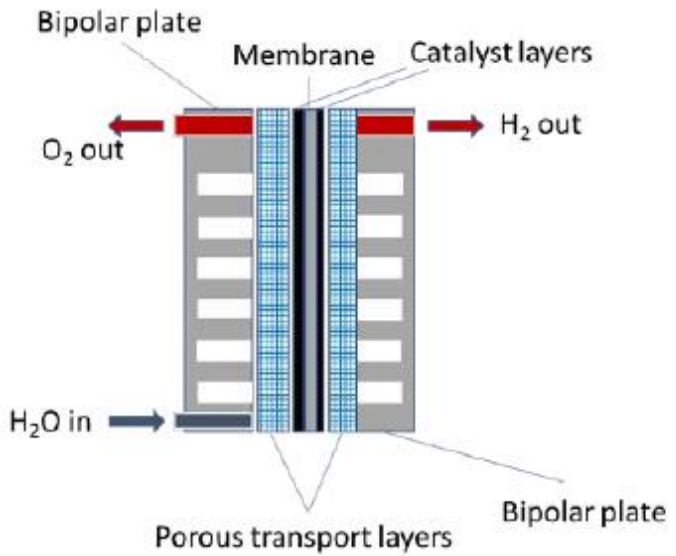
Transition to Bryan

Meeting Agenda* – Day 1

Day 1: Expert Presentations & Panels
(Q&A to follow each individual session)

11:00 AM	**Welcome, Context, & Overview of Workshop Goals** Speaker: Dr. Sunita Satyapal & Dr. Ned Stetson, DOE HFTO
11:15 AM	**Component/System Overview & Technoeconomic Analysis** Speaker: Dr. Bryan Pivovar, H2NEW
12:00 PM	**Current Status and Needs: Advanced PEM Materials (Industry Panel)** Dr. Kathy Ayers, Nel Hydrogen Dr. Corkey Mittelsteadt, Plug Power Dr. Nemanja Danilovic, Electric Hydrogen
1:00 PM	**Networking Break**
1:45 PM	**Low-PGM/PGM-free Catalysts and Novel Supports** Speaker: Dr. Debbie Myers, Argonne National Lab
2:30 PM	**Novel Membranes & Ionomers** Speaker: Prof. Mike Hickner, Pennsylvania State University
3:15 PM	**Porous Transport Layers** Speaker: Prof. Iryna Zenyuk, University of California, Irvine
3:45 PM	**Bipolar Plates** Speaker: Dr. Ton Hurkmans, Ionbond
4:15 PM	**Wrap-up and Adjourn**

- Advanced material development/ Component focus



**All times in Eastern Standard Time*

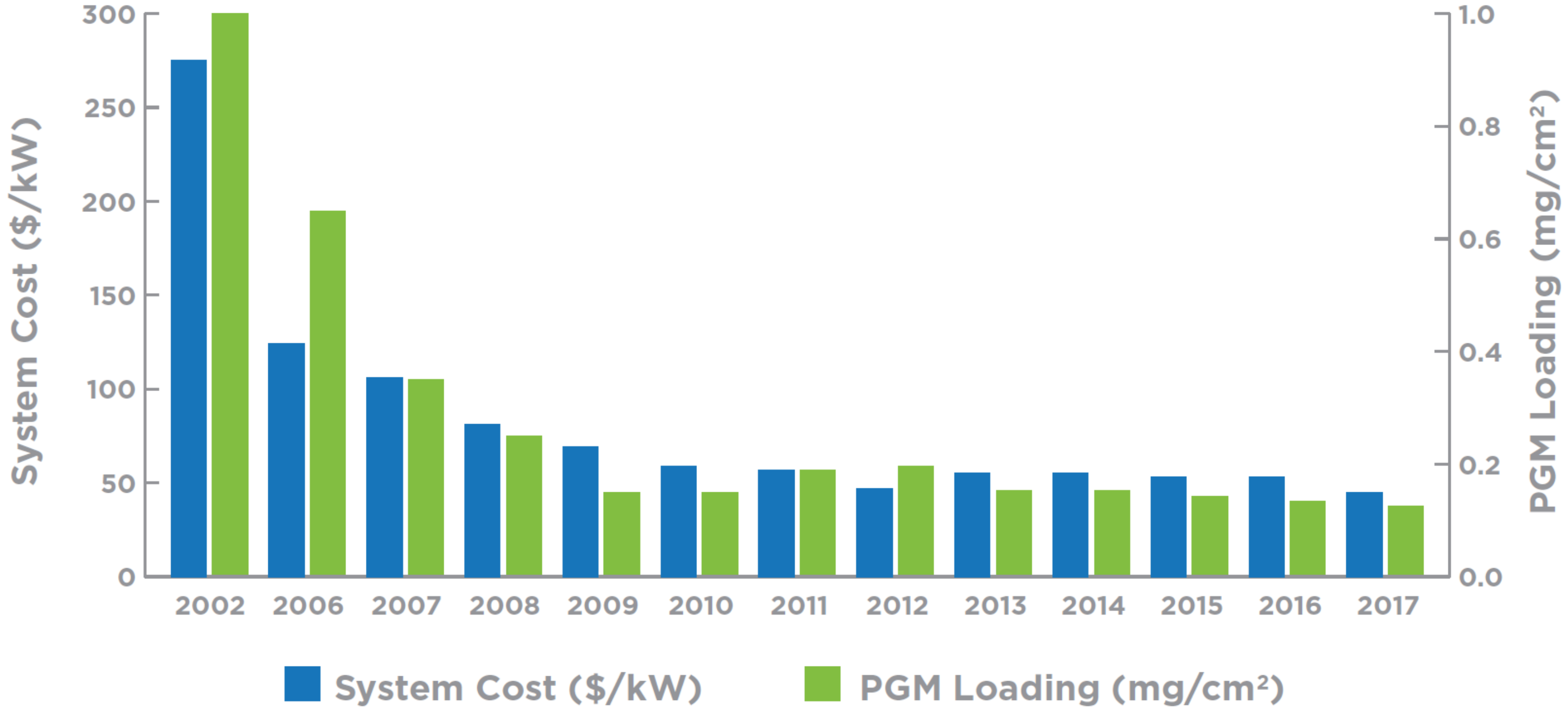
Meeting Agenda* – Day 2

**All times in Eastern Standard Time*

Day 2: Break-out Discussions

11:00 AM	Welcome			
Round 1 11:15 AM - 12:45 PM	Novel Low-PGM OER Catalysts	Novel PGM-free OER Catalysts	Advanced PFSA Membranes	Novel PTL and Interface Materials
12:45-1:15 PM	Break			
1:15-2:00 PM	Report-Out			
Round 2 2:00-3:30 PM	Cathode Improvements	Catalyst Material Discovery & Electrode Structures	PFSA Membrane Alternatives	Bipolar Plates and Coatings
3:30-4:00 PM	Break			
4:00-4:45 PM	Report-Out			
4:45 PM	Wrap-Up and Adjourn			

DOE funded R&D was critical to reducing PEM FC costs



- Advanced material development played key role in reducing FC system costs and PGM loadings.
- Similar cost reductions required for electrolysis

B. Pivovar, Nature Catalysis, 2(7), 562-565, 2019. https://doi.org/10.1038/s41929-019-0320-9

Electrolyzers by Type

Type	Pros	Cons
Alkaline	Well established, lower capital cost, more materials choices at high pH, high manufacturing readiness, can leverage established supply chains, demonstrated in larger capacity	Corrosive liquid electrolyte used, higher ohmic drop, lack of differential pressure operation, shunt currents, limited intermittency capabilities, efficiency
Polymer Electrolyte Membrane	Low ohmic losses/high power density operation, differential pressure operation, DI water only operation, leverages PEM fuel cell development and supply chain, load following capability	Requires expensive materials (Ti, Ir, Pt, perfluorinated polymers), lower manufacturing and technology readiness, efficiency
Solid Oxide	High efficiency, low-cost materials, integration with continuous high temperature electricity sources (e.g., nuclear energy), leverages SOFC development and supply chain, differential pressure operation	High temperature materials challenges, limited intermittency capabilities, thermal integration, lower manufacturing and technology readiness, steam conversion and separation challenges

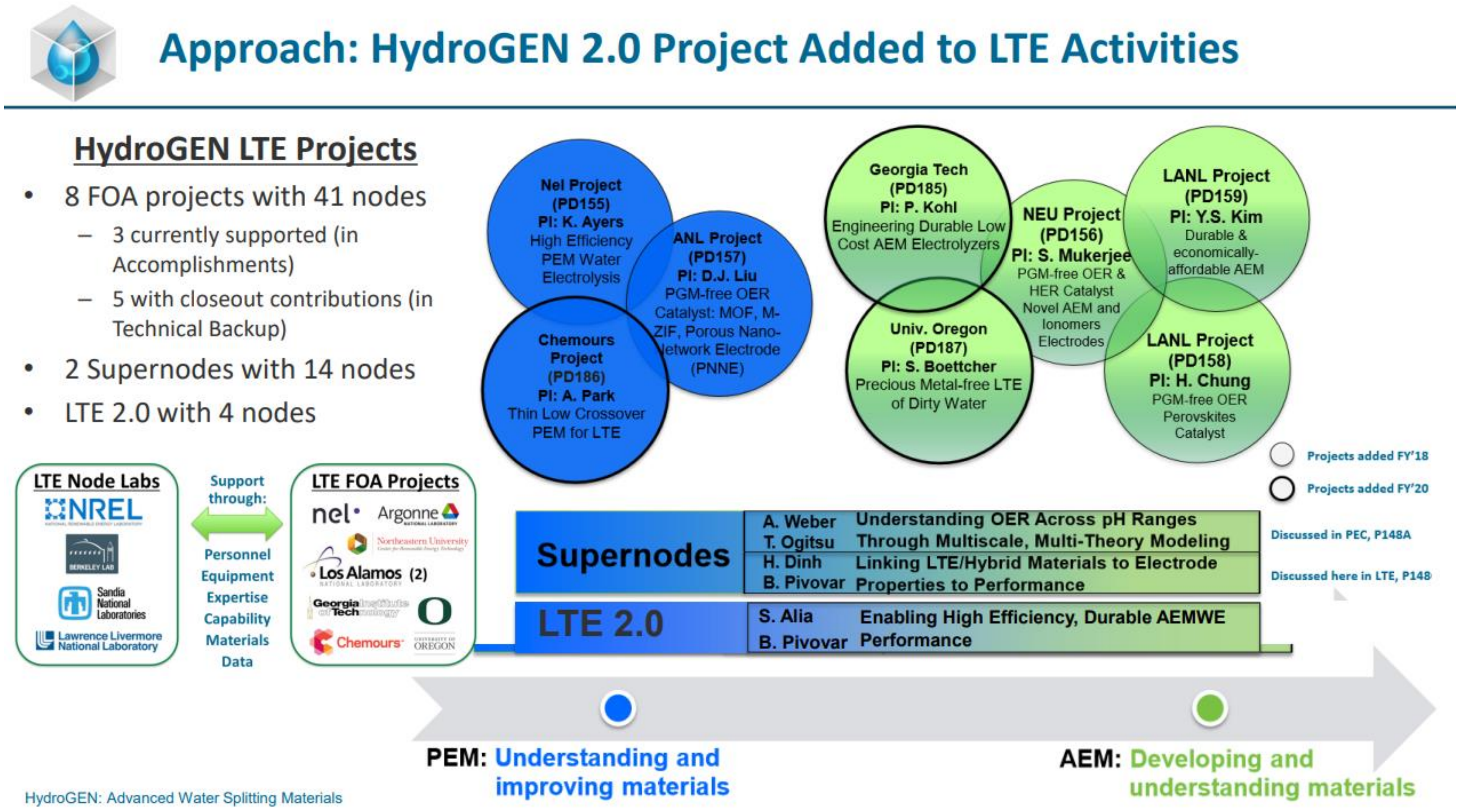
Low Temperature (0 - 200°C) (Alkaline, Polymer Electrolyte Membrane)

High Temperature (>500°C) (Solid Oxide)

Badgett, Ruth and Pivovar, "Economic considerations for hydrogen production with a focus on polymer electrolyte membrane electrolysis," accepted 2021.

DOE-funded Materials Development Efforts in HydroGEN (2.0)

- 3 PEM focused FOA projects.
- Fully relevant for the discussions of this workshop, but only a limited subset of what R&D needs exist within PEMEC space.



https://www.hydrogen.energy.gov/pdfs/review21/p148a_alia_2021_p.pdf

H2NEW : H2 from Next-generation Electrolyzers of Water

A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable & efficient electrolyzers to achieve <$2/kg H_2

- Launching in Q1 FY21
- Both low- and high-temperature electrolyzers
- $50M over 5 years

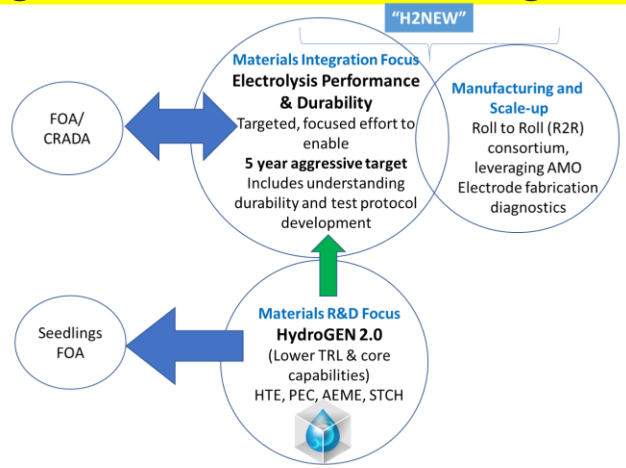
National Lab Consortium Team

NREL – National Renewable Energy Laboratory
INL – Idaho National Laboratory
Argonne National Laboratory
Berkeley Lab
Pacific Northwest National Laboratory
Los Alamos National Laboratory
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
NETL – National Energy Technology Laboratory

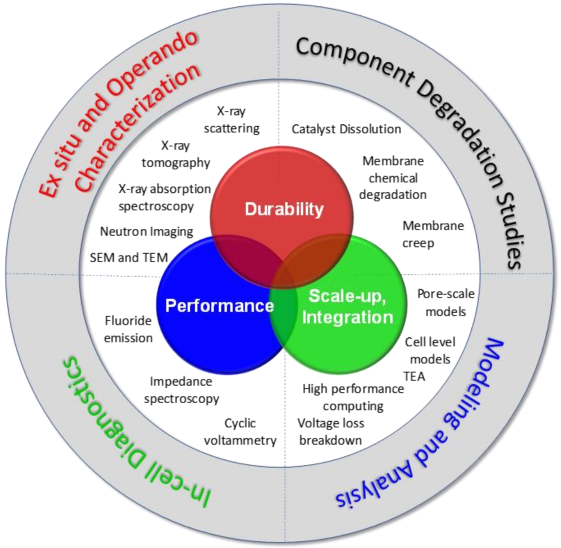
Clear, well-defined stack metrics to guide efforts.

Draft Electrolyzer Stack Goals by 2025		
	LTE PEM	HTE
Capital Cost	$100/kW	$100/kW
Elect. Efficiency (LHV)	70% at 3 A/cm^2	98% at 1.5 A/cm^2
Lifetime	80,000 hr	60,000 hr

The focus is not new materials but addressing components, materials integration, and manufacturing R&D



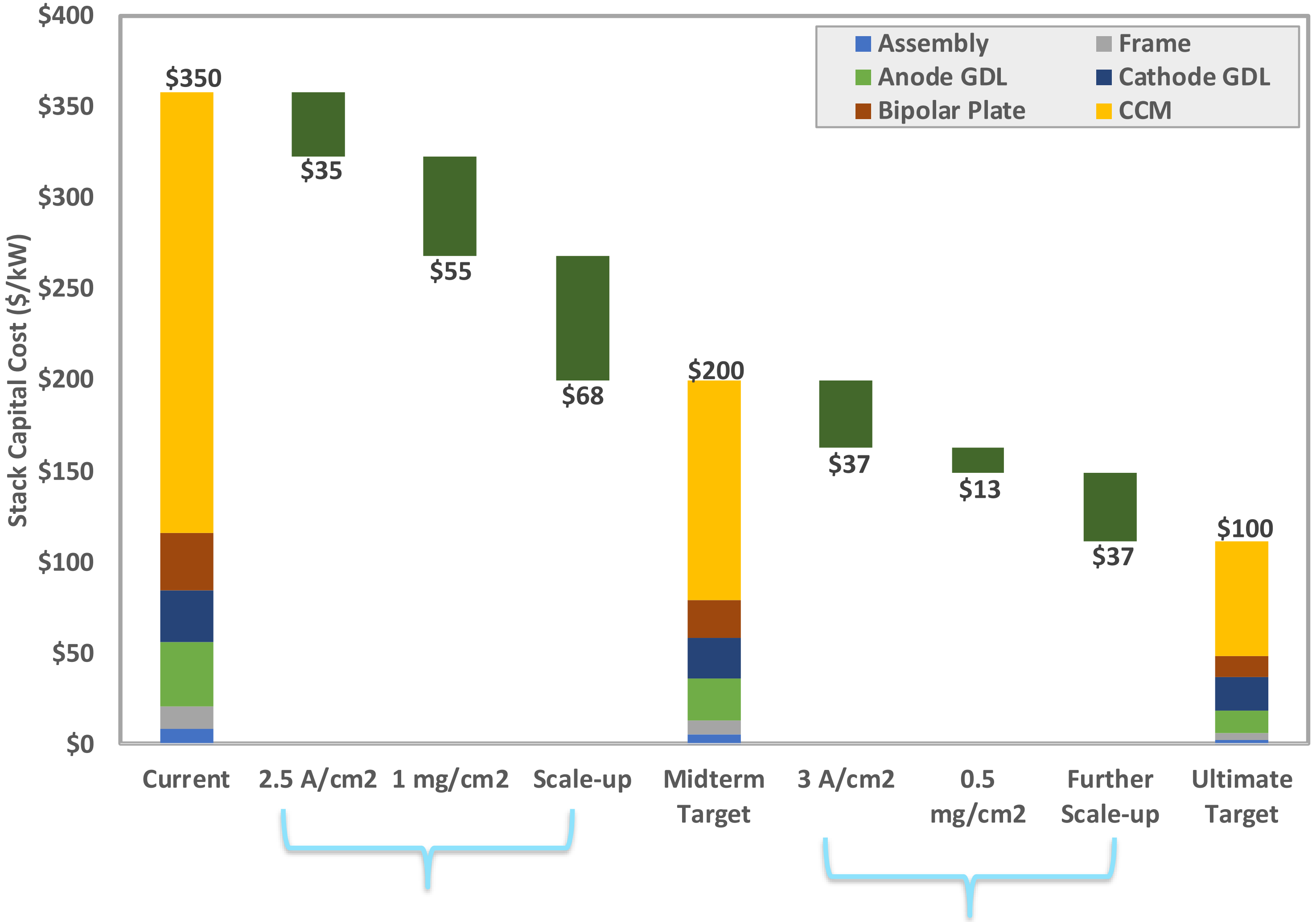
Utilize combination of world-class experimental, analytical, and modeling tools



Durability/lifetime is most critical, initial, primary focus of H2NEW

- Limited fundamental knowledge of degradation mechanisms.
- Lack of understanding on how to effectively accelerate degradation processes.
- Develop and validate methods and tests to accelerate identified degradation processes to be able to evaluate durability in a matter of weeks or months instead of years.
- GRCs and PTLs are in scope for H2NEW and this workshop.

PEM Stack Costs



Stack Targets	Status	2023	2025
Cell (A/cm^2@1.9V)	2.0	2.5	3.0
Efficiency (%)	66	68	70
Lifetime (khr)	60	70	80
Degradation (mV/khr)	3.2	2.75	2.25
Capital Cost ($/kW)	350	200	100
PGM loading (mg/cm^2)	3	1	0.5

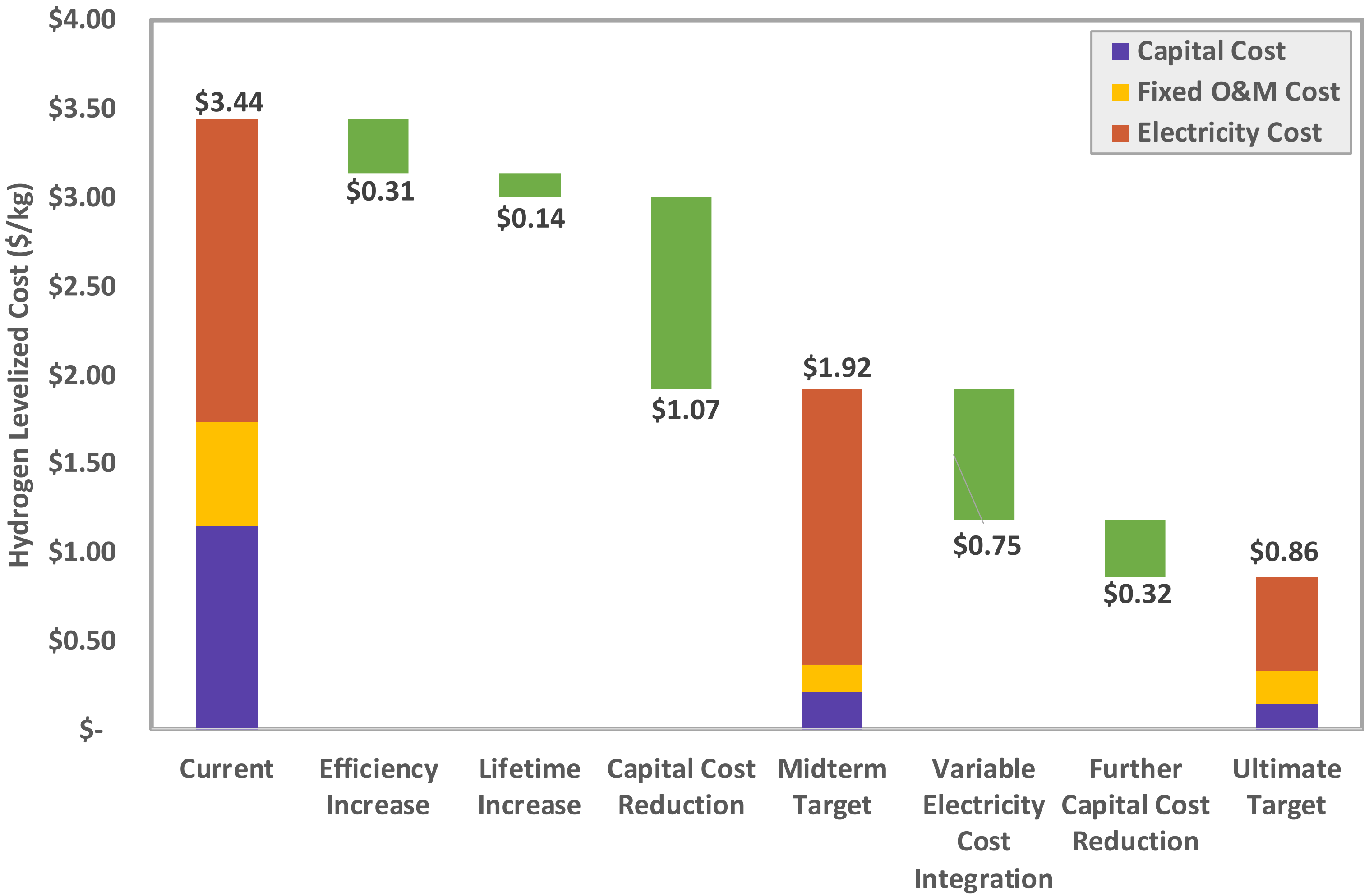
These 3 areas

1. Increased efficiency/current density
2. Decreased PGM loading
3. Scale-up

Are the strongest levers for addressing stack costs.

https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf

Hydrogen Levelized Cost



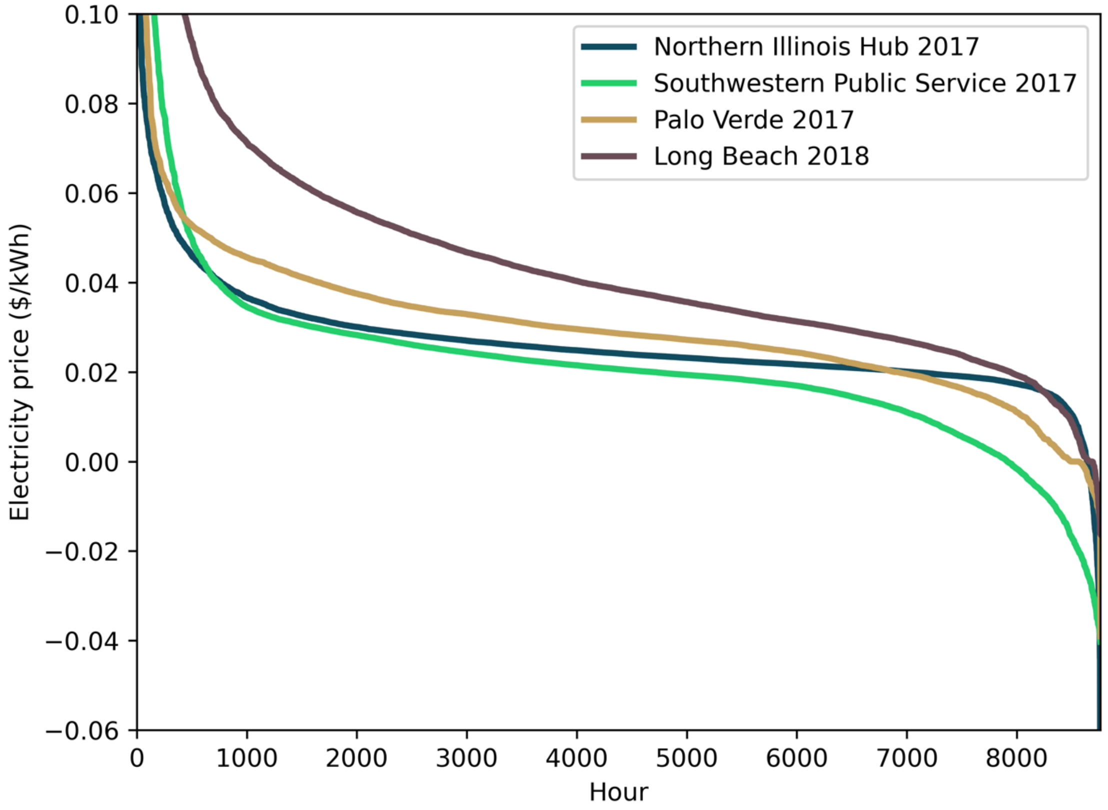
Select pathway to $2/kg and $1/kg identified.

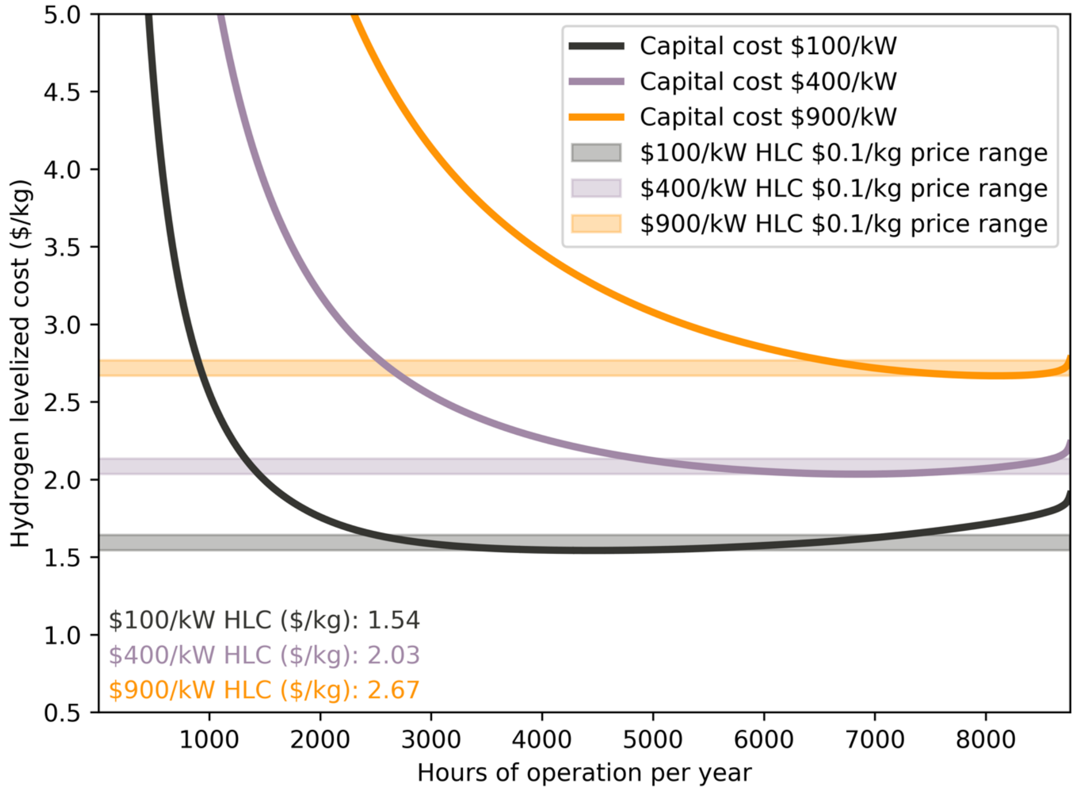
Much of HLC gains possible through greatly decreasing capital costs and enabling lower cost electricity through variable operation.

These advances can't come with compromised durability or efficiency, so all three areas are linked.

https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf

Hydrogen cost coupled to electricity prices



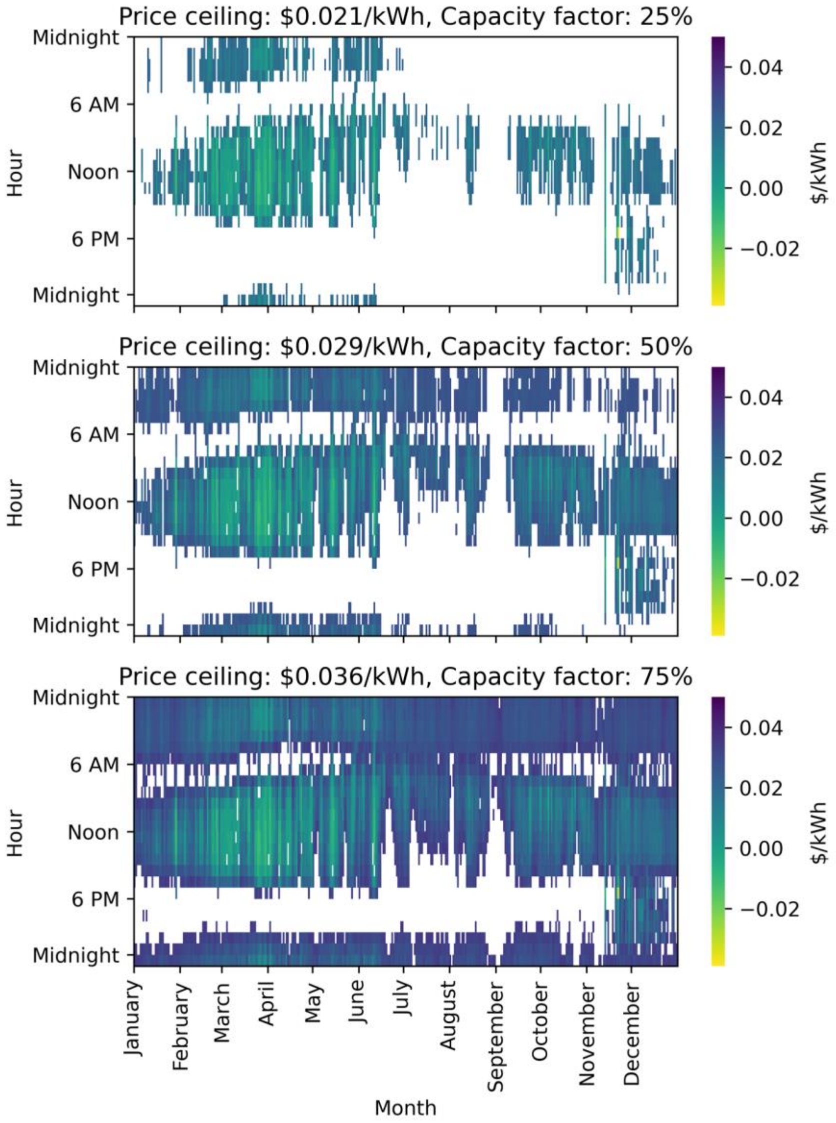


Location Marginal Pricing (LMP) for electricity can be used to explore operating strategies

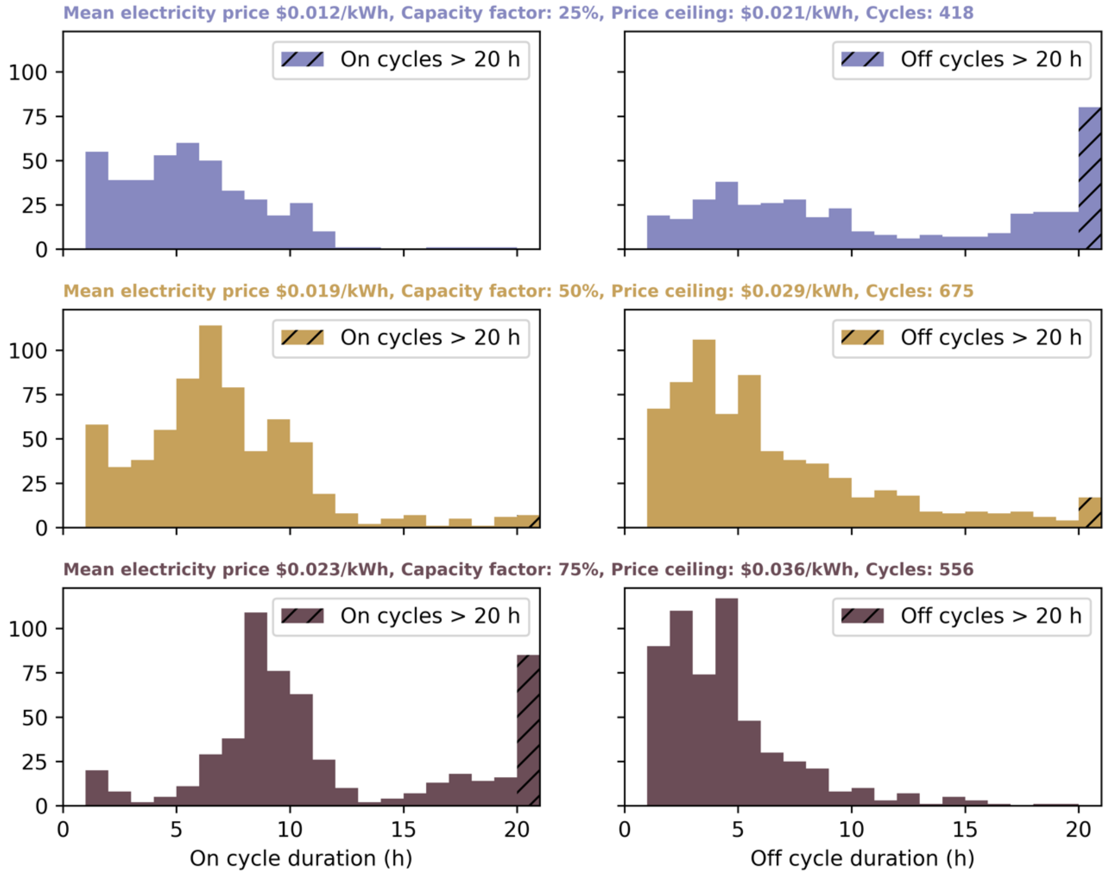
Both capital costs and electricity prices critical to HLC.

Alex Badgett, Mark Ruth, Bryan Pivovar, "Economic considerations for hydrogen production with a focus on polymer electrolyte membrane electrolysis," Electrochemical Power Sources: Fundamentals, Systems, and Applications, 2022, 327-364. https://doi.org/10.1016/B978-0-12-819424-9.00005-7

Duty cycle implications for stresses on components



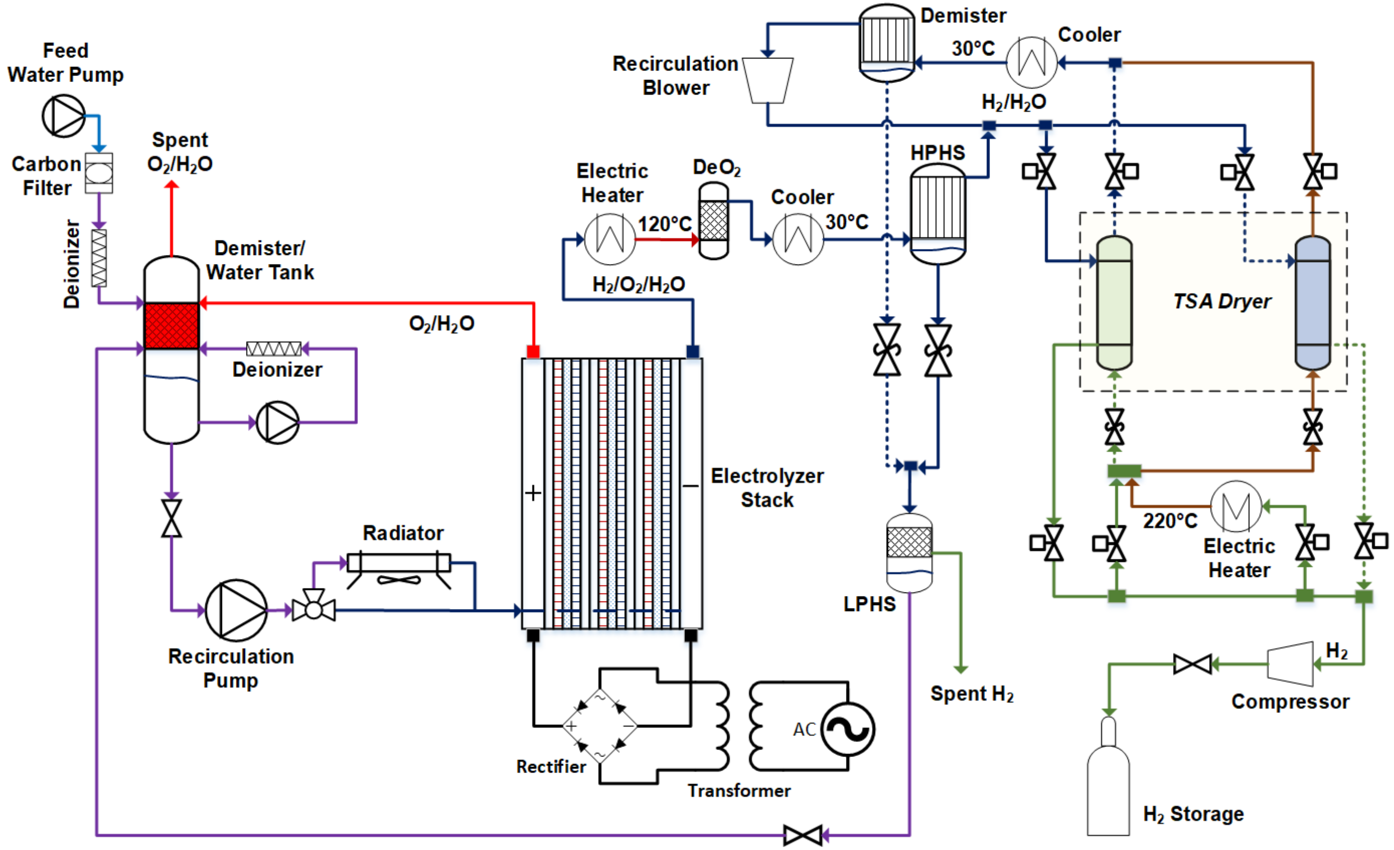
LMP heatmaps can give insight into potential operating strategies



On-off cycle duration and frequency can help support AST development.

Reference PEM Electrolysis System

- GCTool model for accurate representation of the system layout, and BOP components and flows
- Model based losses for H_2 losses because of H_2/O_2 crossover, H_2 purge (LPHS), and O_2 removal (DeO_2)
- Parasitic loads: rectifier/transformer, chiller, TSA dryer (regeneration and blower)



Sample Parasitic Loads

Mechanical BOP	**kWh/kg-H_2**
Water Pumps	0.10
Radiator Fan	0.71
Cooling Tower	0.02
TSA Dryer System	
DeO_2 Electrical Heater	0.14
Regen Electrical Heater	0.19
Tail Gas H_2 Blower	0.00
Electrical BOP	
Rectifier/Transformer	3.69
Hydrogen Loss	
DeH_2	0.22
Crossover H_2 and O_2	0.43
Total	5.51

https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf

Models Contextualize Advances in Cell Components and Quantify Remaining Progress Needed To Achieve DOE Targets

Stack Performance Targets

70% voltage efficiency   97.5% current efficiency   **V/I target**: 1.79 V at 3 A/cm^2, 300 psi, 0.4 mg_{Ir}/cm^2 anode catalyst loading

Target ASR and OER Activity

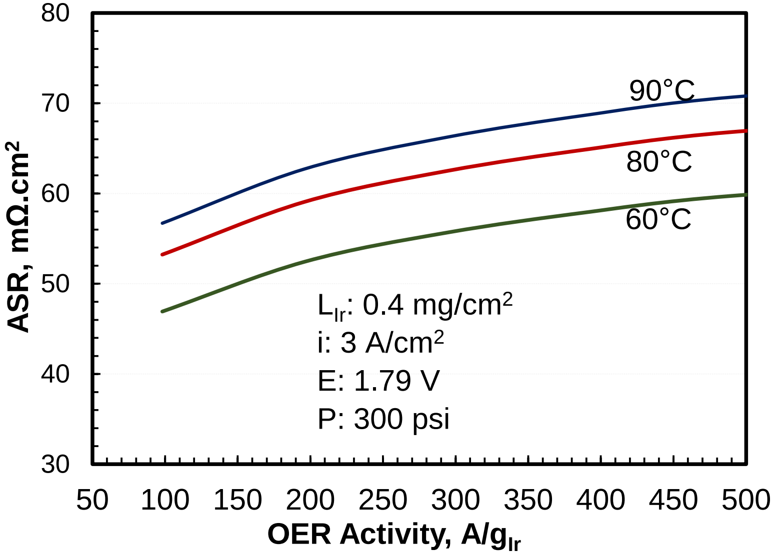
- OER Activity: Shorting-corrected current density at iR-corrected 1.45 V, 80^{o}C, 1 atm; Reference value: ~100 A/g_{Ir} for 0.4 mg_{Ir}/cm^2, 60 mV/dec Tafel slope
- Reference Values of ASR N211 membrane: 20 mΩ.cm^2 at 100% RH, 80^{o}C, 0.1 S/cm conductivity Example contact resistance: 12 mΩ.cm^2
- Possible to meet V/I target at 80^{o}C with N212 membrane and status OER activity

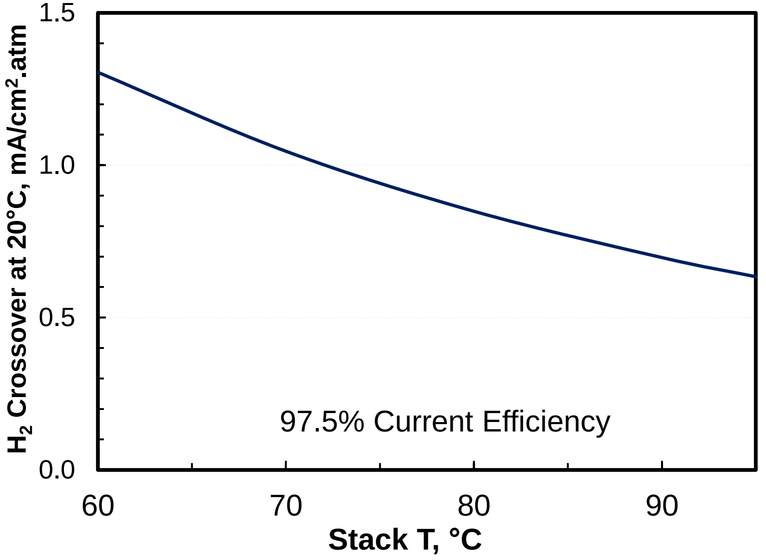
Target H_2 Crossover at 20^{o}C

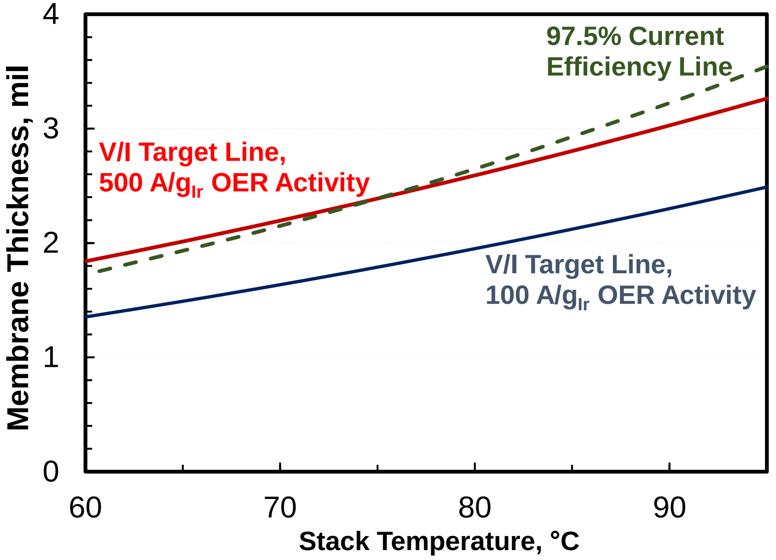
- Stack efficiency = Voltage efficiency (70%) x Current efficiency (97.5%)
- Reference H_2 crossover for N211 in fuel cells: 3 mA/cm^2.atm at 100% RH.
- Meeting current efficiency target at 80^{o}C with N212 membrane requires 40% reduction in H_2 crossover

Example Target Application to PFSA Membrane

- With the status 100 A/g_{Ir} OER activity, it is more difficult to meet the current efficiency target than V/I target
- With 2 to 3.5 mil PFSA membranes and 5x OER activity, possible to meet both V/I and current efficiency targets



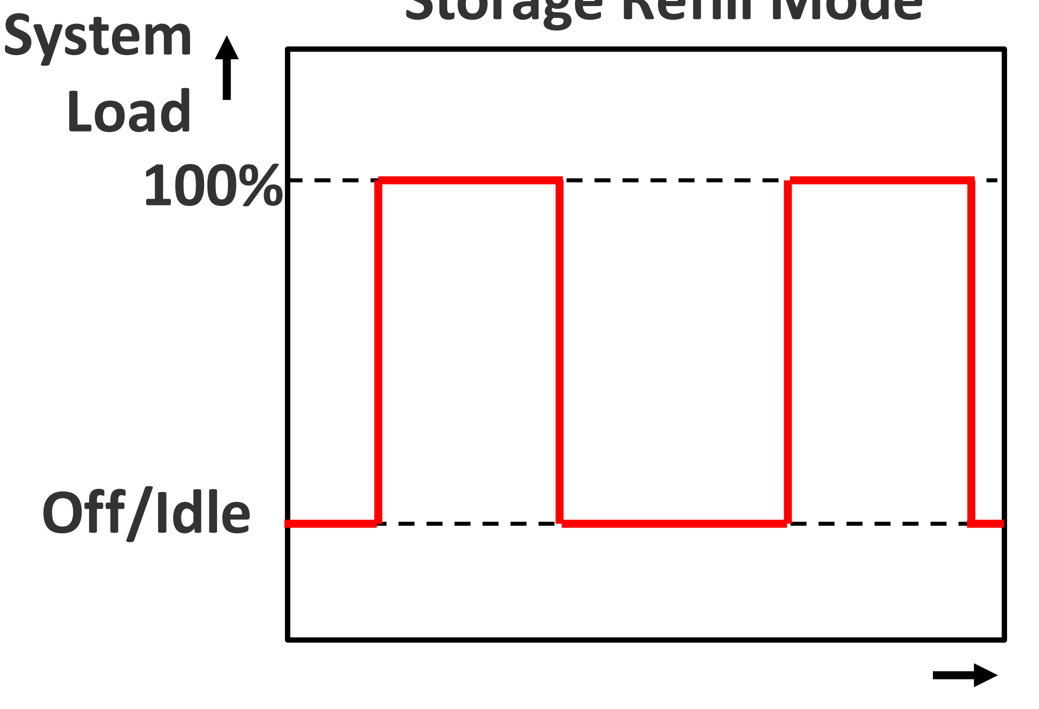




Operating Strategy

Existing Systems

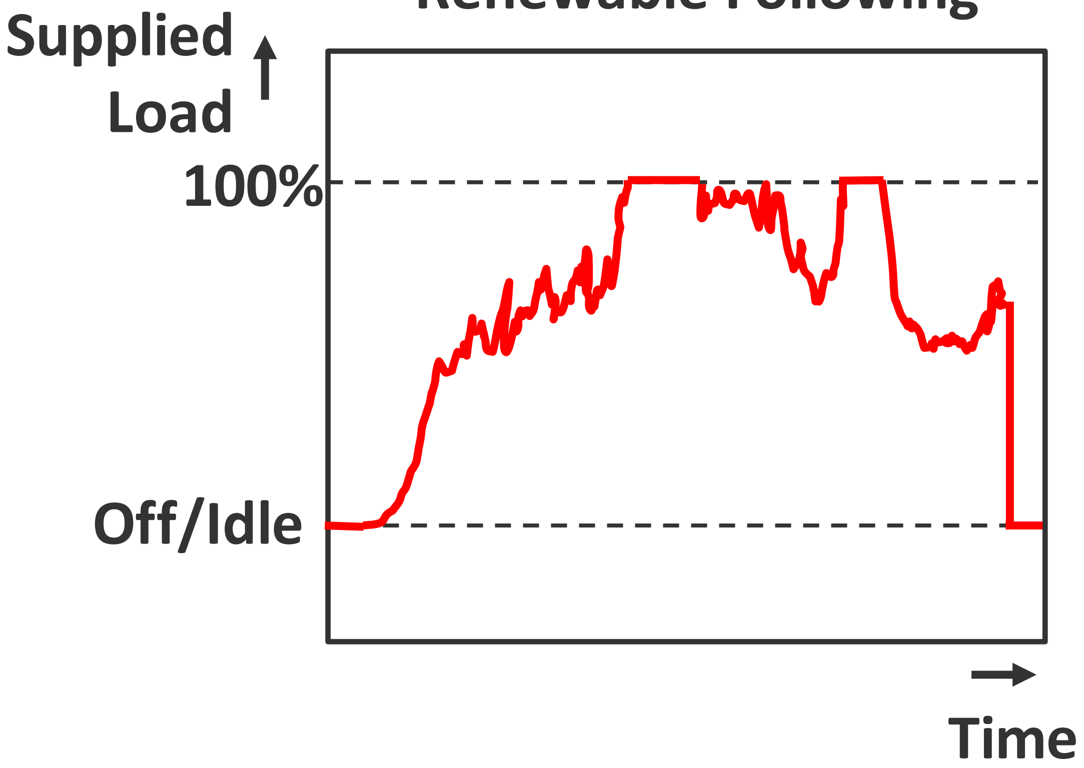
Storage Refill Mode



- Steady state operation
- Turn system on at certain vessel pressure
- Refill system at 100% system power
- Switch system to off or idle

Future Systems

Renewable Following



- Follow renewable energy supply
- Maybe cap high and low performance to minimize degradation

State-of-the-Art vs Future Systems

Existing Systems**

- 2V @ 2A/cm^2
- 2-3 mg/cm^2 PGM catalyst loading on anode & cathode
- 60k – 80k hours in commercial units
- Niche applications
  - Life support
  - Industrial H_2
  - Power plants for cooling
- $3.7/kg H_2 production*

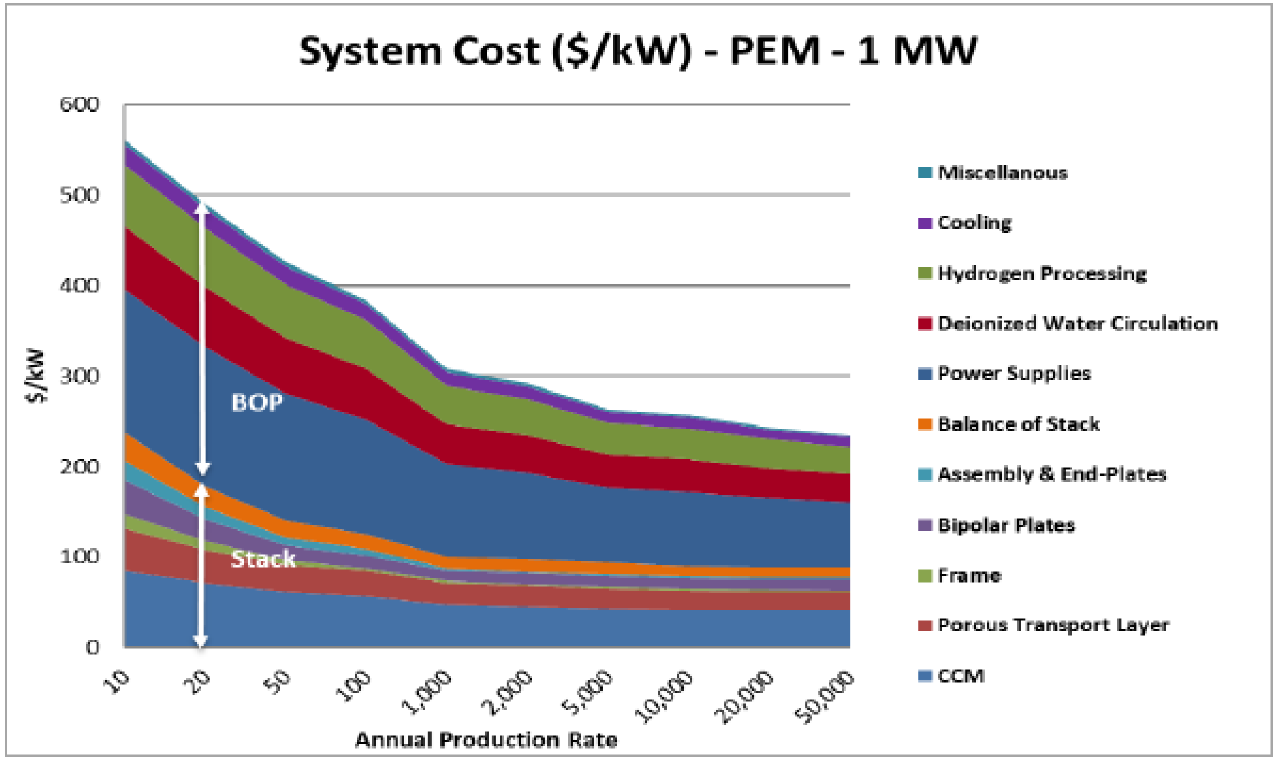
Future Systems

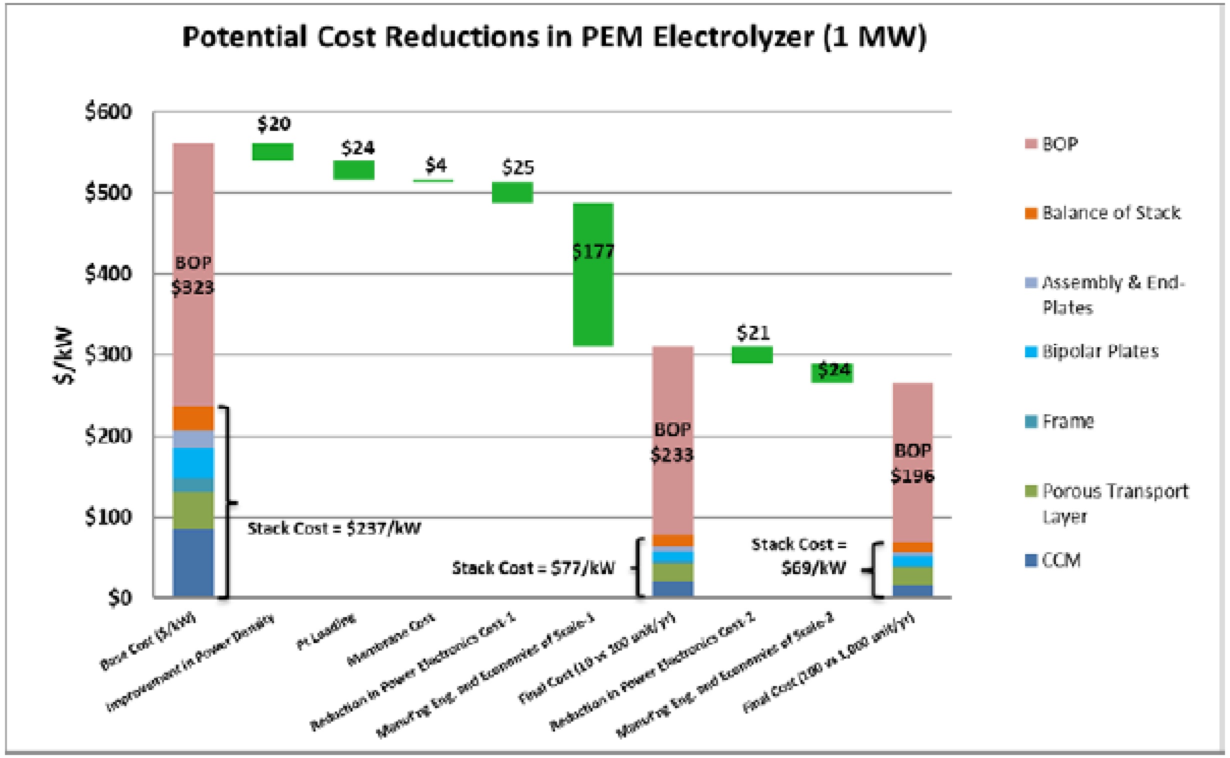
- 2V @ $\geq$ 2A/cm^2
- Thinner membranes
- Lower loadings
- $\geq$ 80k hours
- Supply following
- Renewable & Grid integrated applications
  - Wind
  - Solar
  - Nuclear
- $2/kg H_2 production*

*High volume projection: https://www.energy.gov/sites/prod/files/2017/10/f37/fcto-progress-fact-sheet-august-2017.pdf

** K.Ayers, AMR Presentation PD094, 06/2014

PEMEC Cost Analysis

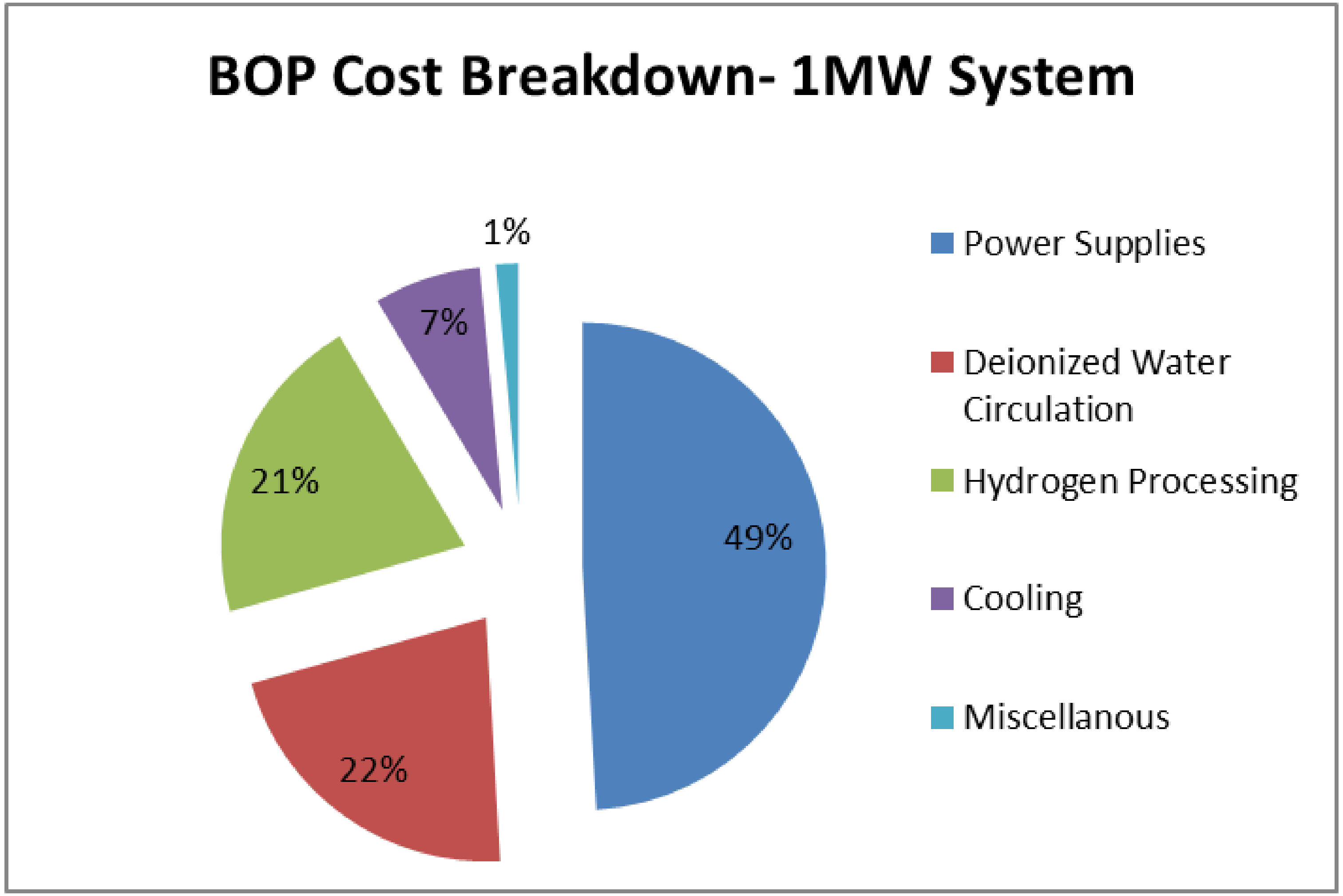




- Scale and supply chain build up significantly decrease costs but not enough, materials advances also required.
- Impact of operating conditions on durability remains poorly understood.

Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers
Ahmad Mayyas, Mark Ruth, Bryan Pivovar, Guido Bender, and Keith Wipke NREL/TP-6A20-72740
August 2019, https://www.nrel.gov/docs/fy19osti/72740.pdf

Balance of Plant Cost (Parts Only)



- Focus of workshop is stack, but BOP is significant cost contribution
- If stack advances enable cheaper balance of plant, can have a strong economic impact
  - Power supplies
  - Cooling

Catalyst Coated Membrane (CCM)

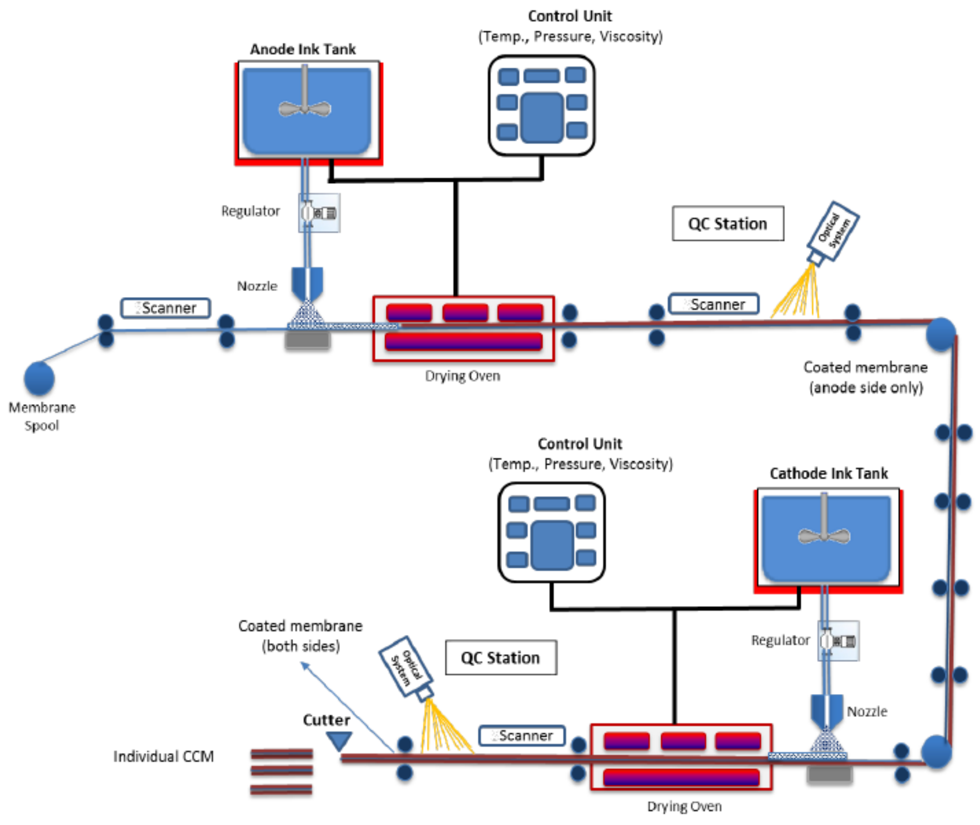
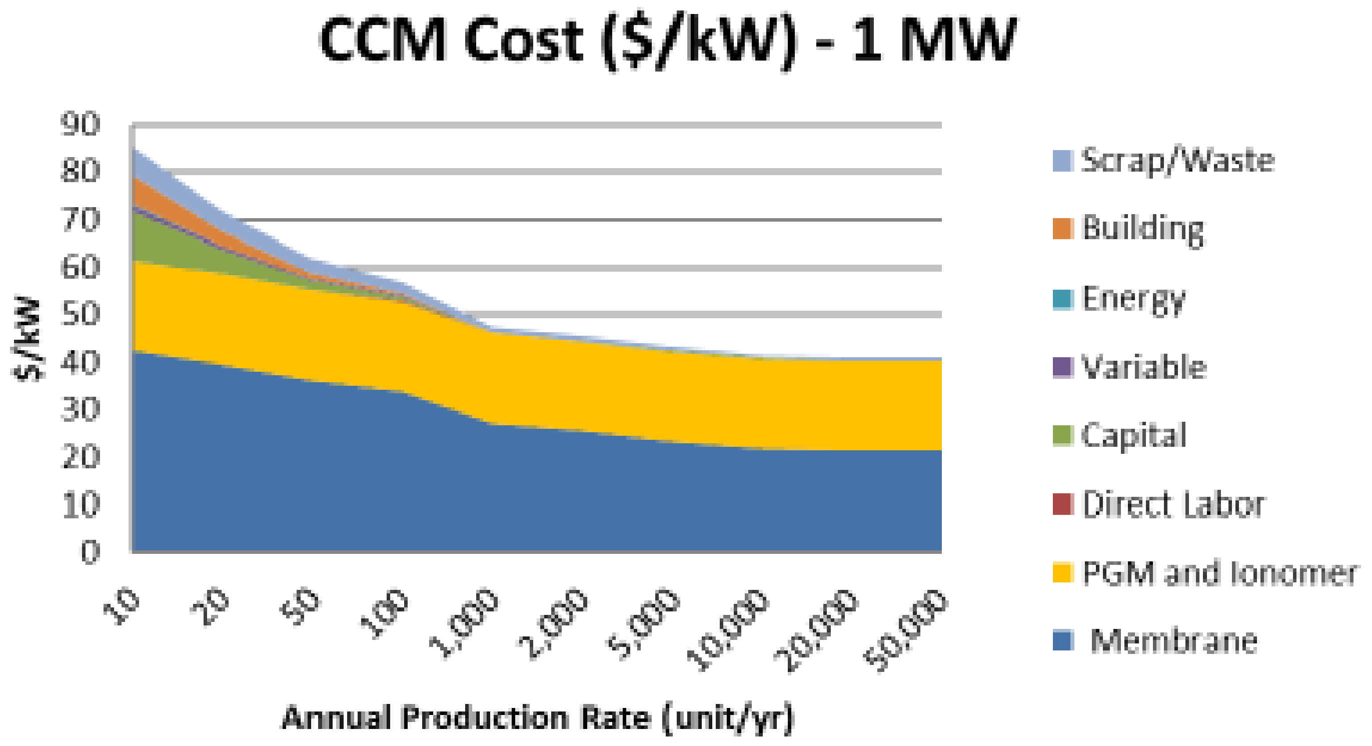


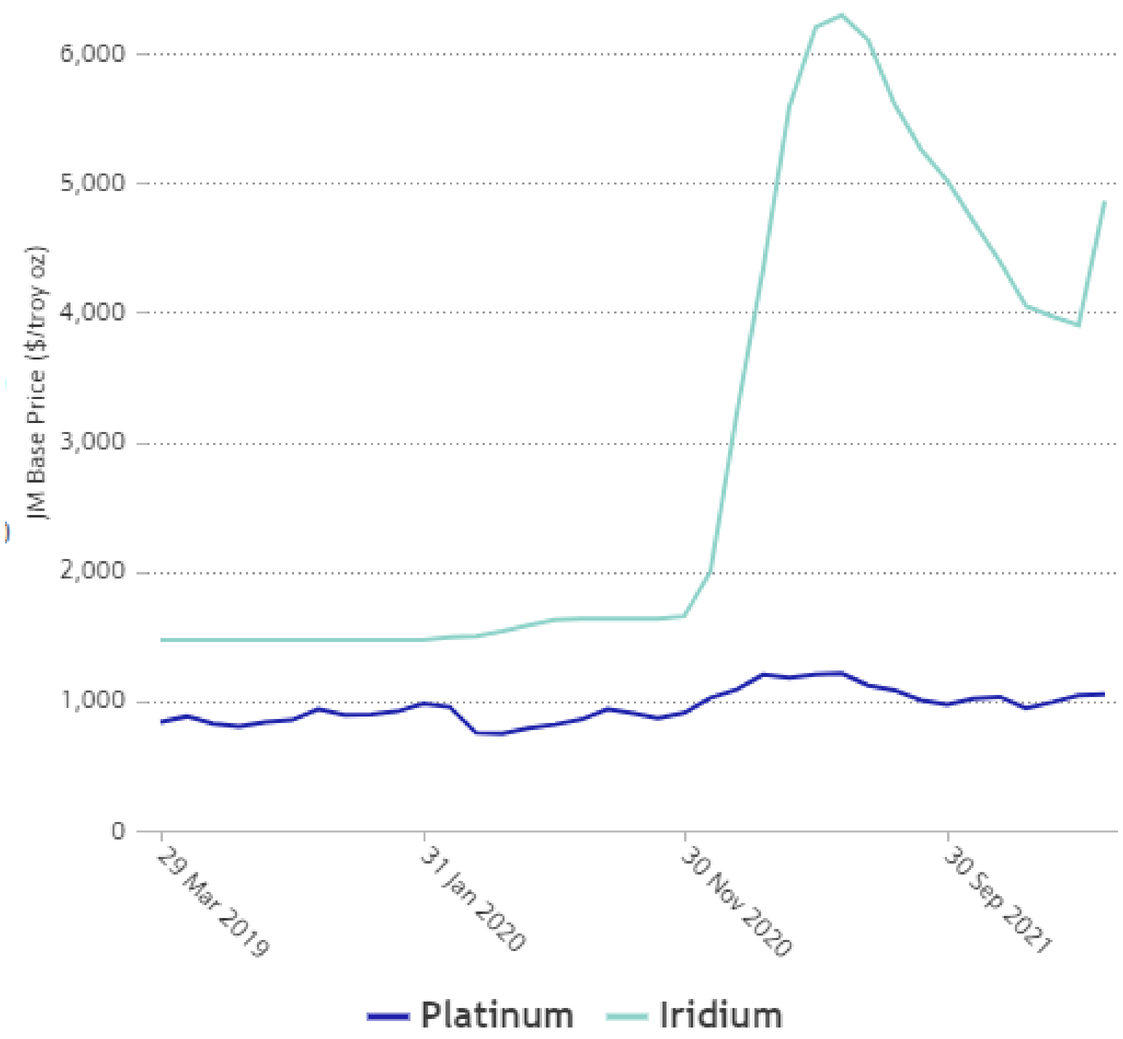
Figure 3. Process flow for catalyst deposition using spray coating

QC = quality control



- Based on 2019 economics, membrane larger cost driver at low scale, similar to electrodes at high scale.
- Thick membranes and high loadings result in large $/kW contributions.

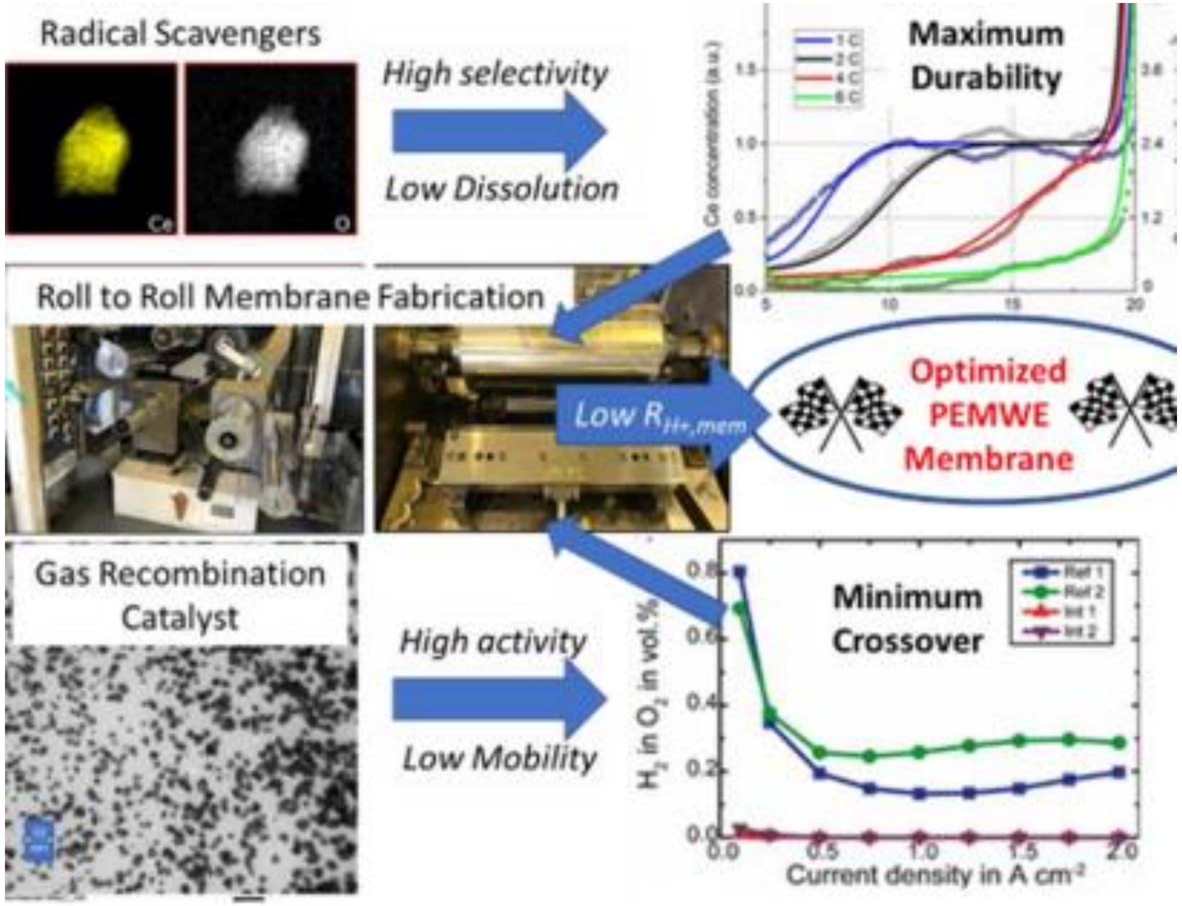
Catalyst



https://platinum.matthey.com/

- Ir cost increase/volatility was not taken into account in previously presented study.
- Ir/Pt had been near parity over longer time scales.
- Significant need to “thrift” or replace (if possible?) Ir.
- Earth abundance and recycling are additional concerns.

Polymer/Ionomer/Membrane



- Polymer materials costs scale with membrane thickness
- Thinner membranes enable lower ohmic losses and decreased polymer costs
- Require gas recombination catalysts/layers (GRCs/GRLs) and added processing steps.
- PFSAs used almost exclusively to date, come with additional concerns.

https://www.hydrogen.energy.gov/pdfs/review21/p186_park_2021_o.pdf

Porous Transport Layer (PTL)

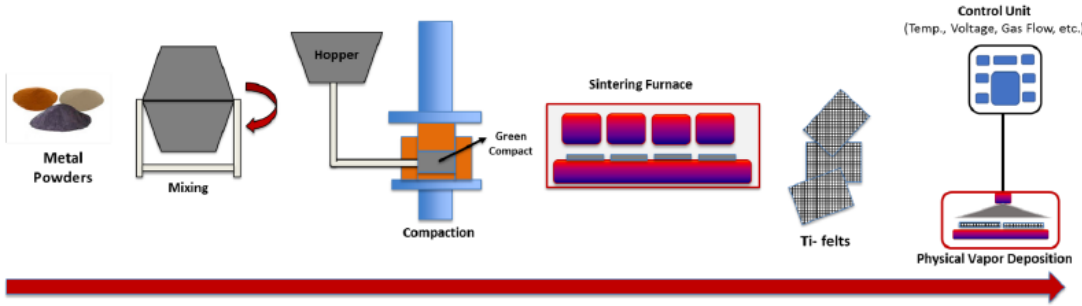
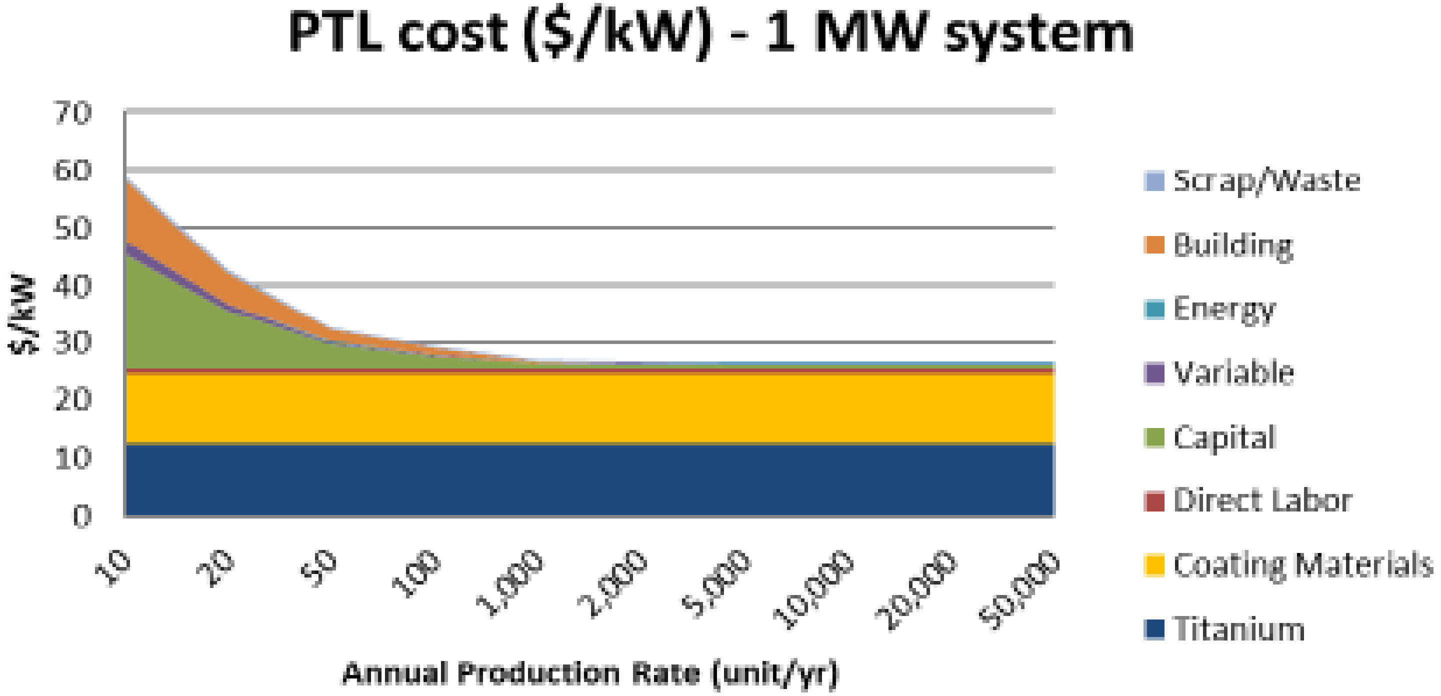


Figure 4. Process flow of the powder metallurgy process for producing titanium felts used as in the PTL



- PTLs are a significant cost, performance and durability concern.
- Relatively unique to PEMEC systems.
- Largely underexplored by the scientific community
- Ti and coating costs are primary drivers at high volumes.

Bipolar Plates

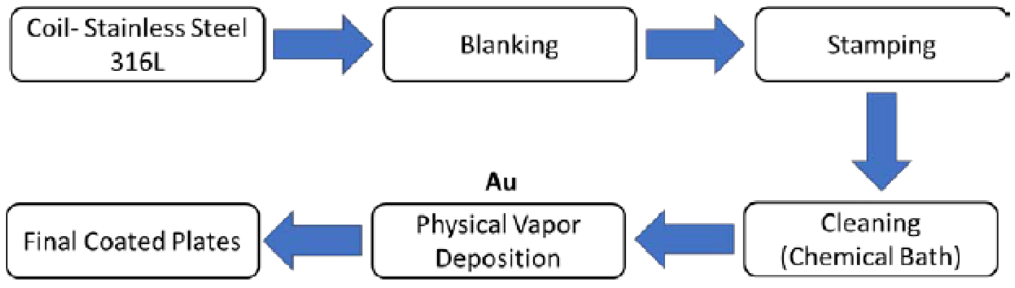
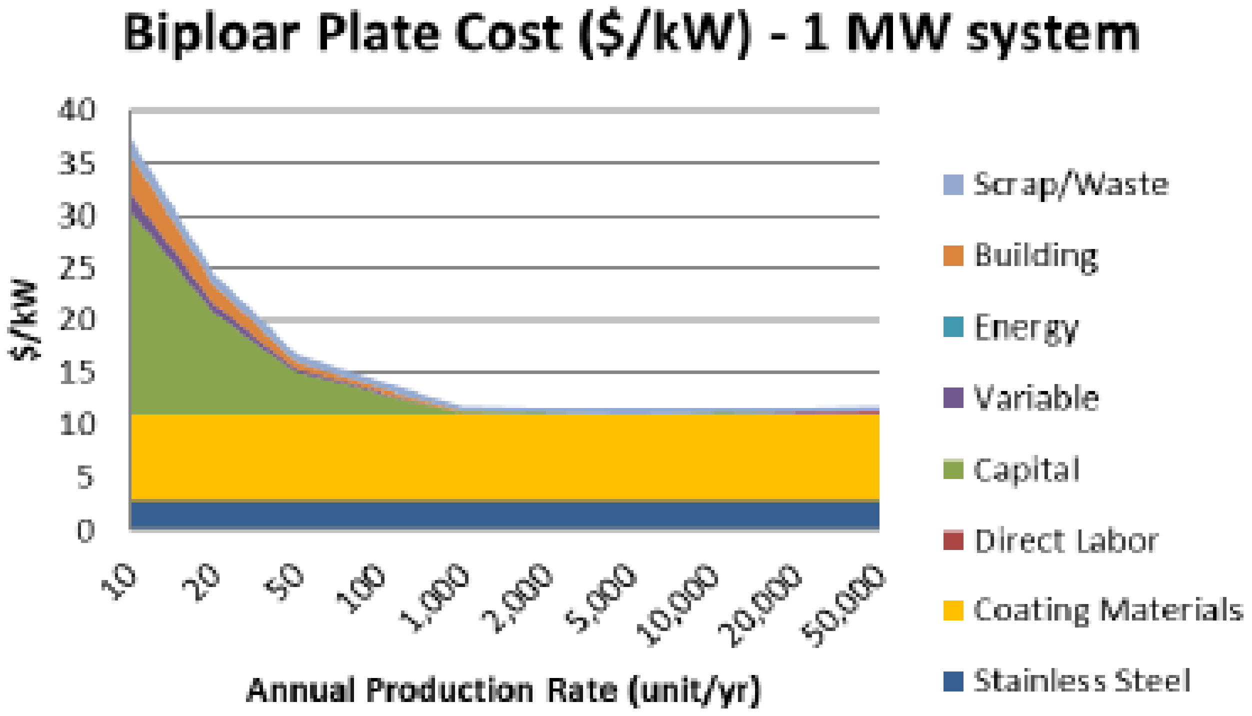
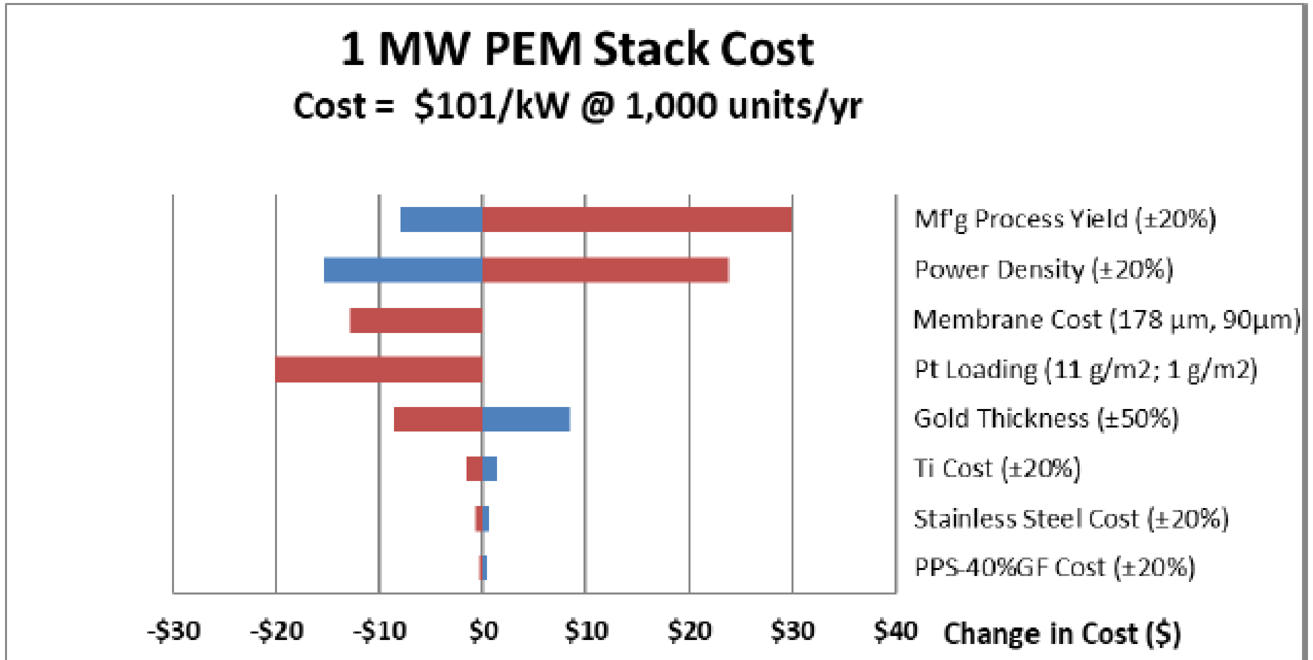


Figure 5. Process flow for producing metal bipolar plates



- At scale, coating materials dominate costs
- Thrifting or removing of precious metals a primary cost concern
- Without sacrificing of performance or durability.

Sensitivity Analysis



	PPS-40%GF Cost (±20%)	Stainless Steel Cost (±20%)	Ti Cost (±20%)	Gold Thickness (±50%)	Pt Loading (11 g/m2; 1 g/m2)	Membrane Cost (178 µm, 90µm)	Power Density (±20%)	Mf'g Process Yield (±20%)
Increase	$0.32	$0.65	$1.48	$8.49	$-	$-	$(15.27)	$(8.01)
Decrease	$(0.32)	$(0.65)	$(1.48)	$(8.49)	$(20.16)	$(12.87)	$23.76	$29.83

- Yield insight into primary cost drivers for PEMEC stacks
- Membrane cost, Pt loading, precious metal coatings are easily identifiable materials advances for impact
- Manufacturing processes and yields are important
- Power density can be impacted by materials advances

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