HydroGEN
Advanced Water Splitting Materials

Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop

Breakout Session Supplemental Slides
Low Temperature Electrolysis (LTE)

March 2 – 3, 2021

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LTE Breakout Sessions

Session ID	Topic	Lead
LTE-1	LTE Technology Roadmap Review & Discussion- Catalysts	Shannon Boettcher (Univ of Oregon)
LTE-2	Technology Roadmap Review & Discussion- Porous Transport Layer (PTL) Tech	Nemanja Danilovic (LBNL)
LTE-3	Techno-Economic Analysis - LTE	Brian James (Strategic Analysis, Inc)
LTE-5	LTE Cell Test Methods & Reference Cell	Marcelo Carmo (Juelich)
LTE-7	Technology Roadmap Review & Discussion - Membranes	Andrew Motz (Nel Hydrogen)

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Techno-Economic Analysis Breakout Session

Low Temperature Electrolysis (LTE)

Session ID: LTE-3
Session Chair: Brian James
Affiliation: Strategic Analysis Inc.
Date: March 2, 2021

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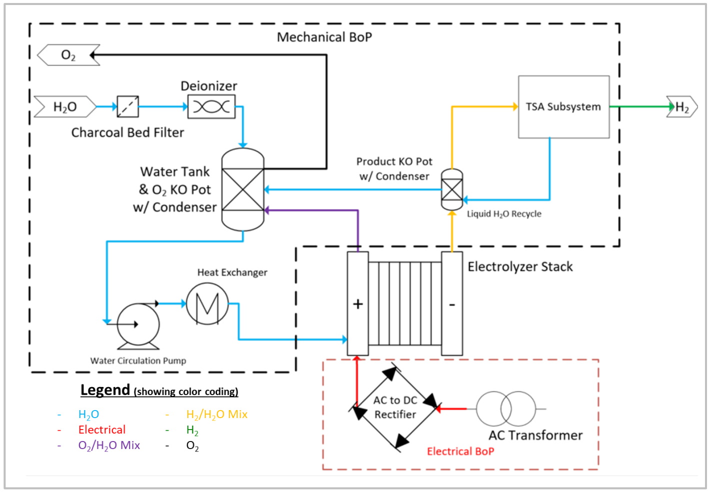
Overview of Techno-Economic Analysis Methodology

- The objective of techno-economic analysis (TEA) is to **evaluate** and **compare** competing technologies and **chart progress** on the basis of cost and technical performance
- **TEA Method Steps**
  - Define system: develop flow schematic and bill of materials
  - Perform system mass & heat balance modeling to identify critical design parameters
  - Enumerate H_2 production plant capital cost
  - Investigate and input technical and financial values into discounted cash flow analysis model H2A to evaluate the levelized cost of hydrogen ($\$/kgH_2$)
- **Results and Post-Analysis**
  - Perform sensitivity analyses to identify components with greatest impact on cost
    - Tornados and Monte Carlo
  - Obtain external review and feedback
  - Use feedback to update models



LTE Case Studies

- Alkaline is industry electrolysis standard

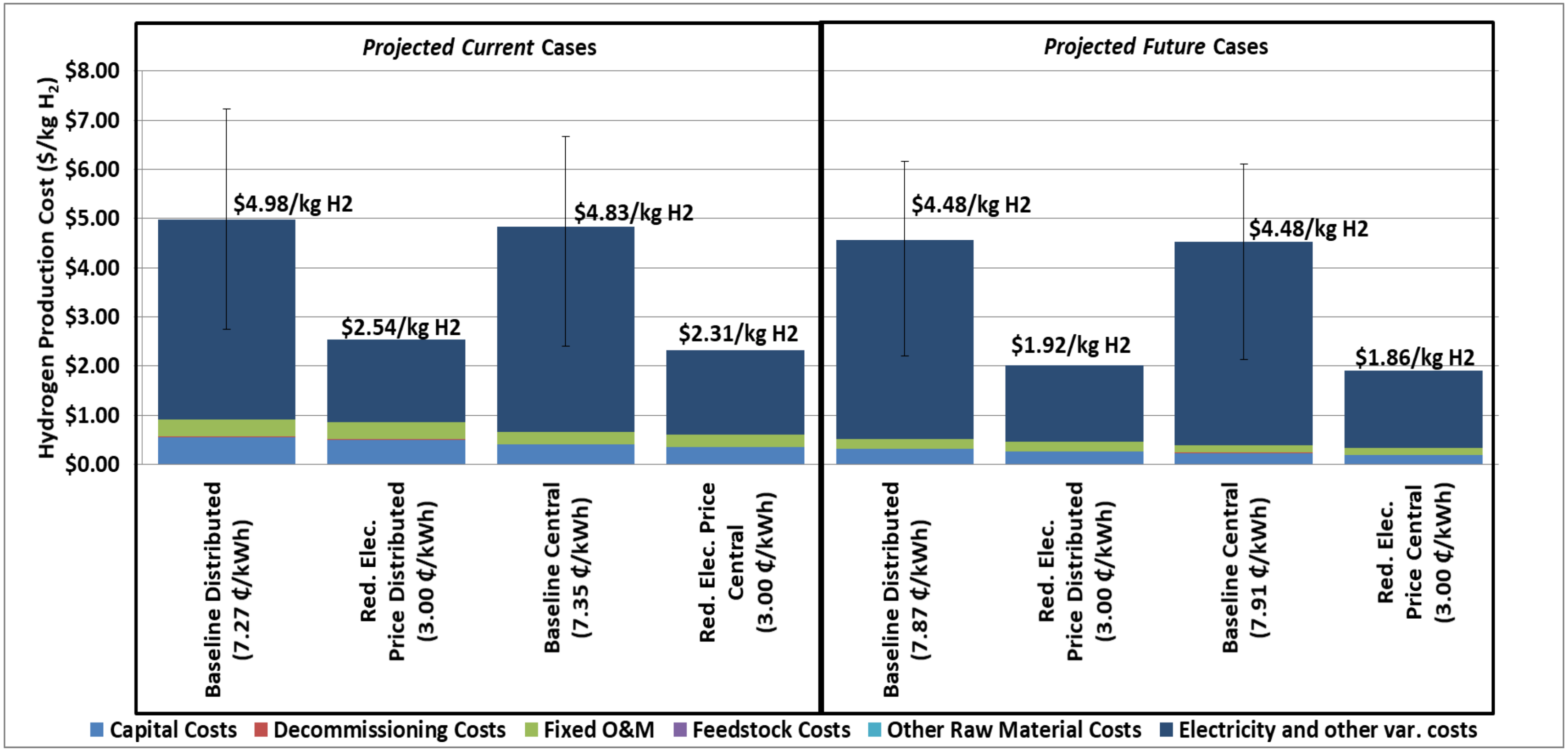
- PEM (2019) – Results and assumptions included in DOE Record
  - Distributed: 1,500 kgH_2/day
  - Central: 50 TPD
  - Two time-frames, both at ~600MW/year
    - "Projected Current" SOA in 2019 (Not "Existing" or "Commercial"!)
    - "Projected Future" SOA in 2035

- AEM (2020) – Preliminary analysis in 2020, however, there has been significant progress in performance and durability in the last year

Hierarchy of LTE Cost Drivers

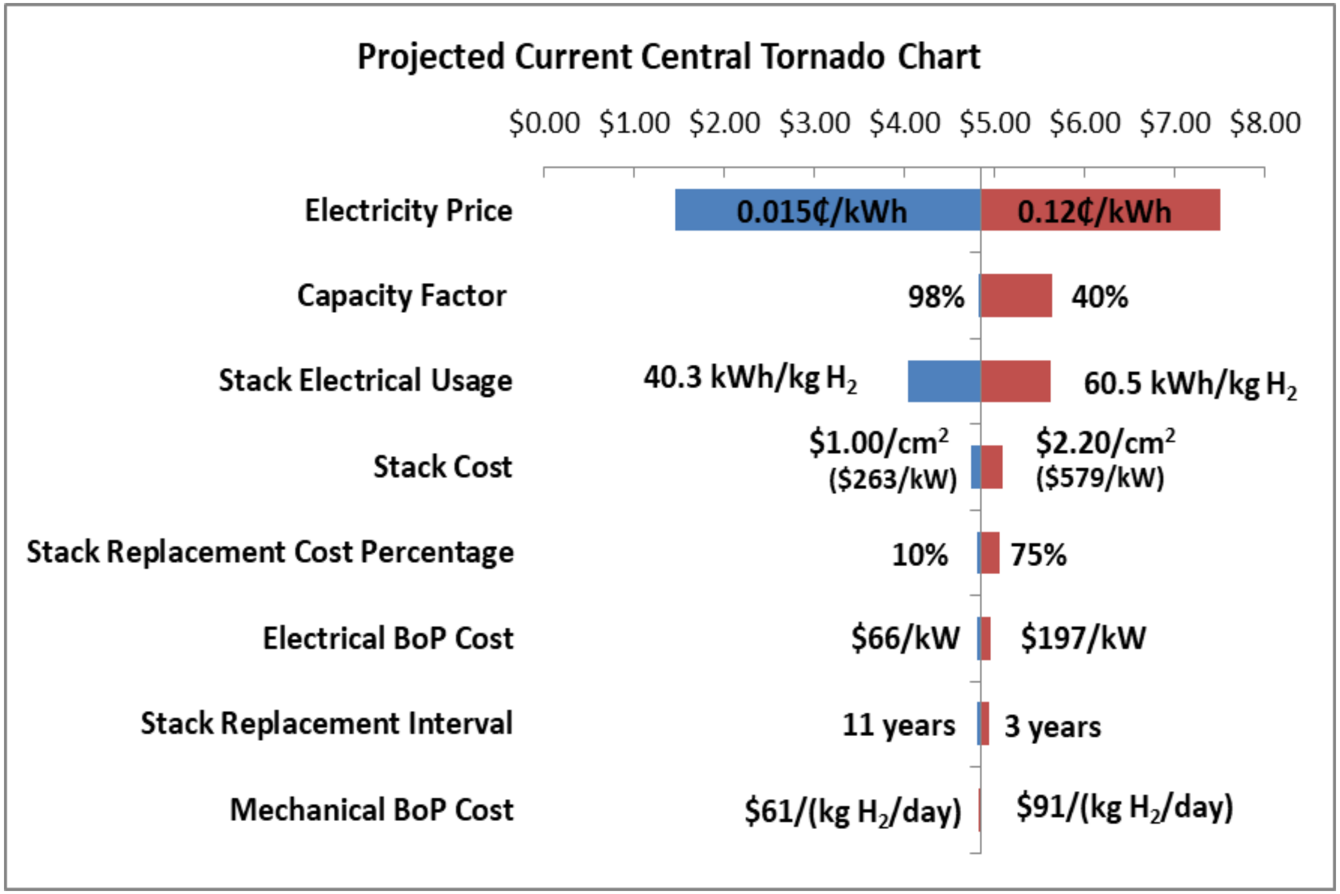
- **Electricity Cost**
  - Electricity price (cents/kWh)
    - Also (possibly by) time-of-day, interruptible, etc.
  - System Electrical Efficiency
    - Primarily Cell Operating Voltage
      - Operating choice influenced by current density (and stack cost)
      - **Main focus has been to improve Polarization Curve**
- **Stack Cost**
  - $/cm^2
    - Material/Manufacturing Costs
      - Catalyst/Loading, Plate Material/Coating, PTL, MEA
      - **Main focus has been to reduce materials/manufac. costs**
  - Current Density (at cell voltage, see above)
- **Stack Durability**
  - Stack degradation rate, mW/1,000 h
    - Desire 90kh to match Alkaline stacks, PEM currently modeled as 1.5mW/1kh
    - **Efforts to improve lifetime**
- **All other cost elements are down in the weeds**

PEM Electrolyzer Results and Sensitivity Study



- Electricity price most impactful but have least control over from stack technology point of view
- Stack electrical efficiency (kWh/kg) is a key parameter design feature

PEM Electrolyzer Results and Sensitivity Study



Central	Existing	Proj. Current	Proj. Future	HydroGEN
Stack	-	$342/kW	$143/kW	$100/kW
BOP	-	$118/kW	$91/kW	
Total	~$1,500/kW	$460/kW	$233/kW	

PEM Electrolyzer TEA Model Assumptions

Parameter	**Current Distributed 1,500 kg/day**	**Future Distributed 1,500 kg/day**	**Current Central 50,000 kg/day**	**Future Central 50,000 kg/day**
Technology Year	2019	2035	2019	2035
Start-up Year	2015	2040	2015	2040
Total Uninstalled Capital (2016$/kW)	$599	$379	$460	$233
Stack Capital Cost (2016$/kW)	$342	$143	$342	$143
BoP CapEx (2016$/kW)	$257	$236	$118	$91
Mechanical BoP Cost (2016$/kW)	$136	$140	$36	$23
Electrical BoP Cost (2016$/kW)	$121	$97	$82	$68
Total Electrical Usage (kWh/kg) [% LHV] (% HHV)	**55.8** **[59.7%] (70.6%)**	**51.4** **[64.8%] (76.6%)**	**55.5** **[60.1%] (71.0%)**	**51.3** **[65.0%] (76.8%)**
Stack Electrical Usage (kWh/kg) [% LHV] (% HHV)	50.4 [66.1%] (78.2%)	47.8 [69.8%] (82.4%)	50.4 [66.1%] (78.2%)	47.8 [69.8%] (82.4%)
BoP Electrical Usage (kWh/kg)	5.4	3.66	5.04	3.54
Stack Current Density (A/cm^2)	**2.0**	**3.0**	**2.0**	**3.0**
Cell Voltage (V)	**1.9**	**1.8**	**1.9**	**1.8**
Electrolyzer Power Consumption at Peak Production (MW)	3.56	3.53	119	118
Effective Electricity Price over Life of Plant (2016¢/kWh)	7.27	7.87	7.35	7.91
Outlet Pressure from Electrolyzer (psi)	300	700	300	700
Installation Cost (% of uninstalled capital cost)	12%	10%	12%	10%
Stack Replacement Interval (years)	7	10	7	10
Stack Replacement Cost Percentage (% of installed capital cost)	15%	15%	15%	15%
Plant Life (years)	20	20	40	40
Stack Degradation Rate (mV/khrs)	1.5	1	1.5	1
Cell Active Area (cm^2)	700	700	1,500	1,500
Capacity Factor (%)	97%	97%	97%	97%

Common Stack Materials

	Alkaline	PEM	AEM
Electrolyte	30 wt% KOH	Polyfluorosulfonic acid (PFSA) membrane	N_4^+/P_4^+ membrane May have dilute KOH on O.E.
Separator	Porous polyphenylene sulfide w/ ZrO2 & polymer coatings (Zirfon)	--	
Hydrogen Electrode	Porous nickel or nickel-coated stainless steel	Platinum on carbon	Platinum on carbon (non-PGM in future)
Oxygen Electrode	Porous nickel or nickel-coated stainless steel	Iridium oxide (in Pt/Ru alloys)	Non-PGM metal alloys (Fe/Ni common)
Transport Layers	Nickel mesh	Porous, coated Ti (HE) Graphite (OE)	Ni foam (OE) Carbon GDL (HE)
Bipolar Plates	Nickel-coated stainless steel	Pt-Coated titanium	Stainless Steel
Frames/Sealing	Polymer	Polymer	Polymer

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Technology Roadmap Review & Discussion - Membranes

Technology: LTE

Session ID: LTE-7
Session Chair: Andrew Motz
Affiliation: Nel Hydrogen
Date: March 3, 2021

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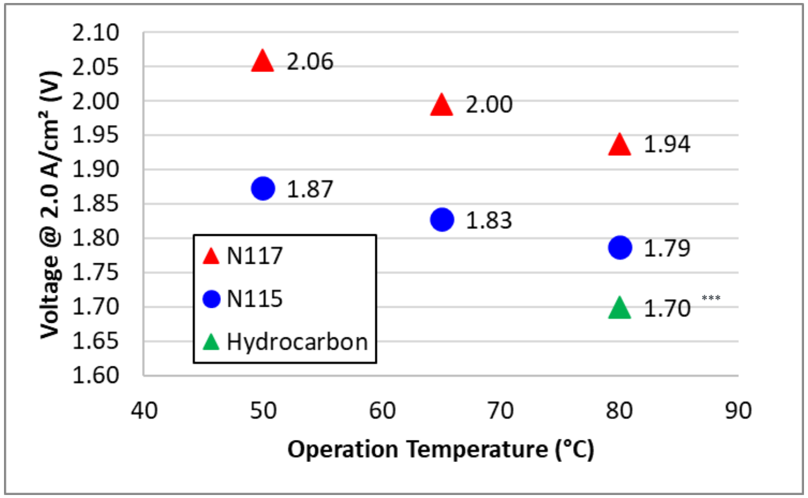
PEM - Temperature and Membrane Thickness

- Starting with a base case of N117 at 50° C
  - Increasing temperature to 80° C can results in an efficiency improvement of about 120 mV
  - Alternatively moving to N115 membrane can result in an efficiency improvement of about 187 mV
  - With thinner membranes, there are diminishing returns on increasing operating temperature
  - Alternative proton exchange membrane chemistries have received minimal investigation

How much further can we reduce operating potential with membranes alone (50, 100, 150 mV)?

Where should the community focus efforts? Membrane thickness, operating temperature, ion transport?



***Hydrocarbon data from reference and had poor durability (C. Klose et. al. 2020 Adv. Energy Mater. 10 pg. 1903995)

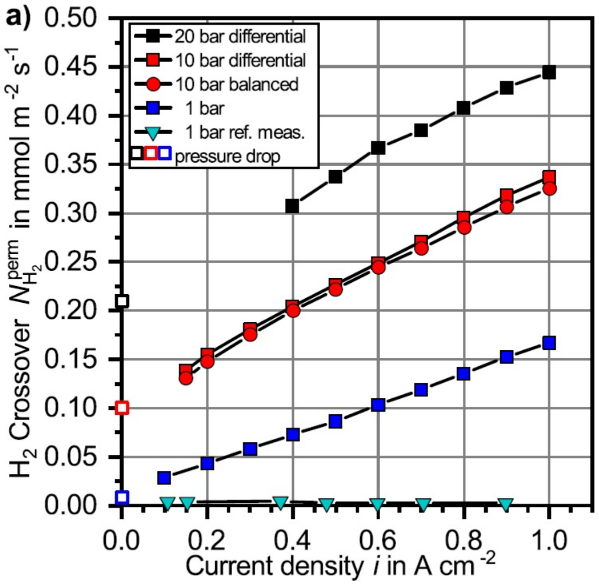
PEM – Thin membrane challenges

- Gas crossover at differential pressure will be greater based on Fickian diffusion

- To add another challenge for thin membranes, there have been reports that at higher current densities and a fixed H_2 pressure, the flux of H_2 across the membrane increases.

What is the mechanism for this phenomena?

Do we need to account for these losses in the reported efficiency?



P. Trinke et al 2018 J. Electrochem. Soc. 165 F502

PEM – Failure Modes

- Chemical Degradation
  - There is some evidence of membrane thinning (S. Grigoriev et al 2014 Int. J. Hydrog. Energy 39 pg. 20440)– 90°C / voltage ~2.3 V / cycling / was still stable for 4000 h before exponential failure. Is this more extreme than we would expect in the field over 80,000 h?
  - Fluoride release rate has also been reported (M. Chandesris et al 2015 Int. J. Hydrog. Energy 40 pg. 1353) – Water fed anode had minimal fluoride release, cathode water (flux across the membrane) had higher fluoride levels detected – How accurate is measuring the water on the cathode? Rate varies with current density and there will be loss of water vapor in the H_2 product.
  - How does metal dissolution into the membrane impact degradation?
  - Are there better approaches to accelerate chemical degradation?

PEM – Failure Modes

- Chemical Degradation - Are there better approaches to accelerate chemical degradation?
- Mechanical Degradation
  - Electronic shorting is a common failure mechanism for many low resistance membranes (i.e. low EW or sub 127 µm)
  - Fully hydrated mechanical properties are rarely reported
  - Is there a valuable ex-situ metric that can come from a fully hydrated tensile or burst strength to avoid failures due to electronic shorting?

PEM – Failure Modes

- Chemical Degradation - Are there better approaches to accelerate chemical degradation?
- Mechanical Degradation - Is there a valuable ex-situ metric that can come from a fully hydrated tensile or burst strength to avoid failures due to electronic shorting?
- Thermal Degradation
  - Increased temperature can accelerate chemical and mechanical degradation through more facile kinetics or softening of the polymer
  - Delamination through freeze thaw cycles or typical on/off cycling is also possible – What level of impact / importance does this have on actual devices?

PEM – Summary

- Chemical Degradation – Are there better approaches to accelerate chemical degradation?
- Mechanical Degradation – Is there a valuable ex-situ metric that can come from a fully hydrated tensile or burst strength to avoid failures due to electronic shorting?
- Thermal Degradation – What level of impact / importance does this have on actual devices?

- Thinner membranes and higher operation temperatures are critical to achieving the roadmap efficiency targets – how do we best advance the field without sacrificing reliability?

AEM – New Materials

- In the last few years, numerous AEMs and ionomers have become commercially available

ORION

IONIX Integrated Ionics

Versogen™
The Hydrogen Generation.

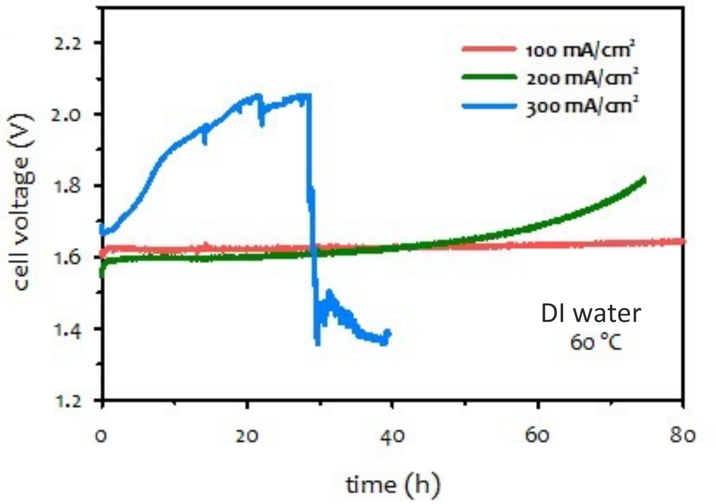
ecolectro

IONOMR
INNOVATIONS

Dioxide Materials™
The CO_2 Recycling Company™

More options is great for improving chances for success, but makes standardization difficult

AEM – Cell Operation / Degradation



D. Li, et al, Nature Energy, 2020, 5, 378-385

- Mode of operation
  - Should we run these cells in DI water, K_2CO_3, KOH? Should there be a standard concentration?
- Degradation
  - Most AEMWE degradation rates are over an order of magnitude higher than comparable PEMWE – is it feasible to close this gap? How soon? Is it a requirement for the technology?
  - Mechanical degradation – AEMs used in literature are often much thinner than standard PEMs . Is the answer to simply use thicker AEMs? When does water flux become a challenge?
  - Chemical degradation – Is the able to be overcome to achieve
  - Thermal Degradation – is high temperature required to take advantage of non-PGM catalysts?