Nel Hydrogen

Proton exchange membrane electrolyzer technology: Challenges and advancements

Kathy Ayers
Vice President, R&D

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Key points

- Electrolyzers have a long history as a viable product
- Renewable hydrogen is needed to address decarbonization
- Market is expanding rapidly but economics are currently challenging
- High potential for cost and efficiency improvements
- Scaling presents many challenges:
  - Materials
  - Components
  - Qualification
- Fundamental understanding is needed to drive progress

WHERE WE COME FROM

Commercial history

- Long history in electrolyzer manufacturing
- >3500 systems in >80 countries
- Expanding capacity in both technologies

Alkaline manufacturing sites

United Technologies

PROTON ON SITE

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1955
GE develops PEM
Military & Aerospace
(Grubb & Neidrach)

1985
GE sells the technology
Military & Aerospace

1996
Proton develops
commercial products

2017
Nel purchases Proton

PEM manufacturing site

Nel Values

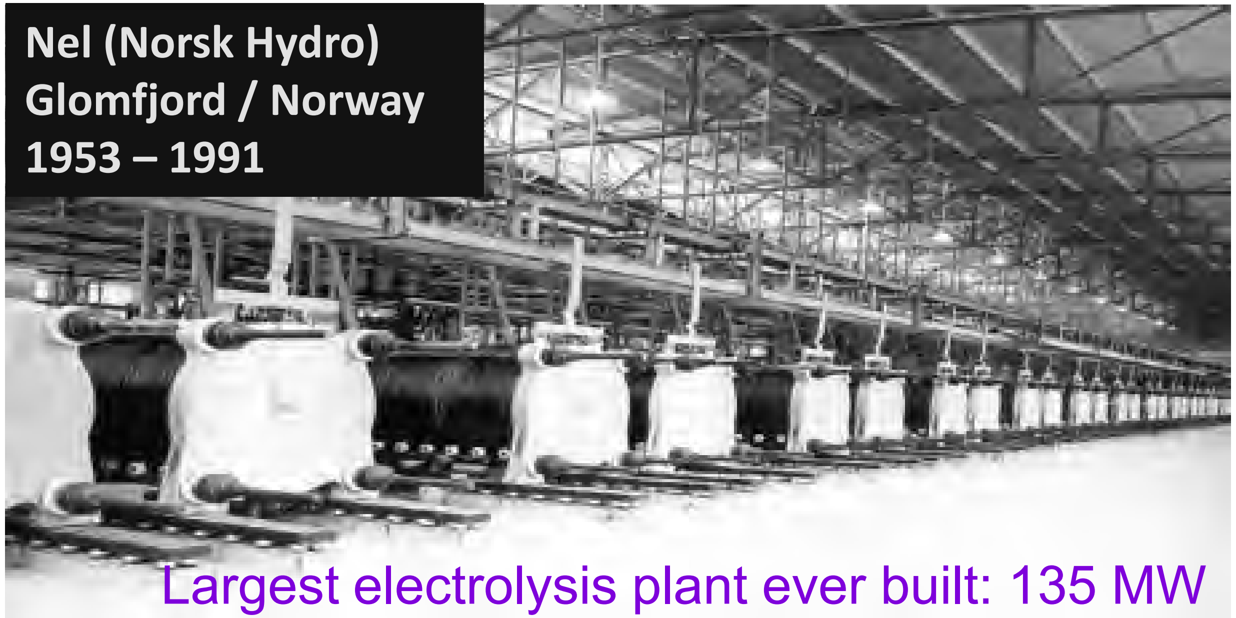
Commitment

Honesty

Boldness

COST AND EFFICIENCY DRIVERS

Electrolyzer scale – commercial technologies



Largest electrolysis plant ever built: 135 MW

KOH at scale since 1950’s; similar technology today

Can leverage advanced electrode designs and separator materials

Higher current density at same efficiency (2-3x)

20 MW PEM system

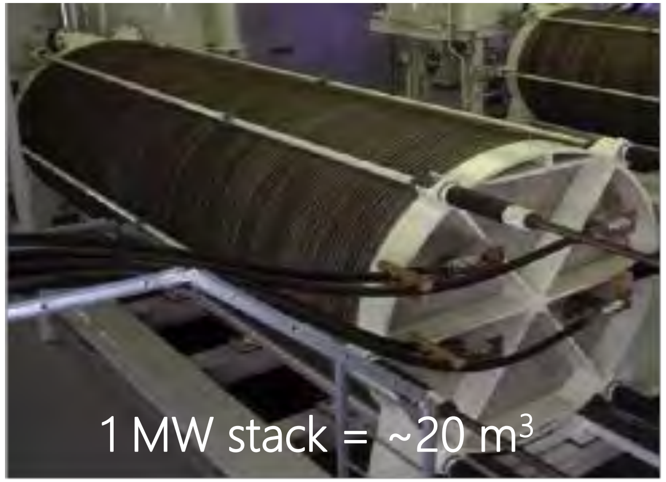
PEM originally used for life support (O_2) in closed environments: design legacy still in place

Opportunity to follow fuel cell material and manufacturing curves

Higher efficiency through thinner membrane; lower cost through manufacturing

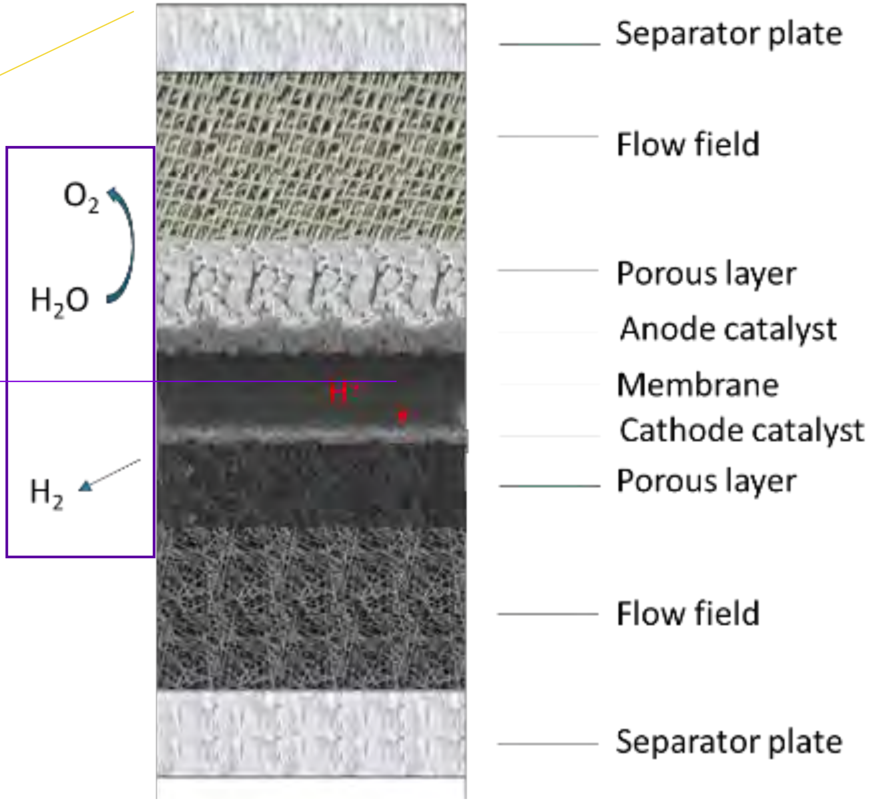
Commercial technologies

- Liquid KOH (base):
  - Catalysts are common metals (Ni, Co, Mn, etc.)
  - Corrosive electrolyte
  - Ambient, passive bubble mgmt
  - Low output, high efficiency



- Proton exchange membrane (PEM/acid):
  - Catalysts are rare metals (Pt, Ir, Ru)
  - High output, benign electrolyte
  - Differential pressure

1 MW stack = ~0.5 m^3

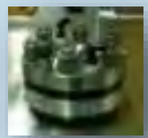


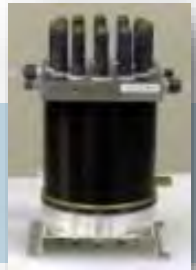
Commercial low temperature (50-80C) – MW scale, demonstrated reliability

SCALE UP 1996-2023

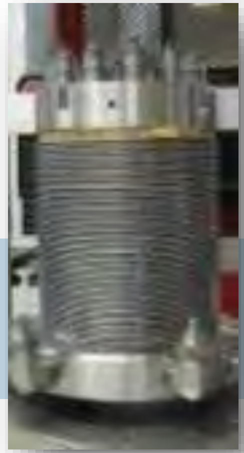
PEM Stack Progression

28 cm^2





~100 cm^2
0.5-4 kg/day



~200 cm^2
22-65 kg/day

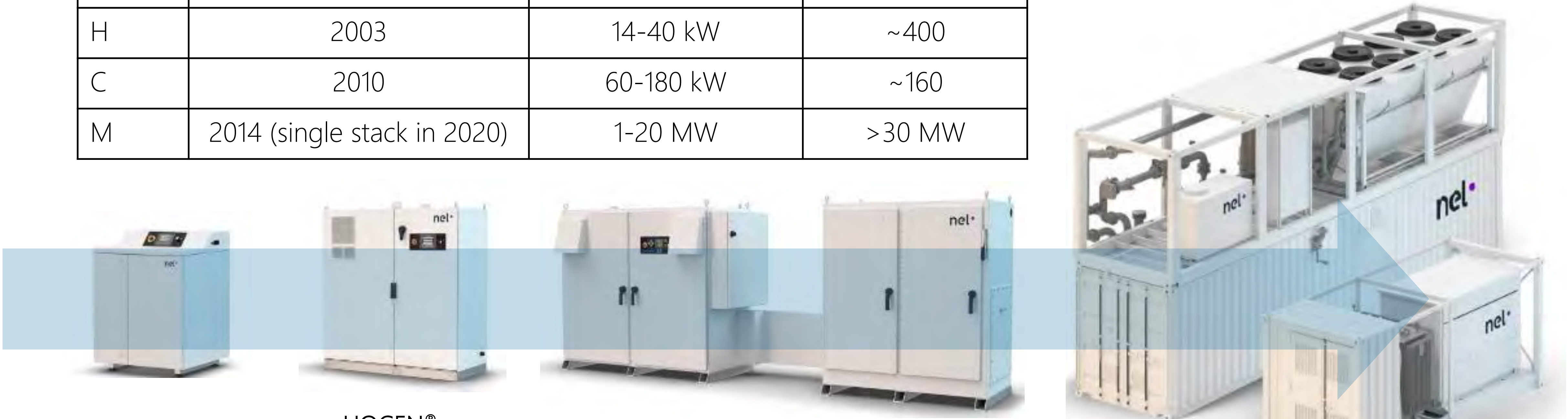
~700 cm^2
22-100 kg/day

~1600 cm^2
500 kg/day

COMMERCIAL MARKETS HAVE GROWN WITH SYSTEM SIZE

System progression

Unit	Year introduced	Capacity	# Fielded
G (lab)	1998 (disc. 2020)	<1 kW	>>1000
S	2000	4-7 kW	~800
H	2003	14-40 kW	~400
C	2010	60-180 kW	~160
M	2014 (single stack in 2020)	1-20 MW	>30 MW



HOGEN®
S Series
0.5 – 1 kg/day

HOGEN®
H Series
4-13 kg/day

HOGEN®
C Series
22-65 kg/day

M Series
500-1000 kg/day

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Our factories producing electrolyzers today

CT PEM System Manufacturing

Norway Automated Electrode Manufacturing

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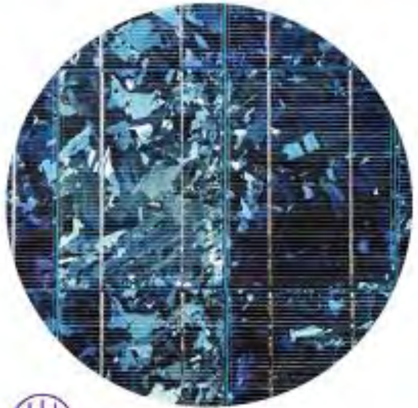
Traditional electrolyser market / niche applications

Food Industry

Glass Industry

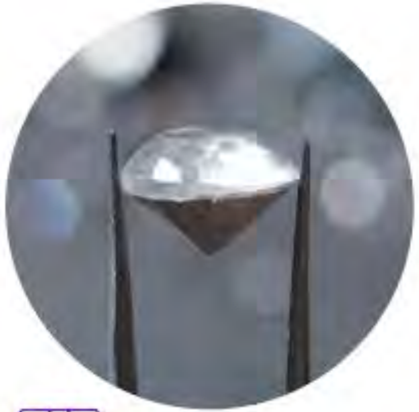


Polysilicon Industry

Laboratories

Life Support

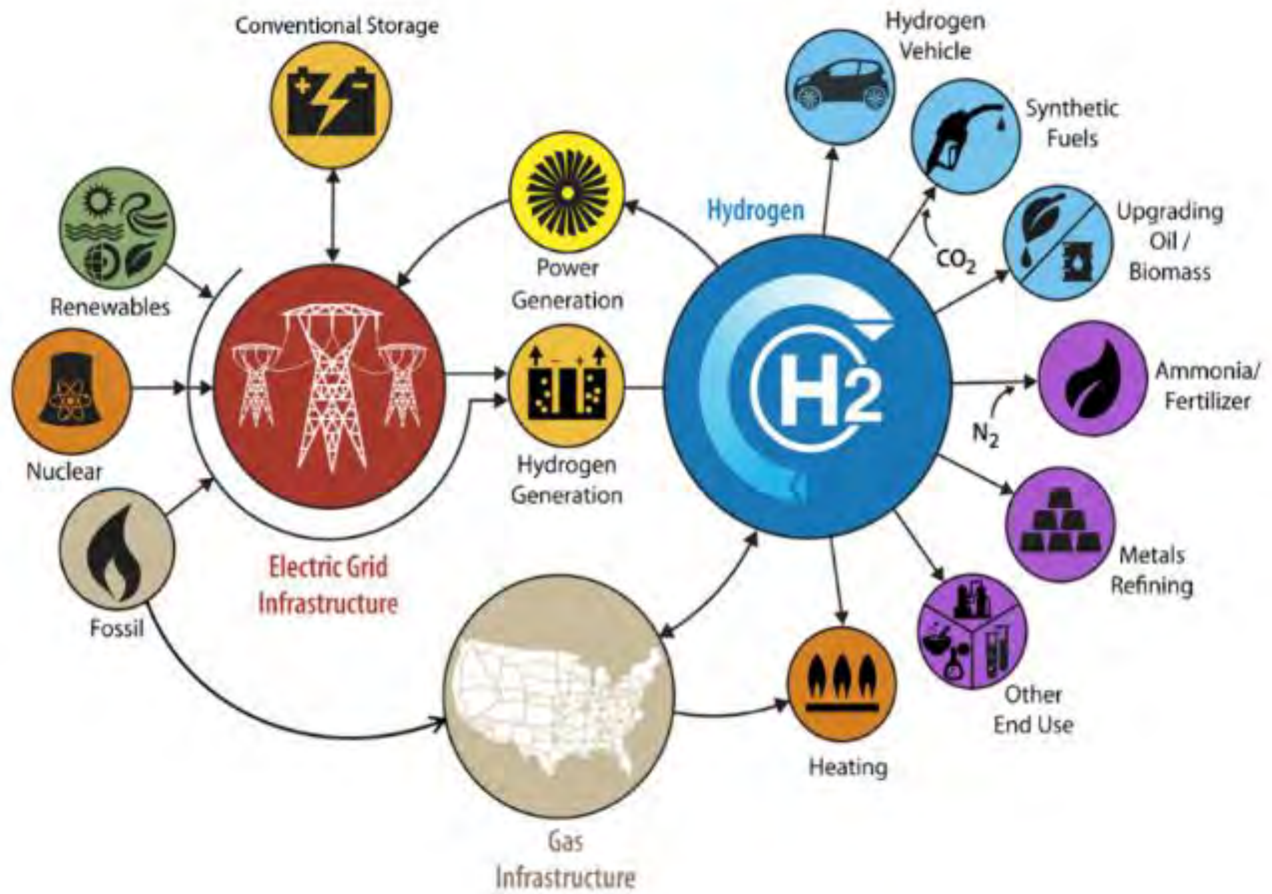
Thermal processing



Chemical vapor deposition

Power Industry

Electrolysis at scale needed for decarbonization



DOE H2@Scale Initiative: Connection of Various Infrastructures

- Chemical industry requires renewable hydrogen source
  - Ammonia, hydrocarbons
  - Includes CO_2 conversion
- Fuels needed for some applications
  - Long term energy storage
  - Aviation

Electrolyzer cost (capex and opex) needs to be reduced to make this happen

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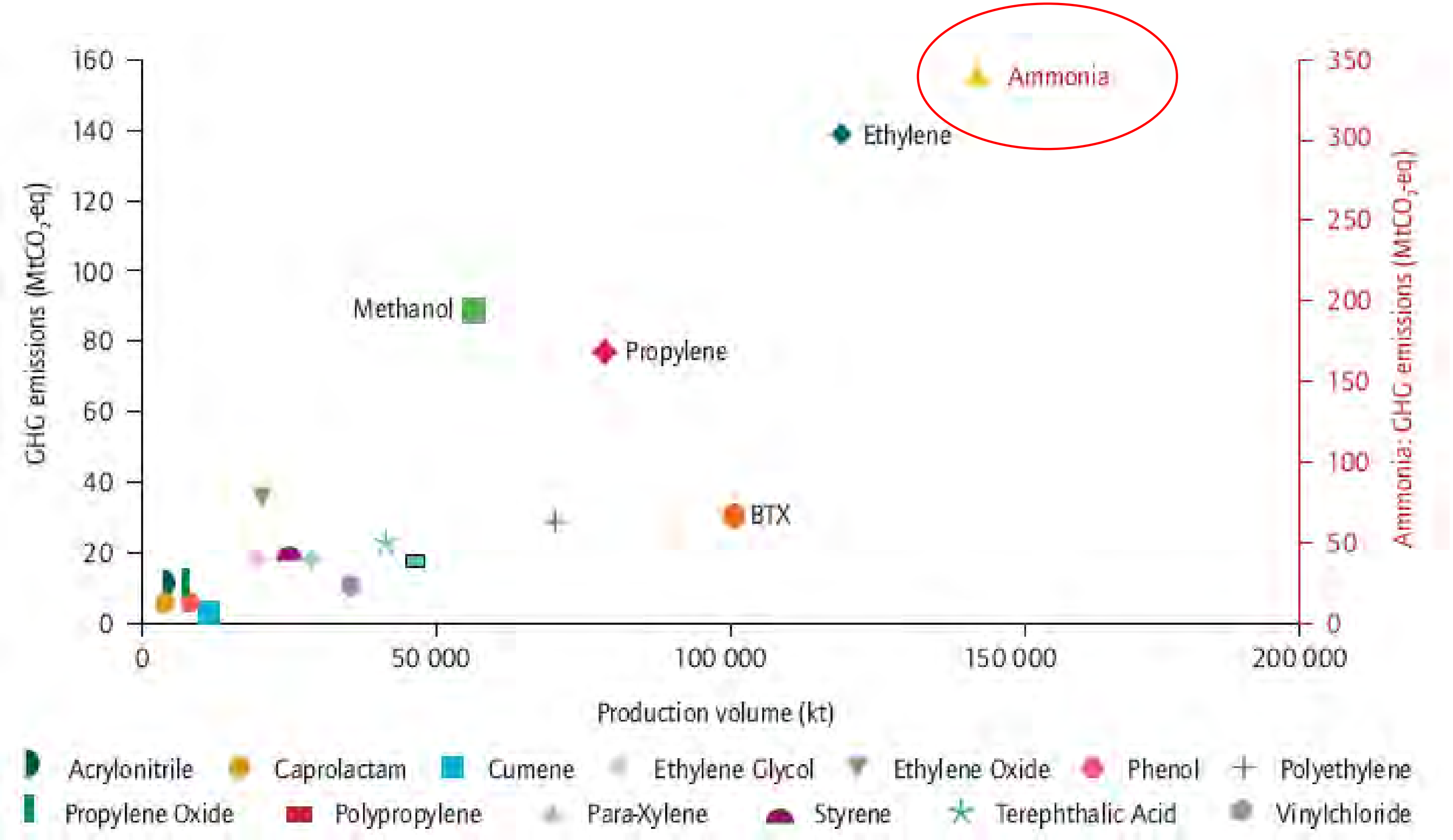
Ammonia production creates 1% of CO_2 emissions

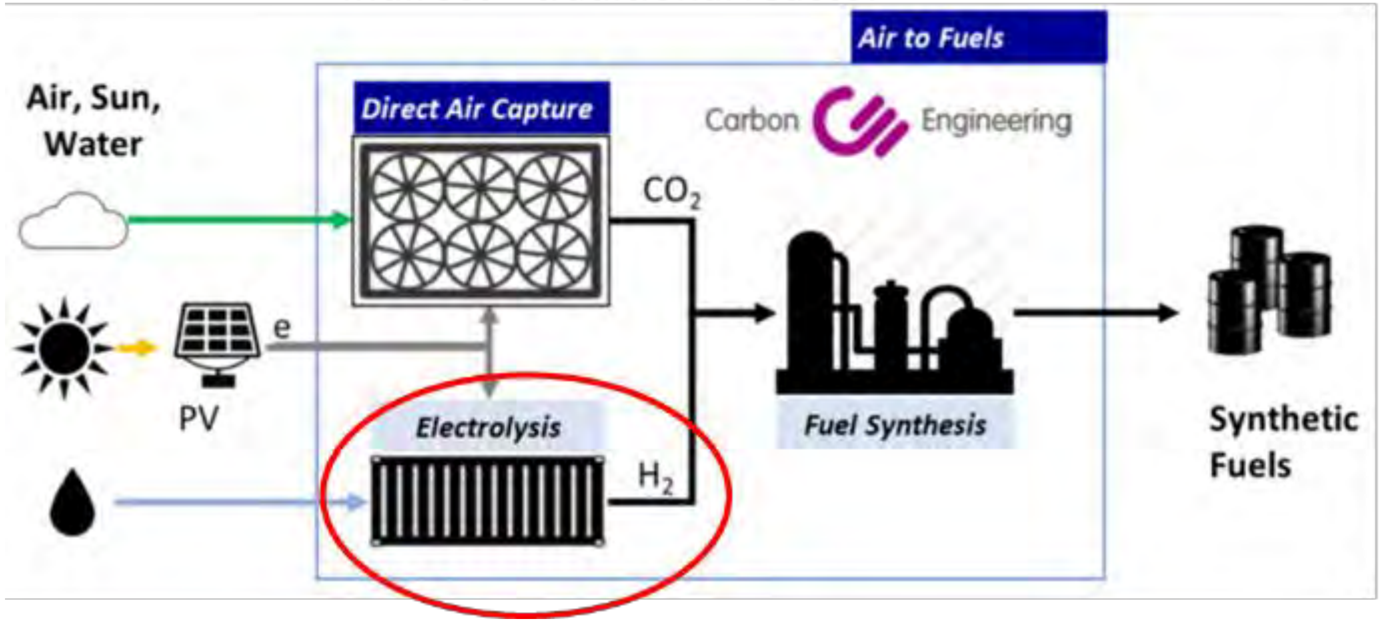
- Highest CO_2 emissions of any mass-produced chemical
- Based on hydrogen production step from natural gas:
- $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$



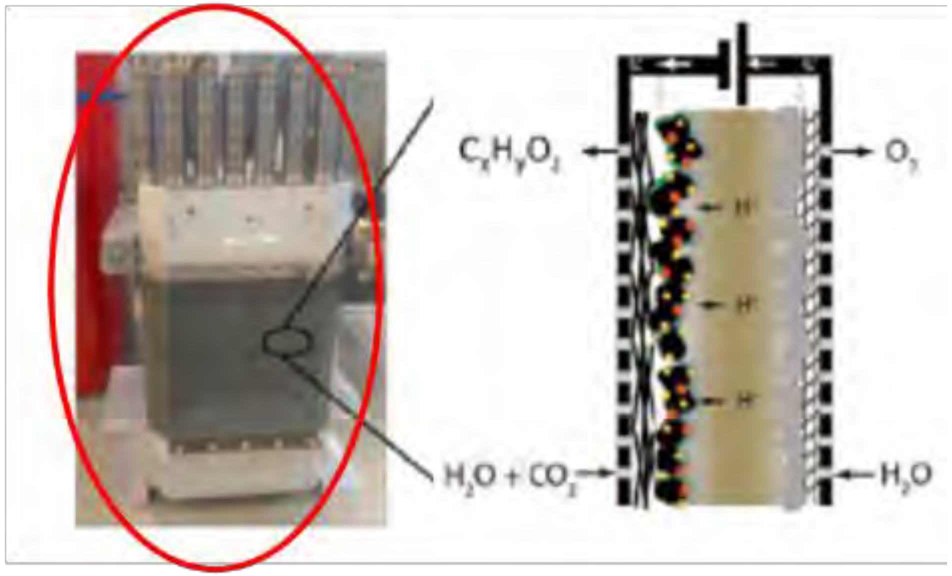
Source: DECHEMA

Any recycling process for CO_2 requires renewable protons

Indirect – traditional reactor



Direct – based on electrolyzer stack



Source: Carbon Engineering; Opus 12

Large scale potential markets

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Accelerated focus on industrial hydrogen applications

>2,000 GW electrolysis potential

Ammonia

Refinery

Steel

2

Strong momentum within mobility, especially within HDV

>2,000 GW electrolysis potential*

IVECO & Nikola partnering in European fuel cell HDV market

Anglo American/ENGIE to develop fuel cell electric mining trucks

Hyundai reveals HDV concept – plan to deliver 1,600 trucks to Switzerland

* At 50% market share. Image credits: Nikola Corporation, Anglo American, Hyundai

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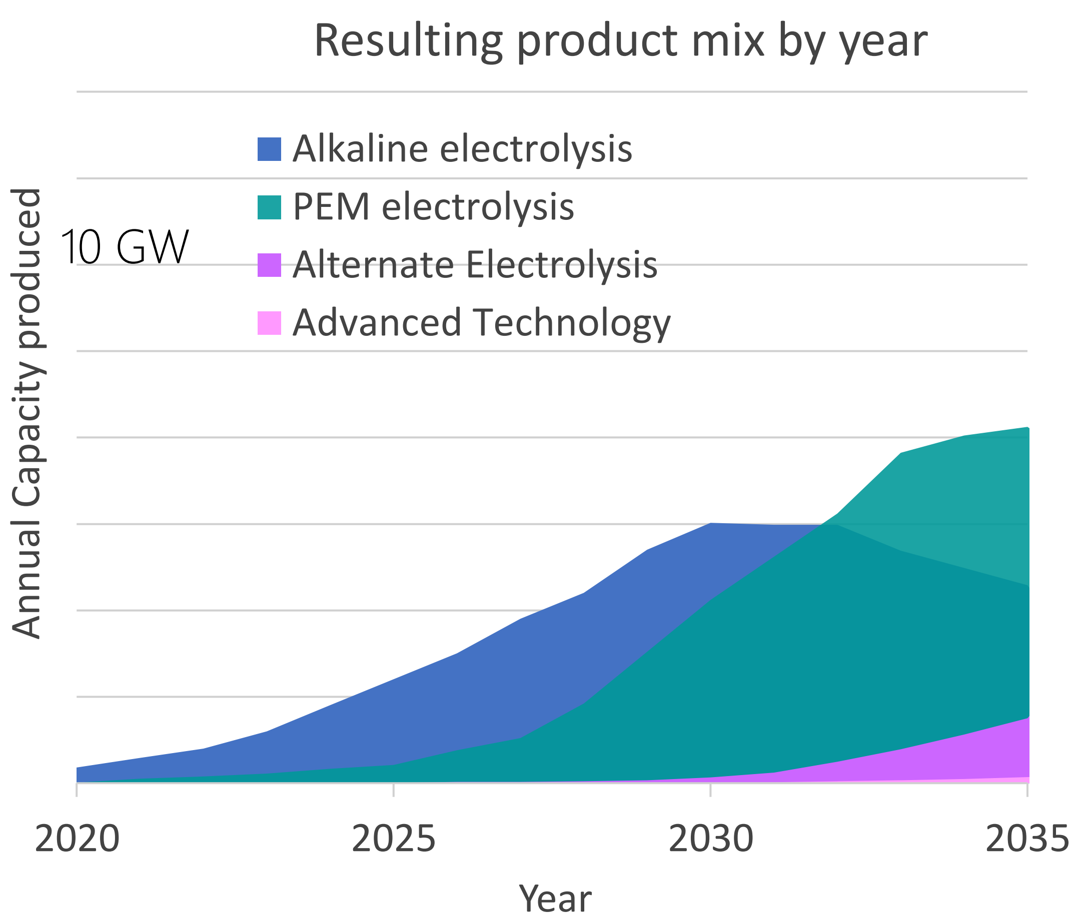
Realities of Near Term Renewable Hydrogen Systems

- **Assume:** 100 MW PEM electrolyzers in 2-3 years (conservative)
  - Currently have MW systems fielded
  - Projects in concept phase already
- **Then assume** (wildly positive):
  - Alternate technologies start now and follow PEM scale trajectory
  - Advanced technologies (PEC etc.) get to 100 kW scale by 2026 and 5 MW by 2036
    - 5 MW solar represents 50,000 m^2 active area



Similar conclusion reached in German study
(Stolten, 2014: 20 years from research completion to full market penetration of technology)

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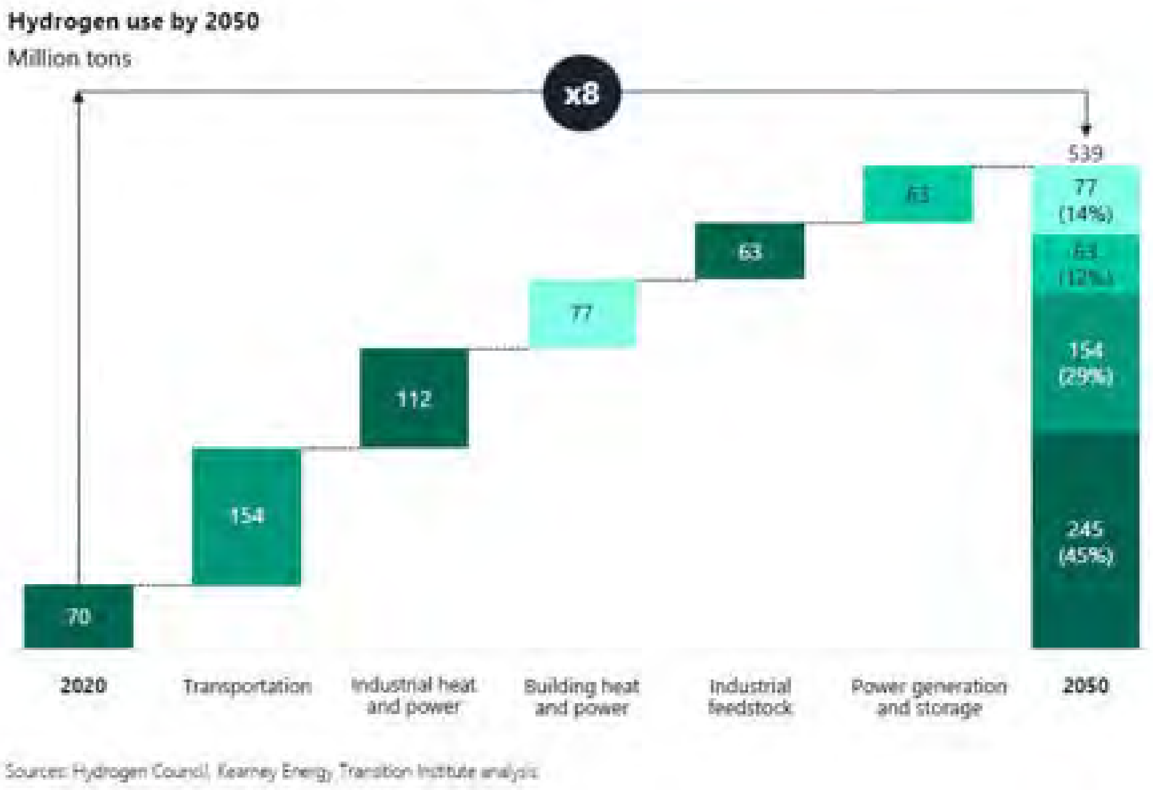
Potential markets and learnings

Hydrogen demand expected to grow 8x
Electrolysis industry would have to grow 800x to meet 100%



PEM electrolyzers vs. fuel cells

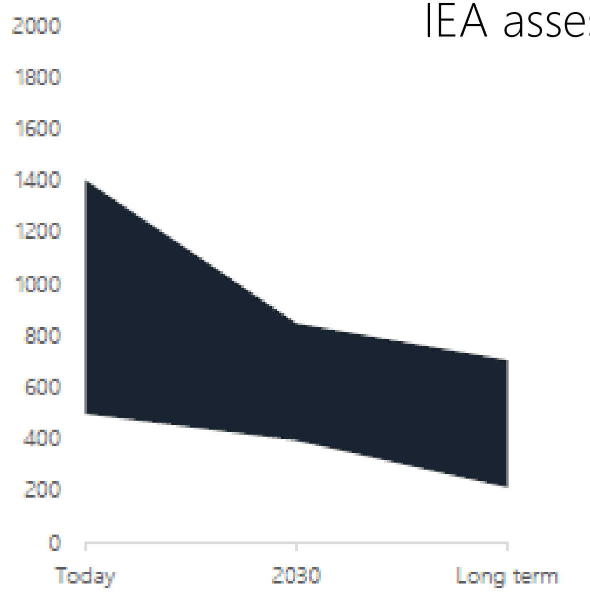
- Significantly higher material usage
  - 8-10x PGM usage
  - 10x membrane thickness
  - ~3-5x cell thickness
- Slow batch vs. high speed processes
- 100-1000x lower cell volumes

Leverage fuel cell manufacturing development to advance electrolyzers

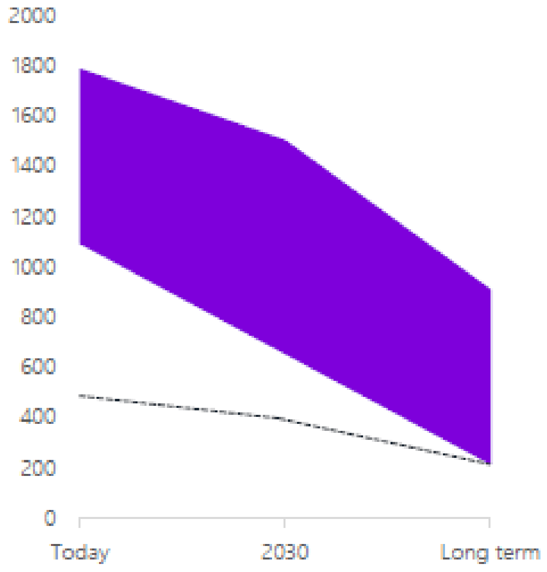
PEM / Alkaline potential

AE CAPEX Evolution
(2010-2030, $ per kW)

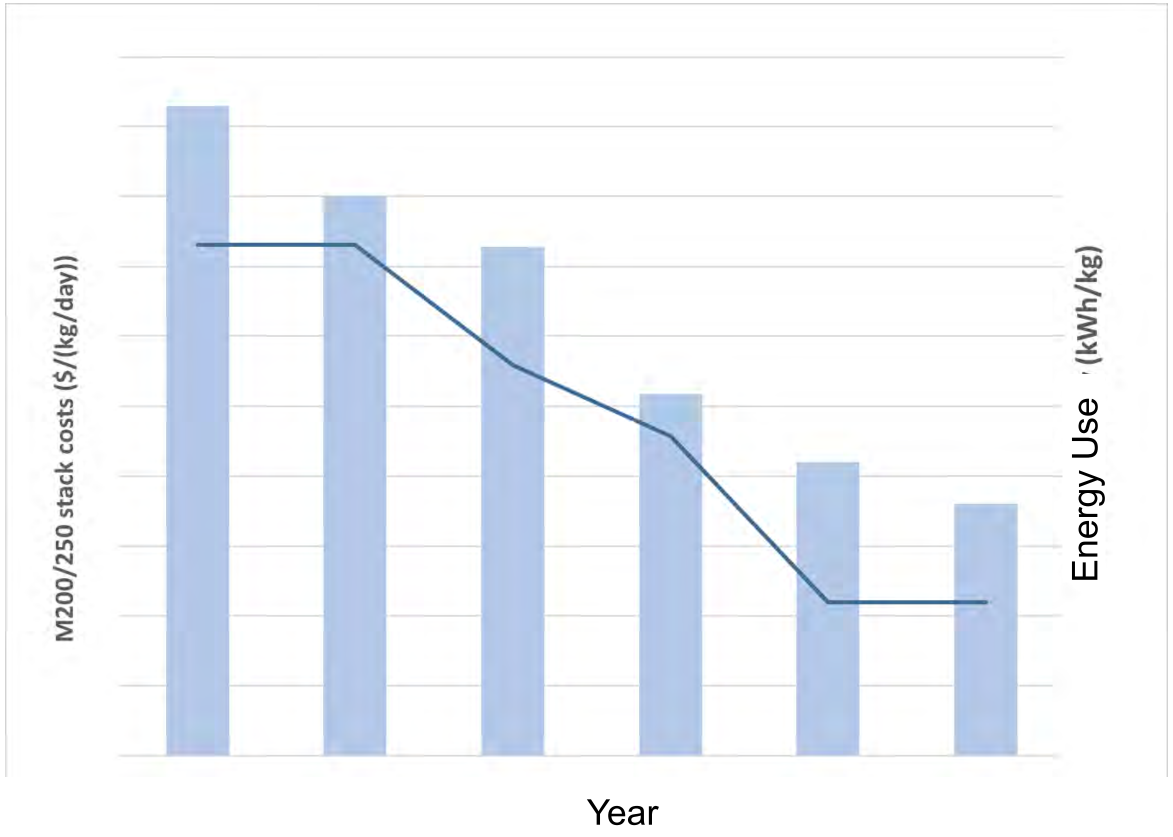
IEA assessment



PEM CAPEX Evolution
(2010-2030, $ per kW)



Nel: Improvements demonstrated in lab; staged implementation



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System will largely benefit from elimination of redundant components

PEM 30 Nm^3/hr solution

Cost parity

KOH 30 Nm^3/hr solution

Cost differences largely based on stack and system capacity, not technology

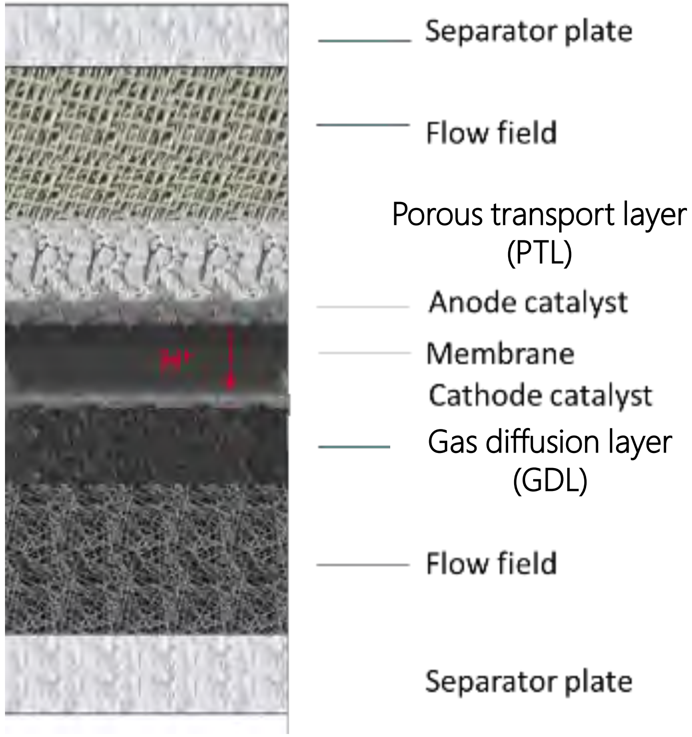
PEM 150 Nm^3/hr solution

Not cost parity

KOH 150 Nm^3/hr solution

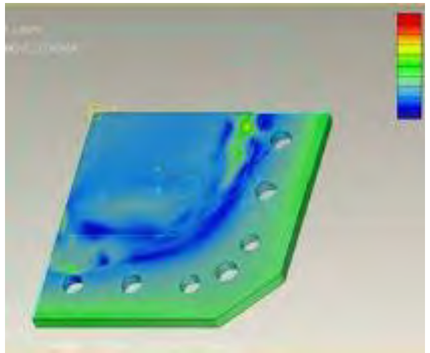
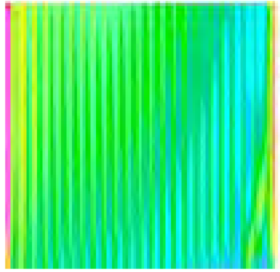
PEMWE materials research needs

- Commercial OER materials are inconsistent blends of IrOx, unoptimized nanostructure
- No acceptable OER supports exist
- Understanding of ionomers and transport through catalyst layer; local pH
- Materials not designed for use; adapted from other industries
  - Polymers
  - GDLs/PTLs
- All components have to work together in the device



Starting with a successful example…

Fundamental R&D to Prototyping

Component modeling

Accelerated embrittlement

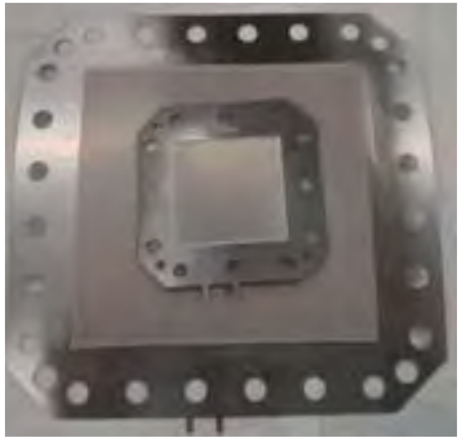
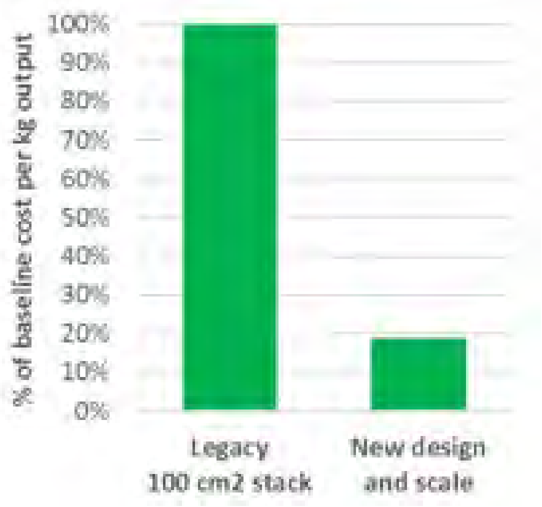
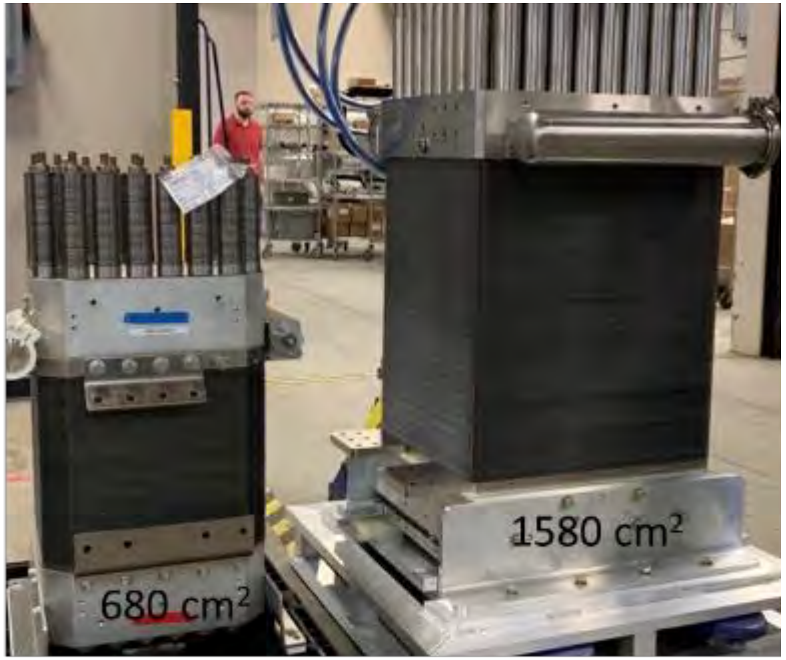


Plate manufacturing



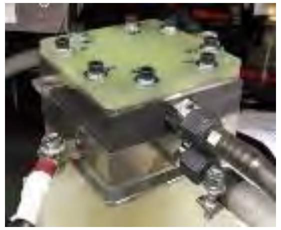
Products from kW to MW scale

90 cm²



Nel scale up and commercialization: MW stack based on same platform

Translation from Lab to Product at Scale



Test cell: 25 cm^2 active area

1 MW PEM electrolyzer: 272,000 cm^2
11,000x test cell

135 MW KOH plant: 257,000,000 cm^2
10,000,000x test cell

Challenges to implementing new designs based on promising materials

- Have to be able to do the same thing millions of times
- Lifetime expectations of 7-10 years (>50,000 hours)
- How to ensure process is robust enough to field product?

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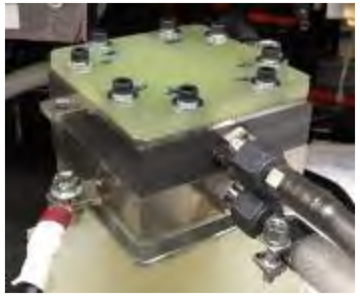
99% accuracy is not enough at scale

- 99/100 successful experiments would be considered great

High likelihood of successful result at this scale



- 99/100 good cells would be a manufacturing disaster

High likelihood of failing every stack at this scale

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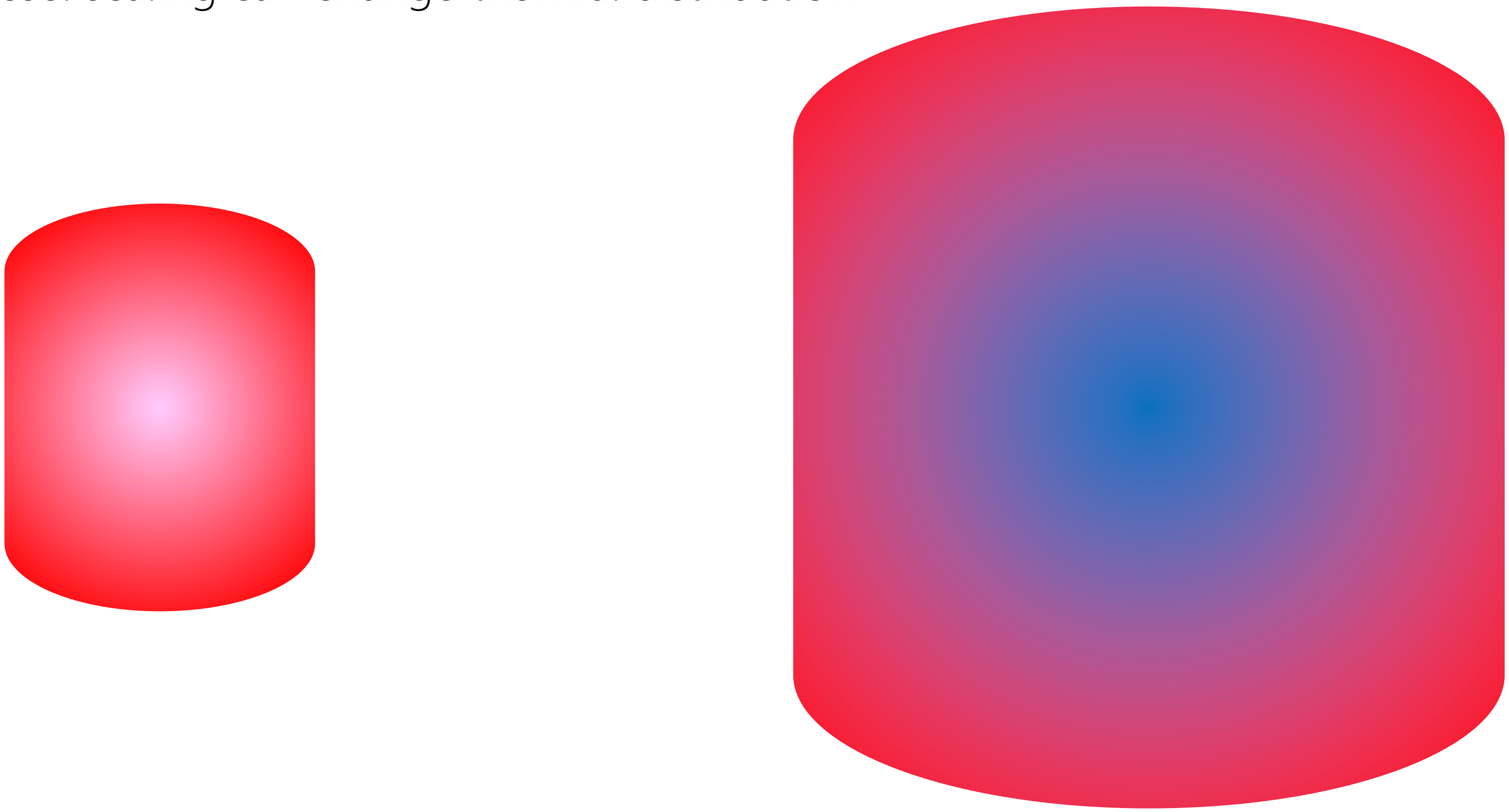
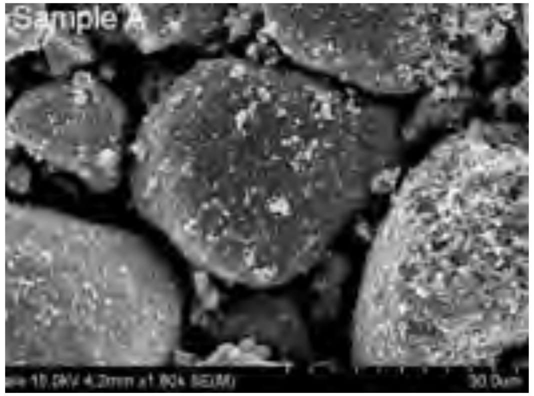
Scaling impacts the whole supply chain - catalyst

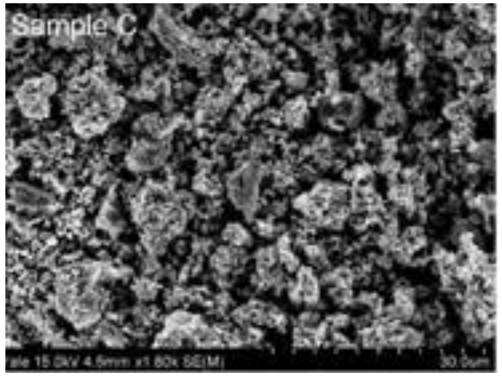
- Reaction vessel scaling can change thermal distribution

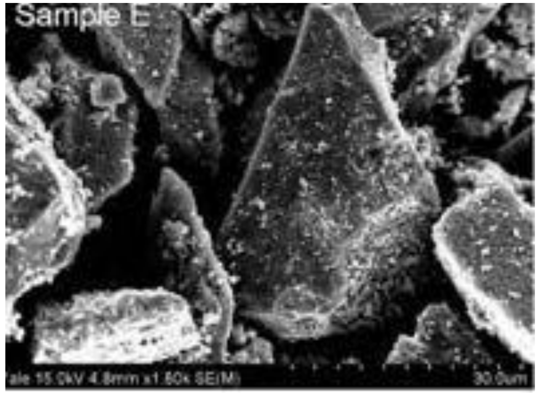


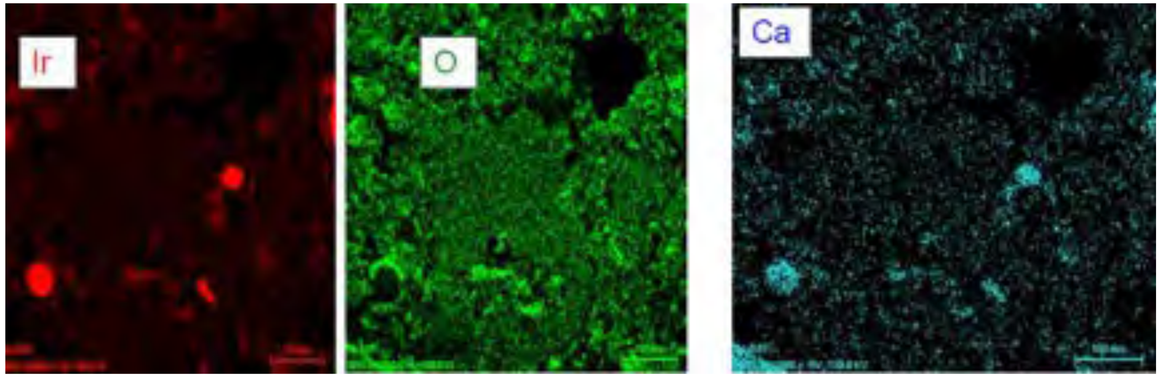
Potential impact of variation in reaction conditions

- Particle size, shape and purity can be impacted









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Scaling impacts the whole supply chain - membrane

- Small sheets, small batches of ionomer
  - Can be hand cast
  - Even drying
  - Beaker chemistry

- Large Rolls
  - Subject to inclusions, uneven hydrolysis
  - Huge areas that need to be +/- microns in thickness

https://www.nature.com/articles/s41467-023-38350-7/figures/1

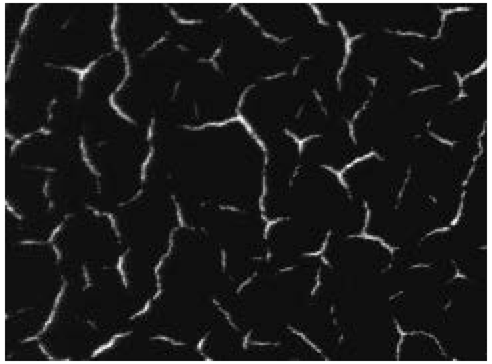
Scaling fundamentals – electrode production

- Bench coating can simulate process to a degree
  - Rough estimate of viscosity and loading required
- Roll to roll at scale involves different fluid dynamics
  - Also generate a lot of scrap really quickly if wrong

Types of defects and causes

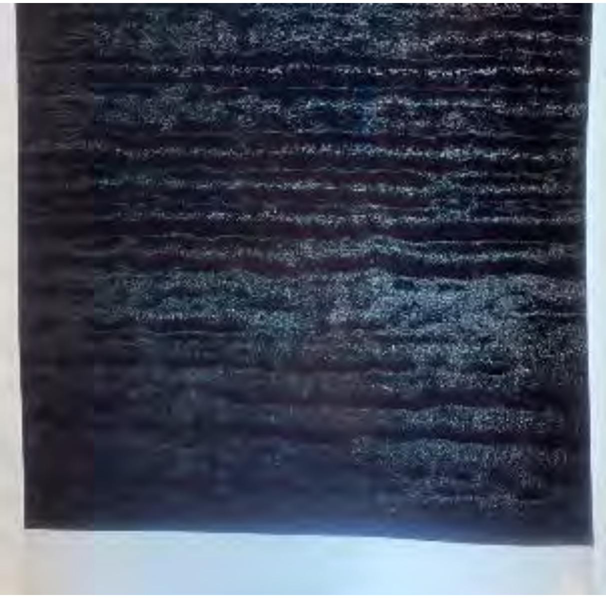
Bubbles in layer

Mud cracking



Viscosity/surface tension issues

Striations



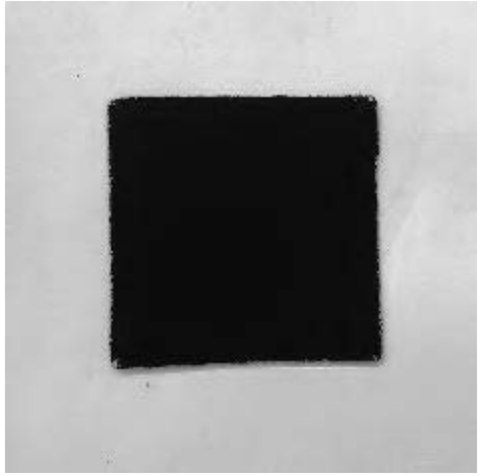
Uneven drying
(flow while drying)

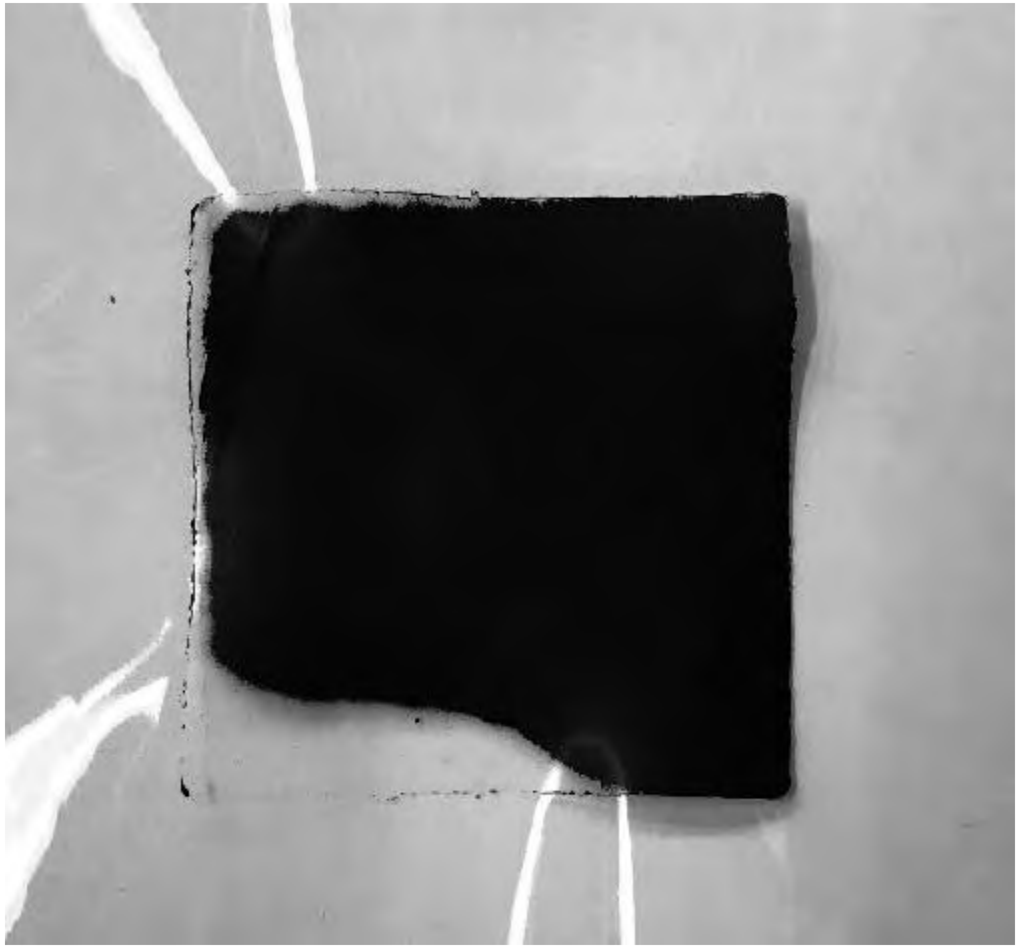
Streaking and voids

Poor/uneven contact with
substrate during print

Lamination

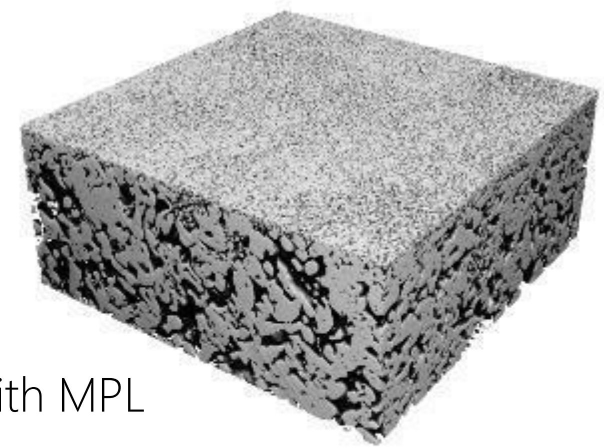
- Much easier to achieve consistent pressure/temperature at small scale
  - Tool flatness, etc harder with scale
  - Can lead to uneven transfer



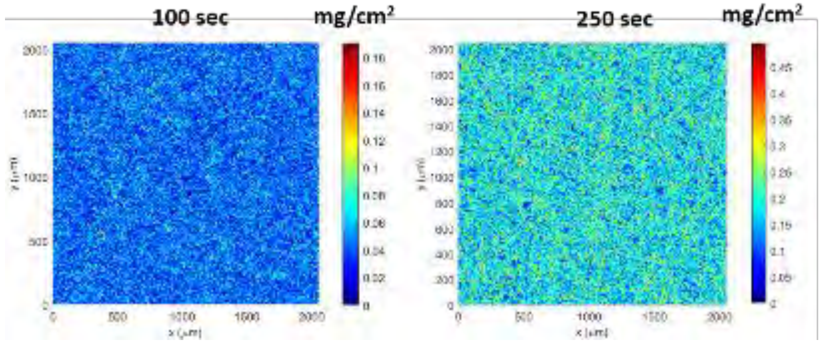


Porous transport layer serves multiple functions

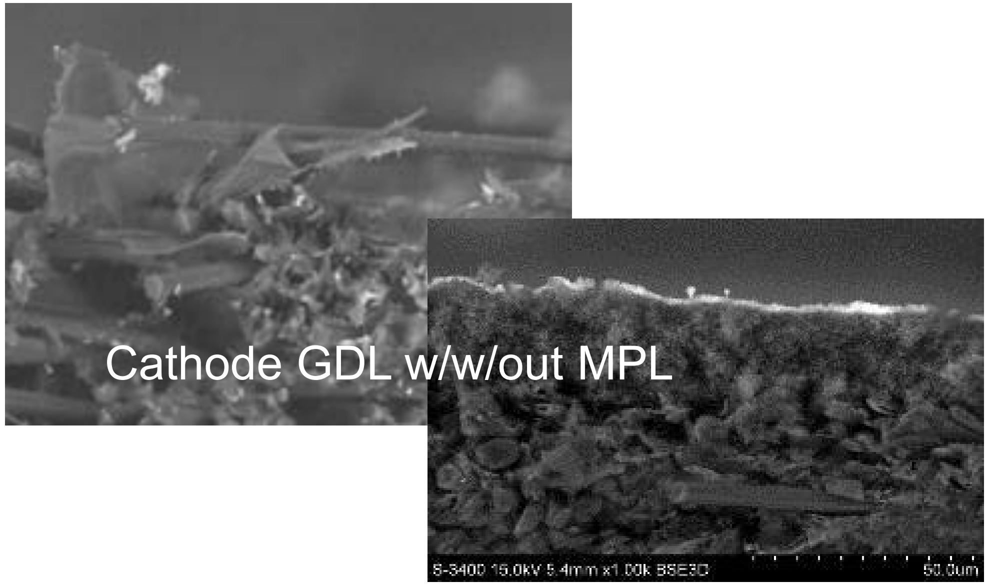
- Requirements:
  - Effective contact to catalyst
  - Support of membrane
  - Transport of fluids
- Development immature



PTL with MPL



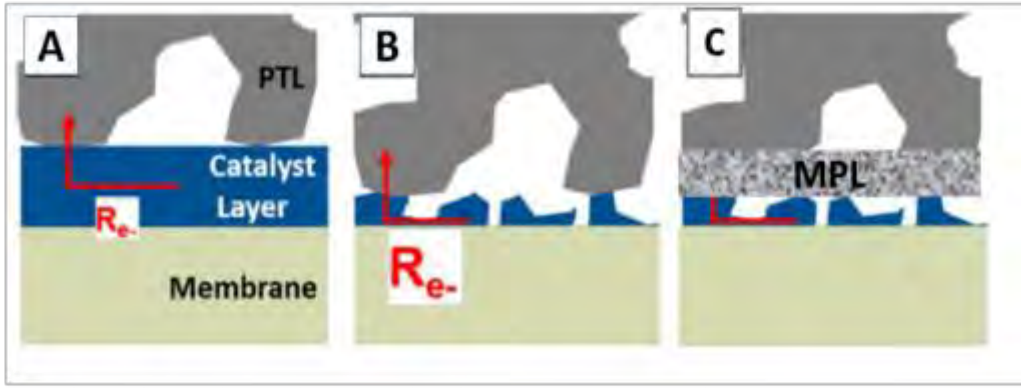
Pt coverage



Cathode GDL w/w/out MPL

Effect of MPLs

Gasteiger, ECS 2018



A – Thick electrode catalyst layer has lower resistance to the porous transport layer
B – Thinner electrode catalyst has very high resistance to porous transport layer
C – Microporous layer effectively contacts catalyst layer

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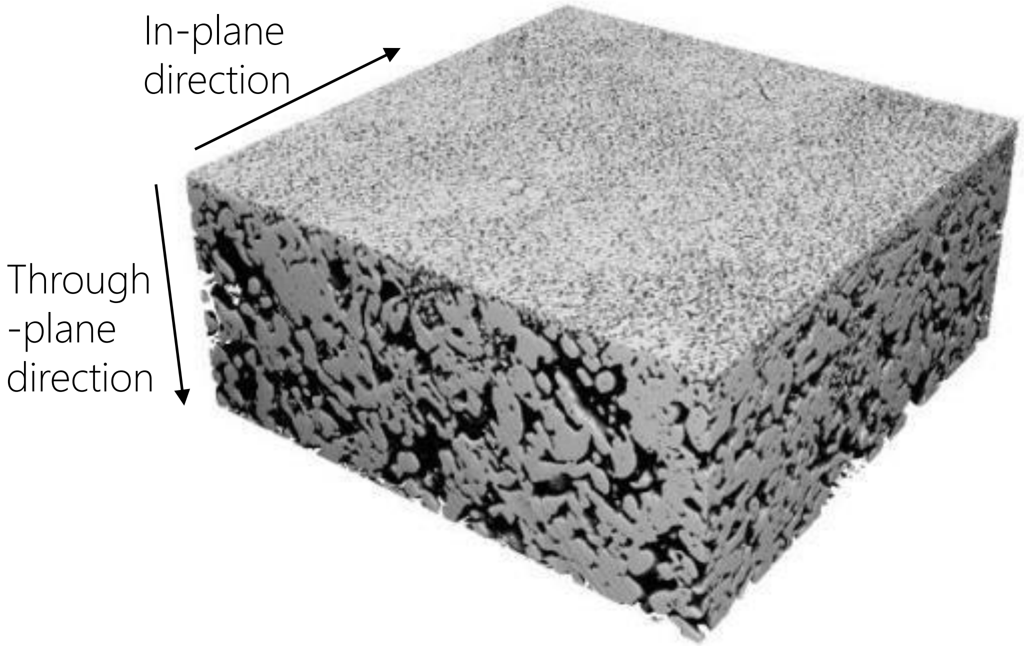
Manufacturability

- 3-D manufacturing methods can make very fine features but slow and costly

https://mottcorp.com/product/3d-printed-filters/3d-printed-porous-metal/

- Porous layer made at large active area by chemical manufacturer

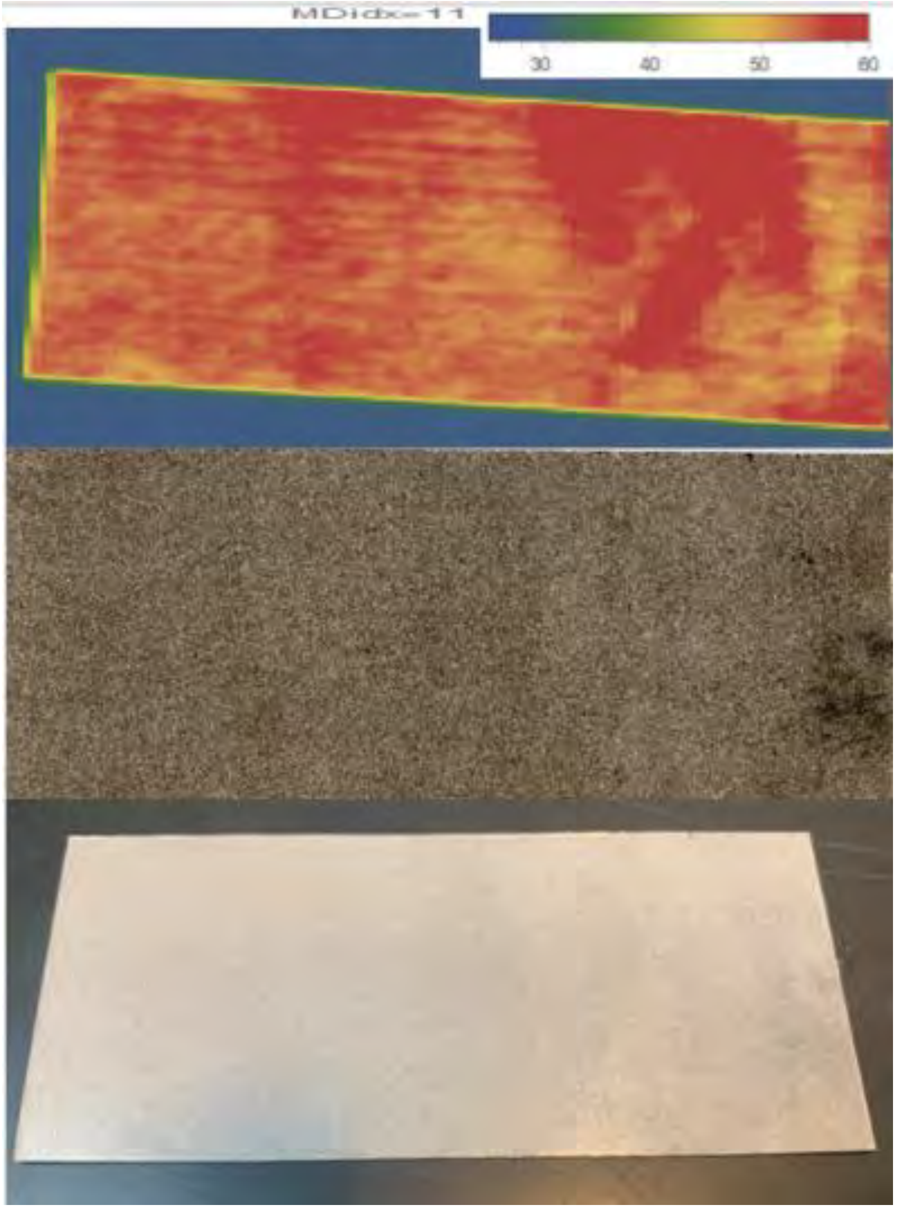


Quality control

- Visual inspection is slow and relies on attention
  - Operator can fatigue

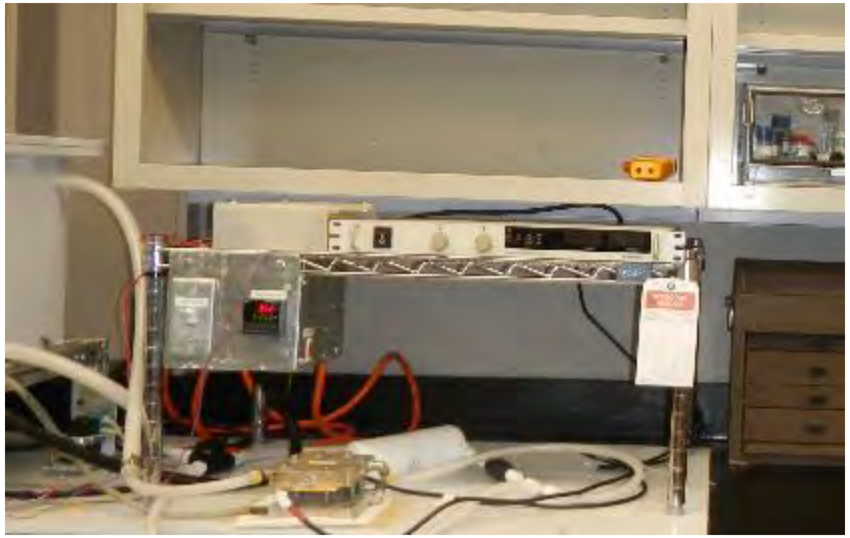
- Computer can image more accurately but has to be trained on defects

- Need a combination to develop accurate control



Design verification

- Bench test:
  - Fast setup
  - $$ to build
  - $ to operate



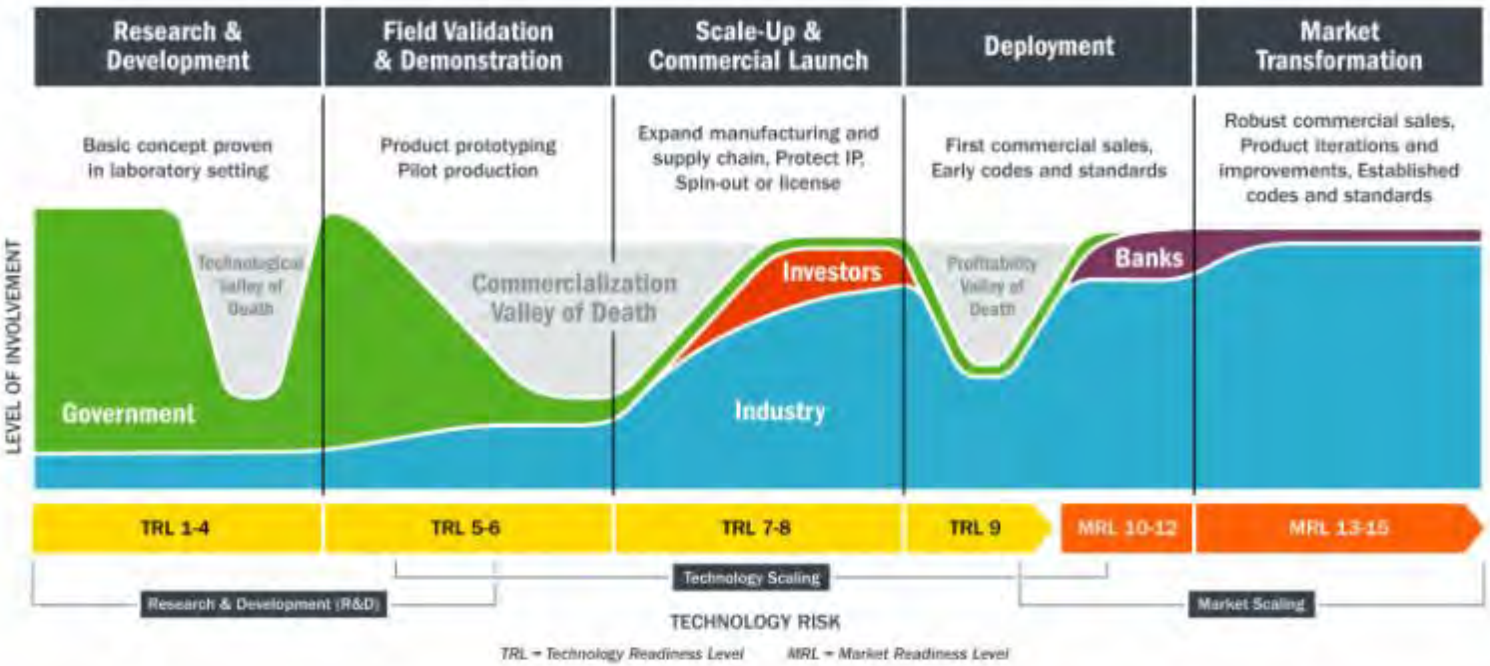
- Full scale test:
  - Days to set up
  - $$$$$$ to build
  - $$$$$$ to operate

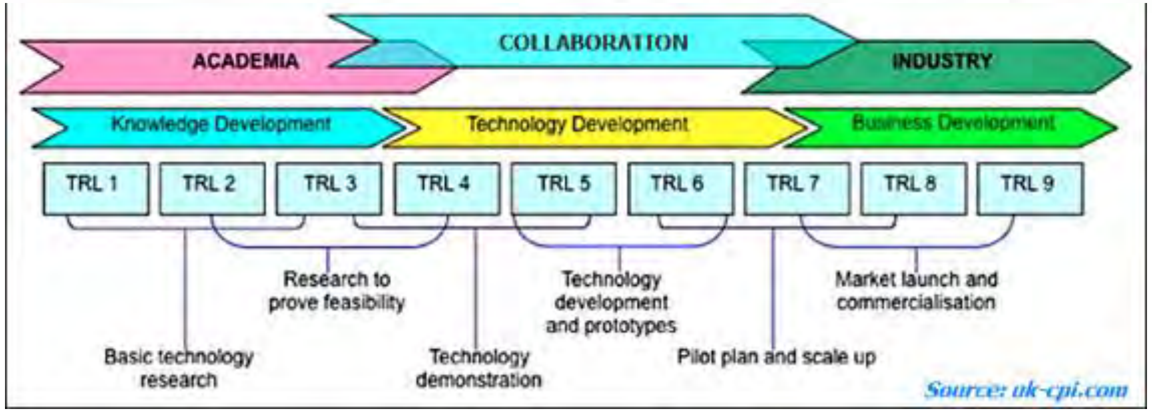
What does this mean for new invention?

Important features:

- Multiple valleys of death
- Both industry and academia need to bridge from traditional roles
- Hands off approach does not work
- Most industries will not license at TRL4 without proof of scalability

https://www.energy.gov/eere/buildings/technology-market





Conclusions

- Electrolysis needs to grow rapidly
- Translating results from the lab to a product is a complex process
- Tools, methods, and parameters often need to change
- Characterization and testing to qualify new designs is expensive
- Understanding the fundamentals is essential for success
- We are poised for expansion!

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number one by nature

Questions?