MIDACE:

Methanol from Integrated Direct Air Capture and Ceramic Electrolysis

Washington State University
AEM — Realize your Vyzion!
Lehigh University
Arizona State University

FECM CONFERENCE

DE-FE0032403

8/8/2024

DR. DUSTIN MCLARTY
FOUNDER OF AEM

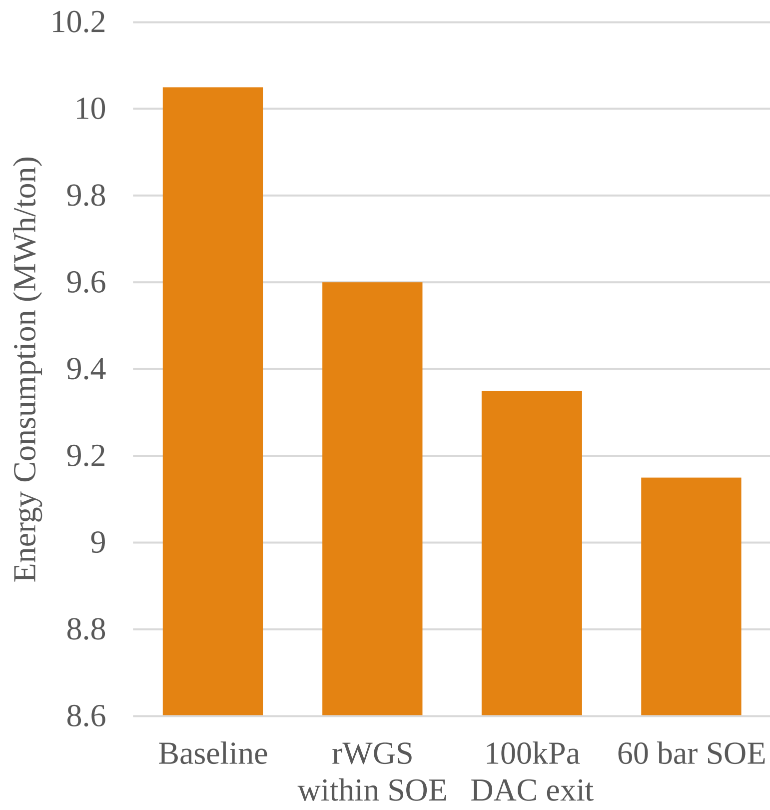
Funding, Cost Share & Project Team

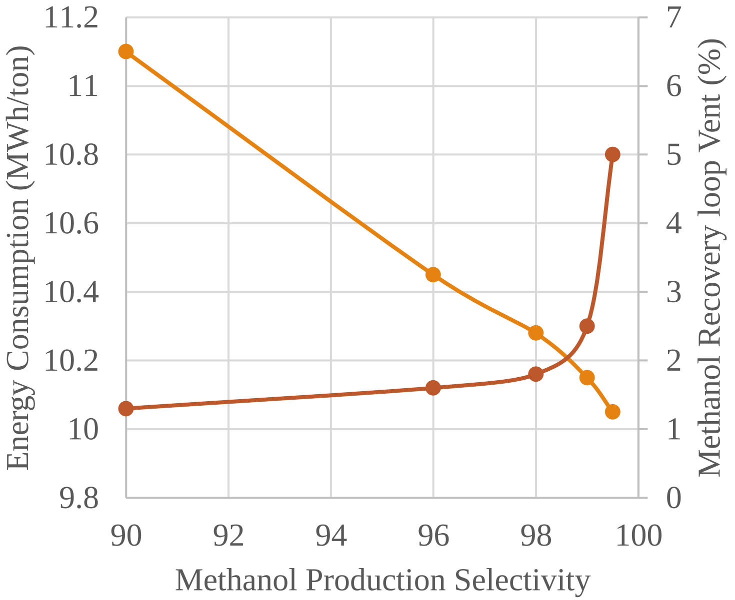
Task	Federal	Non-Federal
TEA / LCA	$120,000	$30,000
Community Benefits	$40,000	$10,000
Experiments	$80,000	$20,000
Conceptual Design	$160,000	$40,000
Total	$400,000	$100,000

Key Personnel	Organization	Role	
Dustin McLarty	WSU & AEM	PI and Pressurized Electrolysis	
Jonas Baltrusaitis	Lehigh University	Methanol Synthesis and Refinement	
Matthew Green	ASU	Carbon Capture	
Justin Flory	ASU	Carbon Capture	
Klaus Lackner	ASU	Carbon Capture	

MIDACE Objectives

- Perform a detailed technoeconomic and life-cycle assessment of a green methanol plant that couples the mass flow and heat transfer between direct air capture (DAC), high temperature electrolysis, and a methanol synthesis reactor
- Using existing experimental facilities and modeling capabilities to address three knowledge gaps:
  - ***Knowledge Gap 1:*** How does elevated temperature improve yield and accelerate sorbent regeneration?
  - ***Knowledge Gap 2:*** Can the electrolyzer directly produce a pressurized syngas feedstock while avoiding in-situ methanation?
  - ***Knowledge Gap 3:*** What reactor feedstock operating conditions maximize reaction kinetics and minimize electrolyzer load?

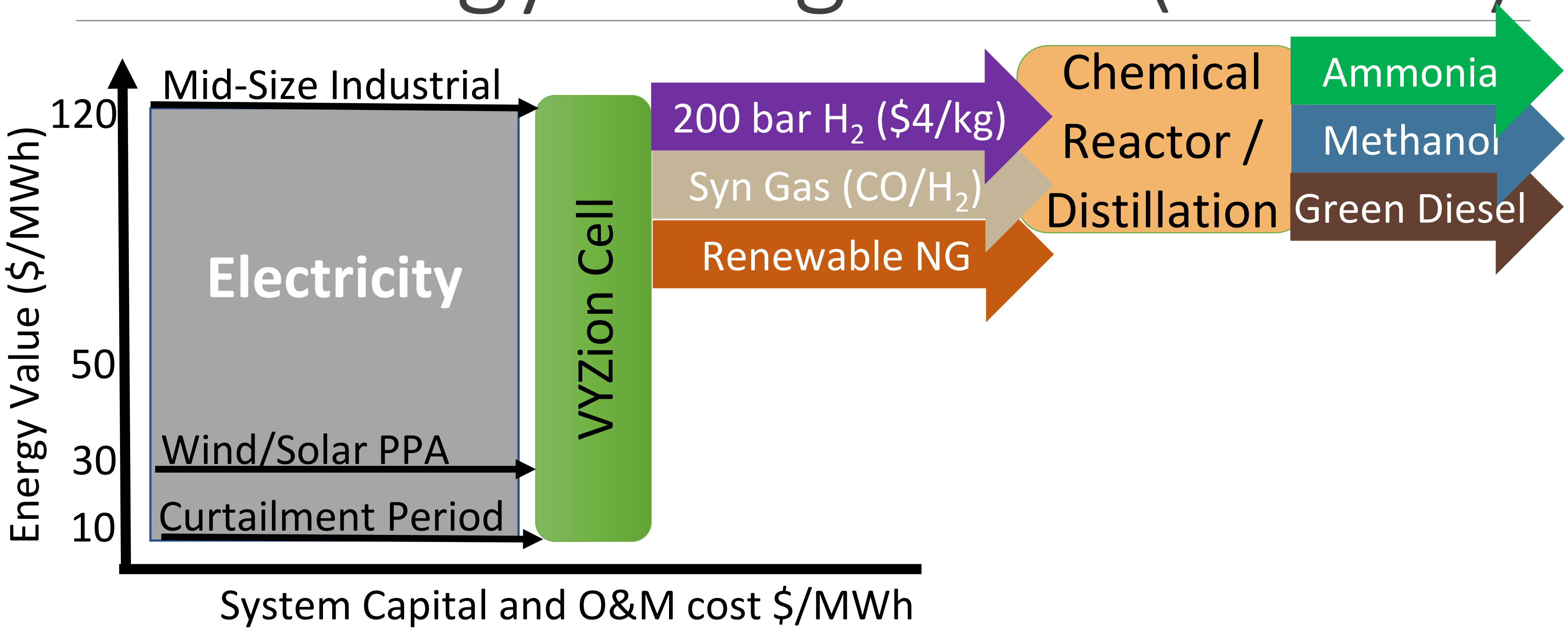




Project Performance Dates

- March 19 – 2024: Complete kickoff, initial community benefits, management plan and technology maturation plan
- June 19 – 2024: Complete initial SOEC co-electrolysis experiments, methanation risk assessment, DAC performance measurements at elevated temperature, rWGS modeling, and feedstock study
- September 19 – 2024: Complete pressurized co-electrolysis experiments, DAC regeneration & purity tests, synthesis reactor sizing, and distillation column sizing
- December 19 – 2024: Complete final TEA, LCA, and community benefits

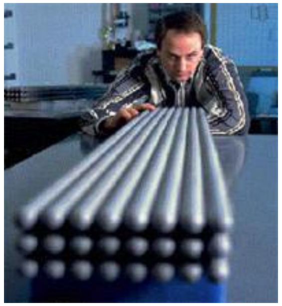
Technology Background (VYZion)



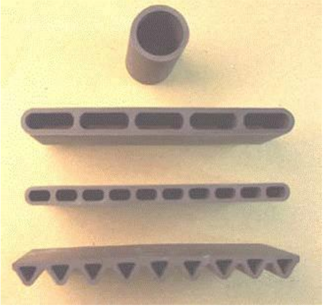
- VYZion converts renewable electricity collected into green hydrogen 20% more efficiently than PEM
- VYZion can directly electrolyze CO2
- VYZion integrates with pressurized thermochemistry to synthesize green methanol
- VYZion increases power density 20x and lowers cost 5x compared to state-of-the-art SOEC

Technology Background (SOC)

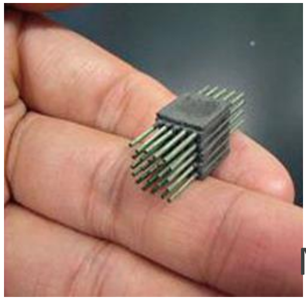
Long history of miniaturization to achieve more active surface per unit material



Tubular cells from Westinghouse in 90’s



Rolls-Royce high density tubular cells 00’s

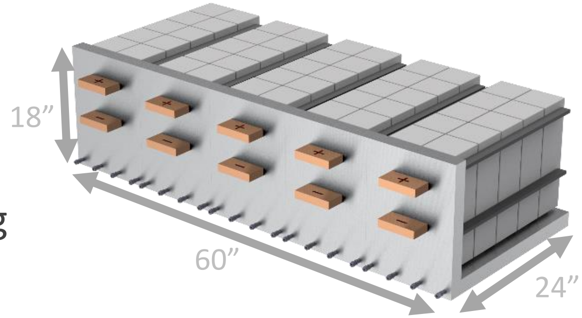


Imperial College microtubular cells 00’s

Manufacturing limits reached

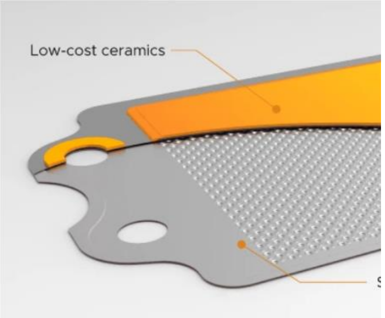
Progress required both a material and manufacturing innovation

5x 10 stacks modules ~ 1MW

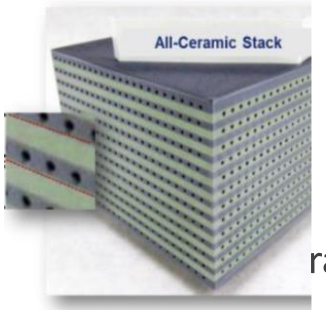


Long history of design and manufacturing evolution to improve seals and lower cost

Bloom Planar Stack 00’s



Ceres Metal supported cells 2010’s



Saint-Gobain Monolith 2010’s

Reactant flow rate and sealing limits reached

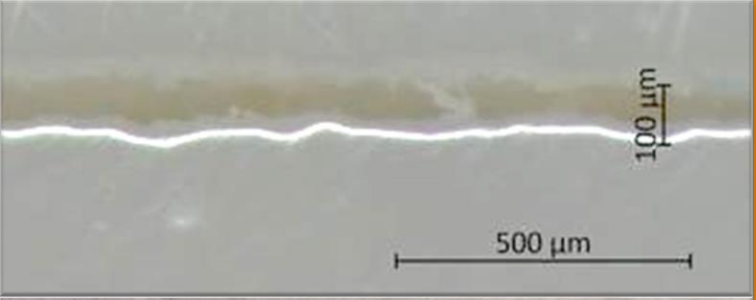
<1/100th volume and mass of competitor

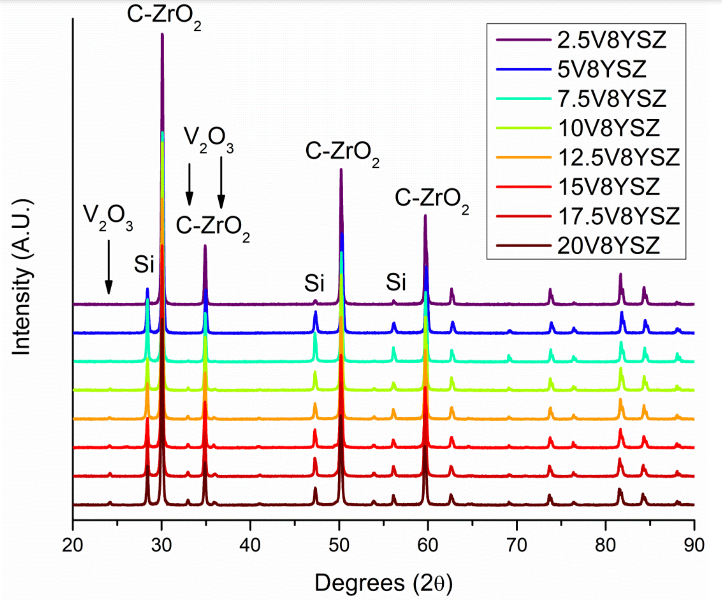
AEM’s VYZion monoliths 2020’s

Innovation # 1: VYZ

Vanadia and Yttria co-doped Zirconia

- Patented new material composition
  - (US 11,594,738 B2)
- Forms same stable cubic compatible with YSZ electrolyte
- Survives at pressure
- Catalyzes reactions

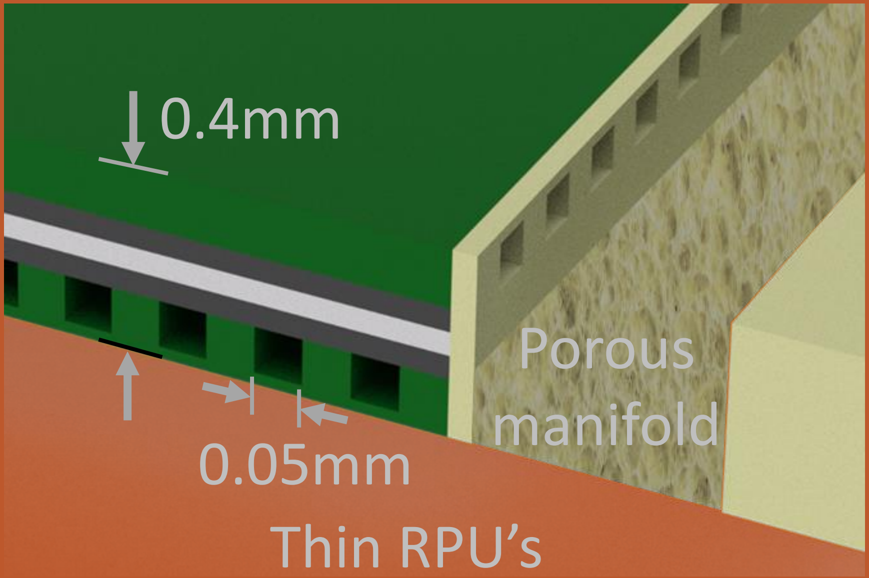




Innovation # 2: DPP-AM

Dry Powder Pressing Additive Manufacture

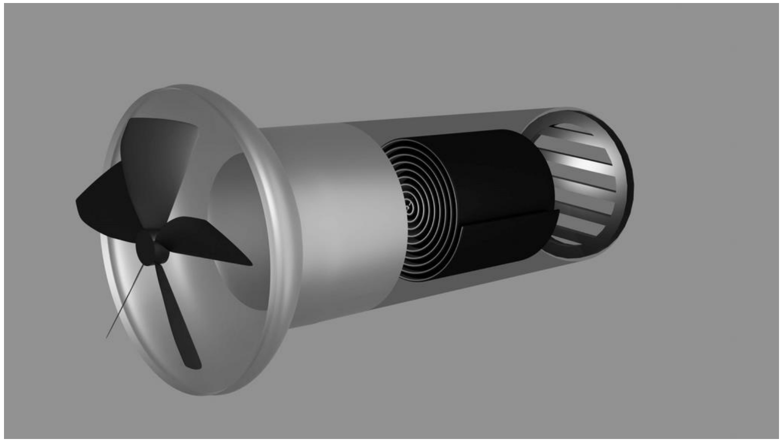
- Deposits multi-compositional powder layers deposited
- Internal gas routing formed via fugitive powder
- Seal less 3-D architecture with topological optimization
- No hot metal components



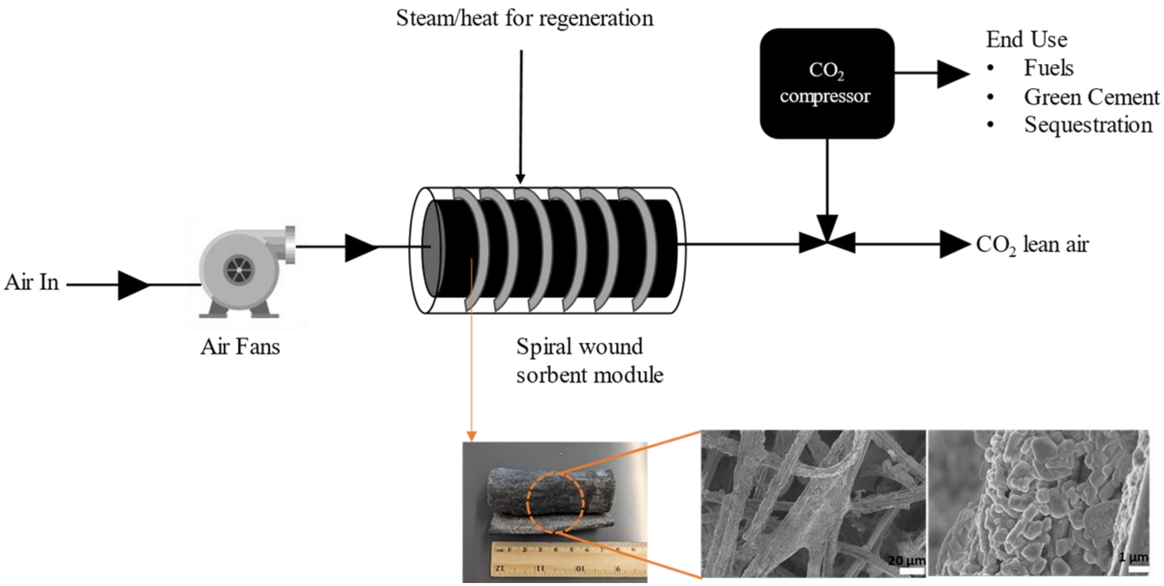
Technology Background (NuAria)

- The sorbent is fabricated in the form of wound membranes.
- The system can be easily scaled by using 100's of these cylindrical modules, working together to capture CO_2 .
- The unique morphology of the composite allows efficient CO_2 capture.

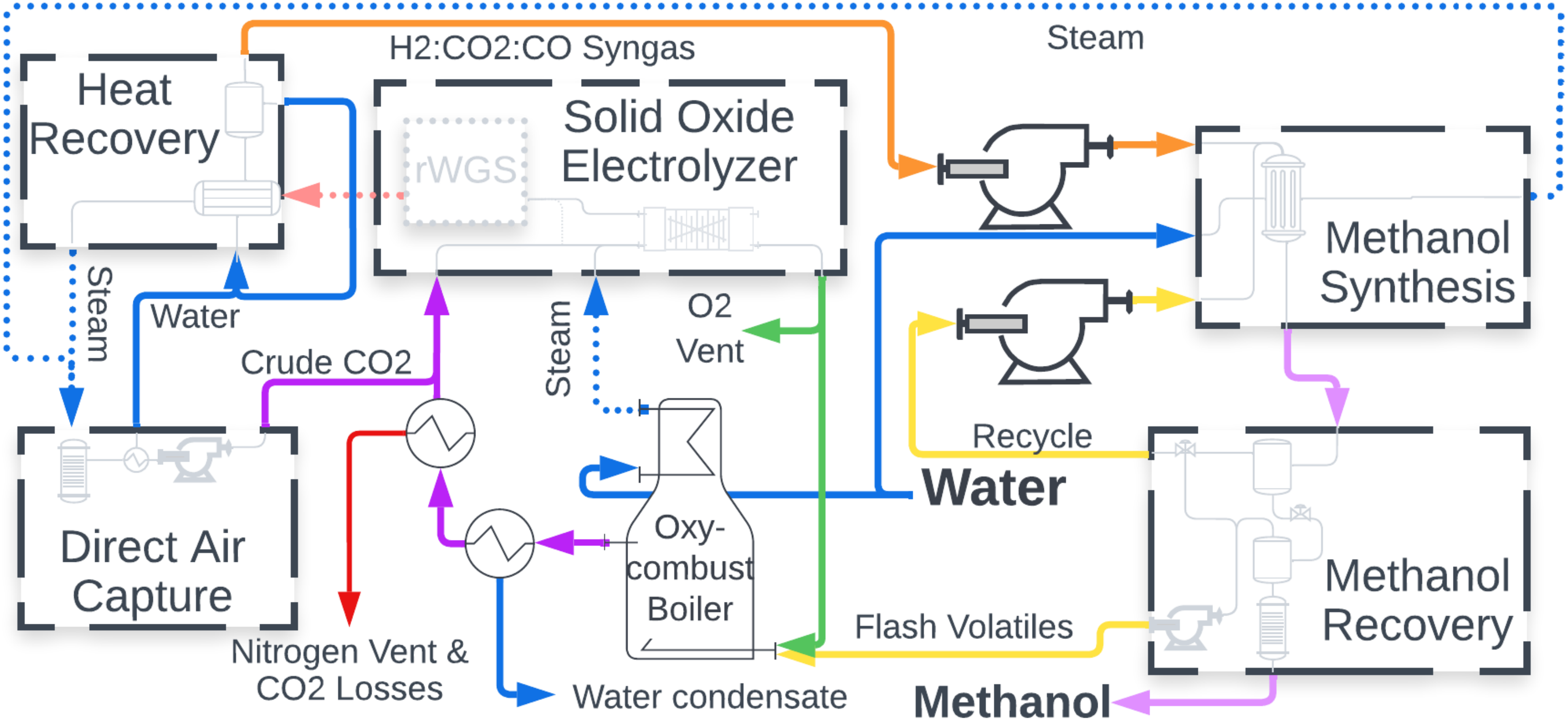
NuAria DAC module



Schematic of proposed sorbent module with capture capacity of 2kg/day



Technical Approach



- High temperature co-electrolysis produces a syngas from water and DAC
- The synthesis volatiles are oxidized to produce heat and retain carbon in the loop

MIDACE Advantages

- Directly utilizes crude CO_2
  - Avoids costly and energy consuming feedstock refining
- High pressure co-electrolysis
  - Pumping liquid water instead of compressing hydrogen saves 10% energy
- Dry syngas feedstock to synthesis reactor
  - Utilize commercial catalysts and reactors optimized for fossil feedstock
- Elevated pressure synthesis improves selectivity and conversion at higher temperature
  - Faster kinetics results in smaller and cheaper reactor
- Oxy-combustion of distillation volatiles
  - Net conversion of >96% captured CO2
  - Produces steam for sorbent regeneration or electrolyzer feedstock
  - Utilizes portion of electrolyzer O2 production
- High temperature sorbent regeneration
  - Increase CO_2 yield per gram of sorbent
  - Reduce regeneration cycle time

Success Criteria

Documented experimental and conceptual design efforts that justify down selection of key technology elements (DAC, SOEC, rWGS) and operating variations (reactor temperatures, pressures, and flows) that minimize risk, cost, and carbon intensity for the prototype and full-scale continuous production systems including:

I. A detailed state table supported by experimental measurements and modeling

II. A technoeconomic analysis quantifying a production cost below $800/ton for 100,000ton/yr

III. A life-cycle analysis carbon intensity estimate

IV. A summary of remaining technological uncertainty within the system components and a clear plan to address the gaps prior to prototype construction

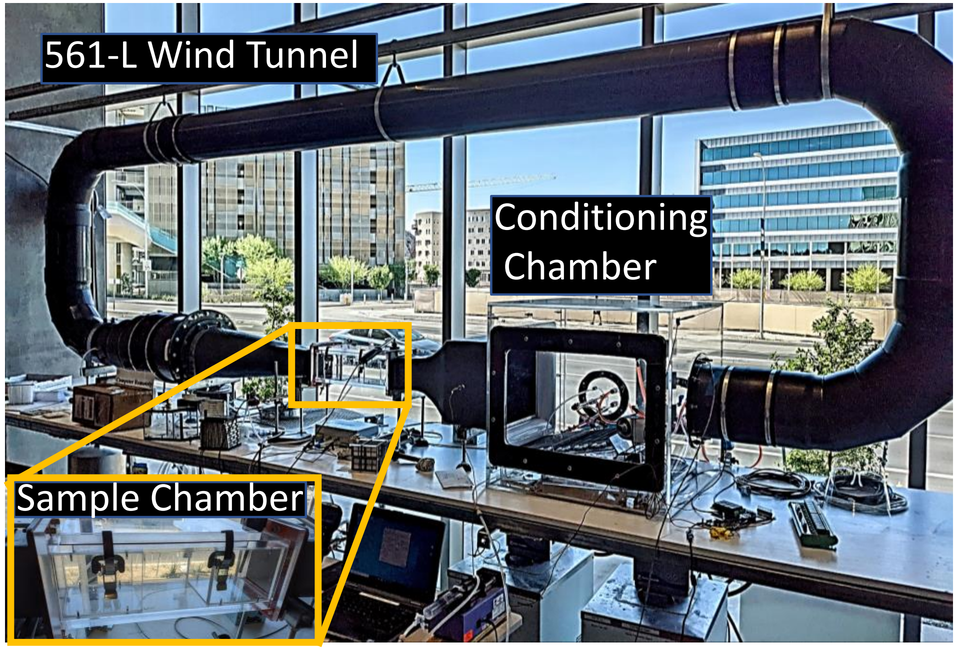
V. A design for hardware integration that demonstrates system viability and addresses environmental health and safety risks

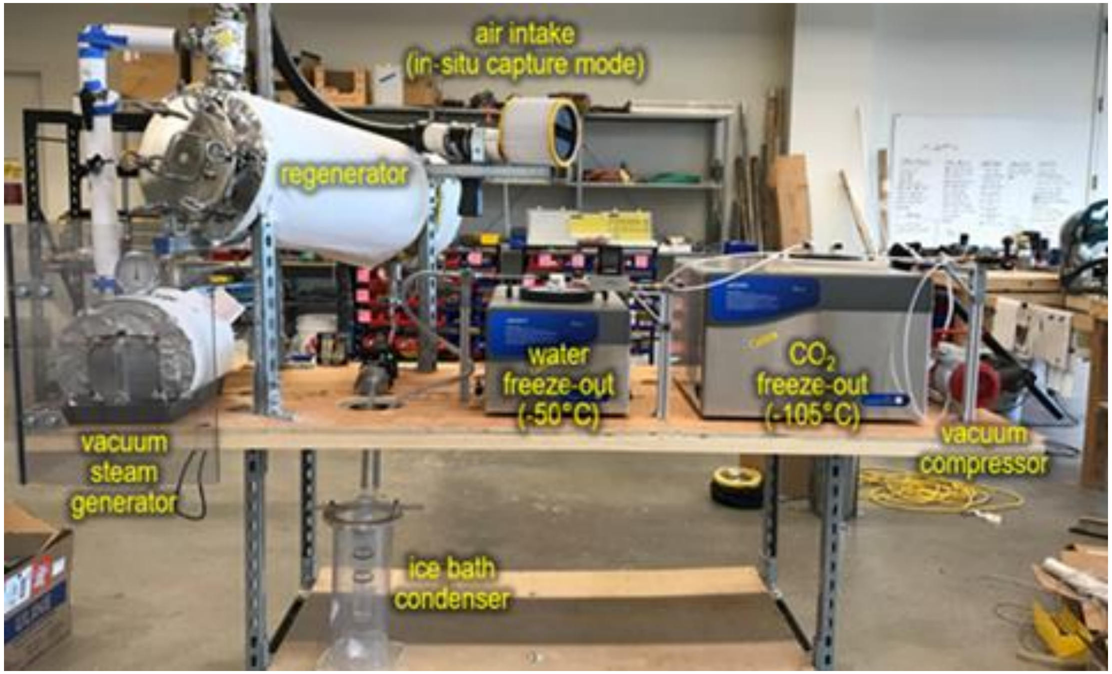
MIDACE Challenges

Perceived Technical Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Non-coincident power and CO_2 production	High	Med	Med	Low pressure crude CO_2 storage and firm the wind/solar with hydroelectric
Low capacity factor	High	Med	Med	Storage capacity and batch reactor
CO_2 accelerating SOEC degradation	Med	Med	Med	Blend CO_2 downstream in a rWGS reactor [12]
Accelerated SOEC degradation at >50bar	High	Low	Low	Maintain baseline design with syngas compressors
Excessive methanation within the electrolyzer	Med	Low	Low	Utilize rWGS to avoid CO_2 in SOEC
High temperature degrades sorbent	Low	Low	Low	Experimental corroboration of model prediction and sorbent stability at 250°C
Accelerated methanol catalyst degradation	Low	Low	Low	Maintain baseline design matching existing operations
Inert accumulation due to carbon recycle loop	Med	Med	Med	Additional N_2/CO_2 separation prior to vent and/or reduce carbon utilization
Recovered steam insufficient for sorbent	Med	Low	Low	Utilize cooling water, add solar thermal and electric heaters

Technical Approach (DAC Testing)

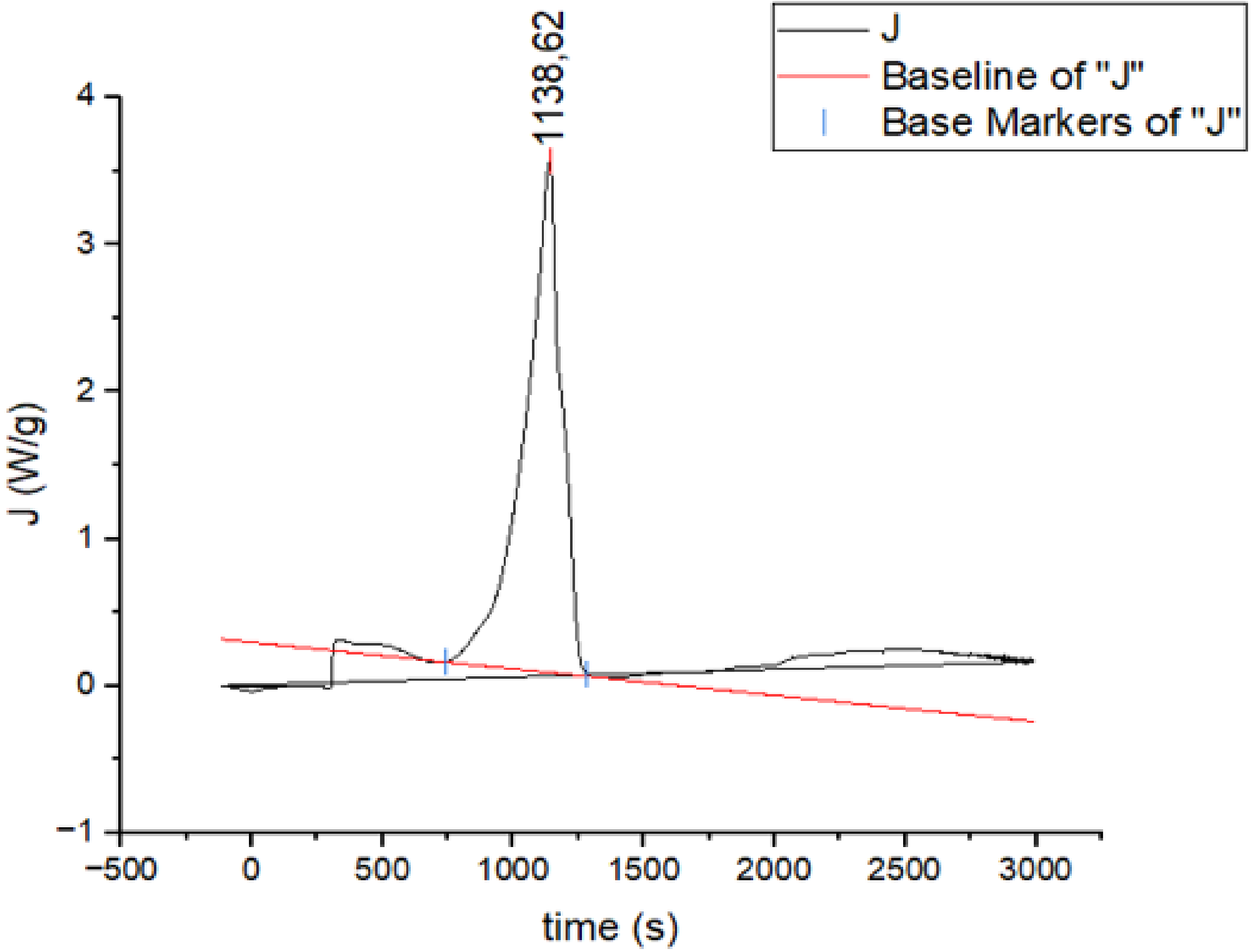
- Regeneration experiments measuring the adsorption of CO2 on up to 250°C with indirect heating
- Corroborate the sorbent thermal stability with cycling experiments
- Design a 'continuous' system operating with the diurnal weather and solar power availability





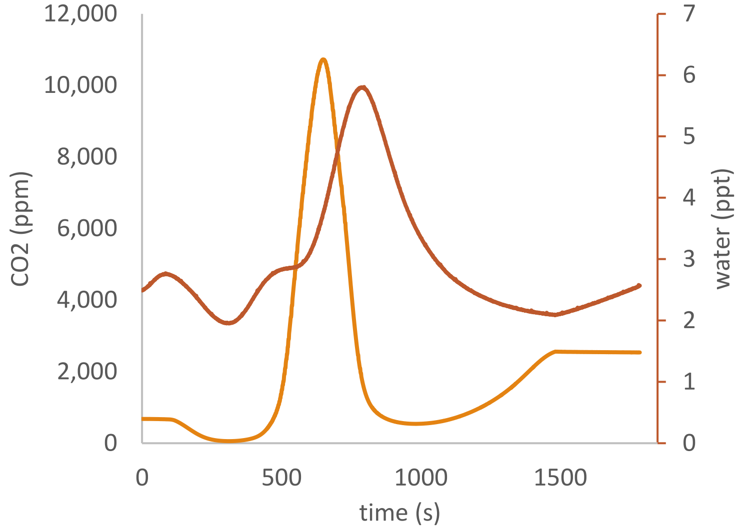
Technical Progress (DAC Testing)

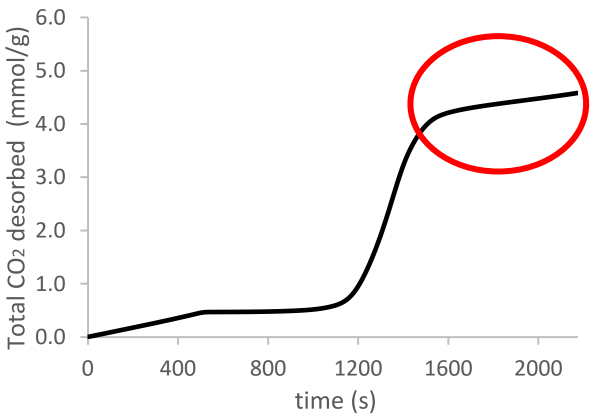
- Measurement taken with differential scanning calorimeter
- 4.7 mg sorbent sample
- Adsorption energy totaling 575 W/g
- TGA and IRGA measurements confirmed adsorbed CO_2 mass of 4.11 mmol/g
- Measured 141.35 kJ/mol, well below the 200 kJ/mol target

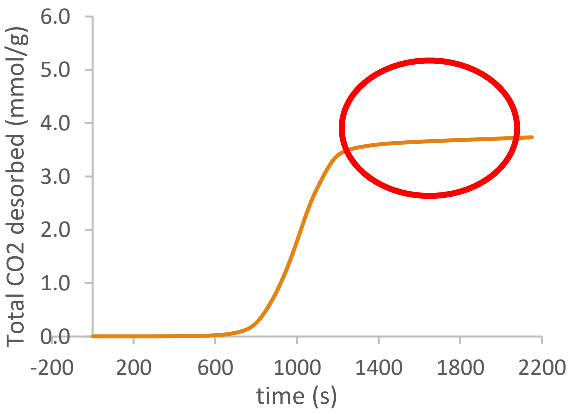


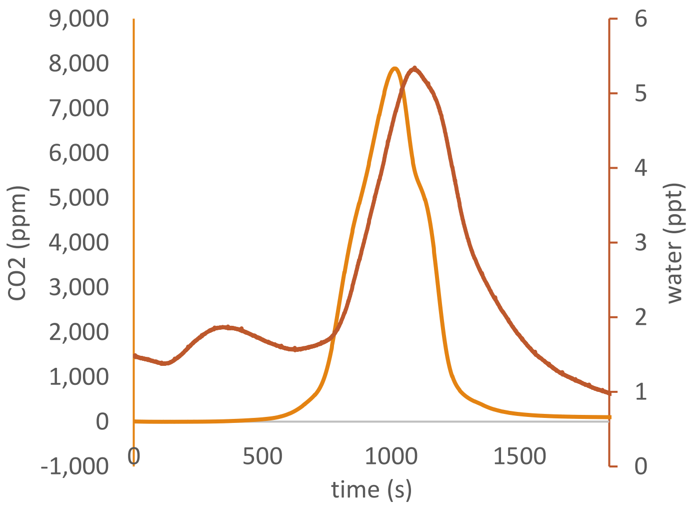
Technical Progress (DAC Testing)

- Confirmed via IRGA that CO_2 adsorption was dominant gas released, e.g. 1000’s ppm vs ppt H2O
- Different heating rates and ultimate temperatures to eliminate measurement of organic residuals from prior TGA/IRGA testing







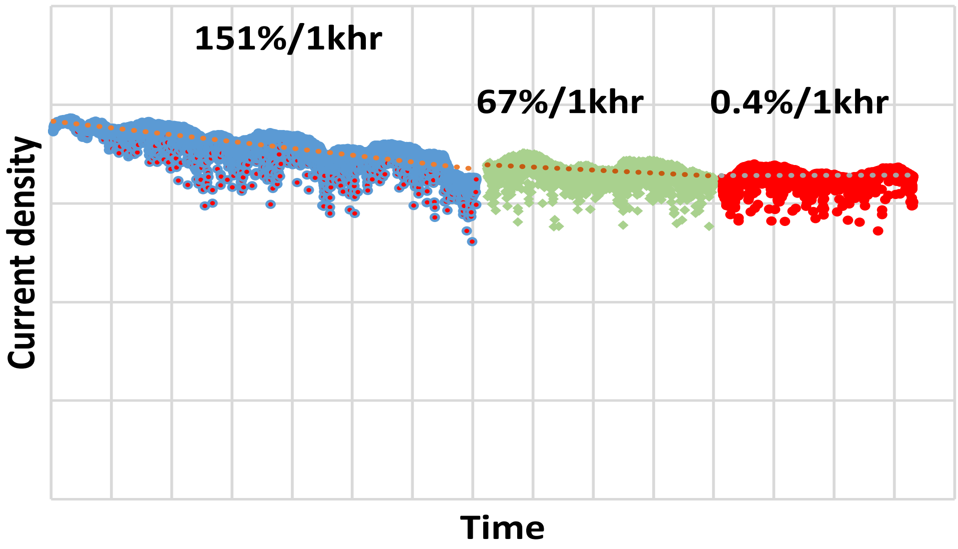


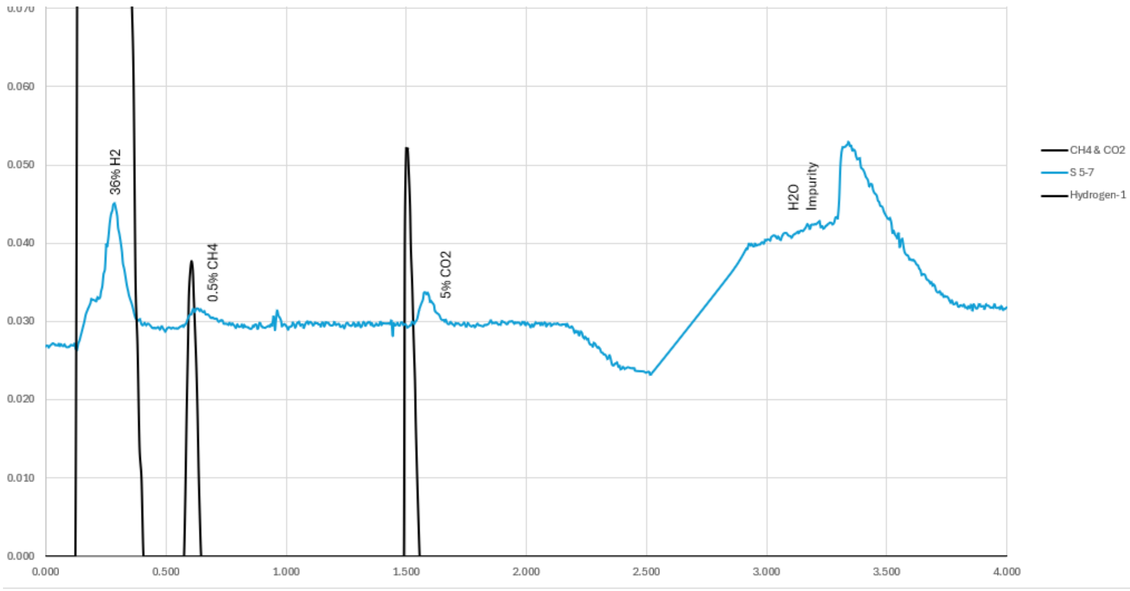
Technical Approach (SOC Testing)

- Expanded existing facilities to compare i) baseline steam electrolysis operation, ii) co-electrolysis, and iii) co-electrolysis with oxygen contaminant
  - Investigate single-pass vs. recirculated feedstock (inlet H2O)
  - Investigate high steam utilization operation (outlet H2O)
- Measure in-situ methane production under changing temperature, pressure and steam utilization conditions
- Test durability of VYZion cells co-electrolyzing steam and CO2

Technical Progress (SOC Testing)

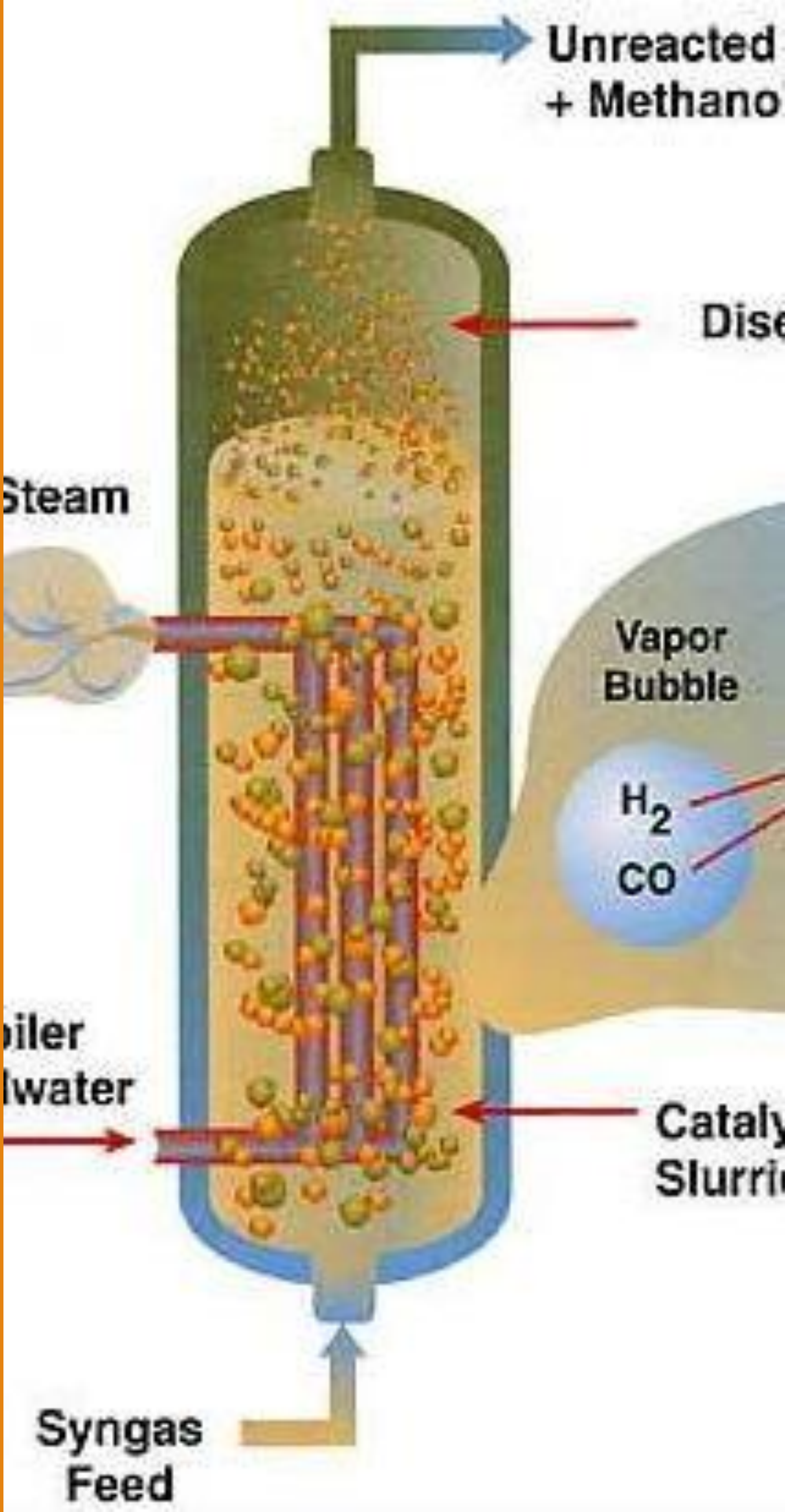
- Witnessed typical break-in period, and transition to steady-state performance
- Degradation equivalent to 6.7 year lifespan to 75% power
- Dimensionless performance shown due to proprietary knowledge of pressurization benefits
- Power density exceeded initial modeling expectations
- Acceptable methane concentrations at 30 bar, awaiting 60+ bar measurements





Technical Approach (CH3OH synthesis)

- Reactor selectivity and conversion sensitivity study (theoretical process modeling study)
  - Vary inlet H2: (CO +CO2) ratio
  - Vary inlet CO:CO2 ratio
  - Vary inlet H2O
  - Vary pressure
  - Vary temperature
  - Vary inert amount
- Distillation column sensitivity study
  - Size vs reflux ratio and recovered methanol purity
- System energy and cost optimization



Technical Progress (CH3OH Synthesis)

- Column design for 131 kg/hr (1,144 Tonne/yr) MeOH at 99% purity
  - At this small capacity a packed column would be better than a 22 cm diameter and 8.4 meters high set of trays, but distillation column scales better to 1Mton/yr

Condenser / Top stage performance

Name	Value	Units
Temperature	38.9845	C
Subcooled temperature		
Heat duty	-86.5916	kW
Subcooled duty		
Distillate rate	4.09125	kmol/hr
Reflux rate	3.36073	kmol/hr
Reflux ratio	0.821444	
Free water distillate rate		
Free water reflux ratio		
Distillate to feed ratio		

Reboiler / Bottom stage performance

Name	Value	Units
Temperature	115.9	C
Heat duty	88.3804	kW
Bottoms rate	1.48817	kmol/hr
Boilup rate	7.52788	kmol/hr
Boilup ratio	5.05848	
Bottoms to feed ratio		

Condenser	CW		Reboiler	LPS	
Duty	-86.5916	kW	Duty	88.3804	kW
Usage	6.70956	tonne/hr	Usage	0.152479	tonne/hr
Cost	0.110352	$/hr	Cost	2.47536	$/hr
CO2 emission rate			CO2 emission rate	0.0209205	tonne/hr

Summary

	Value	Units
Number of Trayed/Packed stages	28	
Total height	8.4	meter
Total head loss (Hot liquid height)	1.51376	meter
Total pressure drop	0.109749	bar
Number of sections	1	
Number of diameters	1	
Pressure drop across sump		bar
Total residence time	0.0313641	hr

Sections

	Start Stage	End Stage	Diameter		Section Height		Internals Type	Tray Type or Packing Type	Section Pressure Drop		% Approach to Flood	Limiting Stage	
CS-1	2	29	0.219561	meter	8.4	meter	TRAY	SIEVE	0.109749	bar	80.0002	2	View

Technical Progress (Sensitivity Study)

Parameter	Primary Component	Units	Min	Nominal	Max
H_2O:CO_2 feedstock	Electrolyzer	Ratio	3:1	3.56:1	4:1
Crude CO_2 impurity	DAC	% O_2	0.25%	1%	4%
Synthesis Purge	MeOH synthesis	%	1%	2%	10%
Synthesis Reactor Length	MeOH synthesis	m	0.125	0.5	1.0
Reactor Tube Diameter	MeOH synthesis	cm	2	10	20
Regeneration Temperature	DAC	°C	200	225	250
Steam Utilization	Electrolyzer	%	80%	90%	95%
Electrolyzer Temperature	Electrolyzer	°C	650	750	800
Synthesis Pressure	MeOH synthesis	Bar	30	90	100
Synthesis Temperature	MeOH synthesis	°C	240	265	290
Vacuum pressure	DAC	kPa_a	1	10	50
Water knockout Temperature	MeOH synthesis	°C	25	150	250

Community Benefits Plan (CBP)

Overarching Intentions:

- Describe plans for an impact assessment of siting a new green methanol plant adjacent to a waterway or port facility

Populations impacted:

- None during Phase I or II
- If commercialized, an undetermined community near a port or waterway with stranded renewable energy potential

SMART Goals and "Commitments":

- DEIA: Complete annual DEIA training provided by University administration.
- J40: Complete the collection of economic, demographic, and labor statistics of two similar waterway or port adjacent communities with and without existing chemical processing plants.
- CSE: Invite the HOA president, planning/zoning official, and fire-chief back to AEM for an additional site visit to identify any safety or equity concerns with existing and planned testing activities.
- Quality Jobs: Estimate the cost to attract, train, and retain a skilled and well-qualified workforce during the construction and operation of a green methanol plant.

Lessons learned

- Preheating necessary to avoid 2-phase CO_2 impacting gas mass flow meters in pressurized SOEC test stand
- Helium needed as gas chromatograph sweep gas for accurate CO measurements
- TGA and IRGA needed to confirm mass loss and composition to accurately determine heat requirement from DSC measurements

Commercialization Plan

2024

- Refine powder deposition for thinner layers and/or faster deposition
- Fabricate >500mL monoliths
- Complete fabrication of second 4000psi test stand
- Optimize material and catalyst composition via high-throughput cell testing

2025-2026

- Test multi-kW monolith > 2,000 hrs
- Test 20m stack-effect sorbent tower
- Demonstrate integrated CH3OH synthesis and distillation at >50kW scale
- Design MW-scale field prototype

2027-2028

- Scale material production and monolith fabrication
- Test thermal and electrical integration of multiple 50kW VYZion modules
- Assemble and validate MW-scale prototype and begin field validation
- Refine and value engineer the electrical and chemical system balance of plant

Summary

- Selected high temperature sorbent exceeds expectations for production vs heat, e.g. requires 141 kJ/mol rather than target 200 kJ/mol
- Negligible methane produced at 30 bar
- Solid oxide degradation at pressure exceeded expectations, e.g. 0.4%/khr
- Synthesis purity exceeded initial estimates, reducing vent requirements
- Development on-track for commercial-scale sub $800/ton methanol production in 2028

Organization Chart

Phase I participants	Key Personnel / Role	Phase I ancillary support
Washington State University: Cameron Bennethum, Stephen Woodward	Dustin McLarty Project PI Pressurized Electrolysis	AEM (Realize Your Vyzion!): Ryan Hamilton
Arizona State University: Emilianny Batista Magalhaes	Matthew Green Sorbent Production and Measurements	NuAria: Mani Modayil Korah
Arizona State University	Justin Flory & Klaus Lackner Advising DAC System Design	
Lehigh University	Jonas Baltrusaitis Methanol Synthesis& Distillation Modeling	

Gantt Chart

	Q1			Q2			Q3			Q4		
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Task 1: Project Management and Planning												
Subtask 1.1: Project Management Plan			**									
Subtask 1.2: Technology Maturation Plan			**									**
Subtask 1.3: State Point Data Table												**
Subtask 1.4: Preliminary Techno-Economic Analysis												**
Subtask 1.5: Preliminary Life Cycle Analysis												**
Subtask 1.6: Technology Gap Analysis												**
Subtask 1.7: Technology EH&S Risk Assessment												**
Task 2: R&D Community Benefits Plan (CBP)			**									**
Task 3: Experimental Work												
Subtask 3.1: Degradation with blended feedstock			**									
Subtask 3.2: Methanation Risk Assessment						**						
Subtask 3.3: Direct Carbon-dioxide Electrolysis									**			
Subtask 3.4: DAC Sorbent Regeneration						**						
Task 4: Conceptual Design												
Subtask 4.1: Pressurized rWGS Reactor Modeling			**									
Subtask 4.2: Synthesis Reactor Feedstock Study						**						
Subtask 4.3: Synthesis Reactor Design Specification									**			
Subtask 4.4: Distillation Column Design Specification									**			
Subtask 4.5: Elevated pressure sorbent regeneration									**			
Subtask 4.6: Continuous Production-Scale Regeneration												**