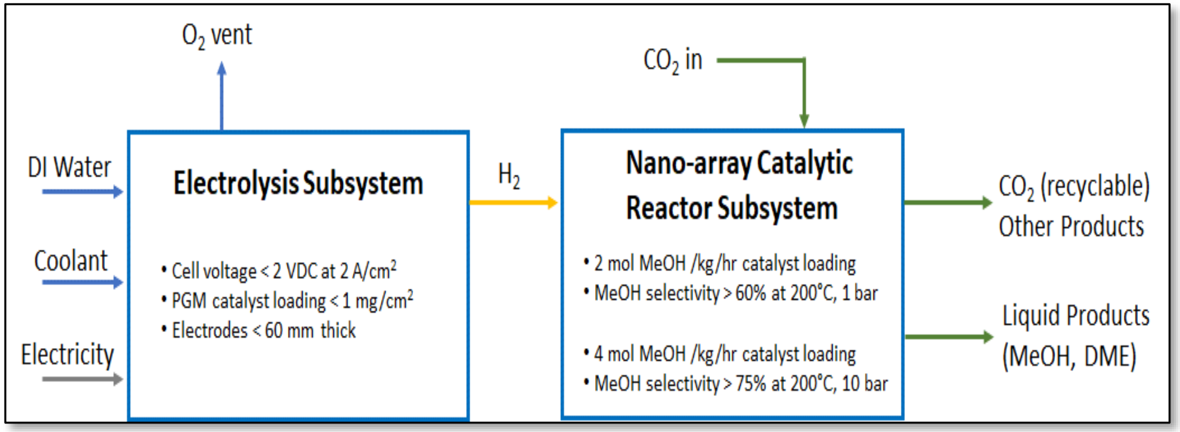
# Electrolyzer Integrated Modular Nano-Array Monolithic Catalytic Reactors for Low Pressure/Temperature and High Flux Synthetic Fuel Production DOE Award DE-EE0008423

Dr. Trent Molter
SKYRE, Inc.
April 23, 2020
tmolter@skyre-inc.com

Project ID # TA032



# OVERVIEW

## Timeline

- Project Start Date: 11/01/2018
- Project End Date: 10/31/2021

## Barriers

- High cost of hydrogen and fuels due to reactor expense/efficiency – particularly relevant when integrated with renewables.
- High cost and low reliability of gaseous and liquid hydrogen fueling infrastructure
- High cost to convert $CO_2$ to chemicals and fuels using intermittent renewable power
- Hydrogen fueling safety

## Budget

- Total Project Budget: $2,540,531
- Total Recipient Share: $2,000,000
- Total Federal Share: $540,531
- Total DOE Funds Spent*: $922,112
- Total Cost-Share Spent*: $350,571

** As of 05/31/2020*

## Partners

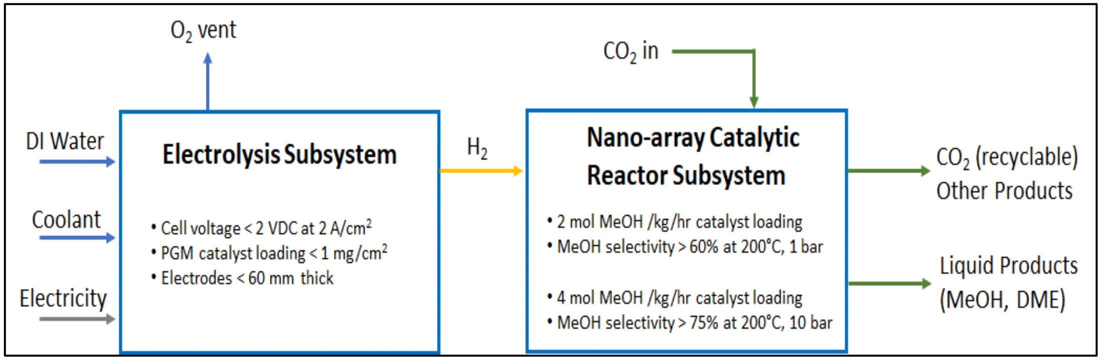
- SKYRE, Inc. - Project lead
- UCONN – Catalyst and catalytic reactor research
- CT Center for Advanced Technology – Catalytic reactor development
- Advanced Manufacturing, LLC – Catalytic reactor development and manufacture
- Stony Brook University – Brookhaven National Laboratory – Catalyst deposition/characterization
- University of Tennessee – Knoxville – Pt nanowires and PEM electrolyzer

# RELEVANCE

## Objectives

- New class of electrolyzer integrated modular nanostructure array monolithic catalytic reactors for high-flux, robust, selective methanol synthesis
- Low-temperature electrolyzer for hydrogen fueling of the reactor
- Cost-effective hydrogenation reactions under low temperature (< 200 °C) and low pressure (<10 atm) conditions, significantly reducing the energy demand
- Development and implementation of nanostructured catalyst materials in catalytic and electrocatalytic reactors to achieve higher operational efficiencies
- Renewable energy integration and $CO_2$ mitigation to produce a widely used chemical and fuel

# APPROACH




## Develop and demonstrate a pathway to low-cost fuel from waste $CO_2$ and renewables through implementation of advanced materials and process technology.

- Electrolysis nanowire electrodes offering efficient high current density operation
- Efficient catalyst systems with known properties that offer enhanced performance and selectivity toward methanol production and hydrogen utilization
- Advanced catalytic reactor systems that leverage additive manufacturing technology to incorporate key fluid dynamics features that boost reactor efficiency
- Close integration of materials and devices to effectively and harmoniously operate the combined reactor approach

# APPROACH

| | Electrolyzer Integrated Modular Nano-Array Monolithic Catalytic Reactors for Low Pressure/Temperature and High Flux Synthetic Fuel Production | Completion (%) | 2019 | | | | | | | | | | | | 2020 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Q1 | | | Q2 | | | Q3 | | | Q4 | | | Q5 | | | Q6 | | |
| | | | J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M | J |
| 1 | **Design and additive manufacture channeled honeycomb substrates** | | | | | | | | | | | | | | | | | | | |
| 1.1 | Design of channeled honeycombs | 100 | | | M1.1 | | | | | | | | | | | | | | | |
| 1.2 | Gas flow simulation through honeycombs | 100 | | | | | | M1.2 | | | | | | | | | | | | |
| 1.3 | Fabrication of channeled honeycombs | 100 | | | | | | M1.3 | | | | | | | | | | | | |
| 1.4 | Fabrication accuracy / capability study | 100 | | | | | | | | | | | | M1.4 | | | | | | |
| 1.5 | Cost analyses and justification | 33 | | | | | | | | | | | | | | | | | | M1.5 |
| 2 | **Synthesize metal oxide nanostructure arrays onto honeycomb substrates** | | | | | | | | | | | | | | | | | | | |
| 2.1 | Wash-coating of metal oxide seeds on honeycombs | 100 | | | M2.1 | | | | | | | | | | | | | | | |
| 2.2 | Hydrothermal synthesis of nano-arrays onto seeded honeycombs | 100 | | | | | | M2.2 | | | | | | | | | | | | |
| 3 | **Decorate catalytically-active species on metal oxide nanostructure arrays** | | | | | | | | | | | | | | | | | | | |
| 3.1 | Wet-chemical coating of nanoparticles onto nano-arrays | 100 | | | | | | | | | M3.1 | | | | | | | | | |
| 3.2 | Inverse micelle coating of nanoparticles onto nano-arrays | 100 | | | | | | | | | M3.2 | | | | | | | | | |
| 3.3 | ALD of nanoparticles onto nano-arrays | 100 | | | | | | | | | M3.3 | | | | | | | | | |
| 4 | **Physicochemical structure, morphology and stability characterization** | | | | | | | | | | | | | | | | | | | |
| | Characterize as-grown nano-arrays | 100 | | | | | | | | | | | | M4.0 | | | | | | |
| 5 | **Evaluation of catalyst activity, selectivity and stability** | | | | | | | | | | | | | | | | | | | |
| 5.1 | $CO_2$ hydrogenation testing over catalysts at 100-300°C | 100 | | | | | | | | | | | | | | | M5.1 | | | |
| 5.2 | $CO_2$ hydrogenation testing over catalysts at 1-10 atm | 70 | | | | | | | | | | | | | | | | | | M5.2 |
| 5.3 | Catalyst stability evaluation | 25 | | | | | | | | | | | | | | | | | | M5.3 |
| 6 | **Design, fabrication, and characterization of electrolyzers, and compatibility optimization with the nano-array reactors** | | | | | | | | | | | | | | | | | | | |
| 6.1 | Electrolyzer fabrication and assembly | 100 | | | | | | | | | | | | M7.1 | | | | | | |
| 6.2 | Electrolyzer characterization and performance evaluation | 85 | | | | | | | | | | | | M7.2 | | | | | | |
| 6.3 | Compatibility of the nano-array reactor and electrolyzer | 100 | | | | | | | | | | | | M7.3 | | | | | | |
| 7 | **Design and implementation of nano-array reactors with electrolyzers** | | | | | | | | | | | | | | | | | | | |
| 7.1 | Fueling protocol design for electrolyzer integration with nano-array reactors | 88 | | | | | | | | | | | | | | | | | | M8.1 |
| **BUDGET PERIOD #1 GO/NO-GO DECISION POINT** | | | | | | | | | | | | | | | | | | | | ✱ |

Actual | Planned

Current Program Status – 18-Month Go-NoGo Criteria Met

# APPROACH

**18-Month Go-NoGo**

Demonstration of nano-array reactors with a 2 mol.kg$^{-1}$.hr$^{-1}$ methanol formation rate and a >60% selectivity at 200 $^{o}$C and 1 bar conditions, and a 4 mol.kg$^{-1}$.hr$^{-1}$ methanol formation rate and a >75% selectivity at 200 $^{o}$C and 10 bar conditions.

Demonstration of a low-temperature electrolyzer having < 60 mm thick liquid/gas diffusion electrodes and a low PGM catalyst loading of < 1 mg/cm$^2$, with a cell voltage < 2 Vdc at 2 A/cm$^2$

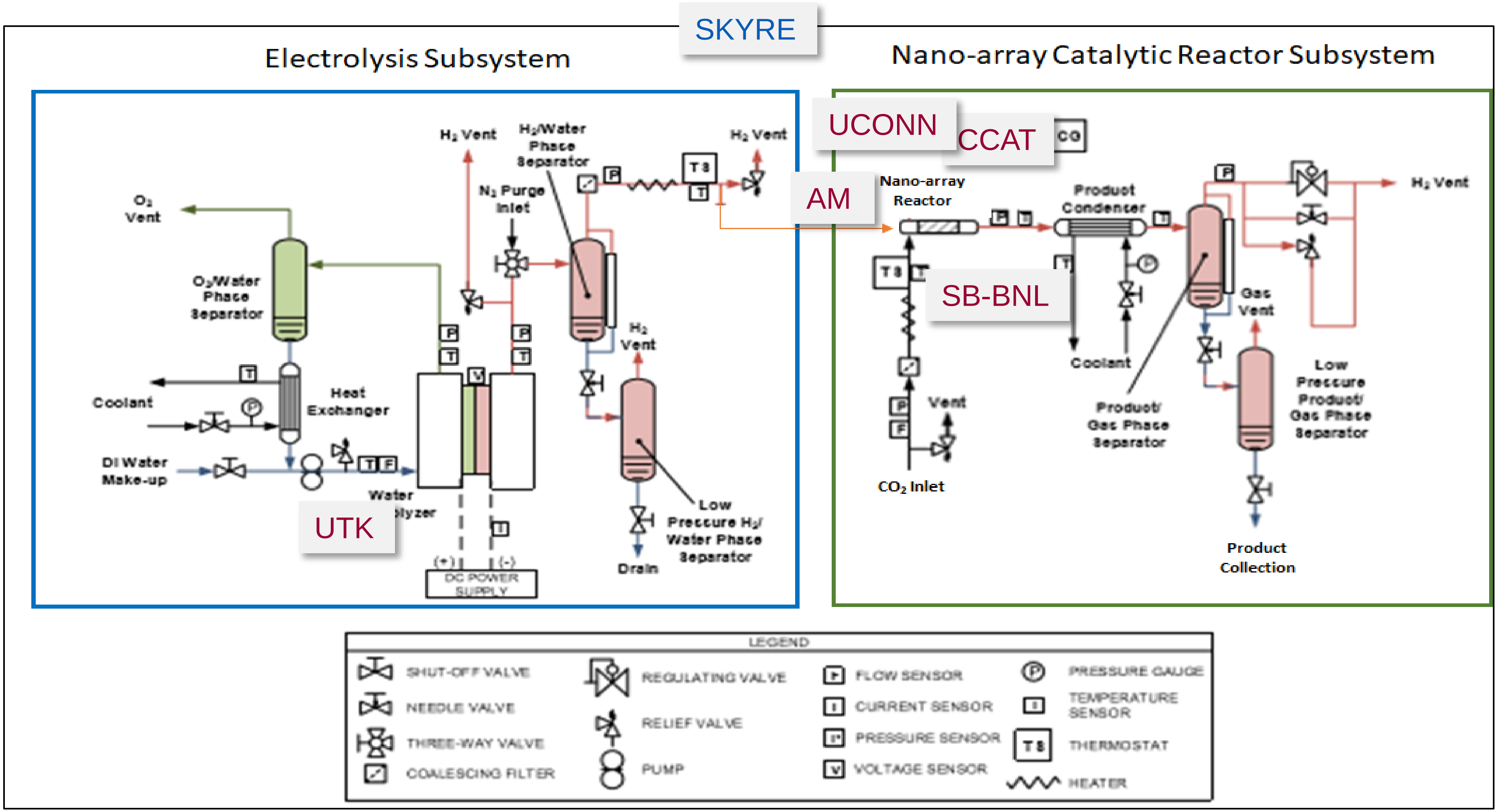
**36-Month Go-NoGo**

Demonstration of cost-effective electrolyzer integrated modular nano-array reactors with selective configurations

| Task descriptions | Year 1 (Q1-4) | | | | Year 2 (Q5-8) | | | | Year 3 (Q9-12) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1: Design/additive manufacture of honeycomb substrates | | | | | | | | | | | | |
| 1.1 Design of channeled honeycombs | M1.1 | | | | | | | | | | | |
| 1.2 Comparison reactor flow simulation | | M1.2 | | | | | | | | | | |
| 1.3 Fabrication of various complex channeled honeycombs | | M1.3 | | | | | | | | | | |
| 1.4 Fabrication accuracy/capability study | | | | M1.4 | | | | | | | | |
| 2: Nano-array synthesis on monolith substrates | | | | | | | | | | | | |
| 2.1 Seeds deposition on honeycombs | | M2.1 | | | | | | | | | | |
| 2.2 Nano-array deposition onto honeycombs | | M2.2 | | | | | | | | | | |
| 3: Metal/oxide nanoparticle decoration | | | | | | | | | | | | |
| 3.1 Wet-chemical processing | | | M3.1 | | | | | | | | | |
| 3.2 Inverse micelle template synthesis | | | M3.2 | | | | | | | | | |
| 3.3 Atomic layer deposition | | | M3.3 | | | | | | | | | |
| 4: Physico-chemical, structure and stability | | | | M4.0 | | | | | | | | |
| 5. Evaluation of nano-array reactors | | | | | | | | | | | | |
| 5.1 Temperature dependent reaction kinetics | | | | | M5.1 | | | | | | | |
| 5.2 Pressure dependent reaction kinetics | | | | | | M5.2 | | | | | | |
| 5.3 Cyclic performance and deactivation | | | | | | M5.3 | | | | | | |
| 6. Optimization and scale up of the reactors | | | | | | | | | | | | |
| 6.1 Scaled reactor substrate design and scale up | | | | | | | M6.1 | | | | | |
| 6.2 Scaled nano-array reactor processing and testing | | | | | | | | M6.2 | | | | |
| 7. Design and assembly of electrolyzers | | | | | | | | | | | | |
| 7.1 Electrolyzer fabrication and assembly. | | | | | | M7.1 | | | | | | |
| 7.2 Electrolyzer component performance evaluation | | | | | | M7.2 | | | | | | |
| 7.3 Compatibility of nano-array reactor and electrolyzer | | | | | | M7.3 | | | | | | |
| **Budget Period 1 Project Go/No-Go** | | | | | | G/N G1 | | | | | | |
| 8. Design and implementation of $H_2$ fueling | | | | | | | | | | | | |
| 8.1 $H_2$ fueling protocol design. | | | | | | | M8.1 | | | | | |
| 8.2 $H_2$ fueling protocol implementation | | | | | | | | M8.2 | | | | |
| 8.3 Demonstrate electrolyzer integrated nano-array reactors | | | | | | | | | M8.3 | | | |
| 9. Cost and life cycle analyses, and infrastructure compatibility | | | | | | | | | | | | |
| 9.1 Materials, energy and cost analyses | | | | | | | | | | M9.1 | | |
| 9.2 Fueling/Infrastructure compatibility analysis | | | | | | | | | | | M9.2 | |
| 9.3 **End of Project Goal:** Demonstration of cost-effective modular reactors | | | | | | | | | | | | M9.3 |
| **Project Success Metrics** | | | | | | | | | | | | |

# Approach

## Detailed System Schematic

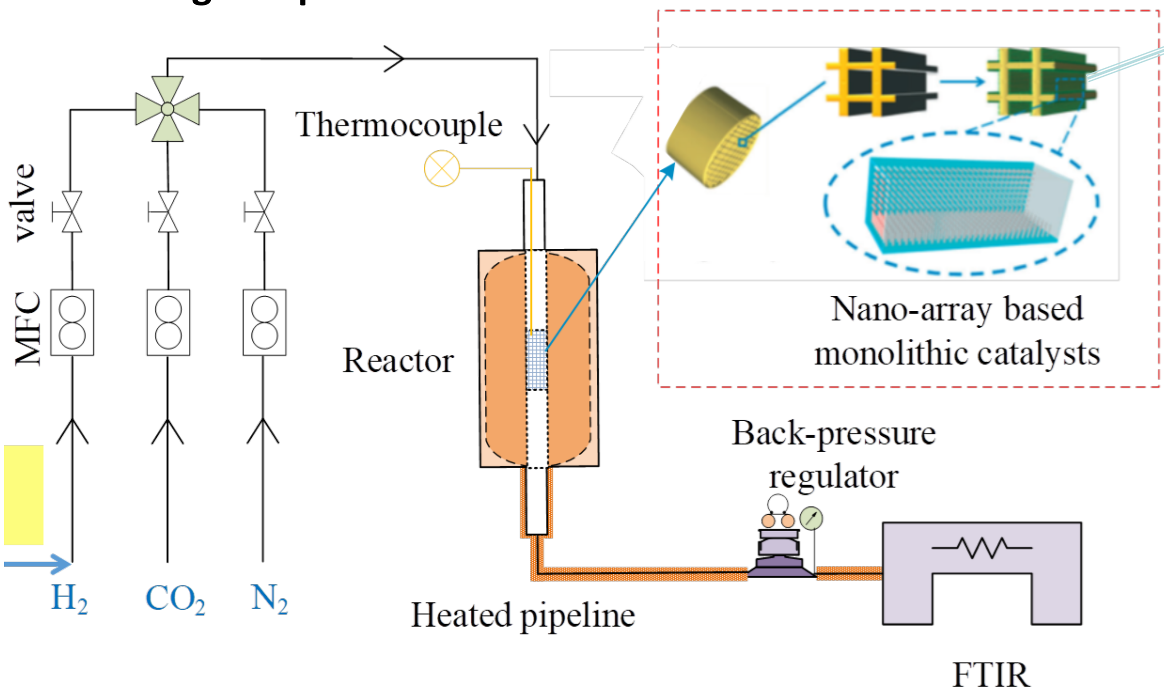


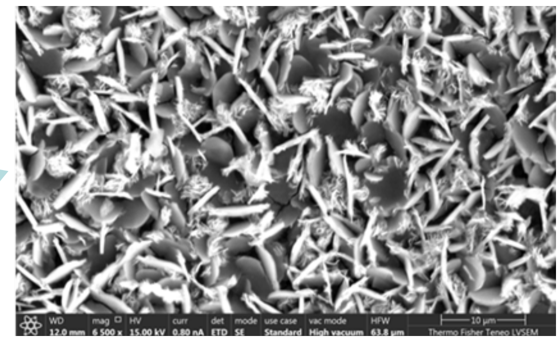
# ACCOMPLISHMENTS

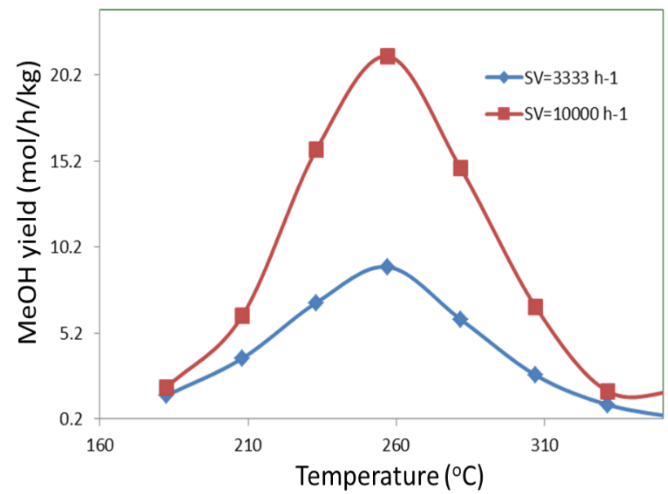
## Catalytic Performance of Nanoarray Reactors at 1 Bar

**Sample:** Cu/Zn/Al (Zn:Al=10) nanoarray; **Testing Pressure:** 1 bar
**Process:** Hydrothermal Cu/Zn/Al nanoarray on Al + 500 °C annealing

**Testing setup schematic :**



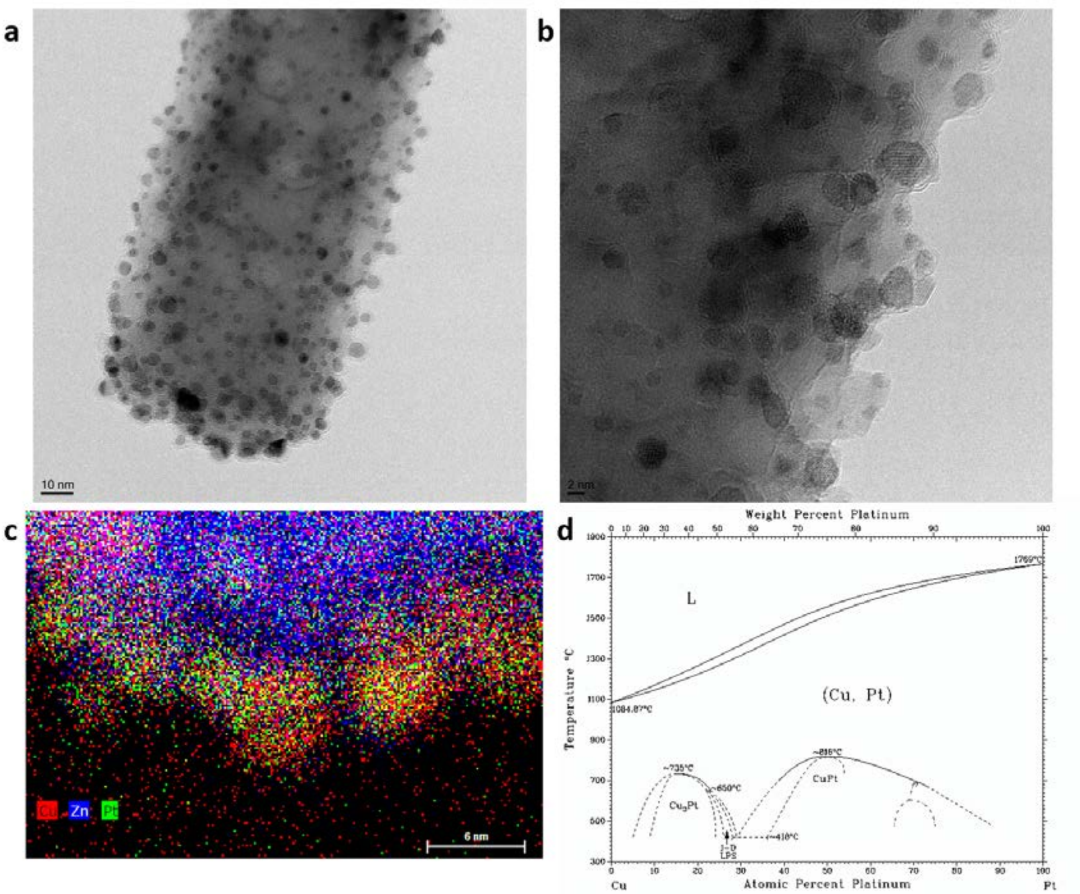


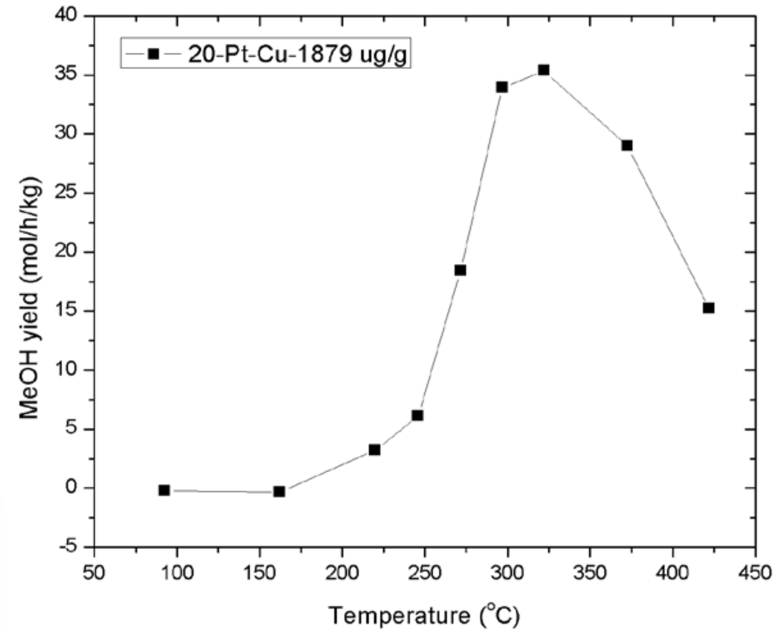

- Methanol yield: ~6.2 mol/h/kg, selectivity: 100%, at 207 °C, 10,000 $h^{-1}$, met go/no-go target.
- Peak methanol yield: ~21.3 mol/h/kg at ~256 °C, 10,000 $h^{-1}$.

# ACCOMPLISHMENTS

## Catalytic Performance of Nanoarray Reactors at 1 Bar

**Sample:** 20-Pt-Cu-ZnO nanoarray; **Testing pressure:** 1 bar
**Process:** Hydrothermal ZnO nanoarray on cordierite+20 cycle ALD Pt nanofilm + block-copolymer (BCP) Cu dip-coating + RTP at 600 °C, 5 min, 4% $H_2$/Ar



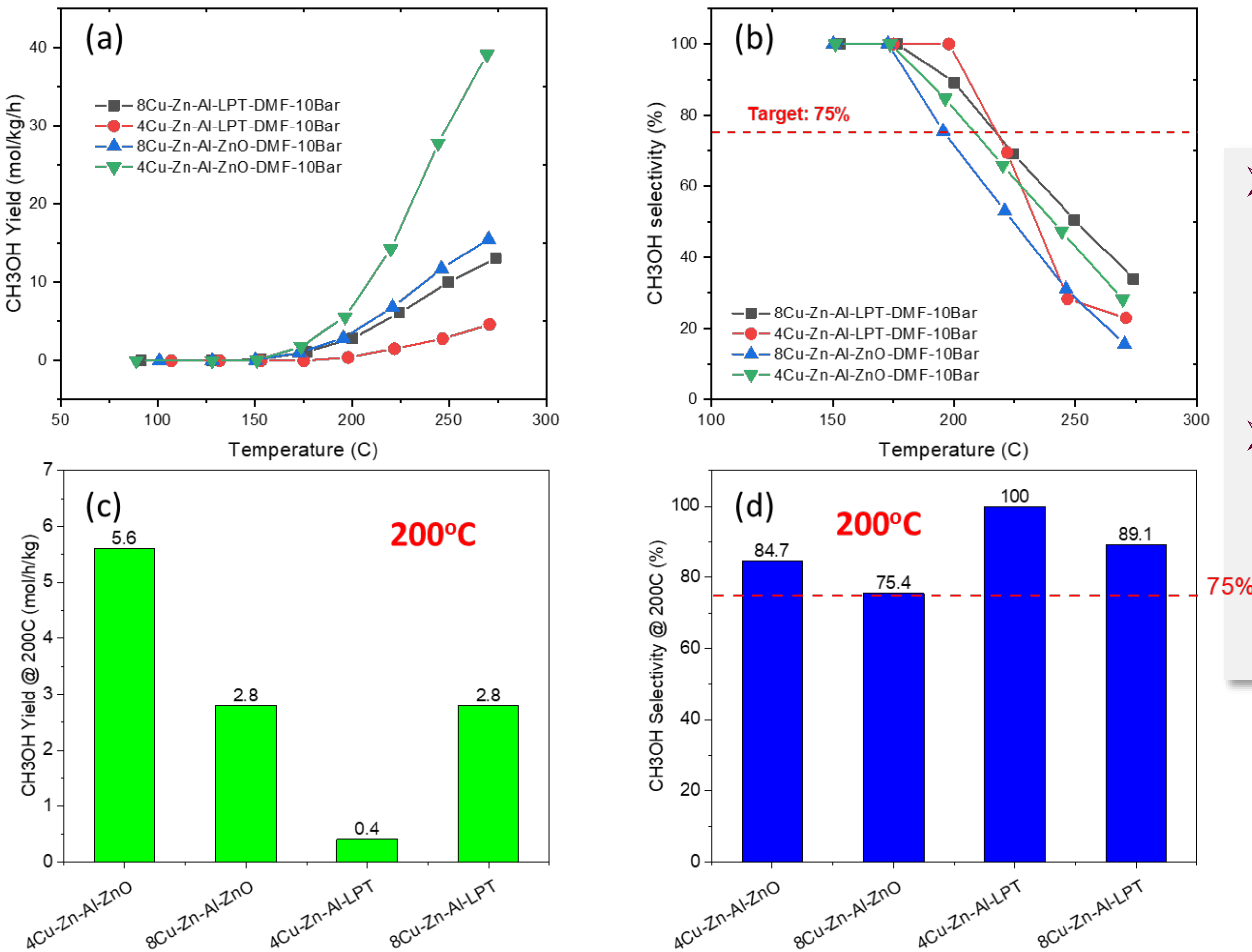




- Methanol yield: 3.2 mol/h/kg, selectivity: 100%, at 220 °C, 17,000 $h^{-1}$.
- Peak methanol yield: ~35 mol/h/kg at 300 °C, 17,000 $h^{-1}$.

# ACCOMPLISHMENTS

## Catalytic Performance of Nanoarray Reactors at 10 Bar

- Nanoarray support effect on Cu/Zn/Al catalysts:



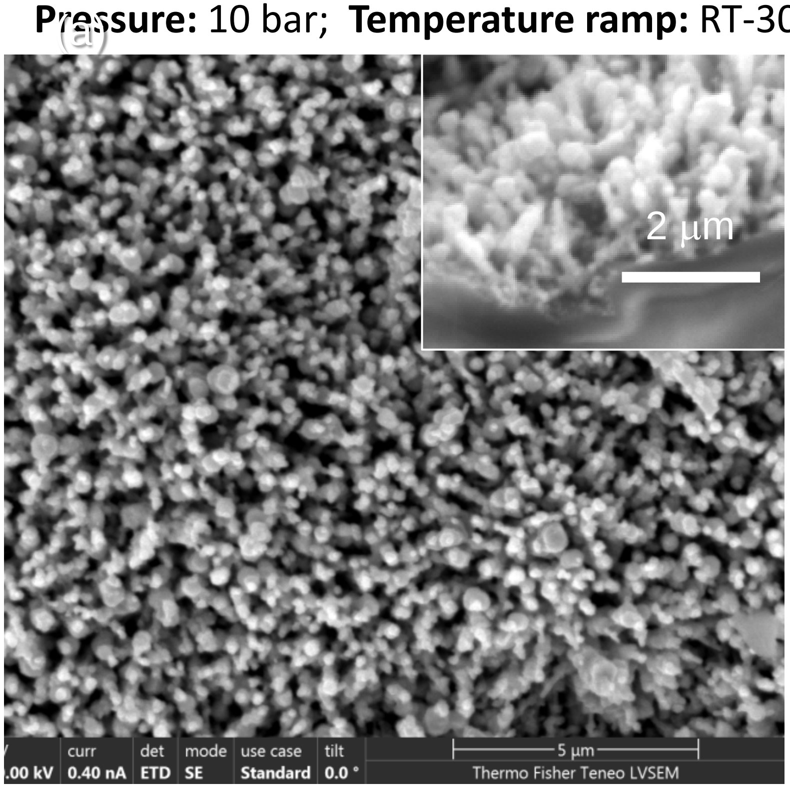

- Methanol yield of 4Cu/Zn/Al-ZnO nanoarray sample: 5.6 mol/kg/h, 200 °C, met the go/no-go target (4 mol/kg/h).

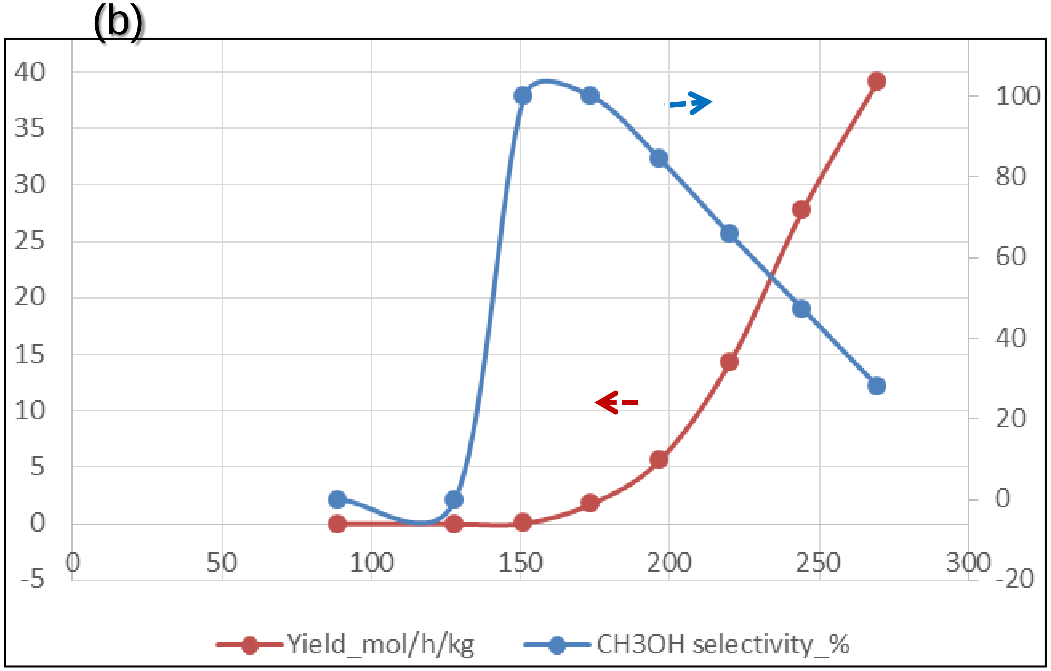
- Methanol selectivity of LPT derived $TiO_2$ and ZnO nanoarray samples at 200 °C > 75%, met the go/no-go target (75%).

# ACCOMPLISHMENTS

## Catalytic Performance of Nanoarray Reactors

**Sample:** 4-Cu/Zn/Al on ZnO nanoarray **Testing pressure:** 10 bar
**Process:** Hydrothermal Cu/Zn/Al on ZnO nanoarray cordierite substrate + 500 $^oC$ annealing
**Pressure:** 10 bar; **Temperature ramp:** RT-300 $^oC$



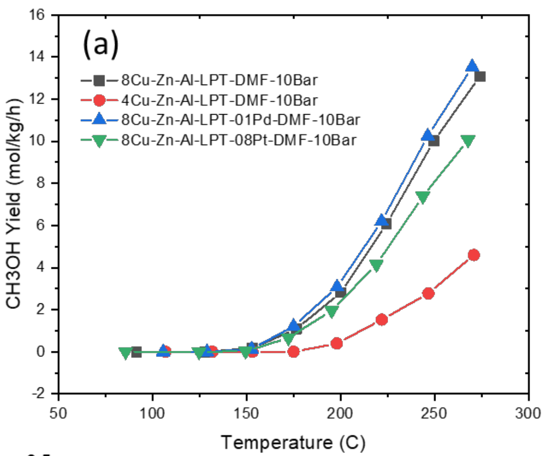



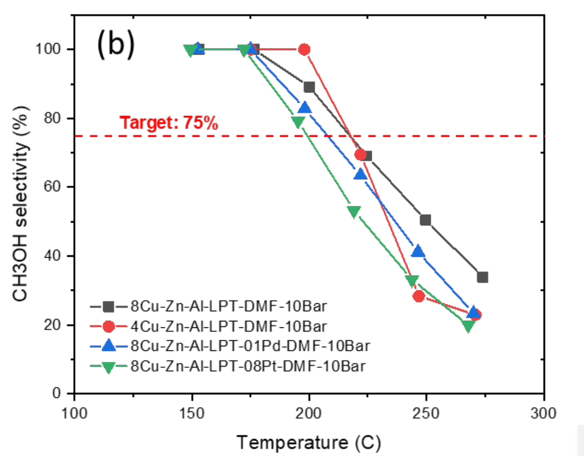

- Methanol yield: ~5.6 mol/h/kg, selectivity: 84.7%, at 196 $^oC$/10 bar, 10,000 $h^{-1}$,
- Met go/no-go performance metrics at 200$^oC$/10 bar, 4 mol/h/kg and 75%.

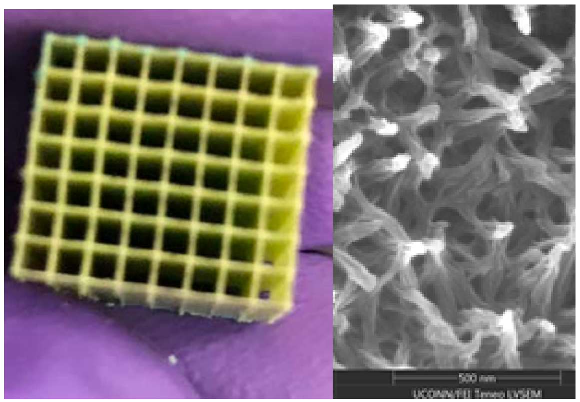
# Accomplishments

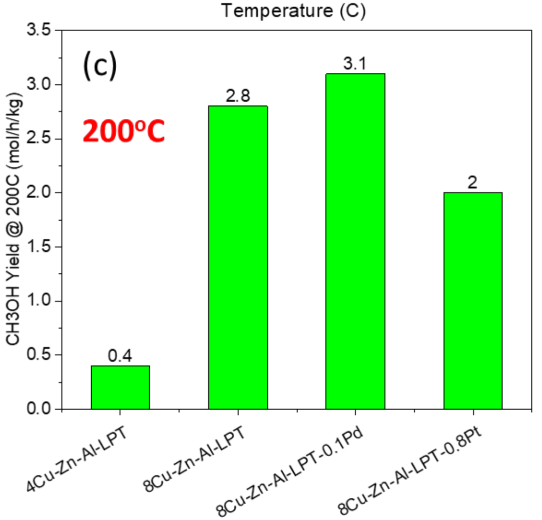
## Catalytic Performance of Nanoarray Reactors at 10 Bar

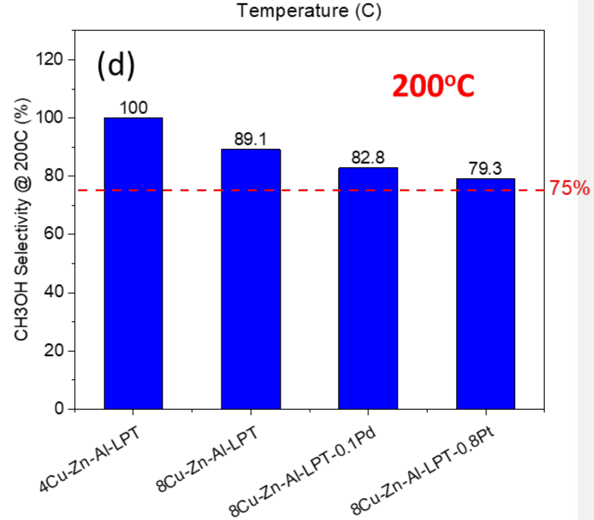
❖ Pt/Pd doping effect on LPT supported Cu/Zn/Al catalysts:





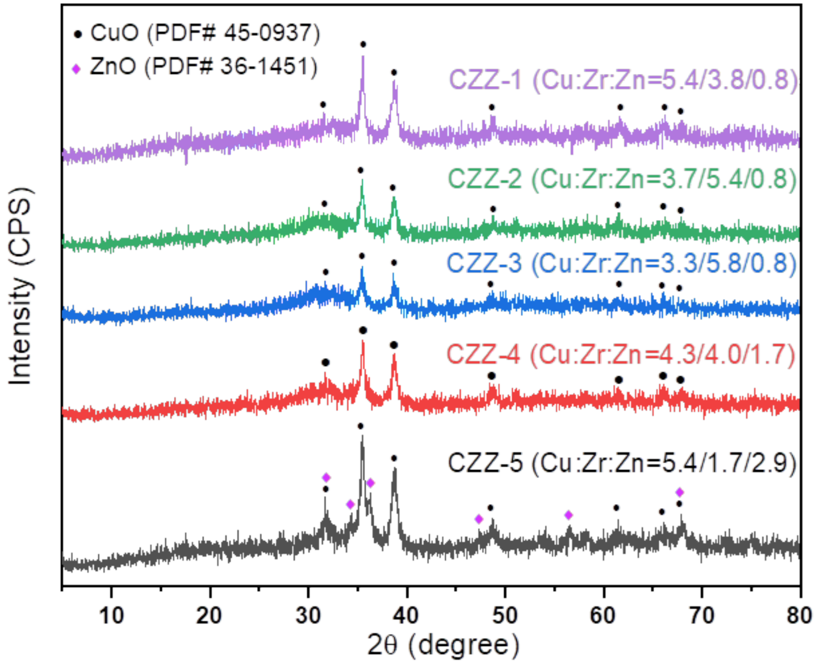




- Better methanol yield on 8Cu/Zn/Al-LPT than 4Cu/Zn/Al-LPT.
- Methanol selectivity of LPT derived $TiO_2$: 4Cu/Zn/Al, ~100%; while 8 Cu/Zn/Al, 90%.
- Pd doping improves the methanol yield, however decrease selectivity, which is still above 75%.

# ACCOMPLISHMENTS

## Catalytic Performance of Cu-Zr-Zn Based Nanopowders

❖ Cu-Zn-Zr based mesoporous nanoparticles using metal dissolution method:



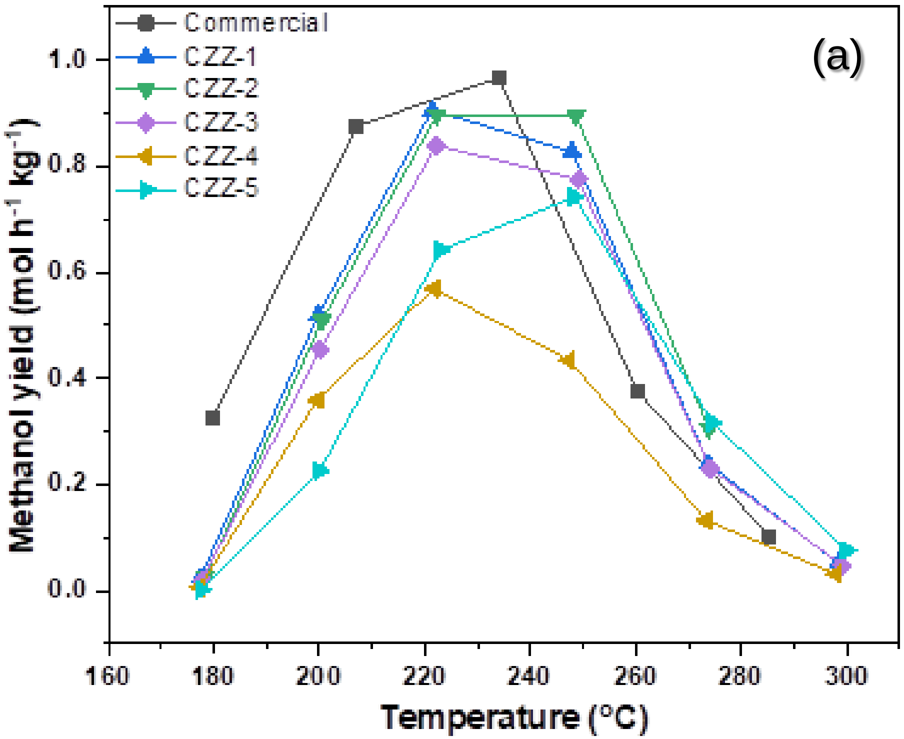

| Name | Material (nominal ratio) | Actual ratio (calculated from **XRF**) | Surface Area ($m^2/g$) | BJH Pore size distribution (desorption) | |
|---|---|---|---|---|---|
| | | | | Pore volume (cc/g) | Pore diameter (nm) |
| Commercial | Commercial catalyst (Cu/Zn/Al) | 6.9/2.4/0.7 | 105 | 0.239 | 5.61 |
| CZZ-1 | Cu:Zr:Zn=6/3/1 | 5.4/3.8/0.8 | 93 | 0.175 | 3.82 |
| CZZ-2 | Cu:Zr:Zn=5/4/1 | 3.7/5.4/0.8 | 131 | 0.202 | 3.82 |
| CZZ-3 | Cu:Zr:Zn=4.5/4.5/1 | 3.3/5.8/0.8 | 164 | 0.237 | 3.82 |
| CZZ-4 | Cu:Zr:Zn=5/3/2 | 4.3/4.0/1.7 | 111 | 0.203 | 3.83 |
| CZZ-5 | Cu:Zr:Zn=6/1/3 | 5.4/1.7/2.9 | 59 | 0.260 | 3.83 |

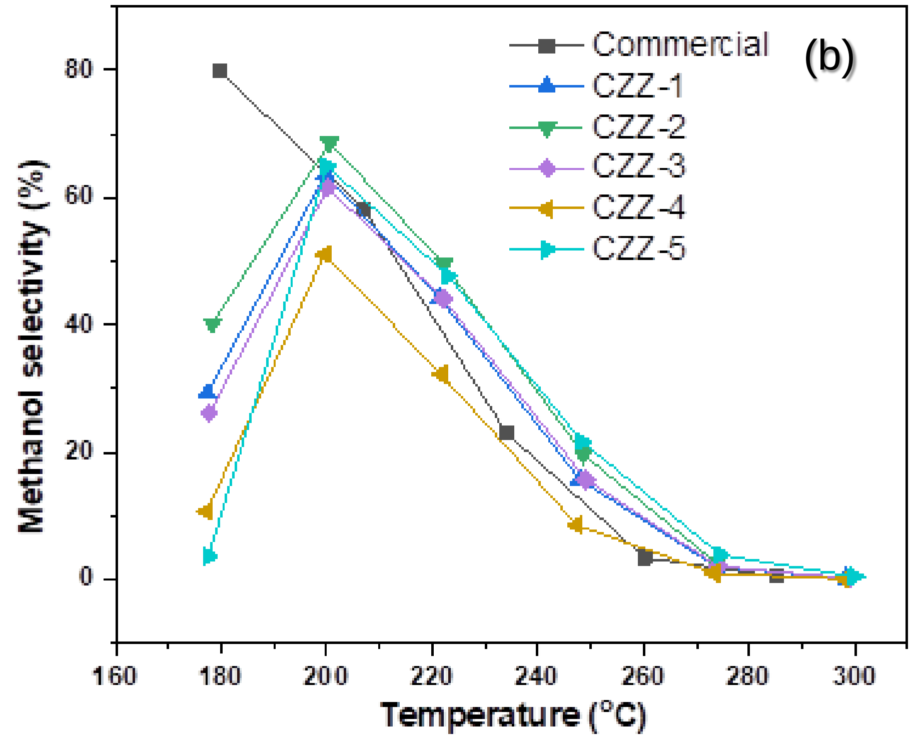
- New synthesis route: metal dissolution method.
- CuO and ZnO are crystalline, while ZrO2 seems to be in the amorphous phase or less crystalline.
- CCZ-2 and CCZ-3  of Cu:Zr:Zn ratios 5/4/1 and 4.5/4.5/1 showed the higher surface area than other samples.

# ACCOMPLISHMENTS

## Catalytic Performance of Cu-Zr-Zn Based Nanopowders

❖ Cu-Zn-Zr based Nanopowders using metal dissolution method:



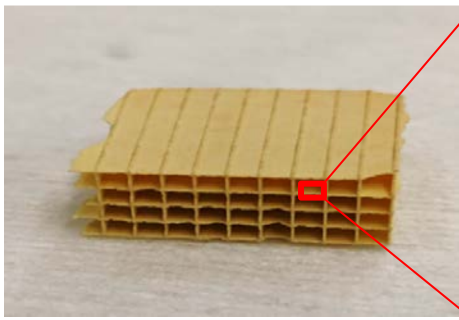

- ➢ Without adding promoters/ dopants, new catalysts showed higher methanol yield and selectivity than commercial Cu/ZnO/$Al_2O_3$ catalyst at 240 °C-300 °C.
- ➢ CZZ-2 with Cu:Zr:Zn ~5/4/1 showed the best yield and selectivity.

# ACCOMPLISHMENTS

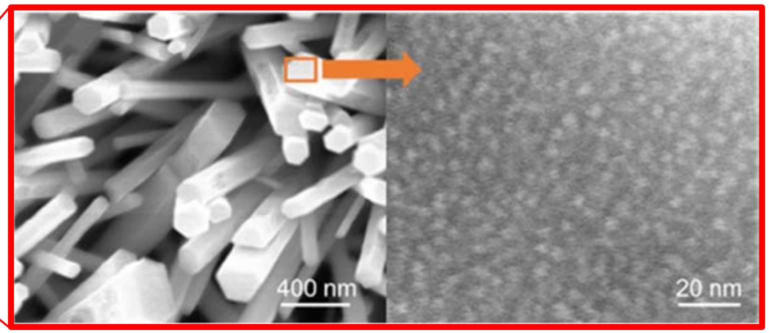
## Synthesis of uniform Pt-Cu NP loaded ZnO nanoarray catalysts on 3D cordierite honeycomb by ALD and BCP methods

Uniform Pt-Cu nanoparticle (NP) loading was achieved on ZnO nanoarray by modified Pt atomic layer deposition (ALD) and Cu nanoparticle dip-coating via block copolymer (BCP) template method

*3D cordierite honeycomb*

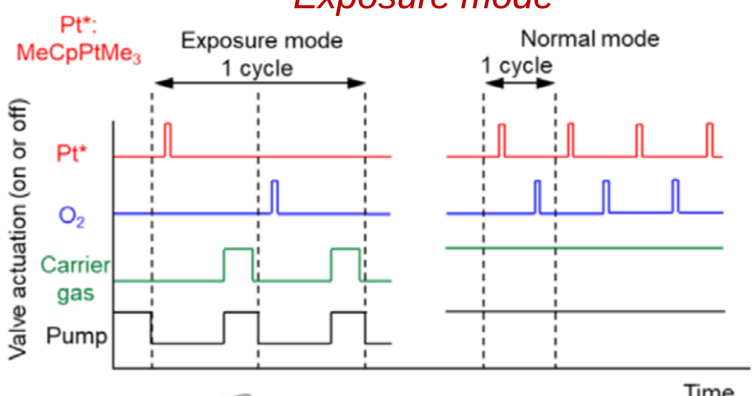


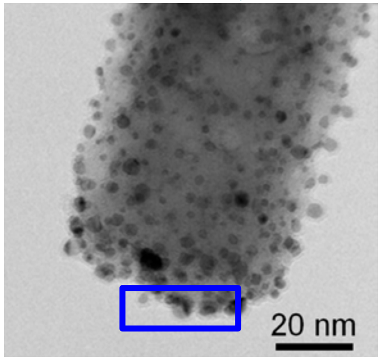
*Uniform Pt NPs on ZnO nanoarray*

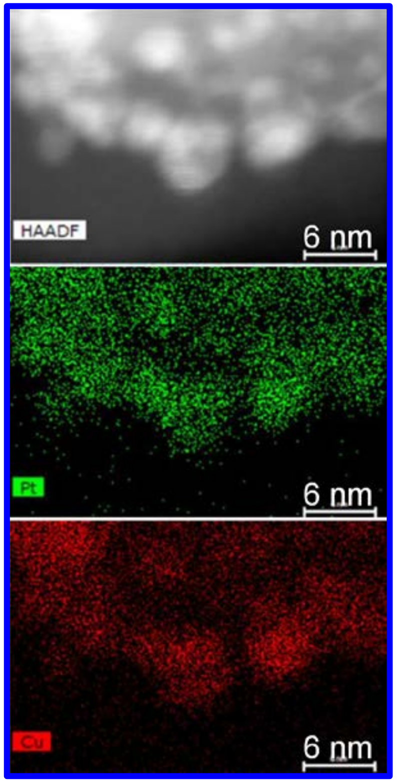



*Cu NPs by BCP & annealing*

*Modified Pt NP ALD protocol ensuring deposition uniformity: "Exposure mode"*




*Pt-Cu alloy NP loaded ZnO nanoarray*

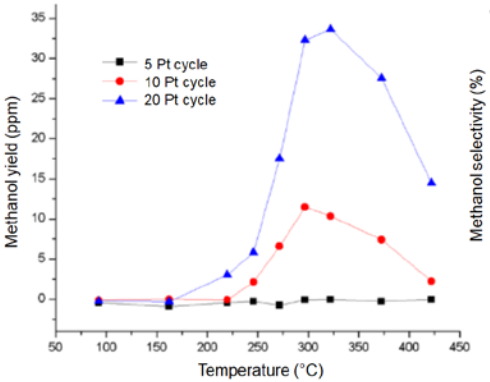
UCONN UNIVERSITY OF CONNECTICUT  BROOKHAVEN NATIONAL LABORATORY  Stony Brook University

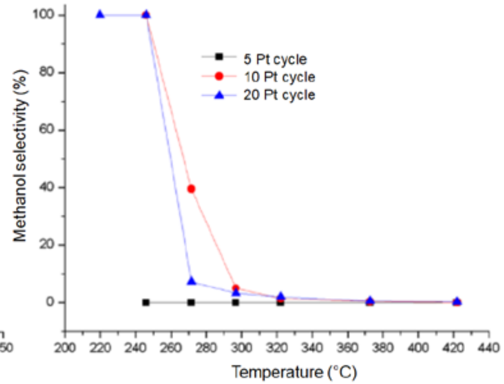
# ACCOMPLISHMENTS

## Enhanced $CO_2$ hydrogenation performance by ALD Pt-BCP Cu NP loaded ZnO nanoarray catalysts

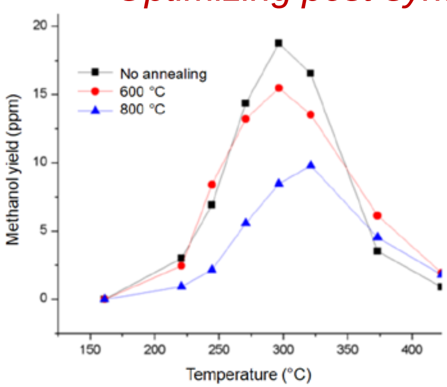
Pt-Cu NP loaded ZnO nanoarray achieves the methanol yield exceeding that of commercial reference via optimized Pt loading and thermal annealing temp.

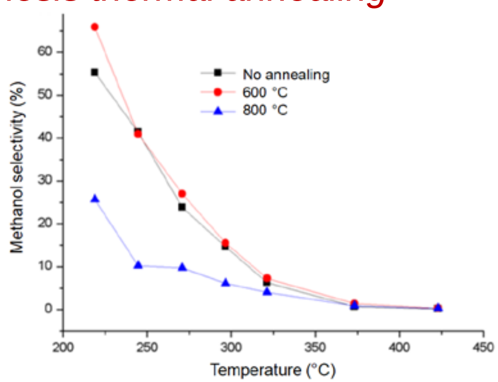
*Optimizing Pt loading by ALD cycles*



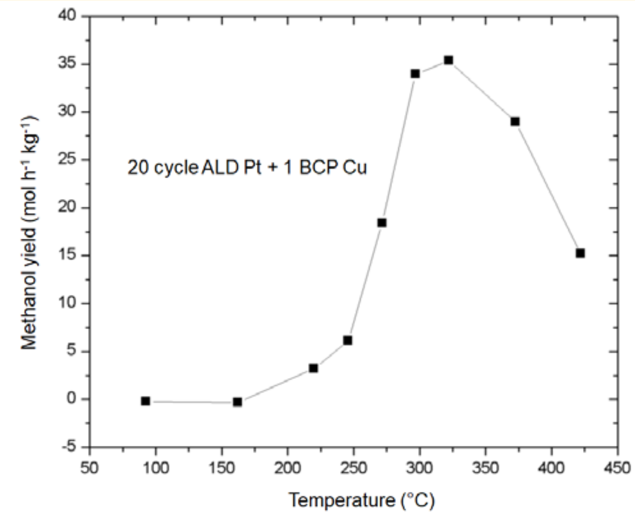




*Optimizing post-synthesis thermal annealing*




*Optimal Pt-Cu NP loaded ZnO nanoarray achieving the maximum methanol yield of 35 mol $h^{-1}$ $kg^{-1}$*




*Methanol yield exceeding commercial reference*

| Catalyst type | Temp. (C) | Selectivity (%) | Yield (mol $h^{-1}$ $kg^{-1}$) |
|---|---|---|---|
| Commercial (Cu-Zn-Al powder) | 197 | 54.3 | 1.25 |
| ALD Pt-BCP Cu NPs on ZnO nanoarray | 220 | 100 | 3.2 |

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Stony Brook University

# ACCOMPLISHMENTS
## Reactor Development

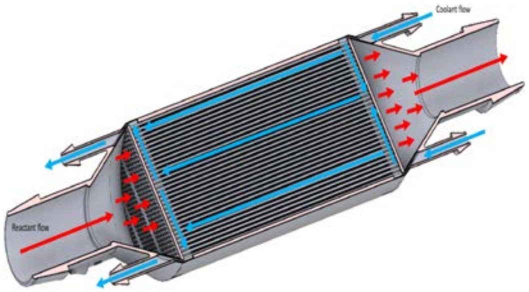
| 1 bar pressure | 200°C | | 300°C | |
|---|---|---|---|---|
| (Preliminary Data) | Equilibrium | Catalytic | Equilibrium | Catalytic |
| $CO_2$ Molar Conversion (single pass) | 59.5% | 5.0% | 56.9% | 12.5% |
| **Selectivity**[(1)] | **0.0%** | **96.6%** | **0.0%** | **97.5%** |
| [(1)]Selectivity = [ $CH_3OH+(CH_3)_2O$ ] / [ $CH_3OH+(CH_3)_2O+CO+CH_4$ ] | | | | |

Catalytic reactions may enable feasibility - selectivity is zero without catalysis

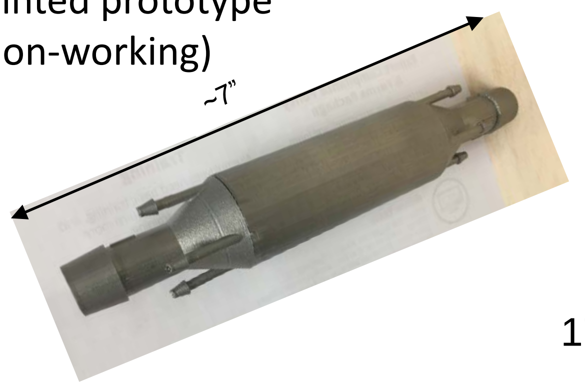
<u>Advanced Catalytic Reactor Design Concepts</u>

- Over 50 reactor substrates fabricated using additive manufacturing with varying channel sizes, shapes (twisted/linear, and cross sectional geometry
- Conceptual design of integrated reactor completed and fabricated using additive manufacturing
- Advance reactor design may enable optimize heat and mass transport

CAD Model




3D printed prototype (non-working)

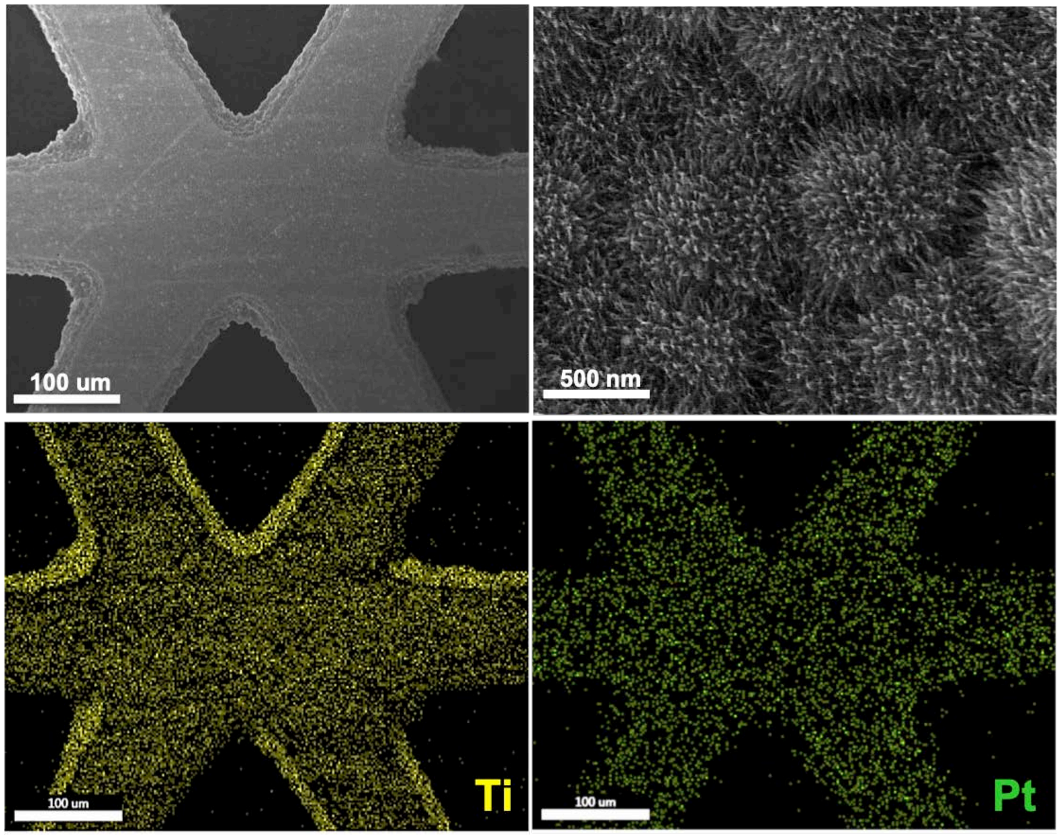


# ACCOMPLISHMENTS

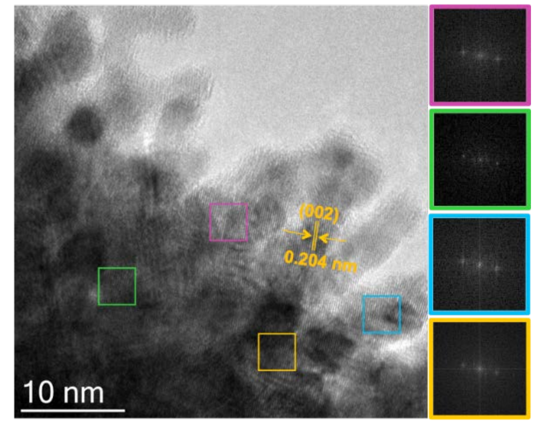
## Successfully Fabricated Thin Pt Nanowire (PtNW) Electrodes

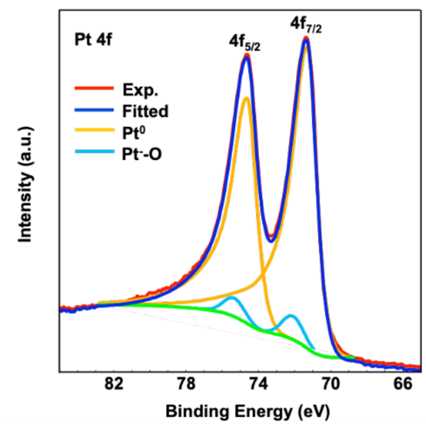
LGDL parameters: 25 µm thick; ~50% porosity; ~400 µm pore opening

SEM-EDS characterization




High-resolution TEM (HRTEM)



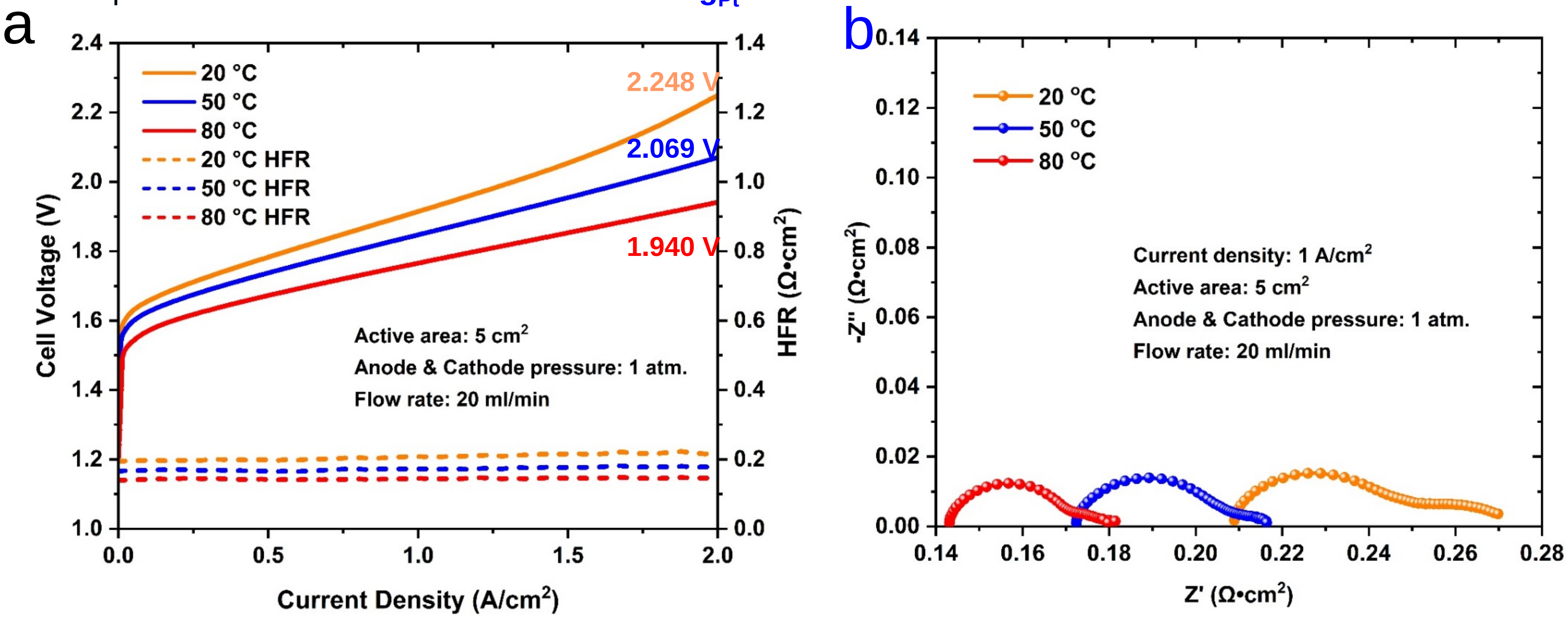

High-resolution XPS spectrum of Pt 4f

- Catalyst layer composed of PtNW was successfully grown on titanium LGDLs via chemical synthesis route at room temperature.
- Crystalline structure and diameter (~5 nm) of PtNW were confirmed by HRTEM
- XPS analysis verified the metallic nature of as-synthesized PtNW

# ACCOMPLISHMENTS

## PEM Electrolyzers With Ultralow-PGM Met Go/No-GO

*In-situ* performance of thin PtNW GDE at **0.05 mg$_{Pt}$/cm$^2$**: **1.94 V at 2 A/cm$^2$**




- Thin PtNW GDE at 0.05 mg$_{Pt}$/cm$^2$ shows cell voltage of 1.94 V at 2 A/cm$^2$ at 80 $^oC$.
- At lower temps 50 $^oC$ and 20 $^oC$, cell voltages are 2.069 V and 2.248 V at 2 A/cm$^2$, respectively.
- Increasing operating temps reduce HFR values from 0.207 Ω*cm$^2$ at 20 $^oC$ to 0.173 Ω*cm$^2$ at 50 $^oC$ and 0.144 Ω*cm$^2$ at 80 $^oC$.
- EIS indicates small mass transport loss at 50 $^oC$ and 80 $^oC$, but much larger transport loss at 20 $^oC$.

# Accomplishments and Progress

## Responses to Previous Year Reviewers' Comments

- This project was not reviewed last year.

# Collaboration and Coordination

| Name | Organization | Primary Role |
| --- | --- | --- |
| Dr. Trent Molter (Principal Investigator) | SKYRE, Inc. (SI) | Component integration, fueling protocols and program management |
| Prof. Pu-Xian Gao | University of Connecticut (UConn) | Nano-array integrated reactor design, fabrication, characterization and testing |
| Prof. Steven Suib | University of Connecticut (UConn) | Catalytic nanoparticle decoration and testing |
| Dr. Tom Maloney | Connecticut Center for Advanced Technology (CCAT) | Additive manufacturing of different reactor substrates |
| Dr. Dongsheng Li | Advanced Manufacturing LLC (AMLLC) | Design, optimization and post-processing of additively-manufactured reactor substrates |
| Prof. Chang-Yong Nam | Stony Brook University (SBU)<br>Brookhaven National Laboratory | Metal catalyst deposition; structural and chemical characterization |
| Prof. Feng-Yuan Zhang | University of Tennessee – Knoxville (UTK) | Electrolyzer assembly and testing |

# Remaining Challenges and Barriers

- Regroup after COVID-19 lab operation pause and resume hardware work.
- Successful scale-up, implementation and integration of materials and process work to produce a viable system.
  - Catalytic reactor
  - Electrolyzer
  - Integrated system

# Proposed Future Work

**Complete the following tasks (BP1):**

- Pressure dependent study of $CO_2$ hydrogenation over various nanopowder and nanoarray reactors.
- Stability study of nanoarray reactors at high pressure
- Kinetics experimental-theory study over nanostructured monolithic reactors.
- Optimization study of Cu-Zr-Zn mesoporous nanopowders for $CO_2$ hydrogenation
- Preliminary economic analysis of utilizing advanced reactor
- Identify the composition and crystalline phase of ALD Pt-BCP Cu NPs on ZnO nanoarray
  - Scanning transmission electron microscopy (STEM)
  - Electron energy loss spectroscopy (EELS)
- Identify the electronic interaction among Pt, Cu, and ZnO
  - X-ray photoemission spectroscopy (XPS) on planar substrates
- Optimization of PtNW electrodes with improved uniformity and surface coverage on thin LGDLs
- Ex-situ materials and electrochemical characterizations of optimized PtNW electrodes

# PROPOSED FUTURE WORK

**Initiate the following work for BP2:**

- Optimization and scale-up of nanoarray reactor fabrication
- Detailed process analysis and economic analysis
- Identify how $CO_2$ hydrogenation performance is influenced by the interaction among Pt, Cu, and ZnO
  - Ultraviolet photoemission spectroscopy (UPS)
  - Ambient pressure XPS (AP-XPS)
- Identify the guiding principles for designing high-performance Pt-Cu alloy $CO_2$ hydrogenation catalysts
- In-situ cell performance evaluations of PtNW electrodes with different catalyst loadings
- Fabrication of the PtNW electrodes for the electrolyzers integrated with nanoarray reactor for $CO_2$RR and their characterization
- Develop and demonstrate the integrated system which leverages individual materials and process technologies

# Technology Transfer Activities

- Conducting outreach to refine market scope and requirements
- Value can be ascribed to aggregated system and selective technologies developed as part of this project
  - Renewable liquid fuels
  - $CO_2$ Utilization/transformation
  - Renewable hydrogen
  - Efficient catalytic reactors
  - Efficient electrocatalytic reactors
  - Additive manufacturing technology

# SUMMARY

Objective: Investigate new electrolyzer integrated modular nanostructure array monolithic catalytic reactors for high-flux, robust, selective methanol synthesis

Relevance: Low-T, efficient electrolyzer for $H_2$ fueling. Cost-effective hydrogenation reactions under low T (< 200 °C) and low P (<10 atm), reducing energy. Nanostructured catalysts for high efficiency catalytic and electrocatalytic reactors. Renewables integration/$CO_2$ mitigation producing widely used chemical and fuel.

Approach: Electrolysis nanowire electrodes offering efficient high current density. Efficient catalysts offering enhanced performance and selectivity toward MeOH production and $H_2$ utilization. Advanced reactors that leverage additive manufacturing to incorporate fluid dynamics features that boost reactor efficiency. Integration of materials/devices to effectively and harmoniously operate reactors.

Accomplishments: Demonstrated catalytic performance of nanoarray reactor (1 bar - Methanol yield: ~6.2 mol/h/kg, selectivity: 100%, at 207 $^oC$, 10,000 $h^{-1}$, met go/no-go target, peak methanol yield: ~35 mol/h/kg at 300 $^oC$, 17,000 $h^{-1}$, 10 bar - Methanol yield: ~5.6 mol/h/kg, selectivity: 84.7%, at 196 $^oC$/10 bar, 10,000 $h^{-1}$, met go/no-go performance metrics at 200$^oC$/10 bar, 4 mol/h/kg and 75%) Demonstrated electrolyzer performance - thin PtNW GDE at 0.05 $mg_{Pt}/cm^2$ shows cell voltage of 1.94 V at 2 $A/cm^2$ at 80 $^oC$.

Collaborations: Strong, diverse team comprised of industry and research. (Skyre, CCAT, Adv. Mfg., UConn, Stony Brook – BNL, University of Tennessee – Knoxville).