

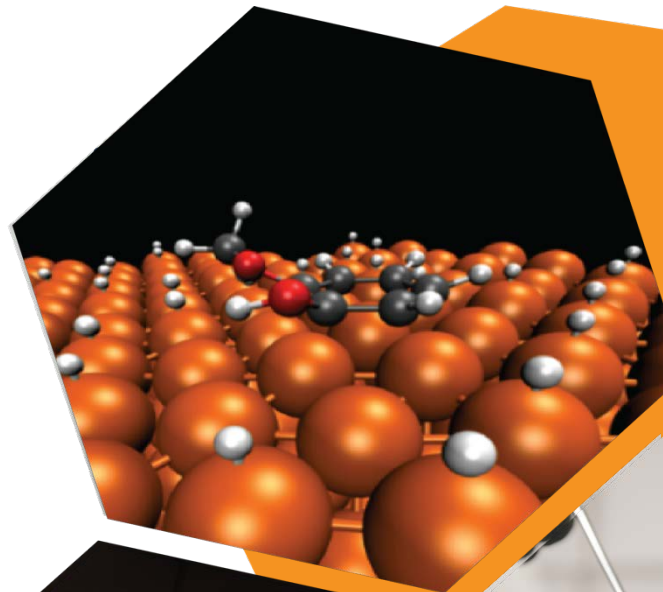


# Upgrading of C1 Building Blocks

## WBS# 2.3.1.305

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Daniel Ruddy  
National Renewable Energy Lab



# ChemCatBio Foundation – FY21

*Integrated and collaborative portfolio of catalytic technologies and enabling capabilities*

## **Catalytic Technologies**

**Catalytic Upgrading of Biochemical Intermediates**

(NREL, PNNL, ORNL, LANL)

**Upgrading of C1 Building Blocks**  
(NREL)

**Upgrading of C2 Intermediates**  
(PNNL, ORNL)

**Catalytic Fast Pyrolysis**  
(NREL, PNNL)

**Electrocatalytic CO<sub>2</sub> Utilization**  
(NREL)

## **Enabling Capabilities**

**Advanced Catalyst Synthesis and Characterization**

(NREL, ANL, ORNL)

**Consortium for Computational Physics and Chemistry**  
(ORNL, NREL, PNNL, ANL, NETL)

**Catalyst Deactivation Mitigation for Biomass Conversion**  
(PNNL)

## **Industry Partnerships** *(Phase II Directed Funding)*

**Opus12** (NREL)

**Visolis** (PNNL)

**Sironix** (LANL)

## **Cross-Cutting Support**

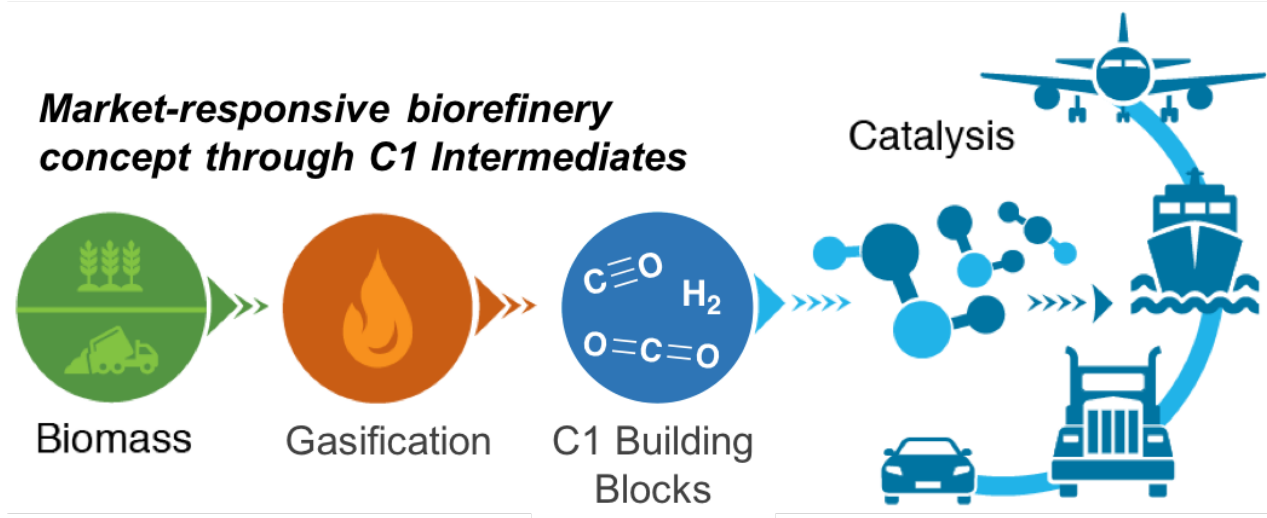
**ChemCatBio Lead Team Support** (NREL)

**ChemCatBio DataHUB** (NREL)

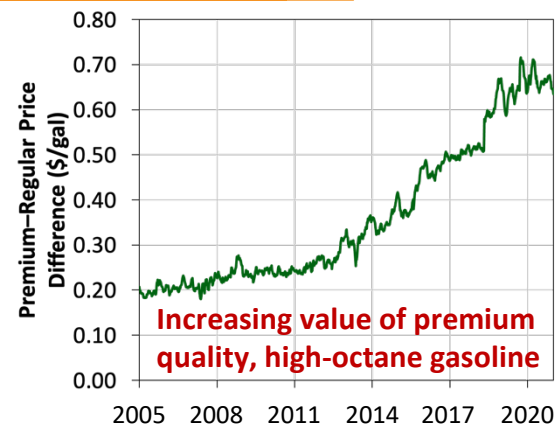
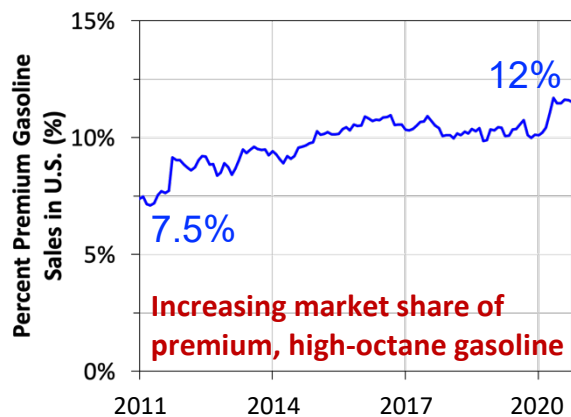
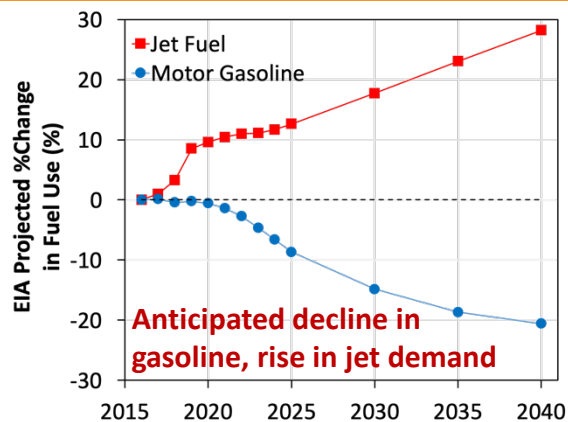
# Project Overview

## Project Goal

Develop the centerpiece technology for a market-responsive, integrated biorefinery concept based on the **conversion of renewable C1 intermediates** to produce a suite of fuels with **improved carbon efficiency, reduced capital expense, and control of the product distribution** to meet market demand.



# Project Overview – Fuel Market Trends



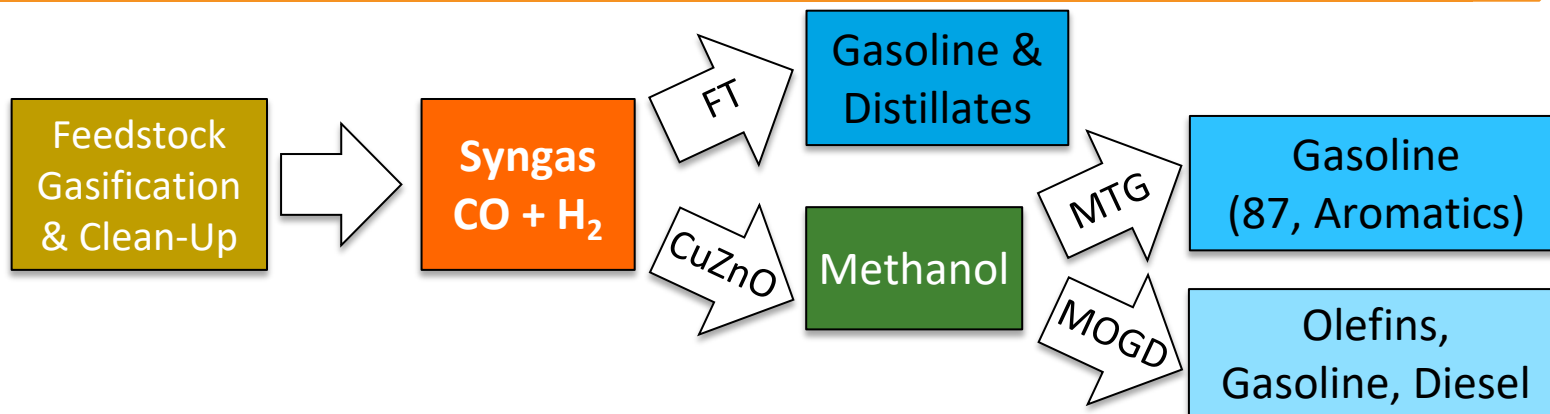
## Project Outcome

- Develop the catalyst and process for **direct conversion of CO<sub>2</sub>-rich syngas (15-20% CO<sub>2</sub>) to high-octane gasoline and jet fuels**
- **Exceed the carbon efficiency** of benchmark Mobil Olefins-to-Gasoline-and-Distillates (MOGD) process with **lower capital expense**

## Key Differentiators

- Address **known drawbacks for traditional syngas-to-fuels** processes at smaller production scales – high capital cost, limited product quality – by focusing on **mild process conditions, high yield and carbon efficiency, high-quality (high-value) fuel products**

# Overview - Traditional Syngas-to-Fuels Processes



## Traditional syngas to hydrocarbon fuels have known drawbacks

- Fischer-Tropsch (FT): Costly catalytic upgrading to produce quality fuels
- Methanol-to-Gasoline (MTG): Capital intensive, high aromatics content
- Mobil Olefins-to-Gasoline-and-Distillate (MOGD): Capital intensive, high number of process steps

### MFSP from biomass (2016 \$)

- FT = \$3.17/GGE
- MOGD = \$4.23/GGE

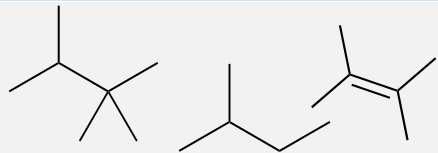
***Advanced upgrading technologies can reduce MFSP through reduced process complexity, reduced separations duty, higher quality fuel products***

E. Tan, et al., *Biofuel Bioprod. Bioref.* **2017**, *11*, 41.

# Overview – An Alternative Methanol-to-Fuels Pathway

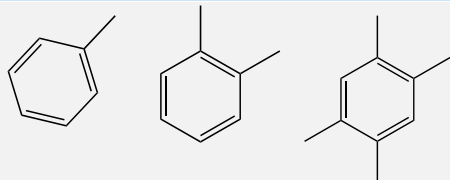
## NREL has been developing the High-Octane Gasoline (HOG) Pathway

### HOG Pathway



### Branched Products

### MTG Pathway



### Aromatic Products

## Key Differentiators of HOG versus MTG

- HOG pathway yields **branched alkanes, not aromatics**
  - Higher octane (102 vs 87), higher value fuel product
    - **Alkylate versus regular-grade gasoline**
  - Lower severity conditions for HOG vs MTG
    - **Higher yield (18% relative), higher C-efficiency**
  - Modeled costs for MeOH-to-HOG of \$0.49–0.66/GGE compare favorably against other alcohol conv tech.
    - EtOH-to-Jet \$0.89–1.19/GGE
- (L. Tao *et al.*, *Green Chem.* 2017, 19, 1082)

# 1. Management

Task management integrated with CCB enabling technologies and analysis team, other BETO projects and consortia, and technology advancement opportunities

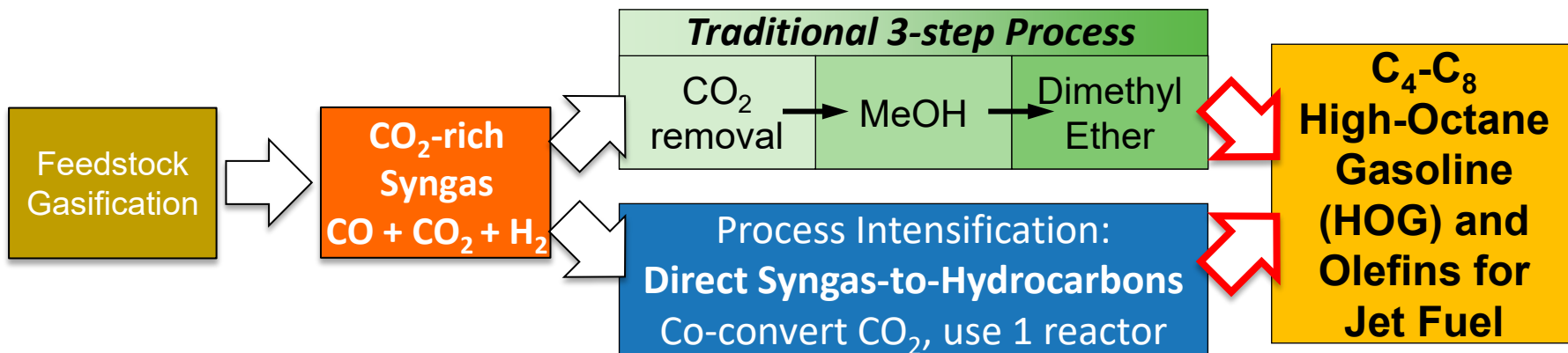
	ACSC	CCPC	CCM	CDM	TEA				TCF
Task 1 (D. Ruddy)	DME/Syngas to High-Octane Gasoline and Jet Fuel					SDI – Eng. of catalyst scale-up	Feedstock-Conversion Interface	Co-Optima	
Task 2 (A. To)	CO <sub>2</sub> Conversion to Jet Fuel								

- **“Constant contact” between PIs and Enabling Technology** points-of-contact
- **Research tasks are cooperative and synergistic**
  - Focus on specific challenges for syngas versus CO<sub>2</sub> conversion
  - Lessons learned from each task inform the common goal of CO<sub>2</sub>-rich syngas conversion
- **TEA-informed metrified milestones and Go/No-Go** to relate catalyst improvements to costs
- Utilized the **TEA-informed FY19 results** to inform FY20 syngas conversion research path





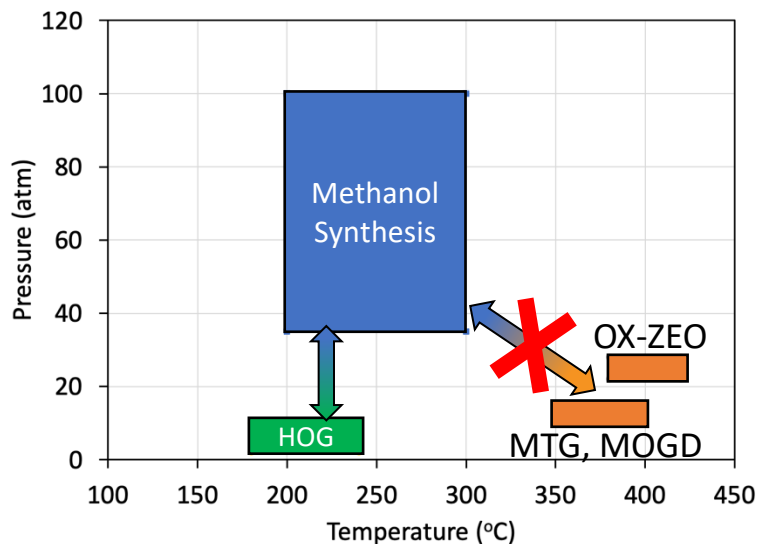
## 2. Approach – Pathways Explored in this Project



### Pathway Objectives

- Catalyst and process development for **cost reduction in the 3-step process** for dimethyl ether (DME) to high-octane gasoline (HOG) over NREL's **Cu/BEA zeolite**
- Utilize **Process Intensification** to evaluate catalytic pathways that will *improve the overall carbon efficiency with reduced capital expense – 5-10% decrease in CapEx*
  - **Leverages research team's experience** with syngas, DME, and Cu/BEA catalyst
  - Compare against benchmark MOGD and recent reports for syngas-to-olefins (STO) processes (e.g., OX-ZEO process)

## 2. Approach – Opportunities and Challenges



**Similar process conditions offer the opportunity for process intensification to enable direct syngas-to-fuels through methanol in a single reactor**

- Utilize commercial, inexpensive Cu-based MeOH synthesis catalyst
- Opportunity to co-convert CO<sub>2</sub> with CO during MeOH synthesis
- Go/No-Go Decision in FY21 for this new, direct syngas-to-fuels pathway

### Research Challenges and Critical Success Factors

- **Activate CO<sub>2</sub>** in the presence of CO, convert to products **for increased C-efficiency**
- **Balance multiple reactions** under low severity conditions
- Maximize yield and carbon efficiency with **multi-functional catalyst system** that performs cascade chemistry
- **Advance technology** with bioenergy industry partners, TCF funding

### 3. Impact – High-Octane Gasoline Product

HOG product targets *growing premium gasoline fuel demand and value*

– Unlike ethanol, **gasoline product has no blend limit**

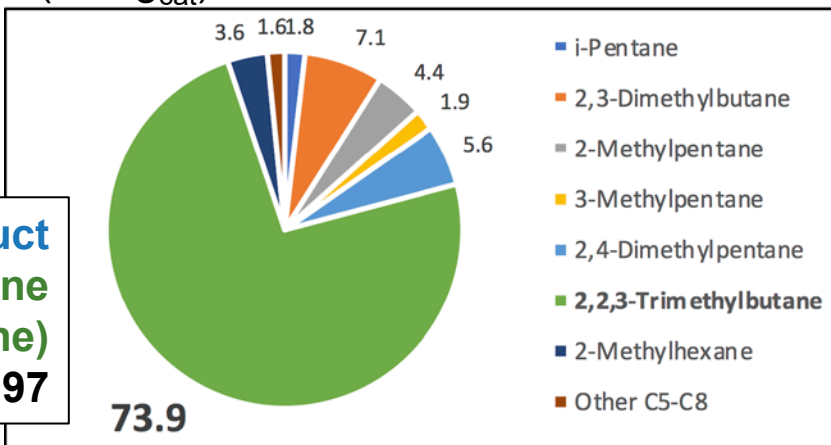
HOG technology awarded a *Technology Commercialization Fund*

*\$740k investment by DOE + \$750k cost-share from Enerkem in 2018-2019*

- Demonstrated HOG production at the **pilot scale** (20-kg<sub>cat</sub>) with **MSW-derived methanol for 500 h time-on-stream**
- Produced **20 L of high-octane gasoline**
- Sent to **refinery industry partners**

#### Composition of High-Octane Product

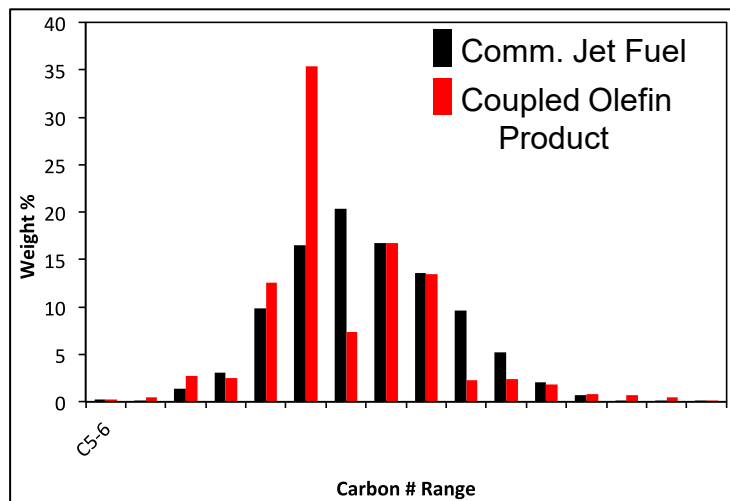
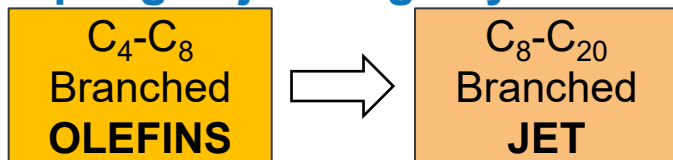
**73.9% Triptane  
(2,2,3-trimethylbutane)  
RON = 108 MON = 97**



- This TCF project was critical to generate liquid product for industry analysis
- Research license to commercialize NREL’s HOG technology with large energy company executed in 2020

# 3. Impact – Jet-range Product

Developed a mild-condition route for olefin coupling to jet-range hydrocarbons



Product meets 5 key ASTM Int'l jet fuel property specifications

Fuel Property	ASTM D1655 Limits	Coupled Olefin - Jet Values
Density (kg/m <sup>3</sup> )	775–840	783
Freeze point (°C)	–40 max	–81
Viscosity (mm <sup>2</sup> /s)	8.0 max	7.6
Net Heat of Combustion (MJ/kg)	42.8 min	43.8
T10 (°C)	205 max	178
T50	Report	188
T90	Report	239
FBP	300 max	281

– Process model and TEA indicates only a minor fuel synthesis cost increase to generate this additional product (+ 3¢/GGE)

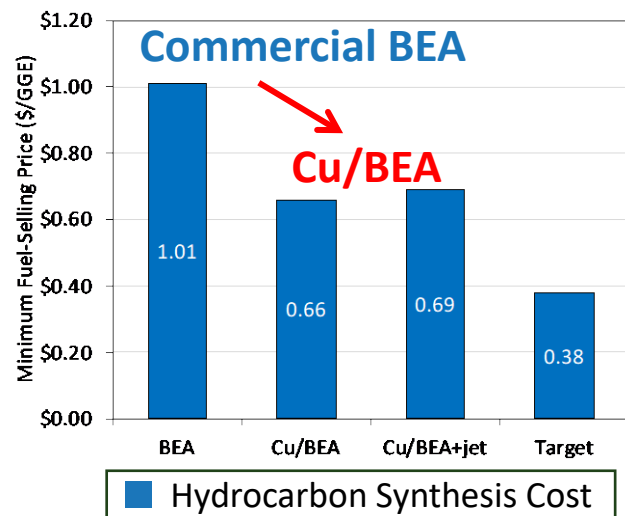
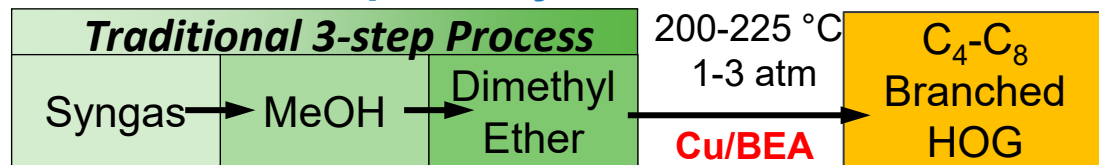
## 4. Progress & Outcomes – Baseline in FY20

	<b>MOGD Benchmark</b>	<b>“3-step” DME-to-HOG</b>	<b>“Direct” Syngas-to-HOG</b>
<b>Catalyst</b>	ZSM-5	Cu/BEA	CZA Cu/BEA
<b>Severity of Process Conditions</b>	350–400 °C 20 atm <i>Frequent regen.</i>	200–225 °C 1–3 atm <i>Stable &gt;100h</i>	200–240 °C 1–10 atm <i>unknown</i>
<b>Start of FY20 Metrics</b>	–	44% DME conv. 0.070 g/g <sub>cat</sub> /h	New Effort in FY20
<b>Fuel Yield* and MFSP</b>	G= 34 GGE/ton D= 27 GGE/ton <b>\$4.23/GGE</b>	G= 49 GGE/ton <b>\$3.53/GGE</b>	<b>Baseline to be set in FY20</b>

- FY19 TEA data **sets the stage for catalyst and process development**
  - TEA-directed research goals to target most impactful metrics
  - Comparison against benchmark MOGD process

# 4. Progress & Outcomes – Advancing DME-to-HOG

## Overview of the pathway



## Differentiators versus MTG

- **Catalyst** – BEA vs MFI
- **Product composition**
  - Alkylate vs regular-gasoline
- **Higher product RON** – ≥95 vs 92
- **Lower coking rate**
- **Higher yield from biomass** – +18%

- **Cu/BEA catalyst reduces MFSP versus commercial BEA by 20% with C<sub>4</sub> by-product recycle and reactivation**
  - MeOH-to-HOG cost reduced by 30–35% (FY18-19)

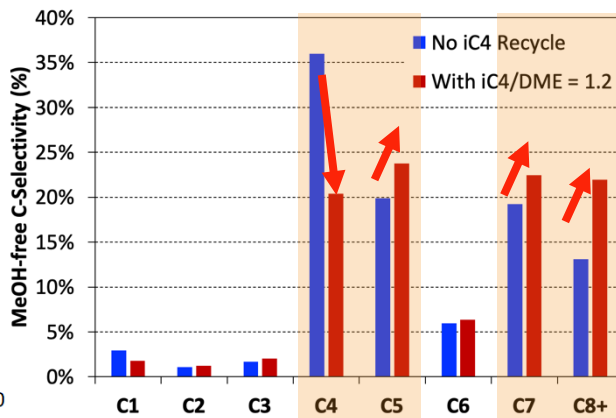
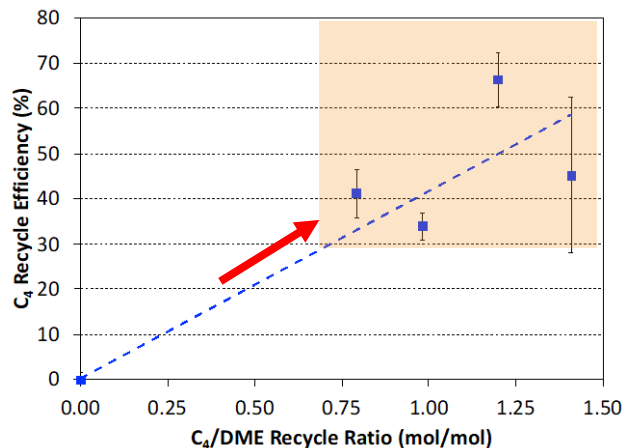
– Coupled process models and TEA with fundamental and applied catalysis research **to quantify the impact of catalyst development on process economics** in the production of HOG and jet fuel from DME

Schaidle et al. *ACS Catal.* 2015; Tan et al., *Biofpr* 2016; Farberow et al., *ACS Catal.* 2017; **Ruddy et al., *Nature Catalysis* 2019**; Dupuis et al., *Appl. Energy* 2019; Wu, To, et al., *Appl. Catal. B Environ.* 2021, 287, 119925.

# 4. Progress & Outcomes – Advancing DME-to-HOG

**Goal:** Increase  $C_4$  recycle efficiency to increase yield, C-efficiency and reduce MFSP (*with TC Platform Analysis*)

– Explored  $C_4H_{10}$  recycle at higher  $C_4H_{10}/DME$  ratios that simulate **continuous recycle** in a fixed-bed reactor

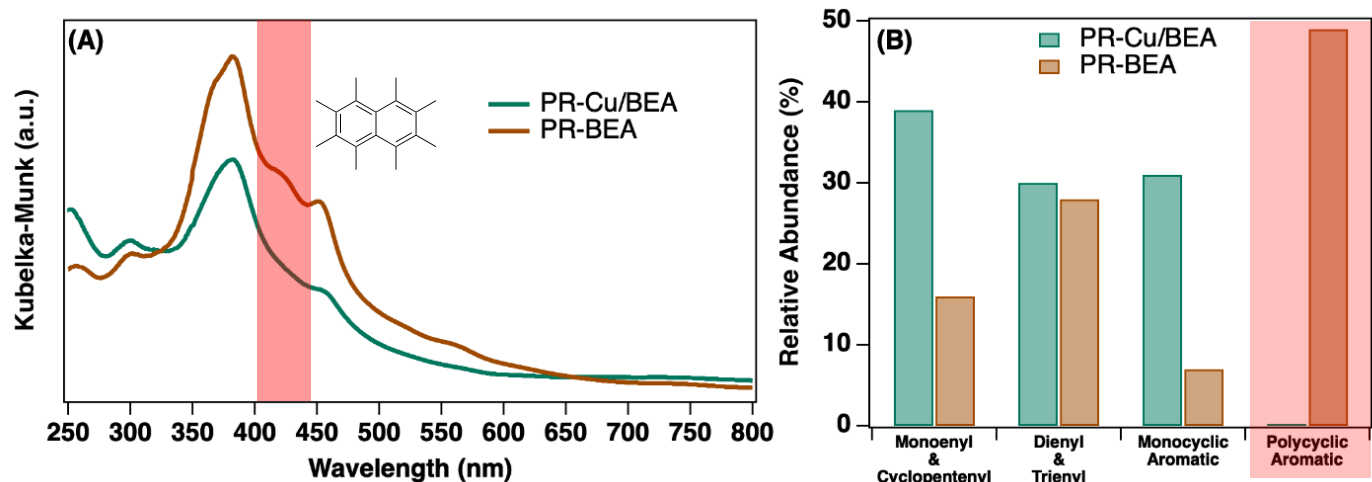


- **Recycle efficiency increases with  $C_4/DME$  ratio**
- **Shift in product C-selectivity with higher  $C_4/DME$  ratio**
  - Decrease in  $C_4$
  - Increase in  $C_5, C_7, C_8$
  - $C_4$  converted to  $C_{5+}$

- Modeled yield increased from 49 to 55 GGE/ton, C-efficiency from 24.8 to 26.1%
- **MFSP reduced from \$3.53/GGE to \$3.45/GGE (34% decrease vs BEA)**
  - Continuing progress towards FY22 Target of \$3.30/GGE
  - **MeOH-to-HOG cost reduced from \$0.54/GGE (FY19) to \$0.45/GGE (FY20)**

# 4. Progress & Outcomes – Advancing DME-to-HOG

**Goal:** Determine differences in carbon speciation for BEA vs Cu/BEA leading to catalyst deactivation, **develop regeneration protocol** (*with Adv. Cat. Synth. & Char.*)



- Cu/BEA prevented polycyclic aromatic formation that was observed on BEA
- **Cu promoted carbon removal at 200 °C lower temperature** versus BEA
- Activity of Cu/BEA was **fully recovered** using the regen procedure

Schaidle et al. *ACS Catal.* 2015; Tan et al., *Biofpr* 2016; Farberow et al., *ACS Catal.* 2017; Ruddy et al., *Nature Catalysis* 2019; Dupuis et al., *Appl. Energy* 2019; **Wu, To, et al., *Appl. Catal. B Environ.* 2021, 287, 119925.**



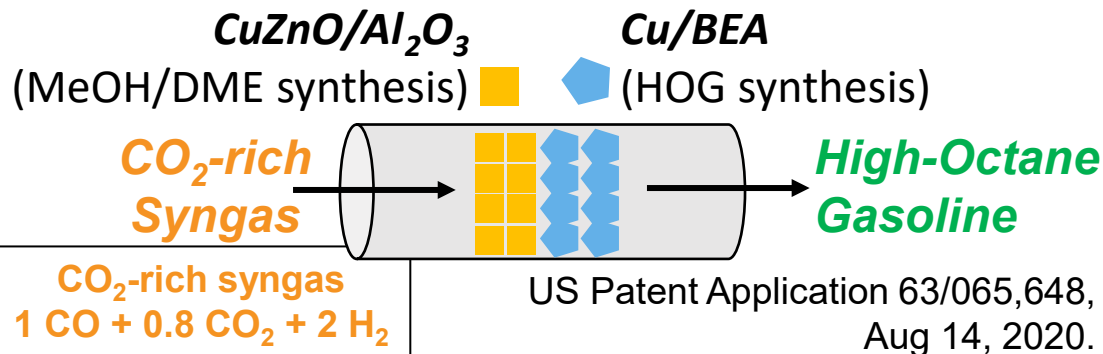
# 4. Progress & Outcomes – Direct Syngas-to-HOG

## Overview of the pathway

Process Intensification:  
**Direct Syngas-to-Hydrocarbons**  
Co-convert  $\text{CO}_2$ , use 1 reactor

200-240 °C  
1-10 atm  
**CZA+**  
**Cu/BEA**

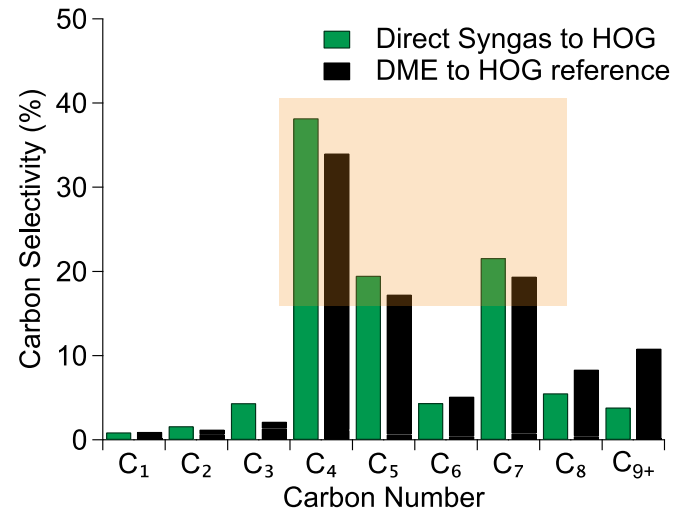
$\text{C}_4\text{-C}_8$   
Branched  
HOG



- **Product selectivity similar to DME-to-HOG**
- High-octane, high-value product direct from syngas
- **Stacked-bed outperformed mixed-bed**
- **Cu/BEA outperformed BEA**

## Differentiators versus OX-ZEO

- **Catalysts**
  - $\text{CuZnO}/\text{Al}_2\text{O}_3$  vs  $\text{ZnCrO}_x$
  - BEA vs AEL
- **Intermediate**
  - MeOH vs Ketene
- **Product composition**
  - Alkylate vs Olefins



# 4. Progress & Outcomes – Direct Syngas-to-HOG

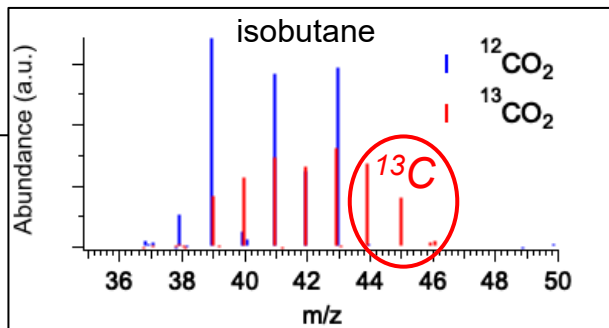
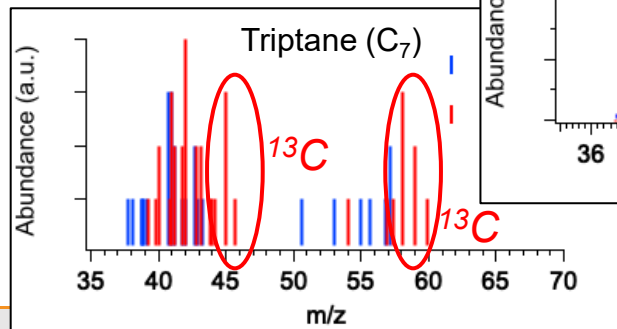
**Goals:** Achieve high C-yield to C<sub>4+</sub> products from syngas and syngas+CO<sub>2</sub>, follow C from CO<sub>2</sub> using <sup>13</sup>CO<sub>2</sub> and mass-spectroscopy of hydrocarbon products

Key Results from FY20	Catalyst composition (CZA:Cu/BEA = 1:1)	
	No	Yes
CO <sub>2</sub> co-feed		
CO+CO <sub>2</sub> conversion (%)	77.3	27.0
C <sub>4+</sub> HC yield (%)	44.9	23.8
CO <sub>2</sub> C-selectivity (%)	38.8	28.4
Total <sub>HC</sub> Prod. (g <sub>HC</sub> -g <sub>Cu/BEA</sub> <sup>-1</sup> -h <sup>-1</sup> )	0.10	0.054

- Exceeds initial 10% target
- Greatly exceeds 2-12% in STO literature
- Decrease suggests activation
- Comparable to DME feed

STO Review: W. Zhou *et al.*, *Chem.Soc.Rev.* **2019**, 48, 3193.

## Mass spectra of major hydrocarbon products



- High single-pass C<sub>4+</sub> yield achieved with co-fed CO<sub>2</sub>
- Mass spectra peaks at *m/z*+1 with <sup>13</sup>CO<sub>2</sub> provide **critical data for CO<sub>2</sub> conversion into desired products**

## 4. Progress & Outcomes – Summary

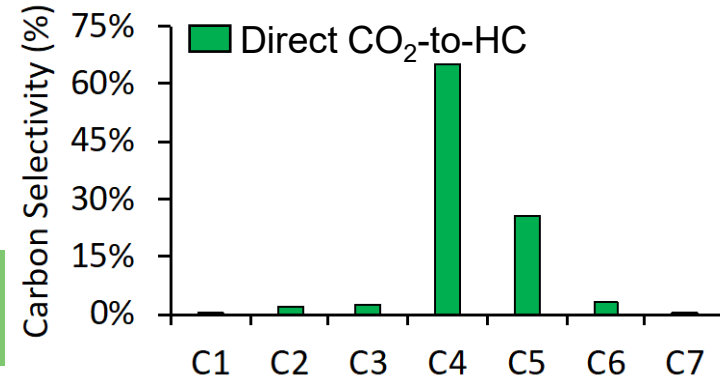
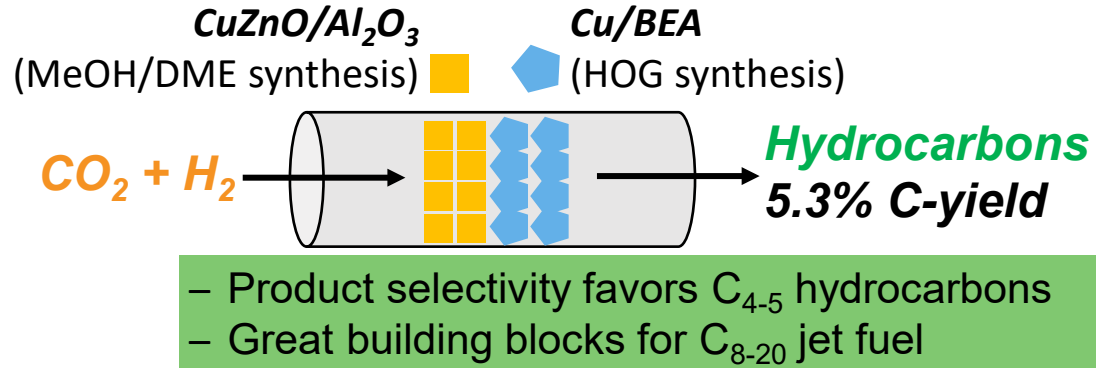
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<b>Severity of Process Conditions</b>	350–400 °C 20 atm <i>Frequent regen.</i>	200–225 °C 1–3 atm <i>Stable &gt;100h, Multiple Regens demonstrated</i>	200–240 °C 1–10 atm <i>Stable &gt;50 h</i>
<b>Current Metrics</b>	–	44% DME conv. <b>0.094 g/g<sub>cat</sub>/h</b>	<i>High-yield to C<sub>4+</sub> products, CO<sub>2</sub> incorporation</i>
<b>Fuel Yield* and MFSP</b>	G= 34 GGE/ton D= 27 GGE/ton <b>\$4.23/GGE</b>	G= <b>55 GGE/ton</b> <b>\$3.45/GGE</b>	Baseline set in FY20, Compared at FY21 Go/No-Go

- Continued process advancement and cost reduction of the 3-step process achieved
- Catalyst performance in direct process exceeded initial targets
- FY21 Go/No-Go (June 2021) will compare processes to inform future research

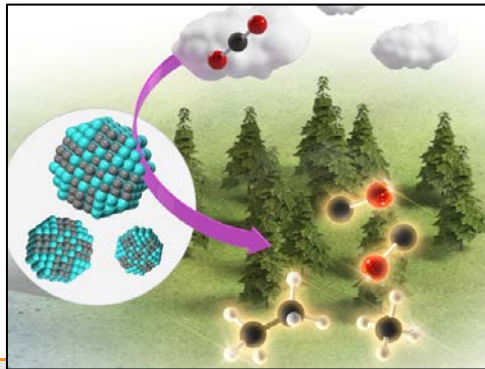
## 4. Progress & Outcomes – CO<sub>2</sub>-to-HCs (Task 2)

**Goals:** Separately explore approaches for conversion of CO<sub>2</sub> to hydrocarbons

### 1. Stacked-bed Approach – informs and supports analogous direct syngas-to-HOG pathway



### 2. New Materials Approach – opportunity for new pathway to olefins for jet fuel



- New synthetic method to prepare colloidally-stable  $\alpha\text{-MoC}_{1-x}$  **nanoparticles** developed *with ACSC Project*

- 2X greater per-site activity in CO<sub>2</sub>-to-Hydrocarbons AND 2X greater selectivity to C<sub>2+</sub> hydrocarbons vs bulk  $\alpha\text{-MoC}_{1-x}$

F.G. Baddour *et al.*, *J. Am. Chem. Soc.* **2020**, 142, 1010.

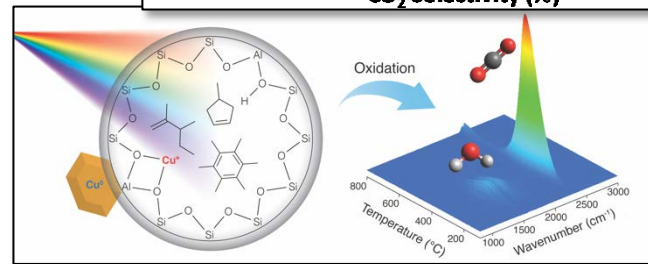
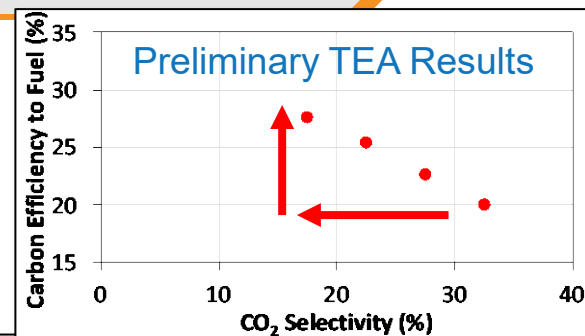
# 4. Progress & Outcomes – Future Research

Determine the effect of CO<sub>2</sub>/CO ratio on catalyst performance and product selectivity in the direct syngas-to-HOG reaction

- Reduce CO<sub>2</sub> selectivity
- Quantify gasoline versus olefins for jet product yield

Utilize in situ spectroscopy to compare surface carbon speciation from syngas versus DME

- Develop an efficient catalyst regeneration protocol for the CZA+Cu/BEA catalyst system



**FY21 Go/No-Go:** Use comparative TEA for DME-to-HOG versus direct syngas-to-HOG to determine the process model for State-of-Technology (SOT) reports going forward

- Complete the FY21 SOT based on Go/No-Go process choice

**FY22:** Demonstrate 200 h time-on-stream for direct conversion of CO<sub>2</sub>-rich syngas to HOG in a single reactor

- Use experimental data in process models to target 31.8% C-efficiency

# Quad Chart Overview

## Timeline

- 10/01/2019
- 09/30/2022

	FY20	Active Project
DOE Funding	\$1.6 M	\$4.8 M

## Project Partners

- Univ. of Minnesota, Prof. Aditya Bhan (\$99k)

## Barriers addressed

### Ct-F: Increasing the Yield from Catalytic Processes

- Developing catalysts that enable processes with higher carbon efficiency and yield

### Ct-G: Decreasing the Time and Cost to Develop Novel Industrially Relevant Catalysts

- Developing catalysts that meet cost and performance targets assessed on a year-by-year basis

## Project Goal

Develop the centerpiece technology for a market-responsive, integrated biorefinery concept based on the conversion of renewable C1 intermediates to produce a suite of fuels with improved carbon efficiency, reduced capital expense, and control of the product distribution to meet market demand.

## End of Project Milestone

Demonstrate 200 h time-on-stream with 14% relative improvement in C-efficiency for direct conversion of CO<sub>2</sub>-rich syngas to high-octane gasoline in a single reactor using the developed catalyst and process technology.

## Funding Mechanism

ChemCatBio Consortium  
AOP Lab Call 2019

# Summary

## Project Goal

**Develop new, low-severity catalytic upgrading technologies** for renewable C1 building blocks to to **high-value fuels** that address the **shifting gasoline/distillate demand**

## Approach

- **Process intensification** with **multi-functional catalysts** to perform selective, cascade reactions, leading to **low operating costs, high C-yields, and high C-efficiency**
- Interdisciplinary, **collaborative approach** within ChemCatBio leveraging enabling technologies

## Impact

- Demonstrated **technology transfer with the bioenergy industry** (e.g., TCF with Enerkem, research license) **to reduce risk of commercialization**
- **Patented** intellectual property, and published results in **top-tier peer-reviewed journals**

## Research Progress & Outcomes

- Significant **increase in yield and reduction in MFSP** demonstrated in DME-to-HOG technology with Cu/BEA catalyst
- Direct conversion of **CO<sub>2</sub>-rich syngas-to-HOG demonstrated** with high single-pass C<sub>4+</sub> yield
- Evidence for **CO<sub>2</sub> incorporation into hydrocarbon products** using <sup>13</sup>CO<sub>2</sub>

# Acknowledgements

## *NREL Catalyst Development Team*

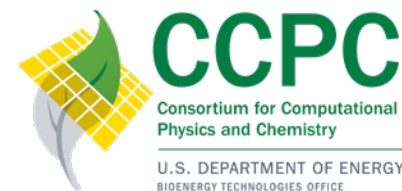
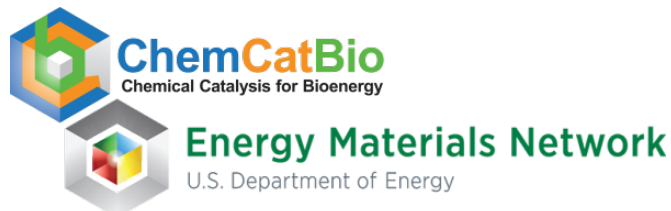
Anh To	Connor Nash
Jesse Hensley	Carrie Farberow
Joshua Schaidle	Daniel Dupuis
Fred Baddour	Susan Habas
Nicole LiBretto	Claire Nimlos
Qiyuan Wu	Martha Arellano-Trevino
Matthew Yung	Andy Young
Seth Noone	Jason Thibodeaux
Jacob Miller	Rianna Martinez

## *TEA Team*

Abhijit Dutta (NREL)  
Eric Tan (NREL)  
Kylee Harris (NREL)

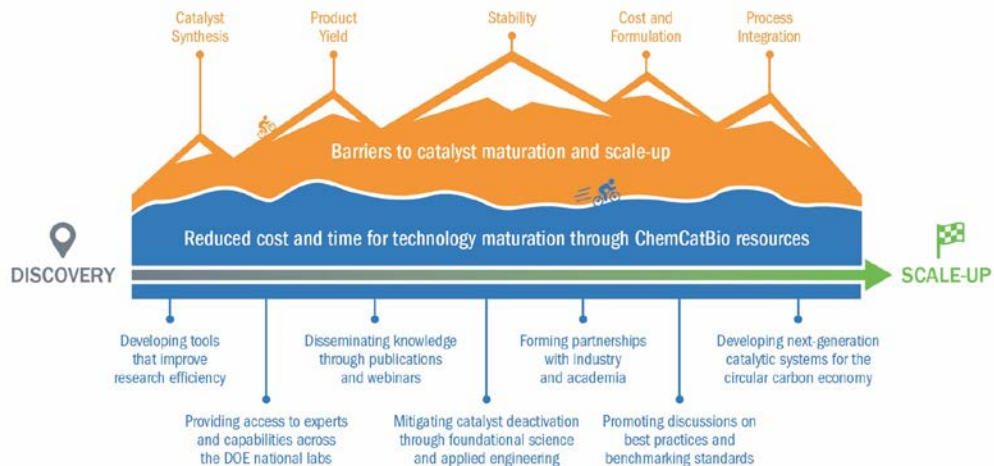
## *Collaborators*

Ted Krause (ANL)  
Kinga Unocic (ORNL)  
Jeffrey Miller (Purdue)  
Earl Christensen (NREL)  
Bruce Adkins (ORNL)  
Aditya Bhan (Minn.)





The path to catalyst deployment is slow and difficult.



ChemCatBio is accelerating the catalyst and process development cycle.

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**ChemCatBio**  
Chemical Catalysis for Bioenergy

NREL/PR-5100-79306

U.S. DEPARTMENT OF  
**ENERGY**

Office of ENERGY EFFICIENCY  
& RENEWABLE ENERGY

BIOENERGY TECHNOLOGIES OFFICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Bioenergy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

# Additional Slides

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# Responses to Previous Reviewers' Comments

- In general, the project has very focused tasks to develop a wide range of potential full candidates from low molecular weight oxygenates. The team successfully leverages interactions with many groups within ChemCatBio to enhance the project. The majority of the project has seen activity and selectivity metrics met, though room to improve catalyst reusability remains. In general, future studies appear to build on prior successes and will leverage capabilities in ChemCatBio to attempt to further catalyst performance. The project is productive in both connecting with fundamental science, publications in field-leading journals, technology, and several patents and a successful technology transfer with one of the processes.
  - *We agree that catalyst reusability remains an important part of our research. This is the focus of our end-of-year goal, where we will explore deactivation and regeneration in all three of our oxygenate conversion pathways.*
- This project is making great progress already by delivering a promising pathway with several others to follow. This is the type of technology platform pipelining that BETO needs to continue funding in order to remain an innovative leader in bioenergy technology for the future. These types of processes that are rooted in alcohol conversion over modified zeolite chemistry will accelerate the progress toward the 2022 target. The information received from TEA and the CCPC make this project approach very robust. The team should stay vigilant and not trivialize the oligomerization chemistry and related unit operations required to drive the carbon-carbon bond formation to distillate-range material.
  - *Although our focus is on the catalyst development for oxygenate conversion to versatile hydrocarbon intermediates, the reviewer is correct that the oligomerization cannot be trivialized. Due to time limitations, these results were not presented. However, this is an active area of research in the project, and based on these comments, it will remain as such.*
- Scaling is an important consideration on this project. It would be beneficial to evaluate modular processes as well and evaluate how synthetic catalysts work on large-scale processes.
  - *In addition to our on-going efforts around catalyst reusability, the reviewer presents a useful suggestion to consider varying scales and modular processes. Our initial assessment of smaller scales suggested less favorable process economics, as typically associated with small-scale gasification technologies. However, we acknowledge that the opportunity to utilize renewable carbon sources may someday favor modular systems, and we will consider how our technology scales.*

## Publications

- D.A. Ruddy, J.E. Hensley, C.P. Nash, E.C.D. Tan, E. Christensen, C.A. Farberow, F.G. Baddour, K.M. Van Allsburg, J.A. Schaidle, “Methanol to high-octane gasoline within a market-responsive biorefinery concept enabled by catalysis”, *Nature Catalysis* 2019, 2, 632.
- R.G. Grim, A.T. To, C.A. Farberow, J.E. Hensley, D.A. Ruddy, J.A. Schaidle, “Growing the bioeconomy through catalysis: A review of recent advancements in the production of fuels and chemicals from syngas-derived oxygenates” *ACS Catalysis* 2019, 9, 4145.
- D.P. Dupuis, R.G. Grim, E. Nelson, E.C.D. Tan, D.A. Ruddy, S. Hernandez, T. Westover, J.E. Hensley, D. Carpenter, “High-octane gasoline from biomass: Experimental, economic, and environmental assessment” *Applied Energy* 2019, 241, 25.
- E.C.D. Tan, D. Ruddy, C. Nash, D. Dupuis, K. Harris, A. Dutta, D. Hartley, H. Cai, “High-octane gasoline from lignocellulosic biomass via syngas and methanol/dimethyl ether intermediates: 2019 State of Technology” NREL Technical Report, NREL/TP-5100-76619, April 2020.
- F.G. Baddour, E.J. Roberts, A.T. To, L. Wang, S.E. Habas, D.A. Ruddy, N.M. Bedford, J. Wright, C.P. Nash, J.A. Schaidle, R.L. Brutchey, N. Malmstadt, “An exceptionally mild and scalable solution-phase synthesis of molybdenum carbide nanoparticles for thermocatalytic CO<sub>2</sub> hydrogenation” *Journal of the American Chemical Society* 2020, 142, 1010.
- Q. Wu, A.T. To, C.P. Nash, D.P. Dupuis, F.G. Baddour, S.E. Habas, D.A. Ruddy, “Spectroscopic insight into carbon speciation and removal on a Cu/BEA catalyst during renewable high-octane hydrocarbon synthesis” *Applied Catalysis B: Environmental* 2021, 287, 119925.
- C.A. Farberow, J. Miller, E.C. Wegener, A. Kumar, D.P. Dupuis, S. Kim, J.T. Miller, S.E. Habas, D.A. Ruddy “Connecting cation site location to alkane dehydrogenation activity in Ni/BEA catalysts” *Journal of Catalysis*, submitted.

## Patents

- J. E. Hensley, D. A. Ruddy, J. A. Schaidle, M. Behl, US Patent 9,714,387 B2 “Catalysts and methods for converting carbonaceous materials to fuels”, July 25, 2017.
- J. E. Hensley, D. A. Ruddy, J. A. Schaidle, M. Behl, US Patent 9,796,931 B1 “Catalysts and methods for converting carbonaceous materials to fuels”, October 24, 2017.
- J. E. Hensley, D. A. Ruddy, J. A. Schaidle, M. Behl, US Patent 9,803,142 B1 “Catalysts and methods for converting carbonaceous materials to fuels”, October 31, 2017.
- “Catalysts and systems for the production of liquid fuels and chemicals” US Patent Application 62/482,315, April 6, 2017.
- “Catalysts and systems for the production of liquid fuels and chemicals” US Patent Application 62/515,087, June 5, 2017.
- “High-octane synthetic fuels” US Patent Application 62/935,692, November 15, 2019
- “Methods, systems, and catalysts for the direct conversion of syngas to high-octane hydrocarbons” US Patent Application 63/065,648, August 14, 2020.
- “High-octane synthetic fuels” US Patent Application 17/098,785, November 16, 2020

# Publications, Patents, Presentations, Awards, and Commercialization

## Presentations

- *Invited*: Ruddy, D.A. “Catalysis to enable high-octane gasoline within a market- responsive bio-refinery concept”. Presented at the 28th International Materials Research Congress, Cancun, Mexico, August 19, 2019.
- A. To, et al., “Improving Long-chain Hydrocarbon Formation in DME Homologation over Cu/mesoporous-BEA catalysts”. Presented at AIChE Annual Meeting, Orlando, FL, Nov 11, 2019.
- D. Dupuis, et al., “Tuning the paraffin-to-olefin ratio in high-octane gasoline synthesis using bimetallic BEA zeolite catalysts”. Presented at AIChE Annual Meeting, Orlando, FL, Nov 14, 2019.
- J. Hensley, et al., “Triptane Production in a Pilot Reactor: Opportunities and Challenges”. Presented at AIChE Annual Meeting, Orlando, FL, Nov 12, 2019.
- D. Ruddy, R. Dagle, Z. Li, “Gasification pathways: Indirect Liquefaction (IDL) SOT”. Presented at BETO Quarterly Meeting, Washington, D.C., Feb 5, 2020.
- *Invited keynote*: D.A. Ruddy “Molybdenum carbide catalysts for biomass upgrading – from bulk to nanoscale”. Presented at the Catalysis Club of Chicago 2020 Symposium, Virtual Meeting, Aug 28, 2020.

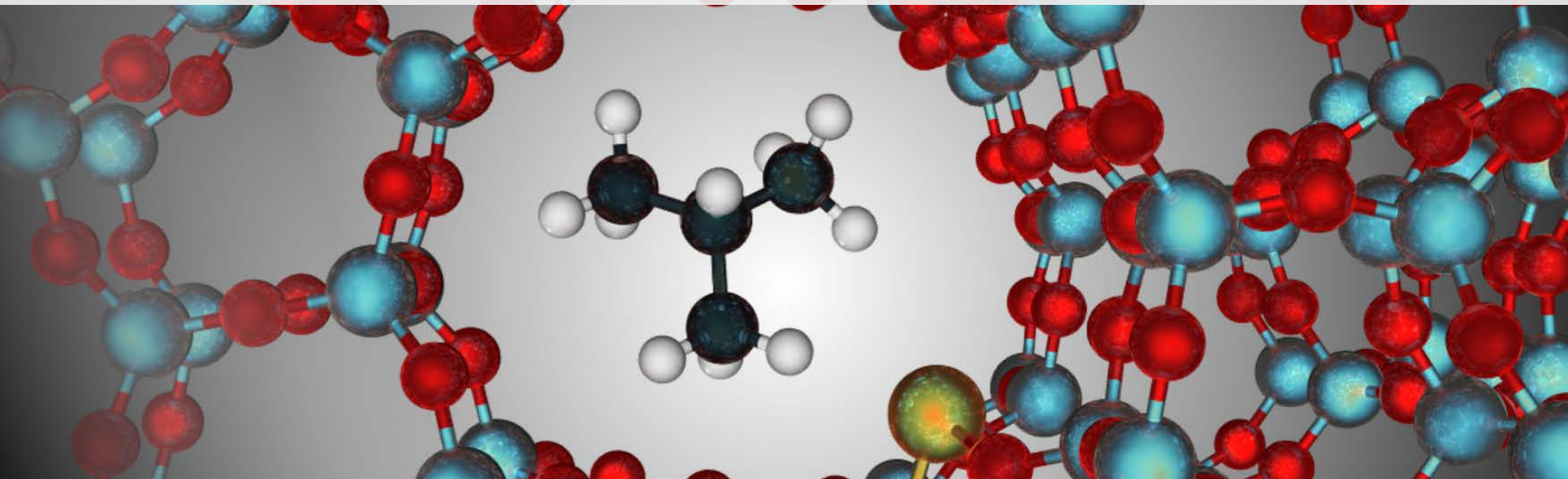
## Commercialization

- Research license to commercialize NREL high-octane gasoline technology, executed Jan 2020.

# *Methanol to HOG within a Market-Responsive Biorefinery Concept Enabled by Catalysis*

D. Ruddy, J. Hensley, C. Nash, E. Tan, E. Christensen, C. Farberow, F. Baddour, K. Van Allsburg, J. Schaidle

*Nature Catalysis* **2019**, 2, 632-640.



- Coupled process models and TEA with fundamental and applied catalysis research
- Quantified the impact of catalyst development on process economics for NREL's Cu/BEA catalyst in the production of HOG and jet fuel

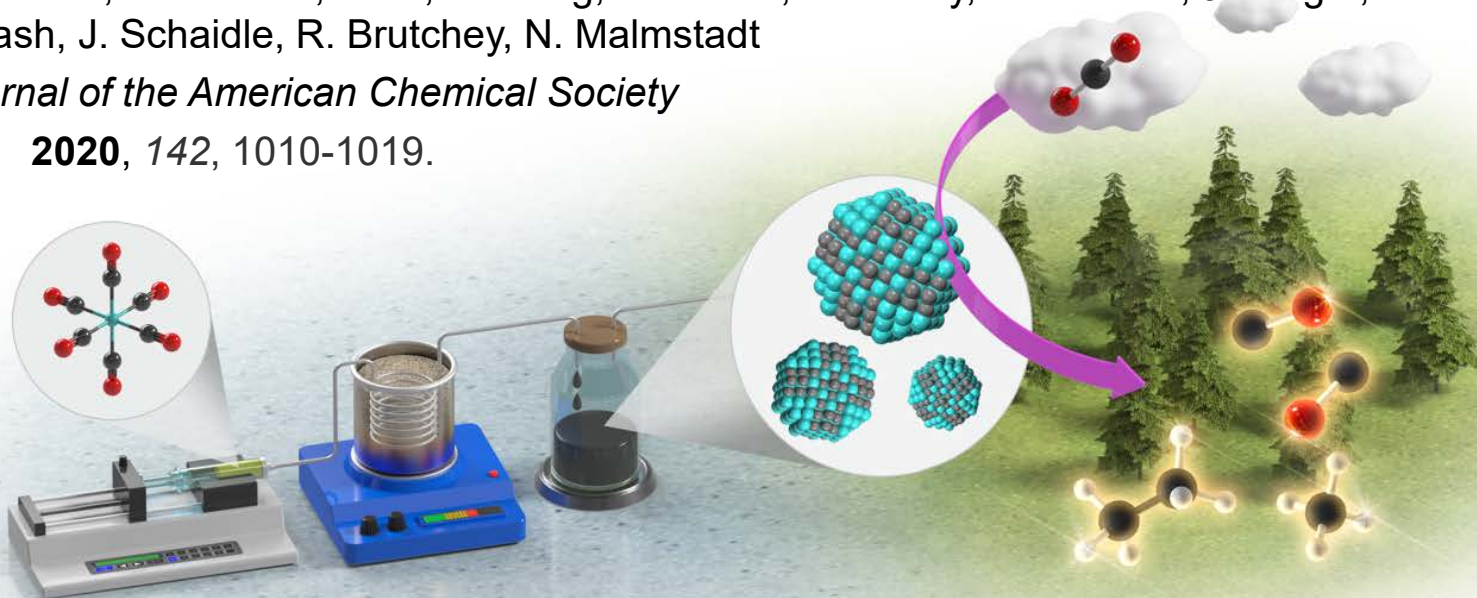


# An Exceptionally Mild and Scalable Solution-Phase Synthesis of Molybdenum Carbide Nanoparticles for Thermocatalytic CO<sub>2</sub> Hydrogenation

F. Baddour, E. Roberts, A. To, L. Wang, S. Habas, D. Ruddy, N. Bedford, J. Wright, C. Nash, J. Schaidle, R. Brutchey, N. Malmstadt

*Journal of the American Chemical Society*

**2020**, 142, 1010-1019.

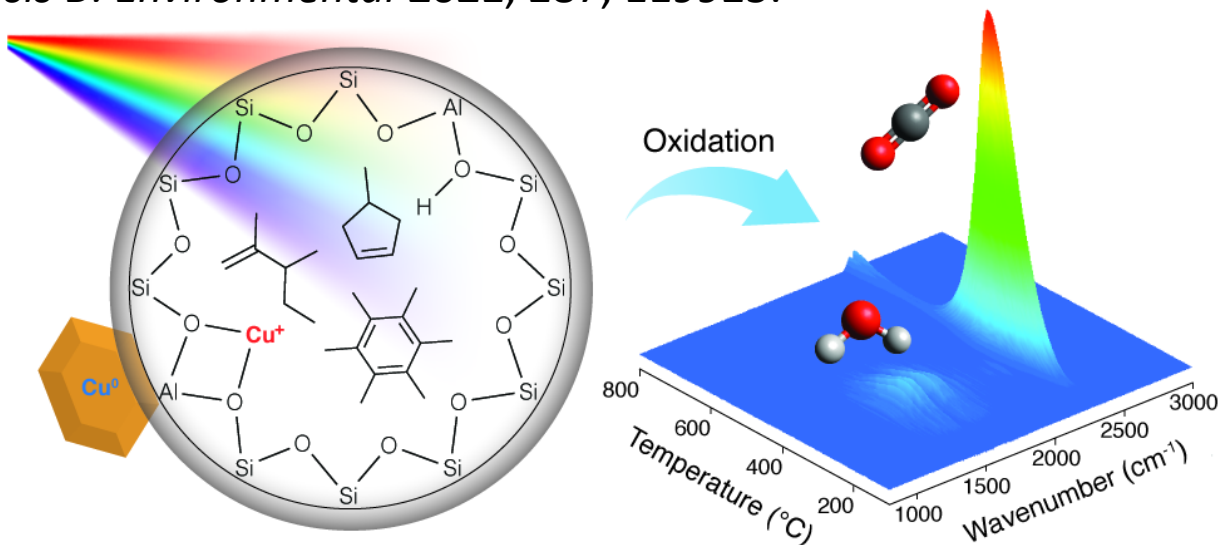


- New synthetic method to prepare colloidally-stable  $\alpha\text{-MoC}_{1-x}$  nanoparticles from a commercially-available, air-stable precursor at 300-320 °C
  - Previous approaches require reactive gases (CH<sub>4</sub>, H<sub>2</sub>) and thermal treatments >550 °C
- Translated the synthesis to a continuous millifluidic flow reactor, enabling 99% yield and production of up to 18.6 g of NP-MoC<sub>1-x</sub> product per 24 h, 450 g of 4 wt% catalyst
- NP-MoC<sub>1-x</sub> catalyst exhibited a 2X increase in per-site activity and 2X increase in C<sub>2+</sub> hydrocarbon selectivity versus bulk  $\alpha\text{-MoC}_{1-x}$  in CO<sub>2</sub> reduction reaction



# Spectroscopic insight into carbon speciation and removal on a Cu/BEA catalyst during renewable high-octane hydrocarbon synthesis

Q. Wu, A.T. To, C.P. Nash, D.P. Dupuis, F.G. Baddour, S.E. Habas, D.A. Ruddy  
*Applied Catalysis B: Environmental* **2021**, 287, 119925.



- Surface carbon species were identified and compared for BEA and Cu/BEA catalysts
- Cu/BEA had lower polycyclic aromatic content and more defective graphitic carbon
- Presence of Cu promoted carbon removal at lower temperature by activating O<sub>2</sub>
- In situ spectroscopy informed a regeneration procedure for Cu/BEA
- Activity of Cu/BEA for DME-to-HOG was fully recovered following developed procedure