# DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

## WBS 2.1.0.302
## Thermochemical Platform Analysis – NREL

Session: Catalytic Upgrading

Date: March 5, 2019

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National Renewable Energy Laboratory

# Acronyms Used

**BETO:** Bioenergy Technologies Office

**CFP:** Catalytic Fast Pyrolysis

**DME:** Di-Methyl Ether

**HOG:** High-Octane Gasoline

**LCA:** Life-Cycle Analysis

**MFSP:** Minimum Fuel Selling Price

**MYP:** Multi-Year Plan (BETO)

**SOT:** State of Technology

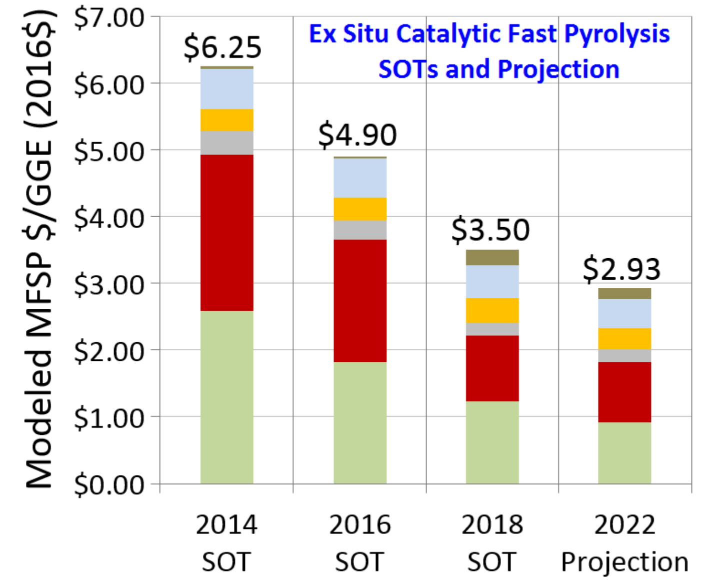
**TEA:** Techno-Economic Analysis

# Overview and Approach

# Goal Statement

Provide process design and techno-economic analysis (TEA) for thermal-catalytic conversion processes to inform and guide NREL/BETO R&D priorities

- Benchmark research goals through detailed models
- Track advancements in the State of Technology (SOT) and sustainability metrics based on experimental data
- Constant research feedback to and from TEA
- Build predictive TEA models




**Outcome: Enable technology viability and modeled cost reduction** through specific research improvements guided by TEA

**MFSP**: Minimum Fuel Selling Price. Technical and cost projection details at: https://www.nrel.gov/docs/fy19osti/71954.pdf

# Quad Chart Overview – NREL TC Platform Analysis

## Timeline (*current merit review cycle*)

| | |
|---|---|
| Start Date | October 1, 2016 |
| End Date | September 30, 2019 |
| % Complete | 80% (29 months of 3 years) |

## Budget (WBS 2.1.0.302):

| | FY14 – FY16 Costs | FY17 Costs | FY18 Costs | Planned FY19-End Date |
|---|---|---|---|---|
| **DOE Funded** | 4,452k | 1,553k | 1,115k | *768k* |
| **Cost Share** | No cost share (100% DOE-BETO funding) | | | |

†TEA: Techno-Economic Analysis, ‡LCA: Life-Cycle Assessment

## Key Barriers Addressed:

**Ct-F:** Yield from catalytic processes

**ADO-A:** Process integration

## Objective:

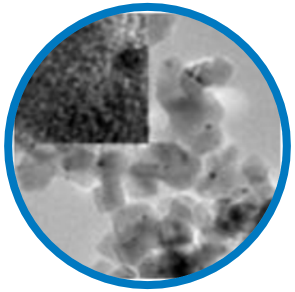
To inform and guide R&D priorities for thermal and catalytic conversion processes through process-design-based TEA† and LCA‡.

## Partners:

- NREL & ChemCatBio (expt. & research)
- PNNL (TEA/sustainability/hydrotreating)
- Idaho National Lab & FCIC (feedstock)
- Argonne National Lab (LCA)
- DWH Consulting (modeling / capital costs)
- NIST (phase equilibrium modeling)
- Consortium for Computational Physics and Chemistry (reactor modeling)
- Johnson Matthey (catalyst technologies)
- Petrobras (petroleum refiner) via CRADA

# Project Overview – Core Research & Supporting Work

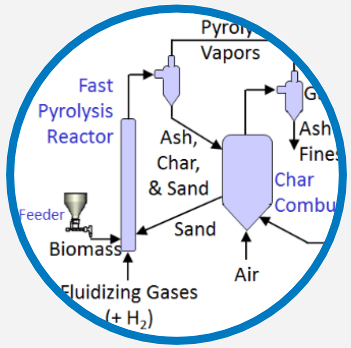
## Core Research Areas (Catalyst Development Driven)



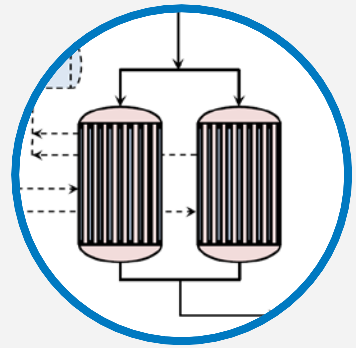
Catalyst R&D, Experimental Data, & Catalyst Cost

**Collaboration with**

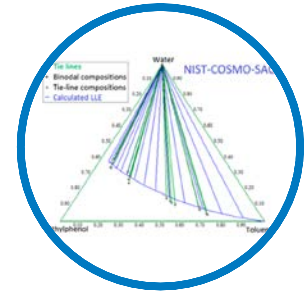
ChemCatBio & NREL Researchers, Johnson Matthey




Catalytic Fast Pyrolysis



Syngas Conversion



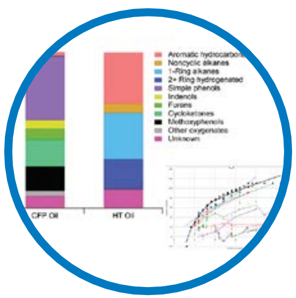
Predictive Phase Equilibrium

**Collaboration with**

NIST

**Emerging Technology Options**

(e.g. Co-processing, $CO_2$ upgrading)




Model Prediction of Fuel Quality & Experimental Data

**Collaboration with**

NREL Biomass Researchers and Fuels Group

Feedstock Specifications & Cost

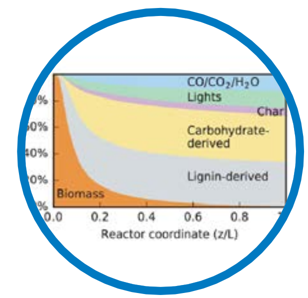
**Collaboration with**

Idaho National Laboratory

Sustainability & Life-Cycle Analysis

**Collaboration with**

Argonne National Laboratory




Reactor & Kinetic Modeling

**Collaboration with**

CCPC

Consortium for Computational Physics and Chemistry

# Technical Approach

## Rigor Based on Requirement and Stage of Research

Quick Turnaround Analysis → More Detailed Analysis → Detailed Design Report

## Tools Used and Other Inputs

| Aspen Plus | Excel | GREET ANL |
|---|---|---|
| **Process Model** | **Economics** | **Life-Cycle Analysis** |

- **Research Data:** Experiments, researchers, and literature
- **Capital & Operating Costs:** Literature, vendor quotes, Aspen Capital Cost Estimator
- **Financial and Feedstock Assumptions:** Consistent with BETO guidelines & related feedstock research

## Outputs

- **MFSP (Minimum Fuel Selling Price)** based on n$^{th}$ plant economics & financial assumptions
  - SOT (State of Technology)
  - Projections
- **Technical metrics** to achieve MFSP
- **Sustainability metrics** of the conversion process
- Full **LCA by ANL**
- Review comments and **feedback from stakeholders are incorporated**

**LCA:** Life-Cycle Assessment, **ANL:** Argonne National Laboratory

# Management Approach

**Annual Operating Plan, Milestone Driven**
All Milestones Executed on Time
→ Listed in Additional Slides

## Critical Success Factors

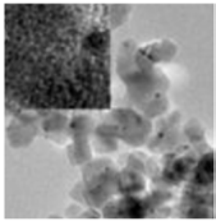
- Impactful research: technical & cost goals
- Use critical feedback from stakeholders
- Provide alternative R&D strategies
- Assess & enable infrastructure integration for commercial relevance

## Technical Challenges [mitigation]

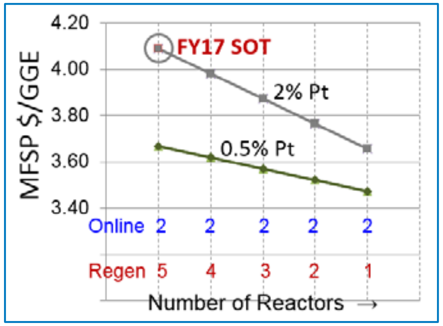
- **Limited data** [sensitivity analysis]
- **Provide alternate R&D approaches** [versatile models with adaptability]
- **Rigor vs speed** [impact-specific efforts]
- **Predictive modeling** [strategic partnerships]

**Example of Interaction with Research to Reduce CFP MFSP from FY17 to FY18**

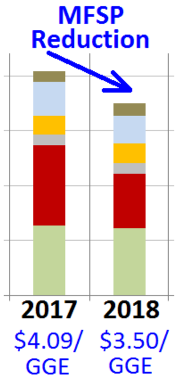
New Fixed Bed CFP Catalyst in FY17



TEA-Identified Cost Drivers
- Pt loading
- Online/regeneration time



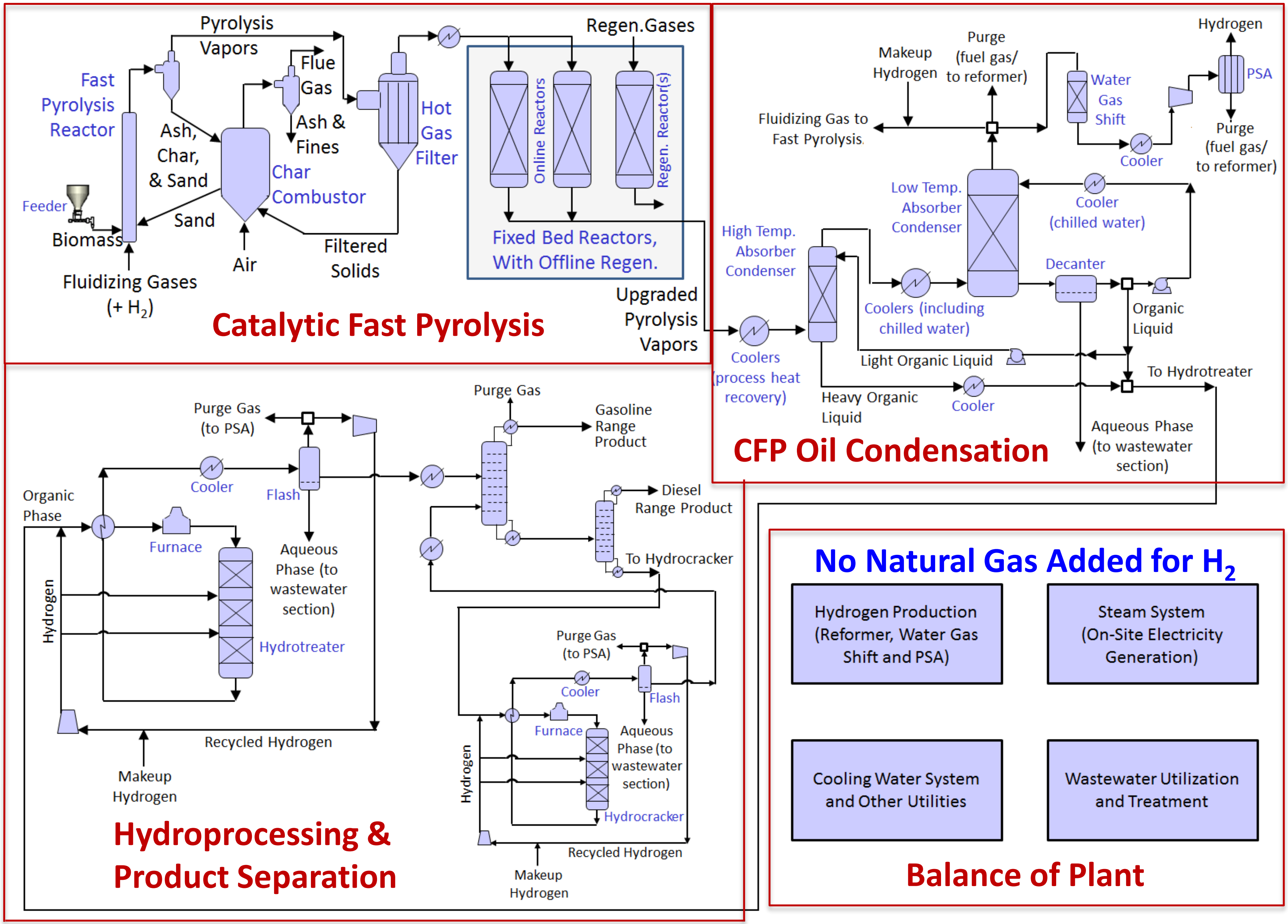

Implemented by Research
- Lower Pt loading
- Shorter regeneration time




**CFP:** Catalytic Fast Pyrolysis, **MFSP**: Minimum Fuel Selling Price, **TEA:** Techno-Economic Analysis, **SOT:** State of Technology

# Technical Progress and Accomplishments

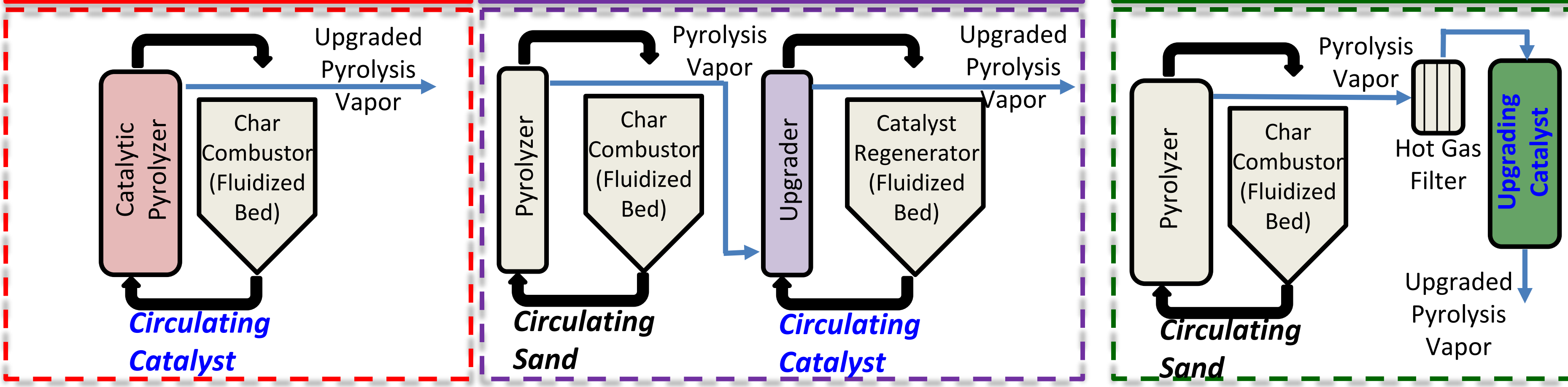
# Fixed Bed *Ex Situ* CFP Conceptual Process




**Details at:** https://www.nrel.gov/docs/fy15osti/62455.pdf and https://www.nrel.gov/docs/fy19osti/71954.pdf

# CFP Technology Options

| *In Situ* CFP | *Ex Situ* Entrained Bed CFP | *Ex Situ* Fixed Bed CFP |
|---|---|---|




| Modified Zeolites and Metal Oxide Catalysts | Catalyst Flexibility |
|---|---|

- Lower capital investment
- Operating conditions tied to fast pyrolysis
- Catalyst mixed with biomass, char, and ash
- Higher catalyst replacement rates

- Operating conditions can differ from fast pyrolysis
- Biomass, ash, and char are reduced or removed; more benign environment for catalyst
- Higher capital investment
- Lower catalyst replacement rates

- More diverse catalysts are feasible
- Access to greater catalytic chemistry
- Long catalyst lifetimes required
- Hot gas filter required
- Limited coking allowable

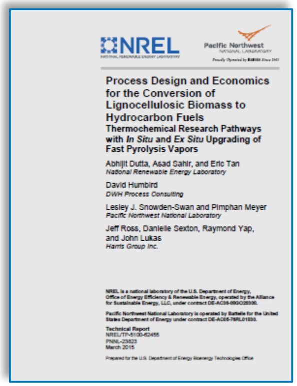
**Hybrids of all or some of these systems are also possible**

**CFP:** Catalytic Fast Pyrolysis

# CFP Timeline and Accomplishments

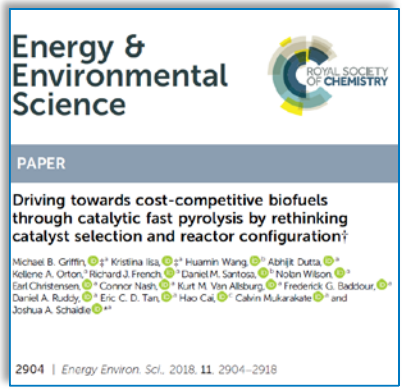
## Timeline of CFP Technology Development Guided by TEA

| FY 2014-2015 | FY 2016 | FY 2018 | FY 2018-2019 |
|---|---|---|---|
| (Design Report) | (Journal Article) | (Journal Article) | (Technical Report) |
| ***In Situ* & *Ex Situ* CFP in Fluidized Systems** | ***Ex Situ* Fixed Bed for Yield Risk Mitigation** | **Publish Cost Reduction via New Catalyst** | **Update Technical & Cost Goals for 2022** |
| 2022 Goals | More Catalyst Options | Fixed Bed Results | Achieve <$3.00/GGE |




https://www.nrel.gov/docs/fy15osti/62455.pdf


https://link.springer.com/article/10.1007/s11244-015-0500-z




Energy Environ. Sci., 2018, 11, 2904


https://www.nrel.gov/docs/fy19osti/71954.pdf

**CFP:** Catalytic Fast Pyrolysis, **TEA:** Techno-Economic Analysis

# *Ex Situ* Catalytic Fast Pyrolysis – Progress

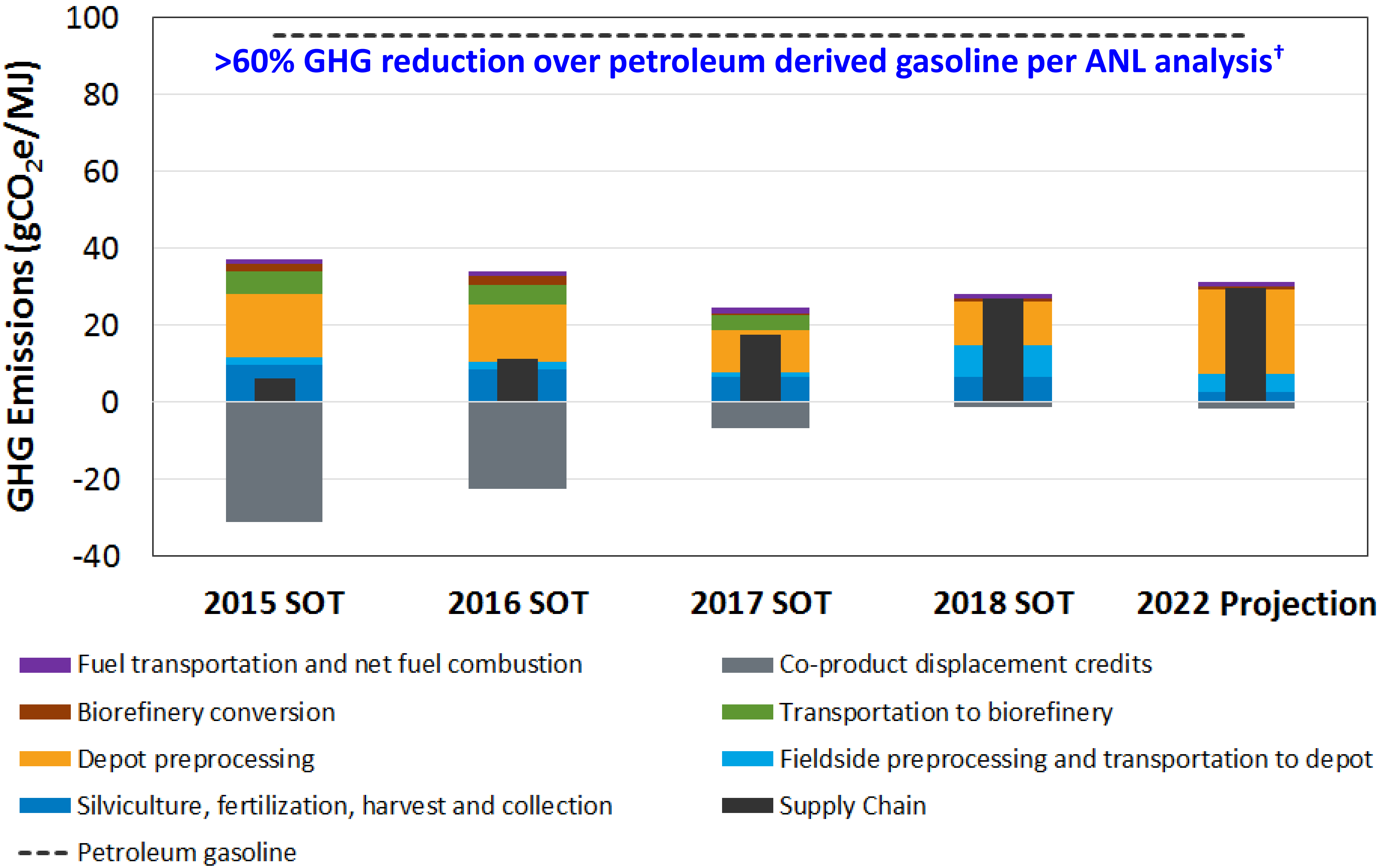
**TEA-Guided Modeled-Cost Reduction from $4.90/GGE in 2016 to $3.50/GGE in 2018**

| Process Parameter | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2022 Projection |
|---|---|---|---|---|---|---|
| **Key Improvements** | **Yield improvements in fluidized system through catalyst and process modifications** | | | **2%Pt/$TiO_2$ in fixed bed. Large yield increase** → | **Reduced to 0.5% Pt, faster catalyst regen.** | **Higher yield, use lower cost feed, scale-up, robust long-life catalyst** |
| Vapor Products | ***Fluidized system for 2014-2016 SOT*** → ***Fixed bed system for 2017-2022 Models*** | | | | | |
| Non-Condensable Gases | 35 | 36 | 34 | 31 | 31 | 31 |
| Aqueous Phase (% C Loss) | 25 (2.9) | 25 (2.9) | 24 (3.4) | 27 (2.9) | 23 (5.0) | 23 (3.0) |
| Solids (Char + Coke) | 12 + 11 | 11 + 9.5 | 12 + 8.3 | 10.4 + 3.3 | 11.7 + 3.3 | 11.7 + 3.2 |
| Organic Phase | 17.5 | 18.6 | 21.8 | 28.3 | 30.8 | 31.4 |
| H/C Molar Ratio | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 |
| Carbon Efficiency (%) | 27 | 29 | 33 | 42 | 45 | 47 |
| Oxygen Content (% of organic) | 15.0 | 13.3 | 16.8 | 16.5 | 18.5 | 16.4 |
| Hydroprocessing C Eff. (% of org.liq.) | 88 | 90 | 87 | 91 | 89 | 91 |
| Carbon Eff. to Fuel Blendstocks (%) | 23.5 | 25.9 | 28.3 → | 38.1 | 39.7 | 42.3 |
| Energy Efficiency to Fuels (% LHV) | 30.4 | 33.4 | 37.0 | 50.2 | 52.1 | 56.1 |
| Diesel-Range Product (% GGE basis) | 15 | 15 | 15 | 52 | 52 | 52 |
| Minimum Fuel Selling Price ($/GGE) | $6.25 | $5.45 | $4.90 → | $4.09 → | $3.50 | $2.93 |

**Note:** All costs are presented in 2016$. **Reference:** https://www.nrel.gov/docs/fy19osti/71954.pdf. **SOT:** State of Technology

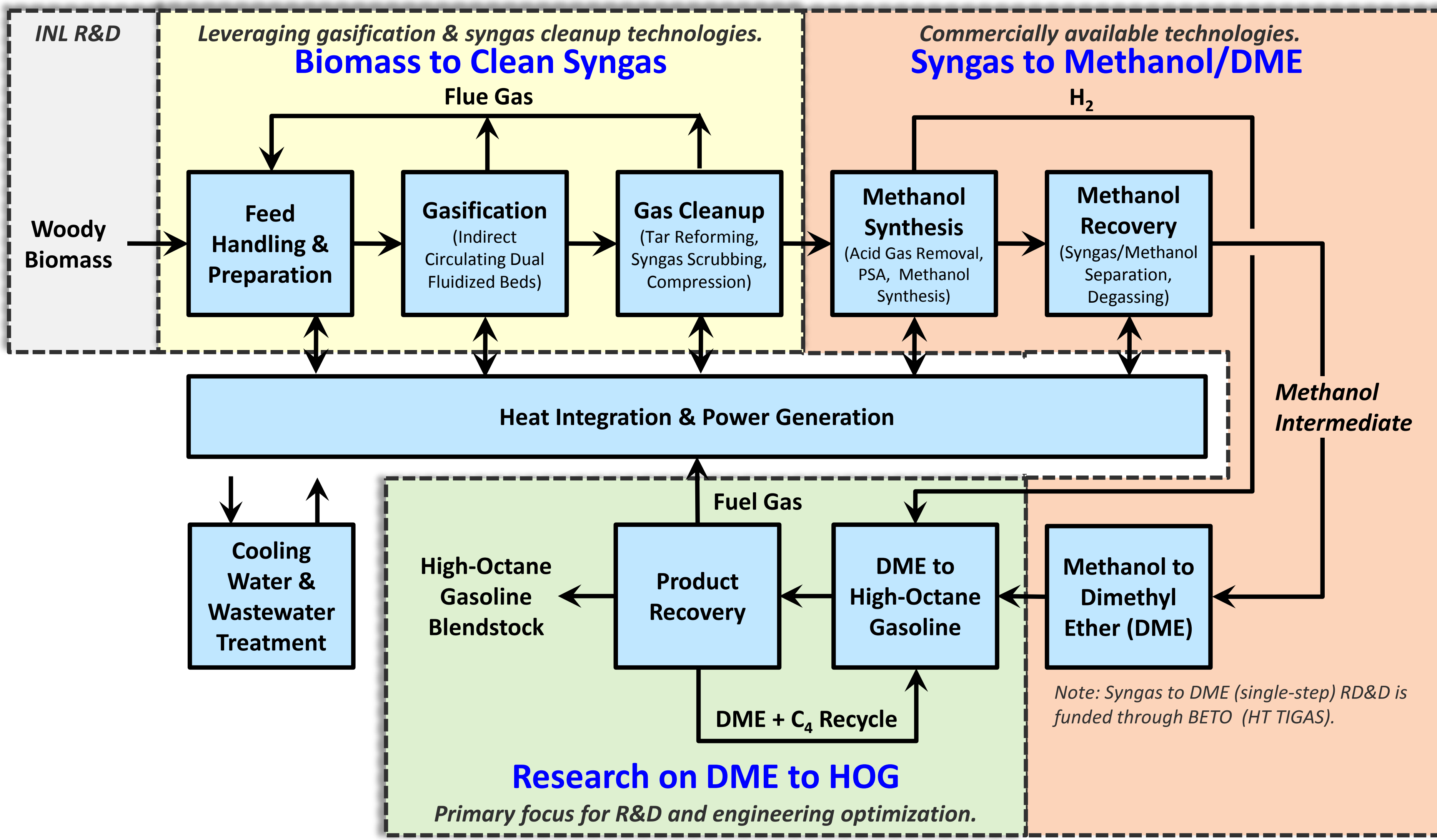
# *Ex Situ* CFP – Sustainability

****Other Sustainability Metrics for Conversion Process in Additional Slides****



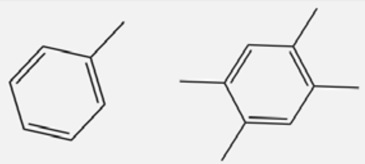
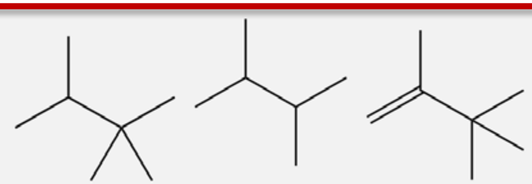

† **Reference:** Cai et al. Argonne National Laboratory report, ANL/ESD-18/13, 2018. **SOT:** State of Technology

# Syngas to High-Octane Gasoline Conceptual Process




**HOG:** High-Octane Gasoline. **Details at:** https://www.nrel.gov/docs/fy15osti/62402.pdf and https://www.nrel.gov/docs/fy19osti/71957.pdf

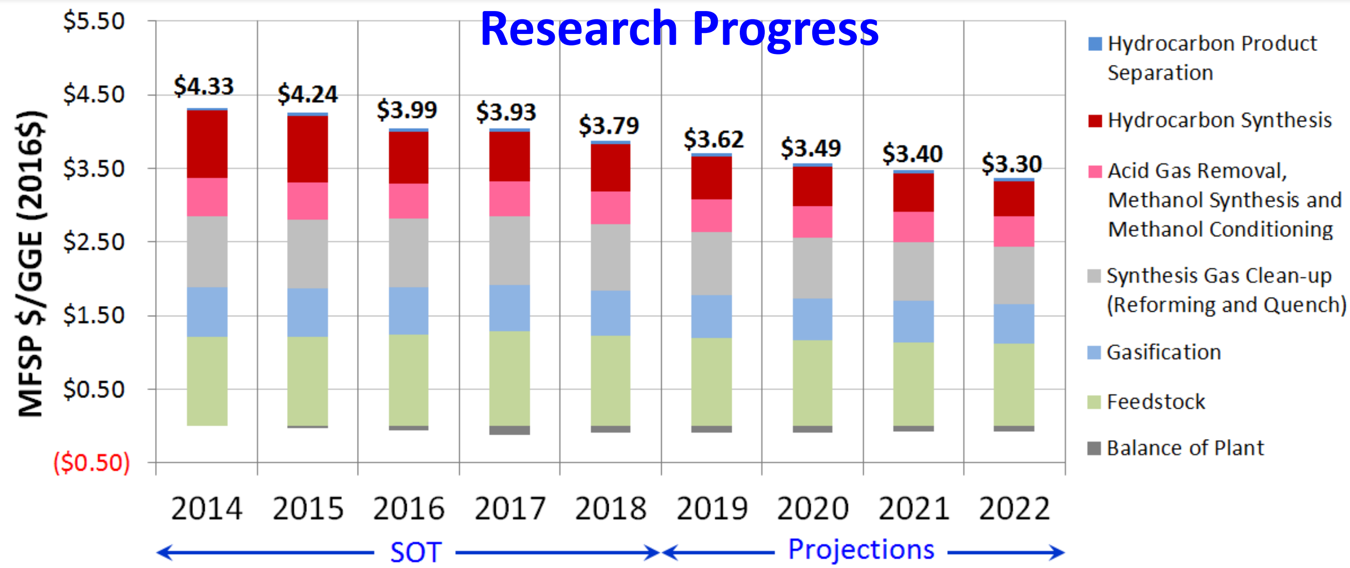
# High-Octane Gasoline vs. Traditional MTG

| Methanol to Gasoline (MTG) Pathway | High-Octane Gasoline (HOG) Pathway | Advantage of HOG Pathway |
|---|---|---|
|  |  | ***Branched HC product, minimal aromatics*** |
| **ZSM-5 catalyst** | **Beta-zeolite catalyst** | |
| **350 – 500 °C**<br>**20 atm** | **175 – 225 °C**<br>**1-10 atm** | ***Lower severity conditions, lower coking rate*** |
| **RON: 92**<br>**MON: 83** | **RON: 95+**<br>**MON: 90+** | ***High octane synthetic alkylate*** |
| **100 gal*** | **118 gal*** | ***Higher yield (18%)*** |

***relative yield from same carbon source**

**MTG:** Methanol to Gasoline

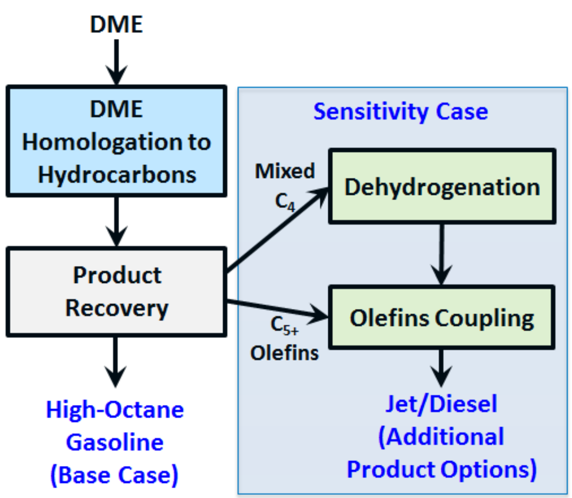
# Syngas Conversion to High-Octane Gasoline (HOG)

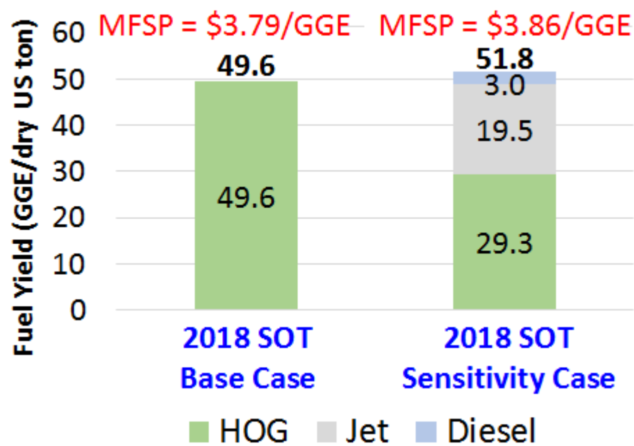



## Analysis of $CO_2$ Utilization & Quantification of Future Opportunities

- Benefits of **process intensification**
- Use of low-cost feedstock and **bio-gas** utilization
- Supplemental **renewable electricity and hydrogen**

## Analysis to Help Expand Product Options to Jet/Diesel




**References:** https://www.nrel.gov/docs/fy15osti/62402.pdf and https://www.nrel.gov/docs/fy19osti/71957.pdf. **SOT:** State of Technology

# Syngas to High-Octane Gasoline – Progress

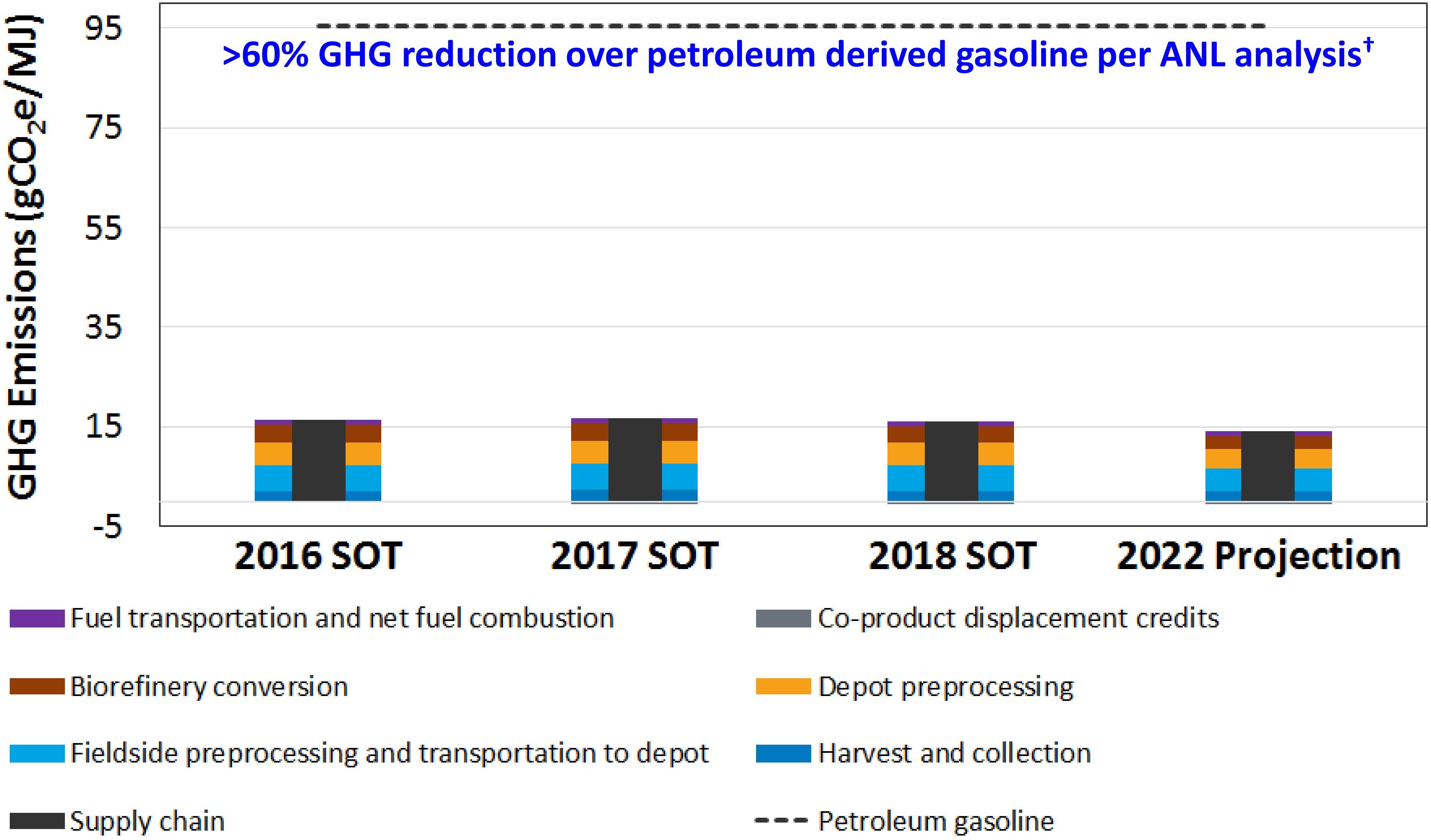
**TEA-Guided Modeled-Cost Reduction from $3.99/GGE in 2016 to $3.79/GGE in 2018**

| Process Parameter | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2022 Design |
|---|---|---|---|---|---|---|
| Hydrocarbon Synthesis Catalyst | Commercially available beta-zeolite | | **NREL beta-zeolite modified with promoter metal(s)** → | | | |
| $H_2$ Addition to HC Synthesis | No | Yes → | | | | |
| Utilization of $C_4$ Reactor Products | Co-Product | | **Recycle to Synthesis Reactor** → | | | |
| Single-Pass DME conversion | 15% | 15% | 19.2% → | 27.6% → | 38.9% | 40% |
| Productivity of Hydrocarbon Synthesis Catalyst (kg/kg-cat/h) | 0.02 | 0.03 | 0.04 | 0.09 | 0.07 | 0.10 |
| Carbon Selectivity to $C_5$+ Product | 46.2% | 48.3% | 81.8% → | 74.8% → | 72.3% | 86.7% |
| Carbon Selectivity to Aromatics (HMB represents coke / pre-cursers) | 25% Aromatics (10% HMB) | 20% Aromatics (9% HMB) | 4% Aromatics (4% HMB) | 4% Aromatics (4% HMB) | 8% Aromatics (4% HMB) | 0.5% as HMB |
| Coupling of $C_4$-$C_8$ Olefins to Jet | No | ← Sensitivity Scenarios → | | | | |
| $C_5$+ Product Yield (Gallons / Ton) | 36.2 | 36.4 | 51.4 | 50.0 | 51.4 | 56.0 |
| Carbon Efficiency to $C_5$+ Product | 19.3% | 19.4% | 25.2% | 24.3% | 25.5% | 27.9% |
| $C_4$ Product Yield (Gallons / Ton) | 16.3 | 16.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Carbon Efficiency to $C_4$ Product | 7.0% | 6.9% | 0.0% | 0.0% | 0.0% | 0.0% |
| Minimum Fuel Selling Price ($ / GGE) | $4.33 | $4.24 | $3.99 → | $3.93 → | $3.79 | $3.30 |
| Conversion Impact to MFSP ($ / GGE) | $3.13 | $3.03 | $2.76 | $2.64 | $2.56 | $2.18 |

**Note:** All costs are presented in 2016$. **Reference:** https://www.nrel.gov/docs/fy19osti/71957.pdf. **SOT:** State of Technology

# Syngas to High-Octane Gasoline – Sustainability

****Other Sustainability Metrics for Conversion Process in Additional Slides****




† **Reference:** Cai et al. Argonne National Laboratory report, ANL/ESD-18/13, 2018. **SOT:** State of Technology

# Milestones and Some Other Highlights

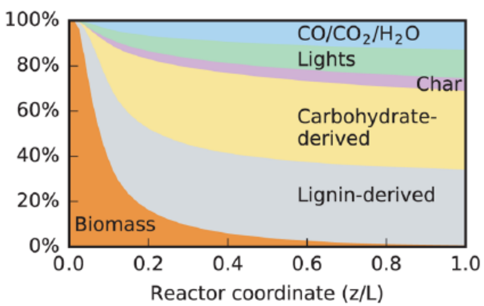
## Milestones & Publications

- All milestones completed (see additional slides for complete list)
  - Go/No-Go: Identify a path to <$3.00/GGE by 2022, with potential for <$2.50/GGE by 2030
- Publications listed in additional slides

## Support of Work Related to Catalytic Conversion

- Biological and catalytic upgrading of CFP aqueous phase
- Separations consortium, FCIC, Co-Optima, ChemCatBio and others

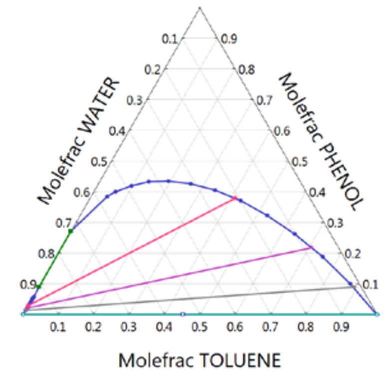
## Entrained Flow Reactor Models for Pyrolysis and Gasification




- Compatible with process simulations
- Ability to include kinetics being developed by the CCPC*
- Helps understand flow and scaling assumptions for process modeling

**Reference:** ACS Sustainable Chem. Eng. 2017, 5, 3, 2463-2470.
***CCPC:** Consortium for Computational Physics and Chemistry

## Integration of Predictive Phase Equilibrium Models from NIST



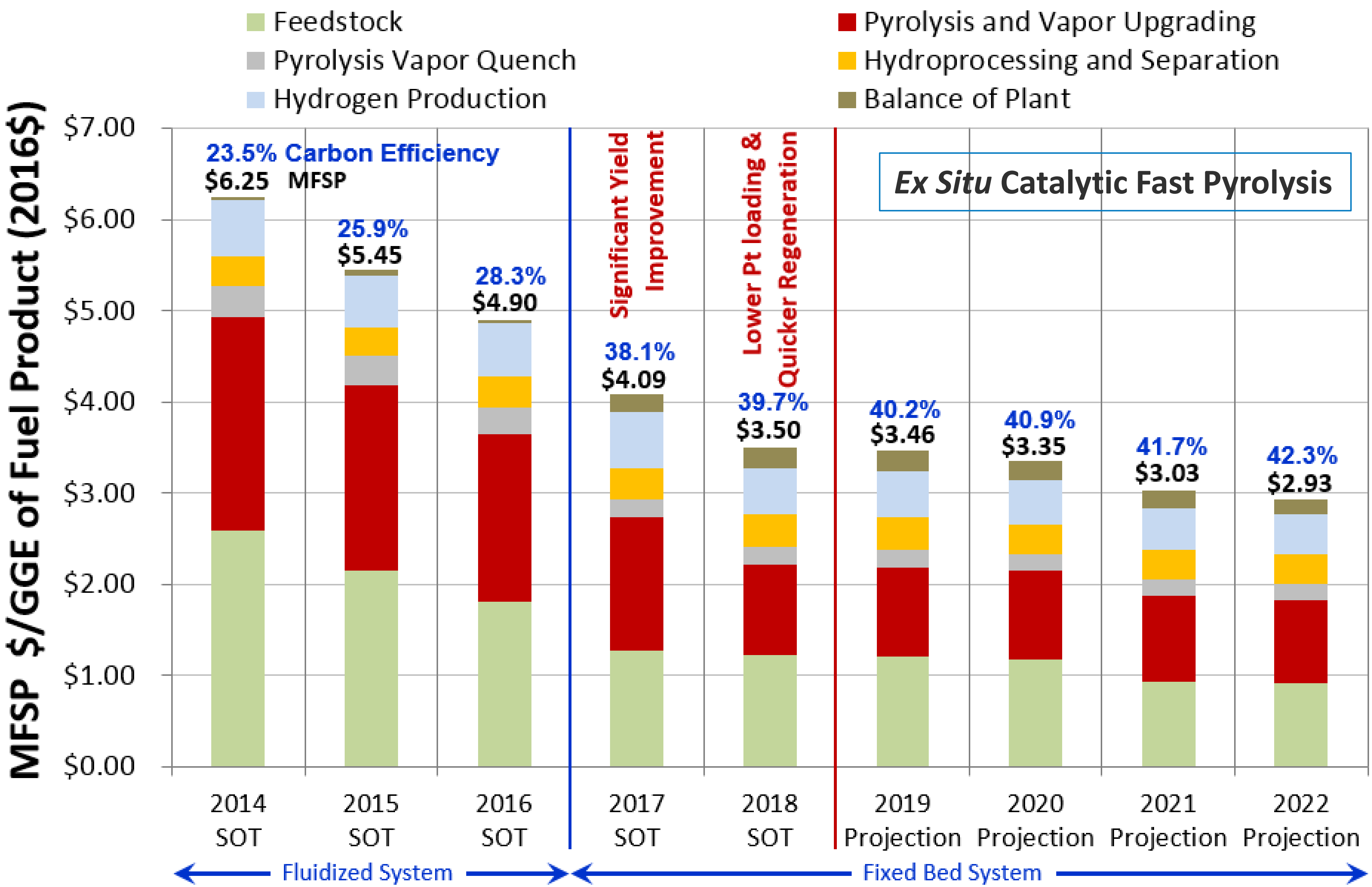

Example of Ternary Diagram for Liquid-Liquid Equilibrium in Aspen Plus using the NIST-COSMO-SAC *Fully Predictive Model*.

Previous Pub: J. Chem. Eng. Data 2017, 62, 1, 243-252

# Relevance

# Provide Research Specifics for Achieving < $3.00/GGE

**Associated Technical Parameters and Sustainability Metrics in Additional Slides**

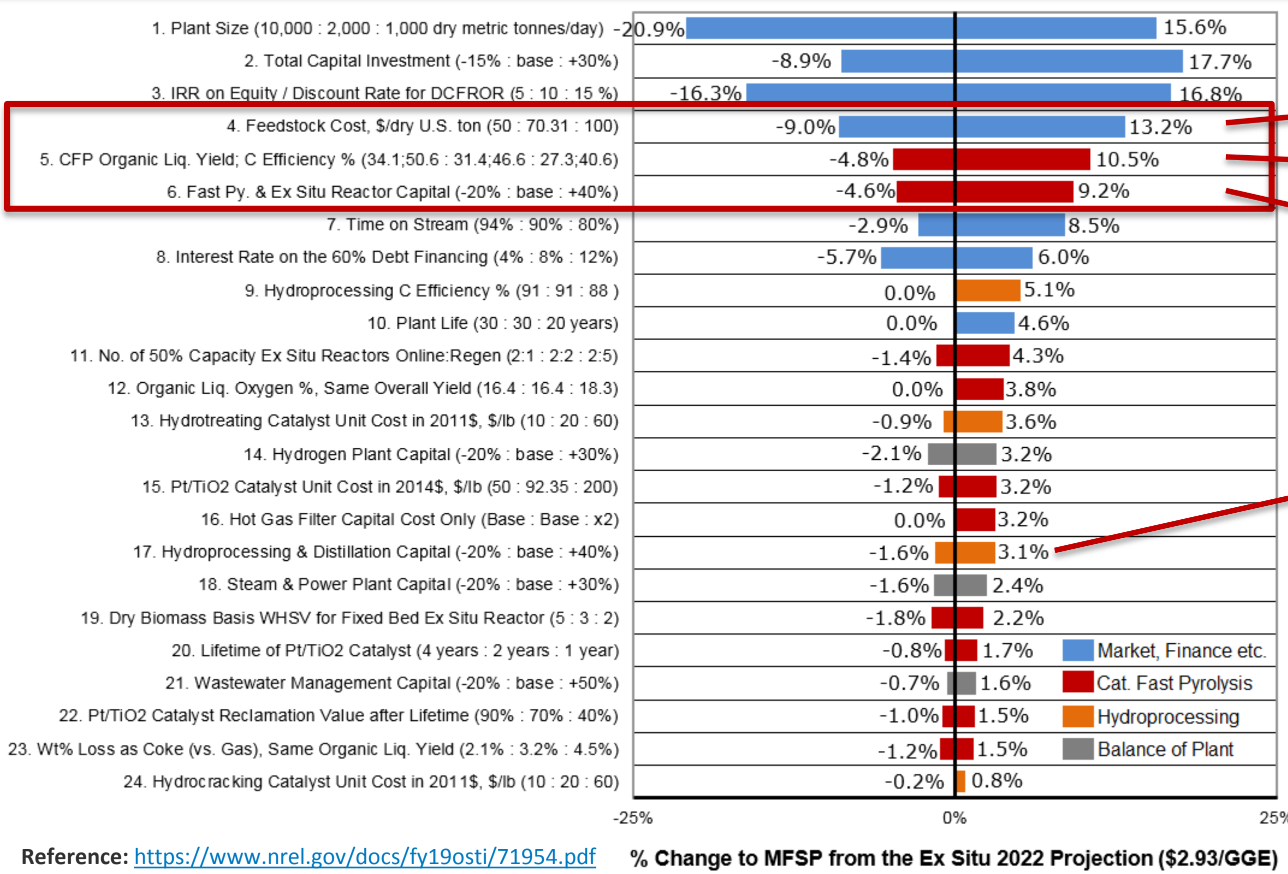



**MFSP**: Minimum Fuel Selling Price. **SOT:** State of Technology. Reference: https://www.nrel.gov/docs/fy19osti/71954.pdf

# Enabling Productive Research under BETO

- Detailed analysis for **lowering costs**
- **Sensitivity** analysis and **options** for impactful research
- Deliberate attention towards enabling **future commercial implementation**

## E.g. CFP (Catalytic Fast Pyrolysis) Sensitivity Analysis




**Reference:** https://www.nrel.gov/docs/fy19osti/71954.pdf

**Biggest Research Impacts:**
- **Feedstock**
- **CFP Carbon-Efficiency**
- **CFP Capital**

**Hydroprocessing** is important, but **not the biggest cost driver** (because of upfront CFP)

# Relevance to Industry and Other Stakeholders

## Work Towards **Commercial Viability** & **Product Compatibility**

- **Cost reduction** to enable adoption
- **Product quality improvement** (e.g. cetane and octane)
  - Analysis for quality improvement to make fuel products more attractive
- Tailor intermediates towards higher value
  - Quantify **requirements for refinery integration** of CFP oil
- **Analysis for scale-up**
  - Direct support to facilitate pilot verification
  - Model projections for commercial implementation

## **Direct Use of Analysis Products** by Industry, Academia, & National Labs.

- Detailed **reports and journal articles** to enable related research
- Simplified *in situ* and *ex situ* CFP **TEA models made publicly available**

**Related requests are received on a regular basis**

# Future Work

# Future Goals

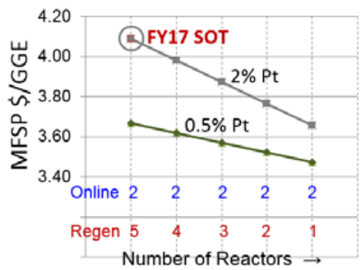
**Develop for Future Commercial Implementation**
**Achieve Modeled MFSP of <$3.00/GGE by 2022, and potentially $2.50/GGE by 2030 (in 2016$)**

**2019-2022**

Enable use of lower quality **feedstock**

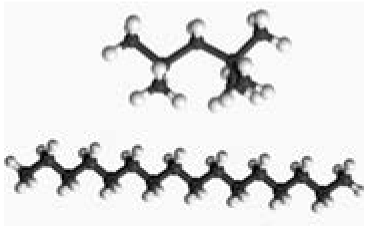
**2019-2022**

**Catalyst robustness** & **scale-up** of CFP




**2019-2022**

Improve CFP **fuel** blendstock **quality**



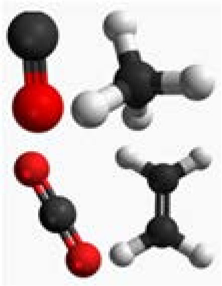
**2019-2030**

**Higher yields** and carbon-efficiency

ChemCatBio
Chemical Catalysis for Bioenergy

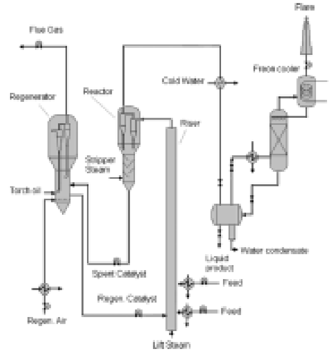
**2019-2030**

Efficient utilization of **light gases**



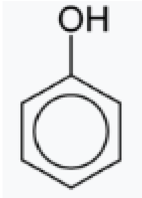
**2019-2025**

Refinery **co-processing** to lower capital cost




**2022-2030**

Develop CFP & other **co-product** options




**2022-2030**

Facilitate direct blend of **CFP oil into fuel**

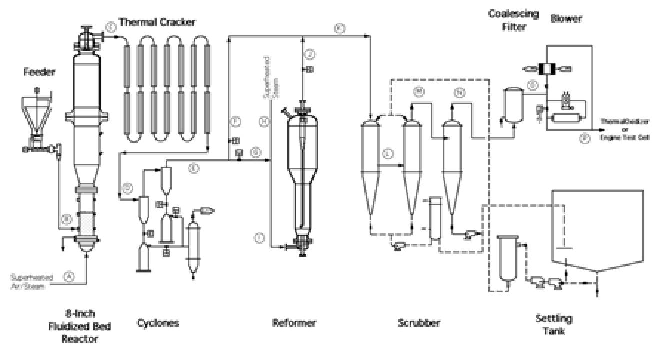
Co-Optimization of Fuels & Engines

# Future Milestones and Decision Points

## Proposed Go/No-Go (March 2021)

(**For Pilot Verification of <$3.00/GGE in 2022**)

NREL Thermochemical Pilot Plant

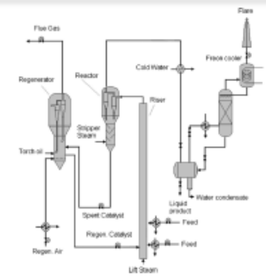



Use all available experimental results to assess the chances of success for demonstrating a modeled fuel cost of <$3.00/GGE during the 2022 verification

- Identify any gaps
- Provide options for additional cost reduction (necessary if falling short of verification goals)

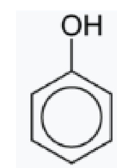
## Some Longer Term Work

(**For Refinery Integration & Co-Products**)



**Refinery integration** of CFP streams:

- TEA for most promising options
- Quality & CFP processing requirements
- Identify metrics for success




Development of **CFP co-products**:

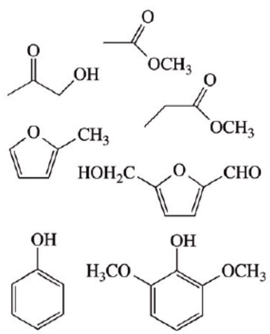
- TEA for identified co-products
- Identify selectivity & separation goals

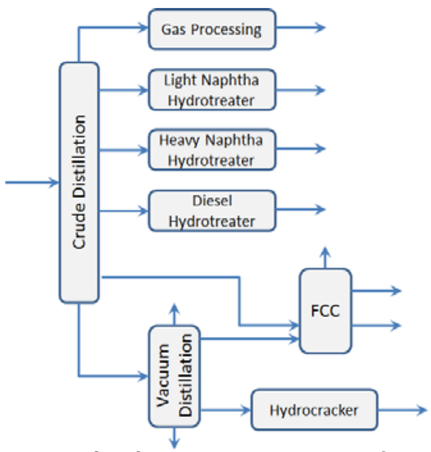
****Proposed Future Milestones and Go/No-Go included in Additional Slides****

(proposed milestones beyond FY19 will be subject to merit review)

# Some Specific Enablers for TEA

## **Chemistry-Based TEA Modeling** for **Conversion Technologies** and **Refinery Integration** of CFP Fuels

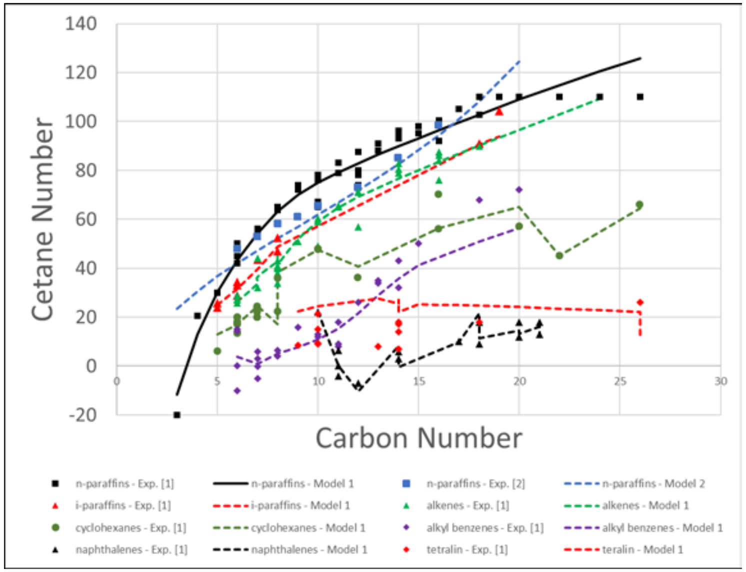





Integrate experimental chemistry and related models into TEA:

- Effective feedback for catalyst development goals
- Quantify refinery co-processing requirements for integration

## Tracking & Driving **Fuel Quality**




**Models used are from literature**

Implement integrated process model tracking of key fuel quality attributes with experimental speciation. Aim for predictive capability of fuel properties

**Identify synergistic use of multiple technologies for more effective biorefineries**

# Summary

# Summary

- **Overview and Approach:**
  - **State-of-the art process modeling** for TEA (includes predictive capabilities)
  - Advancements via **management plan for research** and **impactful feedback**
  - Key **success factors**: **Impactful research & future commercial implementation**
- **Technical Progress and Accomplishments** *(all milestones were met)*
  - Significant **TEA-guided advancements** for CFP – **effective research options**
  - Additional **product options** analyzed for **jet/diesel** from syngas
    - Analysis of **process intensification**, utilization of **$CO_2$**, **biogas**, **renewable $H_2$ & electricity**
- **Relevance**
  - **Directly enables** BETO goal of **<$3.00/GGE** by 2022
  - Analysis **feedback and options** used **for effective research**
  - **Commercial relevance:** Cost reduction, product compatibility, scale-up
  - Detailed **analysis products**, including **example models externally available**
- **Future Work** *(proposed future milestones & go/no-go in additional slides)*
  - **TEA for continued cost reduction** for CFP and syngas pathways
  - **Go/No-Go** for success of the <$3.00/GGE verification

**CFP:** Catalytic Fast Pyrolysis, **TEA:** Techno-Economic Analysis

# Acknowledgements


**DOE BETO** for funding and support

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**Johnson Matthey**

**ChemCatBio**

**Consortium for Computational Physics and Chemistry (CCPC)**

**Co-Optima**

**Petrobras**

**Separations Consortium**

# Additional Slides for Reviewers

# Additional Slides – Table of Content

- **Project Abstract and PI Biography**
- **Milestones & Go/No-Go (completed and future)**
- **Responses to 2017 Peer Review Comments**
- **Additional Technical Content - CFP**
- **Additional Technical Content – Syngas to HOG**

# Project Abstract and PI Biography

## NREL Thermochemical Platform Analysis (WBS 2.1.0.302)

The objective of the NREL Thermochemical Platform Analysis (WBS 2.1.0.302) project is to inform and guide R&D priorities for thermal and catalytic conversion processes by providing process design and techno-economic analysis (TEA). This is achieved through close collaboration with researchers and external experts, along with the use of both commercially-available modeling tools and the development or use of partner-developed domain-specific tools and resources, such as refinery integration, kinetic and reactor models, phase equilibrium models, and pertinent bio-products market studies.

This project is directly aligned with DOE-BETO goals; this includes the reduction of projected conversion costs for biomass derived fuels and products by enabling research advancements. TEA-guided research has helped achieve significant modeled cost reductions for the *ex situ* catalytic fast pyrolysis (CFP) pathway since the previous peer review in 2017 and we have identified specific research steps to help reduce the modeled Minimum Fuel Selling Price (MFSP) to <$3.00/GGE by 2022. Further cost reduction through refinery integration, development of valuable co-products, and other options are being identified for future research to help reduce the modeled MFSP to $2.50/GGE by 2030. Additional priorities anticipated in the future, such as the use of renewable electricity for liquid fuels and products, and emphasis on waste utilization are also being explored in conjunction with research on catalytic utilization of syngas and other gases. Industry-relevant parameters are given deliberate attention as part of the work done under this project to help answer questions important for future commercialization.

## Abhijit Dutta, Principal Investigator

Abhijit Dutta is a senior engineer in the National Bioenergy Center (NBC) at the National Renewable Energy Laboratory (NREL). He has a Master’s degree in Chemical Engineering with more than 20 years of experience in process engineering and simulator development. His expertise includes process modeling and techno-economic analysis for thermal and catalytic conversion processes. He has led the analysis work for the Thermochemical Platform Analysis (NREL) project for nearly a decade and has multiple publications based on his work at NREL. Prior to joining NREL, Dutta worked at Bloom Energy and Aspen Technology on process control and simulator development.

NREL Employee Webpage: https://www.nrel.gov/research/abhijit-dutta.html

# Milestones (FY2017)

**All milestones completed on time**

| **Milestone Description** | **Type<br>Due Date<br>Status** |
|---|---|
| FY16 State of Technology (SOT) Assessments: Develop and report on SOT assessments for the (i) ex situ catalytic fast pyrolysis and (ii) IDL high octane gasoline (HOG) pathways with respect to the FY2016 cost targets of (i) $5.34/GGE and (ii) $3.95/GGE, respectively (2014 dollars). Technical, economic and sustainability metrics from the SOT analyses are published in the BETO MYPP. | Quarterly<br>11/11/2016<br>Completed |
| Quick-Turnaround Analysis (QTA) Proof-of-Concept: Demonstrate proof-of-concept with an initial QTA model, propose options for next steps, and confirm future scope with BETO. The model will be developed as simplified pathway analysis tool(s) to enable users to quickly estimate the impact of conversion process improvements from emerging R&D on costs and sustainability of biomass-derived fuels and co-products. | Quarterly<br>3/31/2017<br>Completed |
| Kinetic Model for DME Homologation: Develop a kinetic model for DME homologation on a Cu-modified BEA catalyst with parameters estimated by fitting the model to bench-scale kinetic data. The model will describe DME conversion and the rate of production of (1) the C2-C3 fraction, (2) the C4 fraction and (3) gasoline range hydrocarbons (C5+) over the range of conditions (i.e., temperatures and pressures) studied experimentally. This work will serve as the basis for the kinetic model for DME homologation on a Cu-modified BEA catalyst, which will be completed and incorporated into the Aspen Plus process model used for techno-economic analysis in FY18. | Quarterly<br>6/30/2017<br>Completed |
| FY17 State of Technology (SOT) Assessments: SOT assessment(s) for at least one of two pathways (i) ex situ catalytic fast pyrolysis and (ii) IDL high octane gasoline (HOG) pathways with respect to the FY2017 cost targets of (i) $4.67/GGE and (ii) $3.80/GGE, respectively (2014 dollars). | **Annual**<br>9/30/2017<br>Completed |

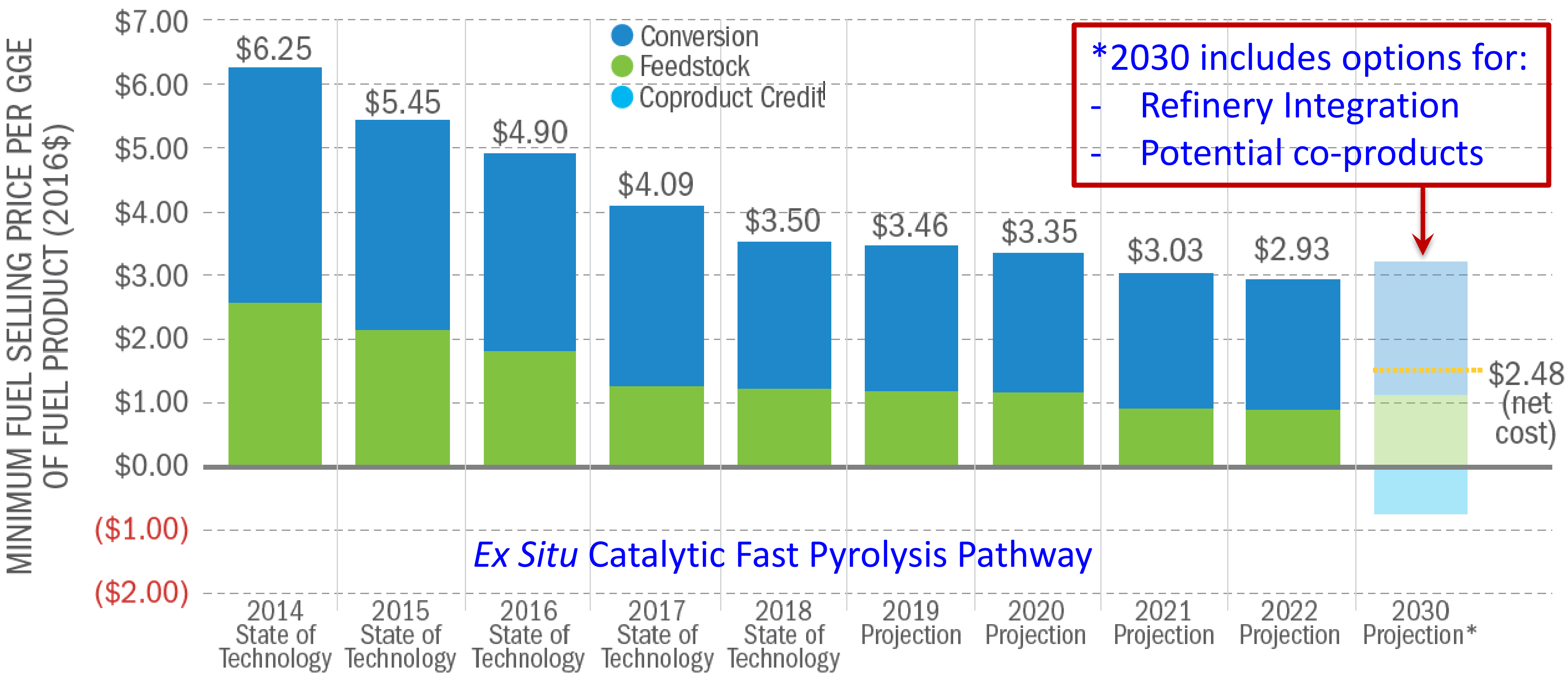
# Milestones (FY2018)

**All milestones completed on time**

| **Milestone Description** | **Type<br>Due Date<br>Status** |
|---|---|
| State of technology assessment for the ex-situ catalytic fast pyrolysis pathway based on experimental results from FY2017. | Quarterly<br>12/31/2017<br>Completed |
| Outline at least one pathway with modeled MFSP below $3.00/GGE using options such as co-products, co-processing, process optimization etc. along with future performance targets / data outlined in previous publications / experiments / design reports. Provide options for path(s) forward for achieving <$2.50/GGE (modeled) in the future along with 50% GHG reduction over petroleum sources. Pathways may include IDL (indirect liquefaction), CFP (catalytic fast pyrolysis), co-processing of CFP oil and/or other biomass derivatives, etc. | **Go/No-Go (Annual)**<br>3/31/2018<br>Completed |
| Public outreach efforts: Plan for additional outreach with available resources. Options such as making additional models available and presenting TEA related efforts/methodology via webinars will be considered. The aim will be to determine at least one outreach activity to be executed before the end of the fiscal year. | Quarterly<br>4/30/2018<br>Completed |
| Prioritize the development and application of tools in a reduced funding scenario; outline future applications, further development opportunities and resource requirements for these tools. Some of the tools to be considered include the Quick Turnaround Analysis (QTA), custom modeling, kinetic and reactor models, refinery integration tools, and phase equilibrium models. | Quarterly<br>6/30/2018<br>Completed |
| Expand the DME homologation kinetic model developed in FY17 to describe paraffin/olefin ratio, production rate of the C7 fraction, and catalyst deactivation. This model will be developed in collaboration with the Liquid Fuels via Upgrading of Syngas Intermediates (WBS 2.3.1.305) project. | Quarterly<br>9/30/2018<br>Completed |
| Provide high-level TEA for new low TRL research in FY18 under lab calls and other research efforts. The exact work will be determined based on research progress and requirements of specific projects, with focus on identifying the most impactful areas for research. We will also look into opportunities and costs for smaller scale deployment of biomass conversion systems and provide initial assessments. | Quarterly<br>9/30/2018<br>Completed |
| FY18 SOT for at least one conversion approach (e.g., in situ, ex situ, dual bed, co-processing/hydrotreating) demonstrating a reduction in the modeled MFSP by $0.25/GGE compared to the FY17 SOT. | Quarterly<br>9/30/2018<br>Completed |

# FY2018 Go/No-Go Summary

Identify options for cost reduction to <$3.00/GGE by 2022 with potential for <$2.50/GGE by 2030




*2030 projections are based on high-level estimates that will be modeled in detail in future years

**Reference**: BETO Multi-Year Plan 2019

# Milestones (FY2019)

**All milestones (to date) completed on time**

| **Milestone Description** | **Type<br>Due Date<br>Status** |
|---|---|
| Description: Develop updated 2022 technical targets and cost projections for (1) the fixed bed ex situ catalytic fast pyrolysis (CFP) and (2) indirect liquefaction high-octane gasoline (HOG) pathways. Publication of this work will be cited in the updated MYPP. Technical targets and modeled Minimum Fuel Selling Price (MFSP) projections for 2022 will be developed for the CFP and IDL-HOG pathways. CFP pathway will target <$3.00/GGE, while the IDL-HOG pathway will use conversion improvements alongside lower-cost feedstocks for projections to achieve a lower MFSP compared to the previous MYPP projection of $3.47/GGE. | Quarterly<br>10/30/2018<br>Completed |
| Description: Comparative TEA assessment of CO2 recycle to increase carbon efficiency in the high-octane gasoline (HOG) pathway. Criteria: The formation of CO2 during biomass gasification, reforming, and acid-gas clean-up represents a significant carbon loss of ca. 20%. The ability to recycle and reactivate this CO2 back into the process will enable a significant increase in overall carbon-efficiency and reduction in MFSP. At least 2 process models with TEA will be used to identify the most impactful unit operation where CO2 can be recycled to increase carbon efficiency, considering (1) recycle to methanol synthesis versus, (2) process intensification that enables direct syngas conversion to HOG in a single reactor. Process and catalyst performance metrics for CO2 activation (e.g., recycle concentration, targeted single-pass conversion) will be established and correlated with the increase in carbon efficiency and reduction in MFSP. Joint with WBS#2.3.1.305 | Quarterly<br>12/31/2018<br>Completed |
| Description: Demonstrate liquid-liquid equilibrium (LLE) predictions using NIST-developed model(s) with comparisons to the Wiltec experimental information used for the model development and validation. Criteria: Assess predictive capabilities of NIST developed predictive models with respect to experimental data for multicomponent model systems. | Quarterly<br>3/31/2019<br>Ongoing |
| Description: Quantify the benefits of the new GC for improved carbon balance closures on NREL's 2FBR ex situ (fixed bed) CFP system. Criteria: Determine whether 90% or greater carbon balance closure was achieved, and what further improvements will be necessary if carbon balance closure is less than 90%. (Joint milestone with CFP experimental task – WBS #2.3.1.314) | Quarterly<br>6/30/2019<br>Future |
| Description: FY19 State of Technology Assessments for ex situ catalytic fast pyrolysis (CFP) and indirect liquefaction (IDL) high-octane gasoline (HOG) pathways. Criteria: (1) FY19 SOT for fixed bed ex situ CFP demonstrating a reduction in the modeled MFSP by $0.50/GGE compared to the FY17 SOT, (2) FY19 SOT assessment for the IDL High-Octane Gasoline pathway with respect to the updated technical and cost targets established in FY2018. Quantify associated sustainability metrics for the SOT cases. | Quarterly<br>9/30/2019<br>Future |
| FY19 TC Analysis "Stretch" Milestone: Identify specific research approaches to help achieve further conversion cost reductions beyond 2022 to enable minimum fuel selling prices (MFSPs) of $2.50/GGE or lower by 2030. Criteria: Co-products, refinery integration, off-gas utilization including $CO_2$, lower cost feedstocks may be included among the strategies. This work will not include final technical targets out to 2030; it will identify key bottlenecks and related metrics for required breakthroughs. E.g. if refinery co-hydroprocessing of catalytic fast pyrolysis oils is identified as a strategy, then current data will be used to show the anticipated quality metrics requirements for successful implementation. | **Annual**<br>9/30/2019<br>Future |

# Future Milestones (Preliminary)

**Preliminary & subject to merit review before execution**

| Milestone Description | Type<br>Due Date |
|---|---|
| Integration of fuel quality predictions in CFP process model: Demonstrate octane and cetane number predictions in the process model. Further tuning of the predictions will be part of a subsequent milestone. | Quarterly<br>12/31/2019 |
| Use custom entrained flow reactor model for quantifying scaling impacts and capital cost sensitivity for 3 different scales (e.g. 200, 500, 1000 tons of biomass per day). | Quarterly<br>3/31/2020 |
| Reconfigure CFP process model for hydroprocessing fuel quality improvements: Experimental results from modified hydroprocessing options will be used to modify the fixed bed ex situ CFP model, quantify additional costs, and benefits from improved fuel quality. The overall impact on the MFSP in $/GGE will be compared with a corresponding case with identical CFP oil yields, but using the hydroprocessing steps documented in the 2015 design report. | **Annual**<br>6/30/2020 |
| FY20 State of Technology (SOT) Assessments: SOT assessments for the (i) ex situ catalytic fast pyrolysis and (ii) syngas to high octane gasoline (HOG) pathways with respect to the FY2020 cost projections documented in BETO's Multi-Year Plan. Analysis using experimental data will be used to provide TEA based guidance for future improvements to reduce the modeled MFSP. | Quarterly<br>9/30/2020 |
| Include blending methods for fuel quality predictions for CFP and assess effectiveness in comparison to experimental data: Add and assess blending capability to process models, and tune the blending methods for the best prediction of experimental data. Effectiveness of prediction trends will be analyzed and quantified for one or more experimental oil samples. | Quarterly<br>12/31/2020 |
| Consolidate all experimental results for CFP, including the potential incorporation of forest residues into the feedstock, initial scale-up impacts, fuel quality improvements, and re-benchmark the process model to determine whether the modeled MFSP goal of <$3.00/GGE (in 2016 dollars) will be achievable during the 2022 verification. Identify gaps and cost-reduction options if it is deemed that current technology will fall short of the MFSP goal. | **Go/No-Go**<br>3/31/2021 |
| Quantify improvements and feasible modeled improvements in carbon efficiencies for syngas conversion processes using technologies for improved gas and solid phase carbon utilization. Propose path forward for additional research driven improvements and quantify cost reductions expected from using compatible waste feedstock. | Quarterly<br>6/30/2021 |
| FY21 State of Technology (SOT) Assessments: SOT assessments for the (i) ex situ catalytic fast pyrolysis and (ii) syngas to high octane gasoline (HOG) pathways with respect to the FY2021 cost projections documented in BETO's Multi-Year Plan. Analysis using experimental data will be used to provide TEA based guidance for future improvements to reduce the modeled MFSP | Quarterly<br>9/30/2021 |

# Responses to 2017 Peer Review Comments

## Overall Impressions/Comments from Reviewers (key excerpts):

- Some complementary excerpts (selected a few): Strong project with a history of successfully providing key information; earlier work matched the results from the analysis from my similar process development work. Well-managed with clearly defined barriers and critical issues.
- Some comments with specific recommendations (paraphrased): **(i)** Use the tools to evaluate outside work and validate the tools using well understood technologies; **(ii)** include risk & outside factors that influence the values; **(iii)** large project with many aspects made it difficult for the reviewer fully understand; more examples would be helpful for reviewers; **(iv)** more dissemination of work and some of the products allowing evaluation of outside work.

## PI Response to the Above Comments (with current information):

- Thank you for your helpful feedback and guidance. We will continue to be diligent in the recommended areas. Here are some responses/actions for the specific comments/recommendations: **(i)** The methods used & correctness of our economic spreadsheet tool (subject to our assumptions), have been validated by multiple organizations (including industry and academia) since we started making the tools publicly available (close to the year 2000). Our process modeling efforts include rigorous heat and energy balances in Aspen Plus, industrial data/results (for published and mature processes), and experimental data and research projections (for our research areas). While we do not have the funding or scope to extensively evaluate outside technologies, our methods make significant use of published industrial information wherever available (and an industry-standard capital cost estimation tool). We use experimental validation for our tools, whenever feasible, e.g. our predictive phase equilibrium work with NIST has an experimental validation component. We engage engineering firms for larger design report projects, with significant review by external experts (including from industry). One of the peer reviewers commented that results from our analysis matched the analysis done for similar process development done by that reviewer. **(ii)** We have the capability to include risk information, and report some of it as part of sensitivity analysis. Our base case values are used to benchmark research goals and progress (hence don't directly include risk information – this allows a clean comparison of research progress using consistent metrics). **(iii)** The project scope is now significantly streamlined, reflecting a smaller scope and associated funding reductions. This 2019 presentation includes examples. **(iv)** We made additional models publicly available since the previous peer review. Also, our major publications most often contain sufficient details for re-creating the models.

**Previous details available at:** https://www.energy.gov/sites/prod/files/2018/02/f48/2017_peer_review_thermochemical_conversion.pdf

# Publications and Presentations since 2017 Peer Review

***Slide 1 of 2***


- Griffin, M.B; Iisa, K.; Wang, H.; Dutta, A.; Orton, K.A.; French, R.J.; Santosa, D.M.; Wilson, N.; Christensen, E.; Nash, C.; Van Allsburg, K.M.; Baddour, F.G.; Ruddy, D.A.; Tan, E.C.D.; Cai, H.; Mukarakate, C.; Schaidle, J.A.. Driving towards cost-competitive biofuels through catalytic fast pyrolysis by rethinking catalyst selection and reactor configuration. Energy Environ. Sci., 2018. http://dx.doi.org/10.1039/C8EE01872C
- Dutta, A.; Iisa, K.; Mukarakate, C.; Griffin, M.; Tan, E.C.D.; Schaidle, J.; Humbird, D. et al. 2018. Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2018 State of Technology and Future Research. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-71954. https://www.nrel.gov/docs/fy19osti/71954.pdf.
- Tan, E.C.D.; Ruddy, D.; Nash, C.; Dupuis, D.; Dutta, A.; Hartley, D.; Cai, H. 2018. High-Octane Gasoline from Lignocellulosic Biomass via Syngas and Methanol/Dimethyl Ether Intermediates: 2018 State of Technology and Future Research. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-71957. https://www.nrel.gov/docs/fy19osti/71957.pdf.
- Dunn, J.B; Biddy, M.; Jones, S.; Cai, H.; Benavides, P.T.; Markham, J.; Tao, L.; Tan, E.; Kinchin, C.; Davis, R.; Dutta, A.; Bearden, M.; Clayton, C.; Phillips, S.; Rappé, K.; Lamers, P. Environmental, economic, and scalability considerations and trends of selected fuel economy-enhancing biomass-derived blendstocks. ACS Sustainable Chem. Eng., 2018, 6 (1), pp 561–569.
- Zhang, Y.; Sahir, A.H.; Tan, E.C.D.; Talmadge, M.S.; Davis, R.; Biddy, M.J.; Tao, L. Economic and Environmental Potentials for Natural Gas to Enhance Biomass-to-Liquid Fuels Technologies. Green Chem., 2018,20, 5358-5373.
- Iisa, K.; Robichaud, D.J.; Watson, M.J.; ten Dam, J.; Dutta, A.; Mukarakate, C.; Kim, S.; Nimlos, M.R.; Baldwin, R.M. Improving biomass pyrolysis economics by integrating vapor and liquid phase upgrading. First published Nov 24, 2017. Green Chemistry. DOI: 10.1039/c7gc02947k.
- Iisa, K.; French, R.J.; Orton, K.A.; Dutta, A.; Schaidle, J.A. Production of low-oxygen bio-oil via ex situ catalytic fast pyrolysis and hydrotreating. Fuel 207 (2017) 413–422.

# Publications and Presentations since 2017 Peer Review

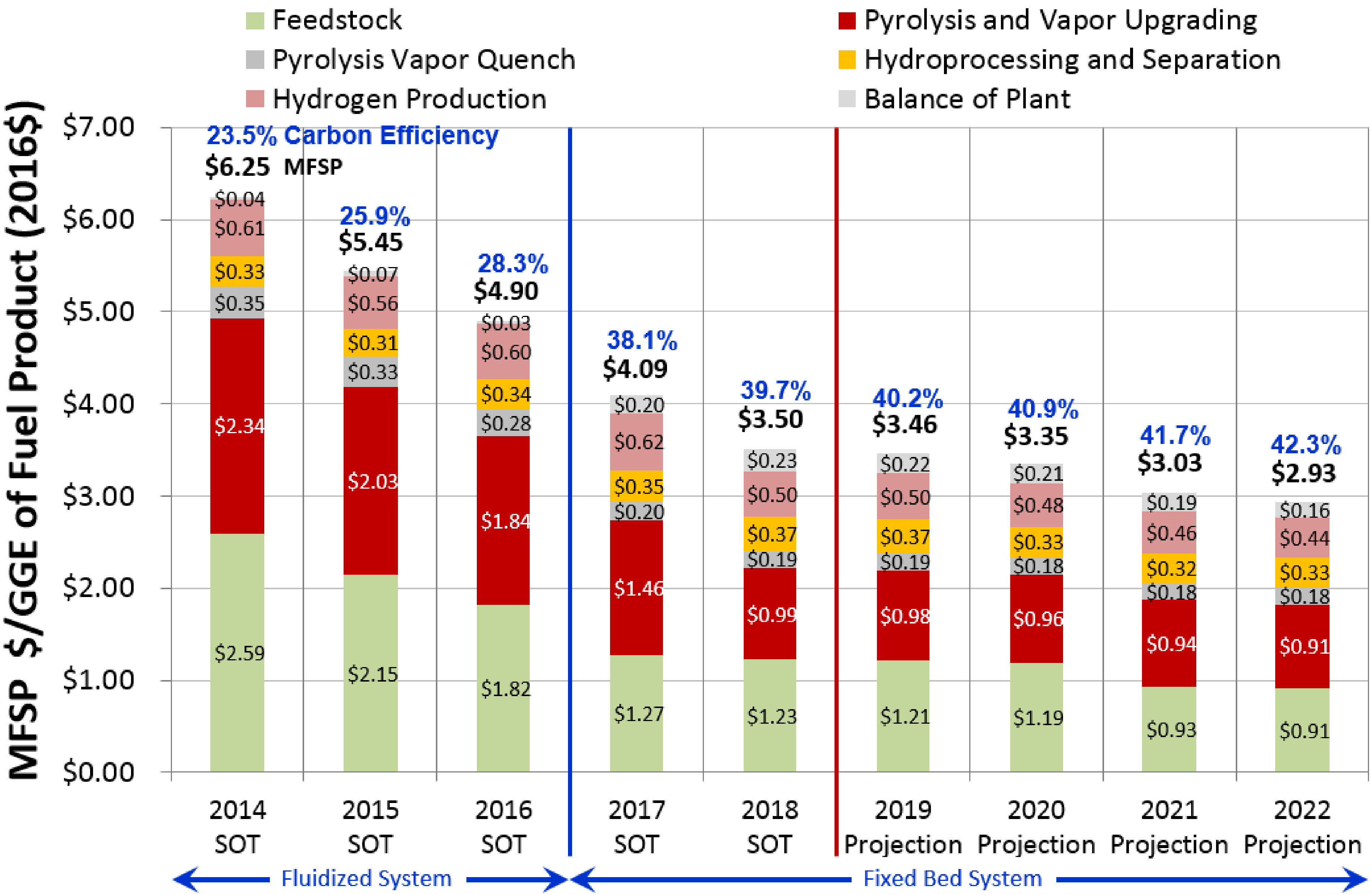
***Slide 2 of 2***

- Tan, E.C.D.; Biddy, M. An Integrated Sustainability Evaluation of Indirect Liquefaction of Biomass to Liquid Fuels. 7th International Congress on Sustainability Science & Engineering (ICOSSE ’18: Industry, Innovation and Sustainability), Cincinnati, OH, August 12-15, 2018. **(Presentation)**
- Tan, E.C.D.; Cai, H.; Talmadge, M. Relative Sustainability of Natural Gas Assisted High-Octane Gasoline Blendstock Production from Biomass. 2017 AIChE Annual Meeting, Minneapolis, MN, October 29–November 3, 2017. **(Presentation)**
- Ruddy, D.A.; Nash, C.; Hensley, J.; Schaidle, J.; Farberow, C.; Cheah, S.; Tan, E.; Talmadge, M. Isobutane Activation over a Cu/BEA Catalyst and Re-Incorporation into the Chain-Growth Cycle of Dimethyl Ether Homologation. 25th North American Meeting of the Catalysis Society, Denver, CO, June 4-9, 2017. **(Presentation)**

**Additional content for conversion pathways:**

- Catalytic Fast Pyrolysis (CFP)
- High-Octane Gasoline (HOG)

# Catalytic Fast Pyrolysis – SOT and Projections




Details included in tables on following slides

# Catalytic Fast Pyrolysis– Tables from MYP (1)

| Processing Area Cost Contributions and Key Technical Parameters | Units | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2019 Projection | 2020 Projection | 2021 Projection | 2022 Projection | 2030[d] Projection |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Process Concept: Hydrocarbon Fuel Production via *Ex Situ* Upgrading of Fast Pyrolysis Vapors** | | **Clean Pine** | **Clean Pine** | **Clean Pine** | **Clean Pine** | **Clean Pine** | **Clean Pine** | **Clean Pine** | **Residues + Pine** | **Residues + Pine** | **Residues + Pine** |
| Year Dollar Basis | | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 |
| Projected MFSP[a] | $/GGE[b] | $6.25 | $5.45 | $4.90 | $4.09 | $3.50 | $3.46 | $3.35 | $3.03 | $2.93 | $2.48 |
| Conversion Contribution | $/GGE[b] | $3.66 | $3.30 | $3.08 | $2.82 | $2.28 | $2.25 | $2.16 | $2.10 | $2.02 | $1.34 |
| Total Project Investment per Annual GGE | $/GGE-yr | $18.50 | $16.46 | $14.94 | $12.17 | $11.35 | $11.20 | $10.76 | $10.42 | $10.22 | $11.13 |
| Plant Capacity (Dry Feedstock Basis) | metric tons/day | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 |
| Total Gasoline Equivalent Yield | GGE/dry ton | 42 | 46 | 51 | 69 | 72 | 73 | 74 | 76 | 77 | 62 |
| Diesel-Range Product Proportion (GGE[b] Basis) | % of fuel product | 15% | 15% | 15% | 52% | 52% | 51% | 52% | 51% | 52% | 52% |
| ***Feedstock*** | | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $2.59 | $2.15 | $1.82 | $1.27 | $1.23 | $1.21 | $1.19 | $0.93 | $0.91 | $1.14 |
| Capital Cost Contribution | $/GGE | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| Operating Cost Contribution | $/GGE | $2.58 | $2.14 | $1.81 | $1.27 | $1.22 | $1.21 | $1.18 | $0.93 | $0.91 | $1.13 |
| Feedstock Cost | $/dry ton | $108.43 | $98.56 | $92.69 | $87.82 | $87.82 | $87.82 | $87.82 | $70.31 | $70.31 | $70.31 |
| Feedstock Moisture at Plant Gate | wt % $H_2O$ | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| Feed Moisture Content to Pyrolyzer | wt % $H_2O$ | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| Energy Content (LHV, Dry Basis) | Btu / lb | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 |
| ***Pyrolysis and Vapor Upgrading*** | | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $2.34 | $2.03 | $1.84 | $1.46 | $0.99 | $0.98 | $0.96 | $0.94 | $0.91 | $1.14 |
| Capital Cost Contribution | $/GGE | $0.95 | $0.82 | $0.74 | $0.65 | $0.54 | $0.54 | $0.53 | $0.51 | $0.51 | $0.63 |
| Operating Cost Contribution | $/GGE | $1.39 | $1.21 | $1.09 | $0.80 | $0.45 | $0.44 | $0.43 | $0.43 | $0.40 | $0.51 |
| *Ex Situ* Reactor Configuration | reactor type | fluidized bed | fluidized bed | fluidized bed | fixed bed | fixed bed | fixed bed | fixed bed | fixed bed | fixed bed | fixed bed |
| Ratio of Online:Regenerating Fixed Bed Reactors | ratio | N/A | N/A | N/A | 2:5 | 2:3 | 2:3 | 2:3 | 2:3 | 2:2 | 2:2 |
| Gas Phase | wt % of dry biomass | 35% | 36% | 34% | 31% | 31% | 31% | 31% | 31% | 31% | 31% |
| Aqueous Phase | wt % of dry biomass | 25% | 25% | 24% | 27% | 23% | 23% | 23% | 23% | 23% | 23% |
| Carbon Loss | % of C in biomass | 2.9% | 2.9% | 3.4% | 2.9% | 5.0% | 4.5% | 4.0% | 3.5% | 3.0% | 3.0% |

# Catalytic Fast Pyrolysis– Tables from MYP (2)

| Processing Area Cost Contributions and Key Technical Parameters | Units | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2019 Projection | 2020 Projection | 2021 Projection | 2022 Projection | 2030[d] Projection |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Organic Phase | wt % of dry biomass | 17.5% | 18.6% | 21.8% | 28.3% | 30.8% | 31.0% | 31.1% | 31.2% | 31.4% | 31.4% |
| H/C Molar Ratio | ratio | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| Oxygen | wt % of org. phase | 15.0% | 13.3% | 16.8% | 16.5% | 18.5% | 18.0% | 17.6% | 17.1% | 16.4% | 16.4% |
| Carbon Efficiency | % of C in biomass | 27% | 29% | 33% | 42% | 45% | 45% | 46% | 46% | 47% | 47% |
| Solid Losses (Char + Coke) | wt % of dry biomass | 23% | 21% | 20% | 14% | 15% | 15% | 15% | 15% | 15% | 15% |
| Char | wt % of dry biomass | 12.0% | 11.0% | 12.0% | 10.4% | 11.7% | 11.7% | 11.7% | 11.7% | 11.7% | 11.7% |
| Coke | wt % of dry biomass | 11.0% | 9.5% | 8.3% | 3.3% | 3.3% | 3.3% | 3.3% | 3.2% | 3.2% | 3.2% |
| ***Pyrolysis Vapor Quench*** | | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.35 | $0.33 | $0.28 | $0.20 | $0.19 | $0.19 | $0.18 | $0.18 | $0.18 | $0.23 |
| Capital Cost Contribution | $/GGE | $0.20 | $0.19 | $0.16 | $0.12 | $0.11 | $0.11 | $0.11 | $0.10 | $0.10 | $0.13 |
| Operating Cost Contribution | $/GGE | $0.15 | $0.14 | $0.12 | $0.08 | $0.08 | $0.08 | $0.08 | $0.08 | $0.08 | $0.10 |
| ***Hydroprocessing and Separation*** | | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.33 | $0.31 | $0.34 | $0.35 | $0.37 | $0.37 | $0.33 | $0.32 | $0.33 | $0.04 |
| Capital Cost Contribution | $/GGE | $0.17 | $0.16 | $0.18 | $0.19 | $0.19 | $0.19 | $0.18 | $0.17 | $0.17 | $0.00 |
| Operating Cost Contribution | $/GGE | $0.15 | $0.14 | $0.16 | $0.16 | $0.18 | $0.18 | $0.16 | $0.15 | $0.15 | $0.04 |
| Carbon Efficiency of Organic Liquid Feed to Fuels | % | 88% | 90% | 87% | 91% | 89% | 89% | 90% | 91% | 91% | 91% |
| Hydrotreating Pressure | psia | 2,000 | 2,000 | 2,000 | 1,900 | 1,900 | 1,900 | 1,900 | 1,900 | 1,900 | 1,900 |
| Oxygen Content in Cumulative Fuel Product | wt % | 0.8% | 0.8% | 0.8% | 0.6% | 0.5% | 0.5% | 0.5% | 0.5% | 0.6% | 0.6% |
| ***Hydrogen Production*** | | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.61 | $0.56 | $0.60 | $0.62 | $0.50 | $0.50 | $0.48 | $0.46 | $0.44 | $0.46 |
| Capital Cost Contribution | $/GGE | $0.39 | $0.36 | $0.38 | $0.41 | $0.32 | $0.32 | $0.31 | $0.30 | $0.28 | $0.28 |
| Operating Cost Contribution | $/GGE | $0.22 | $0.20 | $0.22 | $0.21 | $0.18 | $0.18 | $0.17 | $0.17 | $0.16 | $0.17 |
| Additional Natural Gas[c] | % LHV of biomass | 0.3% | 0.1% | 0.2% | 0.1% | 0.2% | 0.2% | 0.4% | 0.4% | 0.2% | 0.2% |
| ***Coproducts*** | | | | | | | | | | | |
| Total Cost Contribution | $ / GGE | | | | | | | | | | ($0.74) |
| Capital Cost Contribution | $ / GGE | | | | | | | | | | $0.06 |
| Operating Cost Contribution | $ / GGE | | | | | | | | | | ($0.81) |
| Coproduct Credit | $ / GGE[b] | | | | | | | | | | ($0.83) |

# Catalytic Fast Pyrolysis– Tables from MYP (3)

| Processing Area Cost Contributions and Key Technical Parameters | Units | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2019 Projection | 2020 Projection | 2021 Projection | 2022 Projection | 2030[d] Projection |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Balance of Plant*** | | | | | | | | | | | |
| Total Cost Contribution | $ / GGE | $0.04 | $0.07 | $0.03 | $0.20 | $0.23 | $0.22 | $0.21 | $0.19 | $0.16 | $0.22 |
| Capital Cost Contribution | $ / GGE | $0.80 | $0.71 | $0.56 | $0.43 | $0.39 | $0.38 | $0.36 | $0.34 | $0.33 | $0.41 |
| Operating Cost Contribution | $ / GGE | ($0.76) | ($0.64) | ($0.54) | ($0.23) | ($0.16) | ($0.16) | ($0.16) | ($0.15) | ($0.17) | ($0.20) |
| Electricity Production from Steam Turbine (Credit Included in Operating Cost Above) | $/GGE[b] | ($1.12) | ($0.96) | ($0.78) | ($0.42) | ($0.36) | ($0.35) | ($0.34) | ($0.32) | ($0.33) | ($0.41) |
| ***Sustainability and Process Efficiency Metrics*** | | | | | | | | | | | |
| Fuel and Coproducts Yield by Weight of Biomass | % w/w of dry biomass | 13.7% | 15.0% | 16.5% | 22.2% | 23.1% | 23.4% | 23.9% | 24.4% | 24.8% | 24.8% |
| Carbon Efficiency to Fuels and Coproducts | % C in feedstock | 23.5% | 25.9% | 28.3% | 38.1% | 39.7% | 40.2% | 40.9% | 41.7% | 42.3% | 42.3% |
| Overall Carbon Efficiency to Fuels and Coproducts | % C in feedstock + NG | 23.5% | 25.9% | 28.3% | 38.1% | 39.7% | 40.2% | 40.9% | 41.7% | 42.3% | 42.3% |
| Overall Energy Efficiency to Fuels and Coproducts | % LHV of feedstock + NG | 30.4% | 33.4% | 37.0% | 50.2% | 52.1% | 52.7% | 53.7% | 54.9% | 56.1% | 56.1% |
| Electricity Production | kWh/GGE | 21.0 | 18.0 | 14.7 | 8.0 | 7.0 | 6.8 | 6.5 | 6.2 | 6.3 | 7.9 |
| Electricity Consumption (Entire Process) | kWh/GGE | 12.7 | 11.0 | 9.6 | 6.4 | 6.7 | 6.6 | 6.3 | 6.0 | 5.9 | 7.4 |
| Water Consumption in Conversion Process | gal $H_2O$/GGE | 1.4 | 1.4 | 1.3 | 1.5 | 1.3 | 1.2 | 1.2 | 1.1 | 1.1 | 1.4 |

[a] Conceptual design results.

[b] Gallon gasoline equivalent on a lower heating value basis.

[c] A negligible stream was maintained in the model to allow natural gas use if necessary.

[d] 2030 projections are based on high-level estimates and will be modeled in detail in future years. It is proposed that hydroprocessing will occur at a petroleum refinery with coprocessing of the catalytic fast pyrolysis oils using existing capital. Capital for hydrogen production is included, while natural gas feed for hydrogen production is not included because credit is not taken for an equivalent amount of fuel gas from the CFP biorefinery. Coproduct credit is based on a preliminary estimate of diverting 20% CFP oil to produce coproducts

**Reference**: MYP – BETO Multi-Year Plan 2019

# *Ex Situ* CFP – Sustainability Metrics Summary

**>60% GHG reduction over petroleum derived gasoline per ANL analysis†**

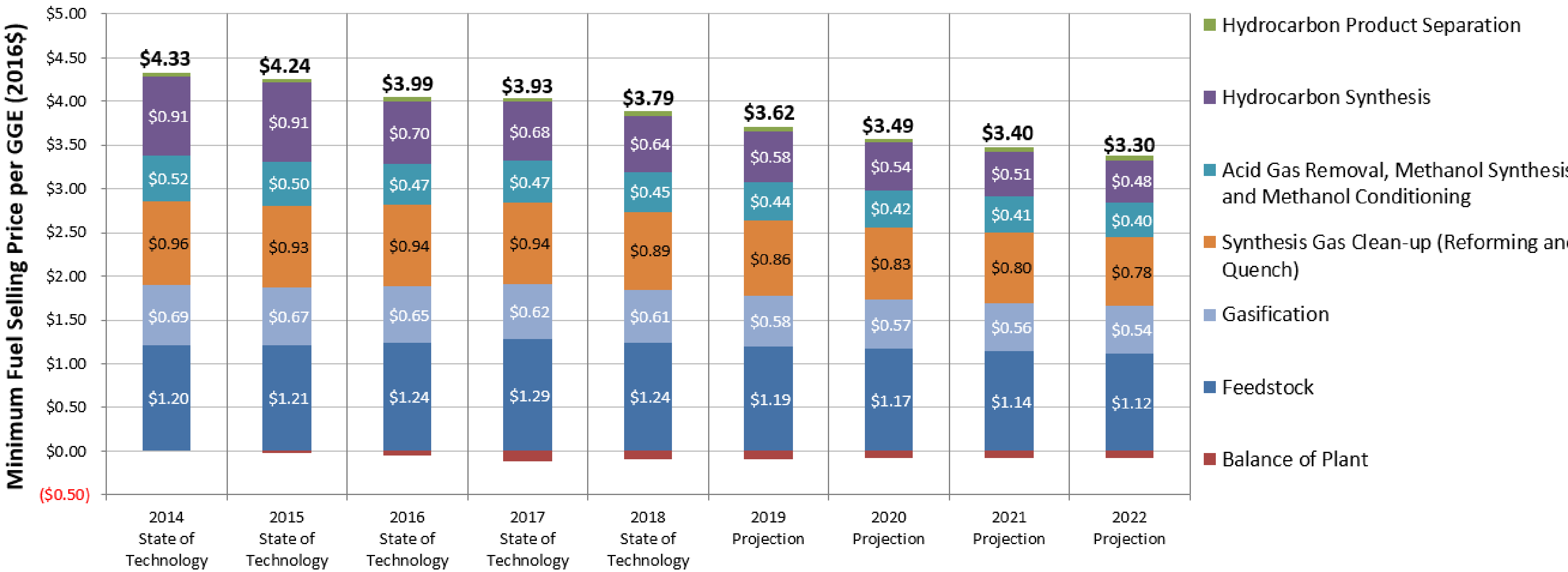
| | FY14 SOT | FY15 SOT | FY16 SOT | FY17 SOT | FY18 SOT | FY22 Projection |
|---|---|---|---|---|---|---|
| Fuel Yield by Weight (% w/w of dry biomass) | 13.7 | 15.0 | 16.5 | 22.2 | 23.1 | 24.8 |
| Total Fuel Yield (GGE / dry US ton) | 42 | 46 | 51 | 69 | 72 | 77 |
| Carbon Efficiency to Fuel Blendstock (%C in Feedstock) | 23.5 | 25.9 | 28.3 | 38.1 | 39.7 | 42.3 |
| Energy Efficiency to Fuel (% LHV of Feedstock) | 30.4 | 33.4 | 37.0 | 50.2 | 52.1 | 56.1 |
| Water Consumption (Gal $H_2O$ / GGE Fuel Blend) | 1.4 | 1.4 | 1.3 | 1.5 | 1.3 | 1.1 |
| Electricity Production (kWh/GGE) | 21.0 | 18.0 | 14.7 | 8.0 | 7.0 | 6.3 |
| Electricity Consumption (entire process, kWh/GGE) | 12.7 | 11.0 | 9.6 | 6.4 | 6.7 | 5.9 |

**Note:** Metrics shown apply to conversion process only

† **Reference:** Cai et al. Argonne National Laboratory report, ANL/ESD-18/13, 2018.

# High-Octane Gasoline – SOT and Projections

Details included in tables on following slides




**Reference**: BETO Multi-Year Plan 2019

# High-Octane Gasoline – Tables from MYP (1)

| Processing Area Cost Contributions and Key Technical Parameters | Units | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2019 Projection | 2020 Projection | 2021 Projection | 2022 Projection |
|---|---|---|---|---|---|---|---|---|---|---|
| **Process Concept: Gasification, Syngas Cleanup, Methanol/DME Synthesis, and Conversion to Hydrocarbons** | | **Woody Feedstock** | **Woody Feedstock** | **Woody Feedstock** | **Woody Feedstock** | **Woody Feedstock** | **Woody Feedstock** | **Woody Feedstock** | **Woody Feedstock** | **Woody Feedstock** |
| Year Dollar Basis | | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 |
| $C_{5}$+ MFSP (per Actual Product Volume)* | $/gal | $4.31 | $4.17 | $3.85 | $3.74 | $3.66 | $3.50 | $3.39 | $3.31 | $3.22 |
| Mixed $C_{4}$ MFSP (per Actual Product Volume)* | $/gal | $3.98 | $3.91 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| MFSP (per GGE)* | $/GGE | $4.33 | $4.24 | $3.99 | $3.93 | $3.79 | $3.62 | $3.49 | $3.40 | $3.30 |
| Conversion Contribution (per GGE)* | $/GGE | $3.13 | $3.03 | $2.76 | $2.64 | $2.56 | $2.43 | $2.33 | $2.25 | $2.18 |
| Year Dollar Basis | | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 | 2016 |
| Total Capital Investment per Annual Gallon | $ | $15.80 | $15.94 | $11.01 | $11.54 | $11.07 | $10.61 | $10.28 | $10.03 | $9.79 |
| Plant Capacity (Dry Feedstock Basis) | metric tons/day | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 |
| High-Octane Gasoline Blendstock ($C_{5}$+) Yield | gal/dry ton | 36.2 | 36.4 | 51.4 | 50.0 | 51.4 | 53.0 | 54.1 | 55.1 | 56.0 |
| Mixed $C_{4}$ Coproduct Yield | gal/dry ton | 16.3 | 16.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| ***Feedstock*** | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $1.20 | $1.21 | $1.24 | $1.29 | $1.24 | $1.19 | $1.17 | $1.14 | $1.12 |
| Capital Cost Contribution | $/GGE | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 |
| Operating Cost Contribution | $/GGE | $1.20 | $1.21 | $1.24 | $1.29 | $1.23 | $1.19 | $1.16 | $1.14 | $1.12 |
| Feedstock Cost | $/dry ton | $60.58 | $60.58 | $60.58 | $60.58 | $60.58 | $60.58 | $60.58 | $60.58 | $60.58 |
| Feedstock Moisture at Plant Gate | wt % $H_2O$ | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% | 30% |
| In-Plant Handling and Drying/Preheating | $/dry ton | $0.72 | $0.70 | $0.70 | $0.69 | $0.69 | $0.69 | $0.69 | $0.69 | $0.69 |

# High-Octane Gasoline – Tables from MYP (2)

| Processing Area Cost Contributions and Key Technical Parameters | Units | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2019 Projection | 2020 Projection | 2021 Projection | 2022 Projection |
|---|---|---|---|---|---|---|---|---|---|---|
| Cost Contribution | $/gal | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 |
| Feed Moisture Content to Gasifier | wt % $H_2O$ | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| Energy Content (LHV, Dry Basis) | Btu / lb | 7,856 | 7,856 | 7,856 | 7,856 | 7,856 | 7,856 | 7,856 | 7,856 | 7,856 |
| ***Gasification*** | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.69 | $0.67 | $0.65 | $0.62 | $0.61 | $0.58 | $0.57 | $0.56 | $0.54 |
| Capital Cost Contribution | $/GGE | $0.43 | $0.41 | $0.38 | $0.35 | $0.34 | $0.33 | $0.32 | $0.31 | $0.30 |
| Operating Cost Contribution | $/GGE | $0.26 | $0.26 | $0.27 | $0.28 | $0.26 | $0.26 | $0.25 | $0.25 | $0.24 |
| Raw Dry Syngas Yield | lb/lb dry feed | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 |
| Raw Syngas Methane (Dry Basis) | mol % | 15.4% | 15.4% | 15.4% | 15.4% | 15.4% | 15.4% | 15.4% | 15.4% | 15.4% |
| Gasifier Efficiency (LHV) | % LHV | 71.9% | 71.9% | 71.9% | 71.9% | 71.9% | 71.9% | 71.9% | 71.9% | 71.9% |
| ***Synthesis Gas Clean-Up (Reforming and Quench)*** | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.96 | $0.93 | $0.94 | $0.94 | $0.89 | $0.86 | $0.83 | $0.80 | $0.78 |
| Capital Cost Contribution | $/GGE | $0.51 | $0.49 | $0.46 | $0.43 | $0.41 | $0.39 | $0.38 | $0.37 | $0.36 |
| Operating Cost Contribution | $/GGE | $0.45 | $0.45 | $0.48 | $0.51 | $0.48 | $0.46 | $0.45 | $0.44 | $0.42 |
| Tar Reformer (TR) Exit $CH_4$ (Dry Basis) | mol % | 1.7% | 1.7% | 1.7% | 1.7% | 1.7% | 1.7% | 1.7% | 1.7% | 1.7% |
| TR $CH_4$ Conversion | % | 80.0% | 80.0% | 80.0% | 80.0% | 80.0% | 80.0% | 80.0% | 80.0% | 80.0% |
| TR Benzene Conversion | % | 99.0% | 99.0% | 99.0% | 99.0% | 99.0% | 99.0% | 99.0% | 99.0% | 99.0% |
| TR Tars Conversion | % | 99.9% | 99.9% | 99.9% | 99.9% | 99.9% | 99.9% | 99.9% | 99.9% | 99.9% |
| Catalyst Replacement | % of inventory/day | 0.15% | 0.15% | 0.15% | 0.15% | 0.15% | 0.15% | 0.15% | 0.15% | 0.15% |
| ***Acid Gas Removal, Methanol Synthesis, and Methanol Conditioning*** | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.52 | $0.50 | $0.47 | $0.47 | $0.45 | $0.44 | $0.42 | $0.41 | $0.40 |
| Capital Cost Contribution | $/GGE | $0.35 | $0.33 | $0.30 | $0.28 | $0.28 | $0.27 | $0.26 | $0.25 | $0.24 |
| Operating Cost Contribution | $/GGE | $0.17 | $0.17 | $0.17 | $0.19 | $0.18 | $0.17 | $0.17 | $0.16 | $0.16 |

# High-Octane Gasoline – Tables from MYP (3)

| Processing Area Cost Contributions and Key Technical Parameters | Units | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2019 Projection | 2020 Projection | 2021 Projection | 2022 Projection |
|---|---|---|---|---|---|---|---|---|---|---|
| Methanol Synthesis Reactor Pressure | psia | 730 | 730 | 730 | 730 | 730 | 730 | 730 | 730 | 730 |
| Methanol Productivity | kg/kg-cat/h | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 |
| Methanol Intermediate Yield | gal/dry ton | 143 | 142 | 138 | 144 | 141 | 139 | 137 | 136 | 134 |
| ***Hydrocarbon Synthesis*** | | | | | | | | | | |
| Total Cost Contribution | \$/GGE | \$0.91 | \$0.91 | \$0.70 | \$0.68 | \$0.64 | \$0.58 | \$0.54 | \$0.51 | \$0.48 |
| Capital Cost Contribution | \$/GGE | \$0.56 | \$0.56 | \$0.46 | \$0.44 | \$0.42 | \$0.38 | \$0.36 | \$0.34 | \$0.32 |
| Operating Cost Contribution | \$/GGE | \$0.35 | \$0.35 | \$0.24 | \$0.23 | \$0.22 | \$0.20 | \$0.19 | \$0.17 | \$0.16 |
| Methanol to DME Reactor Pressure | psia | 145 | 145 | 145 | 145 | 145 | 145 | 145 | 145 | 145 |
| Hydrocarbon Synthesis Reactor Pressure | psia | 129 | 129 | 129 | 129 | 129 | 129 | 129 | 129 | 129 |
| Hydrocarbon Synthesis Catalyst | | commercial BEA | | National Renewable Energy Laboratory-modified BEA with Cu as active metals for activity and performance improvement | | | | | | |
| Hydrogen Addition to Hydrocarbon Synthesis | | no $H_2$ addition | supplemental $H_2$ added to hydrocarbon synthesis reactor inlet to improve selectivity to branched paraffins relative to aromatics | | | | | | | |
| Utilization of $C_4$ Reactor Products | | coproduct | coproduct | recycle | recycle | recycle | recycle | recycle | recycle | recycle |
| Single-Pass DME Conversion | % | 15.0% | 15.0% | 19.2% | 27.6% | 38.9% | 39.2% | 39.5% | 39.7% | 40.0% |
| Overall DME Conversion | % | 83% | 85% | 83% | 88% | 92% | 90% | 89% | 90% | 90% |
| Hydrocarbon Synthesis Catalyst Productivity | kg/kg-cat/h | 0.02 | 0.03 | 0.04 | 0.09 | 0.07 | 0.08 | 0.09 | 0.09 | 0.10 |
| Carbon Selectivity to $C_{5+}$ Product | % C in reactor feed | 46.2% | 48.3% | 81.8% | 74.8% | 72.3% | 76.3% | 80.1% | 83.4% | 86.7% |
| Carbon Selectivity to Total Aromatics (Including HMB - Hexamethylbenzene) | % C in reactor feed | 25.0% | 20.0% | 4.0% | 4.0% | 8.0% | 6.1% | 4.2% | 2.4% | 0.5% |
| Carbon Selectivity to Coke and Pre-Cursors (HMB proxy) | % C in reactor feed | 10.0% | 9.3% | 4.0% | 4.0% | 4.0% | 3.0% | 2.2% | 1.4% | 0.5% |

# High-Octane Gasoline – Tables from MYP (4)

| Processing Area Cost Contributions and Key Technical Parameters | Units | 2014 SOT | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2019 Projection | 2020 Projection | 2021 Projection | 2022 Projection |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Hydrocarbon Product Separation*** | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.04 | $0.05 | $0.05 | $0.05 | $0.05 | $0.05 | $0.05 | $0.05 | $0.05 |
| Capital Cost Contribution | $/GGE | $0.03 | $0.03 | $0.04 | $0.04 | $0.04 | $0.04 | $0.04 | $0.03 | $0.03 |
| Operating Cost Contribution | $/GGE | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 | $0.01 |
| ***Balance of Plant*** | | | | | | | | | | |
| Total Cost Contribution | $/GGE | $0.01 | ($0.02) | ($0.05) | ($0.11) | ($0.09) | ($0.09) | ($0.08) | ($0.08) | ($0.07) |
| Capital Cost Contribution | $/GGE | $0.42 | $0.40 | $0.36 | $0.34 | $0.33 | $0.32 | $0.30 | $0.29 | $0.28 |
| Operating Cost Contribution | $/GGE | ($0.41) | ($0.42) | ($0.42) | ($0.45) | ($0.42) | ($0.40) | ($0.38) | ($0.37) | ($0.36) |
| ***Sustainability and Process Efficiency Metrics*** | | | | | | | | | | |
| Carbon Efficiency to $C_{5}$+ Product | % C in feedstock | 19.3% | 19.4% | 25.2% | 24.3% | 25.5% | 26.3% | 26.9% | 27.4% | 27.9% |
| Carbon Efficiency to Mixed $C_4$ Coproduct | % C in feedstock | 7.0% | 6.9% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Overall Carbon Efficiency to Hydrocarbon Products | % C in feedstock | 26.3% | 26.3% | 25.2% | 24.3% | 25.5% | 26.3% | 26.9% | 27.4% | 27.9% |
| Overall Energy Efficiency to Hydrocarbon Products | % LHV of feedstock | 37.7% | 37.7% | 36.6% | 35.1% | 36.6% | 37.9% | 38.8% | 39.6% | 40.4% |
| Electricity Production | kWh/gal $C_5$+ | 11.7 | 11.8 | 7.9 | 8.4 | 8.1 | 7.7 | 7.4 | 7.2 | 7.0 |
| Electricity Consumption | kWh/gal $C_5$+ | 11.7 | 11.8 | 7.9 | 8.5 | 8.1 | 7.7 | 7.4 | 7.2 | 7.0 |
| Water Consumption | gal $H_2O$/gal $C_5$+ | 12.9 | 10.1 | 3.1 | 3.3 | 3.2 | 3.0 | 2.9 | 2.8 | 2.8 |

* Conceptual design results.

**Reference**: MYP – BETO Multi-Year Plan 2019

# HOG – Sustainability Metrics Summary

**>60% GHG reduction over petroleum derived gasoline per ANL analysis†**

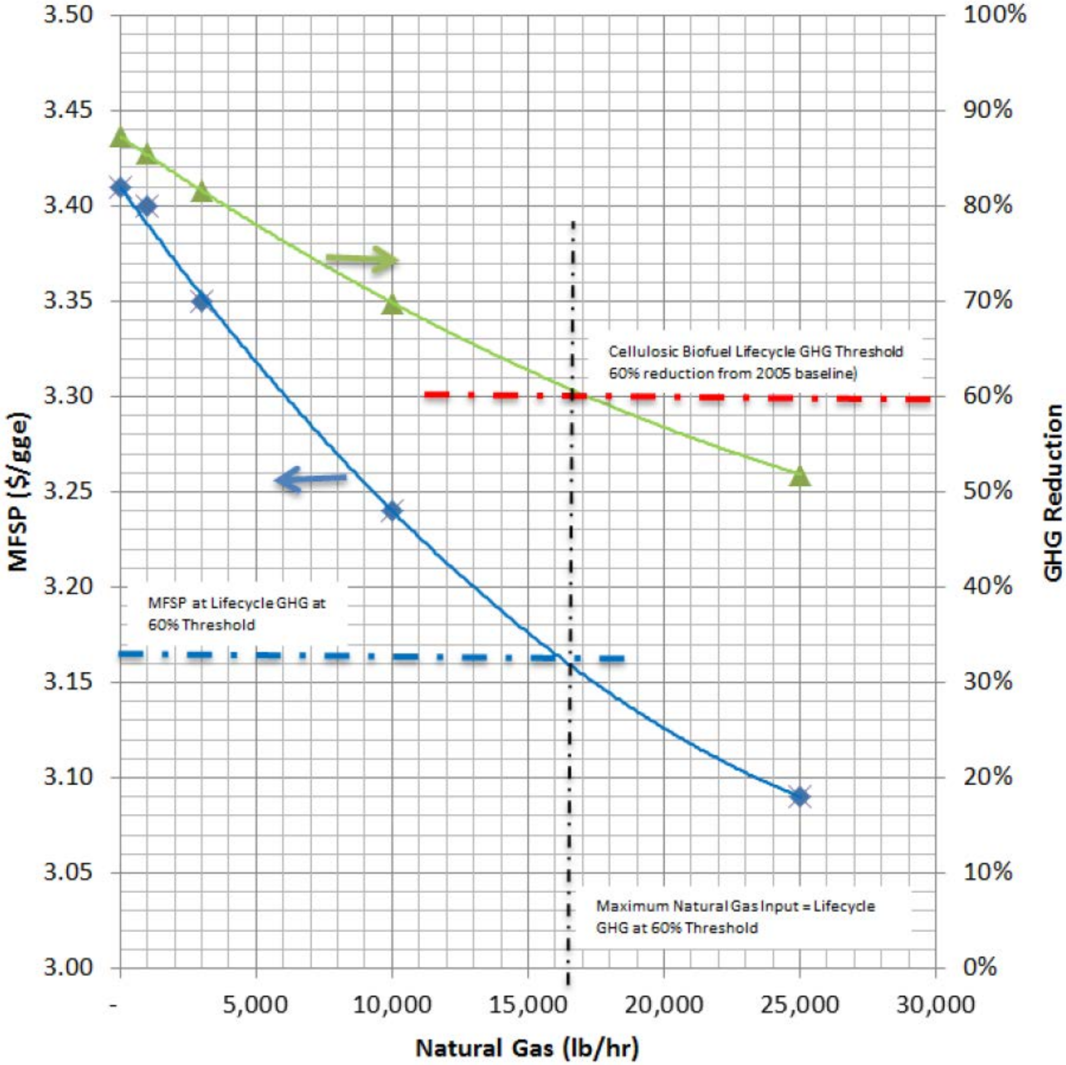
| Trends in Modeled Sustainability Metrics | 2015 SOT | 2016 SOT | 2017 SOT | 2018 SOT | 2022 Projection |
|---|---|---|---|---|---|
| Overall Energy-Efficiency to Hydrocarbon Products (% feed LHV basis) | 37.7* | 36.6 | 35.1 | 36.6 | 40.4 |
| Overall Carbon Efficiency (% C in feedstock) | 26.3* | 25.2 | 24.3 | 25.5 | 27.9 |
| Total Fuel Yield (Gal / Ton) | 36.4 | 51.4 | 50.0 | 51.4 | 56.0 |
| Total Fuel Yield (GGE / Ton) | 35.8 | 49.5 | 47.6 | 49.6 | 54.7 |
| Electricity Production (& consumed in process) (kWh / Gal C5+) | 11.8 | 7.9 | 8.4 | 8.1 | 7.0 |
| Water Consumption (Gal H2O / Gal C5+ HCs) | 10.1 | 3.1 | 3.3 | 3.2 | 2.8 |

**Note:** Metrics shown apply to conversion process only. *Includes LPG product

**†Reference:** Cai et al. Argonne National Laboratory report, ANL/ESD-18/13, 2018.

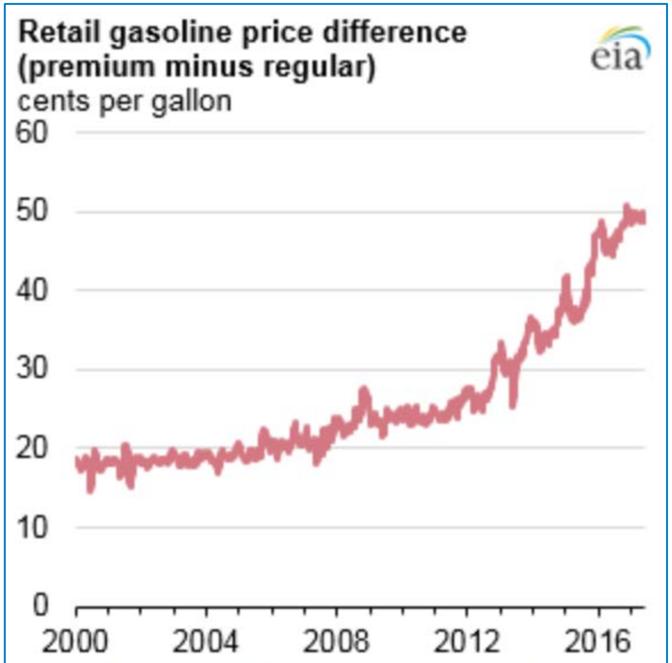
# HOG Pathway Related Information

## Previously Published Sensitivity Analysis with Natural Gas Co-Feed




**Details at:** https://www.nrel.gov/docs/fy15osti/62402.pdf

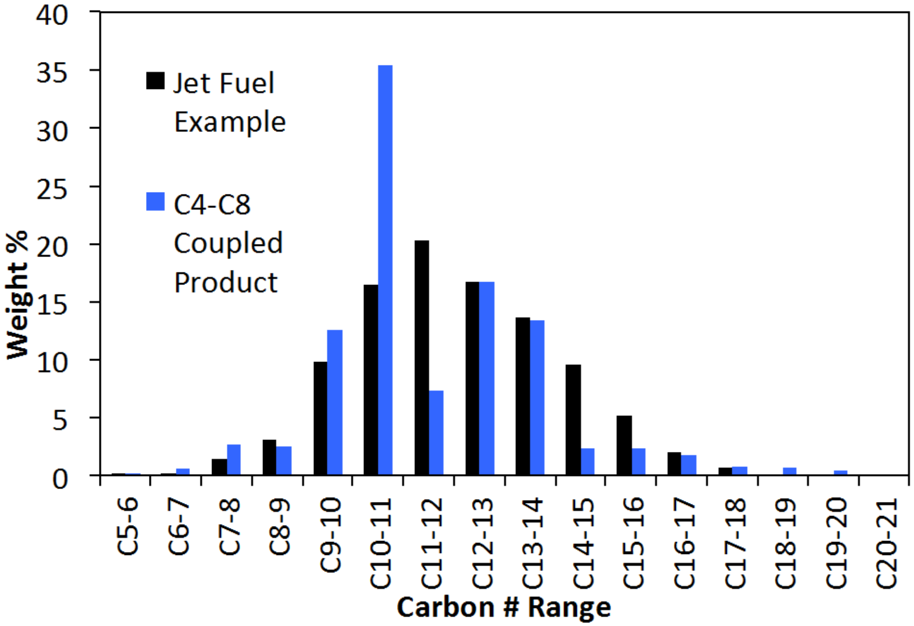
## Margin for Premium Gasoline

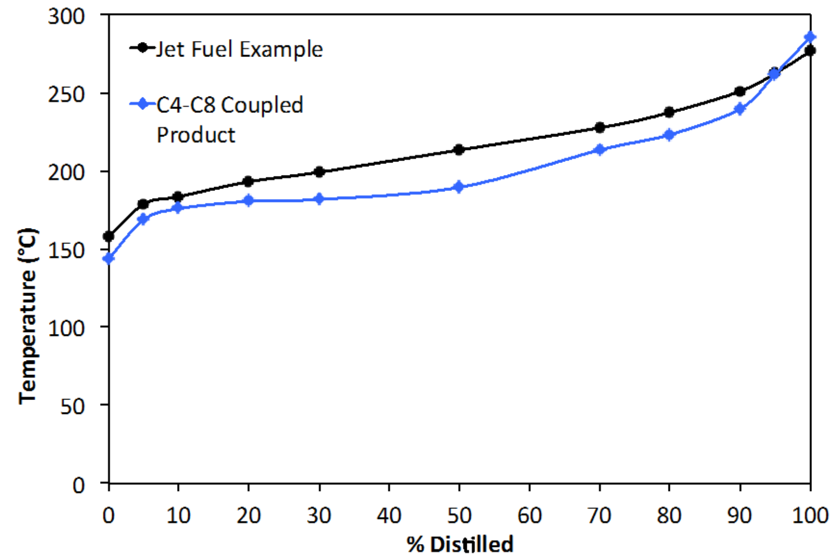



**https://www.eia.gov/todayinenergy/detail.php?id=31732**

# HOG Pathway Sensitivity: Jet Fuel Analysis

## $C_4$-$C_8$ olefin coupling produces a $C_8$-$C_{20}$ distribution of HCs, with >90% being suitable as a jet fuel blendstock




| Fuel Properties | Jet Fuel ASTM D1655 Limits | Synthetic Fuel from Olefin Coupling |
|---|---|---|
| Viscosity ($mm^2/s$) | 8.0 max | 7.6 |
| Freeze Point (°C) | –40 max | –81 |
| Density ($kg/m^3$) | 775 – 840 | 783 |
| LHV (MJ/kg) | 42.8 min | 43.8 |

M. Behl, et al., *Energy & Fuels* 29 **2015** 6078, NREL Milestone Report Dec 2015.