NREL
Transforming ENERGY

BETO 2021 Peer Review Thermochemical Platform Analysis – NREL

WBS: 2.1.0.302

March 9, 2021
Catalytic Upgrading Session
PI: Abhijit Dutta
National Renewable Energy Laboratory

Acronyms Used

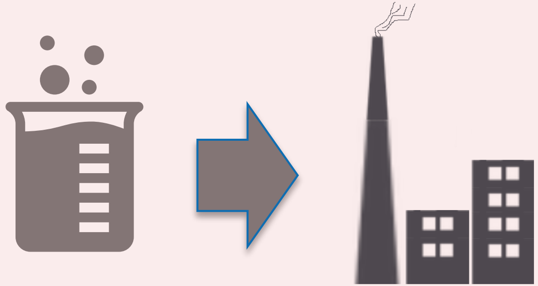
BETO: Bioenergy Technologies Office
CCPC: Consortium for Computational Physics and Chemistry
CFP: Catalytic Fast Pyrolysis
DME: Di-Methyl Ether
FCC: Fluid Catalytic Cracking
FCIC: Feedstock-Conversion Interface Consortium
FP: Fast Pyrolysis
FY: Fiscal Year (e.g., FY21 is fiscal year 2021)
HOG: High-Octane Gasoline
GGE: Gallon Gasoline Equivalent
LCA: Life-Cycle Analysis
MFSP: Minimum Fuel Selling Price
MYP: Multi-Year Plan (BETO)
SOT: State of Technology
TEA: Techno-Economic Analysis

Project Overview

- Primarily focused on **techno-economic analysis (TEA)** and process sustainability
- Helps **guide research** in productive directions
- Provides **industrial context and risk information** for research activities

High-Level Goals

Provide Context for Research



What is a scaled-up implementation?

Add Value with Predictive Models

Aspen Plus By AspenTech for process

Excel for economics

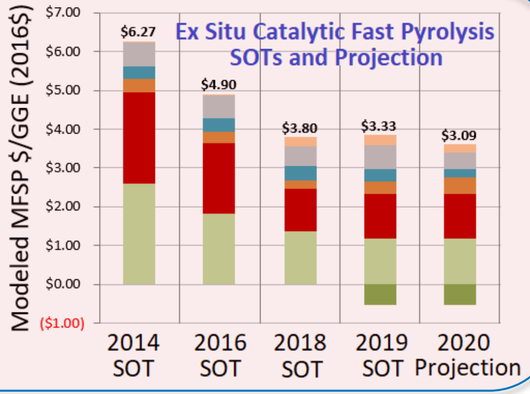
Focus experimental efforts on most impactful areas to fill data and research gaps

Help Identify and Fill Gaps & Risks

Mitigate scale-up risks within lab/pilot research

Develop Technical Targets Associated with Modeled Costs

Track achievement of technical targets and research advancements



Provide Alternatives for Research Roadblocks

Research Interaction to Solve Problems

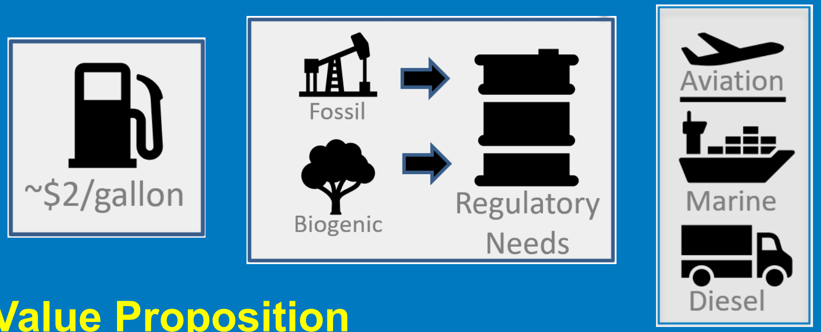
MFSP: Minimum Fuel Selling Price. **SOT:** State of Technology. Technical and cost projection details at: https://www.nrel.gov/docs/fy20osti/76269.pdf.

Overview

Relevant Market Trends

Product	Anticipated decrease in gasoline/ethanol demand; diesel demand steady
Product	Increasing demand for aviation and marine fuel
Product	Demand for higher-performance products
Product	Increasing demand for renewable/recyclable materials
Feedstock	Sustained low oil prices
Feedstock	Decreasing cost of renewable electricity
Feedstock	Sustainable waste management
Feedstock	Expanding availability of green H_2
Feedstock	Closing the carbon cycle
Capital	Risk of greenfield investments
Capital	Challenges and costs of biorefinery start-up
Capital	Availability of depreciated and underutilized capital equipment
Social Responsibility	Carbon intensity reduction
Social Responsibility	Access to clean air and water
Social Responsibility	Environmental equity

Major Trends since 2019 Peer Review



Value Proposition

- Enable efficient research for biogenic liquid transportation fuels

Differentiators

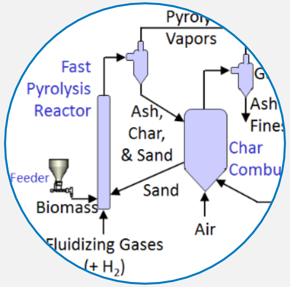
- **Predictive process modeling**
  - Magnifies impact of experimental research
- **Core domain knowledge**
  - Provides expert guidance on biomass conversion technologies
- **Industrially relevant models/reports**
  - Serves industry, academia, other research institutions, and BETO needs

Management

Overview – Core Research & Supporting Work

Core Research Areas

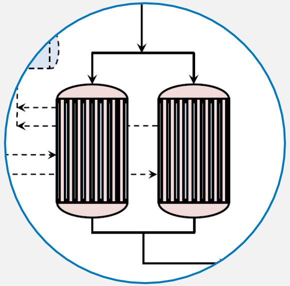
Thermo-Catalytic Conversion



Catalytic Pyrolysis

WBS 2.3.1.314

Catalytic Upgrading of Pyrolysis Vapors



Syngas Conversion

WBS 2.3.1.305

Upgrading of C1 Building Blocks

Current Focus

Refinery Coprocessing & Compatibility

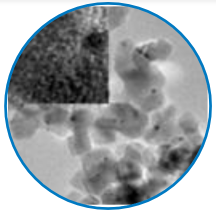
- Co-hydrotreating
- Co-FCC processing
- Industrial input on assumptions
- Closeout standalone catalytic (Pt/TiO_2) fast pyrolysis pathway

Synthetic Liquid Fuels

- High-Octane Gasoline
- Jet and diesel
- Process intensification
- Waste & CO_2 use

Risk Mitigation

Support & Collaboration

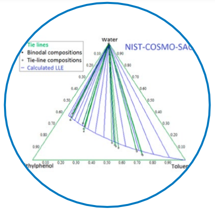


Catalyst R&D, Experimental Data

Collaboration with ChemCatBio (Chemical Catalysis for Bioenergy)

Feedstock

Collaboration with INL Idaho National Laboratory, fcic



Predictive Phase Equilibrium

Collaboration with NIST

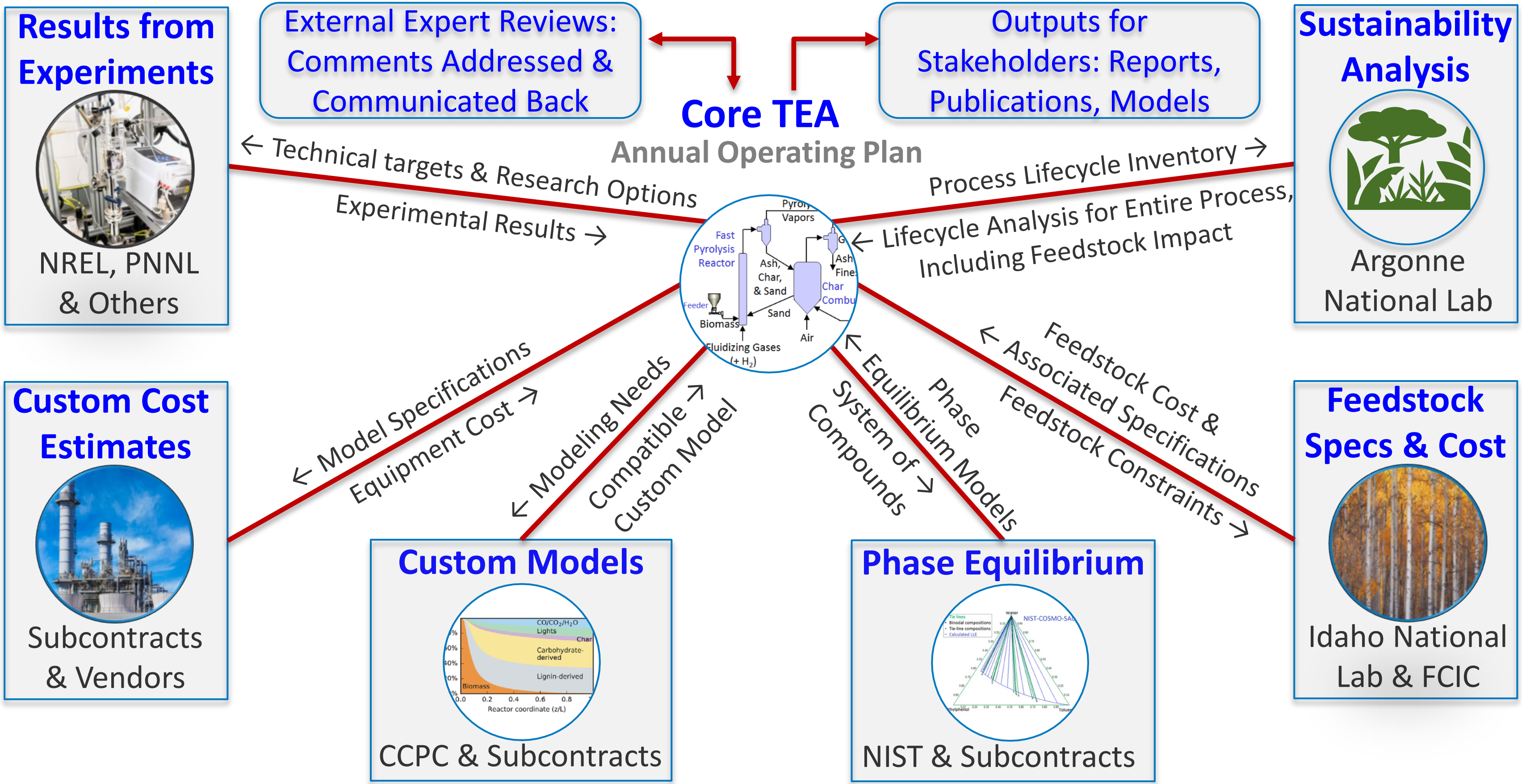
Some other collaborations:

Johnson Matthey; Pacific Northwest National Laboratory; Consortium for Computational Physics and Chemistry; ExxonMobil*; Argonne National Laboratory

*EMRE is working with NREL on biomass pyrolysis

Management

Management – Collaborators and Communication



NIST: National Institute of Standards and Technology. **CCPC:** Consortium for Computational Physics and Chemistry. **FCIC:** Feedstock-Conversion Interface Consortium. **TEA:** Techno-Economic Analysis

Management of Risk, Communication, Advisory Boards

Built into Overall Project Workflow

Risks/challenges and mitigation approach *for this project*

- Specifics on **Slide 12**

Technology risk identification and mitigation *for overall research*

- Specific example on **Slide 18**

Communication and collaboration with *related projects and/or advisory boards*

- Specific examples on **Slide 19** and **Slide 26**

Approach

Approach

Technical Approach for Analysis Work

Rigor Based on Requirement & Stage of Research

- Quick Turnaround Analysis
- More Detailed Analysis
- Detailed Design Report

Tools Used and Other Inputs

Aspen Plus	Excel	GREET LIFE-CYCLE MODEL 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

Approach for Addressing Project Challenges

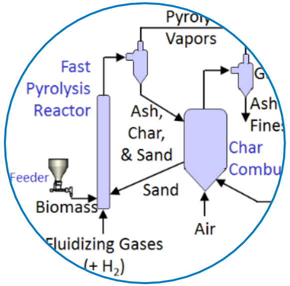
Key Risks and Challenges for this project [mitigation]

- **Limited data**
  - [sensitivity analysis / request more experiments]
- **Provide alternate R&D approaches**
  - [versatile predictive models with adaptability]
- **Rigor vs speed**
  - [efforts planned based on impact of analysis]
- **Predictive modeling**
  - [strategic partnerships and subcontracts]

Technical Approach for Current Focus Areas

Analysis to enable broader pyrolysis oils use in refineries - Hydrotreating and FCC

Catalytic Fast Pyrolysis



*Details in slide 22

- **Closeout* of standalone hydrotreating pathway in FY21**
  - Final report to document learnings, gaps, and risks
- **Shift focus to pyrolysis oils coprocessing**
- **Co-hydrotreating TEA developed**
  - Based on preliminary experimental yields
- **Lower quality feed and solid waste (MSW)**

Experimental project: WBS 2.3.1.314 Catalytic Upgrading of Pyrolysis Vapors

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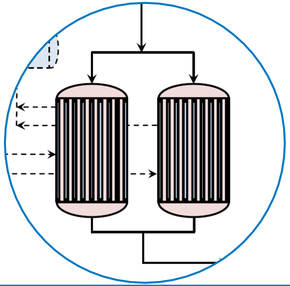
Enable Efficient Conversion to Gasoline, Diesel, Jet

Syngas Conversion



- **Understand and optimize research results in the context of a process with recycles**
  - Recommendations of more optimal conditions
  - Separation strategies in integrated process
- **Process intensification for single-step syngas to fuels**
- **Diversified feedstocks: Solid waste and CO_2**

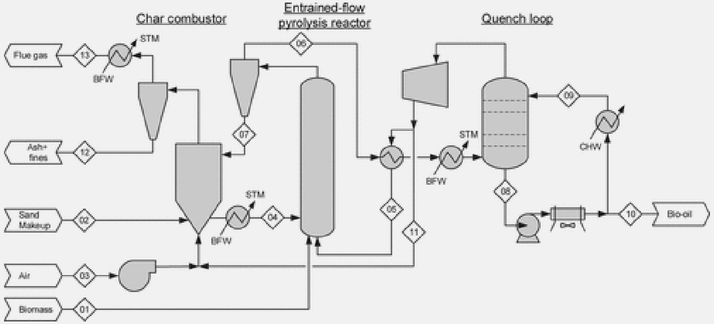
Experimental Project: WBS 2.3.1.305 Upgrading of C1 Building Blocks

Technical and economic metrics developed & tracked via research interaction

Subcontract Work to Advance Modeling Capabilities

Examples of Subcontract Work Integrated into Core TEA

Design and cost evaluations of biomass pyrolysis systems



Prior Reference for Figure: ACS Sustainable Chem. Eng. 2017, 5, 3, 2463–2470

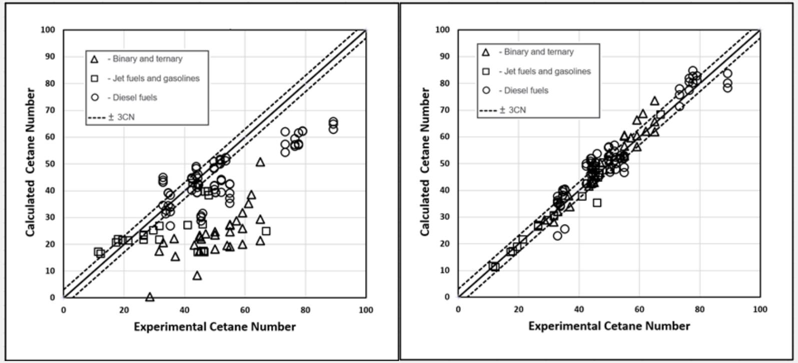
Impact: Allow design, sizing, cost estimates for custom pyrolysis equipment for TEA

Work performed by Humbird.

TEA: Techno-Economic Analysis

Prediction of Fuel Properties in Models using Representative Surrogate Molecules

Existing Literature | Current Work



Example of Cetane Number Predictions

Impact: Enable predictive fuel properties for *Refinery Integration*

Work performed by Watanasiri

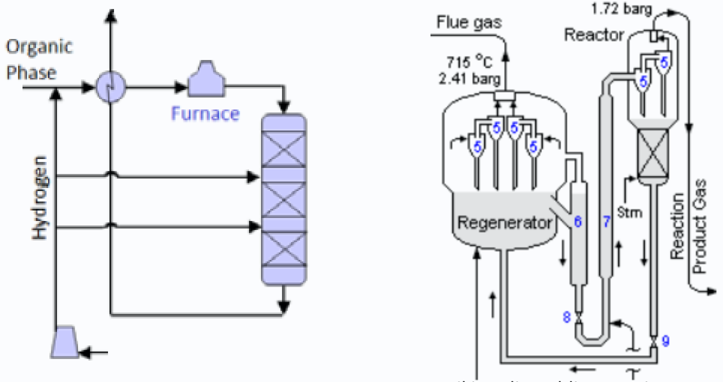
Publication of above and other subcontract work anticipated in FY2021

Focus Starting FY21 – Refinery Coprocessing of Py-Oil

Use Domain Knowledge and Predictive Modeling to Understand the Impact of Heterogeneous Feedstocks in Petroleum Refineries

Hydroprocessing

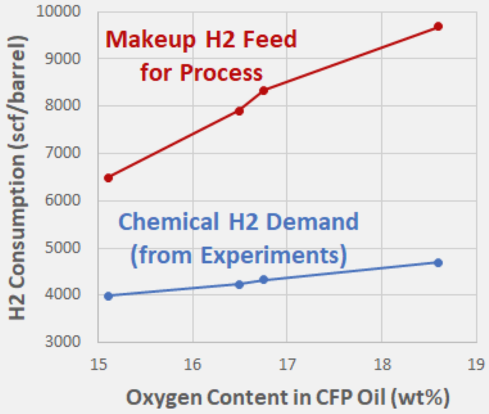
FCC



Wikimedia Public Domain Image

Example: Put Lab-Scale Experimental Work in the Context of Refinery Processes

Oxygen Content → ; Aromatics Saturation → ; ← Hydrogen Purity ; ← Reactor Heat Removal



Leverage Existing Modeling Capabilities

(Example plot using FY16-FY19 Catalytic Fast Pyrolysis State of Technology Analyses)

Workflow – Process & SCR Analysis

CFP Oil Focus → **Value to Refiner**

Aspen Plus By AspenTech

Aspen PIMS By AspenTech

Process Analysis – under this project

Assessment under SCR Analysis

SCR: Strategies for Co-processing in Refineries (separate BETO project); **CFP:** Catalytic Fast Pyrolysis; **FP:** Fast Pyrolysis.

Impact

Impact

Broad Impact

Direct Collaboration with Industry Partners

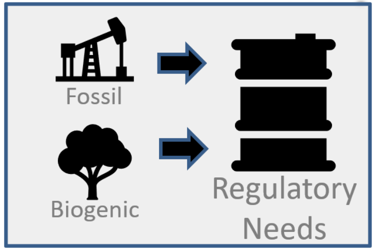
Leverage Knowledge & Modeling Capabilities from BETO Research

ExxonMobil*

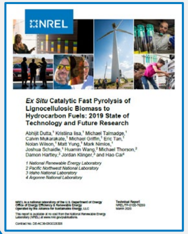
*EMRE is working with NREL on biomass pyrolysis

Other industrial entities (not listed) engaged via experimental projects

Facilitate Biogenic Carbon in Fuels and Products via Detailed Analysis

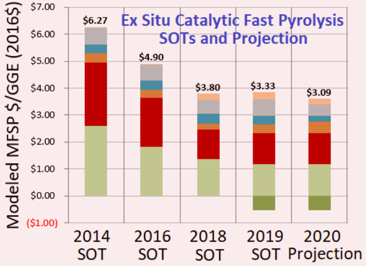


Publications to Disseminate Knowledge & Learnings



- Detailed design reports
- State of Technology updates
- Journal articles

Annual State of Technology to Track & Guide Research



Other Products

- Software records for **detailed models** – available for licensing
- **Patents**/applications (led by experimental team)

Sample Models Publicly Available

https://www.nrel.gov/extranet/biorefinery/aspen-models/

NREL Transforming ENERGY

Biorefinery Analysis Process Models

Download and use by stakeholders, including academia and industry

List of publications, reports etc. since 2019 review is included in the Additional Slides section

Impact

Risk Identification and Management – CFP Pathway

Underlying Goal to Achieve <$3/GGE Modeled MFSP during 2022 Verification

(**CFP**: Catalytic Fast Pyrolysis; **MFSP**: Minimum Fuel Selling Price; **GGE:** Gallon Gasoline Equivalent; **SOT:** State of Technology)

Conversion Process from 2019 Peer Review

Biomass → CFP*

Fluidizing Gas & H_2

CFP Oil ↓

Standalone Hydrotreating

↓ Fuel Blendstock Product

*Pt/TiO_2 CFP Catalyst

Gap in Carbon Balance Closure

R Assumption of **Prorated Distribution** of Missing Carbon to Gas, Char, Liquid

M Sensitivity Analysis for Uncertainty

Higher Yield (+8.6%)	Base Case	Lower Yield (-13%)
Lower Cost -4.8%	From 2018 SOT Report NREL/TP-5100-71954	Higher Cost +10.5%

~100% Carbon Balance Closure

Most of the Missing Carbon in **Acetaldehyde, Acetone, 2-Butanone (MEK)**

2018 MFSP Revised from **$3.50/GGE to** R **$3.80/GGE**

From: NREL/TP-5100-76269

TEA Options with Preliminary Experiments

Adsorption-Based M Recovery of **Acetone & 2-Butanone (MEK) (~$0.50/GGE)**

M **Refinery Co-Hydrotreating (~$0.25/GGE)**

From: NREL/TP-5100-76269

Risk from ~88% C-Balance Closure → Add Experimental Analytics M → Identify Cost Reduction with Current Catalyst

R Risk

M Mitigation/ Management

Experimental project: WBS 2.3.1.314 Catalytic Upgrading of Pyrolysis Vapors

Impact

Go/No-Go Decision for 2022 Verification (Ex-Situ CFP)

Go/No-Go for using this pathway for 2022 Verification to Achieve <$3/GGE Modeled MFSP

Work done jointly with experimental teams at NREL, PNNL, INL, and sustainability at ANL

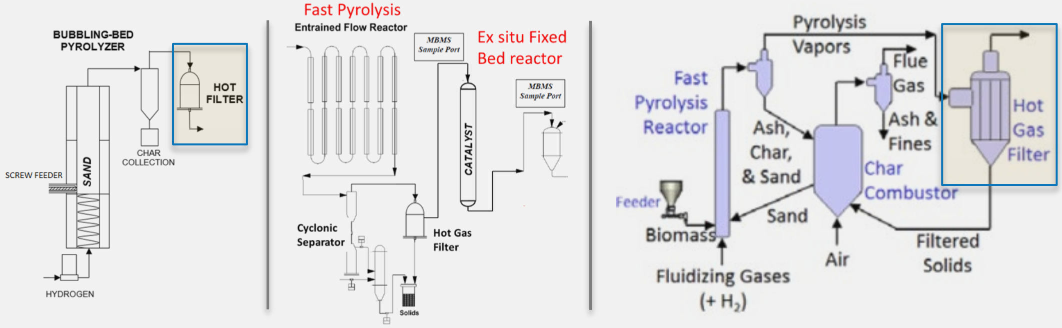
NREL Transforming ENERGY — Catalytic Fast Pyrolysis

Pacific Northwest National Laboratory — Hydrotreating

Idaho National Laboratory — Feedstock Specs & Cost

Argonne National Laboratory — Lifecycle Analysis

Detailed Scale-up Assumptions for CFP Verification



Bench Scale → **Pilot Scale** → **Conceptual Scaleup**

List of Key Risks and Experimental Mitigation Strategies Developed

Independent Engineering, BETO, and Lab Reviews

No-Go for Verification

Some key reasons:

Short timeline for **lower TRL** light oxygenates recovery and co-hydrotreating

Opportunity

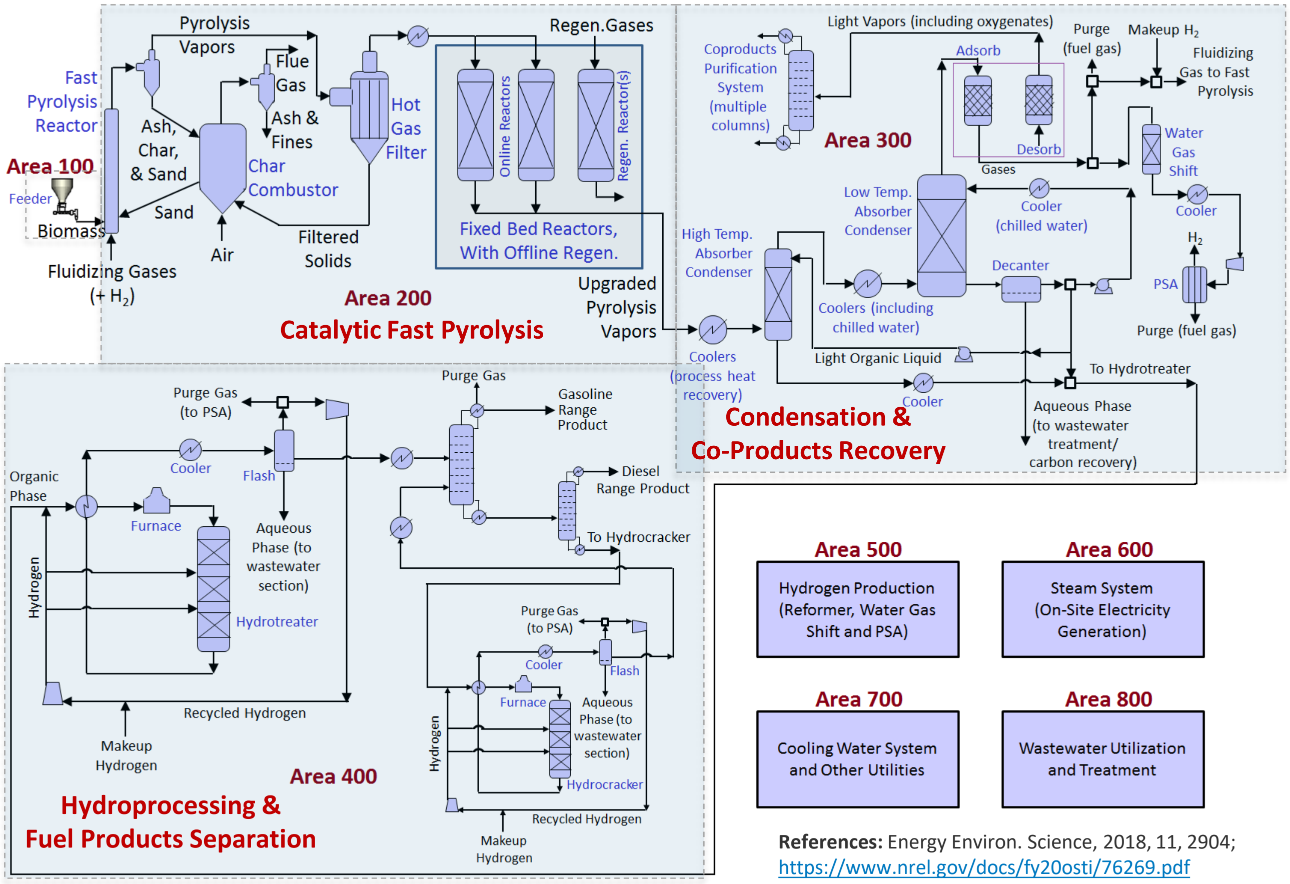
Broaden for Liquid Biogenic Carbon:

Expand approaches for **refinery use** of pyrolysis-derived oils

Experimental Catalytic Fast Pyrolysis (CFP) project: WBS 2.3.1.314 Catalytic Upgrading of Pyrolysis Vapors

Progress and Outcomes

CFP with Standalone Hydrotreating – Process Flow



References: Energy Environ. Science, 2018, 11, 2904; https://www.nrel.gov/docs/fy20osti/76269.pdf

Area 100: Feedstock

Area 200: Fast Pyrolysis and Ex-Situ Catalytic Upgrading

Area 300: Condensation & Light Oxygenates Recovery

Area 400: Hydroprocessing & Fuel Product Separation

Area 500: Hydrogen Production from Off-Gases

Area 600: Steam System & Power Generation

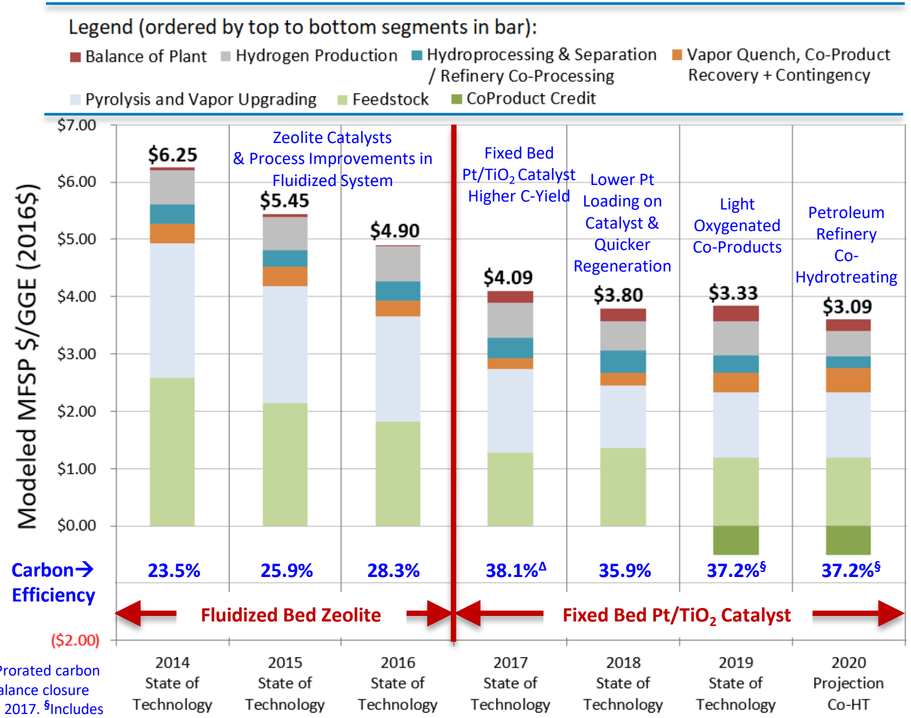
Area 700: Cooling Water & Utilities

Area 800: Wastewater Treatment

Progress & Outcomes

CFP with Standalone Hydrotreating –Closeout in FY21

Considerable progress towards reducing the MFSP
- Significant risks remain for scale-up
- TEA data gaps to be addressed during closeout



ΔProrated carbon balance closure in 2017. §Includes coproducts.

>60% GHG reduction over petroleum-derived gasoline for all cases

Closeout Process*

- *TEA using new experimental data (FY21 Q2)*
  - Light oxygenates recovery
  - Co-hydrotreating CFP-oil with diesel (SRD)
- ***Document & help reduce risks for future adoption***
  - Leverage research since 2014 & FY21 expt. info.
  - Document risks, e.g. for catalyst regeneration

***Further details presented under**

WBS 2.3.1.314

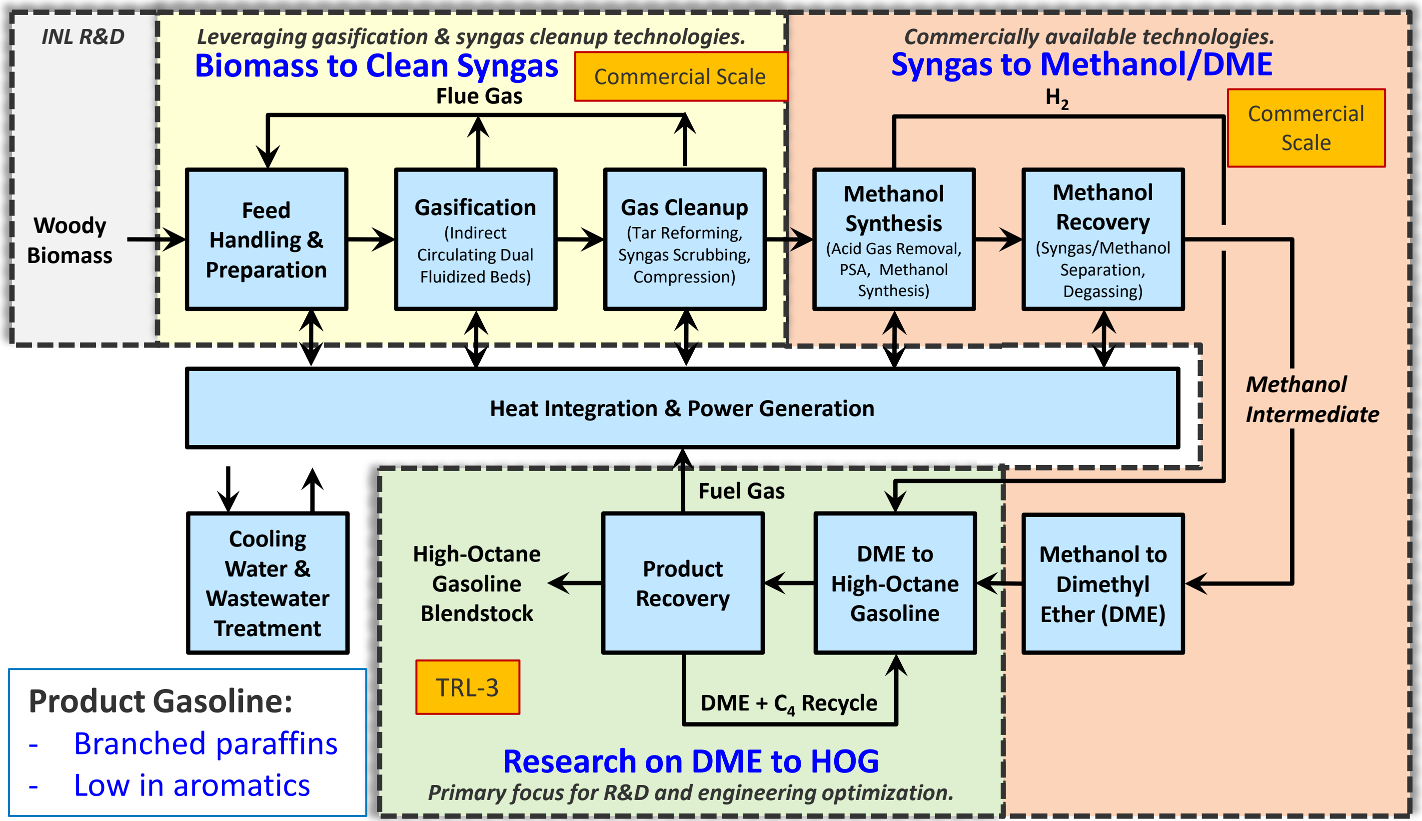
Catalytic Upgrading of Pyrolysis Vapors

References: Energy Environ. Science, 2018, 11, 2904; https://www.nrel.gov/docs/fy20osti/76269.pdf

SOT: State of Technology; **MFSP:** Minimum Fuel Selling Price; **Co-HT:** Co-hydrotreating (at petroleum refinery); **SRD:** Straight run diesel

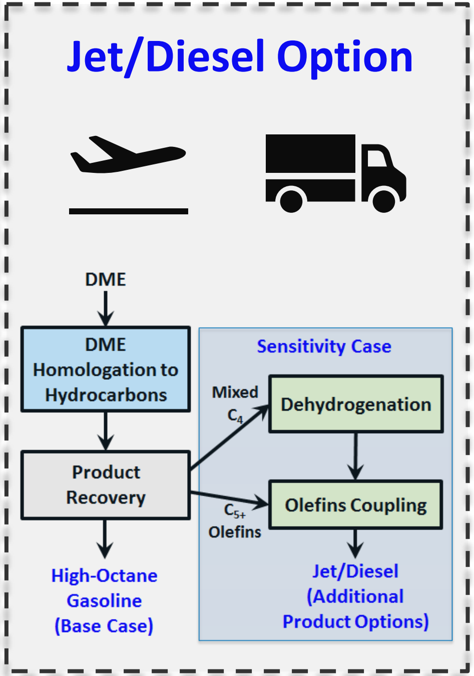
Syngas to High-Octane Gasoline Conceptual Process

Progress & Outcomes



Product Gasoline:

- Branched paraffins
- Low in aromatics



Related Presentation

WBS 2.3.1.305

Upgrading of C1 Building Blocks

Analysis includes use of waste material and CO_2

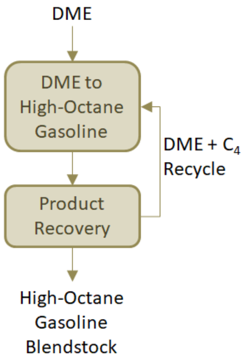
References: Nature Catalysis, Vol 2, pages 632–640 (2019); https://www.nrel.gov/docs/fy20osti/76619.pdf; https://www.nrel.gov/docs/fy15osti/62402.pdf

HOG: High-Octane Gasoline. **TRL:** Technology Readiness Level.

State of Technology – Challenges and Gaps

Research progress

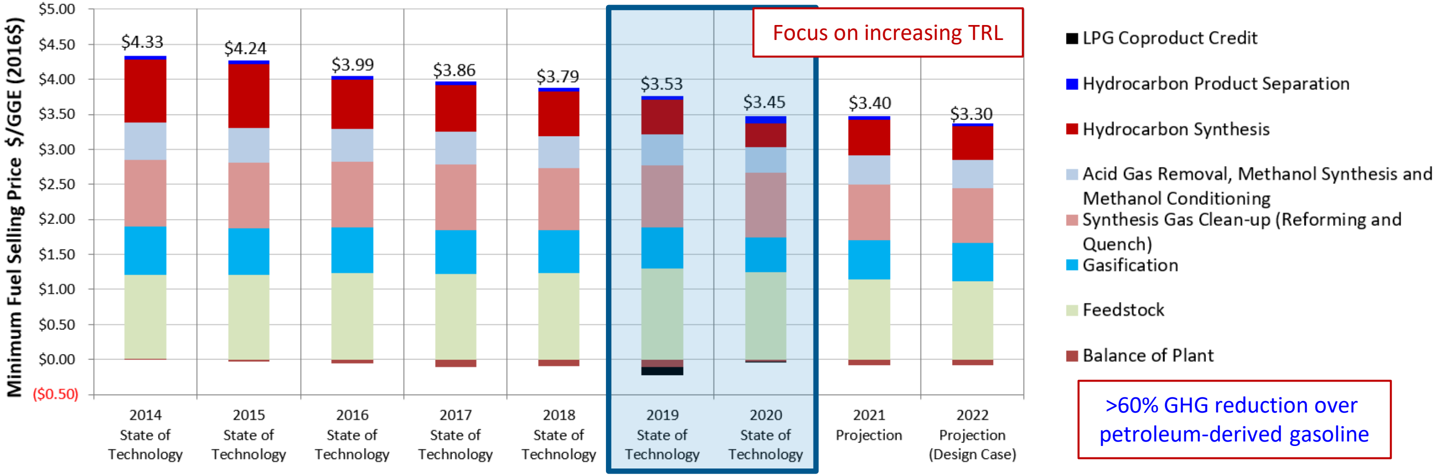
- Increased conversion & selectivity
- Increased C5+ products via reaction of recycled C4
- Reduced aromatics formation



Risks & challenges for increasing TRL

- Catalyst related (ongoing research):
  - Scale-up, regeneration, longevity
- Current experiments not integrated
  - DME used in first step
  - Simulated recycle via co-fed C4
- Full range of C4 recycle tests
  - Tests being run

Additional information under : WBS 2.3.1.305 Upgrading of C1 Building Blocks



>60% GHG reduction over petroleum-derived gasoline

TRL: Technology Readiness Level.

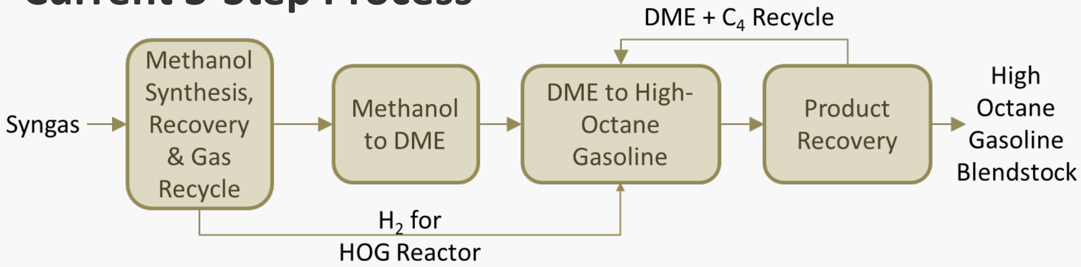
References: Nature Catalysis, Vol 2, pages 632–640 (2019);
https://www.nrel.gov/docs/fy20osti/76619.pdf; https://www.nrel.gov/docs/fy15osti/62402.pdf

1-Step Conversion & Related FY21 Go/No-Go Decision

Go/No-Go decision for adopting single-step process will be based on experimental data and TEA

Due Date: 6/30/2021

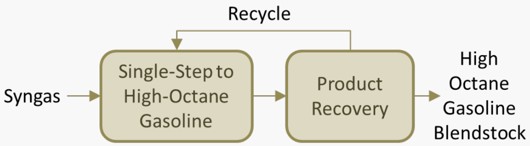
Current 3-Step Process



Take Advantage of Sequential Reactions & Overcome Reaction Equilibrium Limitations

Lower Capital Cost Option

1-Step Syngas to HOG



Initial exploratory TEA completed FY20 Q4

Key Challenges & Research:

- Optimal catalyst formulation
- Syngas conditioning
  - Improvements with more H_2
- Reduce C4 and CO_2 selectivity
- System pressure and space velocity optimization

Related Presentation
WBS 2.3.1.305
Upgrading of C1 Building Blocks

HOG: High-Octane Gasoline;
TEA: Techno-Economic Analysis

References: Nature Catalysis, Vol 2, pages 632–640 (2019); https://www.nrel.gov/docs/fy20osti/76619.pdf; https://www.nrel.gov/docs/fy15osti/62402.pdf

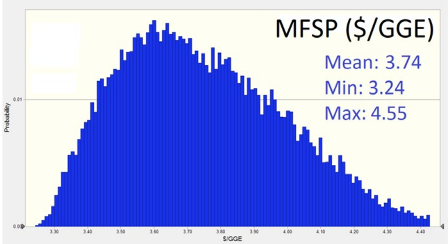
Example of Collaboration with Other Projects – FCIC / CCPC

Modeling Cost Impacts of Feedstock Material Attributes on CFP Process:

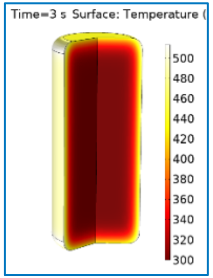
Integration of Multi-Scale Models into TEA

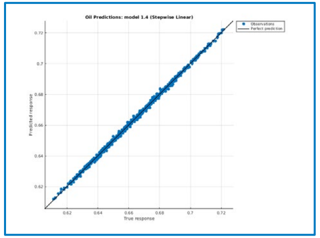
Varied Feed/Reactor Parameters	
Feedstock Material Attributes	• mineral matter content • moisture content • particle size • extractives content
Fast Pyrolysis Process Parameters	• reactor temperature

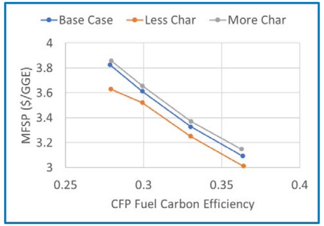
Input Parameters → **Output MFSP**



MFSP Distribution







Validated Particle-Scale Model (FCIC/CCPC) → **Multiple Linear Regression Models (FCIC/CCPC)** → **Link with MFSP from CFP TEA models (FCIC/TEA Task)** → Monte-Carlo Simulation → **MFSP Distribution**

FCIC: Feedstock-Conversion Interface Consortium; **MFSP**: Minimum Fuel Selling Price; **FP**: Fast Pyrolysis; **CFP**: Catalytic Fast Pyrolysis; **TEA**: Techno-Economic Analysis; **CCPC:** Consortium for Computational Physics and Chemistry; **GGE:** Gallon Gasoline Equivalent

Summary

Summary

Value Proposition

- Help address **immediate industry needs for biogenic carbon** in liquid fuels
- Continue to **guide and establish research metrics** in the context of scale-up
  - Help identify and address **associated risks**

Accomplishments

- Detailed analysis for **key decision points** & related changes
  - Catalytic Fast Pyrolysis pathway
  - Syngas conversion to high-octane gasoline (with options for jet and diesel) pathway

Quad Chart Overview

Timeline

- Project start date: October 1, 2019
- Project end date: September 30, 2022

	FY20	Active Project
DOE Funding	$700k	$2,100k (for 3 years)

Barriers addressed

Ot-B: Cost of production

Ct-F: Increasing the yield from catalytic processes

Project Goal

To inform and guide R&D priorities for thermal and catalytic conversion processes through process-design-based TEA† and LCA‡. Specific conversion pathways of focus are Catalytic Fast Pyrolysis (CFP) and syngas to high-octane gasoline (HOG) or indirect liquefaction (IDL)

End of Project Milestone

Analyze and quantify refinery integration approaches and feasible coproducts from fast pyrolysis based pathways, associated risks, and cost reduction impacts. Additional approaches may include indirect liquefaction of waste streams for low-cost fuels production. This milestone will help set up a combination of potential thermo-catalytic options (at least 2 combinations) for specific approaches towards achieving the BETO goal of $2.5/GGE by 2030. Provide analysis support (as requested) to the BETO office for the verification of a biomass to finished fuels pathway towards achieving a modeled MFSP of <$3.00/GGE in 2016$.

Funding Mechanism

National laboratory project funded by BETO.

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

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Thank you

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Additional Slides

Responses to Previous Reviewers' Comments

Comment 1: A very critical component to the activities of CCB as a whole. Milestones were met throughout the prior funding periods and the milestone planning both near and long term seem appropriate. **Response:** Thank you for the feedback.

Comment 2: Overall, this is a very important enabling technology for emerging biomass processing technologies. My only concern based on past exposure to TEA is that they are based on a large number of assumptions and often may invoke the most optimistic case rather than most likely cases. The team may want to consider that attainable yields/selectivities/rates are probably uncertain and should forecast that impact (e.g., Monte Carlo based TEA to consider uncertainty). **Response:** The projections for future research, presented in design reports, are based on researchers' and reviewers' feedback about attainable performance goals. We include sensitivity analysis to show the impacts of various parameters and the effects of over- and under-performance compared to the baseline analysis. The State of Technology assessments are based on experimental data, but at smaller scales compared to the conceptual designs. We thank the reviewer for the comment, and will continue to emphasize and expand on areas where we need to assess uncertainty (Monte Carlo analysis may be helpful at times, but may not always help develop additional insights as compared to single-point sensitivities). *Current example: A case study with Monte Carlo included in presentation.*

Comment 3: Overall, this is a strong well managed project with solid deliverables thus far. The TEA work is probably the most impactful work to BETO because of its influence on R&D direction. It is extremely important to get this right. I would encourage the project team not to settle on the current tools and in fact, continue to explore ways of enhancing the modeling capability that allows multiple scales to be incorporated into the analysis. Please continue to harmonize with the work of the Biochemical Platform Analysis project. The less severe condition and shape selective pivot away from MTG is small and the premise is still the same; small alcohol conversion over modified zeolites. This is a winning formula. **Response:** Thank you for the feedback. We work with the computational consortium (CCPC) that does multi-scale modeling. We will continue to pay attention to their work and include any tools that are useful for TEA into our work. An example of such a collaboration is the development of a 1-d entrained reactor model compatible with the TEA modeling framework. We will continue to harmonize with the Biochemical Platform Analysis project; please note that we use the same set of assumptions and modeling frameworks as the work done under that project and our tools and methods have the same genesis. *Current example of integration of multi-scale model with CCPC included in presentation.*

Comment 4: The thermochemical conversion team has produced significant advances over the past two years and now appears to be on target to meet BETO cost and sustainability objects. The new process scheme and catalysts have performed as predicted. The next steps would be to address operability issues that have plagued other efforts. A detailed feasibility study by an independent outside group would confirm these results. The project shows great synergy with other groups INL and Argonne, NIST and other groups. The outputs included Technical Metrics, LCA, MFSP, Reports and Journal Articles. The TEA shows a path for biomass to fuel of less than $2.50 per gallon, however, it should be noted that this is a comparative number valid for comparing DOE projects. The initial costs of the fuel produced by early plants is likely to be significantly higher. The progress made by this project is impressive, the thermal conversion team addressed many of the comments from the last peer review and has found new catalysts and other improvements that greatly improve the likelihood of success. **Response:** We appreciate the comments and agree with the reviewer about operability issues that we plan to address through pilot scale tests. Although higher costs and problems associated with pioneer plants are not explicitly mentioned, we are working closely with other groups, including the FCIC, to understand and address those uncertainties. *Current example of critical evaluation and due diligence included in this presentation.*

Publications, Patents, Presentations, Awards, and Commercialization (1)

- Ruddy, D.A.; Hensley, J.E.; Nash, C.P.; Tan, E.C.D.; Christensen, E.; Farberow, C.A.; Baddour, F.G.; Van Allsburg, K.M.; Schaidle, J.A. Methanol to high-octane gasoline within a market-responsive biorefinery concept enabled by catalysis. **Nature Catalysis**, Vol 2, pages 632–640 (2019).
- Wilson, A.N.; Dutta, A.; Black, B.A.; Mukarakate, C.; Magrini, K.; Schaidle, J.A.; Michener, W.E.; Beckham, G.T.; Nimlos, M.R. Valorization of aqueous waste streams from thermochemical biorefineries. **Green Chemistry**, 2019. DOI: 10.1039/c9gc00902g.
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- Tan, E.C.D. "Sustainable Biomass Conversion Process Assessment", **book chapter** in *Recent Advances in Process Intensification and Integration for Sustainable Design* Wiley VCH (ISBN-13: 978-3527345472). Accepted for publication in May 2020.
- Tan, Eric C.D., Dan Ruddy, Connor Nash, Dan Dupuis, Kylee Harris, Abhijit Dutta, Damon Hartley, and Hao Cai. 2020. High-Octane Gasoline from Lignocellulosic Biomass via Syngas and Methanol/Dimethyl Ether Intermediates: 2019 State of Technology. Golden, CO: National Renewable Energy Laboratory. **NREL/TP-5100-76619**. https://www.nrel.gov/docs/fy20osti/76619.pdf.
- Cai, H., L. Ou, M. Wang, E.C.D. Tan, R. Davis, and A. Dutta et al. 2020. Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2019 State-of-Technology Cases and Design Cases. **ANL/ESD-20/2**. Lemont, IL: Argonne National Laboratory. https://greet.es.anl.gov/publication-renewable_hc_2019.

Publications, Patents, Presentations, Awards, and Commercialization (2)

- Integrated Strategies to Enable Lower-Cost Biofuels, July 2020, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2020/07/f76/beto-integrated-strategies-to-enable-low-cost-biofuels-july-2020.pdf.
- Yeonjoon Kim, Anna E. Thomas, David J. Robichaud, Kristiina Iisa, Peter C. St. John, Brian D. Etz, Gina M. Fioroni, Abhijit Dutta, Robert L. McCormick, Calvin Mukarakate, Seonah Kim. A perspective on biomass-derived biofuels: From catalyst design principles to fuel properties. **Journal of Hazardous Materials**. Volume 400, 5 December 2020, 123198. https://doi.org/10.1016/j.jhazmat.2020.123198.
- Dell'Orco, Stefano; Christensen, Earl; Iisa, Kristiina; Starace, Anne; Dutta, Abhijit; Talmadge, Michael; Magrini, Kimberly; Mukarakate, Calvin. On-line Biogenic Carbon Analysis Enables Refineries to Reduce Carbon Footprint during Co-processing Biomass- and Petroleum-derived Liquids. **Analytical Chemistry**. Accepted Feb 16, 2021.
- Gina Fioroni, Brad Zigler, Jon Luecke, Abhijit Dutta, Robert L. McCormick, T. Bays, E. Polikarpov, C. Taatjes. Fuel Property Characterization and Prediction. 2019 Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting, 10-13 June 2019.
- Suphat Watanasiri; Abhijit Dutta. Octane and Cetane Number Predictions for Use in Biomass Conversion Process Models. Poster presented at **TC Biomass, 2019**, Chicago, Oct 7-9 2019.
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- Dutta, Abhijit. Ex Situ and In Situ Catalytic Fast Pyrolysis Models (ASPEN PLUS MODELS). **Computer Software Record**. USDOE Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (EE-3B). 27 Feb. 2019. Web. doi:10.11578/dc.20190515.4.

Additional content for conversion pathways

- Catalytic Fast Pyrolysis (CFP)

Catalytic Fast Pyrolysis (CFP) SOT and Projections (1)

Sustainability and Process Efficiency Metrics	Units	2014 SOT	2015 SOT	2016 SOT	2017 SOT[a]	2018 SOT	2019 SOT	2020 Projection
Process Concept: Hydrocarbon Fuel Production via *Ex Situ* Upgrading of Fast Pyrolysis Vapors		Clean Pine	Clean Pine	Clean Pine	Clean Pine	Clean Pine	50% Residues/ 50% Pine[c]	50% Residues/ 50% Pine[c]
Year Dollar Basis		2016	2016	2016	2016	2016	2016	2016
Projected MFSP	**$/GGE**	**$6.27**	**$5.44**	**$4.90**	**$4.09**	**$3.80**	**$3.33**	**$3.09**
Conversion Contribution	$/GGE	$3.66	$3.30	$3.08	$2.82	$2.44	$2.14	$1.90
Total Project Investment per Annual GGE	$/GGE-yr	$18.50	$16.46	$14.94	$12.17	$12.47	$13.53	$12.32
Plant Capacity (Dry Feedstock Basis)	metric tons/day	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	65	59	59
Diesel-Range Product Proportion (GGE Basis)	% of fuel product	15%	15%	15%	52%	52%	48%	48%
Feedstock								
Total Cost Contribution[d]	$ /GGE	$2.60	$2.14	$1.82	$1.27	$1.36	$1.18	$1.19
Capital Cost Contribution[d]	$/GGE	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Operating Cost Contribution[d]	$/GGE	$2.60	$2.14	$1.81	$1.27	$1.35	$1.18	$1.18
Feedstock Cost[e]	$/dry ton	$109.01	$98.31	$92.70	$87.82	$87.82	$70.15	$70.15
Feedstock Moisture at Plant Gate	wt % H_2O	10%	10%	10%	10%	10%	10%	10%
Feed Moisture Content to Pyrolyzer	wt % H_2O	10%	10%	10%	10%	10%	10%	10%
Energy Content (LHV, Dry Basis)	Btu/lb	8,000	8,000	8,000	8,000	8,000	7,900	7,900
Pyrolysis and Vapor Upgrading								
Total Cost Contribution[d]	$/GGE	$2.60	$2.14	$1.82	$1.27	$1.36	$1.18	$1.19
Capital Cost Contribution[d]	$/GGE	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Reference: Bioenergy Technologies Office | 2019 R&D State of Technology
https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf

Catalytic Fast Pyrolysis (CFP) SOT and Projections (2)

Sustainability and Process Efficiency Metrics	Units	2014 SOT	2015 SOT	2016 SOT	2017 SOT[a]	2018 SOT	2019 SOT	2020 Projection
Operating Cost Contribution[d]	$/GGE	$2.60	$2.14	$1.81	$1.27	$1.35	$1.18	$1.18
Ex Situ Reactor Configuration	reactor type	fluidized bed	fluidized bed	fluidized 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	2:2	2:2
Gas Phase	wt % of dry biomass	35%	36%	34%	31%	35%	38%	38%
Aqueous Phase	wt % of dry biomass	25%	25%	24%	27%	22%	24%	24%
Carbon Loss	% of C in biomass	2.9%	2.9%	3.4%	2.9%	5.0%	4.4%	4.4%
Organic Phase	wt % of dry biomass	17.5%	18.6%	21.8%	28.3%	27.9%	23.2%	23.2%
H/C Molar Ratio	ratio	1.1	1.1	1.1	1.2	1.2	1.2	1.2
Oxygen	wt % of organic phase	15.0%	13.3%	16.8%	16.5%	18.6%	15.1%	15.1%
Carbon Efficiency	% of C in biomass	27%	29%	33%	42%	40%	35%	35%
Solid Losses (Char + Coke)	wt % of dry biomass	23%	21%	20%	14%	15%	14%	14%
Char	wt % of dry biomass	12.0%	11.0%	12.0%	10.4%	11.7%	11.6%	11.6%
Coke	wt % of dry biomass	11.0%	9.5%	8.3%	3.3%	3.7%	2.3%	2.3%
Vapor Quench, Coproduct Recovery + Contingency								
Total Cost Contribution	$/GGE	$0.35	$0.33	$0.28	$0.20	$0.22	$0.34	$0.42
Capital Cost Contribution	$/GGE	$0.20	$0.19	$0.16	$0.12	$0.13	$0.22	$0.26

Reference: Bioenergy Technologies Office | 2019 R&D State of Technology
https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf

Catalytic Fast Pyrolysis (CFP) SOT and Projections (3)

Sustainability and Process Efficiency Metrics	Units	2014 SOT	2015 SOT	2016 SOT	2017 SOT[a]	2018 SOT	2019 SOT	2020 Projection
Operating Cost Contribution	$/GGE	$0.15	$0.14	$0.12	$0.08	$0.09	$0.12	$0.16
Hydroprocessing and Separation/Refinery Co-Processing								
Total Cost Contribution	$/GGE	$0.33	$0.31	$0.34	$0.35	$0.38	$0.30	$0.21
Capital Cost Contribution	$/GGE	$0.17	$0.16	$0.18	$0.19	$0.20	$0.16	$0.00
Operating Cost Contribution	$/GGE	$0.15	$0.14	$0.16	$0.16	$0.18	$0.14	$0.21
Carbon Efficiency of Organic Liquid Feed to Fuels	%	88.4%	89.5%	87.2%	91.0%	89.0%	93.5%	93.5%
Hydrotreating Pressure	psia	2,000	2,000	2,000	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%
Hydrogen Production								
Total Cost Contribution	$/GGE	$0.61	$0.56	$0.60	$0.62	$0.51	$0.61	$0.44
Capital Cost Contribution	$/GGE	$0.39	$0.36	$0.38	$0.41	$0.33	$0.39	$0.28
Operating Cost Contribution	$/GGE	$0.22	$0.20	$0.22	$0.21	$0.18	$0.22	$0.16
Additional Natural Gas at the Biorefinery[f]	% of biomass LHV	0.3%	0.1%	0.2%	0.1%	0.3%	0.1%	0.5%
Coproducts								
Total Cost Contribution	$/GGE						($0.52)	($0.52)
Capital Cost Contribution[g]	$/GGE							
Operating Cost Contribution[g]	$/GGE							
Coproduct Credit	$/GGE						($0.52)	($0.52)
Balance of Plant								
Total Cost Contribution	$/GGE	$0.04	$0.07	$0.03	$0.20	$0.23	$0.27	$0.20

Reference: Bioenergy Technologies Office | 2019 R&D State of Technology
https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf

Catalytic Fast Pyrolysis (CFP) SOT and Projections (4)

Sustainability and Process Efficiency Metrics	Units	2014 SOT	2015 SOT	2016 SOT	2017 SOT[a]	2018 SOT	2019 SOT	2020 Projection
Capital Cost Contribution	$/GGE	$0.80	$0.71	$0.56	$0.43	$0.46	$0.45	$0.52
Operating Cost Contribution[g]	$/GGE	($0.76)	($0.64)	($0.54)	($0.23)	($0.23)	($0.18)	($0.32)
Electricity Production from Steam Turbine (Credit Included in Operational Cost Above)	$/GGE	($1.12)	($0.96)	($0.78)	($0.42)	($0.45)	($0.40)	($0.57)

[a] For the 2017 SOT, the unquantified portion of CFP yields were prorated to solids, liquids, and gases using measured yields.

[b] 2030 projections are based on high-level estimates and will be modeled in detail in future years. It is proposed that co-hydroprocessing of CFP oil will occur at a petroleum refinery. 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, including from the organic liquid phase.

[c] Modeled ash is 1.75% for 2019 and 2020, and less than 1% for all other years.

[d] An additional biomass heater is included as a small additional in-plant cost, as shown in the 2015 process design report: https://www.nrel.gov/docs/fy15osti/62455.pdf.

[e] Small adjustments made to previously published feedstock cost estimates for 2014–2016.

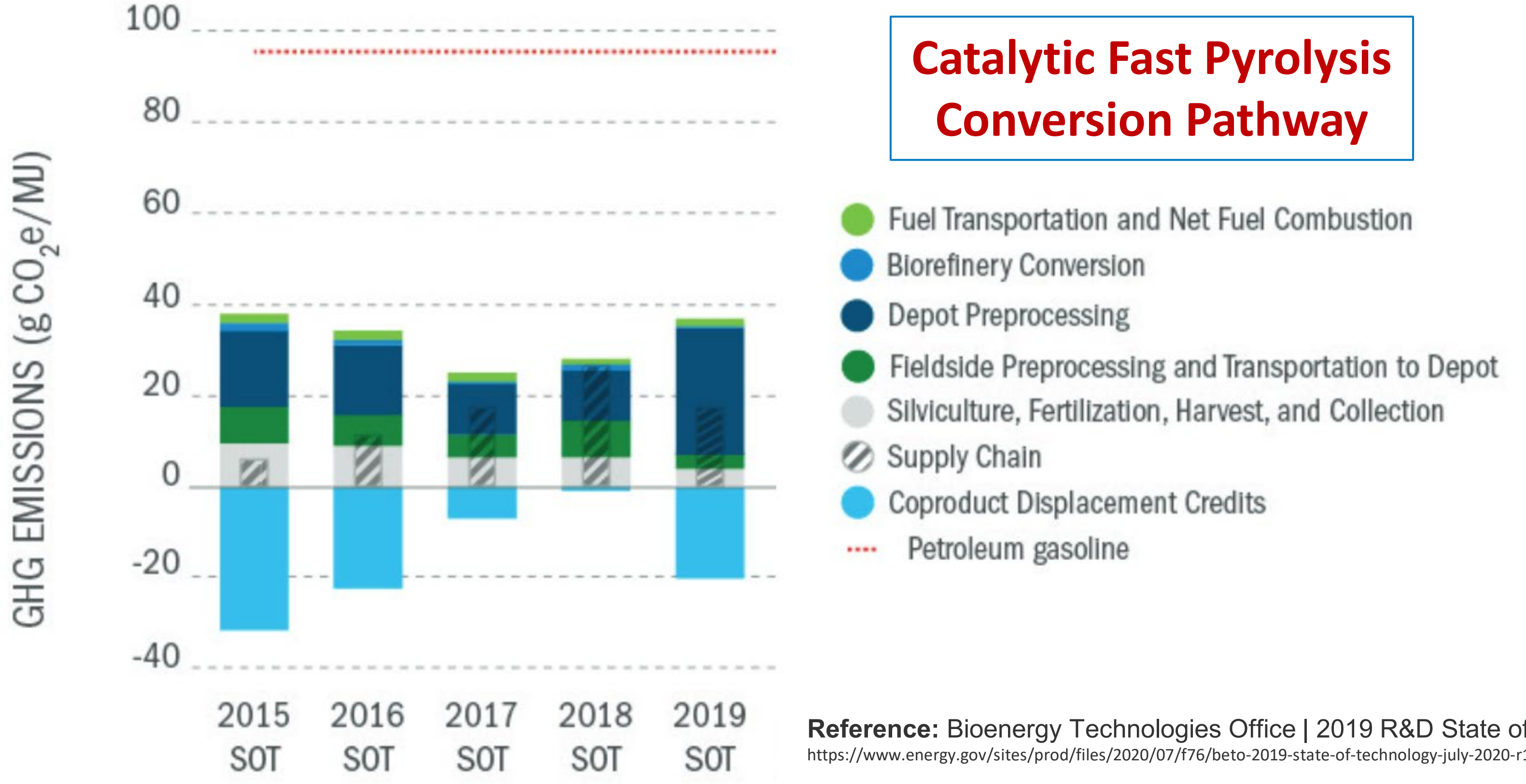
[f] Natural gas stream was negligible in most of the biorefinery models. This was included to maintain model flexibility to allow natural gas use as an option.

[g] Capital and operating costs for coproduct recovery in the 2019–2022 models are included in the "Vapor Quench, Coproduct Recovery + Contingency" section.

Reference: Bioenergy Technologies Office | 2019 R&D State of Technology
https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf

GHG Emissions Including Feedstocks & Conversion

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



Catalytic Fast Pyrolysis Conversion Pathway

Reference: Bioenergy Technologies Office | 2019 R&D State of Technology
https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf

Additional content for conversion pathways

- High-Octane Gasoline (HOG)

Syngas to High-Octane Gasoline SOT and Projections (1)

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT †	2015 SOT †	2016 SOT †	2017 SOT †	2018 SOT †	2019 SOT †	2020 SOT †	2021 Projection	2022 Projection (Design Case)
Process Concept: Gasification, Syngas Cleanup, Methanol / DME Synthesis & Conversion to HCs		**Woody Feedstock**	**Woody Feedstock**	**Woody Feedstock**	**Woody Feedstock**	**Woody Feedstock**	**Woody Feedstock**	**Woody Feedstock**	**Woody Feedstock**	**Woody Feedstock**
C_5+ Minimum Fuel Selling Price (per Actual Product Volume) ▲	$ / Gallon	$4.31	$4.17	$3.85	$3.67	$3.66	$3.35	$3.22	$3.30	$3.22
Mixed C_4 Minimum Fuel Selling Price (per Actual Product Volume) ▲	$ / Gallon	$3.98	$3.91	N/A	N/A	N/A	$1.02	N/A	N/A	N/A
Minimum Fuel Selling Price (per Gallon of Gasoline Equivalent) ▲	$ / Gal GE	$4.33	$4.24	$3.99	$3.86	$3.79	$3.53	$3.45	$3.40	$3.30
Conversion Contribution (per Gallon of Gasoline Equivalent) ▲	$ / Gal GE	$3.13	$3.03	$2.76	$2.64	$2.56	$2.23	$2.21	$2.25	$2.18
Year for USD ($) 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	$11.07	$10.94	$10.03	$9.79
Plant Capacity (Dry Feedstock Basis)	Tonnes / 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	Gallons / Dry Ton	36.2	36.4	51.4	50.0	51.4	51.6	55.1	55.1	56.0
Mixed C_4 Co-Product Yield	Gallons / Dry Ton	16.3	16.2	0.0	0.0	0.0	5.6	0.0	0.0	0.0
Feedstock										
Total Cost Contribution	$ / Gallon GE	$1.20	$1.21	$1.24	$1.22	$1.23	$1.31	$1.24	$1.14	$1.12
Capital Cost Contribution	$ / Gallon GE	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Operating Cost Contribution	$ / Gallon GE	$1.20	$1.21	$1.24	$1.22	$1.23	$1.30	$1.24	$1.14	$1.12
Feedstock Cost	$ / Dry US Ton	$60.58	$60.58	$60.58	$57.28	$60.54	$63.23	$63.23	$60.54	$60.54
Ash Content	wt % Ash	3.00%	3.00%	3.00%	3.00%	3.00%	1.75%	1.75%	3.00%	3.00%
Feedstock Moisture at Plant Gate	Wt % H_2O	30%	30%	30%	30%	30%	30%	30%	30%	30%
In-Plant Handling and Drying / Preheating	$ / Dry US Ton	$0.72	$0.70	$0.70	$0.69	$0.69	$0.69	$0.57	$0.69	$0.69
Cost Contribution	$ / Gallon	$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	7,933	7,930	7,856	7,856
Gasification										
Total Cost Contribution	$ / Gallon GE	$0.69	$0.67	$0.65	$0.62	$0.61	$0.58	$0.50	$0.56	$0.54
Capital Cost Contribution	$ / Gallon GE	$0.43	$0.41	$0.38	$0.35	$0.34	$0.33	$0.28	$0.31	$0.30
Operating Cost Contribution	$ / Gallon GE	$0.26	$0.26	$0.27	$0.28	$0.26	$0.25	$0.23	$0.25	$0.24
Raw Dry Syngas Yield	lb / lb Dry Feed	0.76	0.76	0.76	0.76	0.76	0.77	0.83	0.76	0.76
Raw Syngas Methane (Dry Basis)	Mole %	15.4%	15.4%	15.4%	15.4%	15.4%	15.4%	8.6%	15.4%	15.4%
Gasifier Efficiency (LHV)	% LHV	71.9%	71.9%	71.9%	71.9%	71.9%	72.3%	78.0%	71.9%	71.9%
Synthesis Gas Clean-up (Reforming and Quench)										
Total Cost Contribution	$ / Gallon GE	$0.96	$0.93	$0.94	$0.94	$0.89	$0.88	$0.93	$0.80	$0.78
Capital Cost Contribution	$ / Gallon GE	$0.51	$0.49	$0.46	$0.43	$0.41	$0.39	$0.40	$0.37	$0.36
Operating Cost Contribution	$ / Gallon GE	$0.45	$0.45	$0.48	$0.51	$0.48	$0.49	$0.53	$0.44	$0.42
Tar Reformer (TR) Exit CH_4 (Dry Basis)	Mole %	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.3%	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%

Syngas to High-Octane Gasoline SOT and Projections (2)

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT †	2015 SOT †	2016 SOT †	2017 SOT †	2018 SOT †	2019 SOT †	2020 SOT †	2021 Projection	2022 Projection (Design Case)
Acid Gas Removal, Methanol Synthesis and Methanol Conditioning										
Total Cost Contribution	$ / Gallon GE	$0.52	$0.50	$0.47	$0.47	$0.45	$0.45	$0.36	$0.41	$0.40
Capital Cost Contribution	$ / Gallon GE	$0.35	$0.33	$0.30	$0.28	$0.28	$0.27	$0.20	$0.25	$0.24
Operating Cost Contribution	$ / Gallon GE	$0.17	$0.17	$0.17	$0.19	$0.18	$0.18	$0.15	$0.16	$0.16
Methanol Synthesis Reactor Pressure	psia	730	730	730	730	730	730	730	730	730
Methanol Productivity	kg / kg-cat / hr	0.7	0.7	0.8	0.8	0.8	0.7	0.8	0.7	0.7
Methanol Intermediate Yield	Gallons / Dry Ton	143	142	138	144	141	137	150	136	134
Hydrocarbon Synthesis										
Total Cost Contribution	$ / Gallon GE	$0.91	$0.91	$0.70	$0.67	$0.64	$0.49	$0.34	$0.51	$0.48
Capital Cost Contribution	$ / Gallon GE	$0.56	$0.56	$0.46	$0.44	$0.42	$0.34	$0.11	$0.34	$0.32
Operating Cost Contribution	$ / Gallon GE	$0.35	$0.35	$0.24	$0.23	$0.22	$0.16	$0.23	$0.17	$0.16
Methanol to DME Reactor Pressure	psia	145	145	145	145	145	145	169	145	145
Hydrocarbon Synthesis Reactor Pressure	psia	129	129	129	129	129	129	205	129	129
Hydrocarbon Synthesis Catalyst		Commercial Beta-Zeolite		NREL modified Beta-Zeolite with copper (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 relativete to aromatics							
Utilization of C_4 in Reactor Outlet via Recycle		0%	0%	100%	100%	100%	90%	97%	Recycle	100%
Single-Pass DME Conversion	%	15.0%	15.0%	19.2%	27.6%	38.9%	44.7%	43.4%	39.7%	40.0%
Overall DME Conversion	%	83%	85%	83%	88%	92%	88%	96%	90%	90%
Hydrocarbon Synthesis Catalyst Productivity	kg / kg-cat / hr	0.02	0.03	0.04	0.09	0.07	0.07	0.07	0.09	0.10
Carbon Selectivity to C_5+ Product	% C in Reactor Feed	46.2%	48.3%	81.8%	74.8%	72.3%	73.6%	72.1%	83.4%	86.7%
Carbon Selectivity to Total Aromatics (Including Hexamethylbenzene)	% C in Reactor Feed	25.0%	20.0%	4.0%	4.0%	8.0%	5.8%	3.3%	2.4%	0.5%
Carbon Selectivity to Coke and Pre-Cursors (Hexamethylbenzene Proxy)	% C in Reactor Feed	10.0%	9.3%	4.0%	4.0%	4.0%	2.9%	1.6%	1.4%	0.5%
Hydrocarbon Product Separation										
Total Cost Contribution	$ / Gallon GE	$0.04	$0.05	$0.05	$0.05	$0.05	$0.05	$0.11	$0.05	$0.05
Capital Cost Contribution	$ / Gallon GE	$0.03	$0.03	$0.04	$0.04	$0.04	$0.03	$0.06	$0.03	$0.03
Operating Cost Contribution	$ / Gallon GE	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.05	$0.01	$0.01
LPG Coproduct Credit										
Total Cost Contribution	$ / Gallon GE	$0.00	$0.00	$0.00	$0.00	$0.00	($0.11)	($0.00)	$0.00	$0.00
Balance of Plant										
Total Cost Contribution	$ / Gallon GE	$0.01	($0.02)	($0.05)	($0.11)	($0.09)	($0.11)	($0.03)	($0.08)	($0.07)
Capital Cost Contribution	$ / Gallon GE	$0.42	$0.40	$0.36	$0.34	$0.33	$0.29	$0.31	$0.29	$0.28
Operating Cost Contribution	$ / Gallon GE	($0.41)	($0.42)	($0.42)	($0.45)	($0.42)	($0.41)	($0.33)	($0.37)	($0.36)

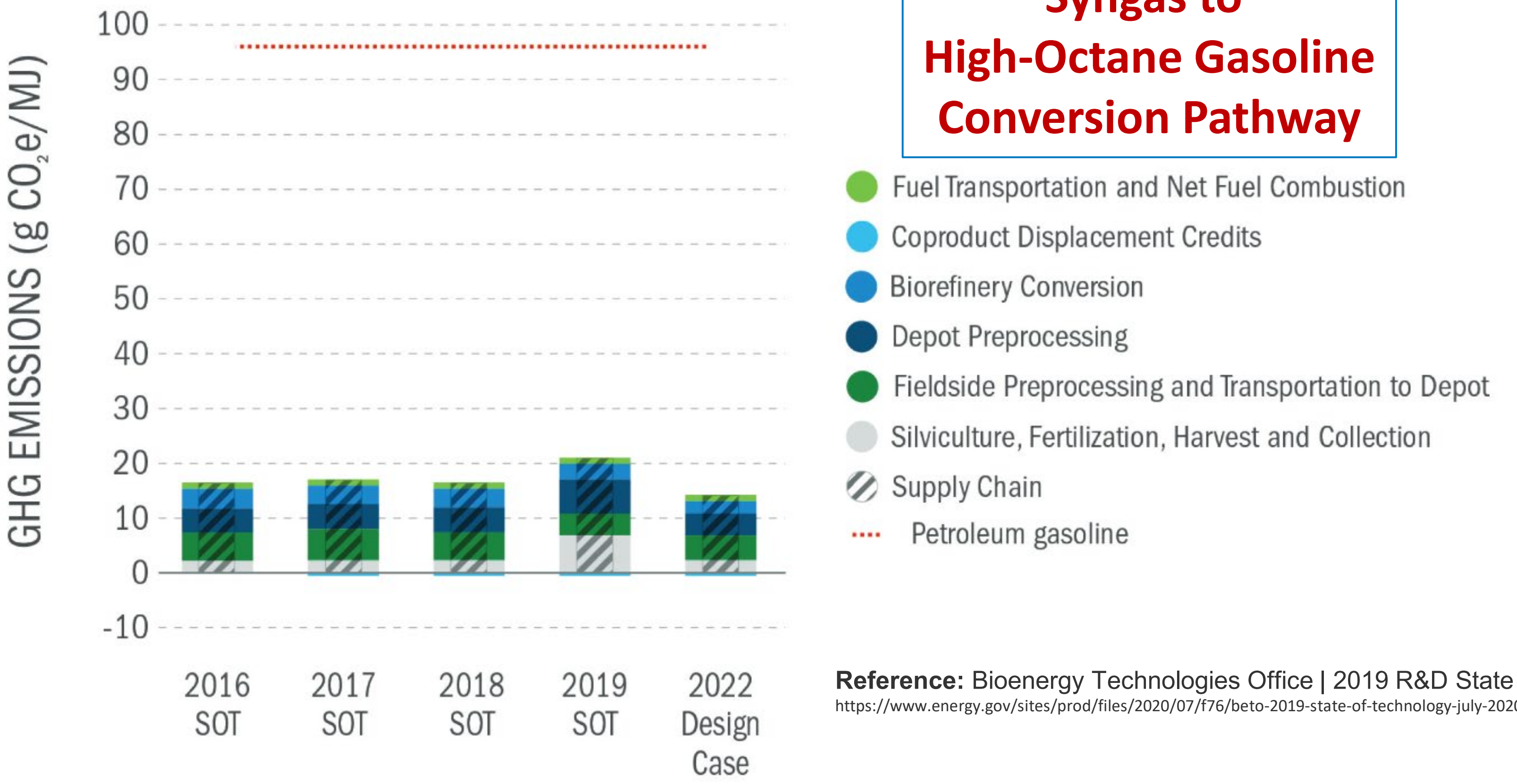
Syngas to High-Octane Gasoline SOT and Projections (3)

Processing Area Cost Contributions & Key Technical Parameters	Units	2014 SOT †	2015 SOT †	2016 SOT †	2017 SOT †	2018 SOT †	2019 SOT †	2020 SOT †	2021 Projection	2022 Projection (Design Case)
Sustainability and Process Efficiency Metrics										
Carbon Efficiency to C_5+ Product	% C in Feedstock	19.3%	19.4%	25.2%	24.3%	25.5%	24.8%	26.1%	27.4%	27.9%
Carbon Efficiency to Mixed C_4 Co-Product	% C in Feedstock	7.0%	6.9%	0.0%	0.0%	0.0%	2.3%	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%	27.1%	26.1%	27.4%	27.9%
Overall Energy Efficiency to Hydrocarbon Products	% LHV of Feedstock	37.7%	37.7%	36.6%	35.1%	36.6%	39.6%	37.6%	39.6%	40.4%
Electricity Production	kWh / Gallon C_5+	11.7	11.8	7.9	8.4	8.1	7.6	12.2	7.2	7.0
Electricity Consumption	kWh / Gallon C_5+	11.7	11.8	7.9	8.5	8.1	7.6	12.2	7.2	7.0
Water Consumption	Gal H_2O / Gal C_5+	12.9	10.1	3.1	3.3	3.2	2.9	3.3	2.8	2.8
Fossil GHG Emissions	g CO2-e / MJ Fuel	0.05	0.05	2.64	2.48	2.40	2.13	2.24	0.67	2.06
Fossil Enegy Consumption	MJ Fossil Energy / MJ Fuel	0.003	0.003	0.042	0.039	0.038	0.034	0.035	0.008	0.032
TEA Reference File		2014 SOT Rev4a 2016$ (high ash)_1.xlsm	2015 SOT Rev6 Comm-HBEA 2016$ FR Rev2_1.xlsm	2016 SOT Base Rev6 Rev2 2016$ FR_1.xlsm	2017 SOT Base Rev1 2016$ FR_1 KH (Feedstock Cost).xlsm	2018SOT_2018-07-20data Rev3_2 KH (Feedstock Cost).xlsm	2019 SOT Oct Update Rev02 - (C4-DME-1_LPG) Rev0_b.xlsm	HOG2020-V117_rev5.xlsm	2021 Target Rev0 KH (Feedstock Cost).xlsm	2022 Design FR Rev5a_2 KH (Feedstock Cost).xlsm

GHG Emissions Including Feedstocks & Conversion

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

Syngas to High-Octane Gasoline Conversion Pathway



Reference: Bioenergy Technologies Office | 2019 R&D State of Technology
https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf