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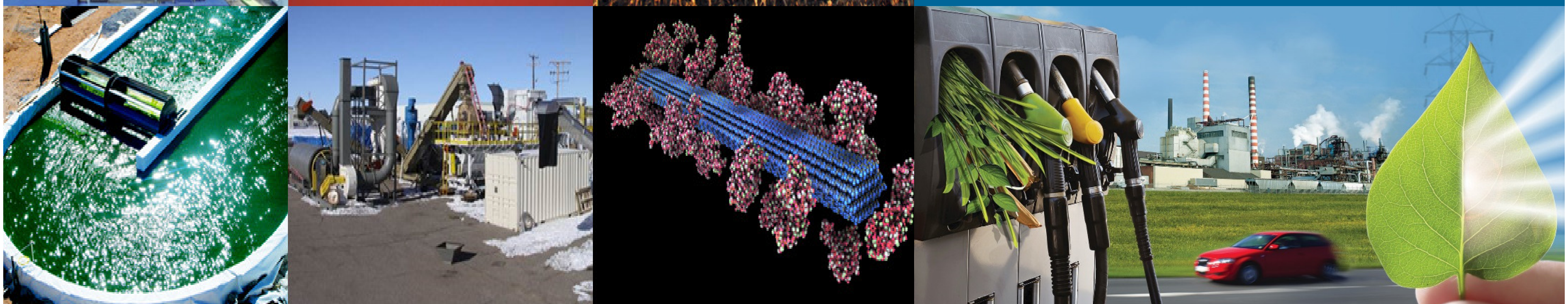

Recent developments in gasification-based aviation biofuels in the U.S.

May 25, 2016

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U.S. Department of Energy

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Outline

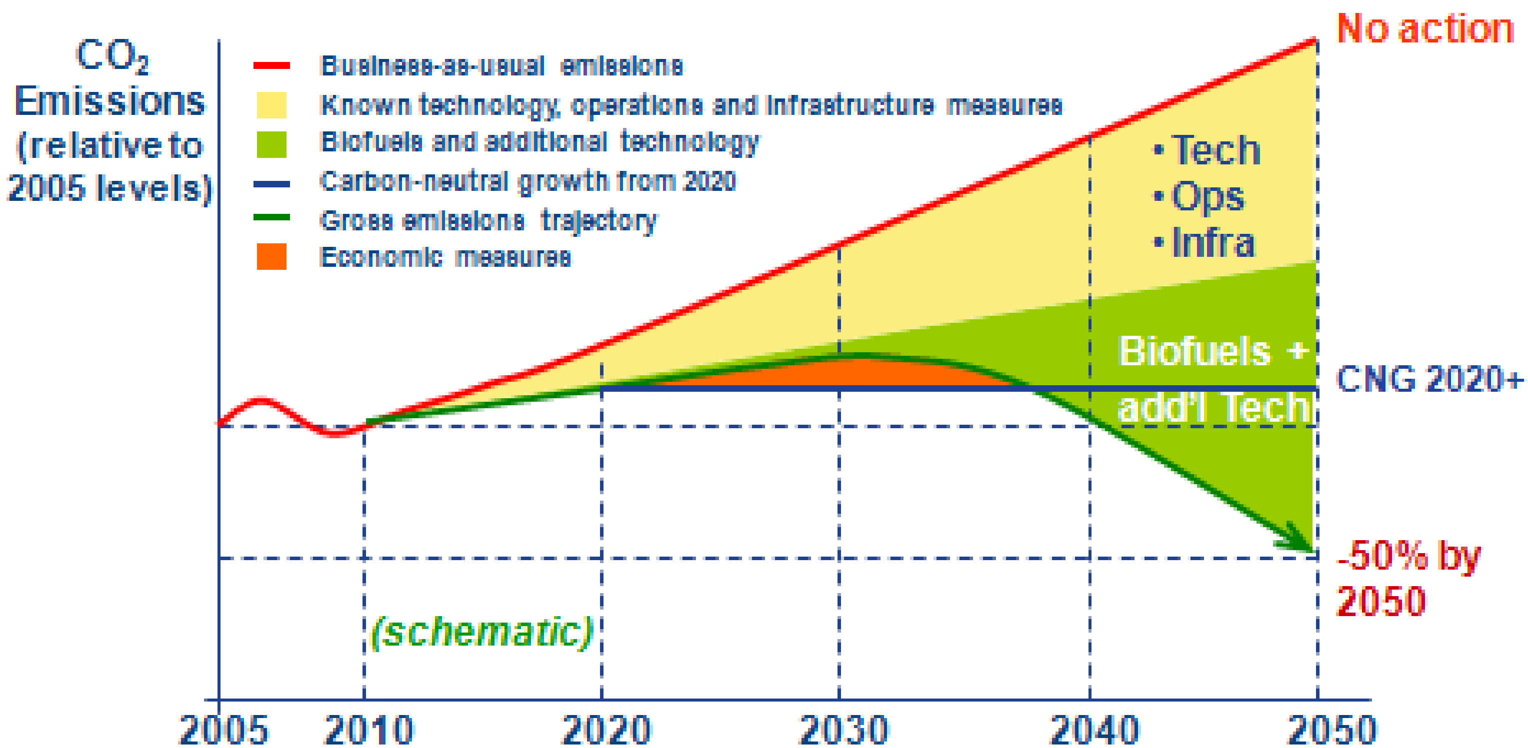
- Aviation Fuels Background
  - Aviation GHG Roadmap – Role of Biofuels
  - Jet Fuel production and consumption
  - ASTM Pathway approval status
  - Farm to Fly
  - Offtake Agreements

- Biomass Gasification in BETO's Portfolio
  - Conversion R&D
  - Pilot, Demonstration & Commercial Projects
  - Defense Production Act (DPA)

Biofuels are key to aviation GHG roadmap

Biofuels key to mitigating growth constraints

Aviation's emissions reduction roadmap



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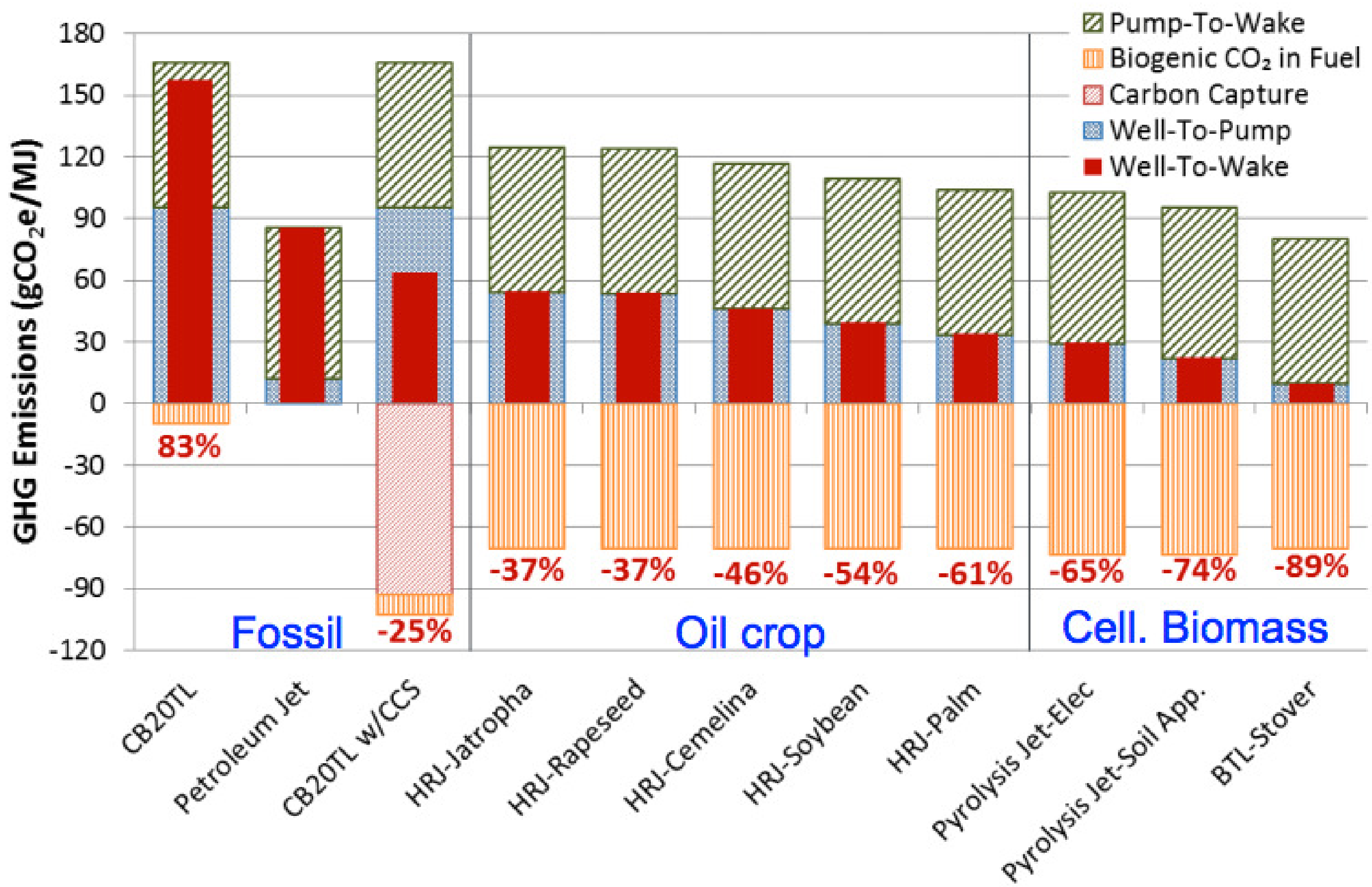
Well-to-Wake GHG Emissions of Alternative Jet Fuels

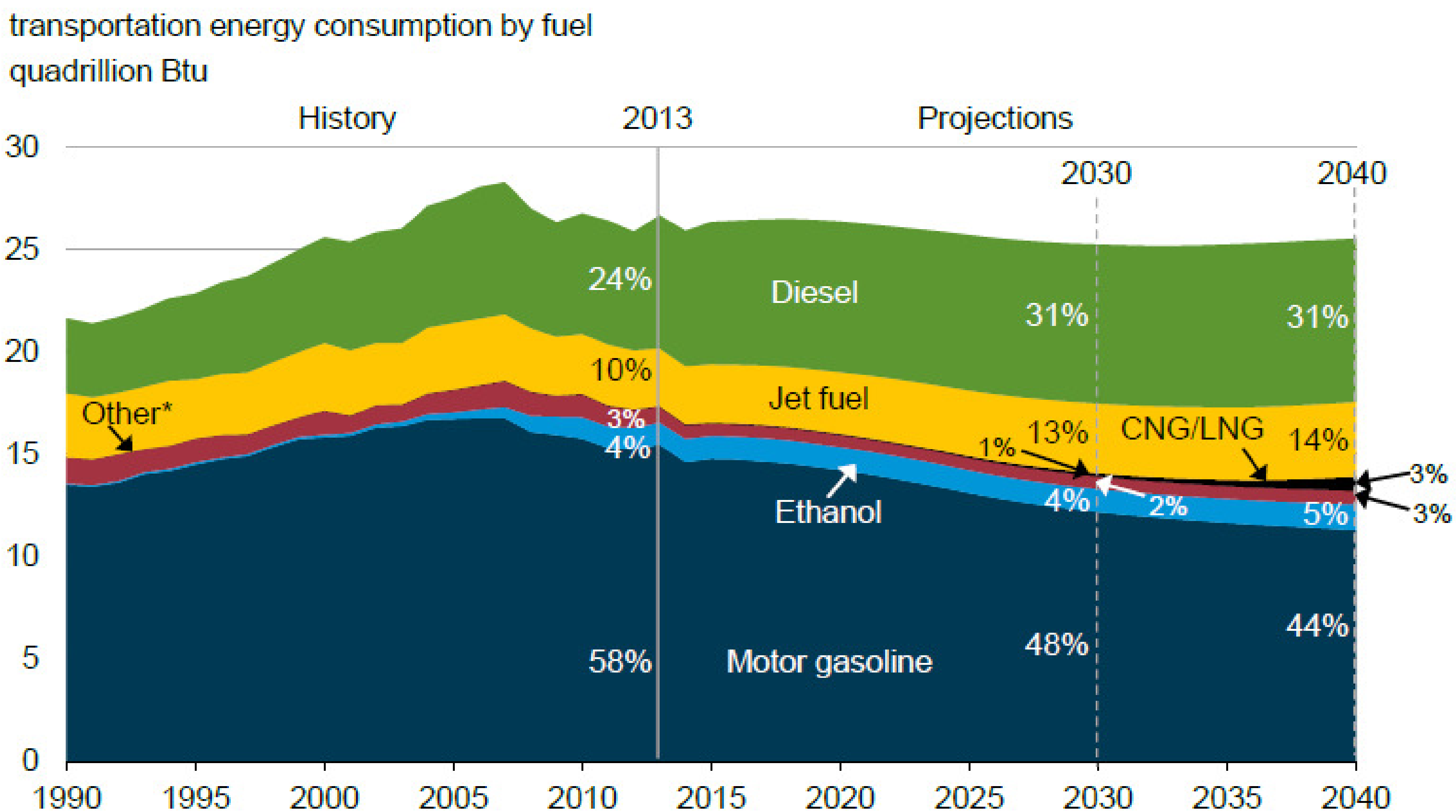


BTL has best GHG profile and at higher TRL than other cellulosic biomass pathways

- Does not Include LUC related emissions
- Other Key Factors: Technology Readiness Level, production costs, resource availability and fuel types

Transportation Energy Consumption

In the transportation sector, motor gasoline use declines; diesel fuel, jet fuel, and natural gas use all grow



Source: EIA, Annual Energy Outlook 2015 Reference case

**Includes aviation gasoline, propane, residual fuel oil, lubricants, electricity, and liquid hydrogen*

High-Priority Approaches

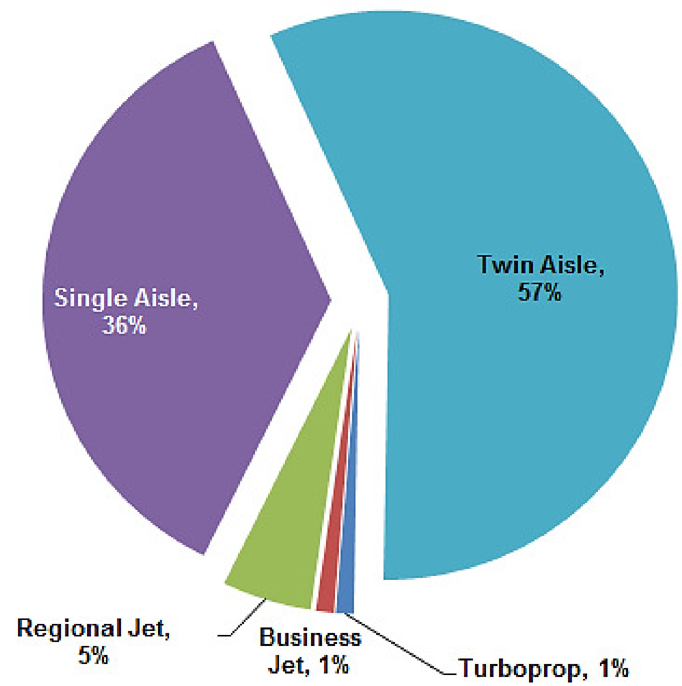
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

National Academies of Sciences, Engineering, and Medicine published May 24, 2016 a report on Commercial Aircraft Propulsion and Energy Systems Research Reducing Global Carbon Emissions

www.nap.edu/catalog/23490

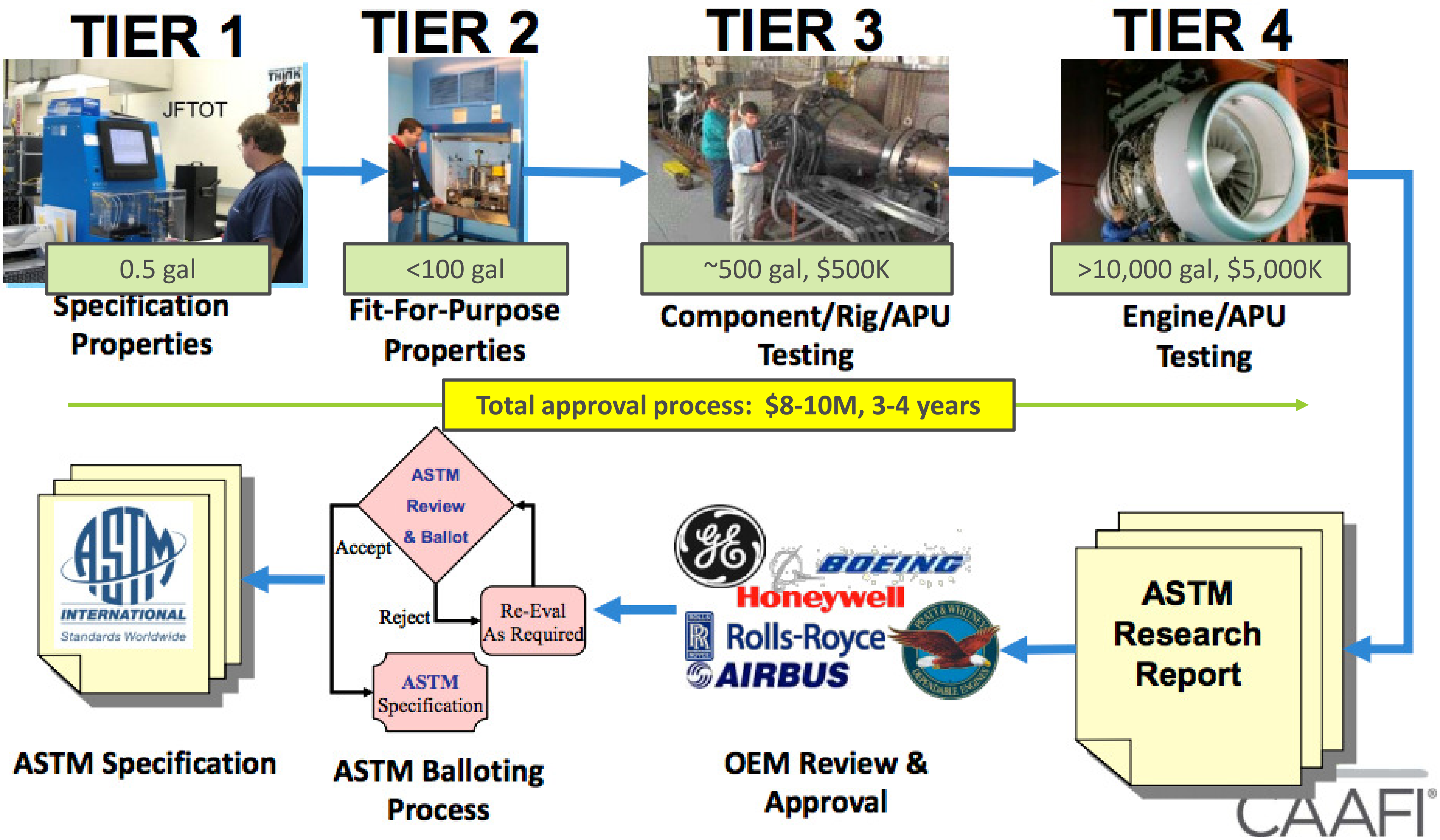
Recommendation: Implement a national research agenda that places the highest priority on the following approaches:

- **Advances in aircraft and propulsion integration**
- **Improvements in gas turbine engines**
- **Development of turboelectric propulsion systems**
- **Advances in sustainable alternative jet fuels (SAJF)**

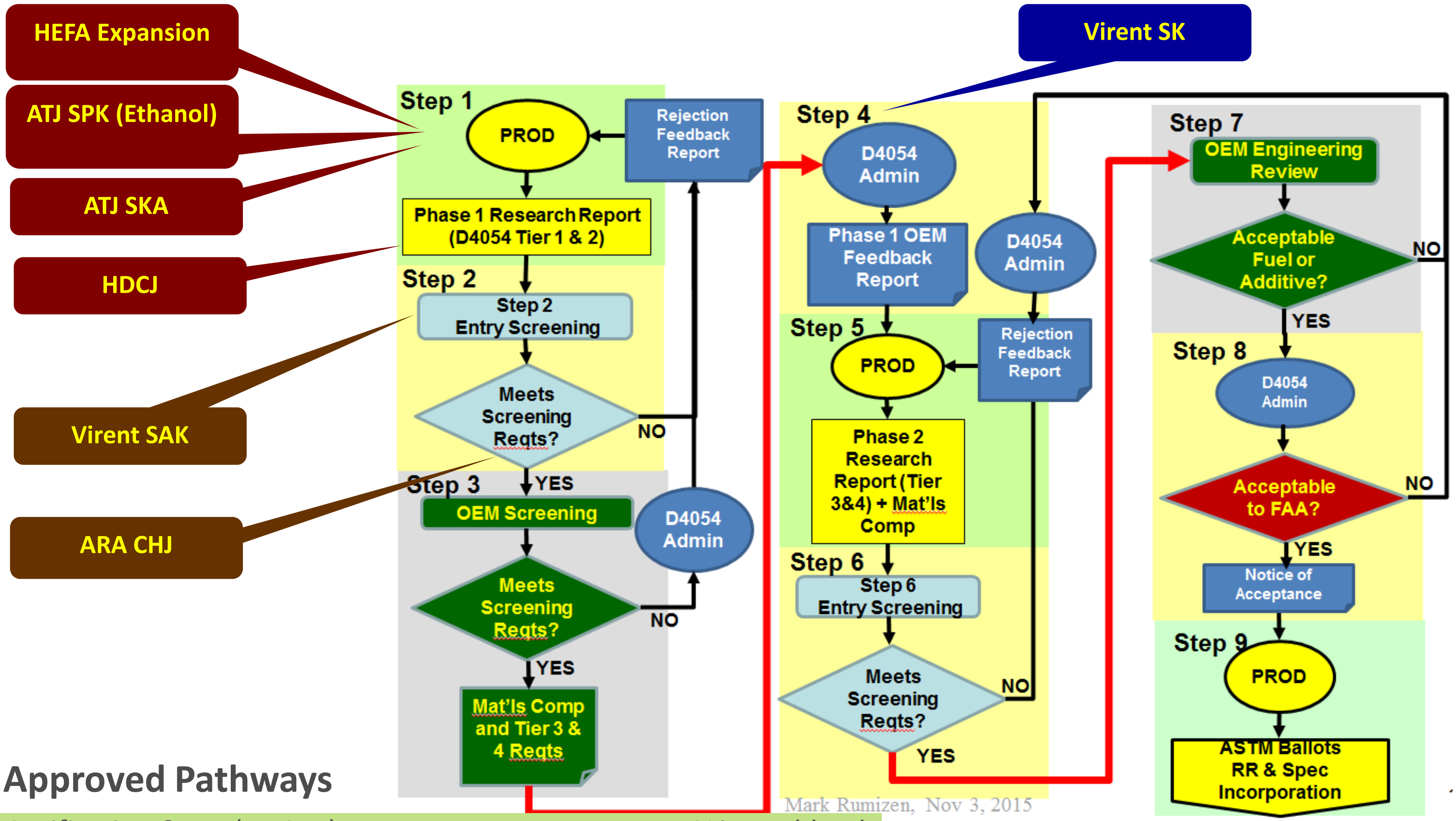


Global civil aviation fuel consumption
Yutko and Hansman, 2011

ASTM D4054 Process



ASTM Approval Pipeline - Alternative Jet Fuels



Approved Pathways

Gasification & F-T (FT-SPK)	50% max blend
Hydroprocessing F.O.G. (HEFA-SPK)	50% max blend
Hydroprocessing of fermented sugars (HFS-SIP)	10% max blend
F-T with Aromatics (FT-SPK/A)	50% max blend
Thermochemical Conversion of Isobutanol to Jet (ATJ SPK)	30% max blend

DOE Joins Farm to Fly 2.0

- In 2013, USDA and FAA made a commitment to the aviation industry to help meet their goals with the Farm to Fly 2.0 agreement. This effort seeks to enable the use of commercially viable and sustainable renewable jet fuel in the United States.

- In July 2014, Secretary Moniz signed an amendment officially making DOE the newest partner agency in this significant initiative.

- We bring technical expertise at our laboratories and years of experience that staff at the Energy Department have to offer.

- Senate FY16 appropriations language requests DOE to indicate commitment to Farm to Fly 2.0.

Airline offtake agreements
… and more in process

UNITED	+	AltAir Fuels	=	5 M gpy from 2016
UNITED	+	Fulcrum BIOENERGY	=	90-180 M gpy Over 10 yrs
CATHAY PACIFIC	+	Fulcrum BIOENERGY	=	375M usg
Southwest	+	RED ROCK BIOFUELS	=	3 M gpy
FedEx	+	RED ROCK BIOFUELS	=	3 M gpy

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Bioenergy Technologies Office

Mission: Accelerate the commercialization of advanced biofuels and bioproducts through RD&D of new technologies supported by public-private partnerships

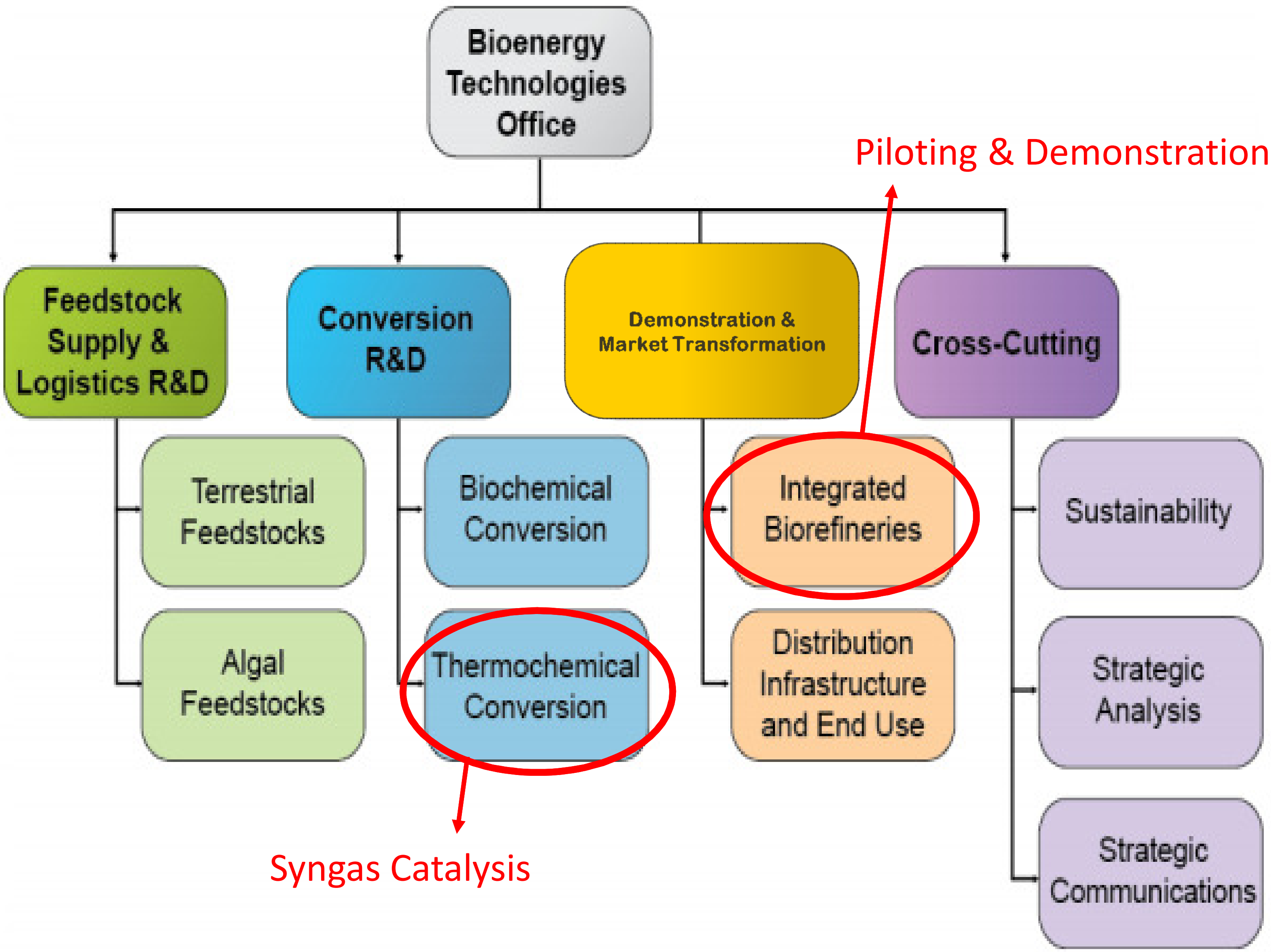
Strategy: Develop technologies to enable the sustainable, nationwide production of biofuels compatible with today's transportation infrastructure

Performance Goal: Validate at least one pathway for $3/GGE* hydrocarbon biofuel with ≥50% reduction in GHG emissions relative to petroleum by 2017

*Mature modeled price at pilot scale.

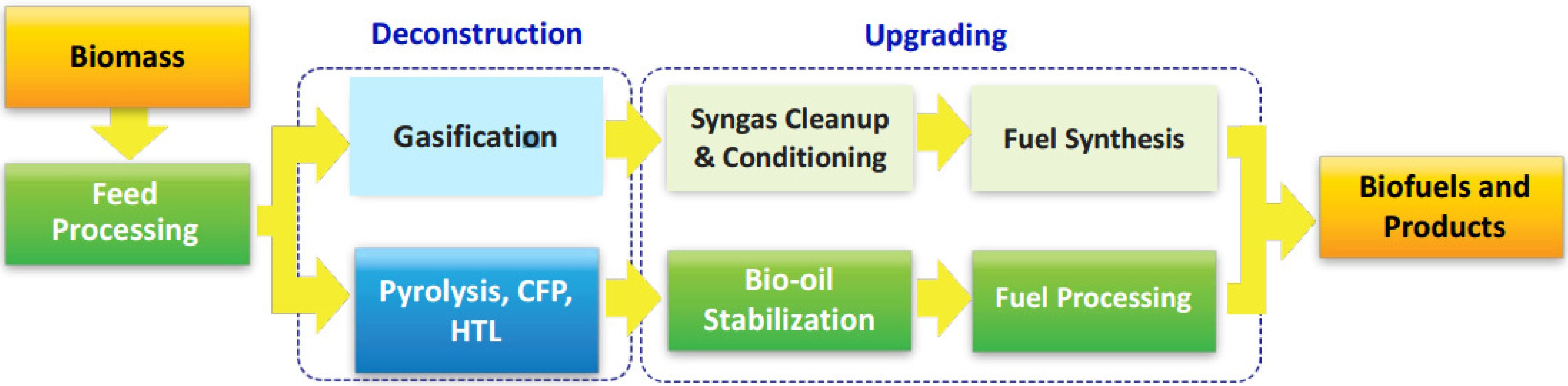
BETO reduces risks and costs to commercialization through RD&D

BETO Program - Biomass Gasification RD&D



Conversion R&D in BETO

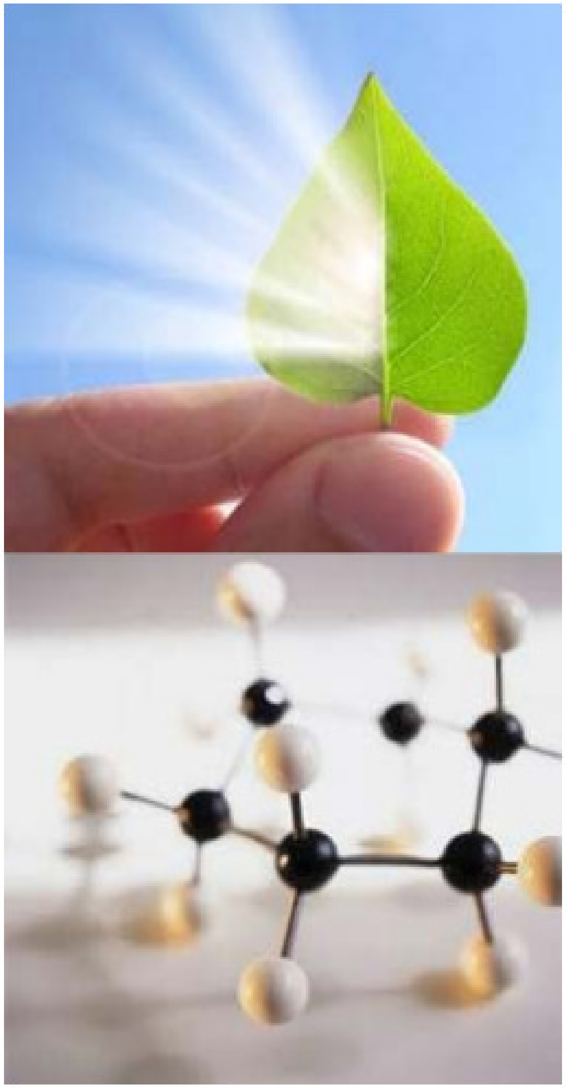
Gasification R&D falls under the BETO Conversion Technology Area



Conversion activities include continued efforts in both core and competitive R&D:

- R&D focuses on gaseous intermediates and mixed oxygenate upgrading to produce gasoline, distillate, and jet range hydrocarbons from biomass in support of the programmatic goal of $3/GGE by 2022

Conversion R&D - Gasification



Continued efforts in core and competitive R&D support the 2022 programmatic goal of $3/GGE:

- Catalytic upgrading of gaseous and liquid intermediate to produce gasoline, distillate, and jet range hydrocarbons from biomass, e.g.:
  - Conversion of syngas to mixed oxygenates followed by conversion to hydrocarbon fuels and oxygenate blendstocks
  - Syngas fermentation to ethanol followed by chemical catalytic conversion to hydrocarbon blendstocks – e.g. **Lanzatech-PNNL ATJ**
  - Conversion of Methanol /DME to high octane gasoline (Triptane – C7H16) and/or **dimerization to distillate/jet.**
- Develop technoeconomic analysis (TEA) and associated design cases that include cost projections and technical targets for indirect liquefaction pathways to make gasoline, diesel, or jet fuels

Gasification R&D Strategy Workshop

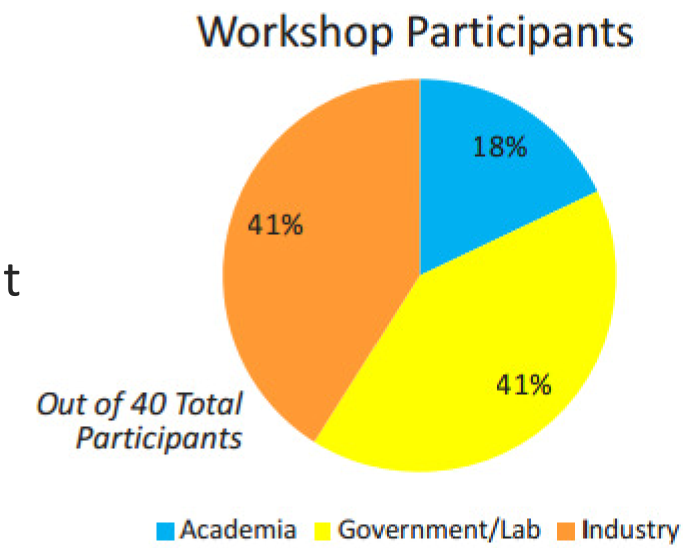
Public workshop occurred March 20-21, 2014 at NREL, in Golden, CO

Workshop's goals:

- To discuss, learn, and document the technical and economic hurdles of cost-competitive biomass gasification;
- To clearly define the research and development needed to overcome those hurdles; and
- To identify a timeline for completing that research, development, and demonstration.

Workshop's outcomes:

- Some key challenges discussed were in the areas of feedstock interface, catalyst production and validation, and accessible modeling.
- Participants highlighted the usefulness of open data and sharing past lessons learned and best practices.
- Report Published – July 2014



Fuels synthesis reactor

Credit: National Renewable Energy Laboratory

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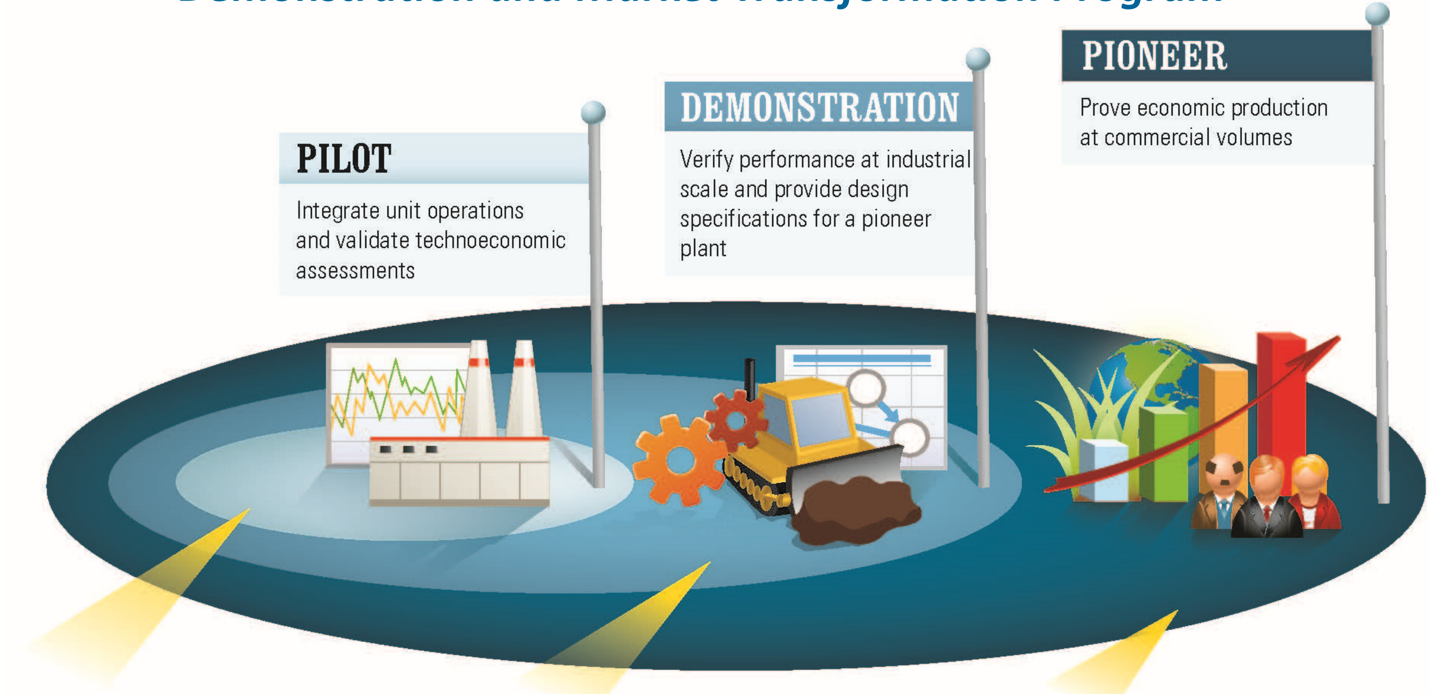
Gasification Pilot & Demonstration Projects in BETO

There are several IBR projects within BETO's Demonstration Program

Demonstration and Market Transformation Program



Examples of indirect liquefaction technologies within the D&MT Program include:

- INEOS: Syngas fermentation to ethanol at 300 tpd
- Haldor Topsoe: Syngas catalysis to gasoline at 20 tpd
- REII: Syngas to F-T liquids and diesel at 10 tpd
- ClearFuels-Rentech: Syngas to F-T liquids and diesel at 20 tpd
- Frontline: Syngas to F-T liquids to jet fuels at 10 tpd

BETO Demonstration Portfolio – Gasification

<u>Completed Projects:</u>

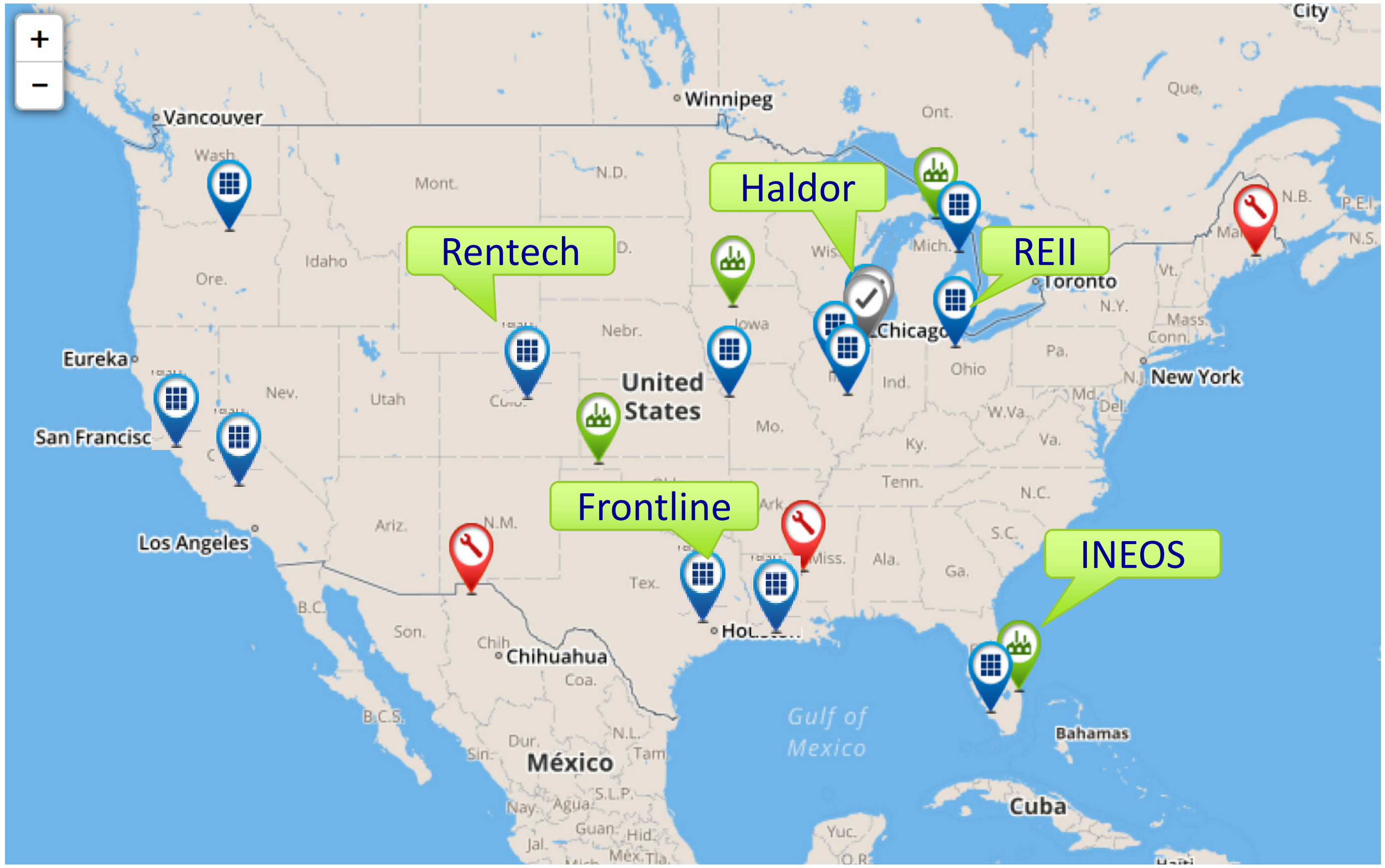
- Rentech (Clearfuels)
- Haldor-Topsoe (GTI-Carbona)
- REII (Red Lion)
- INEOS

<u>Project development:</u>

- Frontline

<u>Phase I only:</u>

- Flambeau (TRI)
- New Page (TRI)
- Enerkem



Pioneer
Demonstration
Pilot

For more information visit:
www.energy.gov/eere/bioenergy/integrated-biorefineries

Defense Production Act (DPA) Initiative

In July 2011, the Secretaries of Agriculture, Energy, and Navy signed a Memorandum of Understanding to commit $510 M ($170 M from each agency) to produce hydrocarbon jet and diesel biofuels in the near term. This initiative sought to achieve:

- **Multiple, commercial-scale integrated biorefineries.**
- **Cost-competitive biofuel with conventional petroleum (without subsidies).**
- **Domestically produced fuels from non-food feedstocks.**
- **Drop-in, fully compatible, MILSPEC fuels (F-76, JP-5, JP8).**
- **Help meet the Navy's demand for 1.26 billion gallons of fuel per year.**
- **Contribute to the Navy's goal of launching the "Great Green Fleet" in 2016.**
- **Demonstration of the production and use of more than 100 million gallons per year will dramatically reduce risk for drop-in biofuels production and adoption.**

On September 19th, 2014 three projects were selected for construction and commissioning: Two are based on gasification with F-T

Company	Location	Feedstock	Conversion Pathway	Off-Take Agreements	Capacity (MMgpy)
Emerald Biofuels	Gulf Coast	Fats, Oils, and Greases	Hydroprocessed Esters and Fatty Acids (HEFA)	TBD	82.0
Fulcrum Bioenergy	McCarran, NV	Municipal Solid Waste	Gasification – Fischer Tröpsch (FT)	United; Cathay Pacific	10.0
Red Rock Biofuels	Lakeview, OR	Woody Biomass	Gasification – Fischer Tröpsch (FT)	FedEx; Southwest Airlines	12.0

DOE BETO Alternative Aviation Fuels Workshop

Public workshop scheduled for September 14-15, 2016 in Macon, GA

- **Workshop's goals:**
  - To advance the understanding of the current technical barriers for increasing the competitiveness of aviation biofuels.
  - The workshop will focus on three technical areas that will be organized as parallel breakout sessions:
    - Enhancing the techno-economic competitiveness of aviation biofuels.
    - Environmental and sustainability considerations and opportunities to improve the life-cycle benefits of aviation biofuels.
    - Ensuring robust feedstock and product supply chains to support aviation biofuels.

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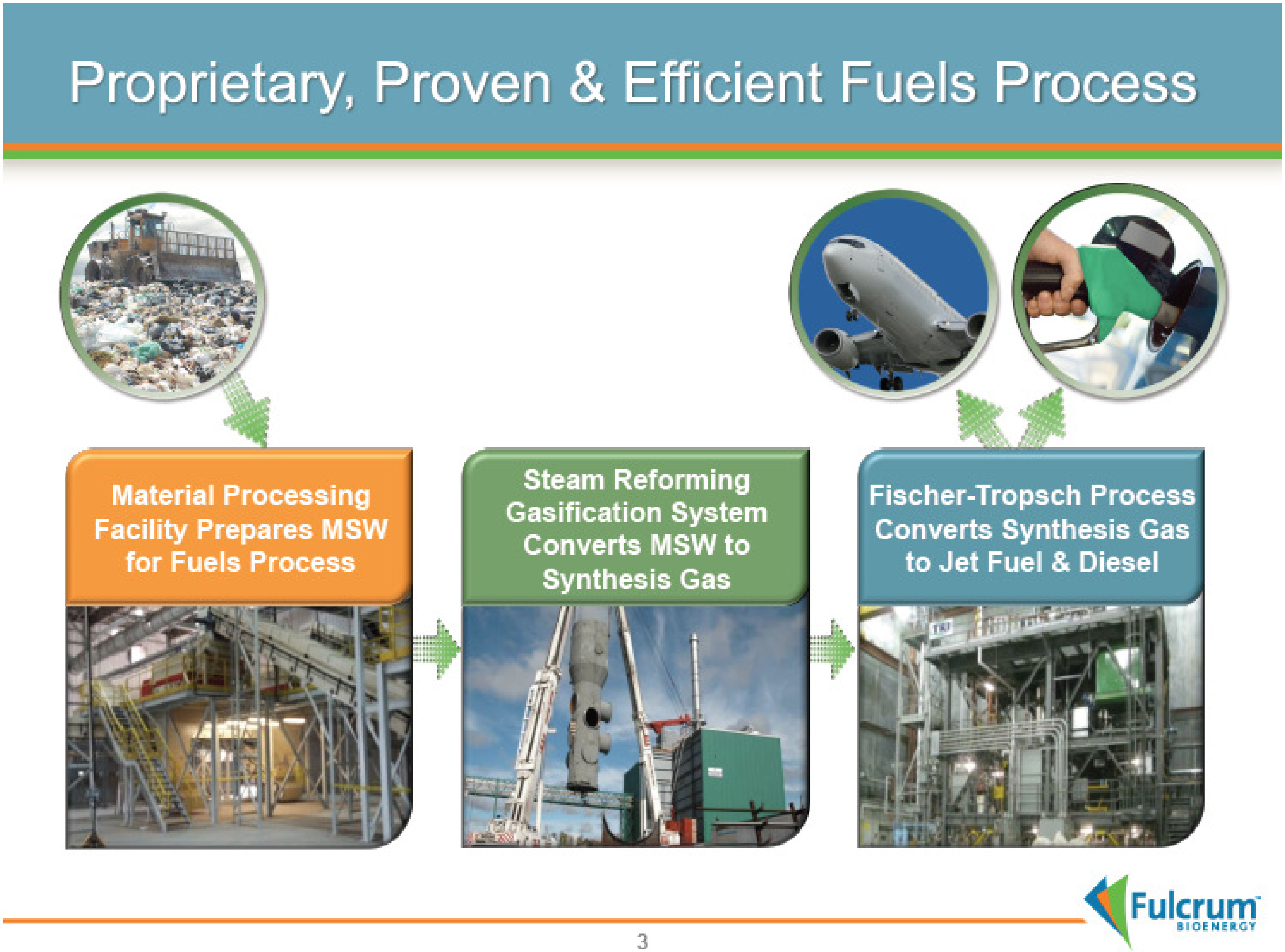
Thank you

Backup

Fulcrum Bioenergy

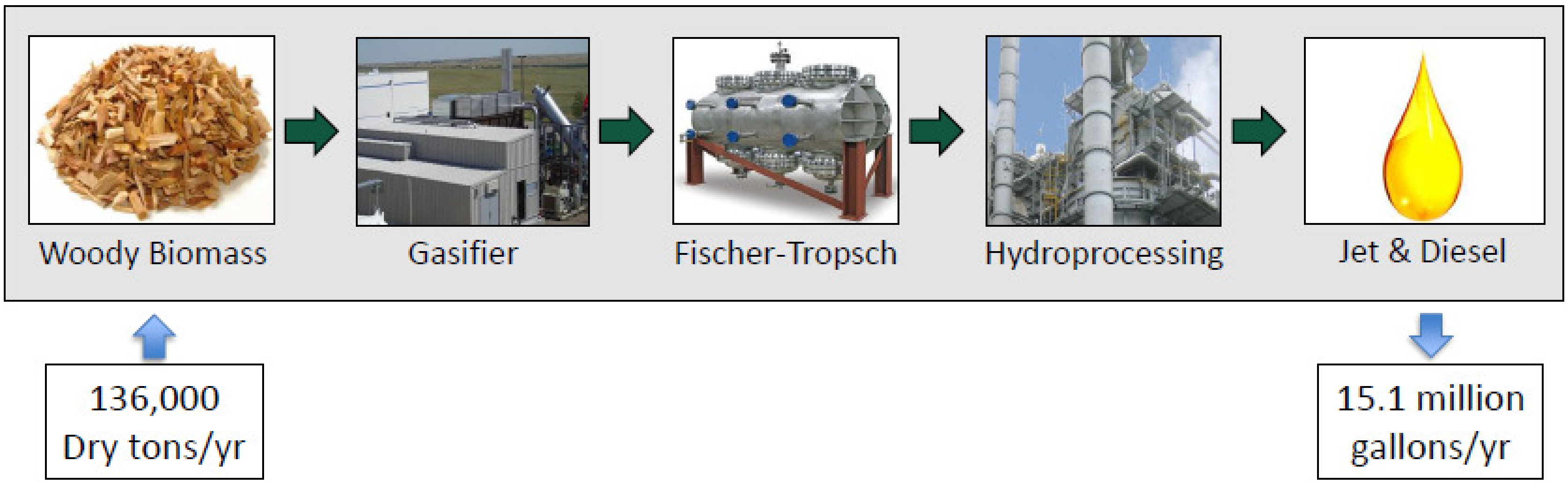


Red Rock Biofuels

FEED/FEL3 Design & Engineering by FLUOR

RED ROCK BIOFUELS

VELOCYS



INEOS and Sebring Green Racing with Cellulosic Ethanol

INEOS Biorefinery

- First commercial production of cellulosic ethanol in the U.S. using gasification and syngas fermentation technology
- Expected to produce 8 million gallons per year of cellulosic ethanol and 6 megawatts of power from wood and vegetative waste.
- Created 400 construction jobs; 65 permanent jobs are expected for operation.
- Major construction began in October 2010, commissioning was completed in June 2013, and commercial production of cellulosic ethanol was announced in July 2013.
- DOE Share = $50 million; cost share = $82 million.

Sebring Green Racing

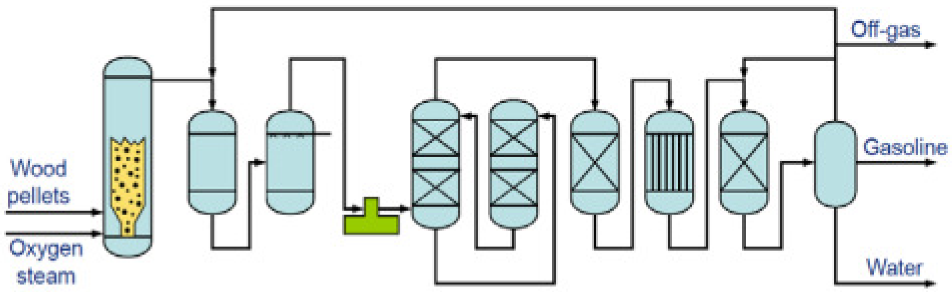
- On Friday, March 14, 2014, DOE officials participated in a green racing event at Sebring International Raceway, Sebring, Florida.
- INEOS Bioenergy provided cellulosic ethanol from its DOE-supported, Vero Beach, Florida biorefinery.
- NASCAR's International Motor Sports Association uses its Green Racing series to help promote and rapidly develop cleaner fuels that can be transferred to consumer vehicles.

Haldor-Topsoe

Location	Houston, Texas (US HQ), Des Plaines, Illinois (Project Site)
Feedstock(s)	Wood pellets
Size	20 tons per day (6% moisture content)
Primary Products	Renewable gasoline
Capacity	345,000 gallons per year (approximate)
Award Date	December 29, 2009
GHG Reduction	92% reduction versus fossil product at commercial scale

- Completed 495 hours of operation
- Produced 10,000 gals of gasoline blendstock.
- Engine emissions testing with 80% blend showed emission levels "substantially similar" to conventional gasoline
- Conducting vehicle testing – 600,000 miles on a 50% blend

HALDOR TOPSØE
CATALYSING YOUR BUSINESS
CARBONA
gti
UPM
PHILLIPS 66



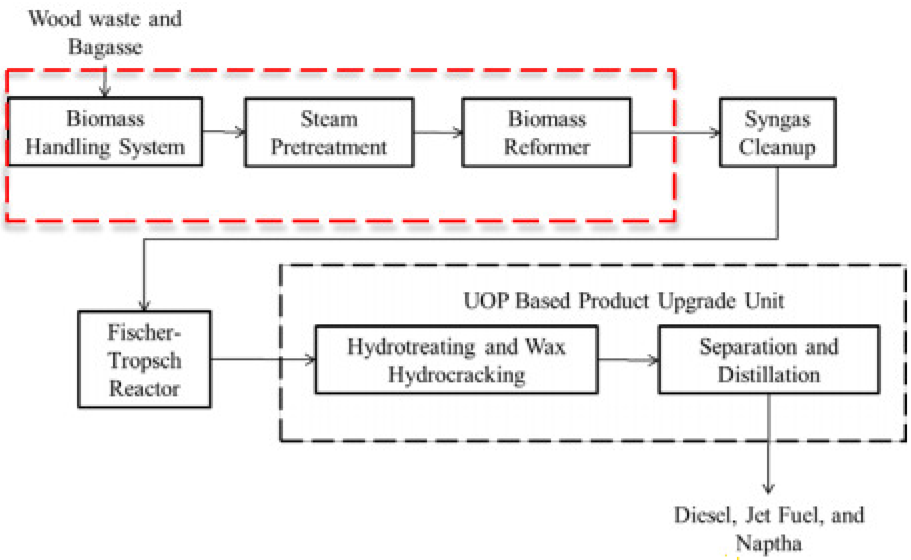
Rentech – Clear Fuels

Diesel/Jet Production by Thermochemical Conversion of Wood Waste

Location	Commerce City, Colorado
Feedstock(s)	Wood waste and Bagasse
Size	Up to 16 dry tons per day
Primary Products	Renewable F-T Diesel and F-T Jet Fuel
Capacity	Up to 420 gallons per day
Award Date	January 2010
GHG Reduction	80% reduction versus fossil product

- Project completed Feb 2013
- Achieved 1000 hours of fully integrated operation.
- Many equipment design & scale-up lessons learned.
- Final report available at: http://www.osti.gov/scitech/servlets/purl/1127171

Equipment added with DOE Grant



Renewable Energy Institute International (REII)

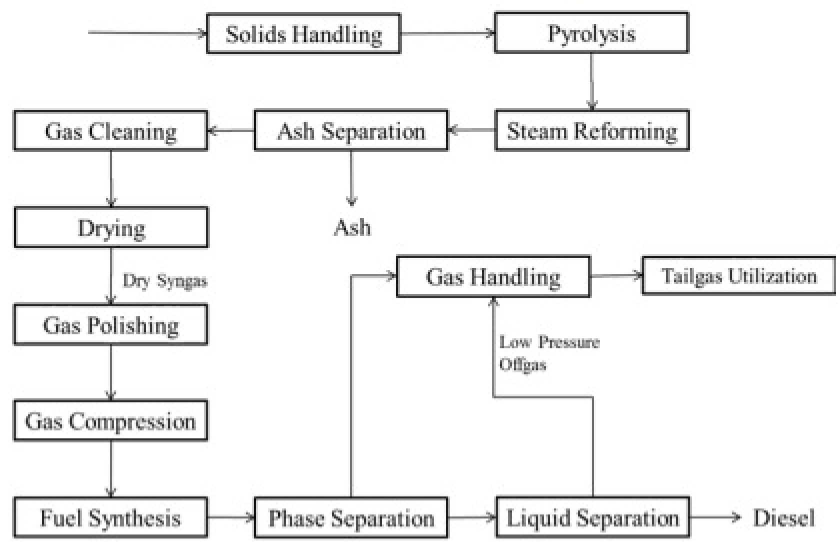
Pilot Integrated Biorefinery for the Economical Conversion of Biomass to Diesel Fuel

Location	Toledo, Ohio (IBR site); Sacramento, California, and Maumee, Ohio (IBR Engineering)
Feedstock(s)	Agriculture and forest residues
Size	25 dry tons per day
Primary Products	Synthetic diesel fuel
Award Date	January 2010
GHG Reduction	89% compared to petroleum-derived fuels

- Project completed in March 2014
- Independent testing on heavy-duty diesel engines showed improved emissions and wear.
- Proprietary Greyrock Energy (formerly Pacific Renewable Fuels) F-T catalyst provides low wax yield.

RED LION BIO-ENERGY

PACIFIC RENEWABLE FUELS

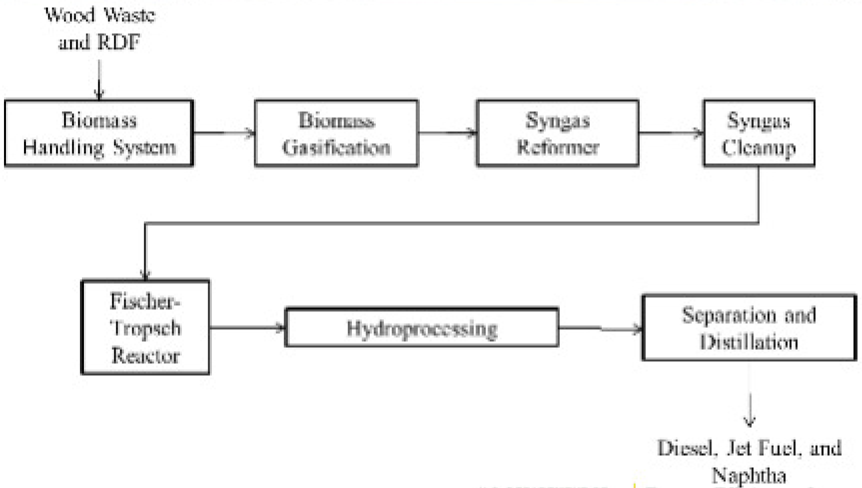


Frontline Bioenergy

Innovative Gasification to Produce Fischer-Tropsch Jet and Diesel Fuel

Location	Ames, Iowa (HQ Office) Houston, TX (Project Site)
Feedstock(s)	Wood Waste and RDF
Size	10 tons per day (oversized to demonstrate new gasifier technology)
Primary Products	F-T liquids upgraded to JP-5, JP-8 and F-76
Capacity	1 barrel per day
Award Date	10/1/2013 – 3/30/2016

- Will be integrated with SGC Energia Fischer-Tropsch pilot plant.
- Project design phase began July 2014



ASTM D7566 pipeline

Pre-Pipeline

Approach	Feedstock	Notes
1) CHyP (syngas, non-FT)	Cellulose	Proton Power
2) Microbial conversion	Sugars - isobutene	Global Bioenergies
3) HTL	Cellulose	Algenol, Genifuel, Sapphire
4) Catalytic HTL	Cellulose	Licella, Muradel, QUT
5) SBI CGC PICFTR	Lipids - biodiesel	SBI Bioenergy
6) CCL	Lipids	Tyton
7) Hydrogenotrophic Conv.	CO_2 / Producer Gas	Kiverdi
8) Cyanobacterial Prod.	CO_2	Joule
9) STG+ GTL	c1-c4 Gas / Syngas	Primus
10) Acid Deconstruction	Cellulose	Mercurius
11) Thermal Catalytic Conv.	Cellulose	Shell/CRI/IH2
12) Thermal Deoxyg.	Lipids	Forge Hydrocarbons
13) Ionic Liquid Decon.	Cellulose	JBEI, tbd
14) Metal Catalytic Conversion	Cellulose	Purdue research
15) Enzymatic Conversion	Lignin	GLBRC & JBEI

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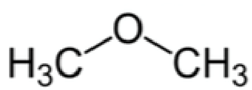
Catalysis R&D Example – DME to High Octane Gasoline

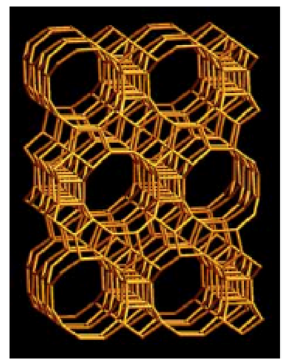
125-275°C, 1-30 bar

Large-pore acidic zeolites (H-BEA)

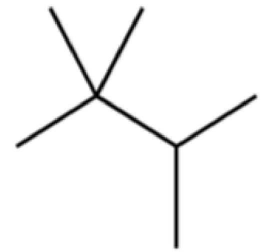
Dimethyl Ether



Methanol



Triptane (for example) C_7H_{16}



(Ahn et al., *Angew. Chem.*, 2009)
(Ahn et al., US Patent, 2009)
(Simonetti et al., *J. Catal.*, 2011)
(Simonetti et al., *ChemCatChem*, 2011)

Key Points on SOT:

- DME and methanol can be synthesized selectively from biomass synthesis gas
- Research octane number of triptane is 112 (gasoline: ~ 92)
- Selectivity to C_7 is ~20-30%
  - selectivity to triptyls (triptane and triptene) within C_7: >70%
- Process selectivity is tunable via operating conditions

Catalysis R&D Example – Moving Toward Distillates

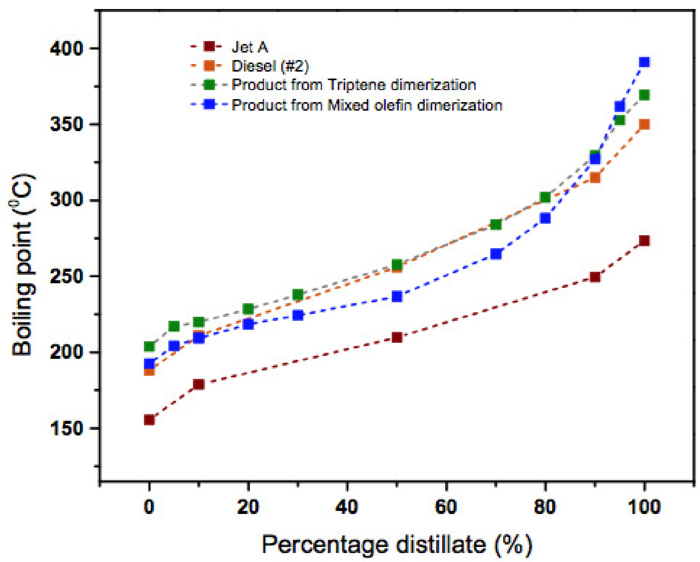
Have confirmed that C_5-C_8 olefinic product can be dimerized over a commercial catalyst (Amberlyst)

- Product has MWs and boiling points within distillate range
- **Properties appear most attractive for jet** (low FP, low CP, correct boiling range)
- Dimerized product highly branched, lower cetane values
- Evaluating for inclusion into design report

Fuel properties	Known values for typical fuels*		As-measured values	
	Commercial fuels		Synthetic fuel from triptene	Synthetic fuel from mixed olefin feed
Cloud point	-48 °C (Jet-A)		-81 °C (ASTM 5773)	< -65 °C
LHV (MJ/kg)	42.8 (Jet-A)		42.87 (ASTM D240)	42.64 (ASTM D240)
BP range (°C)	Diesel(#2)	Jet-A	ASTM-D2887	ASTM-D2887
IBP	180	156	204	193
T10	211	180	220	209
T90	315	251	329	327
FBP	350	274	369	391
Flash point (°C)	≥52	≥38	62.9‡	

* Kook, S.; Pickett, L. M. *SAE Int. J. Fuels Lubr.* 2012 5(2), 647-664

‡(for pure di-triptene $C_{14}H_{28}$)



Behl, M.; Schaidle, J.A.; Christensen, E.; Hensley, J.E. submitted to *Energy & Fuels* for peer review

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