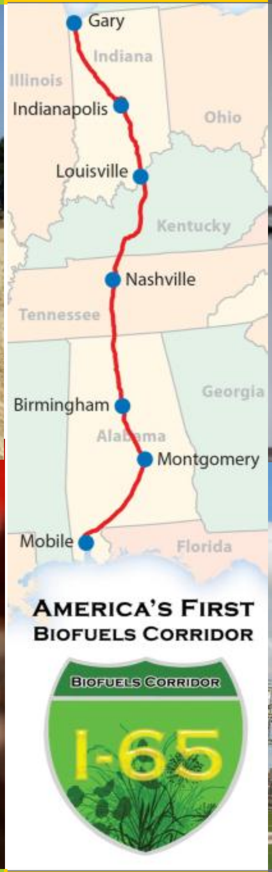
# Bioenergy Technologies Office

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy




## 2017 BETO Project Peer Review – Waste-to-Energy Session Overview

David Babson, Ph.D.
Technology Manager

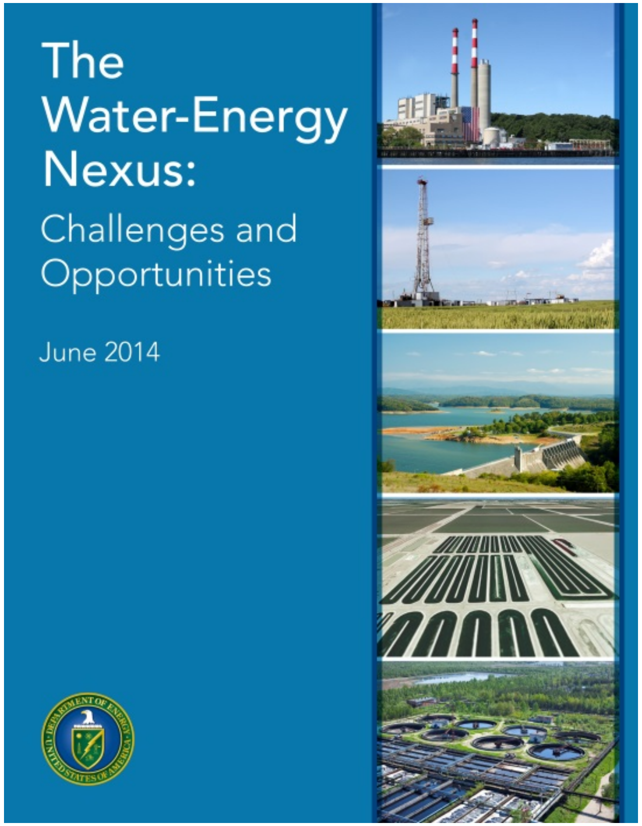
March 7th 2017

# Overview

- Waste-to-Energy reports: key challenges and opportunities in resources and conversion technologies
- Why BETO is interested in wastes and how BETO is looking forward
- Overview of projects under review today
  - National lab AOPs (6 presentations)
  - Competitive FOAs (3 presentations)
- WTE Reviewers

# Water-Energy Nexus: DOE Engagement

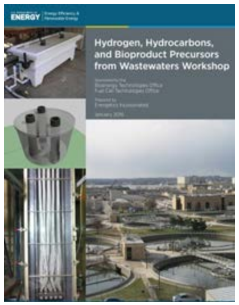
- GAO issued report in Fall 2012, fifth in a series on energy-water nexus
- GAO found that the DOE should be doing more to meet its obligations under the Energy Policy Act of 2005
- DOE launched a cross-cutting Water-Energy Tech Team (WETT)
- Water-Energy Nexus was a priority for Secretary Moniz
- WETT produced a comprehensive report in June, 2014

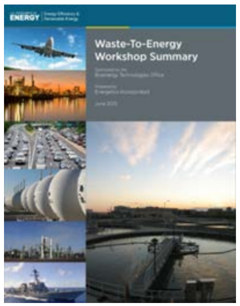


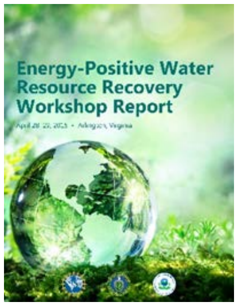

Download the full report at [energy.gov](energy.gov)

# Biofuels and Bioproducts from Wet and Gaseous Waste Streams

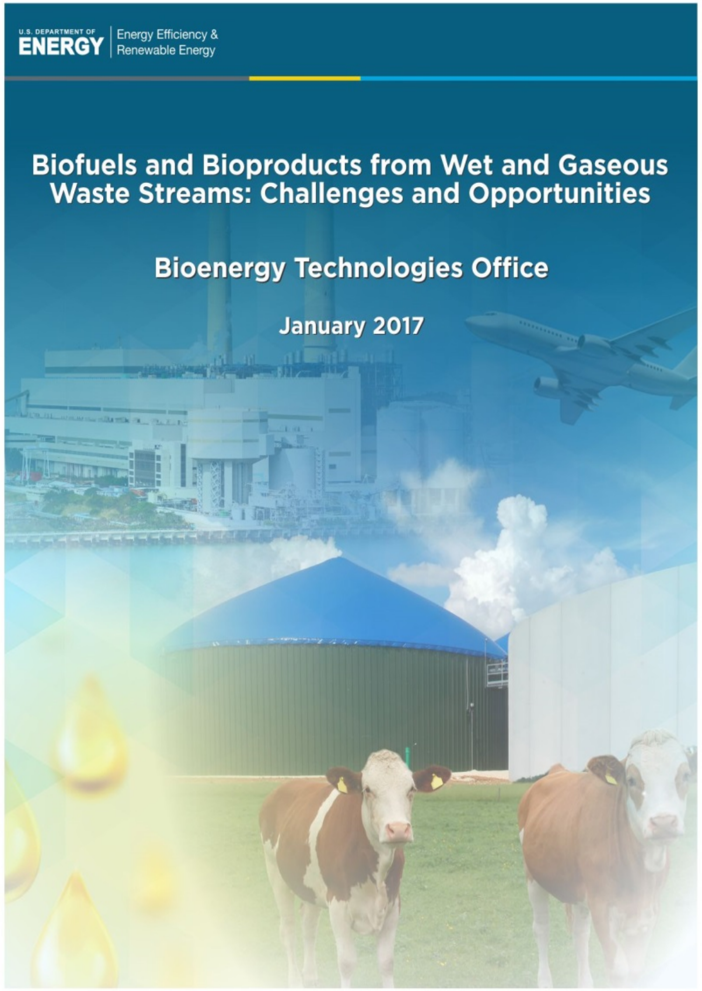
Building off of series of four workshops and other recent interagency collaborations.



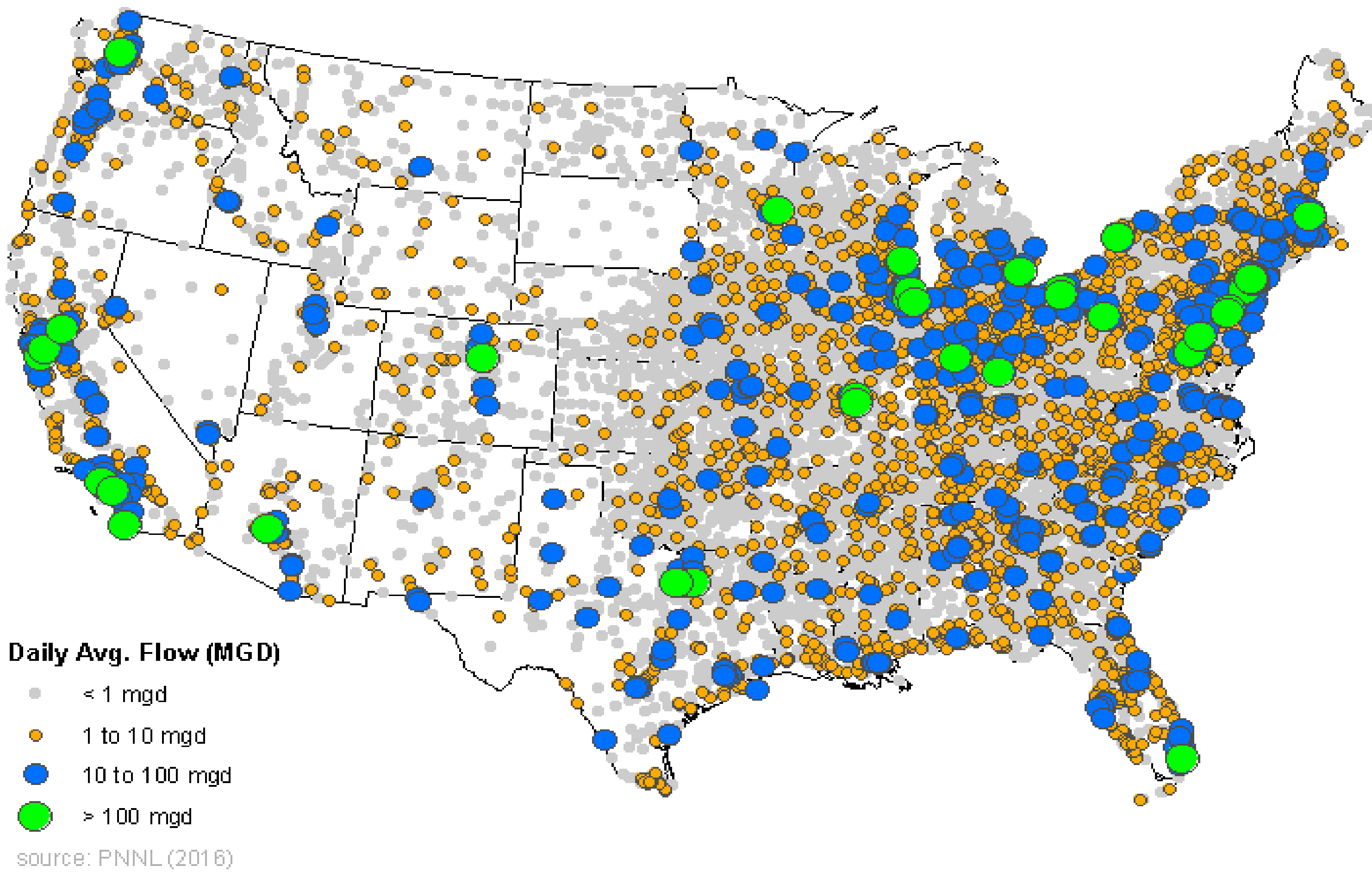




# Wastewater Management in the U.S.

**9 trillion gallons of wastewater is generated and treated annually in the U.S.**

# Distributed Resources: Water Resource Recovery Facilities

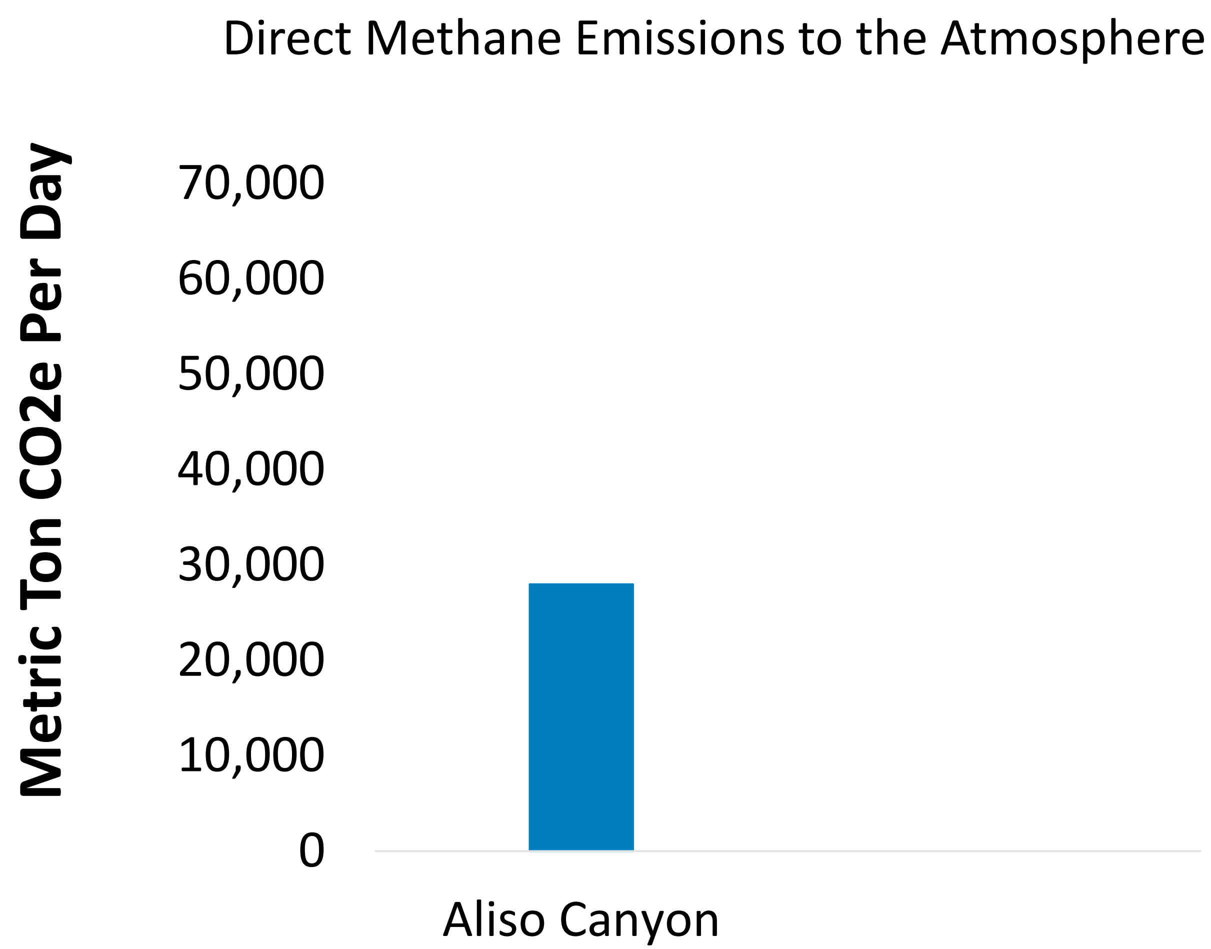



**Spatial distribution and influent range of 14,581 U.S. EPA CWNS 2012 catalogued treatment plants**

# Solid Waste Management in the U.S.

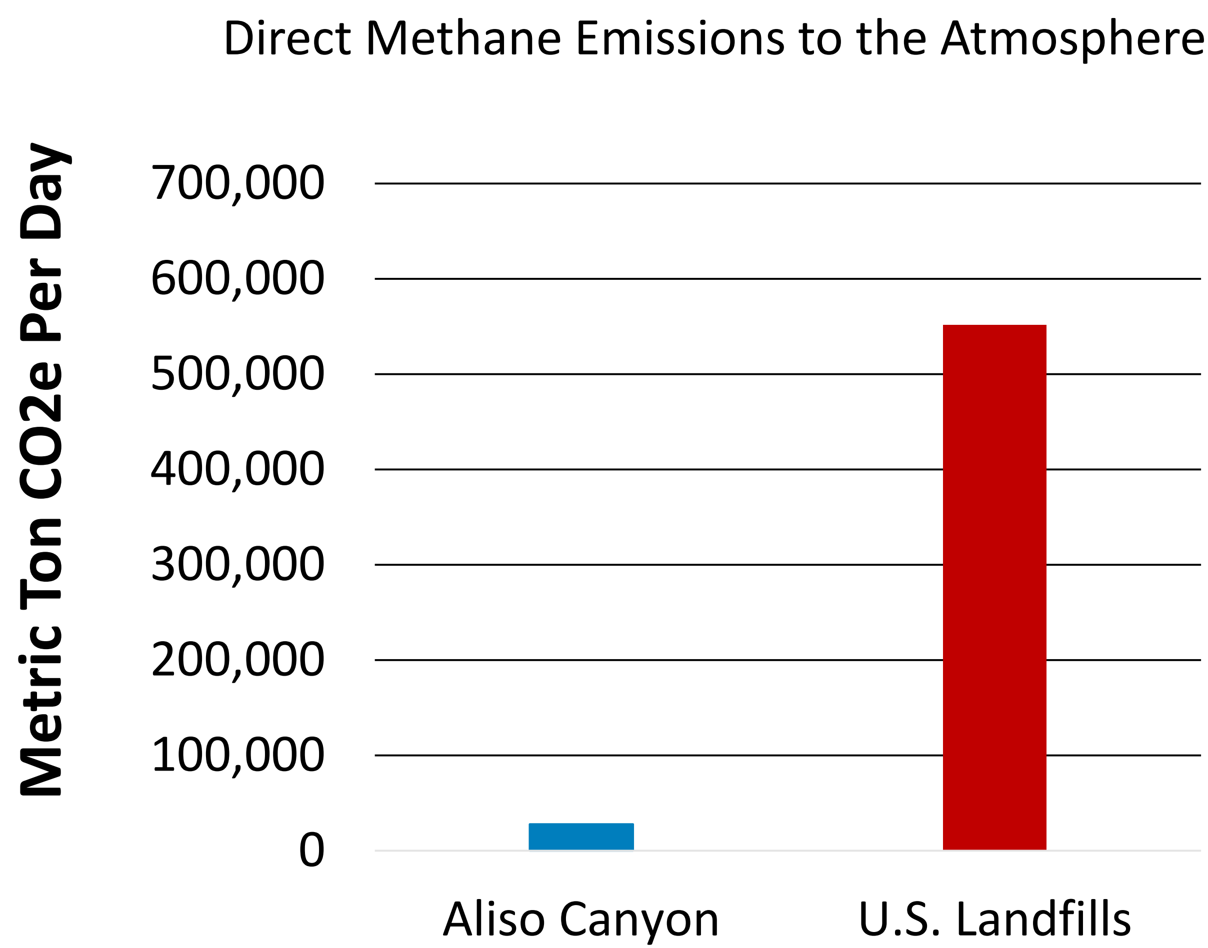
## 250 million tons of waste and 150 million tons to landfills annually; nearly half of this waste is organic

# The climate cost of landfilling




Environmental Protection Agency (EPA). 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014. EPA 430-R-16-002. April 15, 2016. Washington, DC

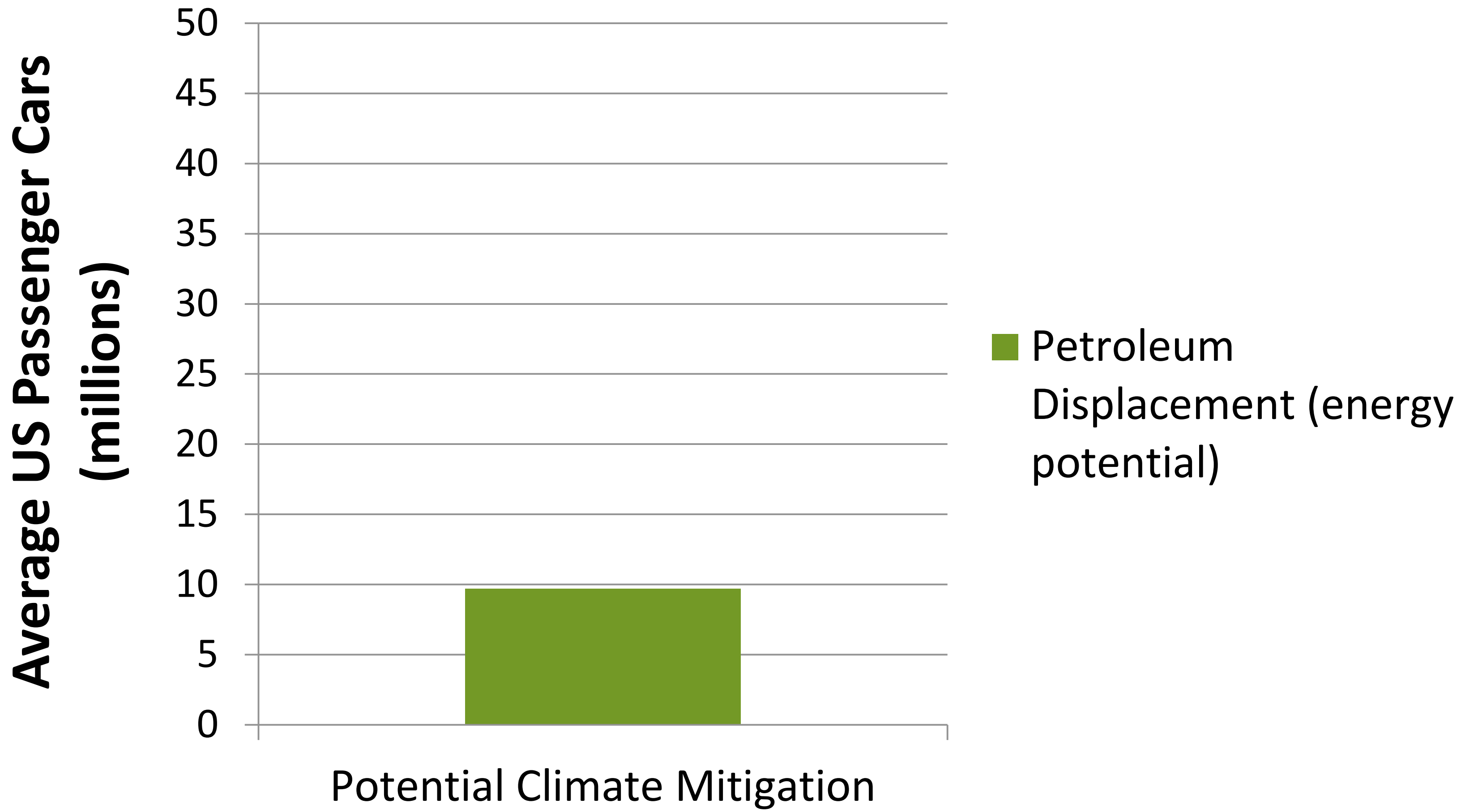
# The climate cost of landfilling




**U.S. landfills emitted nearly 20 times more methane than Aliso Canyon did each day**

Environmental Protection Agency (EPA). 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014. EPA 430-R-16-002. April 15, 2016. Washington, DC

# Organic Waste Potential: Energy versus Carbon

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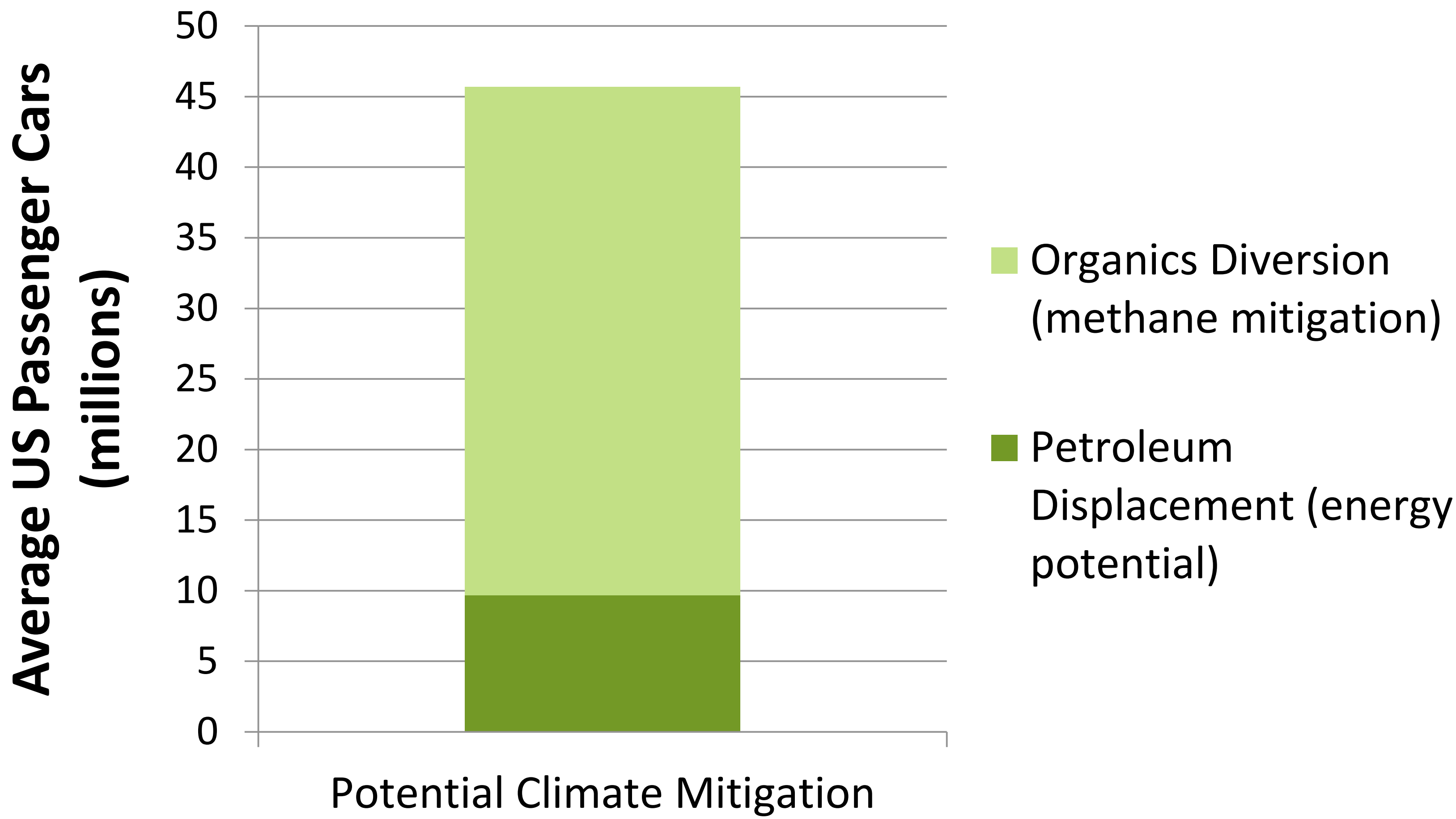
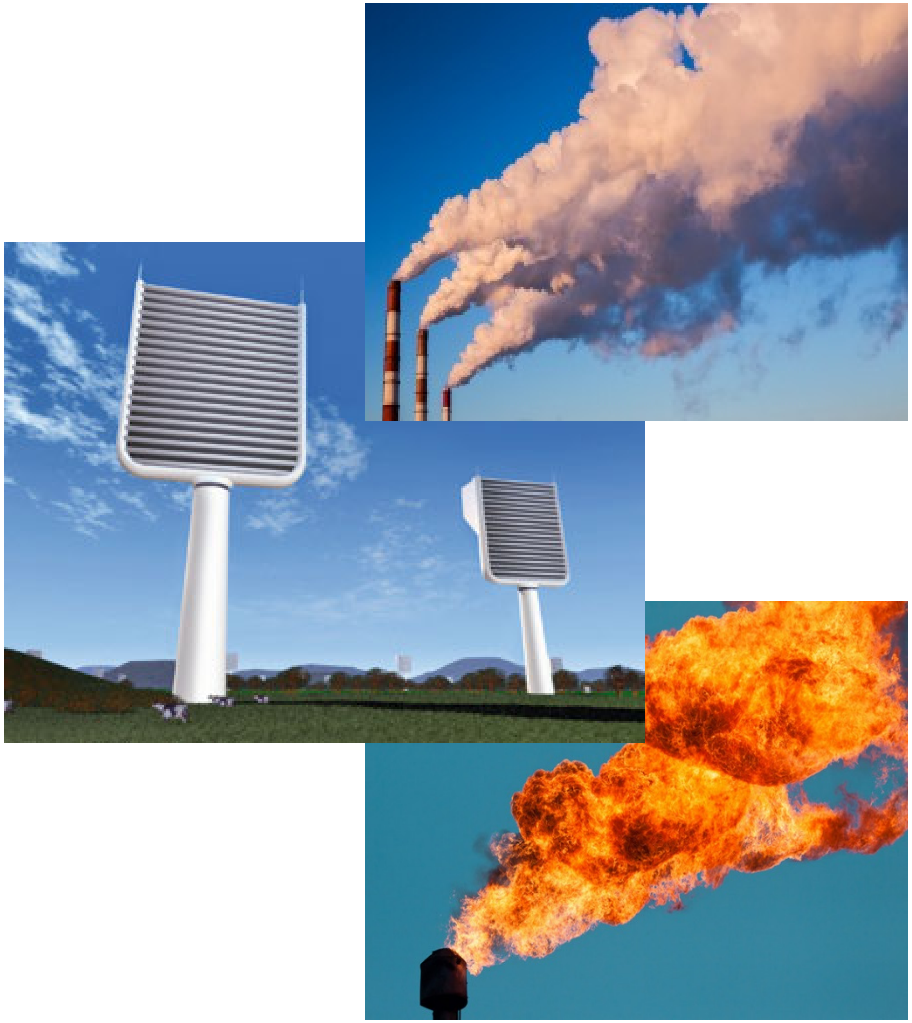


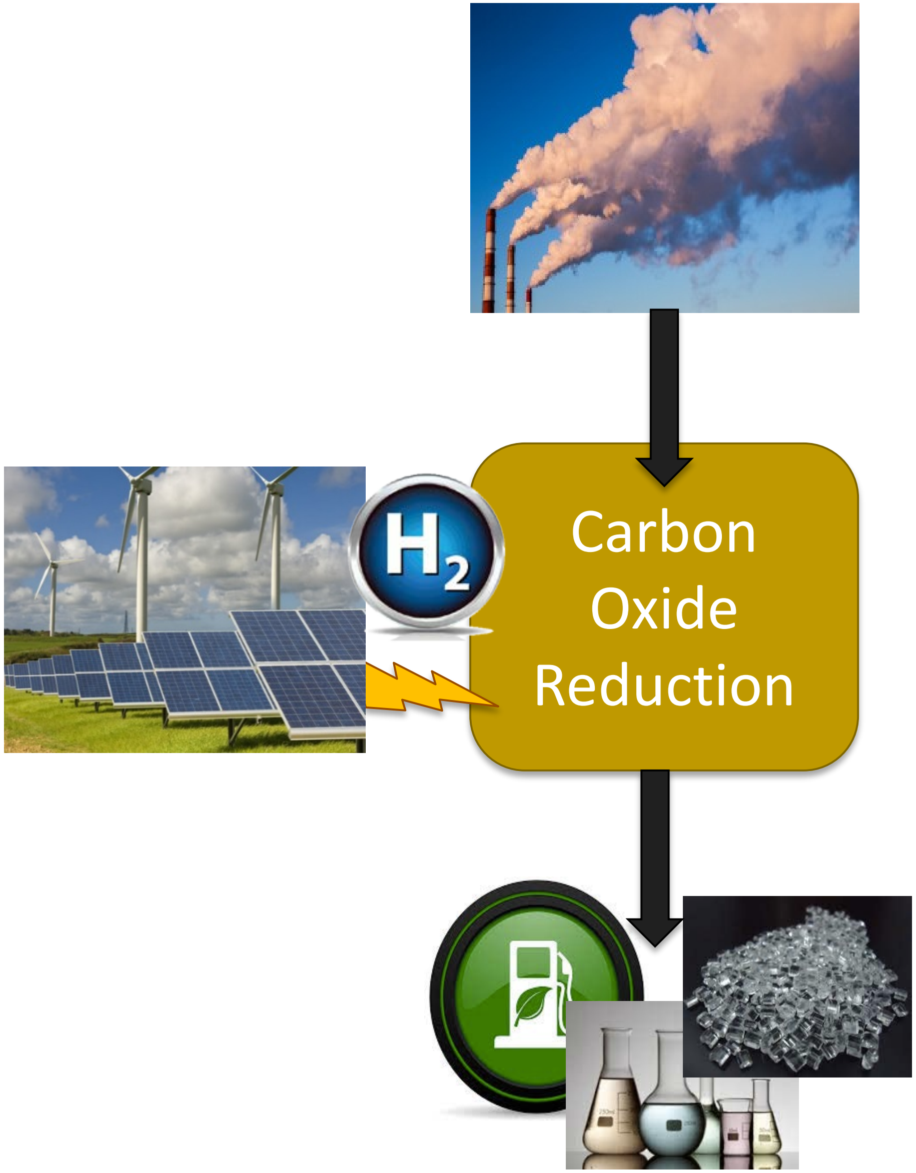

Environmental Protection Agency (EPA). 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014. EPA 430-R-16-002. April 15, 2016. Washington, DC

# Gaseous Wastes and Engineered Carbon Cycling



- Industrial waste gases and GHG mitigation
  - Mitigating flaring through novel strategies for upgrading biogas and stranded natural gas
  - New efforts in engineered carbon cycling
    - Non-photosynthetic carbon reduction – carbon oxides as feedstock
    - Engineering 100% carbon efficient conversion strategies

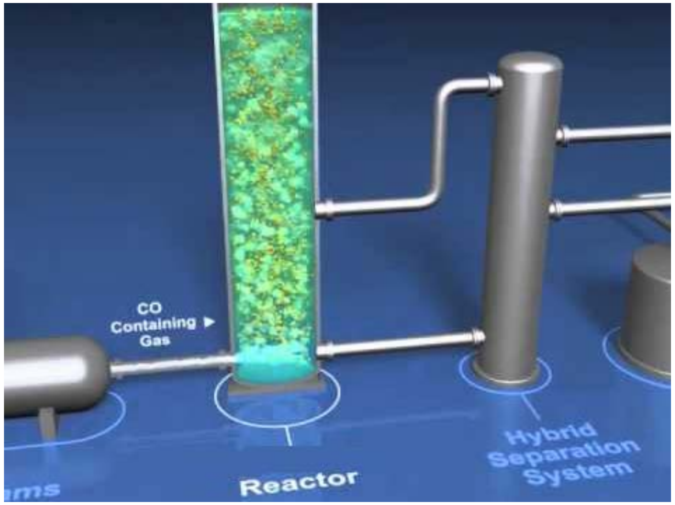
# Re-Imagining the Carbon Cycle



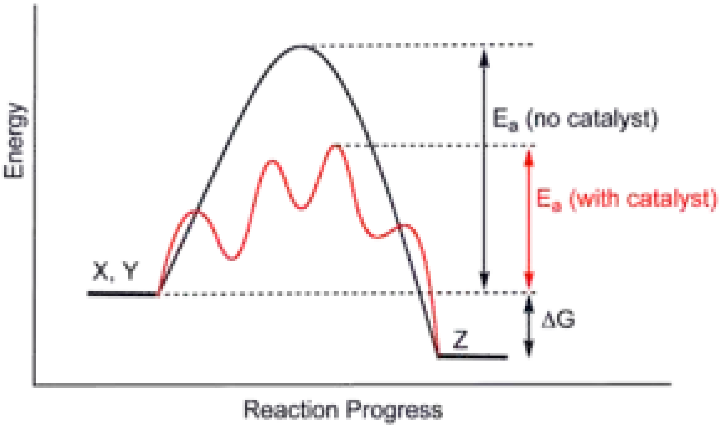

- Limit land-use requirements
- Avoid inefficient photosynthesis
- Leverage carbon-free renewable power
- Directly synthesize more valuable intermediates and feedstocks

# Re-Imagining the Carbon Cycle: Technologies

- Biochemical carbon reduction
  - Whole-cell chemolithoautorophic
    - No $H_2$ (CO reduction)
    - Syngas (CO via $H_2$)
    - High $H_2$ ($CO_2$ via $H_2$)
  - Whole-cell electrolithoautotophic
  - Cell-free biocatalytic

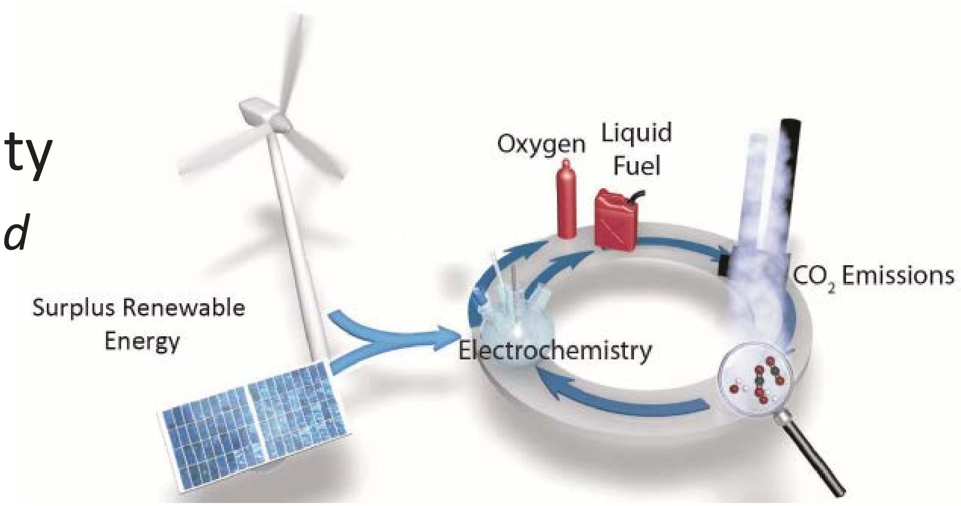



- Catalytic carbon reduction
  - Thermocatalytic
    - Concentrated solar / high temperature
    - Microwave
  - Electrocatlytic



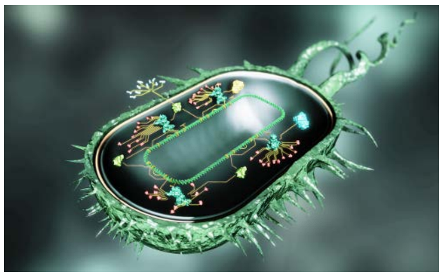
# Re-Imagining the Carbon Cycle: BETO Efforts

- Competitive Projects
  - LanzaTech
    - No $H_2$ (CO reduction)
    - Syngas (CO via $H_2$)
    - High $H_2$ ($CO_2$ via $H_2$)
  - Kiverdi
    - Syngas (CO via $H_2$)
- Targeted Funding Opportunity
  - SBIR FOA-0001619: *Biofuel and Bioproduct Precursors from Gaseous Waste Streams*



# Re-Engineering the Carbon Cycle

**Whole-cell pathway engineering for optimized carbon utilization**



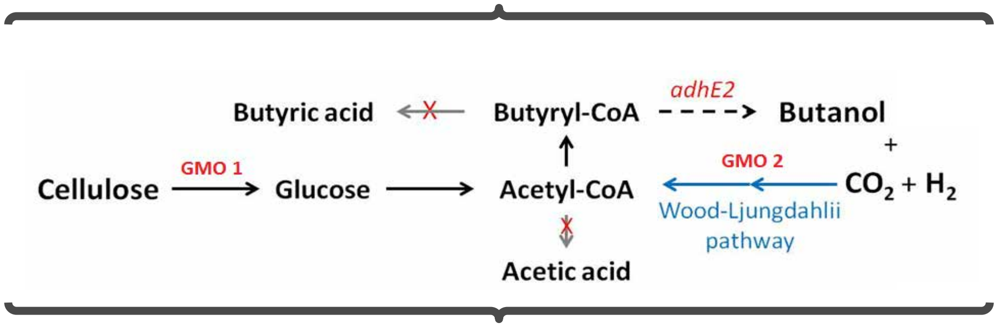
Synthetic Biology

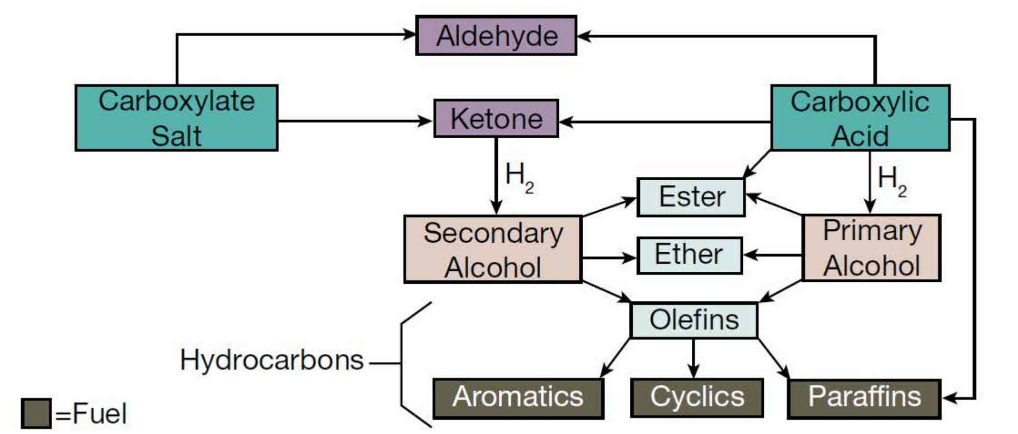

**Engineered mixed microbial systems – the carboxylate platform**

$$
\begin{array}{ll}
C_6H_{12}O_6 \rightarrow 2\ H_3CCO_2H + 2\ CO_2 + 2\ H_2 & \text{Acidogens} \\
2\ CO_2 + 2\ H_2 \rightarrow H_3CCO_2H & \text{Acetogens} \\
\hline
C_6H_{12}O_6 \rightarrow 3\ H_3CCO_2H & \text{Net}
\end{array}
$$

# Re-Engineering the Carbon Cycle: Technologies

- Biochemical
  - Arrested methanogenesis with biological upgrading
  - Whole-cell mixotrophic
- Catalytic
  - Enhanced carbon efficient pyrolysis (e.g. Ford proposal)
- Combined biochemical / thermochemical
  - Arrested methanogenesis with catalytic upgrading

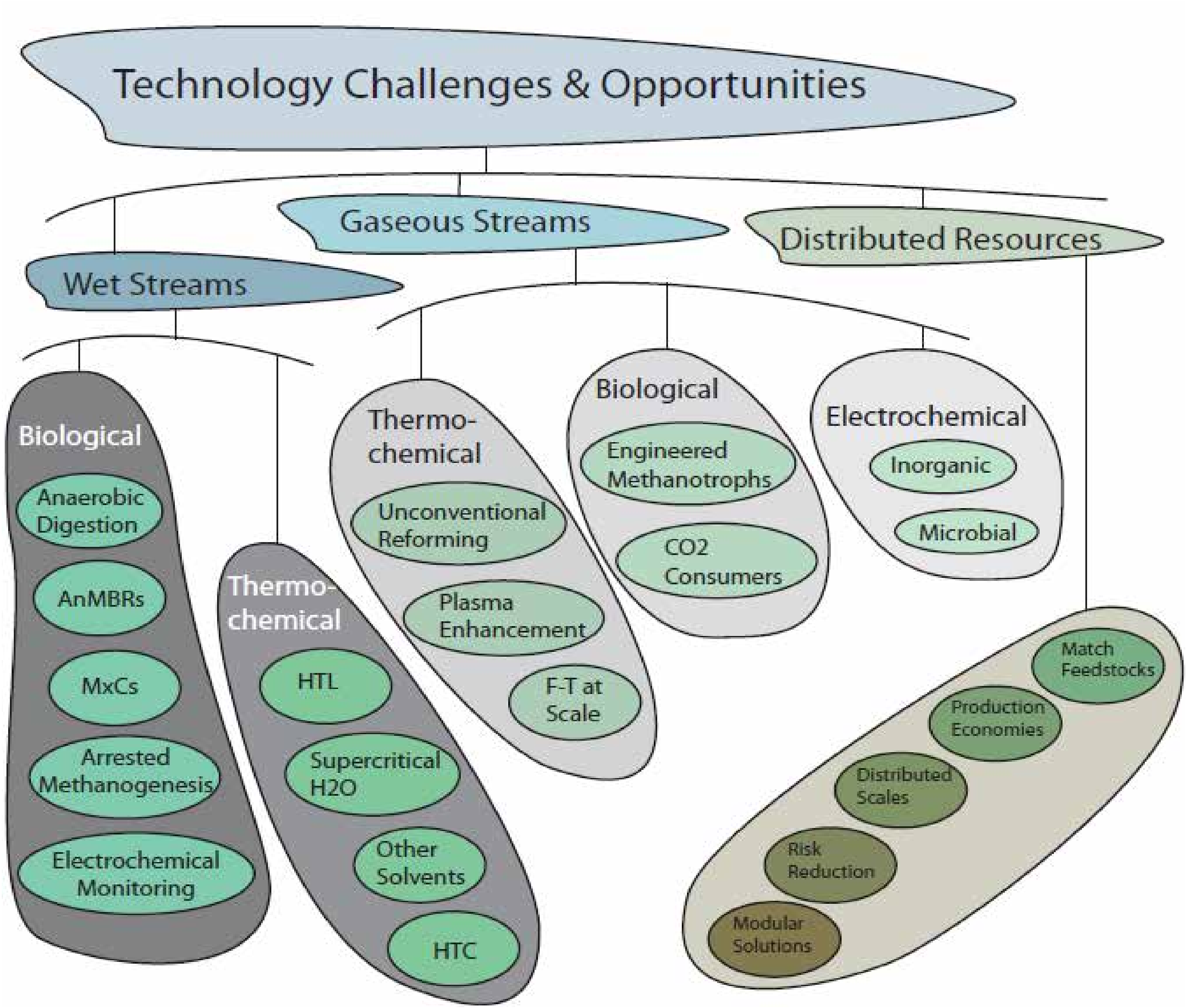


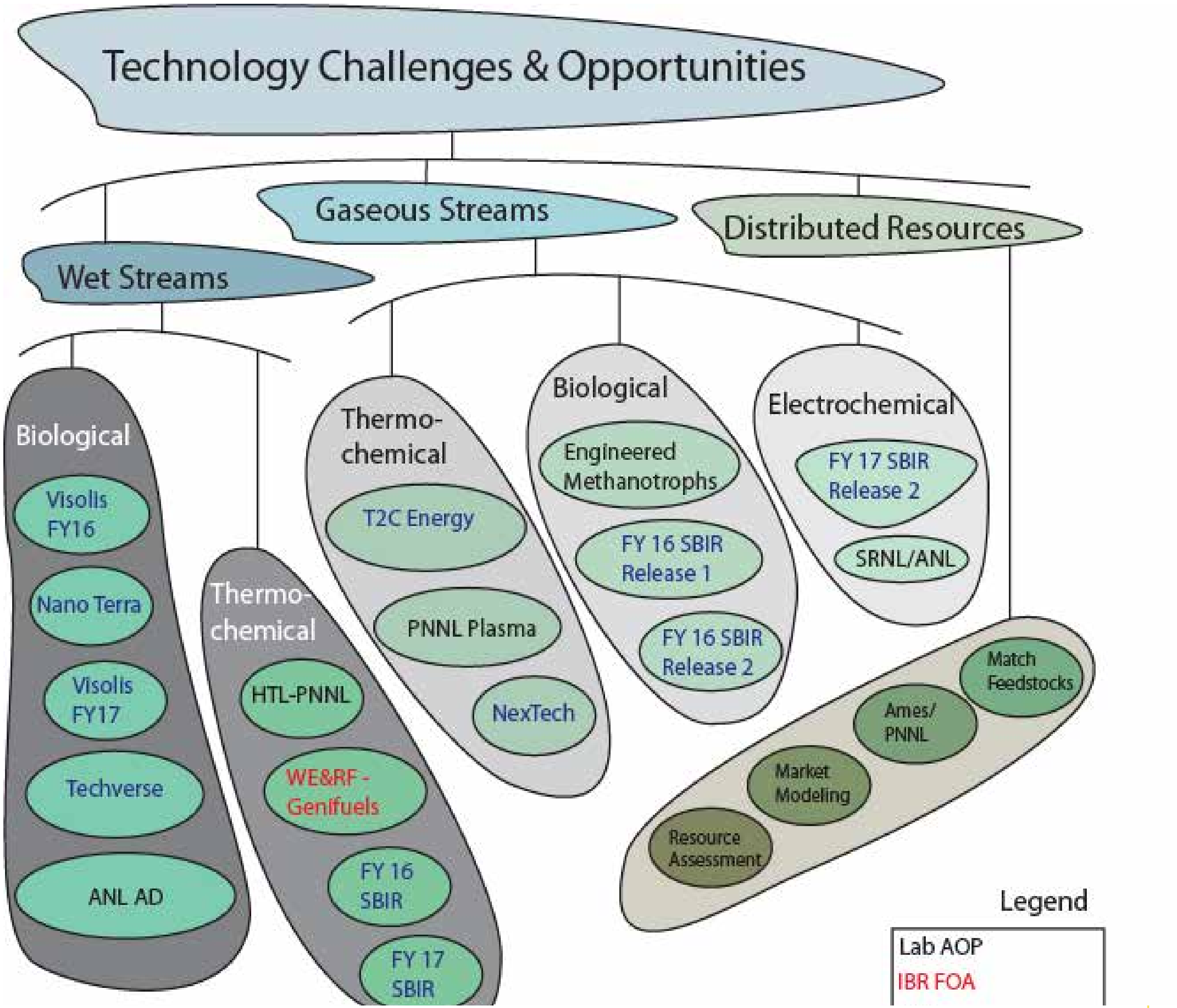
# Re-Engineering the Carbon Cycle: BETO Efforts

- Competitive Projects
  - White Dog Labs
  - Ohio State University
- Targeted Funding Opportunity (Proposed)
  - SBIR FOA: *Leveraging Renewable Power to Enhance Biomass Carbon Conversion Efficiency*
- Analytical efforts (for all BETO strategies - planning)
  - Carbon utilization scenarios as a function of process grid integration, surplus electricity, electricity price, carbon price

# Potential Areas for Technology RDD&D



# Alignment with Existing and Prospective Initiatives



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# Key Considerations Regarding Waste Resources

- Waste feedstocks represent a significant resource that is already available and distributed
- In most cases, wastes are already being managed at cost representing a problem to be solved
  - Problem has garnered serious congressional attention
  - Waste streams are expected to grow along with population
  - Outdated infrastructure presents an opportunity to deploy better technologies and strategies
- Wastes and its conversion is unique in BETO's portfolio
  - Conversion strategies must be uniquely conceived and scaled to fit the resource
  - TEA and LCA considerations for these resources are distinct
  - Unique market conditions present a leading-edge niche opportunity

# Today's Projects: National Lab AOPs

- Waste-to-Energy: Feedstock Evaluation and Biofuels Production Potential (NREL/PNNL); Anelia Milbrandt
- WTE Simulation Model (NREL); Daniel Inman
- Hydrothermal Processing of Biomass (PNNL); PI: Richard Hallen; Presenter: Justin Billing
- Enhanced Anaerobic Digestion (ANL); Meltem Urgun-Demirtas
- Electrochemical Monitoring of Anaerobic Digestion (SRNL/ANL); Charles Turick
- Biogas to Liquid Fuels and Chemicals Using a Methanotrophic Microorganism (NREL); Michael Guarnieri

# Today's Projects: Competitive FOAs

- **Biological and Chemical Upgrading for Advanced Biofuels and Products (BCU)** FY2014 ($13M - *$4M in alternates in FY2015)*: Focused on the integration and development of upgrading and separations in advanced biofuel production systems.
  - 3 of the 7 awardees are WTE projects and will present here today:
    - Biogas Valorization: Development of a Biogas-to-Muconic Acid Bioprocess (NREL); Michael Guarnieri
    - Biomass Electrochemical Reactor for Upgrading Biorefinery Waste to Industrial Chemicals and Hydrogen (Ohio University); John Staser
    - Lactic Acid Producing Methanotrophic Bacteria (LPMB) For Fermentation of Bio-Methane As A Biological Upgrading Technology (NatureWorks LLC); Ken Williams

# WTE Reviewers

- Luca Zullo (Principal at VerdeNero LLC; VP of Business Development and Commercialization at Greenyug LLC) – lead reviewer
- Phil Marrone (Principal Chemical Engineer at Leidos)
- Jeremy Guest (Assistant Professor at University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering)
- Brandon Emme (Principal Scientist at ICM, Inc)

# Contact me to talk trash


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# Backup Slides

# Wet and Gaseous Feedstocks: Resource Assessment

| | Annual Resource Generation | | |
|---|---|---|---|
| Feedstocks | Estimated Annual Resources | Inherent Energy Content (Trillion Btu) | Fuel Equivalent (MM GGE)[1] |
| **Wet Feedstocks** | 77.17 MM Dry Tons | 1,078.6 | 9,290.8 |
| Wastewater Residuals | 14.82 | 237.6 | 2,046.6 |
| Animal Waste | 41.00 | 547.1 | 4,713.0 |
| Food Waste[2] | 15.30 | 79.6 | 685.3 |
| Fats, Oils, and Greases | 6.05 | 214.3 | 1,845.9 |
| **Gaseous Feedstocks** | | 733.6 | 6,319.8 |
| Biogas[3] | 420 BCF | 430.5 | 3,708.6 |
| $CO_2$ Streams | 3,142 MM Tons | - | - |
| Associated Natural Gas | 289 BCF | 303.1 | 2,611.2 |
| **Other Waste Feedstocks** | | 526.1 | 4,531.6 |
| Glycerol | 0.6 MM Tons | 8.7 | 75.1 |
| Black Liquor | 44 MM Tons | 517.4 | 4,456.5 |
| DDGS[4] | 44 MM Tons | n/a | n/a |
| **Total** | | **2,338.3** | **20,142.2** |



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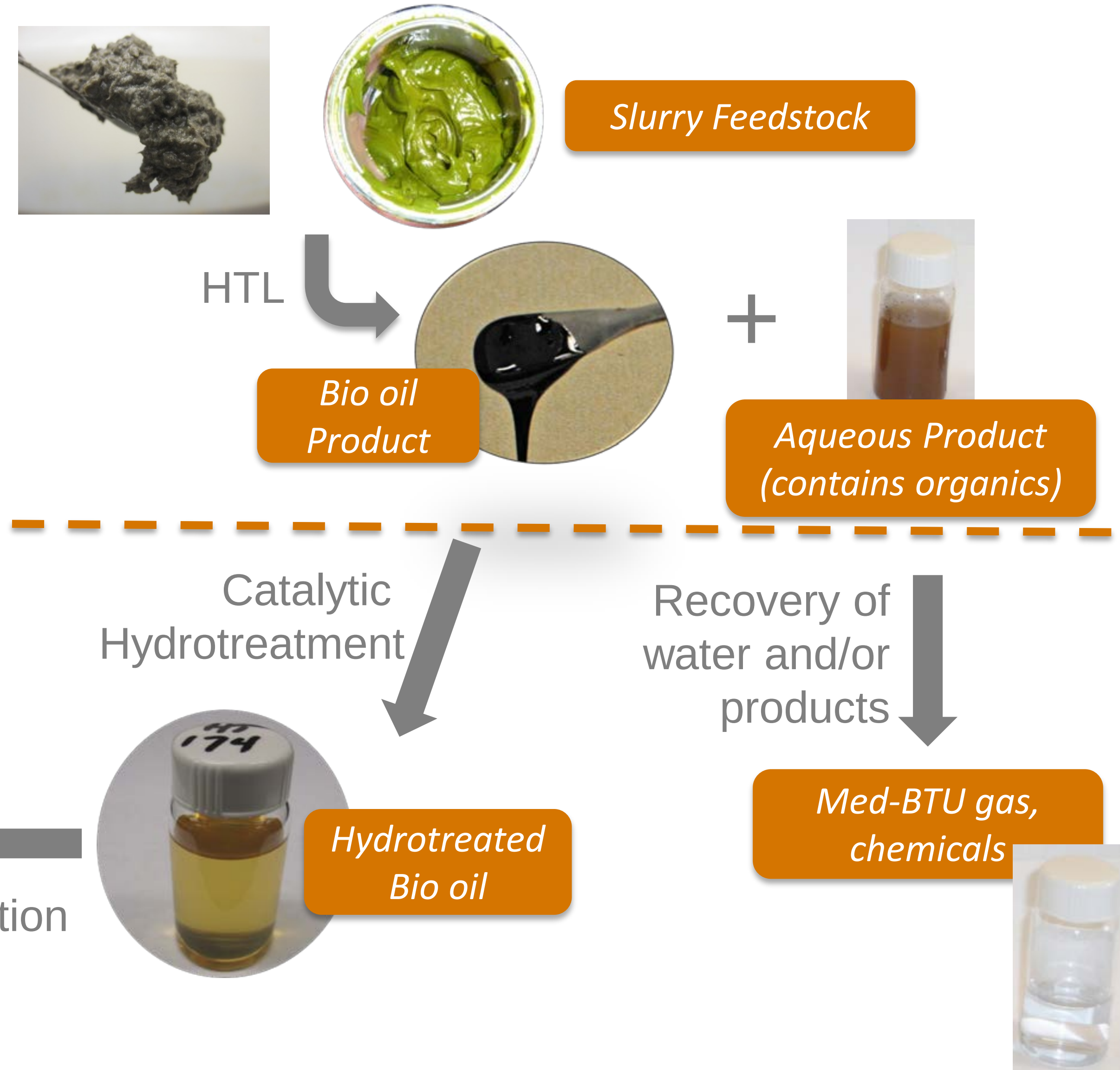
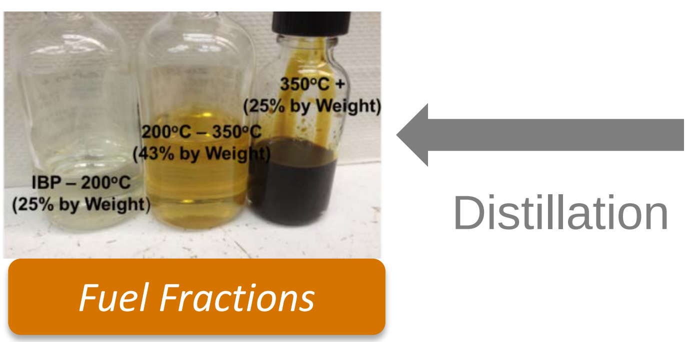
# What is hydrothermal liquefaction (HTL)?

**Hydrothermal Liquefaction (HTL)**

- Conversion of a biomass slurry (e.g., wood, algae, other) to bio oil and aqueous product
  - ~ 350°C
  - ~ 3000 psig



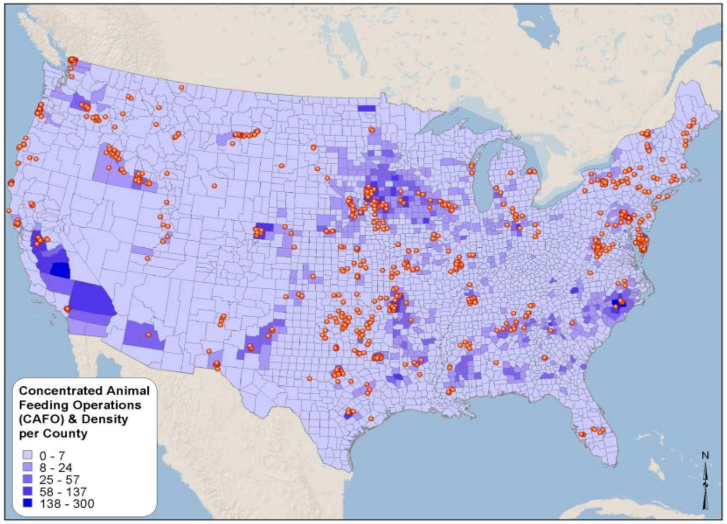

Bio oil product is refined via **Catalytic Hydrotreament** and fractionated by **Distillation** to gasoline, diesel, jet fuel, and bottoms

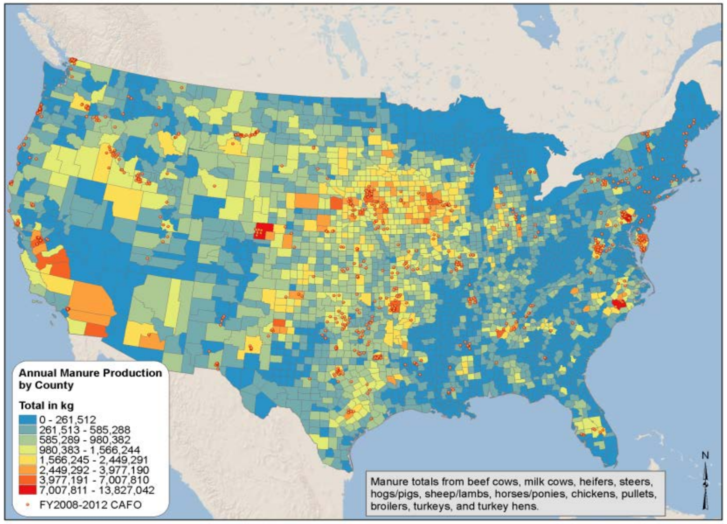


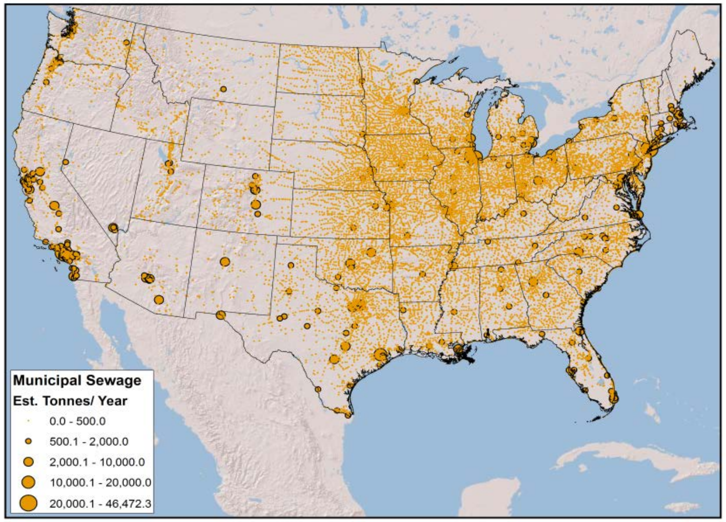

PNNL-SA-12342

# Pairing distributed, wet resources with HTL technology

- Concentrated Animal Feeding Operations
- Animal Manures
- Winery & Distillery residuals
- Municipal sewage




# Waste water treatment plant primary sludge – a case study

Conversion of wastewater treatment plant (WWTP) Primary Sludge into Hydrocarbon Fuels

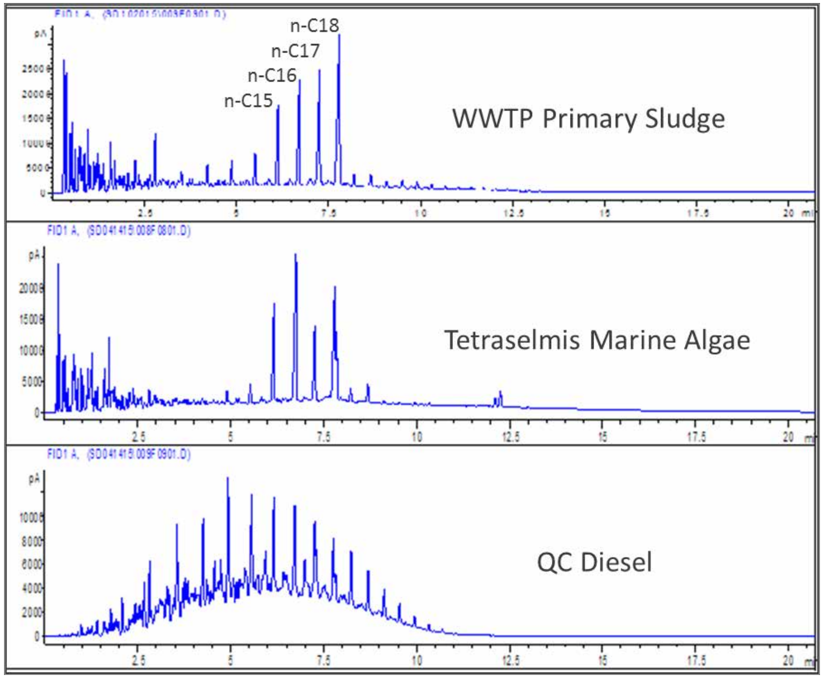
- Hydrothermal Liquefaction of WWTP Primary Sludge
- Upgrading of HTL Biocrude
- Preliminary TEA/LCA

WWTP Industrial Partners

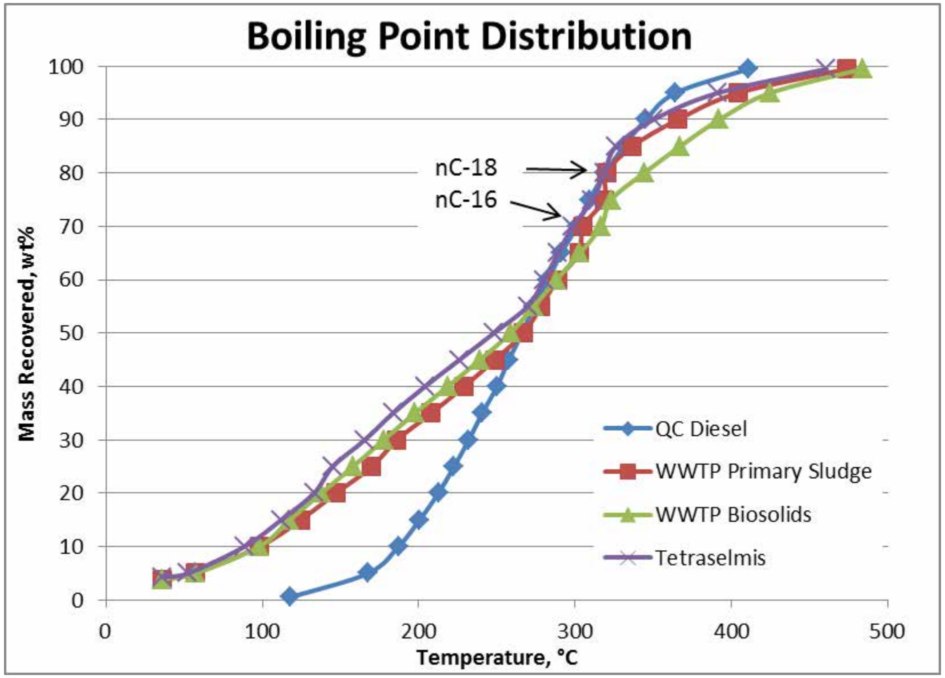
- Organized by Water Environment & Reuse Foundation (WE&RF) as a Leaders Innovation Forum for Technology (LIFT) Project http://www.werf.org/lift
- Research effort led by MetroVancouver, 10 paying participants (WE&RF subscribers representing municipal WWTP)
- Data validated by Leidos, detailed report published LIFT Project Report

# Comparison of products from sludge with reference fuels

GC-FID Comparison



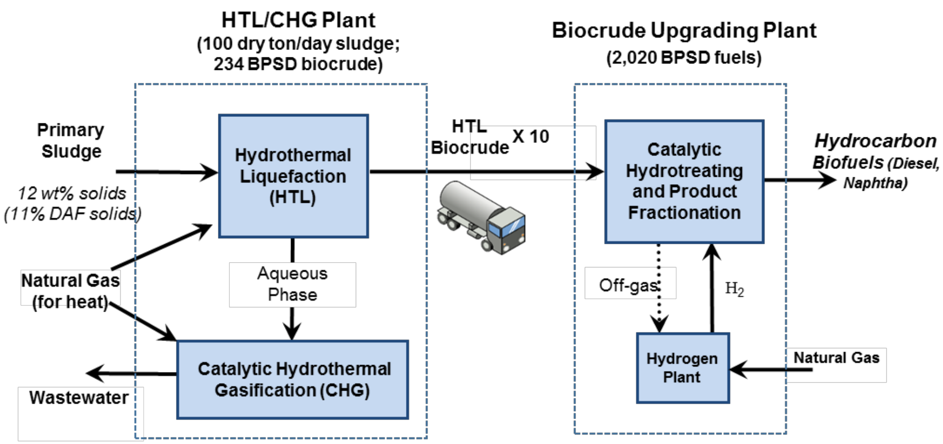

Sim Distillation -- ASTM D2887




Note: GC-FID chromatogram and boiling point mass distribution for petroleum diesel is included for reference.

- Yield and quality of distillate fuel similar to algae feedstock
- WWTP Primary sludge product is high in n-paraffin compounds which provide high cetane value in diesel

# Preliminary WWTP sludge TEA – 100 dry ton/day scale




| HTL Plant | | Upgrading Plant | |
|---|---|---|---|
| Sludge feed rate | 100 dry ton/day | Biocrude feed rate | 34,000 lb/hr (32 mm GGE/yr) |
| Biocrude Yield:<br><br>g dry oil/g dry sludge<br>MM GGE/yr | <br><br>0.41<br>3 | Upgraded Fuel Yield:<br><br>Total, g oil/g biocrude<br>Diesel, MM GGE/yr<br>Naphtha, MM GGE/yr | <br><br>0.78<br>22<br>8 |
| **Capital Costs, $million** | | **Capital Costs, $million** | |
| HTL | $20. | Hydrotreating & Hydrocracking | $20 |
| CHG | $9.1 | Hydrogen Plant | $17.5 |
| Steam Cycle | $0.6 | Steam Cycle | $0.9 |
| Balance of Plant | $1.4 | Balance of Plant | $4.4 |
| Total Installed Capital | $31 | Total Installed Capital | $42.8 |
| **Total Capital Investment** | **$58** | **Total Capital Investment** | **$79** |
| **MFSP - Biocrude** | **$3.8/gge** | **MFSP - Final Fuel** | **$4.9/gge** |

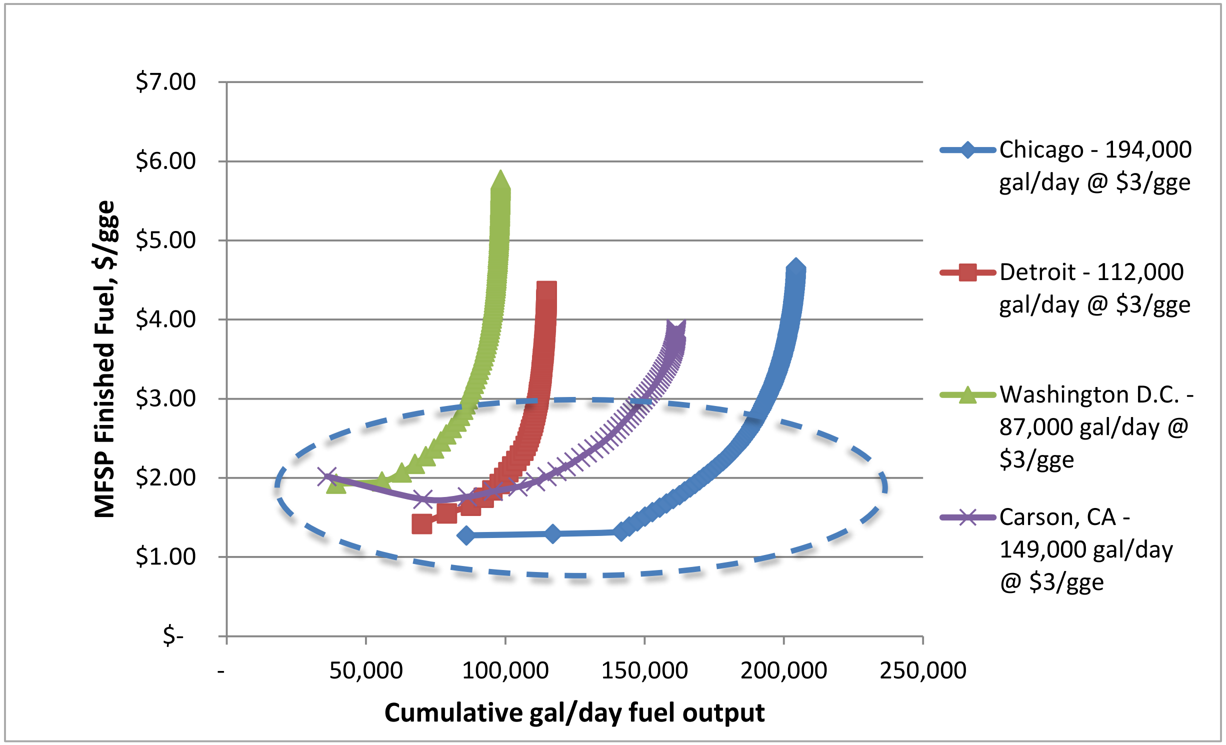
Key Assumptions:

- Feedstock Cost: $-50/dry ton (avoided cost for sludge disposal)
- Biocrude transportation cost: $0.10/gge (200 mile round-trip)
- Algae HTL models employed; adjusted with primary sludge data
- N$^{th}$ plant assumptions; $2011 USD

# Cluster analysis for minimum fuel selling price of $3USD/gge

***Assumptions:***

- Centralized upgrading for 'clusters' of WWTPs
- 100 km drawing radius for biocrudes
- All WWTP capacities included
- 0.4 M gal wastewater → 1 bbl hydrocarbon




***Findings:***

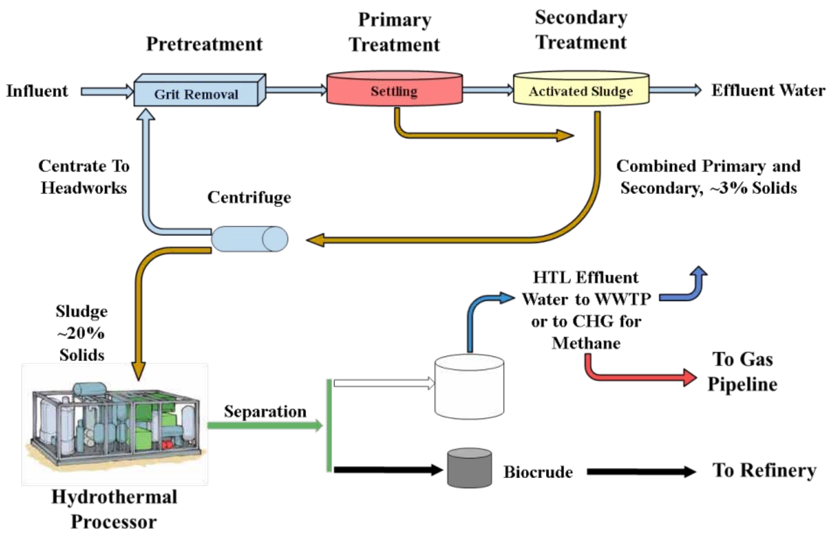
- Drawing from small HTL plants is feasible and can increase fuel production significantly
- Feasible 'clusters' range from 400-8,700 BPD finished fuel, and include <u>all</u> sizes of WWTPs
- Largest plants ***not always best candidates*** for most fuel at $3/gge

# HYPOWERS Project Summary Slide

***Area of Interest***: Quickly and efficiently converts wastewater solids to hydrocarbon fuels while sharply reducing greenhouse gas emissions.
***Applicant :*** Water Environment & Reuse Foundation (WE&RF)
***Project Title:*** HYPOWERS: Hydrothermal Processing of Wastewater Solids
***Principal Investigator:*** Jeff Moeller, M.S., P.E.
***Key Partners:*** Genifuel Corporation, Pacific Northwest National Laboratory, Merrick & Company, Central Contra Costa County Sanitary District, Tesoro Corporation, Southern California Gas Company, MicroBio Engineering, MetroVancouver, Brown and Caldwell, plus 12 contributing utilities.
***Proposed Total Project Cost:*** Phase 1 = $2,457,299
- Applicant funds: $1,228,666 = 50.0% of total
- DOE funds: $1,228,633 = 50.0% of total

***Proposed Phase 1 Project Duration:*** 24 months inc. validation

**Hydrothermal Processing of Wastewater Solids**

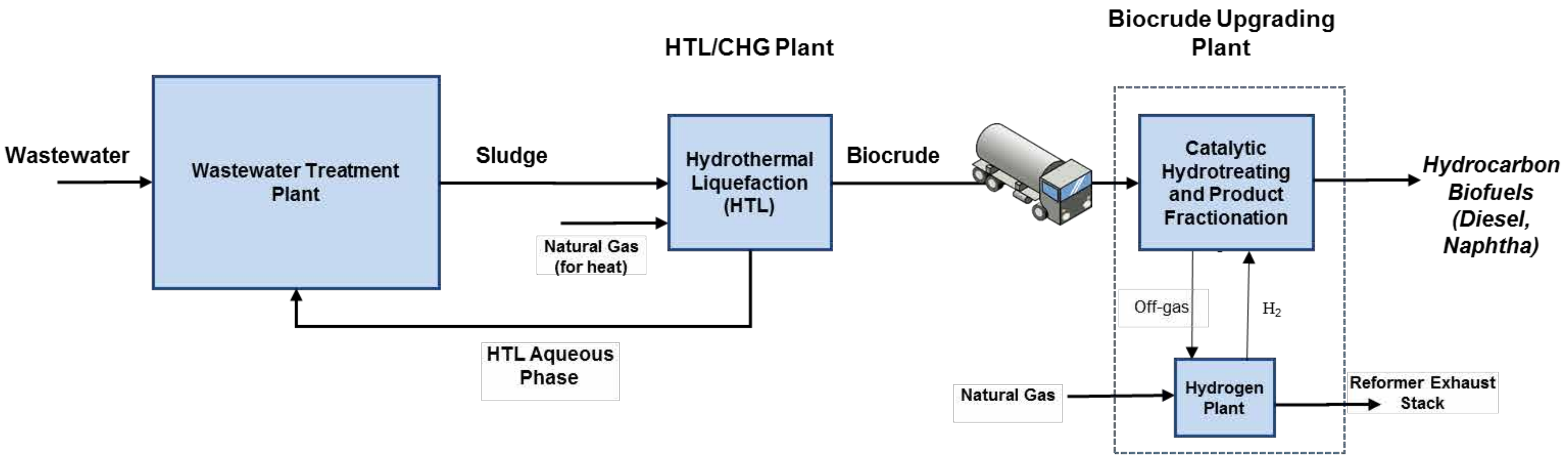



***Technology Summary:*** The HYPOWERS project will tap into a new source of energy—wet waste—to profitably produce biocrude oil and natural gas, replacing fossil fuels while using existing infrastructure. Hydrothermal Processing (HTP) uses water, temperature and pressure to convert wastewater solids to biofuels in less than one hour with automated equipment.
***Description of the Technology's Impact:*** Wastewater treatment produces over 12 million metric tons (dry weight) of solids in the US annually. Converting these solids with HTP will produce the equivalent of 41 million barrels of oil per year and save $2.2 billion in solids disposal costs.

***Proposed Project Objectives/Goals***:
1. Demonstrate Hydrothermal Processing as an integral and reliable step in wastewater treatment at an operating utility.
2. Eliminate the need for management and removal of wastewater solids and their associated costs.
3. Convert more than 40% of the dry mass of wastewater solids to biocrude oil and the remainder to renewable gas.

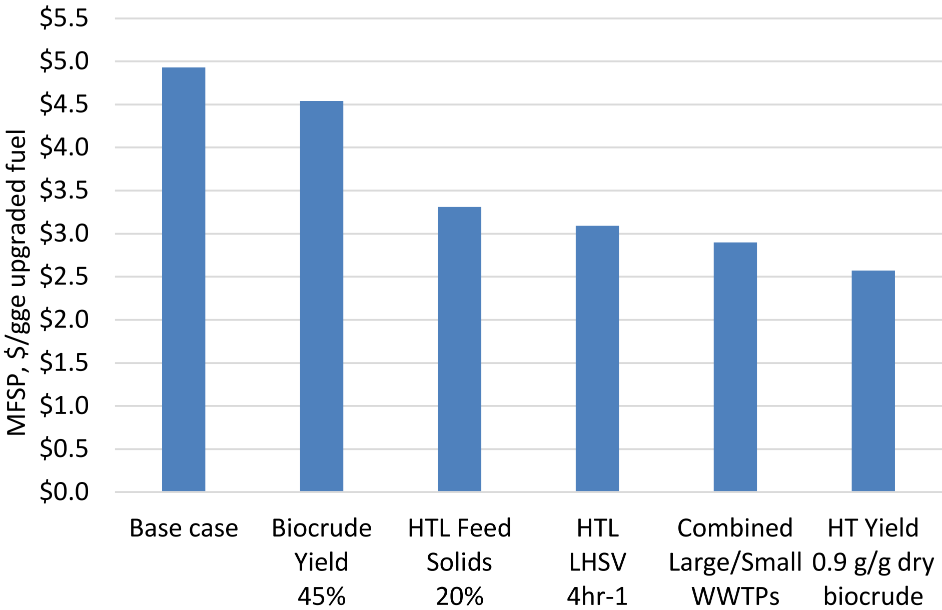
***Project's Key Idea/Takeaway:*** Transform wastewater treatment to eliminate wastewater solids while profitably producing renewable hydrocarbon fuels using existing infrastructure, offsetting fossil fuels, and reducing greenhouse gas emissions.

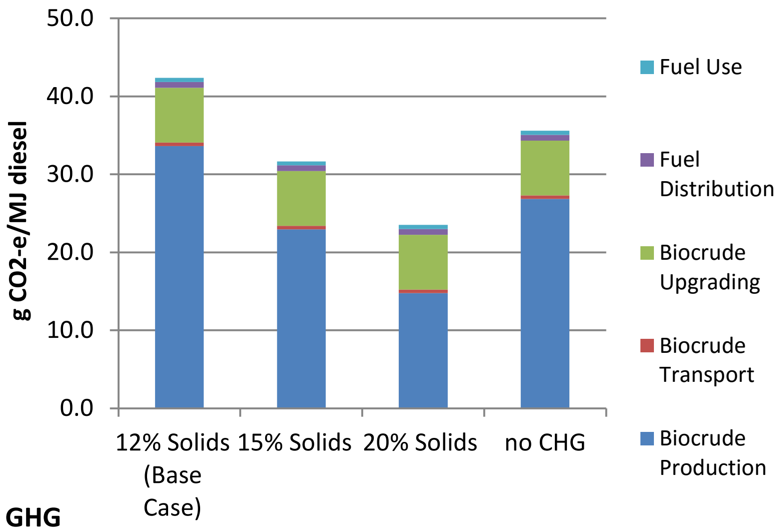
# Distributed HTL with centralized upgrading facility




PNNL-SA-12342

# Preliminary WWTP sludge TEA & LCA




**GHG Reductions:** **54%** **66%** **74%** **61%**

- Increased ***yields***, ***solids loading***, and ***reactor space velocity*** are possible with further testing
- Combined improvements could reduce fuel MFSP by about half

***Assumptions:*** sludge is treated as a waste with no GHG burden or C sequestration

***Outcomes:*** Solids loading impacts GHGs (and $)

***Reduction from petroleum fuel is >50% for all cases***