Envisioning a Circular Bioeconomy: Challenges and Opportunities

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December 7, 2022

Advanced BioSystems Workshop – Toward a Circular Bioeconomy

PNNL-SA-180287

PNNL is operated by Battelle for the U.S. Department of Energy

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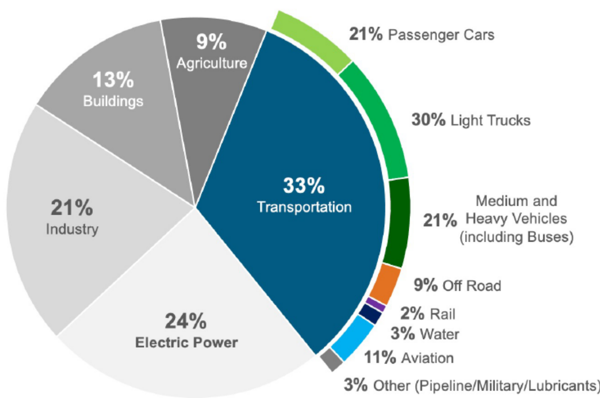
Challenge: Turn carbon into a renewable feedstock for difficult-to-decarbonize fuels and products

2019 U.S. Green House Gas Emissions



- Closing the Carbon Cycle is about recycling carbon and hydrogen with efficient and resilient catalysts
- Success would result in sustainable low-carbon, net-zero carbon fuels and products

Credit: Transportation Decarbonization Strategy by Deputy Assistance Secretary for Sustainable Transportation Michael Berube

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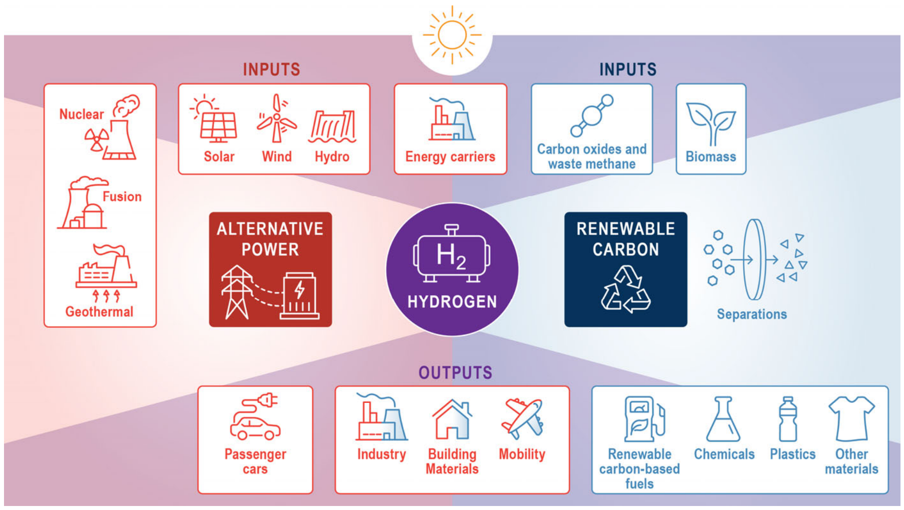
Bioproducts Institute (Bio-In) focused on net-zero carbon solutions in hard to electrify market segments



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Based on Turning off the Tap for Fossil Carbon - Future Prospects for a Global Chemical and Derived Material Sector Based on Renewable Carbon. *Ferdinand Kähler, Michael Carus, Olaf Porc, and Christopher vom Berg, Nova Institute for Ecology and Innovation April 2021*
www.renewable-carbon.eu/publications

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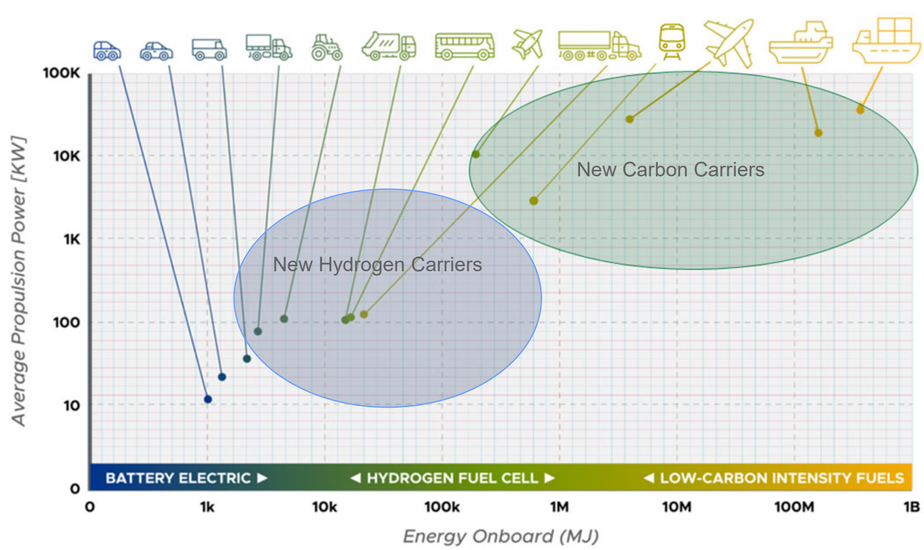
Aviation, marine, and rail will require low carbon intensity fuels for decades



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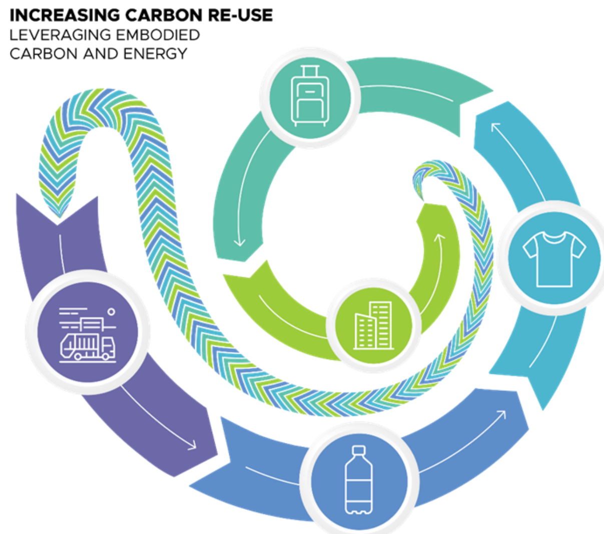
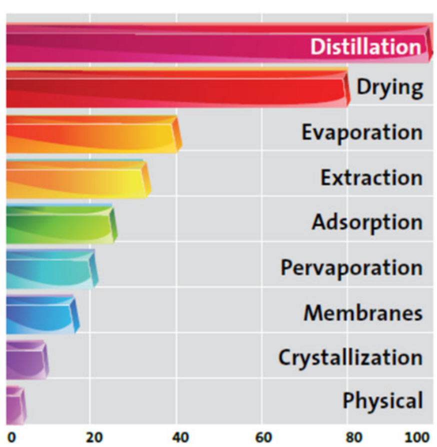
Keeping carbon in play – Every carbon is reused, ideally multiple times

- A spiral economy aims for long life and recyclability of materials and chemicals.
- Once a material or chemical is considered waste, an evaluation determines whether to repurpose it as a similar product or to convert it into a different product.
- At some point, it may be most energetically favorable to break the material or chemical down to a small unit and start over again.
- Opportunity: Develop efficient conversion processes for complex waste streams enabling longer-lived products and reducing the carbon footprint



Energy Efficient Separations



Sustainable Separation Processes: A Road Map to Accelerate Industrial Application of Less Energy-Intensive Alternative Separations (ALTSEP)

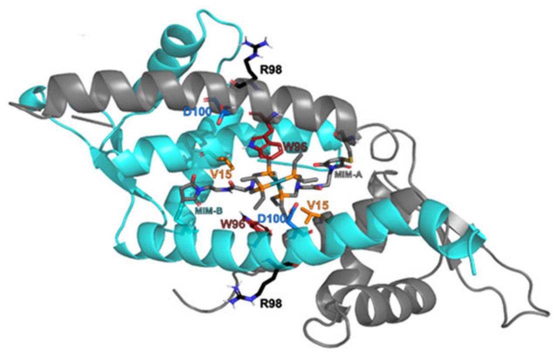
Challenge: Thermal separations consume 10–15% of the nation's energy.

Opportunity: Increase energy efficiency through advanced and reactive separations to concomitantly reduce CO_2 emissions.

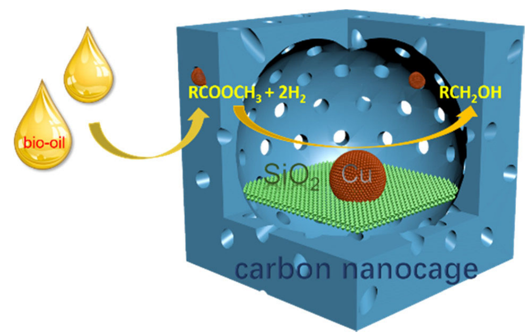
- Create active sites with needed geometry to enable reactive distillations
- Develop membranes for electrochemical separations
- Design cascade processes for the energy-efficient and selective adsorption/release of trace species
- Create separations processes for products from the conversion of complex source streams

Dramatically Improve Catalyst Efficiency and Resilience

Using nature as inspiration . . .



. . . for creating synthetic catalysts



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Analysis that supports strategy and research

TEA and LCA

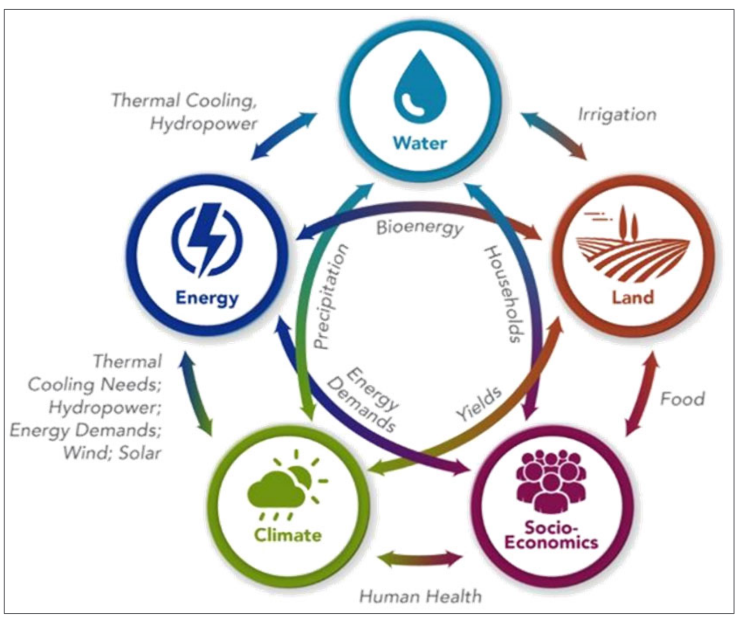
- Flowsheet simulations in ChemCAD or AspenPlus
- Discounted cash flow analysis, lifecycle inventory, and multivariate sensitivity analysis

Assessment tools

- High resolution physical-GIS models
- Full supply chain assessment

Global

- Global modeling of energy, land, water and human activity (GCAM)



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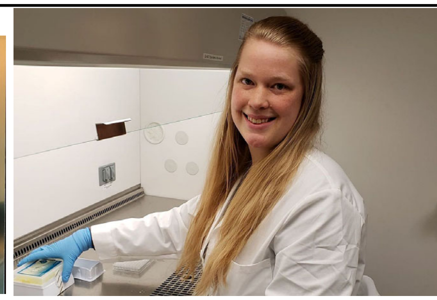
Advancing science that reduces the environmental impact of fuels and products while retaining carbon that must stay in the economy

Pacific Northwest National Laboratory | Washington State University | BIOIN Bioproducts Institute

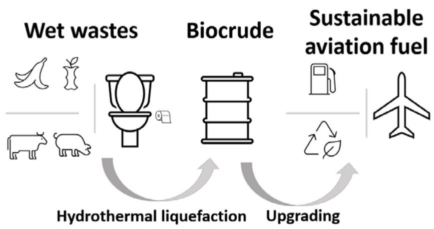
Continued leadership in Sustainable Aviation Fuel



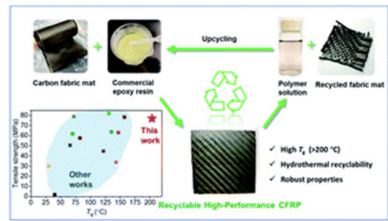
15 Distinguished Research Graduate Program Fellows since 2018, Tutored 11 Post-Docs and Students

Joshua Heyne (WSU)

Jonathan Male (PNNL)



$31 million in new projects



62 research publications

Turning today's waste into tomorrow's carbon resource

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Accelerate technological marketability by solving more than one problem at once

Image from Gas Cleaning Technologies LLC

Steel mill off-gas

Image from Environmental Science & Engineering Magazine

Sewage sludge

Each of these represent:
- **Stranded carbon resources**
- **GHG emissions**
- **Ecological liability**
- **Economic liability**
- **Social liability**

Image by Picasa

Manures

Image from: cementis.com

Municipal solid waste

cost-advantaged feedstocks

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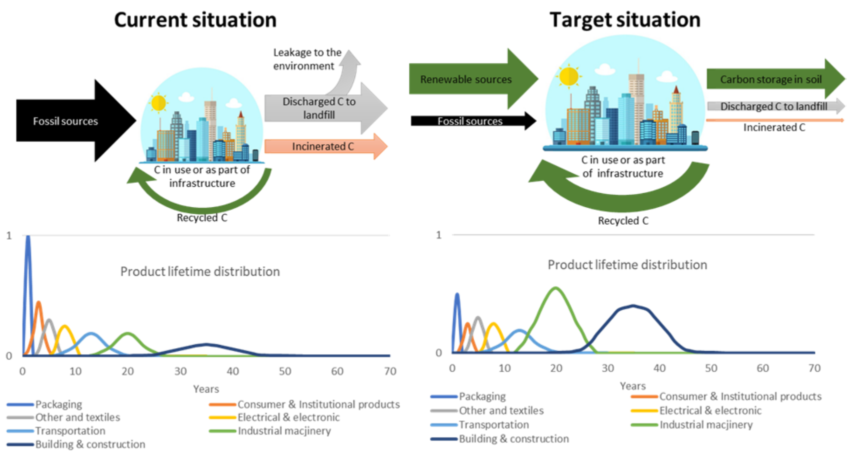
Bio-In is focused on management of carbon fluxes – Polymers challenge



Technology challenges and opportunities:

- Plastic wastes result in environmental problems
- Contaminants are a challenge for recycling
- Opportunities to store carbon in buildings and infrastructure

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Production, use, and fate of all plastics ever made. Geyer, R.; Jambeck, J. R.; Law, K. L. Sci. Adv. 2017, 3, 7, e1700782 DOI: 10.1126/sciadv.1700782

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Bioproducts Institute (Bio-In) science themes

Closing the carbon Loop

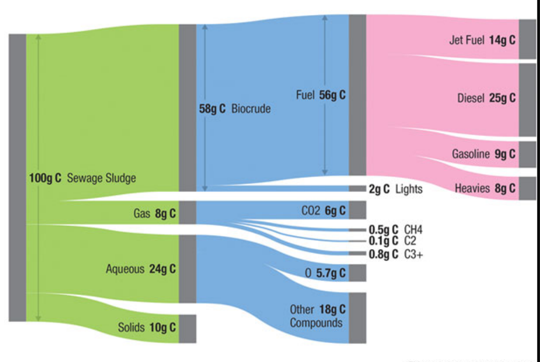
- > 60% carbon efficiency conversion of waste, biomass, CO_x to diesel and jet
- Reusing each carbon atom more than once — in the future we will target > two uses

Distributed processing

- Access more blended feedstocks
- Electrocatalysis and reimagining gasification
- Supply chain analyses and ecosystem services

Decarbonization of hard to electrify market segments

- System level analyses
- Support Institute for Integrated Catalysis and Laboratory Objectives
- Seek most impactful use of renewable carbon



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Aviation offers a unique market for Sustainable Aviation Fuels (SAFs)

- Market size (U.S., 2019, transportation)[1]
  - Jet fuel 26.7 billion gallons (market projected ↑)[2,3]
  - Gasoline 137 billion gallons (market projected ↓)[3]
  - Diesel 47.2 billion gallons
- Consumer set is small
  - Airlines, military
  - Top ten airports: 50% of U.S. commercial aviation[4]
- Fuel and delivery
  - Few fuel variants
  - Delivered to plane via hydrant system at major airports

[1] Data from EIA, Monthly Energy Review (Table 3.7c); total diesel use 62.6 B gal, total gasoline 142 B gal)
[2] 26 billion gallons contains 3.6 quadrillion Btu of energy
[3] Global consumption 106 billion gallons (current) projected to double over next 30 years to 230 billion gallons in 2050, IEA Annual Energy Outlook
[4] In 2017 the ten largest U.S. airports used 10.5 billion gallons, half of commercial jet fuel use (21 billion), source ASCENT

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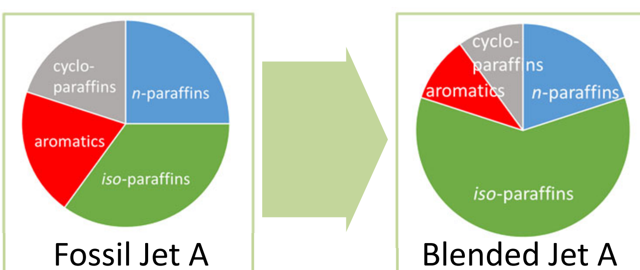
Understanding the critical fuel properties to lead to more Sustainable Aviation Fuels (SAFs)



Make it better by only producing hydrocarbons that contribute to key fuel properties

- Reduce soot
- Increase energy content
- To maintain low temperature fluidity
- To achieve thermal stability
- To maintain seal swelling in older planes

PNNL and WSU are developing an understanding of Sustainable Aviation Fuels at molecular levels to move from 50% blends to 100% blends by 2050

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SAF Grand Challenge: A focus of WSU and PNNL moving forward

By 2030, 3 billion gallons of domestic production

Major national needs:

- Feasibility analysis on the path towards achieving the 2030 goal
- Leverage existing ASTM-approved fuel pathways
- Synthesis gas as a platform for scaling SAF
  - Feedstock expansion
  - Develop more carbon efficient routes for synthesis gas production
- Support ASTM for augmentation of annexes for broader feedstock and process definitions

By 2050, 35 billion gallons of production

Major national needs:

- New pathways and continued support of broader feedstock and process definitions for existing pathways
- A 100% SAF specification(s) for drop-in and non-drop-in (potentially)

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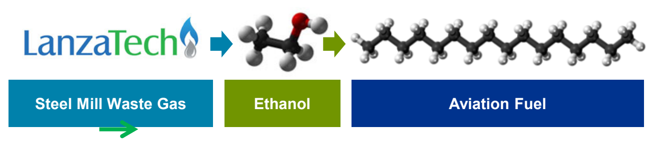
One example of SAF at PNNL is wastes to alcohol to high quality fuels

- **Developed a robust and efficient catalyst that**
  - Converted ethanol to aviation fuel molecules
  - Alcohol to jet (ATJ) ASTM D7566 Annex A5 approved April 2018 for up to 50% blend
  - LanzaTech licensed for scale-up



Bioenergy Technologies Office co-funding

R&D (started in 2010, internally funded)

Build 10M gpy

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LanzaJet

Reformers will be important for H_2 and SAF

Steam-methane reforming (SMR)
- $CH_3OH \rightarrow CO + 2H_2$
- $CH_4 + H_2O \rightarrow CO + 3H_2$
- $H_2O + CO \rightarrow CO_2 + H_2$

Dry methane reforming (DMR)
- $CH_4 + CO_2 \rightarrow 2CO + 2H_2$

Partial oxidation (POX)
- $CH_4 + 1/2O_2 \rightarrow CO + 2H_2$

Methane tri-reforming
- Combines SMR, DMR, and POX of methane

Autothermal reforming (ATR)

WSU and PNNL opportunity for optimization of H_2:CO ratios, heat integration and utilization of the CO_2 generated in making a SAF

In general…
Increasing efficiency, yields and conversion, H_2/CO ratios,CO_2 utilization, and catalyst stability due to presence of H_2O and O_2

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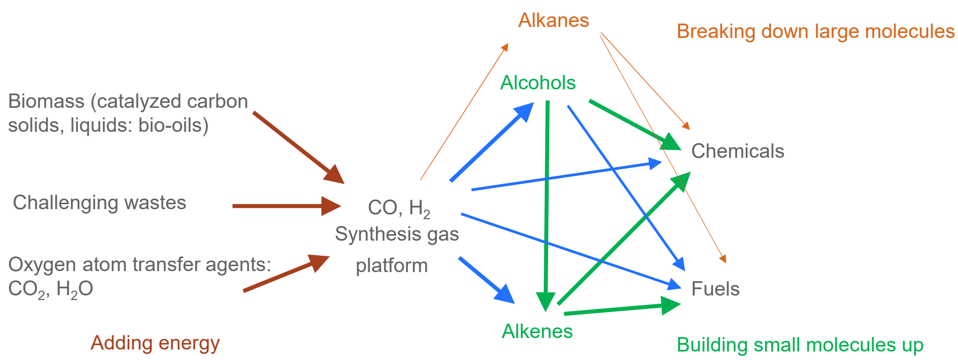
PNNL and WSU will expand SAF through expanding impact of synthesis gas platform



- Develop SAF from more diverse biomass and waste streams
- Minimize and utilize any CO_2 formed along the way
- Drive carbon efficiency to desired products > 60%
- Leverage PNNL's leadership in conversion of alkenes and alcohols to fuels and chemicals

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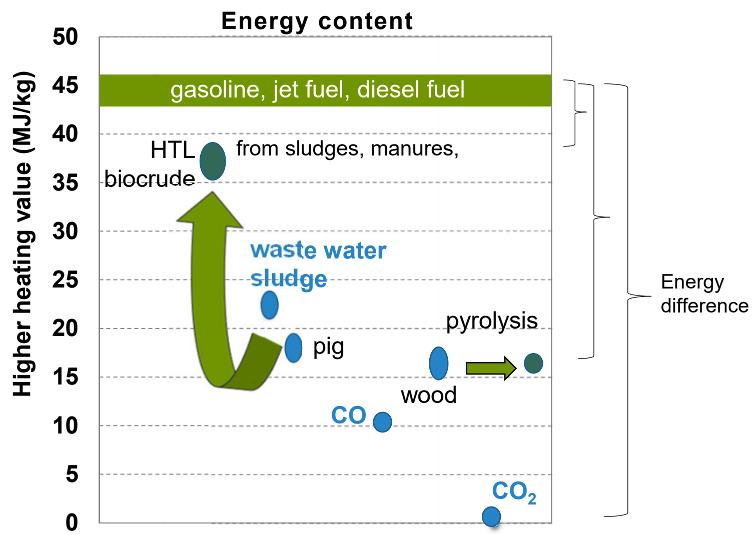
There are other carbon sources, that like CO_2 are a problem, but which contain energy

Many waste carbon sources in the environment still contain energy

Intermediate oils can be produced using low energy
- 6 MJ/kg to convert wastewater sludge to biocrude oil hydrothermal processing[1]
- 0.5 MJ/kg to convert wood to pyrolysis oil[2]

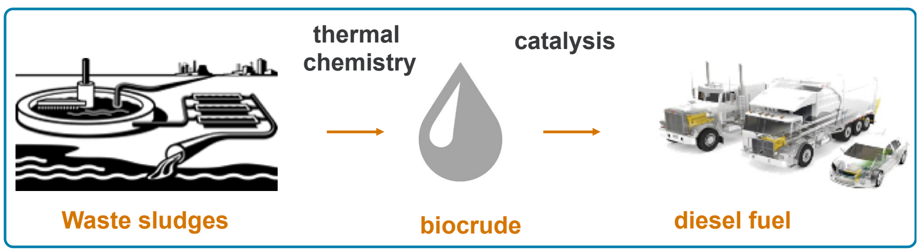
$\Delta G°$ for CO_2 to CO is 9.2 MJ/kg (0.35 MJ/mol)



[1] 4.7 MJ/kg of electricity and 1.6 MJ/kg of natural gas
[2] 0.47 – 0.64 MJ/kg dependent on biomass ash content

Recycling carbon – Produce biofuels while solving another problem

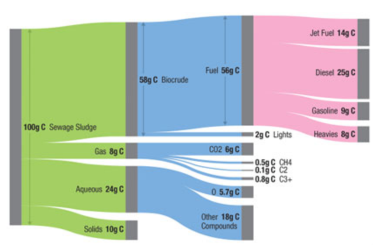
Hydrothermal Liquefaction (HTL) of wet waste streams and hydrotreating to fuels



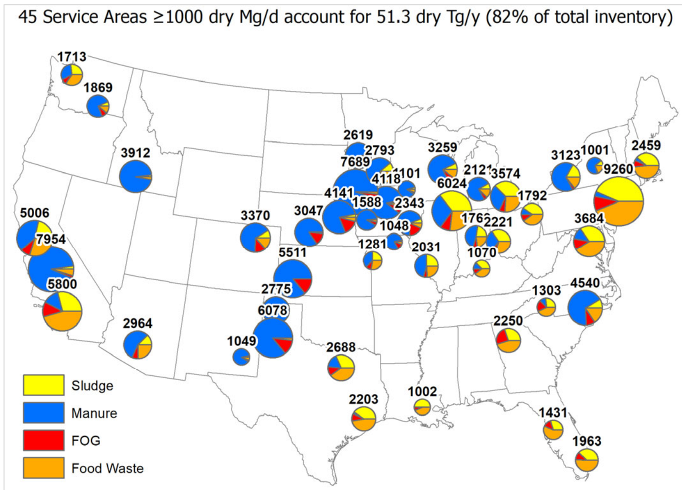
Breaking molecules down

Carbon yield to fuels is typically 60%

An example of industrial symbiosis



Wet wastes: Fats, oils, & greases are limited – What else is out there?



Challenges:

Small scale, distributed, unstable materials

Opportunities:

Wet wastes are highly collocated

- 80% of non-sludge waste occurs within 25 miles of water resource recovery facilities ≥1 Mg/d

Amount of stranded, energy-rich carbon sources is not trivial

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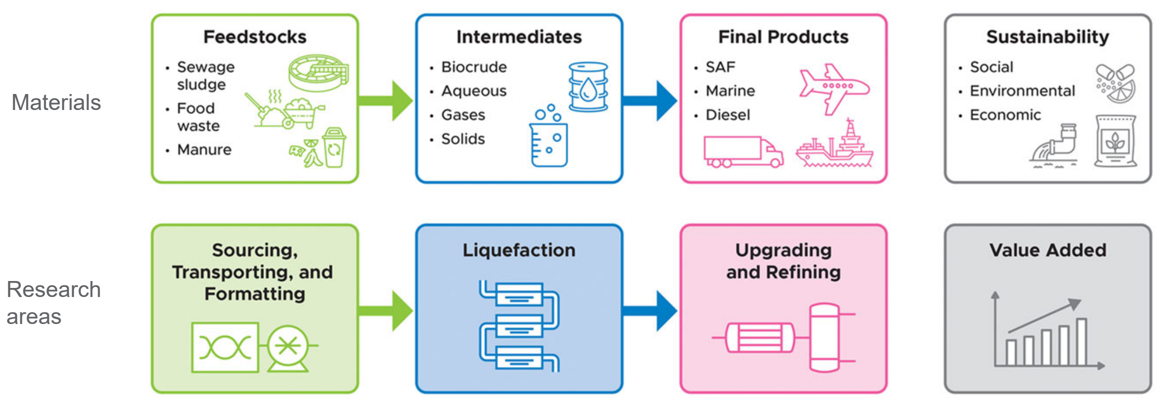
Hydrothermal liquefaction (HTL) provides a means to convert wet carbon-rich waste into fuels



Research and Development needs:

- Optimize value from other HTL streams
- Co-process in petroleum refineries
- Greater control of jet- and diesel-fractions

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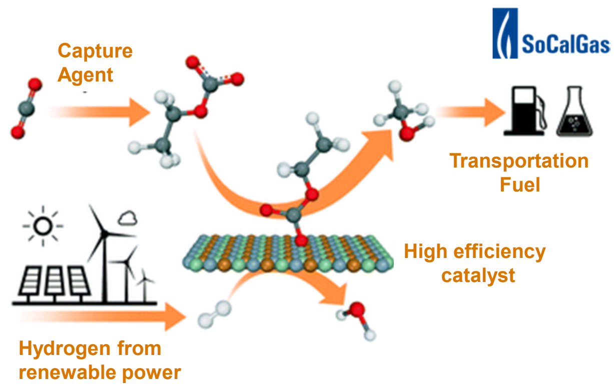
Capture and convert carbon dioxide to methanol

- Invented the capture agent for more effective CO_2 separations
  - Converted the bound CO_2 directly to methanol
- Future:
  - Implement pilot-scale demonstration
  - Create new separation materials for other waste carbon
  - Expand catalytic reactions of bound CO_2 to chemical building blocks



U.S. Patent 10,961,173 Integrated capture and conversion of CO_2 to methanol process technology

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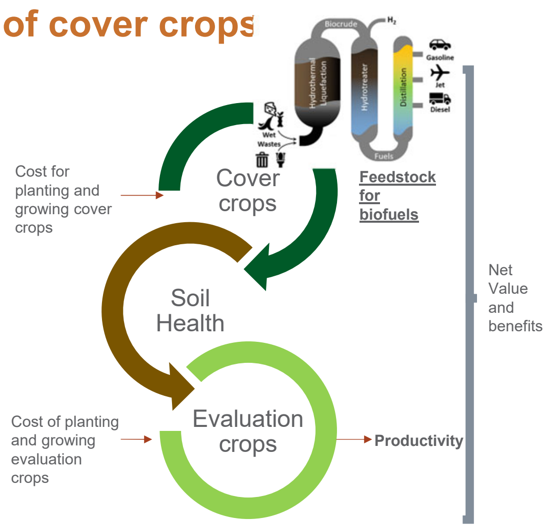
An example of lowering the carbon intensity of feedstocks: Maximizing the value of cover crops

- Goal: Derive greater value from cover crops compared to off-season oil crop.
- Challenge: Develop an understanding of the trade-off impacts of cover crops growth for soil benefits or growth for fuel.
- Approach: Grow cover crops in at least two growing seasons to be able to characterize critical materials attribute (CMA) for fuels production
- Outcome: Leveraging of an underutilized feedstock source for fuel source, and improve agricultural and agronomic practices



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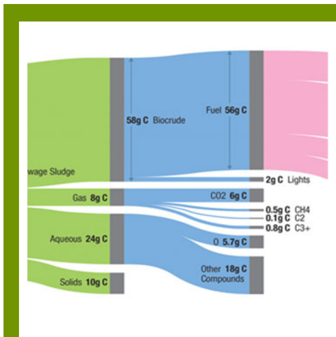
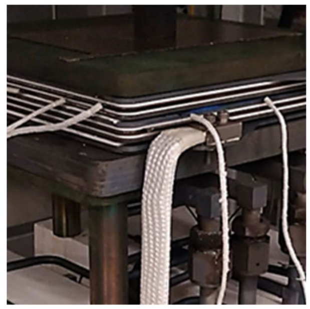
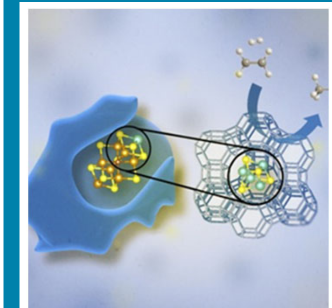
PNNL and WSU focused on closing the carbon cycle



Carbon Recycling & Separations



Hydrogen Production & Energy Carriers



Catalyst & Conversion Science

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Thank you

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