Alternative Fuels Development for Diesel Engines

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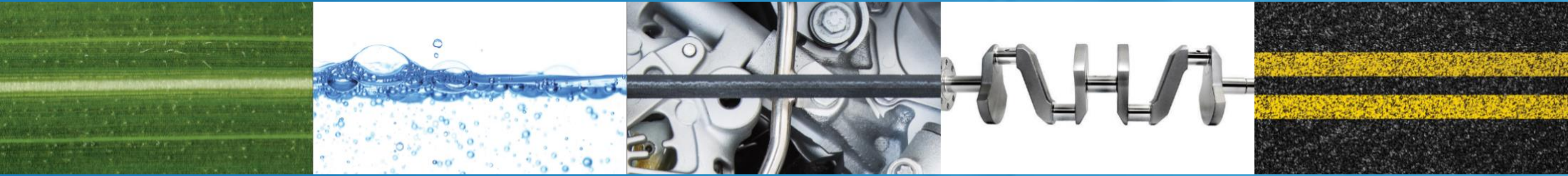
CO-OPTIMIZATION OF **FUELS & ENGINES**

better fuels | better vehicles | sooner

September 28, 2021



U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Alternative Fuels Development for Diesel Engines

Robert McCormick

14th Concawe Symposium

September 28, 2021

Better fuels and better vehicles sooner

The U.S. DOE Co-Optima initiative is **delivering foundational science** to develop fuel and engine technologies that will work in tandem to achieve efficiency, environmental and economic goals

Approach | Research spans on-road from light-duty to heavy-duty

Light-Duty

- **LD boosted SI combustion** is near-term opportunity with improved efficiency at higher load.
- **LD multi-mode combustion**, i.e., boosted SI and ACI, is longer-term opportunity through improved efficiency <u>across</u> the drive-cycle.

Medium/Heavy-Duty

- **MD/HD mixing controlled compression ignition** (MCCI) is near-term opportunity with more conventional diesel combustion.
- **MD/HD Advanced Compression Ignition** (ACI) is longer-term opportunity for improved efficiency and emissions.

OUTCOMES At-a-glance

Light Duty

- 10% fuel economy gain over 2015 baseline
- Potential *additional* 9-14% gain via multimode approaches
- Developed merit function tying fuel properties to fuel economy
- Identified 10 sustainable blendstock options with performance advantages (RON, S, HoV)

Medium- and Heavy-Duty

- **Identified 13 sustainable blendstock options with performance advantages (soot, CN, operability)**
- **Identified potentially lower-cost path to reduced engine-out criteria emissions**
- >4% fuel economy gain and lower emissions via ACI

Crosscutting

- Blendstock options to decrease GHGs by 20%+ in the near term for 30% renewable blends
- Identified potential economic drivers to increase adoption
- Developed new tools, extended and linked simulation approaches
- Created extensible screening methodology

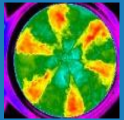
Link properties to engine operation

Hypothesis:

Equivalent fuel properties result in equivalent performance

- Took a fuel-properties-based, composition-agnostic approach
- Considered new engine designs for realizing emission benefits

APPROACH Link properties to engine operability and fuel handling



- Rapid fuel ignition (cetane number)

- Complete evaporation (boiling point or T90)

- Cold temperature operability (cloud point)

- Fuel pump/injector operability (viscosity)

- Safety in handling (flashpoint)

- Stability in storage (oxidation stability)

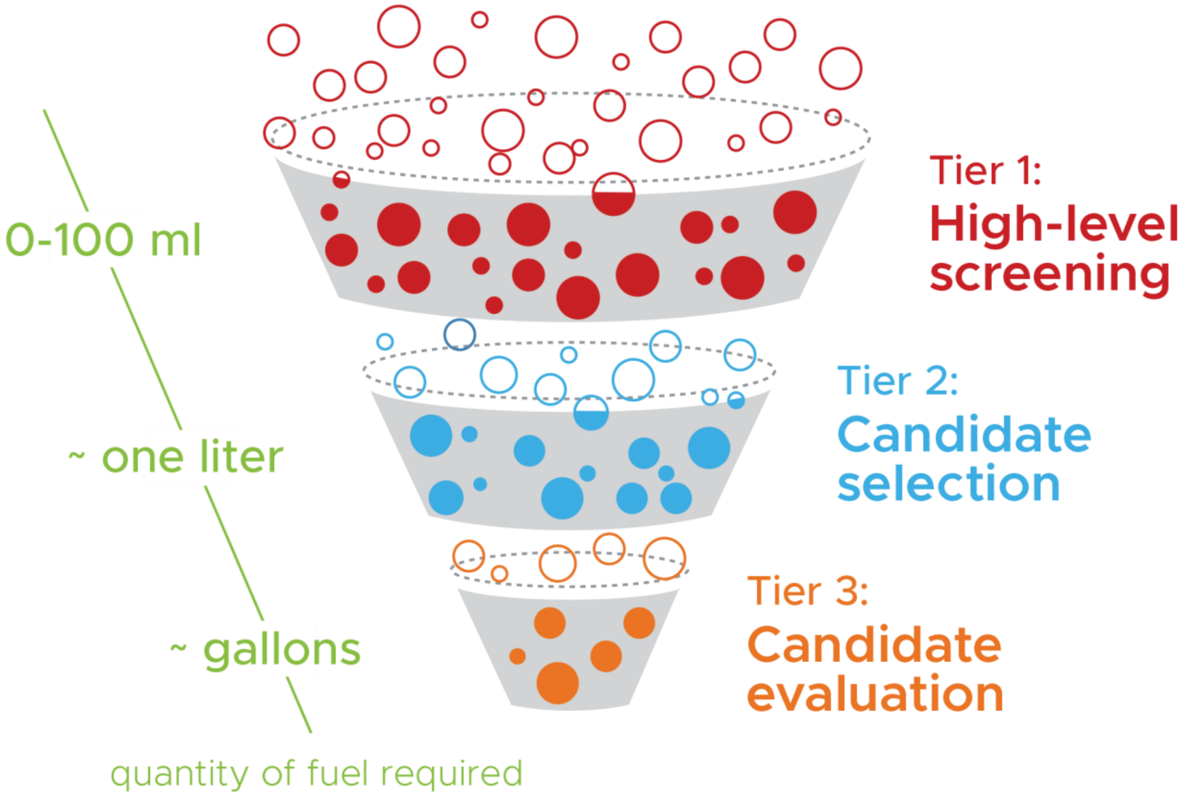
APPROACH Identify bioblendstocks

Screened hundreds of potential fuels to identify those meeting critical diesel properties

- Cetane Number
- Boiling Point Or T90
- Cloud Point
- Viscosity
- Flashpoint
- Oxidation stability

Evaluation of impacts

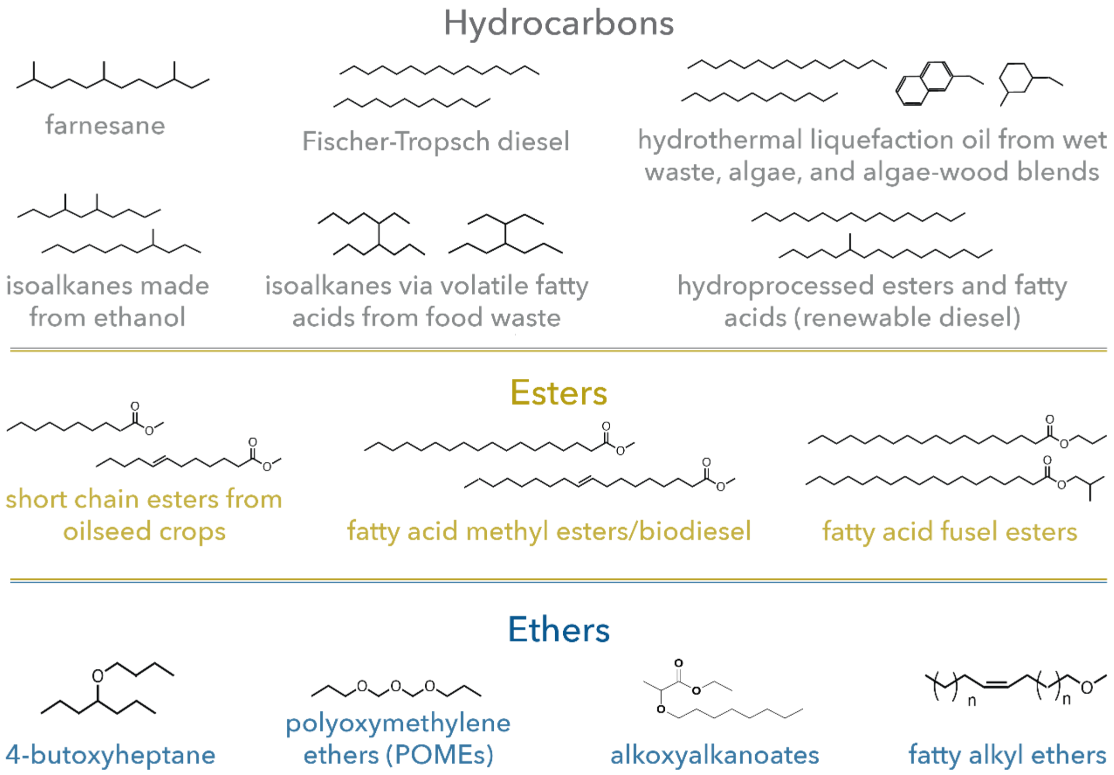
- Impact on criteria emissions
- WTW GHG emissions (GREET)
- Technoeconomic analysis



RESULTS

Thirteen blendstocks identified with potential to reduce GHG by 60%+ and criteria emissions

- Potential to reduce criteria emissions vs. market diesel
- Potential for production at larger scale in most cases
- CN > 40 (most > 48), LHV > 28 MJ/kg, acceptable flashpoint and cloud point
- Blendstock GHG emissions reduced by 50% or >60% in many cases

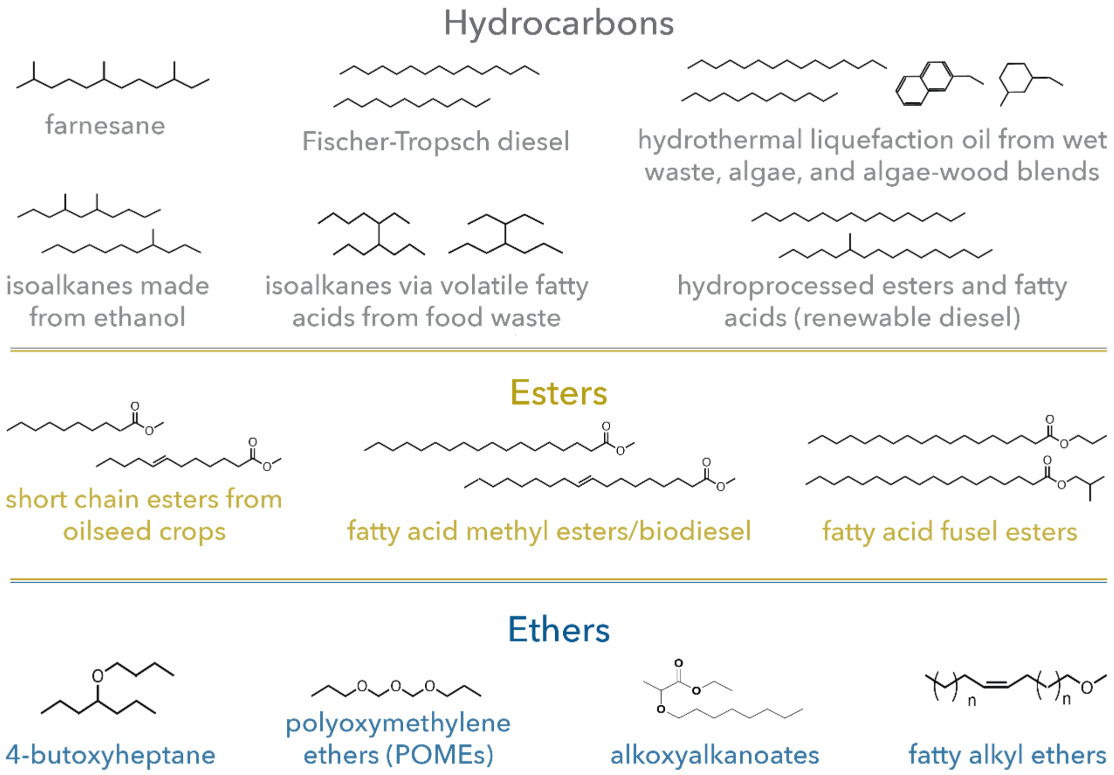


https://www.osti.gov/servlets/purl/1806564

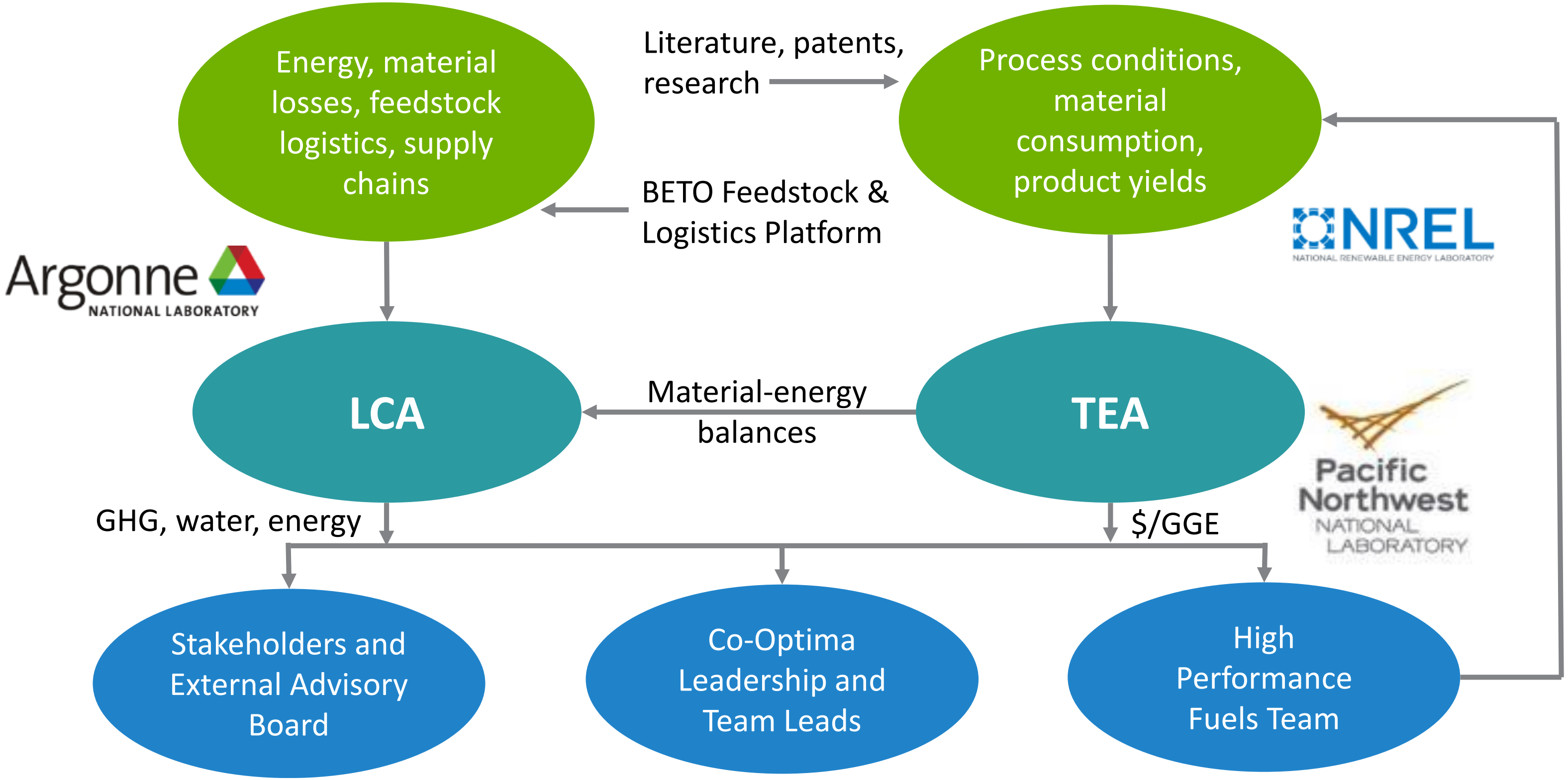
RESULTS

Thirteen blendstocks identified with potential to reduce GHG by 60%+ and criteria emissions

- **Hydrocarbons (lowest barriers)**
  - HEFA RD, FT fuels from natural gas produced commercially today
- **Esters (some barriers at high blend levels)**
  - Biodiesel produced today
- **Ethers (highest barriers)**
  - Storage stability examined; some will require antioxidants
  - Assessment of toxicity and biodegradation is ongoing



APPROACH TEA and LCA inform research direction



BETO = Bioenergy Technologies Office, GGE = gasoline gallon equivalent, LCA = life cycle analysis, TEA = techno-economic analysis

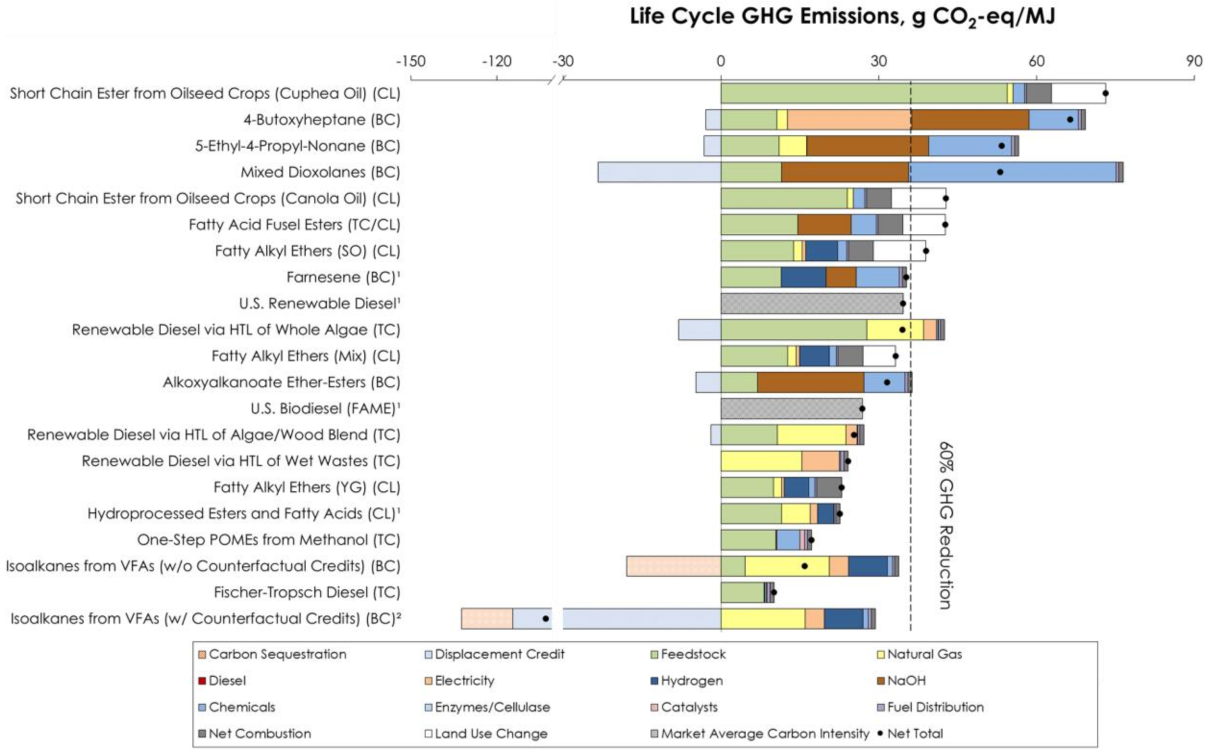
RESULTS Potentially significant GHG reductions

…but not guaranteed for all biofuels

Variety of feedstocks and pathways could provide low-carbon MCCI fuels

Opportunities to improve GHG emissions

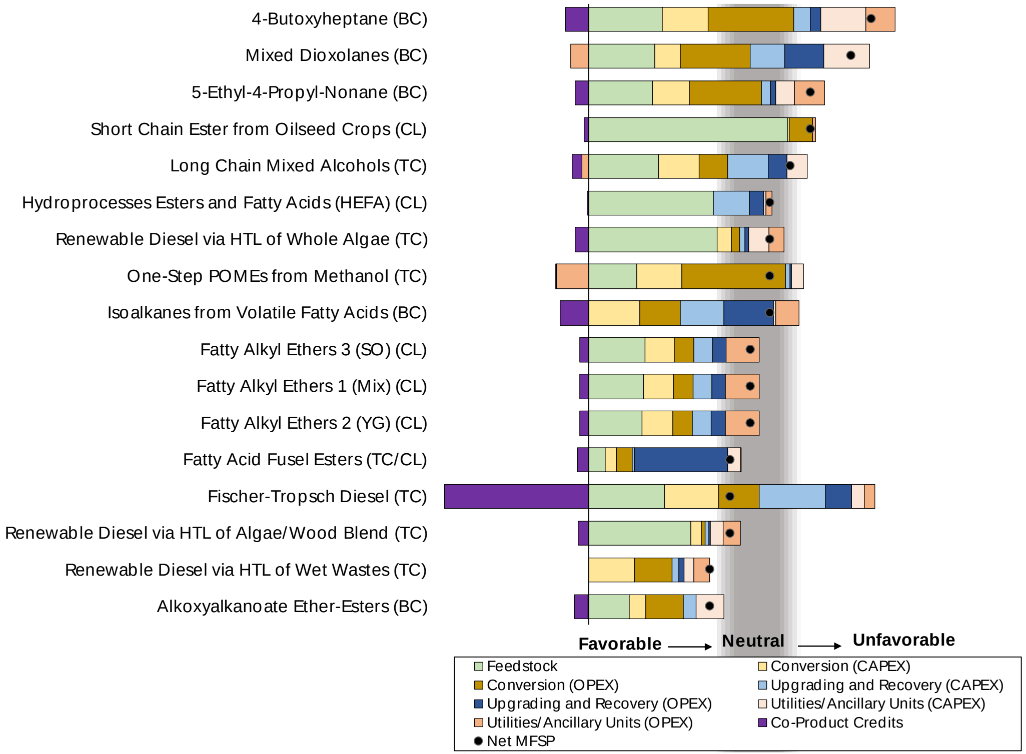
- Feedstock production
- NaOH for feedstock pretreatment
- Chemical input



Life cycle GHG emissions for MCCI blendstock candidates by GHG source. Blue dashed bars reflect credits associated with displacing emissions for co-products of bioblendstock production. Two blendstocks already on the market (U.S. Renewable Diesel and U.S. Biodiesel) were included. The life cycle GHG emissions were evaluated using Argonne National Laboratory's 2020 GREET model.

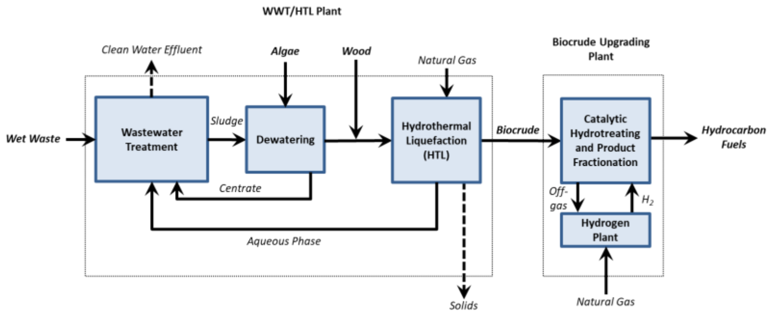
RESULTS Reducing cost is a key challenge

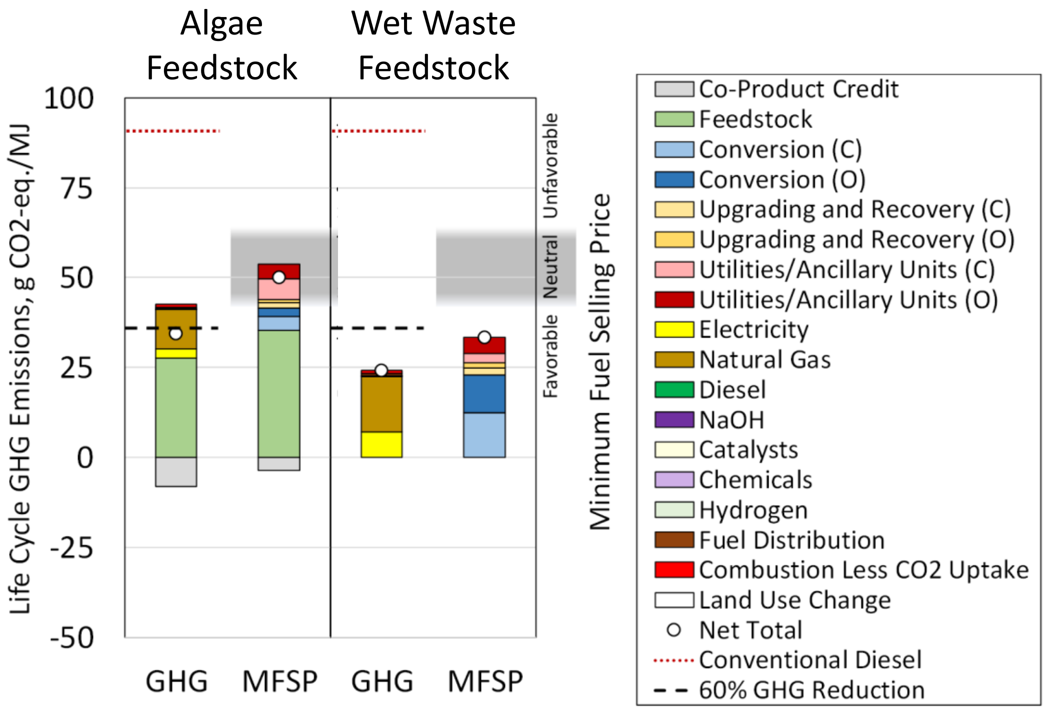
- Feedstock costs are major Minimum Fuel Selling Prices (MFSP) contributor
  - Identifying waste pathways could reduce cost
- Conversion costs highest for biochemical pathways
  - Caustic used in pretreatment
  - Glucose used in enzyme production
- Co-product credits are typically low
- Upgrading and recovery costs typically low



Cost breakdown of MFSP for selected MCCI bioblendstocks evaluated under Co-Optima. Costs broken down by overarching process hierarchies areas and further broken down to contributions by capital expense (CAPEX) and operational expenses (OPEX).

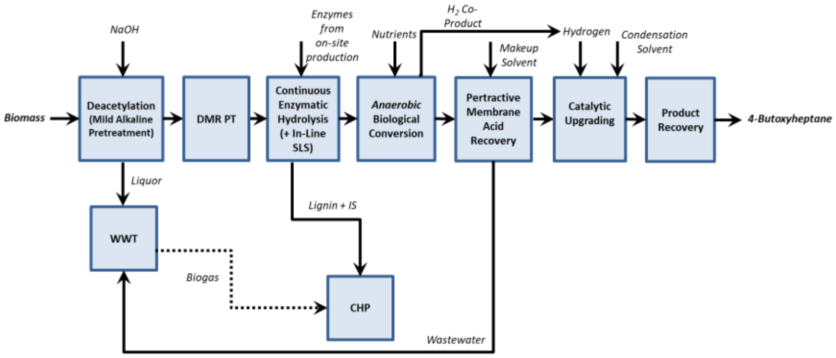
Opportunity for hydrothermal liquefaction

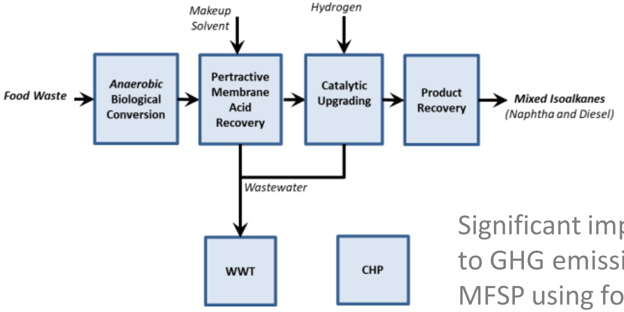




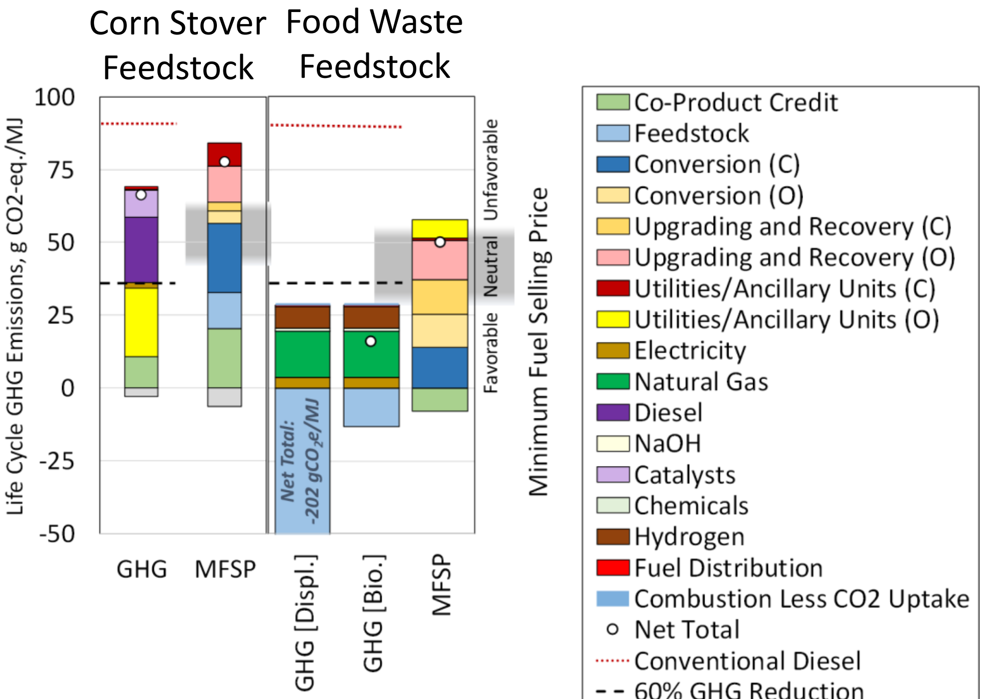
Comparison of life-cycle GHG emissions and MFSP breakdowns for two HTL pathways. Using wet waste feedstocks (right) can significantly reduce both cost and emissions *versus* algae (left) or lignocellulosic feedstocks.

RESULTS Isoalkanes and acids pathways





Significant improvements to GHG emissions and MFSP using food waste



Diesel Engine-Out Emissions

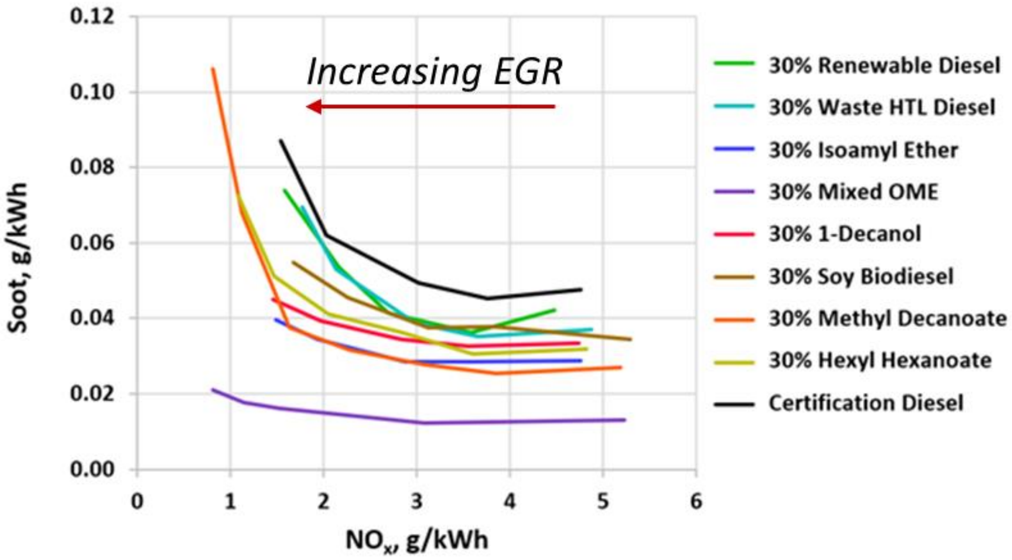
Single Cylinder Engine Specifications	
Base Engine Architecture	Ford Powerstroke® 6.7L Scorpion (MY2017)
Displ. Volume	0.83 L
Comp. Ratio	16.2:1
Bore × Stroke	99 mm × 108 mm
Connecting Rod Length	177 mm
Fuel System	Direct injection, 8-hole Spray angle 150 deg 2000 bar max pressure

Engine controller has full independent control.

Emissions: Horiba MEXA-One and AVL micro soot sensor.

RESULTS Potentially significant GHG reductions

- All bioblendstocks result in lower soot
- Some blends tolerated higher levels of exhaust gas recirculation (EGR), leading to even lower NO_x

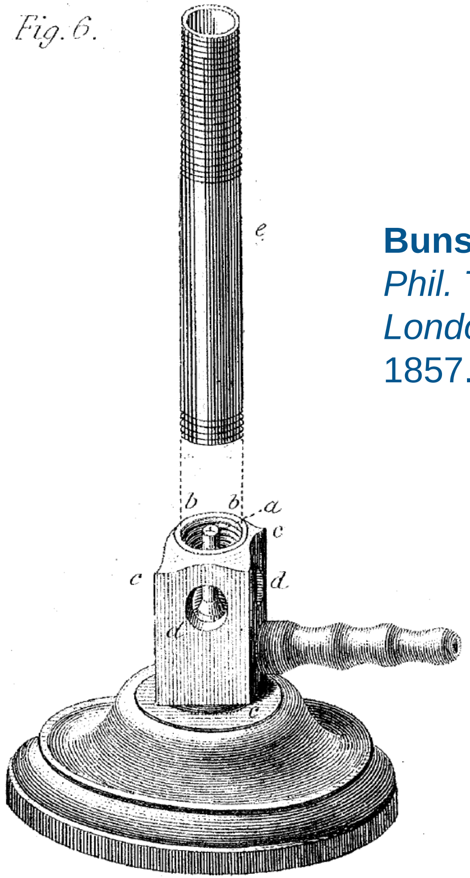


Exhaust gas dilution sweep from 25-43% to investigate NOx-soot tradeoff for nine fuels at 600 rpm and 3.3 bar GMEP; single-cylinder research engine version of MY2017 Ford 6.7L Scorpion diesel engine with stock components.

EGR tolerance = ability to maintain low soot @ high EGR

Introduced ducted fuel injection (DFI)

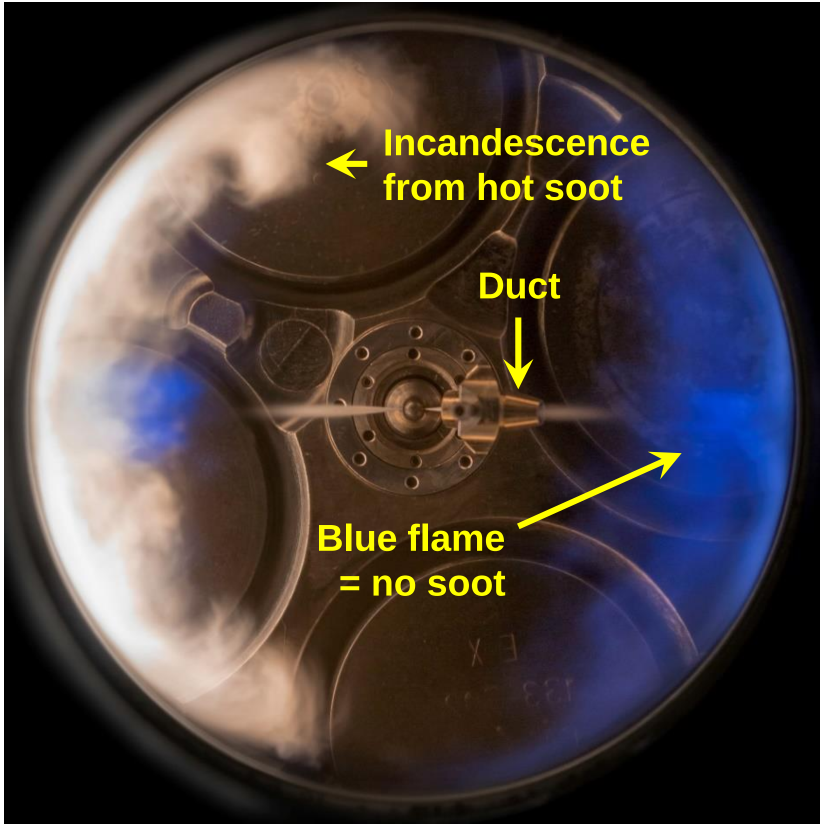
- DFI is a simple, mechanical approach for improving diesel combustion
- Motivated by the Bunsen burner concept



Bunsen and Roscoe, *Phil. Trans. Royal Soc. London* **147**:355-380, 1857.

First-ever engine experiments with DFI

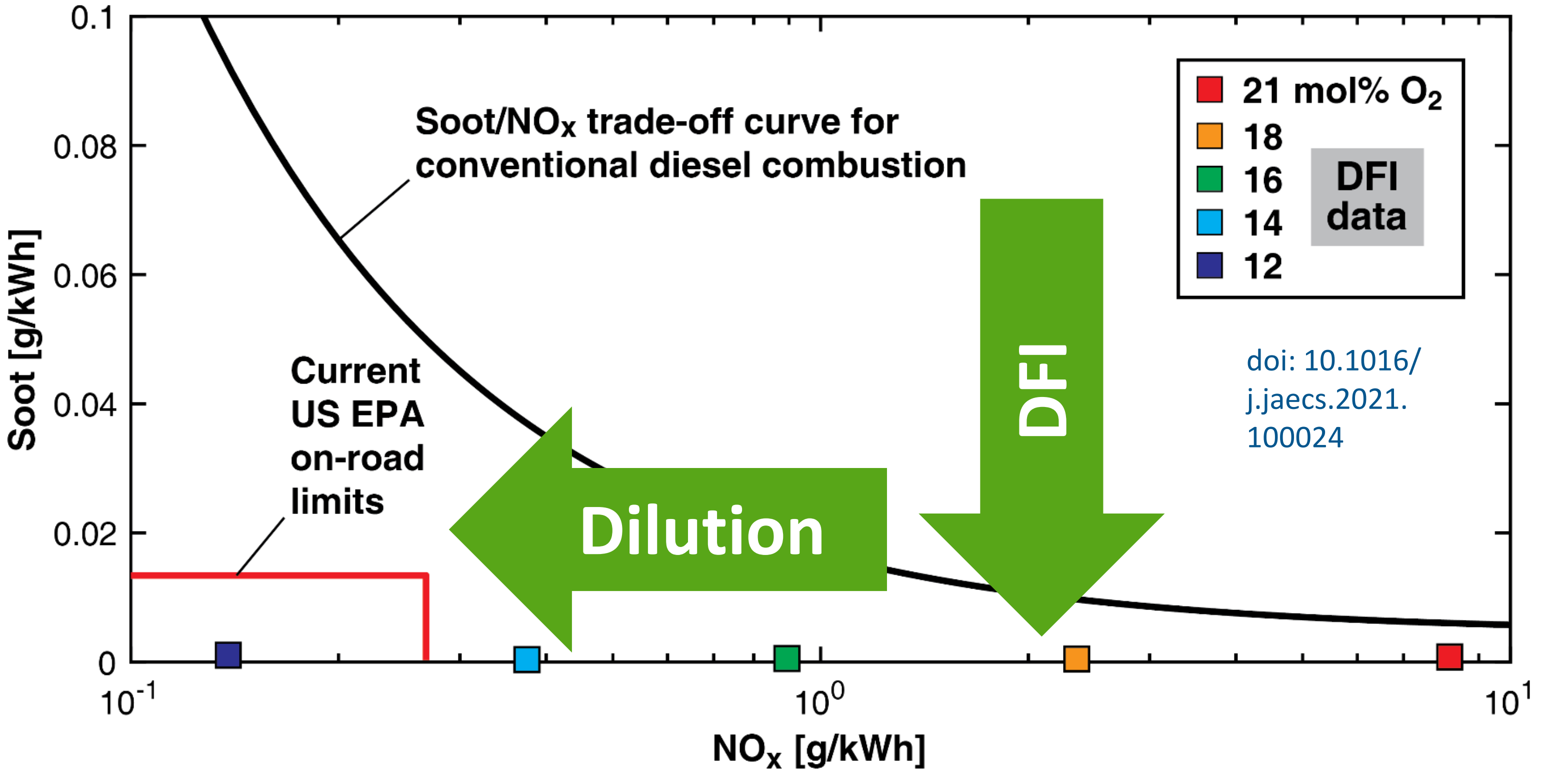
- DFI is a simple, mechanical approach for improving diesel combustion
- Motivated by the Bunsen burner concept
- Initial engine experiments showed that DFI is effective at curtailing/ eliminating soot



S. Ashley, https://www.scientificamerican.com/article/can-diesel-finally-come-clean/

Courtesy C.J. Mueller, Sandia National Laboratories

DFI + dilution breaks the soot/NO_x trade-off

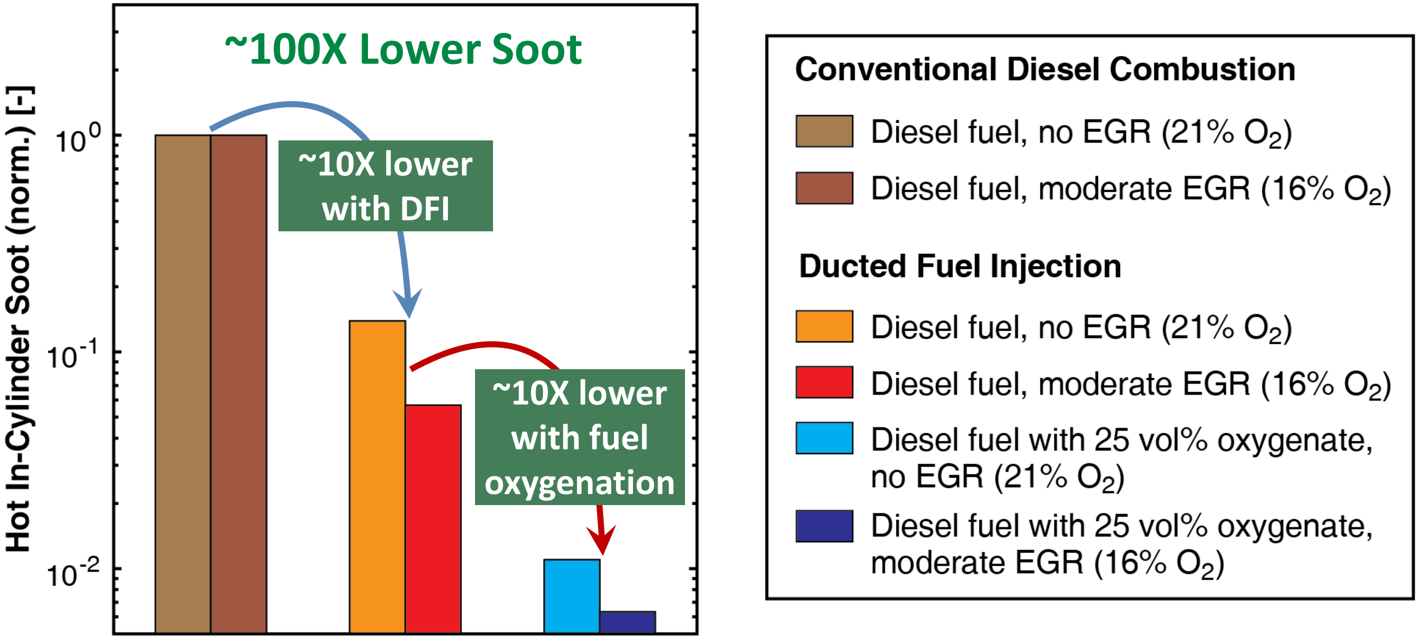


*Results for ~2.6 bar gross indicated mean effective pressure, 1200 rpm, steady state, 2-hole injector, No. 2 diesel fuel

Courtesy C.J. Mueller, Sandia National Laboratories

DFI is synergistic with oxygenated fuels

- Many low-net-CO_2, sustainable fuels are oxygenated



doi: 10.1016/j.jaecs.2021.100024

*Results for ~2.6 bar gross indicated mean effective pressure, 1200 rpm, steady state, 2-hole injector

Courtesy C.J. Mueller, Sandia National Laboratories

Notable Outcomes

- Identified 13 low net carbon blendstocks meeting diesel property requirements
- Identified potentially lower-cost path to reduced engine-out emissions (ducted fuel injection)

CO-OPTIMIZATION OF
FUELS & ENGINES
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Realizing the Potential of Co-Optimization of Fuels and Engines

- Further reduce fuel carbon intensity
- Increase blend level
- Scaling up for commercial production while reducing GHG even further
- Learning to achieve net-zero criteria pollutants
- Overcoming adoption barriers
    - Fuel quality standards
    - Regulatory compliance
    - Engine manufacturer concerns
    - Multimedia assessment

Net-zero-carbon fuel development

Leverage Co-Optima work, extending GHG reduction target from 60% to net zero

Expand scope to include potential e-fuel candidates

Net-zero criteria and GHG emissions

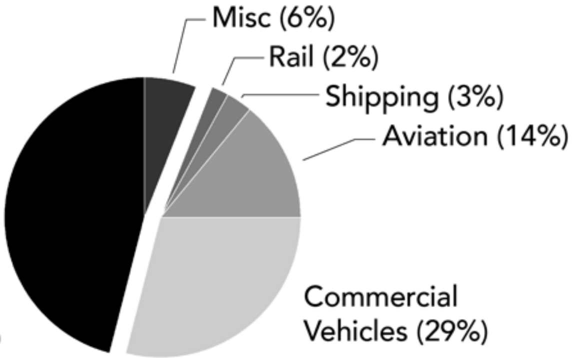
Develop ducted fuel injection for soot-less operation

Develop improved emission control systems for lean NO_x and low-temperature oxidation

The Real Challenge: Low-Carbon Fuels for Large Vehicles

2050 Transport Energy Demand:

190 B gallons (27.6 EJ)



Source: EIA Annual Energy Outlook 2020

"Hard to electrify" transportation segment represents almost half of all demand in 2050

Total demand: 82 billion gallons/year (11.9 EJ)

Acknowledgements

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