Sustainable Aviation Fuel and U.S. Airport Infrastructure

Kristi Moriarty, National Renewable Energy Laboratory
Derek Vardon, National Renewable Energy Laboratory

May 4, 2021
Webinar Housekeeping

- Attendees will be in listen-only mode
- Audio connection options:
  - Computer audio
  - Dial in through your phone (best connection)

- Technical difficulties? Contact us through the chat section, lower right of your screen
- Today’s webinar will be recorded and posted to “BETO Webinars”: energy.gov/eere/bioenergy/beto-webinars

NOTICE: This webinar, including all audio and images of participants and presentation materials, may be recorded, saved, edited, distributed, used internally, posted on DOE’s website, or otherwise made publicly available. If you continue to access this webinar and provide such audio or image content, you consent to such use by or on behalf of DOE and the Government for Government purposes and acknowledge that you will not inspect or approve, or be compensated for, such use.
Sustainable Aviation Fuel and U.S. Airport Infrastructure

Kristi Moriarty, National Renewable Energy Laboratory
Derek Vardon, National Renewable Energy Laboratory

May 4, 2021
Today’s Speakers

Kristi Moriarty
Senior Engineer, NREL

Derek Vardon
Senior Research Engineer, NREL
Sustainable Aviation Fuel and U.S. Airport Infrastructure

Kristi Moriarty, National Renewable Energy Laboratory
Derek Vardon, National Renewable Energy Laboratory
May 4, 2021
Sustainable Aviation Fuel: Delivery to Airports

May 4, 2021
Kristi Moriarty
What is Sustainable Aviation Fuel?

The International Civil Aviation Organization (ICAO) defines Sustainable Aviation Fuel (SAF) as a fuel which should:

• Achieve net greenhouse gas emissions reduction on a lifecycle basis.

• Respect the areas of high importance for biodiversity, conservation, and benefits for people and ecosystems, in accordance with international and national regulations.

• Contribute to local social and economic development, and competition with food and water should be avoided.

• ICAO’s baseline lifecycle emissions value for jet fuel is 89 grams of carbon dioxide equivalent per Megajoule (CO₂e/MJ); Per Argonne National Laboratory’s GREET analysis, SAF values range between 5.2 to 65.7 CO₂e/MJ depending on feedstock and technology.
CORSIA

- Aviation accounts for 2% of human-caused CO₂ emissions and 12% of all transportation CO₂ emissions.
- In 2016, ICAO adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to cap net CO₂ aviation emissions at 2020 levels through 2035.
- The aviation industry has a goal of reducing CO₂ emissions by 50% compared to 2005 levels by 2050.

International flights and offsetting requirements.
International flights between voluntary (green) countries began in 2021 and expand to flights to/from blue countries in 2027. International flights to and from yellow countries are exempt.
SAF-Estimated Production

Source: EPA. Public RIN Data.
Airports Using SAF

- LAX
  Los Angeles World Airports
- SFO
  San Francisco International Airport
- ONT
  Ontario International Airport
- Telluride Regional Airport
Jet Fuel Quality

• Jet fuel quality is tested at every point it moves along the supply chain.
• Conventional jet fuel is issued a Refinery Certificate of Quality (RCQ) which serves as a traceability document.
• A Certificate of Analysis (COA) is generated by a certified and accredited third-party laboratory downstream from production at each point along the fuel supply chain.
• It is recommended that similar documentation is generated for both neat and blended SAF.

SAF must meet ASTM D 7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons
- There are seven approved SAF production pathways
- % of SAF that can be blended is determined by pathway

When SAF is blended with Jet A, tested and meets all relevant ASTM requirements, the blend is designated as ASTM D1655
- ASTM D1655 blended fuel can be used in aircraft and travel by pipeline; it is a fully fungible/drop-in fuel
• Most large commercial airports receive fuel by pipeline and some have the ability to receive fuel by truck; smaller commercial airports and general aviation airports receive fuel by truck.

• Airports have tank farms with equipment to receive, store, and dispense fuel to aircraft via truck or by a hydrant system.

• Tank farms are sized for peak weeks and to accommodate future growth; they generally store 4-6 days of airport fuel usage.

• Typically, tank farms are owned by the airport and leased to an airline fuel consortium who generally hire a third-party operator.

• Airline fuel consortiums enable airlines to ensure timely delivery of fuel through shared infrastructure and source fuel from multiple producers.
• Conventional jet fuel travels primarily by pipeline
• Biofuels travel by rail, truck, and barge (larger volumes)
SAF and Jet A Blending Options

• SAF co-processed at a petroleum refinery would be business as usual for the supply chain and airports
• SAF produced at stand-alone plants must be blended prior to use in aircraft
• Neat (unblended) SAF cannot travel by pipeline
• NREL considered the following locations for blending SAF and Jet A
  • Terminals
  • Airports
  • Refineries
  • Greenfield/brownfield sites
• Terminals represent the best option for blending SAF and Jet A due to existing infrastructure and fuel quality standard requirements
Deliver SAF to terminal that serves an airport. Store SAF and Jet A in separate tanks and blend them into a third tank at the desired blend ratio. Test the blended fuel to meet ASTM requirements and generate a Certificate of Analysis. Ship the fuel via pipeline to the airport (or truck for those airports without a pipeline).
SAF and Jet A Blending at Terminals-Option 2

Offload SAF into a Jet A storage tank at a terminal. Test the blended fuel to meet ASTM requirements and generate a Certificate of Analysis. This option may require the addition of mixing equipment on the tank to address potential differences in fuel gravities. Careful control of metering and fuel inventory will be necessary to identify the percent of SAF blended into Jet A and ensure it does not exceed allowable levels. Ship the fuel via pipeline to the airport (or truck for those airports without a pipeline).
SAF and Jet A Blending at Terminals-Option 3

• It is possible to store Jet A and SAF in separate tanks and inject them both into the airport pipeline, however, this would result in the first instance of establishing SAF as ASTM D1655 at the airport.
• Although it may be expected that turbulent flow in the pipeline would mix the fuels, the fuel property test results at the terminal must match fuel property tests at the airport.
• This option may result in the need for more off-spec fuel storage at an airport.
SAF and Jet A Blending at Airports

- Airports are not the ideal location for blending as it would be the first instance of establishing the SAF and Jet A blend as ASTM D1655
- Airport infrastructure would need to be upgraded with blending equipment, more storage for off-spec fuel, software, and staff
- Increased truck traffic to airport to deliver SAF (neat SAF cannot travel by pipeline per federal regulations)
- Tank farm insurance would need to be updated to reflect blending activity
SAF and Jet A Blending at Refineries and Greenfield/Brownfield Sites

• Refineries are an unlikely location for blending
  • They do not have equipment to receive third-party fuel by truck or rail
  • Their storage is size to accommodate refinery capacity
  • Introduction of another fuel to the jet fuel tank(s) would require recertification of the fuel batch
• Greenfield and Brownfield site are an option but not ideal
  • Significant investment compared with leasing or adding equipment at an existing terminal
  • Permitting for the facility and a pipeline tie in would take considerable time
SAF Airport Impacts
(assumes blending at terminal)

No changes to airport fuel infrastructure or procedures

SAF/Jet A blend will be stored in the existing tank farm and dispensed as done today to aircraft
SAF Airport Impacts

• SAF and Jet A blended fuel will not be directed towards specific airlines or flights
• All airlines operating at an airport need to agree to the use of SAF
• Only those airlines purchasing SAF would receive carbon credits regardless of which flights use the fuel

What an airport can do to prepare for SAF delivery

• Identify who is supplying airport with fuel
• Ask fuel terminals
  • By what methods they can receive fuel (barge, pipeline, rail, truck, ship/vessel)
  • If they do not receive fuel by truck or rail today, what would need to happen to enable that
• Identify infrastructure needed for fuel receipt and off-loading to an airport by pipeline, truck, or barge
Terminal Operations

- Terminals are owned by a variety of organizations including oil/refiners, pipeline companies, and other entities.
- They provide fuel storage, blending, and off-loading services for a fee.
- They lease tanks and associated equipment for terms of one year or more.
- It is expected that adding SAF to a terminal would require some dedicated equipment to avoid contamination.
  - This would impact lease terms or capital could be paid upfront.
• Fuel terminals are regulated by EPA with strict standards for fuel storage that encompass requirements to prevent, detect, and contain leaks; mitigate impacts from stormwater; contain/reduce emissions; and protect waterways.

• Terminals are able to add SAF without impacting their EPA operating permit.

• EPA generally regulates above-ground fuel storage tank systems. Airport tank farms are the rare exception to this regulation and are regulated by individual states.
  • It is assumed that state regulations closely mirror EPA’s.
  • Airport fuel hydrant systems are regulated by EPA.
• SAF Incentive Analysis: [https://www.nrel.gov/docs/fy21osti/79356.pdf](https://www.nrel.gov/docs/fy21osti/79356.pdf)
• Commercial Aviation Alternative Fuels Initiative (CAAFI): [https://www.caafi.org](https://www.caafi.org)
• IACO SAF website: [https://www.icao.int/environmental-protection/pages/SAF.aspx](https://www.icao.int/environmental-protection/pages/SAF.aspx)
• ASCENT Alternative Fuel Projects: [https://ascent.aero/topic/alternative-fuels/](https://ascent.aero/topic/alternative-fuels/)
Towards decarbonizing aviation with sustainable aviation fuel (SAF)

Presented by Derek Vardon, PhD
NREL Catalytic Carbon Transformation & Scale-up Center
May 4th, 2021
Towards decarbonizing aviation with Sustainable Aviation Fuel (SAF)

1. Motivation to decarbonize with sustainable aviation fuel
2. What makes SAF distinct from other biofuels
3. New routes to produce SAF with renewable & waste C
1. Motivation to decarbonize with SAF

Need for low carbon intensity fuels for aviation industry

- Air travel expected to nearly double by 2050 with jet fuel consumption making up 8-12% of transportation emissions
- U.S. consumes 26 billion gallons of jet fuel with limited prospects of commercial flight electrification; current state-of-the-art batteries store 2.5% energy per mass as jet fuel

1. **Motivation to decarbonize with SAF**

**Stakeholder commitment to expand current SAF production**

- SAF is a critical component of the decarbonization strategy for commercial aviation with increasing global policy and regulation to support adoption.

- International Civil Aviation Organization set goal of 50% reduction of carbon emissions relative to 2005 by 2050.

---

**Carbon Offsetting & Reduction Scheme for International Aviation**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>carbon-neutral growth as global sector approach</td>
</tr>
<tr>
<td>2050</td>
<td>reduce carbon emissions by 50% relative to 2005</td>
</tr>
</tbody>
</table>

---

Source: International Civil Aviation Organization CORSIA
1. **Motivation to decarbonize with SAF**

**Current SAF production in U.S. limited and competes with diesel**

- Commercial SAF currently produced by hydroprocessing fats, oils, and greases into drop-in hydrocarbons called (HEFA)

- HEFA for SAF competes with HEFA for renewable diesel; U.S. diesel consumption 46 billion gallons per year (BGPY)

- U.S. refining capacity for HEFA growing rapidly to 4 BGPY; but non-food lipids limited at 1.7 BPGY

---

**Sources:** Holladay et al. (2020) DOE/EE-2041 8292; EIA.gov; https://adi-analytics.com
1. Motivation to decarbonize with SAF

Current SAF production in U.S. limited and competes with diesel

<table>
<thead>
<tr>
<th>Year</th>
<th>Company</th>
<th>Capacity (MPGY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>World Energy</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Neste</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Gevo</td>
<td>Demo</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>TBD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Company</th>
<th>Capacity (MPGY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Fulcrum Bioenergy</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>SkyNRG</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Red Rock Biofuels</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Company</th>
<th>Capacity (MPGY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022</td>
<td>Neste</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>LanzaJet</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>World Energy</td>
<td>150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Company</th>
<th>Capacity (MPGY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2023</td>
<td>Fulcrum Bioenergy</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Gevo</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Readifuels</td>
<td>24</td>
</tr>
</tbody>
</table>

- New SAF capacity coming online within next 3 years with several pathways that expand feedstocks beyond HEFA
- New feedstocks includes lignocellulosic biomass, alcohol from industrial waste gas, and gasification of municipal waste and forestry residues

Source: Commercial Aviation Alternative Fuels Initiative CAAFI.org
2. What makes SAF distinct from other biofuels

Jet fuel is an engineered liquid energy carrier

- Safety, operability, and performance are core criteria for aviation fuel as an engineered liquid energy carrier
- Jet fuel unique from gasoline and diesel fuel based on fuel property requirements – no oxygen or olefins, among other specifications
- ASTM qualification ensures SAF meets same standard of jet fuel performance, regardless of fossil or renewable origin

Source: ASTM D1655; ASTM D7566; ASTM D4054; Holladay et al. (2020) DOE/EE-2041 8292
2. What makes SAF distinct from other biofuels

Jet fuel has a typical hydrocarbon distribution and chain length

- Jet fuel comprised of 4 hydrocarbon types:
  1. Straight (normal paraffin)
  2. Branched (isoparaffin)
  3. Saturated ring (cycloparaffin)
  4. Unsaturated ring (aromatic)

- Typical jet fuel average carbon number is C11 with the majority of carbon chain lengths between C8 and C15

Sources: ASTM D1655; ASTM D7566; ASTM D4054; Holladay et al. (2020) DOE/EE-2041 8292
2. What makes SAF distinct from other biofuels

Jet fuel specifications are highly defined by ASTM

- Jet fuel requires high energy density; low temp performance for high altitude; minimum flash point for safe handling; amongst other specs

- Jet fuel property specifications defined by ASTM International for conventional jet (D1655) and jet with SAF (D7566)

<table>
<thead>
<tr>
<th>Select Fuel Properties</th>
<th>ASTM D7566</th>
<th>Fossil Jet A</th>
<th>HEFA SAF (tallow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Heat of Comb (MJ/kg)</td>
<td>42.8, min</td>
<td>43.0</td>
<td>44.1</td>
</tr>
<tr>
<td>Acidity, total (mg KOH/g)</td>
<td>0.1, max</td>
<td>0.005</td>
<td>0.010</td>
</tr>
<tr>
<td>Aromatics (vol%)</td>
<td>25, max</td>
<td>18</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>Sulfur, total (ppm)</td>
<td>3000, max</td>
<td>421</td>
<td>&lt;300</td>
</tr>
<tr>
<td>Distillation Temp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10% recovery (°C)</td>
<td>205, max</td>
<td>177</td>
<td>179</td>
</tr>
<tr>
<td>Final boiling point (°C)</td>
<td>300, max</td>
<td>271</td>
<td>255</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>38, min</td>
<td>48</td>
<td>55</td>
</tr>
<tr>
<td>Freeze point (°C)</td>
<td>-40, max</td>
<td>-52</td>
<td>-62</td>
</tr>
<tr>
<td>Viscosity @ -20°C (cSt)</td>
<td>8, max</td>
<td>4.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Density @ 15°C (g/mL)</td>
<td>0.775-0.840</td>
<td>0.802</td>
<td>0.758</td>
</tr>
</tbody>
</table>

Sources: ASTM D1655; ASTM D7566; ASTM D4054; ASTM D7566; Holladay et al. (2020) DOE/EE-2041 8292; Zhang et al. (2016) Renewable and Sustainable Energy Reviews, 54, 120-138
2. What makes SAF distinct from other biofuels

New SAF routes require ASTM evaluation and balloting process

- ASTM D4054 requires evaluating new SAF routes through tiered testing, reporting, and balloting process
- ASTM added new Fast Track approval process in 2020 that limits SAF to 10 vol% but greatly accelerates evaluation process to < 2 years

Sources: ASTM D4054; Rumizen (2019) Jet Screen Stakeholder Workshop; Holladay et al. (2020) DOE/EE-2041 8292
2. What makes SAF distinct from other biofuels

Currently seven ASTM annexes approved to produce SAF

- Currently 7 ASTM approved SAF routes with intermediates that include lipids, alcohols, syngas, and biobased hydrocarbons (D7566)

- Several new SAF routes in ASTM evaluation process that include aqueous phase sugars to jet (Virent), catalytic pyrolysis to SAF (Shell IH2), alcohol to jet with aromatics (several)

<table>
<thead>
<tr>
<th>SAF Route</th>
<th>Starting Feedstock for SAF Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1: FT-SPK 50% blend</td>
<td>Syngas: CO + H₂</td>
</tr>
<tr>
<td>A2: HEFA-SPK 50% blend</td>
<td>Triglycerides &amp; Fatty Acids</td>
</tr>
<tr>
<td>A3: HFS-SIP 10% blend</td>
<td>Farnesene</td>
</tr>
<tr>
<td>A4: FT-SKA 50% blend</td>
<td>Syngas: CO + H₂</td>
</tr>
<tr>
<td>A5: ATJ-SPK 50% blend</td>
<td>Ethanol &amp; Isobutanol</td>
</tr>
<tr>
<td>A6: CHJ 50% blend</td>
<td>Triglycerides &amp; Fatty Acids</td>
</tr>
<tr>
<td>A7: HC-HEFA SPK 10% blend</td>
<td>Algal Botryococcene</td>
</tr>
</tbody>
</table>

Source: ASTM D7566-20; Wang et al. (2016) NREL TP-5100-66291; Holladay et al. (2020) DOE/EE-2041 8292
3. New routes to produce SAF from renewable and waste C
Emerging routes to produce SAF from biomass and waste C

- Multiple biofuel technologies can produce SAF-range fuels from biomass and waste C
- Processes range from thermochemical, biological, hybrid, and electrochemical for biomass, waste, and CO2 feedstocks

Sources: Wang et al. (2016) NREL TP-5100-66291; Holladay et al. (2020) DOE/EE-2041 8292; Zhang et al. (2020) Recent Treads, Opportunities and Challenges of Sustainable Aviation Fuel; DOE (2021) BETO Project Peer Review
3. **New routes to produce SAF from renewable and waste C**

**Additional feedstocks needed with new SAF conversion routes**

### Lignocellulosic Biomass (23 BGOPY jet potential)

- Agricultural residues*  
  - 9.0 BGOPY jet
- Forestry trimmings and residues*  
  - 7.1 BGOPY jet
- Bioenergy crops by 2030*  
  - 7.4 BGOPY jet

Assumes 34 gal of SAF range hydrocarbons per dry tonne of biomass, excluding other fuel cuts

### Other Waste C Sources (10 BGOPY jet potential)

- Inedible animal fats**  
  - 1.8 BGOPY jet
- Animal manure**  
  - 4.7 BGOPY jet
- Wastewater sludge**  
  - 2.0 BGOPY jet
- Food waste**  
  - 2.7 BGOPY jet
- MSW (paper, wood, yard)***  
  - 0.9 BGOPY jet
- Industrial waste gas***  
  - 1.3 BGOPY jet

**BGOPY = billion gallons per year; estimates of jet potential will vary based on conversion technology and feedstock composition**

Sources: *2030 estimate from DOE 2016 Billion-Ton Report; **Bhatt et al. (2020) iScience, 23, 101221; ***CAAFI U.S. Jet Fuel production potential from wastes

- **U.S. biomass and waste carbon availability has embedded energy content on par with current jet fuel consumption of 26 BGPY**

- **SAF provides links to agriculture, food security, and waste management with opportunities for cross-sector benefits at the intersection of energy and environment**
3. New pathways to produce SAF from renewable and waste C

SAF technology development from bench-to-commercial scale

- New SAF conversion pathways at varying stages of technology readiness and fuel readiness level – both of key importance

- Stage-gate approach allows for derisking new SAF routes at increasing scale to ensure iterative and cost-effective learning cycles during development

Sources: Euhus et al. (2021) The Catalyst Review, 34, 3, 6; DOE (2011) Technology Readiness Assessment Guide 413.3-4A; CAAFI Fuel Readiness Level
To aid in informing SAF pathway development, low-volume fuel property evaluation tools being developed within DOE and elsewhere.

Leverage latest analytical chemistry techniques with fuel molecule structure-property relationships to inform neat and blended SAF development.

3. New pathways to produce SAF from renewable and waste C

Techno-economic analysis to determine SAF cost drivers

- Techno-economic modeling provides a framework for assessing major cost drivers as a function of unit operation, performance, and scale

- Strategies to reduce SAF price and increase revenue include:
  1. Feedstock (waste materials, symbiotic services, strategic offtake agreements)
  2. Operating expenses (increase fuel yields, improve energy efficiency)
  3. Capital expenses (leverage existing infrastructure, refinery integration)
  4. Carbon credits & RINs (optimize process for lower carbon intensity)
## 3. New pathways to produce SAF from renewable and waste C

### Lifecycle analysis to determine SAF reduction in carbon intensity

- **Lifecycle analysis provides a framework for comparing SAF carbon intensity to fossil jet that includes field-to-fuel production**

- **Multiple avenues to reduce overall process carbon intensity for SAF:**

  1. Feedstock (divert methane emissions, soil carbon sink with agricultural practices)
  2. Operating energy (more efficient unit operations, renewable electricity)
  3. Hydrogen source (RNG-biogas steam reforming to H₂, electrolysis)
  4. Co-products (soil fertilizer, compost, biobased electricity etc.)

---

### Life Cycle Analysis for Fossil Jet Fuel and SAF

<table>
<thead>
<tr>
<th>Process</th>
<th>Carbon Intensity gCO₂eq/MJ</th>
<th>SAF Reduction</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Oil Extraction</td>
<td>84</td>
<td>-80</td>
<td><em>electrolysis with displacement</em></td>
</tr>
<tr>
<td>Fossil Oil Transport</td>
<td>27</td>
<td>-60</td>
<td><em>landfill methane diversion</em></td>
</tr>
<tr>
<td>HEFA Waste Oil</td>
<td>47</td>
<td>-40</td>
<td></td>
</tr>
<tr>
<td>Camelina Oil</td>
<td>9</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>FT Corn Stover</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FT Forestry Residue</td>
<td>18</td>
<td>-6</td>
<td></td>
</tr>
<tr>
<td>HTL Forestry Residue</td>
<td>35</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>ATJ Corn Stover</td>
<td>22</td>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis Forestry Residue</td>
<td>-6</td>
<td>-55</td>
<td></td>
</tr>
<tr>
<td>VFA Food Waste</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sources: de Jong et al. (2017) Biotech for Biofuels, 10, 64; Gelfand et al. (2020), 54, 28961-2974; Ringsred et al. (2021) Applied Energy, 287, 116587; Huq et al. (2021) PNAS, 118, 13
Questions?

Kristi Moriarty
Kristi.Moriarty@nrel.gov

Derek Vardon
Derek.Vardon@nrel.gov

Learn more about BETO: energy.gov/bioenergy
BETO Webinar Recording: energy.gov/eere/bioenergy/beto-webinars