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Potential and challenges of sustainable aviation fuels (SAF)/biojet

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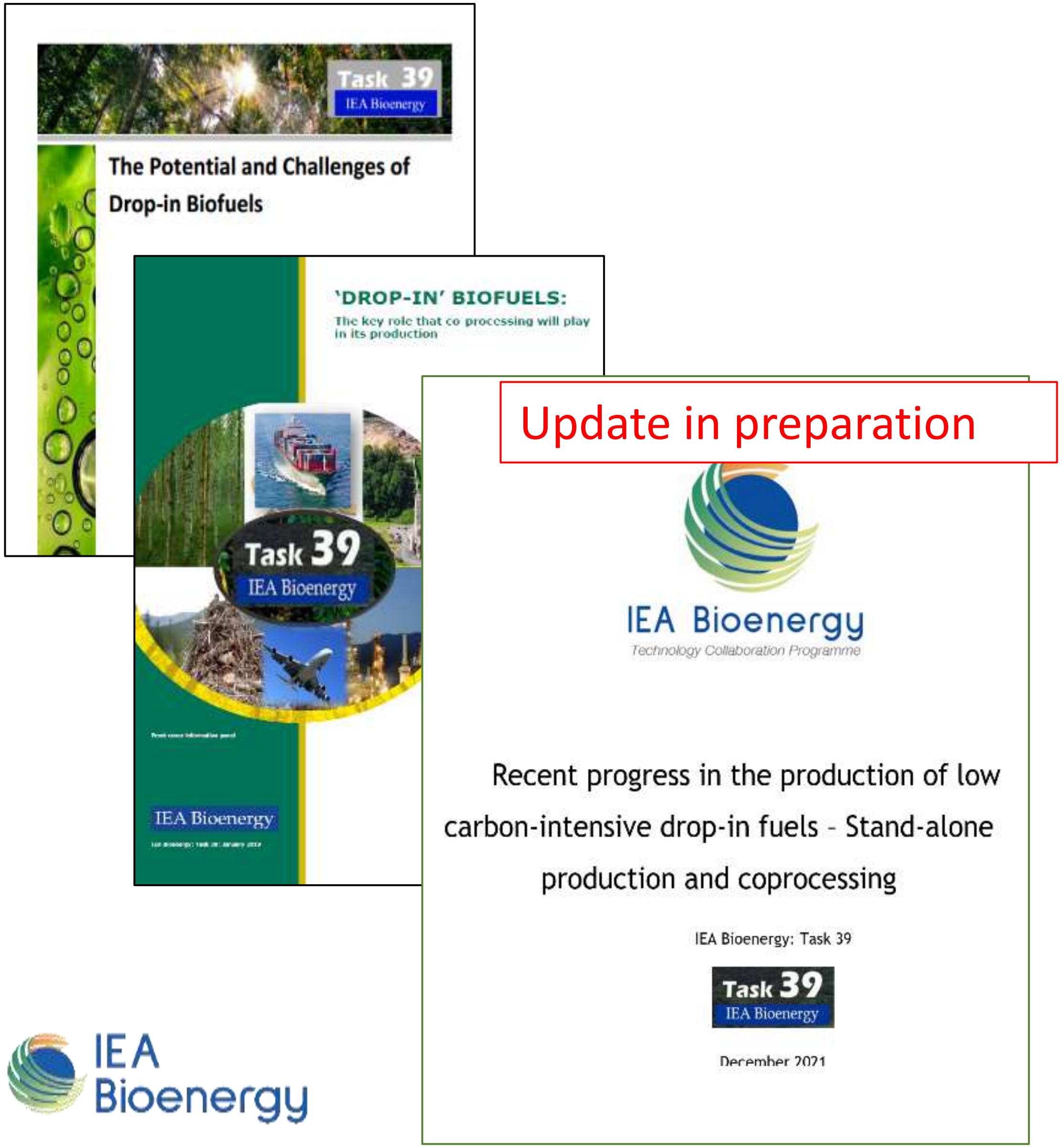
Drop-in biofuels and SAF reports (2014, 2019 & 2021)



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The Potential and Challenges of
Drop-in Biofuels

'DROP-IN' BIOFUELS:
The key role that co processing will play in its production

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Update in preparation

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Recent progress in the production of low carbon-intensive drop-in fuels – Stand-alone production and coprocessing

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December 2021

Update in preparation

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Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF):
Technologies, potential and challenges

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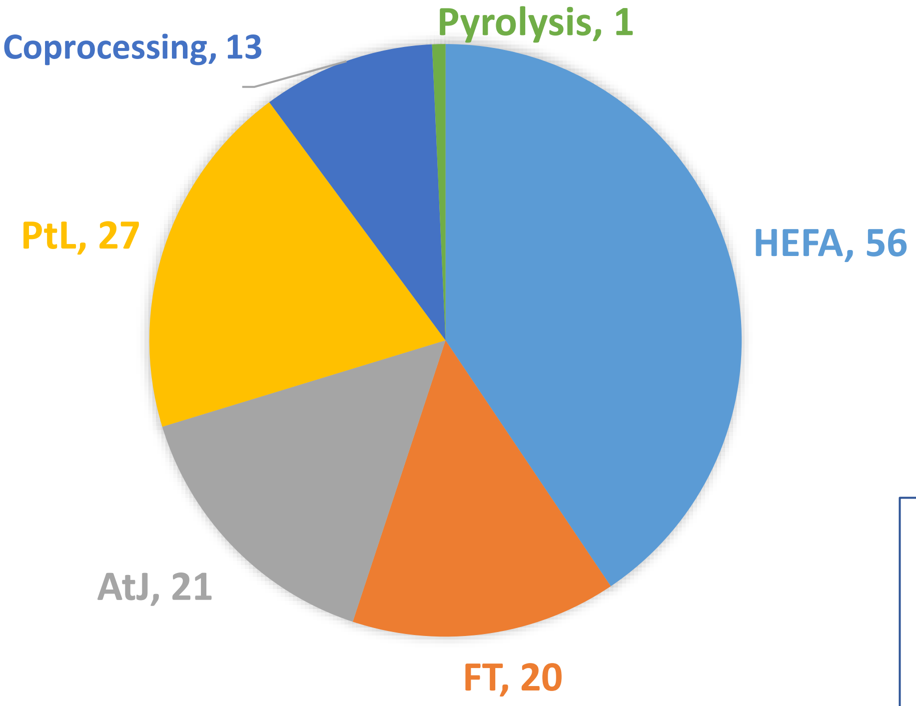
Key take-aways

- SAF will play the biggest role in achieving climate targets in the aviation sector
- However, to produce more than 400 BLPY by 2050 is a daunting task
- ALL technology pathways must be pursued, but many challenges remain
- Only SAF from the HEFA pathway is commercial
- It is critical for other technology pathways to reach commercial scale, but this will take time
- Production cost of SAF is much higher than conventional jet fuel and will remain higher
- But cost reductions can occur once technologies are fully commercial

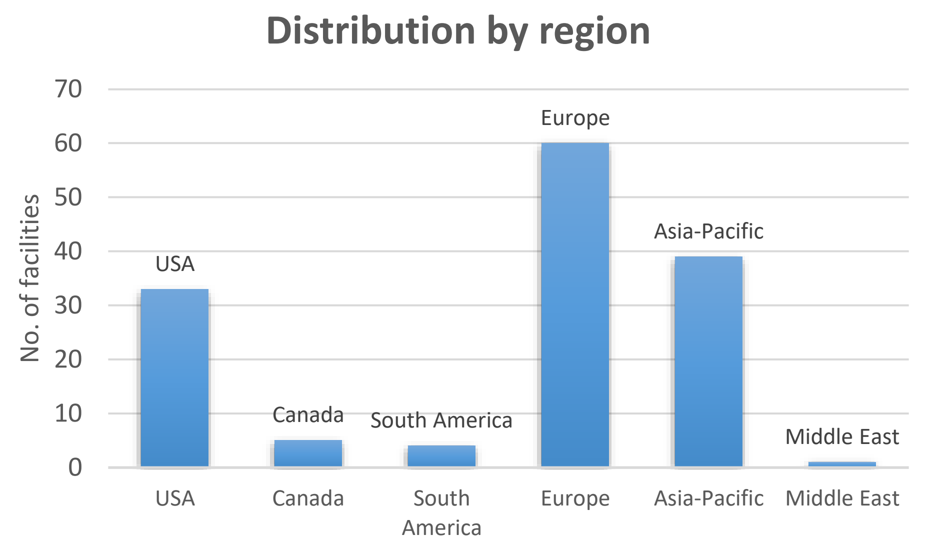
Announcements of SAF production facilities

- Total facilities – 142
- Capacity - ~33 BLPY
- SAF portion not clear
- Mostly announcements!
- Expected completion not clear

(based on information from Argus Media)



Distribution by type of technology



>40 Billion litres in offtake agreements, but this does not represent actual production

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Expected timelines for technology commercialisation?

- Reports try to project the next technologies and the expected volumes by 2030, 2040 and 2050

General conclusions:

- By 2030, the majority of SAF will come from HEFA
- By 2030, availability of waste fats and oils will limit further growth of HEFA, but new feedstock sources?

How fast will other technologies become commercial?

  - Progression across TRL stages (2-3 years?)
  - Timeline from announcement to operation (funding, permitting, construction, commissioning)
  - Some gasification/FT facilities expected to take 5 years to construct

VOLUMES BY TECHNOLOGY CURRENT ANNOUNCEMENTS (BLPY)	
HEFA	24.2
FT	2.24
AtJ	2.84
PtL	2.3
Coprocessing	?
Pyrolysis	0.13

(Based on Argus Media data)

Policy will remain the critical driver for SAF development and expansion

- Policies in Europe and the USA has been the major turning point in SAF development – from one facility routinely producing SAF to 142 facilities
- Main challenges to be addressed:

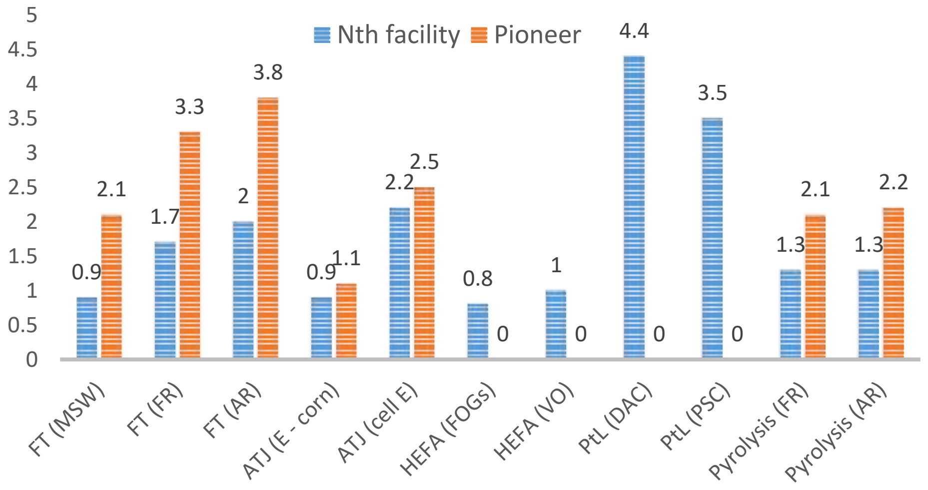
  a) The cost differential with conventional kerosene (jet fuel) and the current higher costs of producing SAF
  b) Limited availability of cost-effective/sustainable SAF feedstocks
  c) Limited investment and the high cost of financing SAF fuel production infrastructure
  d) Competition for resources and incentives with other sectors (e.g., road transport, renewable power) (ICAO CAEP, 2022)

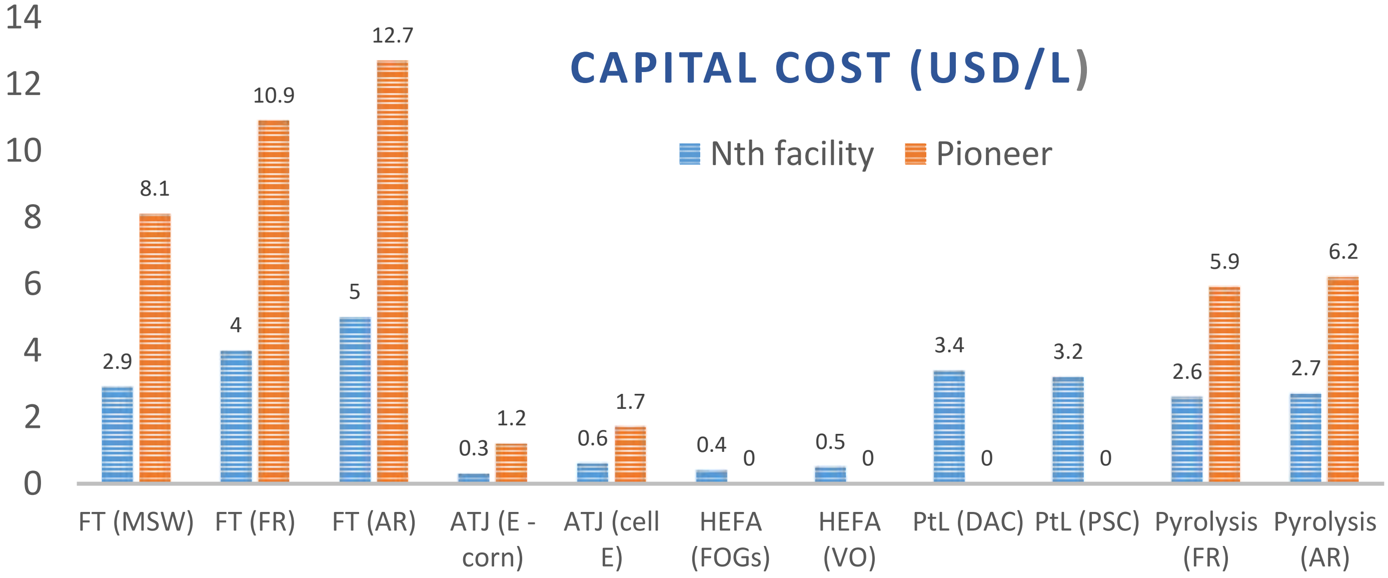
- The cost difference with conventional jet fuel could remain until 2050 for many pathways

ICAO SAF Rules of Thumb - techno-economics

- Cost of pioneer facilities often underestimated
- Cost improvements can only happen once several facilities are operating for that technology
- Current jet A market price (USD 0.76/L)
- Production cost calculated as MSP, where NPV=0 (break-even)

MINIMUM SELLING PRICE- MSP (USD/L)




CAPITAL COST (USD/L)

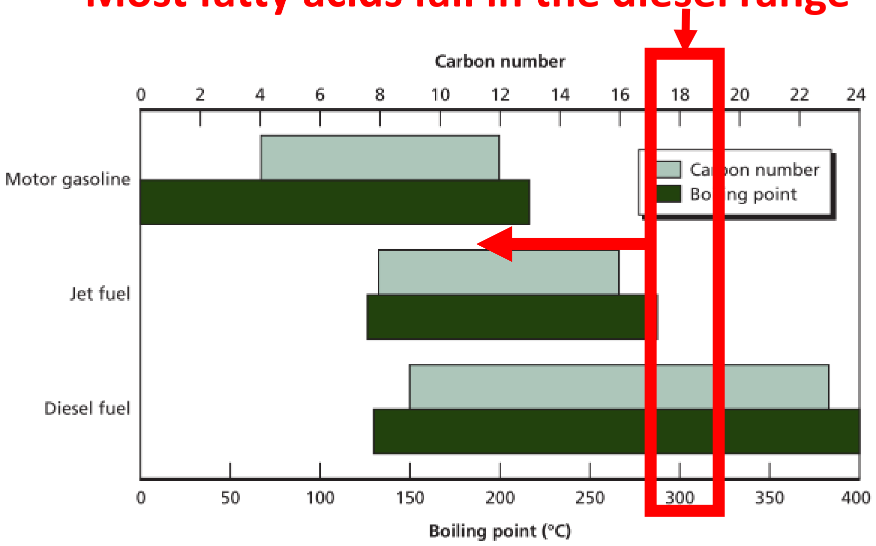
Status of SAF from the HEFA pathway

- Hydrotreatment of fats, oils and greases is fully commercial for production of renewable diesel/HVO
- Producing a high SAF fraction in a HEFA facility is not commercial yet
- Shifting a bigger fraction to the jet range requires hydrocracking but reduces yield of valuable products
- New catalysts on the market to control cracking and minimise low value products
- Claims of 70% SAF fraction
- POLICY is the biggest driver for companies to shift to high SAF

  EU – mandate

  USA – higher incentives for SAF versus renewable diesel

Most fatty acids fall in the diesel range



Carbon no. and boiling point range of gasoline, jet and diesel

Potential and challenges of HEFA SAF

Potential and opportunities

- Most commercial technology; substantial global capacity; large facilities achieve economies of scale; energy dense feedstock with established trade
- A shift to high SAF fraction can supply large volumes in a short time
- Co-processing of lipids can also supply large SAF volumes with a short turnaround time

Challenges

- High feedstock cost; feedstock about 80% of OPEX
- Waste feedstocks no longer cheap
- Limited availability of waste feedstocks (~30-40 million tonnes globally); competition with biodiesel and renewable diesel
- Other low carbon-intensity feedstocks not commercial (e.g. camelina, carinata, jatropha) or very expensive (e.g. algae)
- Low quality of waste feedstocks – requires more pretreatment

Alcohol-to-jet commercialisation

Potential and opportunities

- ASTM approved for ethanol, isobutanol, and mixed alcohols (C2-C5)
- Methanol and n-butanol in the ASTM pipeline
- First commercial facility for ethanol-to-jet near completion and expected to start production in 2024 (Lanzajet – Freedom Pines)

Advantages of the AtJ pathway

- Relatively low CAPEX
- Can use alcohols from any source
- Conventional ethanol production from crops are fully commercial and available at large scale (120 BLPY) at relatively low cost
- Sugarcane ethanol very low carbon intensity
- Can produce large SAF fraction (70-90%)

Challenges of AtJ and trends

- Availability and cost of second generation, advanced alcohols
- Advanced alcohols not commercial and expensive – this will be a significant challenge
    - Production of cellulosic ethanol from agricultural residues or woody biomass – many companies have been unsuccessful
    - Syngas or industrial off-gas fermentation for ethanol production
    - Methanol production from biobased syngas or renewable natural gas
    - Butanol production low yields and other challenges
- Significant volumes of crop-based ethanol available, but carbon intensity and sustainability (and public perception)
- In the US, focus on improving the carbon intensity of corn ethanol through changing farming practices, reducing energy requirements during distillation, using renewable energy, and BECCS

Gasification with Fischer-Tropsch

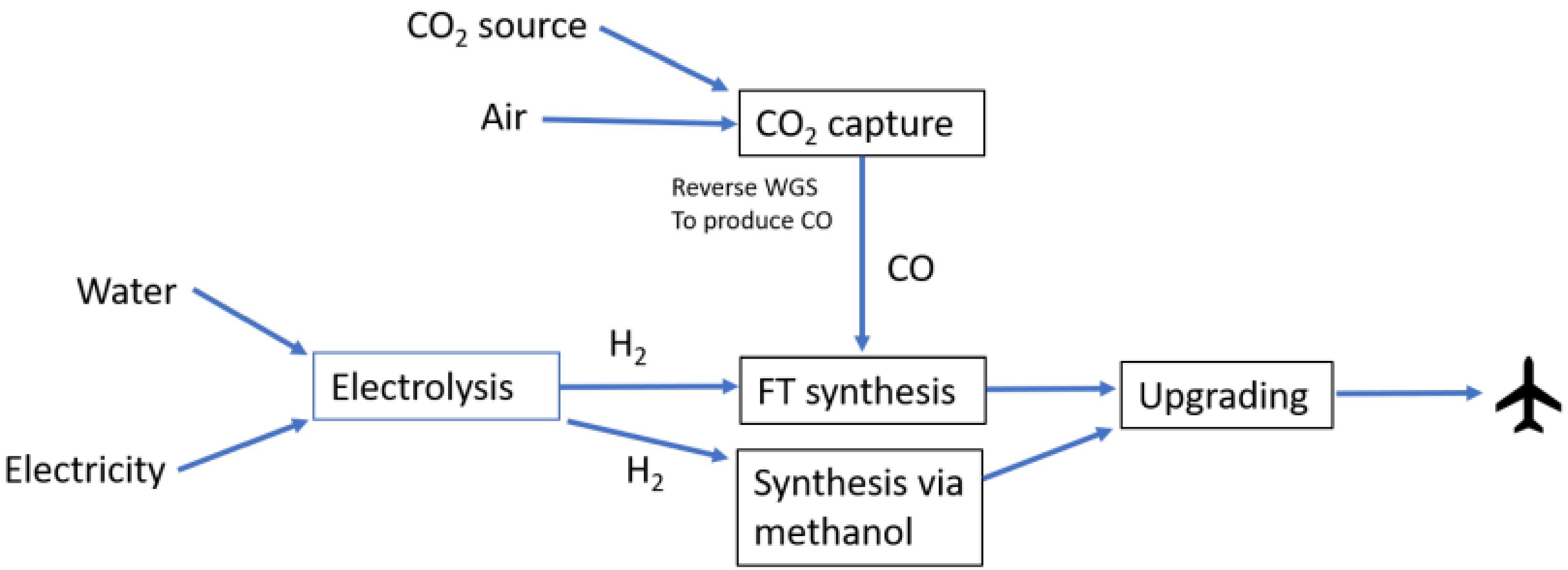
Potential and Opportunities

- Large feedstock resources – forest and agricultural residues, municipal solid waste (MSW)
- One commercial facility operating, Fulcrum – MSW
- Very low carbon intensity

Gasification with Fischer-Tropsch - challenges

- Very high CAPEX (>$1 billion, up to $4 billion)
- Complexity of syngas cleanup (differences for feedstocks)
- Strict feedstock size specifications
- Relatively low yields (18% distillate per tonne of feedstock for forest residues; 14% for agricultural residues)
- Multiple products requires additional processing
- Many types of gasification and FT technologies must all become commercial (not a single technology)

Status of Power-to-liquids technology



- Parts of the process are fully commercial, e.g. Fischer-Tropsch; alkaline and PEM electrolysis
- Other parts at low TRL level – e.g. Reverse Water Gas Shift Reaction at TRL 4-5
- Co-electrolysis can (SOEC technology) only at pilot scale
- The fully integrated process must also be demonstrated, even where components were commercial on their own - still at lower TRL level
- Methanol-to-jet lower TRL than FT

Power-to-liquids – Potential and challenges

Potential and opportunities

- Does not require biobased feedstock
- Can deliver substantial emission reductions (under certain conditions)

Challenges

- High emissions reductions only when direct air capture is used – much more expensive
- Only additional renewable electricity delivers low carbon intensity
- Substantial demand for renewable electricity – competition with other, more efficient applications
- Very energy inefficient
- Multiple fuel products, not just SAF
- High production cost

Direct thermal liquefaction for SAF production (Pyrolysis, hydrothermal liquefaction

- Low commercial status
- Not ASTM approved
- Significant research into SAF production from sludge using hydrothermal liquefaction
- Alder Renewables pursuing SAF production but currently only at pilot scale

Potential and opportunities

- Access to significant volumes of feedstock and HTL has a niche in wet feedstocks
- Liquid intermediates can be used for coprocessing to in existing refineries

Direct thermal liquefaction - challenges

- Significant technical challenges to upgrading
- High oxygen content, low pH, water content
- High nitrogen content for some feedstocks (sludge)
- High hydrogen requirement for upgrading
- Significant variations depending on the feedstock
- High aromatics
- Co-processing of biocrudes for other fuels in commercial trials (Preem), but many challenges
- Limited availability of bio-oils/biocrudes

Sustainability and carbon intensity of SAF

- ICAO Carbon Offset and Reduction Scheme (CORSIA) defines eligible fuels, sets default carbon intensities and established a life cycle methodology
- But does not take into account aspects such as carbon capture and storage or regenerative farming practices
- Regional differences not adequately considered
- Underlying data not current
- CORSIA needs to be improved

- Carbon intensity is not static and can be lowered using various approaches e.g. CCS, added renewable electricity, anaerobic digestion of waste water, etc.
- But this will require higher investment cost for more infrastructure (Velocys, DG Fuels - $4 billion investment)
- More sustainable likely more expensive
- Sustainability AND cost will both be critical for commercial expansion

Feedstocks for SAF - availability and challenges

- Feedstock availability assessments "count" potential feedstocks that are not available yet
- E.g. non-edible oil crops as cover crops or grown on marginal land
- Commercial-scale cultivation must take place, and supply chains developed
- Cost AND sustainability must be considered

- Lignocellulosic feedstocks (forest and agricultural residues)
- Mature supply chains are needed – lessons from cellulosic ethanol failures

- Feedstock commercialisation and supply chain development as important as technology development

Thank you
Questions?

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