Progress in Commercialisation of Biojet fuels/SAF:

Technologies, potential and challenges

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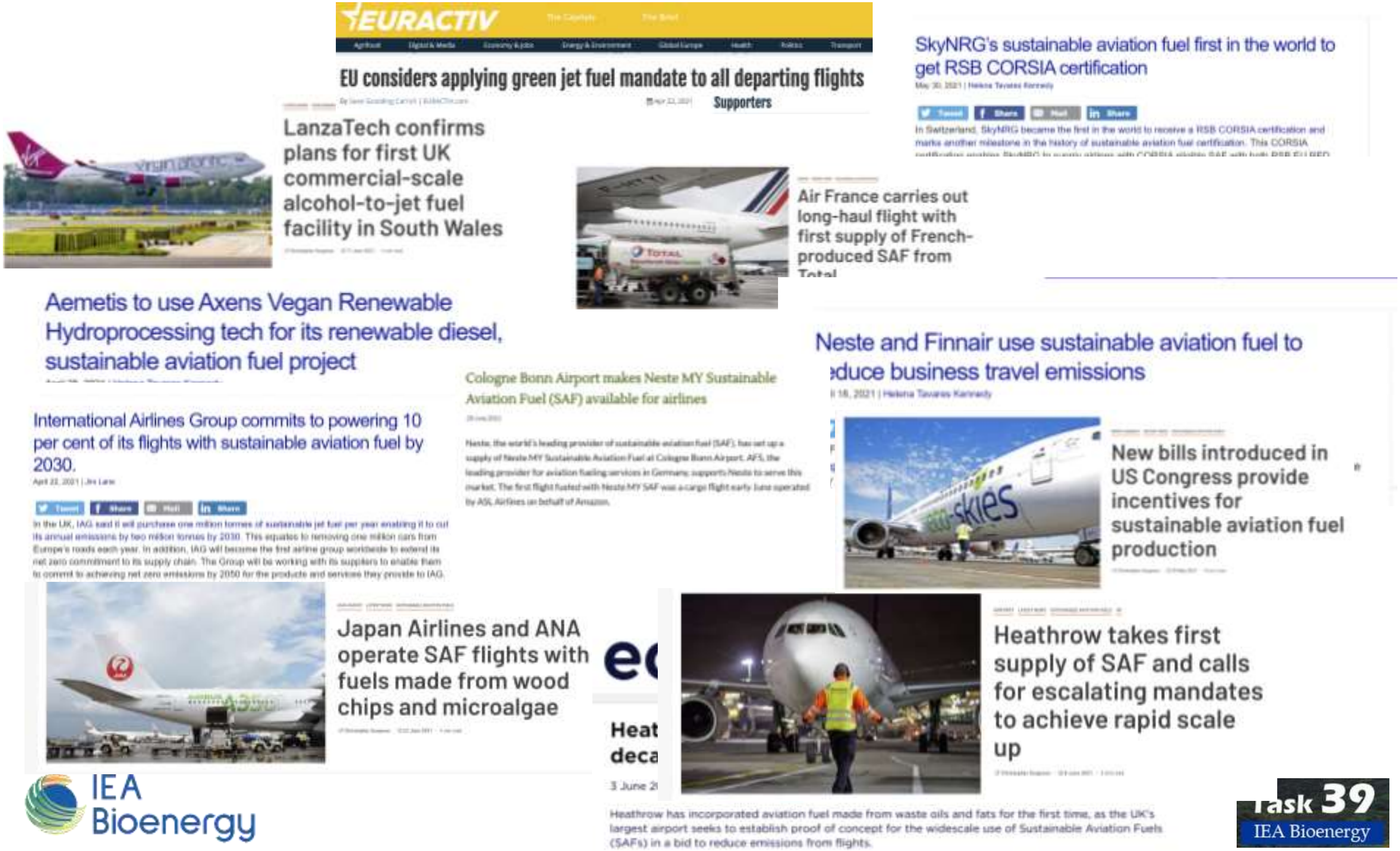
SAF developments has seen a significant acceleration with daily announcements in the media



TAKE-HOME MESSAGES

- There is no "silver bullet" technology - ALL SAF technologies should be commercialized
- The large price gap with conventional jet fuel is the biggest challenge for expansion
- The right combination of policies will be the most important driver of expansion
- HEFA will continue to be the biggest supplier of SAF up to 2030+
- 15% of current HVO/renewable diesel production can immediately be diverted to SAF with low investment ~ 1 BL
- First fully commercial facilities for other technologies will lead to rapid expansion as more facilities follow
- PtL will play an important role but only significant after 2030
- Pyrolysis/HTL technology pathways have great potential but will only become significant after 2030

Topics covered in this presentation

- SAF availability
- Scale-up and commercialization
- Biggest challenges to SAF expansion
- Drivers of SAF production and uptake
- Feedstocks
- SAF Sustainability
- SAF technologies – trends, challenges and potential

SAF production volumes, future capacity, long-term demand

CURRENT PRODUCTION

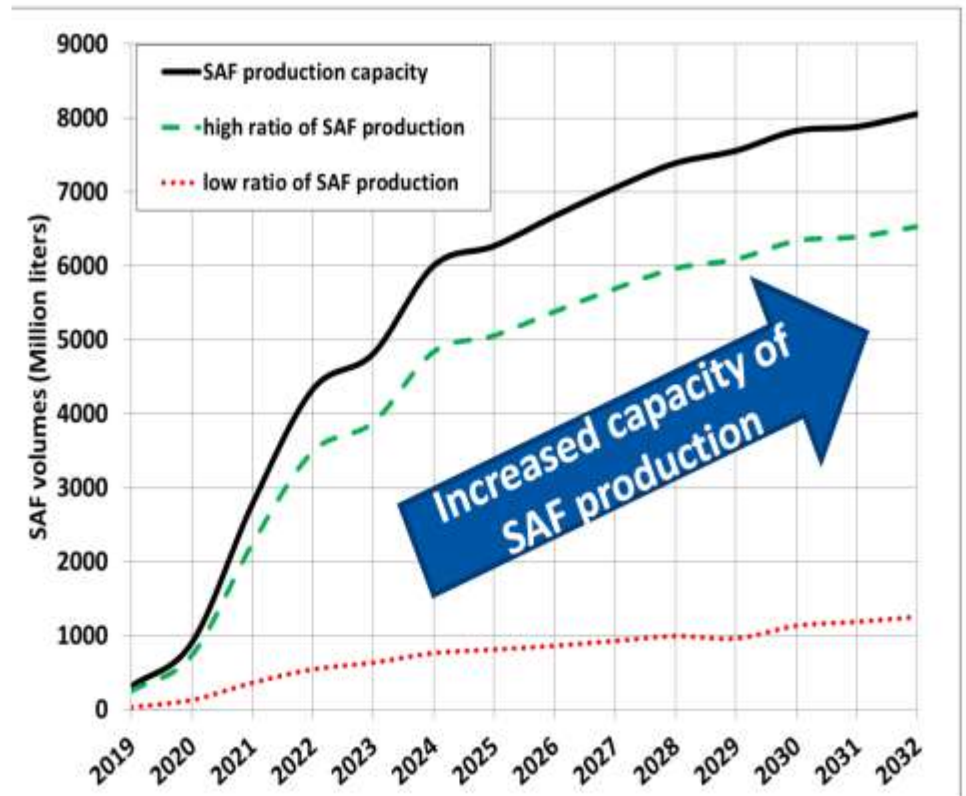
- Average of 0.29 MLPY (2013-2015) to 6.45 MLPY (2016-2018)
- In 2019 Neste produced 125 million litres

Source: ICAO Stocktaking 2019

- Announced SAF capacity for Neste by 2023 – 2 BLPY

- **Current jet fuel demand ~360 billion litres per year**
- **Volumes required by 2050?**

FUTURE PRODUCTION



8 billion litres estimated by 2032

(Source: ICAO Stocktaking 2019)

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Potential technology commercialization and future SAF supply

- There is no "silver bullet" technology!
- All technologies should be commercialized to contribute to volumes and make use of niche feedstocks and regional conditions

Proposed progressive contribution of technologies

2021-2025	2026-2030	2030-2040	2040-2050
HEFA	**HEFA**	**HEFA**	**HEFA**
Gasification-FT	Gasification-FT	Gasification-FT	Gasification-FT
ATJ	ATJ	ATJ	ATJ
CHJ	CHJ	CHJ	CHJ
	Coprocessing lipids	Coprocessing lipids & biocrudes	Pyrolysis/HTL
		Pyrolysis/HTL	**PtL**
		PtL	

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Price of SAF – challenges and future prospects for price parity

- HEFA SAF currently about 3-4 x the price of conventional jet (~USD$2,000 - $2,300) (Argusmedia, Greenea)
- Conventional jet fuel 23 June 2021 - USD$615

- Other technologies are not commercial and only techno-economic analyses are available
- Price based on volume, but VALUE of low carbon intensity
- PRICE considered one of the biggest obstacles to airlines

- SAF will potentially always be more expensive although significant cost reductions will take place over time

SAF-specific policies will have the greatest impact on SAF expansion

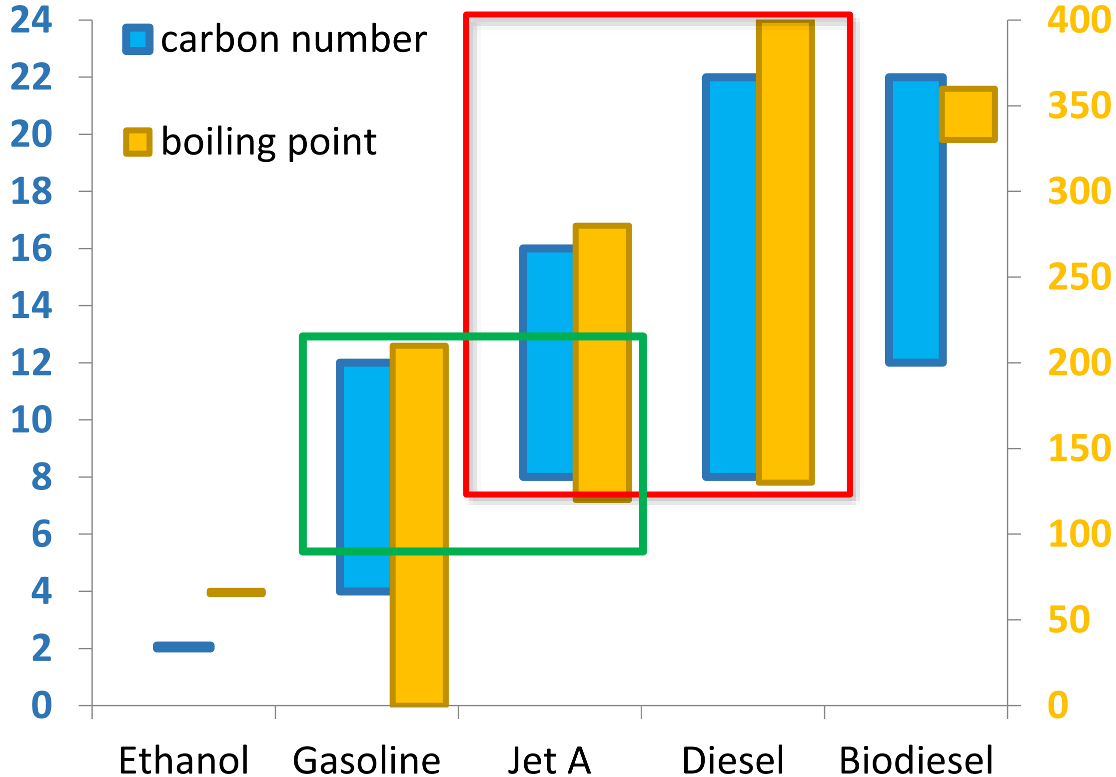
- **California LCFS includes aviation -** linked to **carbon intensity reduction**
- **US RFS includes SAF**
- Mandates and proposed mandates in Norway, Sweden, Finland

- **ReFuelEU** proposed mandate (volumetric) – 2% in 2025, moving to 5% in 2030, 20% in 2035, 32% in 2040, and 63% in 2050
- **Sustainable Skies Act** (USA) – proposed blenders tax credit; linked to **carbon intensity reduction**
  - $1.50 per gallon up to $2 per gallon for 100% emission reduction

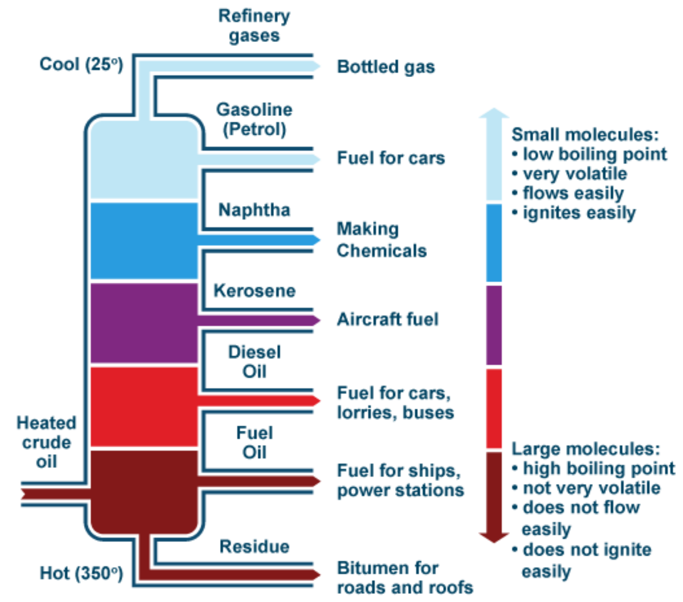
- Voluntary corporate actions & BUYERS ALLIANCES (Sustainable Aviation Buyers Alliance) could create a strong demand signal (irrespective of national policies) (based on SAF certificates)

HVO producers don't HAVE to produce a SAF fraction

- Production of SAF is more expensive than renewable diesel only
- Jet can be sold as diesel, and this creates competition which needs to be addressed through policy, such as a fuel multiplier (SAF earns more credits)



Distillation cuts based on boiling point determines product slate



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Technologies produce multiple fuel products and different ratios of SAF

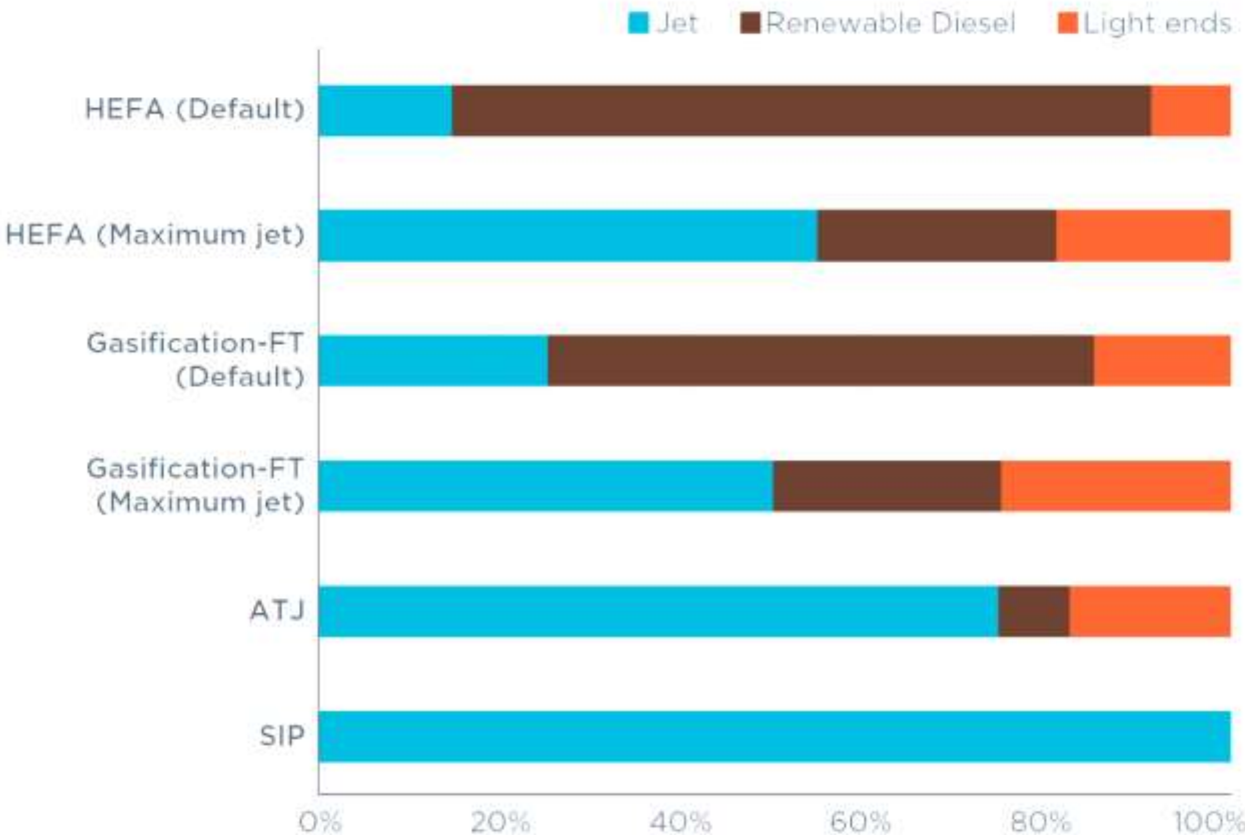

Figure 1. Comparison of product slates across fuel conversion pathways.

- Capacity of a "SAF" facility is not all jet fuel
- SAF fraction can be increased through hydrocracking (and isomerization)
- Maximising SAF fraction comes at a cost – lower liquid fuel yields, higher hydrogen consumption
- Policy can drive an increase in jet production

Source: Pavlenko et al 2019 The cost of supporting alternative jet fuel in Europe. International Council on Clean Transportation

SAF sustainability and potential emissions reductions for different pathways

- CORSIA establishes minimum sustainability criteria – RSB, ISCC
- Potential emission reductions from SAF is only one part of sustainability
- CORSIA sets Default Life Cycle Emissions Values for Eligible fuels
- SAF producers can demonstrate actual values
- Some pathways seem inherently "better" than others, but this is not a static metric
- Many SAF producers moving to net zero fuels based on added renewable energy, carbon capture and storage
- Build for net zero from the start!
- Policy must place a value on carbon intensity

Table 1. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels

Fuel Conversion Process	Region	Fuel Feedstock	Core LCA Value	ILUC LCA Value	LS_f (gCO_2e/MJ)
Fischer-Tropsch (FT)	Global	Agricultural residues	7.7	0.0	7.7
	Global	Forestry residues	8.3		8.3
	Global	Municipal solid waste (MSW), 0% non-biogenic carbon (NBC)	5.2		5.2
	Global	Municipal solid waste (MSW) (NBC given as a percentage of the non-biogenic carbon content)	NBC*170.5 + 5.2		NBC*170.5 + 5.2
	USA	Poplar (short-rotation woody crops)	12.2	-5.2	7.0
	USA	Miscanthus (herbaceous energy crops)	10.4	-32.9	-22.5
	EU	Miscanthus (herbaceous energy crops)	10.4	-22.0	-11.6
	USA	Switchgrass (herbaceous energy crops)	10.4	-3.8	6.6
Hydroprocessed esters and fatty acids (HEFA)	Global	Tallow	22.5	0.0	22.5
	Global	Used cooking oil	13.9		13.9
	Global	Palm fatty acid distillate	20.7		20.7
	Global	Corn oil (from dry mill ethanol plant)	17.2		17.2
	USA	Soybean oil	40.4	24.5	64.9
	Brazil	Soybean oil	40.4	27.0	67.4
	EU	Rapeseed oil	47.4	24.1	71.5
	Malaysia & Indonesia	Palm oil – closed pond	37.4	39.1	76.5
	Malaysia & Indonesia	Palm oil – open pond	60.0	39.1	99.1
	Brazil	Brassica carinata (grown as a secondary crop that avoids other crops displacement)	34.4	-20.4	14.0
	USA	Brassica carinata (grown as a secondary crop that avoids other crops displacement)	34.4	-21.4	13.0
Alcohol (isobutanol) to jet (ATJ)	Global	Agricultural residues	29.3	0.0	29.3
	Global	Forestry residues	23.8		23.8
	Brazil	Sugarcane	24.0	7.3	31.3
	USA	Corn grain	55.8	22.1	77.9
	USA	Miscanthus (herbaceous energy crops)	43.4	-54.1	-10.7
	EU	Miscanthus (herbaceous energy crops)	43.4	-31.0	12.4
	USA	Switchgrass (herbaceous energy crops)	43.4	-14.5	28.9

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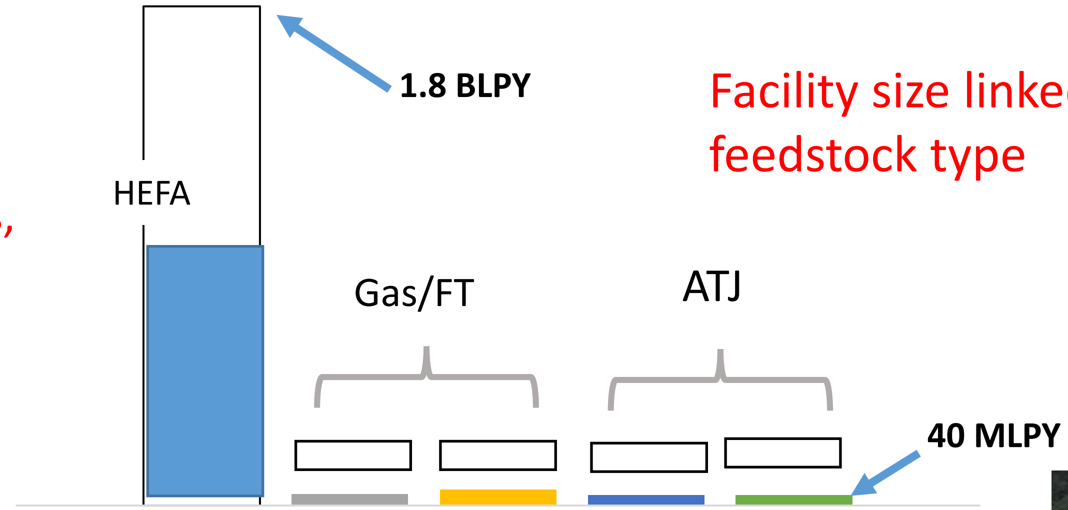
Do we have enough feedstocks for SAF production?

- Feedstocks not considered limiting for SAF expansion in many reports, but may be overly optimistic
  - Cost of feedstock may be ignored
  - Competition for other applications not considered
  - Theoretical vs actual availability
  - "Availability" without established supply chains
- Feedstock density limits transport distances and size of facility
- For most technologies feedstock must be sourced within a limited radius

Lipid feedstocks can be transported long distances, but not most other feedstocks



Facility size linked to feedstock type

Technology platforms and ASTM certification

8 Approved pathways

- Fischer-Tropsch SPK & SKA (2009) (50%)
- HEFA SPK (2011) (50%)
- Synthesized Iso-paraffins (SIP) (2014) (10%)
- Alcohol to jet SPK (isobutanol (2016), ethanol (2018)) (50%)
- Catalytic hydro-thermolysis of lipids to jet fuel (50%)
- HC-HEFA-SPK – lipids from *Botryococcus braunii* algae (10%)
- Co-processing of lipids & FT liquids (5%)

- Several other pathways in progress towards ASTM certification as technology commercialisation is ongoing
- Maximum blends currently limited to 50% - several reasons why this should be increased
- Although fast-track certification is possible, the 10% blend limit is a significant constraint
- Maximum blends for coprocessing (5%) are too low and will limit any contribution from this pathway

SAF blends up to 100%?

- Is this relevant without high SAF availability?
- Is it feasible when some SAF have no aromatics (are not drop-in)?
- 2 reasons for considering 100% SAF – book-and-claim, non-CO2 climate impacts of aviation

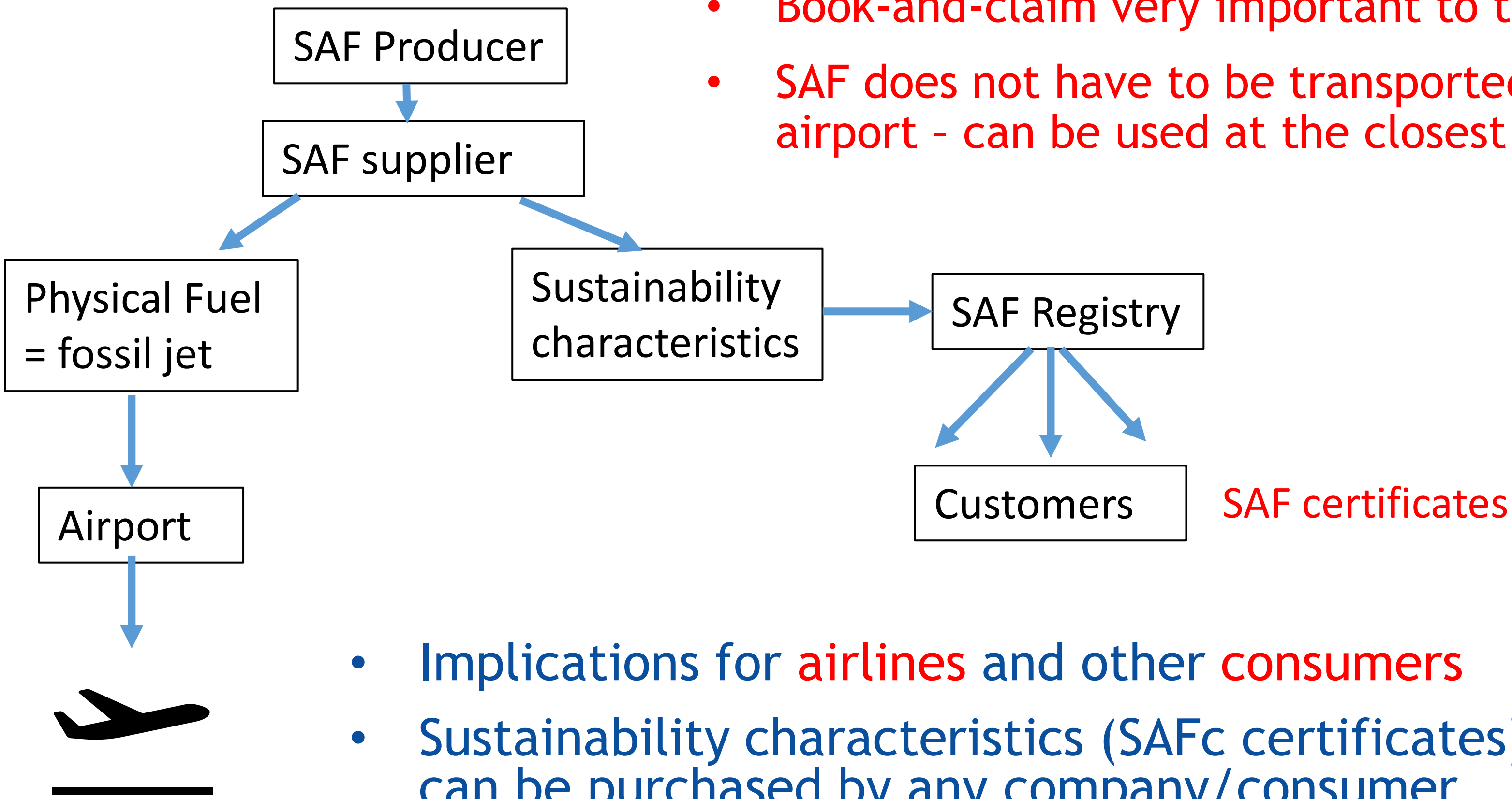
- With the introduction of a book-and-claim system, SAF can be used at one place and claimed at another
- 100% SAF may become necessary at large airports to achieve significant overall SAF consumption

- 100% paraffinic SAF shown to significantly reduce non-CO2 climate impacts of aviation due to reduced soot formation (which reduces persistent contrail formation) (NASA-DLR study)
- But 100% paraffinic SAF (HEFA) is not a drop-in fuel and not compatible with all existing aircraft and fueling infrastructure
- To reduce non-CO2 climate impacts a significant reduction in maximum aromatics in ASTM certification should be targeted (current max 25 vol%)

What is a book-and-claim system?

What are SAF certificates?

- Book-and-claim very important to the sector
- SAF does not have to be transported to every airport – can be used at the closest airport



- Implications for airlines and other consumers
- Sustainability characteristics (SAFc certificates) can be purchased by any company/consumer
- Chain of custody and traceability essential to avoid double counting

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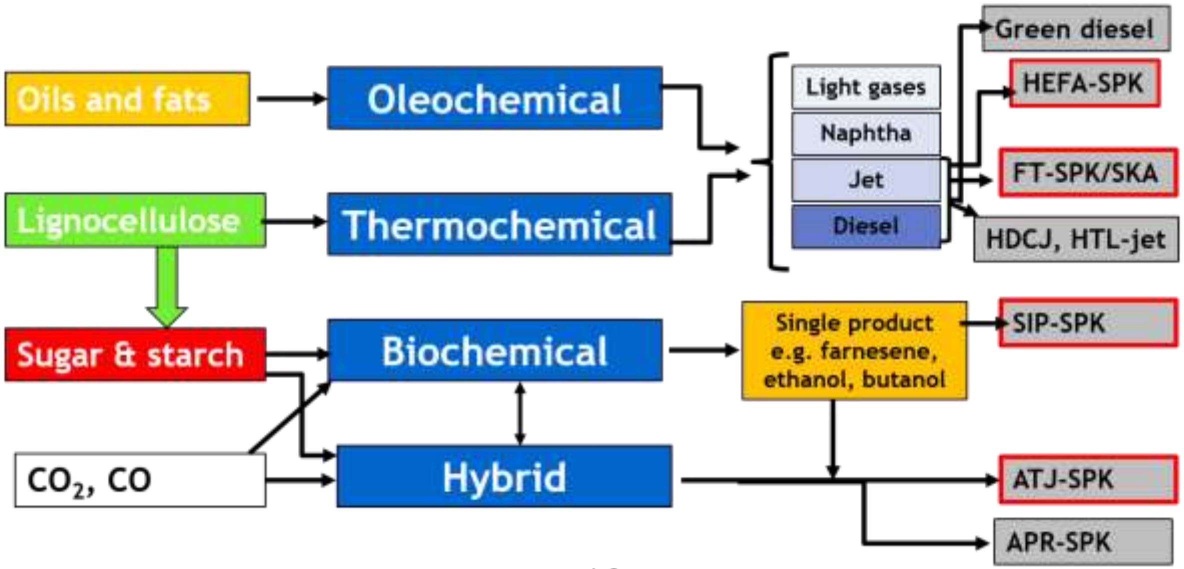
SAF Technologies - trends, potential and challenges

- HEFA technology is currently the only fully commercial pathway and will be the main supplier of SAF over the next 10 years
- Commercial scale facilities for Gasification-FT and ATJ are being built and will proceed towards full commercialization
- Other technologies, such as PtL and thermochemical liquefaction pathways, will take longer to reach commercial scale
- Companies are not limiting themselves to one technology



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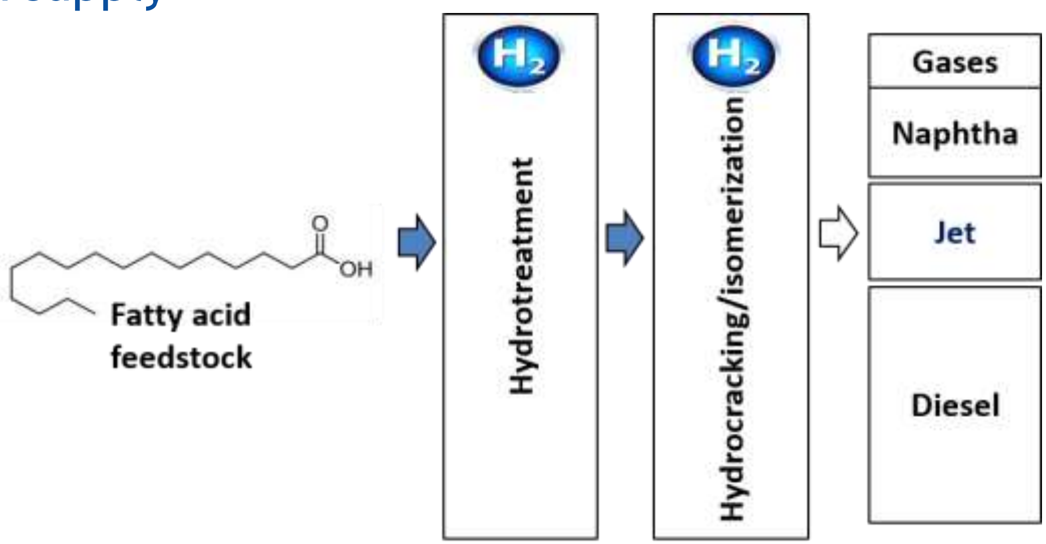
HEFA-SPK from fats, oils and greases - Trends

- Significant expansion of production capacity for (mostly) renewable diesel/HVO
- Increased SAF production by separation of the jet fraction in existing facilities (e.g., Neste making investments at Singapore & Rotterdam)
- Increased sourcing and use of waste fats and oils - pretreatment
- HVO producers invest in or acquire feedstock producers to secure future feedstock supply



HEFA-SPK - CHALLENGES

- Feedstock cost, availability, sustainability and quality

UCO DDP NWE M+1	EUR per ton	725
UCO CIF ARA Flexi M+1 (bid)	USD per ton	730

9 November 2020

Source: Greenea

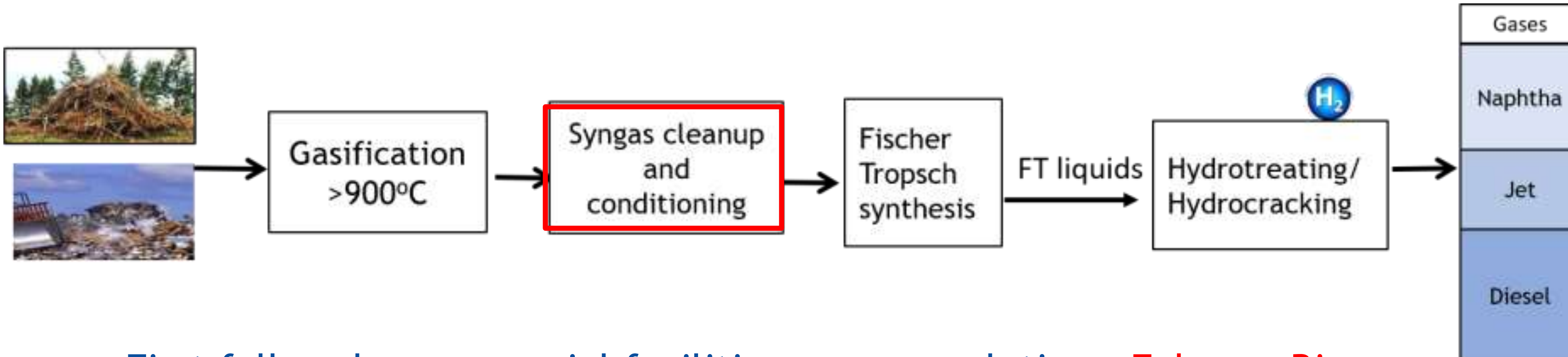
- Varied estimates of feedstock availability – 25 MT (waste), 100 MT (waste, cover crops, crops on marginal lands)
- Crop-based feedstocks?
- Competition with biodiesel for feedstocks
- Immature feedstock supply chains and low availability of new feedstocks (camelina, carinata, Salicornia)

- Competition between HEFA for aviation and HVO for road transportation – policies such as a multiplier can give SAF a competitive advantage

HEFA-SPK - OPPORTUNITIES

- High feedstock density allow large scale facilities and economies of scale
- With limited investment, every current HEFA (renewable diesel) facility can potentially produce ~15% SAF, significantly expanding volumes
- Further expansion to maximum SAF can be achieved with greater investment (needs policy driver)
- Improving sustainability characteristics through green hydrogen (from propane by-product) and very low carbon intensity feedstocks
- Favourable policies can address competition with renewable diesel to increase SAF value proposition

Gasification and Fischer-Tropsch (FT-SPK) - Trends



- First full-scale commercial facilities near completion – Fulcrum Bioenergy just completed Sierra Nevada facility
- Successful operation of pioneer facilities will accelerate full commercialisation
- Two main feedstocks targeted – municipal solid waste and residues

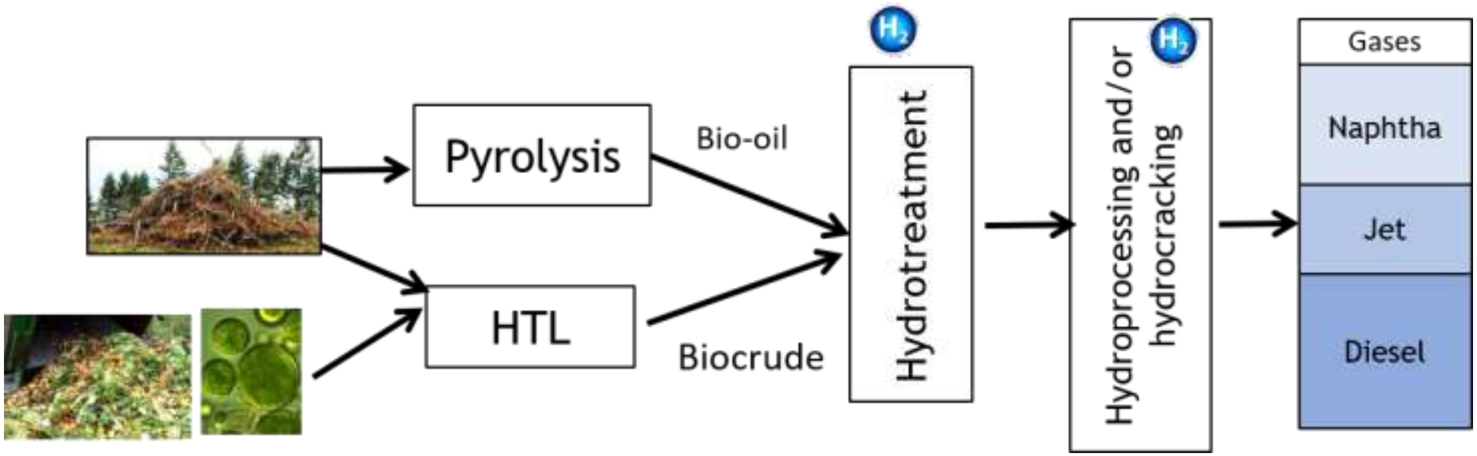
Gasification/FT-SPK Challenges

- Slow commercialisation since ASTM certification in 2009
- Challenges with tar formation and feedstock contaminants in the syngas
- Addressed through gasification technology selection, but also limiting high cost of gasification step
- Syngas cleanup – balancing quality and cost
- Low hydrogen to CO ratio from biobased feedstocks
- Very high capital cost
- Economies of scale difficult based on low feedstock density

Gasification/FT-SPK Opportunities

- Uses waste feedstocks such as MSW, forest and agricultural residues that are available in large quantities
- One of the pathways that can produce very low carbon intensity SAF (>80% reduction)
- FT liquids can also be used in co-processing to lower infrastructure cost related to upgrading
- Current research focus on increasing the jet fraction (up to 70%) by catalyst improvement

Direct thermochemical liquefaction (HTL, Fast Pyrolysis, Catalytic pyrolysis) - Trends



- Technology still at various stages of technology readiness
- Ongoing work into upgrading of bio-oils/biocrudes into finished fuels
- Suitable as a biobased intermediate for co-processing in refineries
- HTL for SAF production very promising
- HTL can use niche feedstocks such as sewage sludge and other wet waste – HyFlexFuel project

Direct thermochemical liquefaction - Challenges

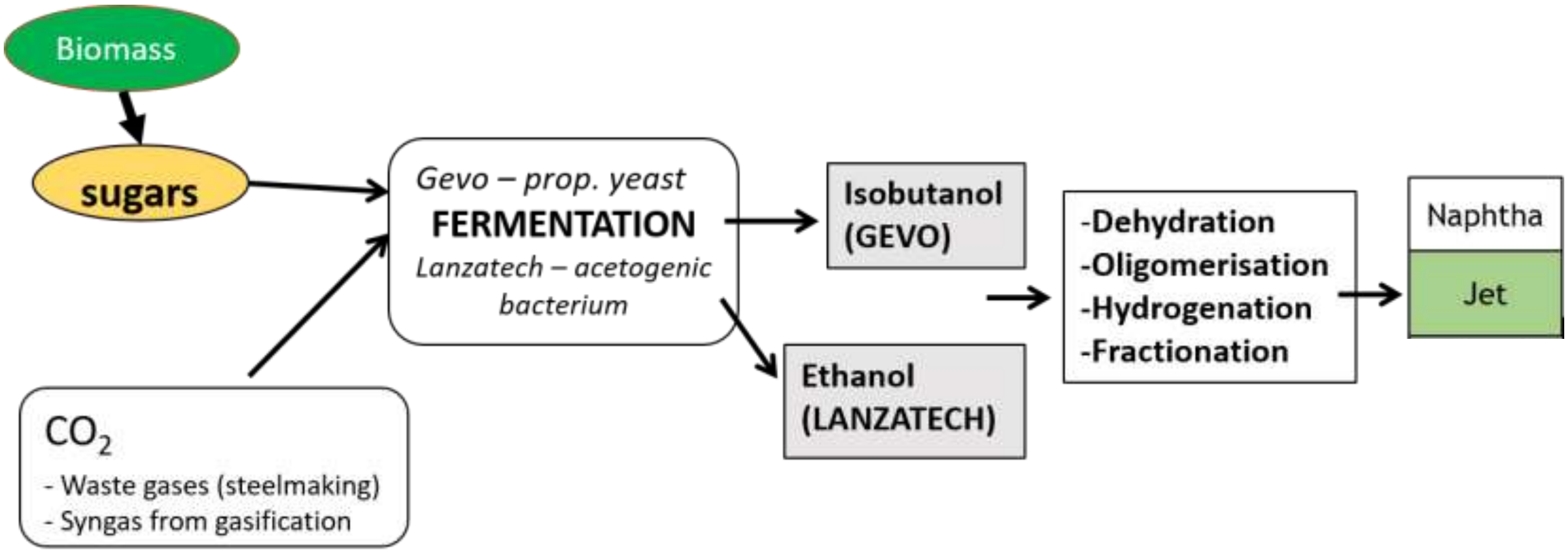
- Complexity of biocrudes & variation with type of feedstock
- Upgrading - technical challenges, catalyst inhibition, (e.g., cost and lifespan)
- High hydrogen requirement for upgrading (depending on oxygen content – ~45% in fast pyrolysis bio-oil)
- High N in biocrudes from algae

- No ASTM application in the pipeline
- Volume availability for testing
- SAF production possible but still needs extensive development

Direct thermochemical liquefaction - Opportunities

- Biocrude production is a form of densification of feedstocks that can be used in a distributed supply chain to deliver large volumes to a final upgrading facility
- Significant potential for co-processing in existing refineries to reduce investment costs in upgrading infrastructure
- Can utilise cheap, sustainable feedstock that is available in large volumes (residues)
- HTL can use a variety of wet feedstocks

Alcohol-to-jet (ATJ-SPK) - Trends



- Jet production step is fully commercial
- Isobutanol to jet currently delivering small commercial volumes
- First full-scale commercial facilities for multiple technologies under construction
- Can produce 70% jet fraction

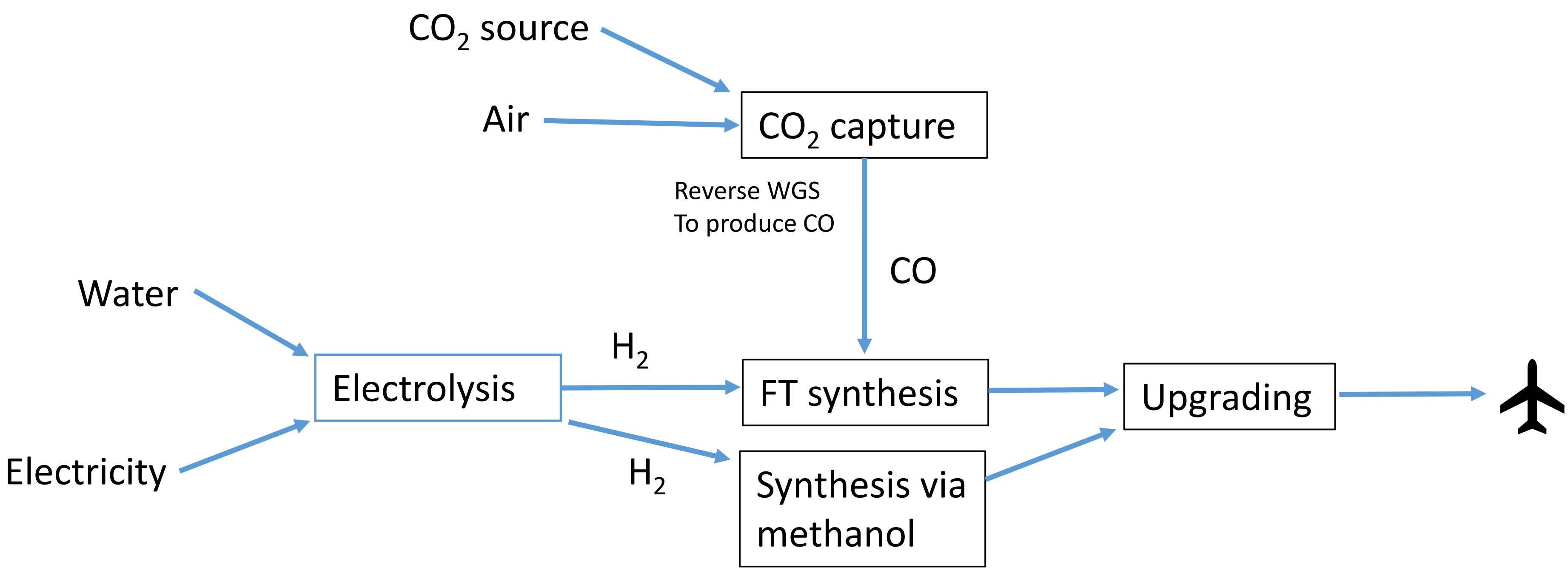
Alcohol-to-jet (ATJ-SPK) - Challenges

- Yields of alcohol can be low where novel organisms are used (compared to *Saccharomyces cerevisiae*)
- Butanol is toxic to the fermentation organism
- Cost of separation of alcohol from fermentation broth
- High value of alcohol intermediate for other applications such as chemical industry
- Use of cellulosic feedstocks for alcohol production has had limited success – projections for ATJ production from biomass are unrealistic
- Use of crop-based feedstocks such as corn easier and cheaper but more controversial (although possible to achieve low carbon intensity fuel)

Alcohol-to-jet (ATJ-SPK) - Opportunities

- Potential for reduced infrastructure cost as ethanol facilities can be repurposed and organisms substituted (e.g., for butanol)
- Genetic modification of strains for higher yields
- Potential to use low-cost waste gases for ethanol production
- High fraction achieved (70%)
- Established ATJ technology, but continued improvements being researched
- Reduction of ethanol-to-jet steps and cost is a research target
- ASTM certified for isobutanol and ethanol
- Combined with carbon capture and storage very low carbon intensity possible

Power-to-Liquids - Trends



- Significant interest – EU, Germany's PtL Roadmap
- Potential dedicated mandate for e-kerosene in the EU from 2030
- Germany funding $10 billion for hydrogen technology for PtL production
- High potential for net-zero with very limited land requirements

Power-to-Liquids - Challenges

- Currently one of the most expensive SAF pathways
- Sufficient and additional renewable energy for hydrogen production is essential to achieve real climate benefits – 100% renewable electricity grid
- Competition for renewable energy – heat, electricity, EVs
- PtL an inefficient way to use electricity – use of electricity for EVs 6x more efficient than e-fuel production
- Very high cost of direct air carbon capture
- Potential problem with point source capture and sustainability (double counting)
- Integrated pathway for e-fuel production still at early stage of development, although some parts are commercial

Power-to-Liquids - Opportunities

- Very significant emission reductions possible
- Theoretically unlimited potential as it does not use biomass feedstocks or need arable land, but sufficient renewable electricity could be limiting
- Could have “electricity grids” as partners with e-fuel as energy storage
- High potential for long-term cost improvements based on cheaper renewable electricity and technology improvements

Other technologies

- Farnesane SIP-SPK
  - Production of farnesene from sugar fermentation and upgrading
  - High value product in cosmetics, etc. and unlikely to be diverted into SAF
  - Very high cost of technology

- Catalytic hydrothermolysis (lipids)
  - ASTM certified and commercial facilities under development
  - Competition for feedstock with HEFA
  - Can produce SAF with aromatics

Conclusions

- HEFA is fully commercial and will continue to be the main technology for the next 10 years at least
- With limited investment all renewable diesel facilities can produce at least 15% biojet fraction or more
- Commercialization of ALL technologies should be pursued as they can utilize different feedstocks and take advantage of regional differences
- Technical challenges remain, but high price difference with conventional jet fuel remains the biggest obstacle
- Policies are essential and there is significant development on this front in the EU and USA that will have a major impact on SAF development
- Policies should be linked with carbon intensity of SAF
- SAF development is gaining momentum and there is a high level of optimism in the sector

Thanks!

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