Tuesday, 06. October 2026

Workshop 1: Sustainable Aviation Fuel Forum

World Ethanol & Biofuels by informa
6 - 8 October 2026
Madrid, Spain

EUROPEAN KEROSENE PRODUCTION TOWARDS COMPETITIVE SAF SUPPLY

Techno Economic and Environmental Assessment of SAF production

Ralph-Uwe Dietrich, Felix Habermeyer, Owais Khokar, Simon Maier, Moritz Raab, Janmejai Sharma, Julia Weyand (DLR e.V.)
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Decarbonising Europe's Aviation
Agenda

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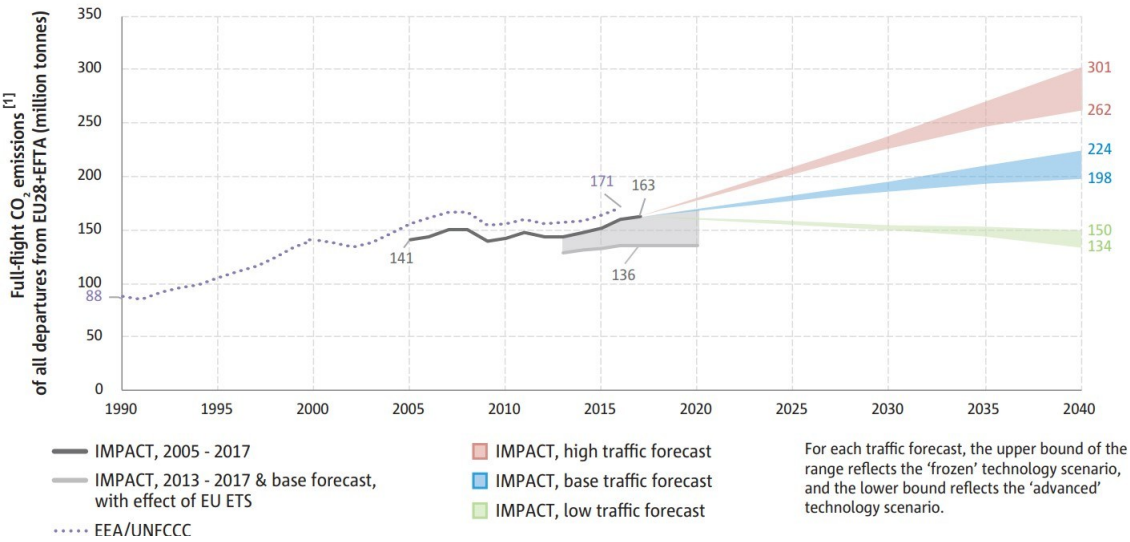
1. Demand and Supply: Certified Alternative Jet Fuels
2. European SAF Feedstocks
3. Technological readiness
4. European SAF roadmap
5. Conclusion and outlook

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EU aviation CO_2 emissions forecast



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[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf

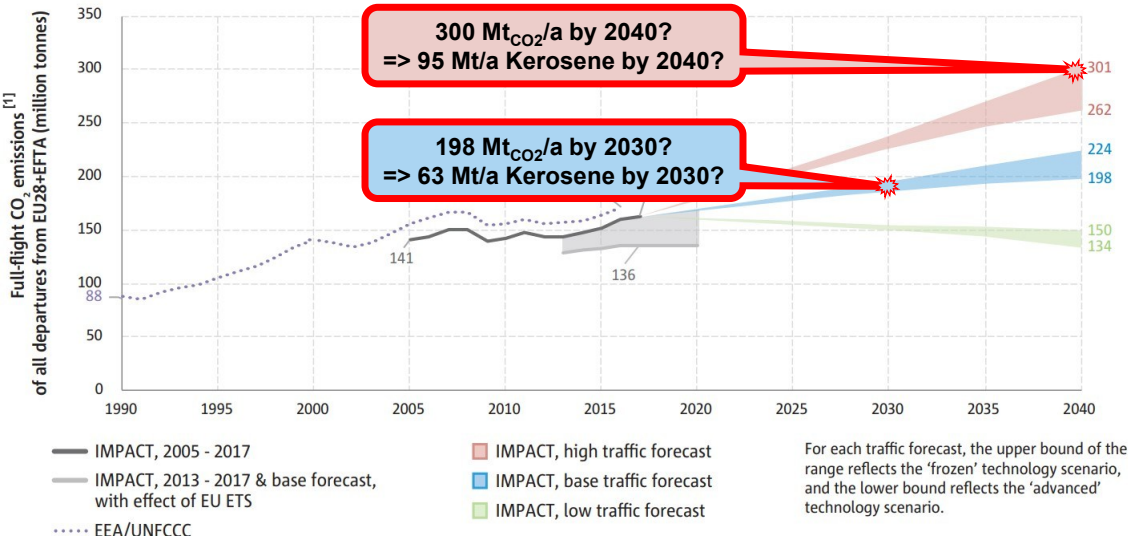
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EU aviation CO_2 emissions mitigation
Solution: SAF



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[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf

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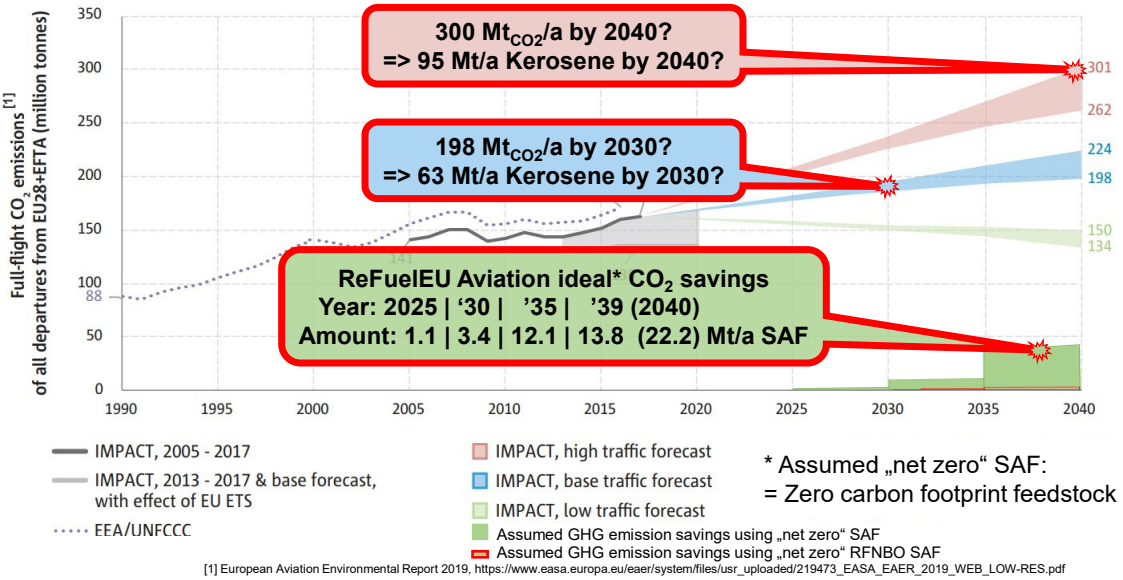
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EU aviation CO_2 emissions mitigation action

Solution: SAF ☞ ReFuelEU Aviation

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* Assumed „net zero" SAF:
= Zero carbon footprint feedstock

[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf

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Certified Alternative Jet Fuels
ASTM D7566 – 26 [1]



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Feedstock	Synthesis technology	Fuel	Blend
~~Coal, natural gas~~, biomass, municipal solid waste agricultural/forestry residues, CO_2 & H_2	Fischer-Tropsch (FT) synthesis → hydro-processing/isomerization → jet fraction	Synthetic paraffinic kerosene (FT-SPK)	≤ 50
Vegetable oils, animal fats, used cooking oil (UCO), other fatty-acid/ester feedstocks (e.g. algae)	hydrotreatment → deoxygenation → hydro-isomerization/hydrocracking → fractionation	Hydroprocessed esters and fatty acids (HEFA-SPK)	≤ 50
Sugar from Biomass	fermentation → hydrocarbons → hydrogenation → fractionation	Synthesized branched iso-paraffins (SIP, Farnesane)	≤ 10
Non-petroleum derived light aromatics (primarily benzene)	Blend aromatics produced by alkylation to FT-SPK	FT-derived synthetic kerosene + aromatics FT/SPK/A	≤ 50
Approved alcohol feedstocks such as ethanol, isobutanol, NEW 2026: work item **WK96698 - methanol to jet**	alcohol → dehydration → olefins → oligomerization → hydrogenation → fractionation	Alcohol-to-Jet synthetic paraffinic kerosene (ATJ-SPK)	≤ 50
Vegetable oils, animal fats, used cooking oil (UCO), other lipid feedstocks (e.g. algae)	Catalytic hydrothermal conversion → upgrading	Catalytic hydrothermolysis jet (CHJ)	≤ 50
Algae produced oil containing a high share of unsaturated hydrocarbons (botryococcenes)	Blend botryococcenes hydrocarbons (HC) prior to hydroprocessing esters and fatty acids (HC-HEFA)	Hydroprocessed HC, esters, fatty acids (HC-HEFA-SPK)	≤ 10
Any C2-C5 alcohols (individually or combined)	ATJ blended with nonaromatic components produced separately	Alcohol to Jet with Aromatics (ATJ-SKA)	≤ 50

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[1] ASTM International, „ASTM D7566-26 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2026

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Certified Alternative Jet Fuels
ASTM D7566 – 26 [1]: 1st generation jet fuels



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Certified Alternative Jet Fuels
ASTM D7566 – 26 [1]: 1st generation jet fuels

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Feedstock	Synthesis technology	Fuel	Blend
~~Coal, natural~~ waste agric			≤ 50
Vegetable (UCO), othe algae)			≤ 50
Sugar from			≤ 10
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Any C2-C5 alcohols (individually or combined)	ATJ blended with nonaromatic components produced separately	Alcohol to Jet with Aromatics (ATJ-SKA)	≤ 50

European deployment of 1st generation jet fuels questionable due to:

- Direct competition with food markets
- Low area-related energy yields and limited cultivation area
- Low technical development potential

➔ **HEFA feedstock detailed assessment**

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[1] ASTM International, „ASTM D7566-26 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2026

Certified Alternative Jet Fuels
ASTM D7566 – 26 [1]: power-based jet fuels

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Feedstock	Synthesis technology	Fuel	Blend
~~Coal, natural gas~~, biomass, municipal solid waste agricultural/forestry residues, CO_2 & H_2	Fischer-Tropsch (FT) synthesis → hydro-processing/isomerization → jet fraction	Synthetic paraffinic kerosene (FT-SPK)	≤ 50
Vegetable oils, animal fats, used cooking oil (UCO), other algae)	hydrotreatment → deoxygenation → hydro-	Hydroprocessed esters and	≤ 50
Sugar from			≤ 10
Non-petrole (primarily b			≤ 50
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Any C2-C5 alcohols (individually or combined)	ATJ blended with nonaromatic components produced separately	Alcohol to Jet with Aromatics (ATJ-SKA)	≤ 50

European deployment of power-based jet fuels questionable due to:

- High demand of renewable electricity
- prevention through RFNBO regulation
- structural cost disadvantage

➔ **Methanol-to-jet detailed assessment**

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[1] ASTM International, „ASTM D7566-26 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2026

Certified Alternative Jet Fuels (SAF)
ASTM D7566 – 26 [1]: Power+Biomass based

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Feedstock	Synthesis technology	Fuel	Blend
biomass, municipal solid waste agricultural/forestry residues, CO_2 & H_2	**Fischer-Tropsch (FT) synthesis → hydro-processing/isomerization → jet fraction**	Synthetic paraffinic kerosene (FT-SPK)	≤ 50
Vegetable oils, animal fats, used cooking oil (UCO), other fatty-acid/ester feedstocks (e.g. algae)	hydrotreatment → deoxygenation → hydro-isomerization/hydrocracking → fractionation	Hydroprocessed esters and fatty acids (HEFA-SPK)	≤ 50
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Approved al… ethanol, is… WK96698			≤ 50
Vegetable … (UCO), oth…			≤ 50
Algae proc… unsaturate…			≤ 10
Any C2-C5… combined)			≤ 50

European deployment of Fischer-Tropsch based Power+Biomass jet fuels :

- Combines sustainable biomass and renewable electricity generation
- Extends sustainable European forestry/pulp&paper industry towards fuel production
- Utilizes solely state-of-the art technology

➔ **Fischer-Tropsch based Power+Biomass SAF roadmap**
➔ **European regulation shall PROMOTE substantial SAF roll-out !!!**

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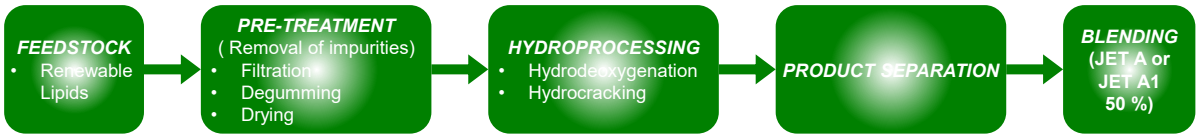
[1] ASTM International, „ASTM D7566-26 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2026



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Certified Alternative Jet Fuels
HEFA SAF certified ASTM D7566 – 26 [1]

Feedstock	Synthesis technology	Fuel	Blend
Vegetable oils, animal fats, used cooking oil (**UCO**), other fatty-acid/ester feedstocks (e.g. **algae**)	hydrotreatment → deoxygenation → hydro-isomerization/hydrocracking → fractionation	Hydroprocessed esters and fatty acids (HEFA-SPK)	≤ 50
Algae produced oil containing a high share of unsaturated hydrocarbons (botryococcenes)	Blend botryococcenes hydrocarbons (HC) prior to hydroprocessing esters and fatty acids (HC-HEFA)	Hydroprocessed HC, esters, fatty acids (HC-HEFA-SPK)	≤ 10



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HEFA SAF feedstock assessment[1]
Multiple sources – multiple issues

- Despite a long feedstock list:
  product quality, reliability, availability, sustainability, …?

Category	Feedstock	Source	Common Fatty Acids
Vegetable Oils	Soybean Oil	Soybean plant	Linoleic acid, Oleic acid
	Rapeseed (Canola Oil)	Canola plant	Oleic acid, Linoleic acid, Erucic acid
	Camelina Oil	Camelina plant	Linoleic acid, Oleic acid
	Palm Oil	Palm tree	Palmitic acid, Oleic acid
	Jatropha Oil	Jatropha plant	Oleic acid, Linoleic acid
Animal Fats	Tallow (Beef/Pork)	Cattle/Pigs,	Palmitic acid, Stearic acid
	Poultry Fat	Poultry (chickens, turkeys)	Palmitic acid, Oleic acid
	Lard	Pigs	Palmitic acid, Stearic acid
Used Cooking Oils (UCO)	Used Cooking Oils	Waste oils from restaurants, food processing	Linoleic acid, Oleic acid
Algal Oils	Algae Oils	Algae species (Eg.Chlorella ,Nannochlropsis etc.)	Omega-3 fatty acids (EPA/DHA), Oleic acid

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[1] Sharma J., et al. (2026).“The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment” (*Under Review*)

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	Poultry Fat	Poultry (chickens, turkeys)	Palmitic acid, Oleic acid
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Algal Oils	Algae Oils	Algae species (Eg.Chlorella ,Nannochlropsis etc.)	Omega-3 fatty acids (EPA/DHA), Oleic acid

Soybean, Palm and Jatropha Oil are not suitable for European SAF

Soybean and Palm oil:
- Palm fatty acid distillate, palm and soy-derived materials don't comply with sustainability and lifecycle emissions savings criteria, Article 29 of RED II

Jatropha:
- requires an agricultural production system to be established - unlikely

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	Camelina Oil		
	~~Palm Oil~~		
	~~Jatropha Oil~~		
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	Poultry Fat		
	Lard		
Used Cooking Oils (UCO)	Used Cooking Oils	Waste oils from restaurants, food processing	Linoleic acid, Oleic acid
Algal Oils	Algae Oils	Algae species (Eg.Chlorella ,Nannochlropsis etc.)	Omega-3 fatty acids (EPA/DHA), Oleic acid

1. European rapeseed oil:

PROS:
- High oil yield per hectare
- Low free fatty acid content suitable for hydro-processing.
- Rich in oleic acid (C_{18})

CONS:
- **Competing with food / road transport** (biodiesel)
- Under **RED II** but needs to scrutinized due intensive land use.
- Requires **hydrogen** and **catalysts** in refining → energy intensive.
- Lower GHG savings.

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[1] Sharma J., et al. (2026). "The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment" (*Under Review*)

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Category	Feedstock	Source	Common Fatty Acids
Vegetable	~~Soy~~ Oil		
	Rapeseed (Canola Oil)		
	Camelina Oil		
	~~Jatropha Oil~~		
Animal Fats	Tallow (Beef/Pork)		
	Poultry Fat		
	Lard		
Used Cooking Oils (UCO)	Used Cooking Oils	Wa	
Algal Oils	Algae Oils	(Eg.Chl	

2. *European camelina oil:*

PROS:
- **High lipid content** (~35–40%)
- **Good proportion of C_{16}/C_{18} fatty acids** – ideal for jet/diesel fuel
  Low sulfur and aromatic content – cleaner burn
- **Non-edible** – avoids food supply conflicts
- Supports **RED II**
- Drought resistant and sustainable as it aids in crop rotation.

CONS:
- **Scale**: Limited global production of Camelina
- **Hydrogen requirement**: HEFA needs high hydrogen input
- **Land Use**: Competes with other low-input crops for marginal lands

[1] Sharma J., et al. (2026). "The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment" (*Under Review*)

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HEFA SAF feedstock assessment[1]
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	Lard		
Used Cooking Oils (UCO)	Used Cooking Oils	Wa	
Algal Oils	Algae Oils	Algae species (Eg.Chlorella ,Nannochlropsis etc.)	Omega-3 fatty acids (EPA/DHA), Oleic acid

3. *European soybean oil:*

PROS:
- **Abundant and renewable**: Widely cultivated and processed globally.
- **Lipid content ≈20%:** suitable for conversion into hydrocarbon fuels.
- **Up to 80% GHG reduction** compared to conventional jet fuel.
- Biodegradable and non-toxic.

CONS:
- Land use concerns as it affects food prices and deforestation.
- Food vs Fuel Debate hence limited scalability.
- Large amount of hydrogen needed for processing.
- Allowed **only on marginal land** by **RED III** update
  ☞ The "Marginal Land" Allowance Escape Hatch

[1] Sharma J., et al. (2026). "The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment" (*Under Review*)

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Multiple sources – multiple issues

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Animal	Tallow (Beef/Pork)		
	Poultry Fat		
	Lard		
Used Cooking Oils (UCO)	Used Cooking Oils		
Algal Oils	Algae Oils	(Eg.C	

4. European animal fats:

PROS:
- **Waste-derived:** Utilizes by-products from meat processing industries.
- **Not food-competitive:** Unlike edible vegetable oils.
- Potential to have lower GHG emissions than fossil fuels.

CONS:
- Must meet **EU RED II** and **ICAO CORSIA sustainability** criteria.
- **Traceability** of the animal source **for certification**.
- **Availability & scale:** Limited supply compared to plant oils.
- **Higher sulfur and other contaminants** than vegetable oils.
- **Cold flow properties:** blending to meet aviation standards.

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[1] Sharma J., et al. (2026). "The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment" (*Under Review*)

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	Rapeseed (Canola Oil)		
	Camelina Oil		
	~~Jatropha Oil~~		
Animal	Tallow (Beef/Pork)		
	Poultry Fat		
	Lard		
Used Cooking Oils (UCO)	Cooking Oils		
Algal Oils	Algae Oils	(Eg.Chlorella ,Nannochlropsis etc.)	Oleic acid

5. European Used Cooking Oil (UCO):

PROS:
- **Sustainable:** Uses **waste oil** → **circular economy**
- **Low GHG**, 60-90% lower than fossil fuels
- **Drop-in fuel** compatibility.

CONS:
- **Limited supply:** UCO availability is finite and region-dependent.
- **Collection logistics:** Requires efficient infrastructure for sourcing.
- Variability in **feedstock quality** → process efficiency.
- **Severe import dependence and traceability fraud risk**

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HEFA SAF feedstock assessment[1]
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	~~Palm Oil~~ ~~Jatropha Oil~~		
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	Poultry Fat		
	Lard		
Used Cooking Oils (UCO)	Cooking Oils		
Algal	Algae Oils	Algae species (Eg.Chlorella ,Nannochlropsis etc.)	Omega-3 fatty acids (EPA/DHA), Oleic acid

6. Micro / Macro Algae:

PROS:
- High lipid yield (up to 50% dry weight).
- **Rapid growth** (up to double the volume in 24 hours)
- Utilizes wastewater or CO_2 ➔ **environmental remediation**

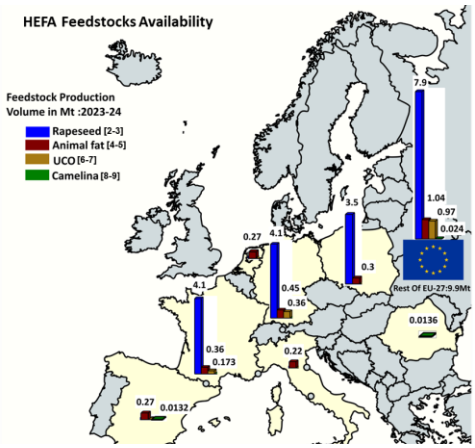
CONS:
- High cost of cultivation and harvesting.
- High energy input in drying and extraction.
- **Low maturity, scale-up issues** due infrastructure constrains.

[1] Sharma J., et … tatus of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment" (*Under Review*)

Realistic HEFA Feedstock Availability[1]

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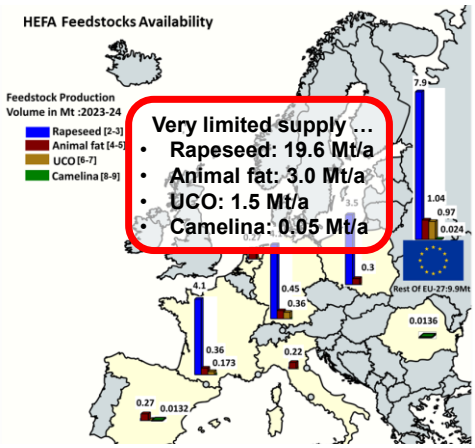


[1] Sharma J., et al. (under review). "The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment"
[2] F. A. S. U.S. Department of Agriculture. Rapeseed: Global production data, U.S. Department of Agriculture, Foreign Agricultural Service.https://www.fas.usda.gov/data/production/2226000
[3] R. Krautgartner et al., "Oilseeds and Products Annual," in "Global Agricultural Information Network," U.S. Department of Agriculture, Foreign Agricultural Service, Vienna, Austria,
[4] C. Malins, "The fat of the land: The impact of biofuel demand on the European market for rendered animal fats," Cerulogy, United Kingdom, Report 2023/05 2023.
[5] European Fat Processors and Renderers Association. (2024, June). EU-27 rendering statistics – 2023 results EFPRA Congress 2024, Amsterdam.
[6] ICCT working paper EU Waste-Oil Feedstock Availability (updated 13 Feb 2025) (ICCT)
[7] A. Stratas, "UCO Imports: Unfair Competition with EU UCO Industry?," Transport & Environment, Brussels, Belgium, Report 2024/06/11 2024
[8] Zanetti, F., et al. (2024). The opportunities and potential of camelina in marginal land in Europe. "Industrial Crops & Products", 198, 115834.

Realistic HEFA Feedstock Availability[1]



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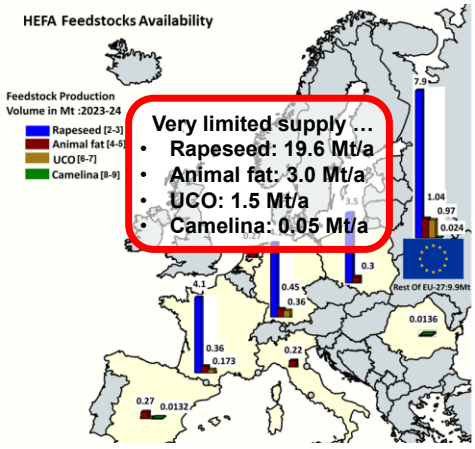


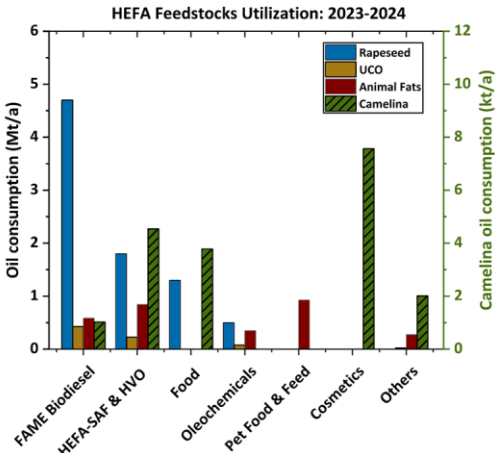
[1] Sharma J., et al. (under review). "The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment"
[2] F. A. S. U.S. Department of Agriculture. Rapeseed: Global production data, U.S. Department of Agriculture, Foreign Agricultural Service.https://www.fas.usda.gov/data/production/2226000
[3] R. Krautgartner et al., "Oilseeds and Products Annual," in "Global Agricultural Information Network," U.S. Department of Agriculture, Foreign Agricultural Service, Vienna, Austria,
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[5] European Fat Processors and Renderers Association. (2024, June). EU-27 rendering statistics – 2023 results EFPRA Congress 2024, Amsterdam.
[6] ICCT working paper EU Waste-Oil Feedstock Availability (updated 13 Feb 2025) (ICCT)
[7] A. Stratas, "UCO Imports: Unfair Competition with EU UCO Industry?," Transport & Environment, Brussels, Belgium, Report 2024/06/11 2024
[8] Zanetti, F., et al. (2024). The opportunities and potential of camelina in marginal land in Europe. *Industrial Crops & Products*, 198, 115834.

Realistic HEFA Feedstock Availability[1]



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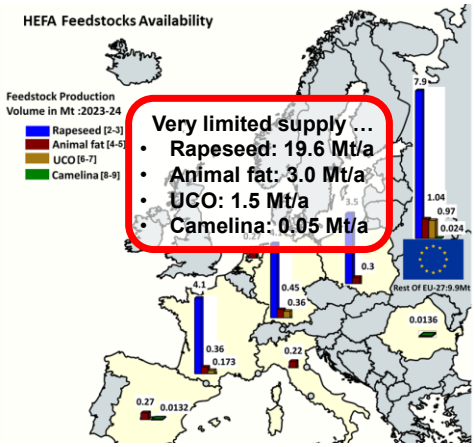
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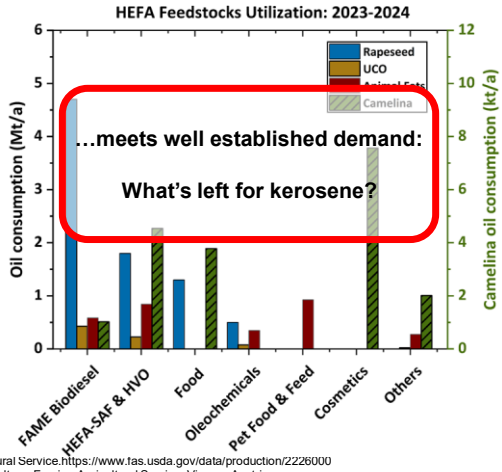
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Realistic HEFA Feedstock Availability[1]

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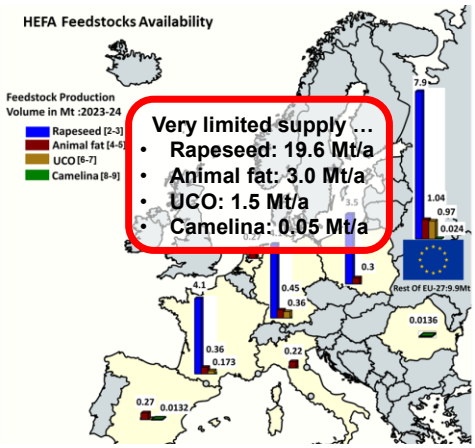
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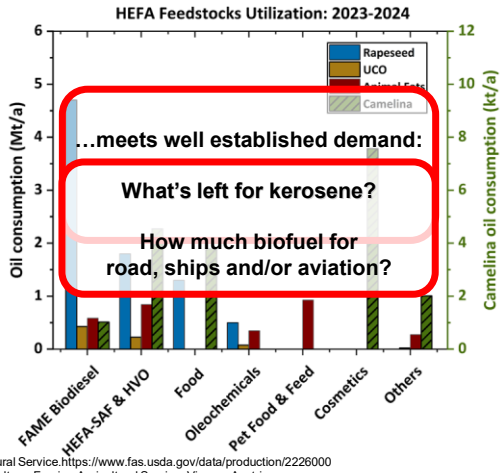
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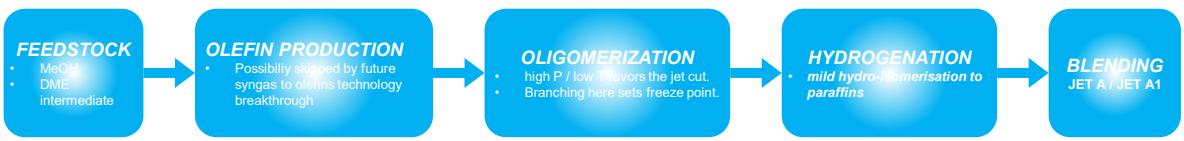
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Power-based jet fuels (e-SAF)
Methanol-to-jet as the new prodigy?



DLR

Feedstock	Synthesis technology	Fuel	Blend
Approved alcohol feedstocks such as ethanol, isobutanol, NEW 2026: work item **WK96698 - methanol to jet**	dehydration → olefins → oligomerization → hydrogenation → fractionation	Alcohol-to-Jet synthetic paraffinic kerosene (ATJ-SPK)	≤ 50



- Methanol as educt with versatile use cases
  → Potential lower investment risk **– really?**

28

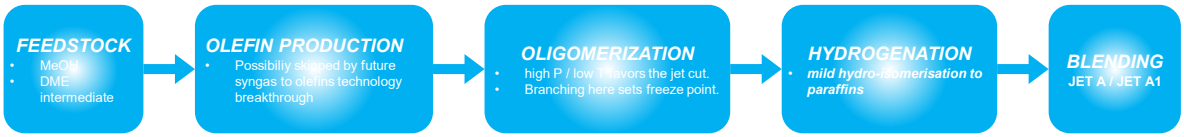
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29

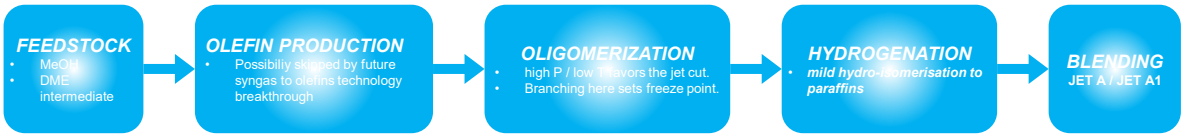
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- Methanol as educt with versatile use cases
  → Potential lower investment risk **– really?**
- Process configuration allows jet fuel-like product composition (aromatics included)
- High product efficiency (> 70% SAF from MeOH), **– higher than Fischer-Tropsch?**
- New MeOH-to-SAF certification procedure achieved

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European e-SAF Feedstock Supply
Feedstock 1: Renewable Electricity (RE)

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Energy Source	Supply 2024 (TWh) [2]	LCOE ($€_{2023}$/MWh) [3]	GWP ($g_{CO_2\text{-eq.}}$/kWh) [4,5]
Wind	39.1% (~450)	30–100	7–56
Hydropower	29.9% (~350)	25–250	1–22
Solar	22.4% (~260)	40–150	7–180
Bioenergy	8.1% (~94)	50–215	0–420
Geothermal	0.5% (~6)	50–85	6–79

[1] https://solida.com.es/en/47-of-europes-electricity-was-generated-from-renewables-in-2024/
[2] https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250319-1
[3] https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023
[4] https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf#page=7
[5] https://www.nrel.gov/docs/fy21osti/80580.pdf

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European e-SAF Feedstock Supply
Feedstock 1: Renewable Electricity (RE)



DLR

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- RE generation in Europe in 2024: 1,160 TWh [1] (≙ 90 $Mt_{e\text{-}MeOH}$/a)
- Levelized Cost of RE ($LCOE_{RE}$) in Europe: ~ 71 $€_{2023}$/MWh (☞ ca. 1.10 $€_{RE}/kg_{e\text{-}MeOH}$)
- Climate change impact (GWP) of RE in Europe: ~ 33 $g_{CO_2\text{-eq.}}$/kWh (☞ ca. 0.39 $kg_{RE\text{-}CO_2\text{-eq.}}/kg_{e\text{-}MeOH}$)

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[3] https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023
[4] https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf#page=7
[5] https://www.nrel.gov/docs/fy21osti/80580.pdf

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European e-SAF Feedstock Supply
Feedstock 2: CO_2 – Industrial Sources & DAC



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- Industrial Point Source – not stable, variable composition

Availability (Mt/a) [1]	Cost (€$_{2019}$/t) [2]	Climate change impact ($g_{CO_2\text{-eq.}}$/kg)
663	28−45	2.3−21.8* 0.07−0.66 kWh/kg_{CO_2} [4]

Constraint: Industrial CO_2 will decrease in future with EU's decarbonisation targets

- Atmospheric CO_2 (DAC)

Availability (Mt/a)	Cost (€$_{2021}$/t) [3]	Climate change impact ($g_{CO_2\text{-eq.}}$/kg)
unlimited	350−600	10−28* 0.3−0.85 kWh/kg_{CO_2} [5]

[1] Eurostat: https://ec.europa.eu/eurostat/databrowser/view/env_ac_ainah_r2/default/table?lang=en
[2] IEAGHG (2019): https://ieaghg.org/publications/co2stcap-cutting-cost-of-co2-capture-in-process-industry/
[3] IEAGHG (2021): https://ieaghg.org/publications/global-assessment-of-direct-air-capture-costs/
[4] IEAGHG (2010): https://ieaghg.org/publications/environmental-evaluation-of-ccs-using-life-cycle-assessment-lca/
[5] IEA (2022): https://www.iea.org/reports/direct-air-capture-2022

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* With RE CC impact from previous slide

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European e-SAF Feedstock Supply
Feedstock 3: Water for electrolysis



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$$2H_2O(l) \rightarrow 2H_2(g) + O_2\,(g), \qquad 8\,kg_{H_2O}/kg_{H_2}$$

EU renewable hydrogen target (by 2030)[1]: 10 Mt_{H2}/a

➢ ~90 million m³/a deionized water

Availability (billion m³/a) in 2020 [2]	Price (€/m³) [3]	Climate change impact ($g_{CO_2\text{-eq.}}$/m³)
2000 (freshwater)	0.005−0.7 (freshwater)	6.6−13.2* (freshwater) 82.5−221* (seawater) 0.2−0.4 kWh/m³ [4] (freshwater) 2.5−6.7 kWh/m³ [4] (seawater)

Constraints:
- Competing uses
- Regional scarcity (e.g. high water stress in Southern Europe)

[1] https://observatory.clean-hydrogen.europa.eu/eu-policy/repowereu
[2] https://water.europa.eu/freshwater/europe-freshwater/freshwater-themes/water-resources-europe?utm_source=chatgpt.com
[3] EEA(2013): https://op.europa.eu/en/publication-detail/-/publication/915da975-1452-427a-9949-ef09348c6b41/language-en
[4] Kim et al. (2019): https://doi.org/10.1016/j.apenergy.2019.113652

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* With RE CC impact from previous slide



FT-KEROSENE FROM WASTE WOOD (PBTL)

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SAF options: Why Fischer-Tropsch?

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Feedstock availability towards 63 Mt/a

Feedstock	Synthesis technology	Fuel
~~Coal, natural gas~~, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis using Fe or Co catalyst,	Synthetic paraffinic kerosene (FT-SPK)

- Feedstock
  - Synthesis gas available from almost any carbon and hydrogen source ➔ Sustainability?
    - European wind power potential[1] for **sustainable H**:
      12,200 – 30,400 TWh_e **≈ 10 - 20 times of SAF demand!**
    - Annual sequestration of carbon in European forest biomass[2] for **sustainable C**:
      155 Mt/a **≈ 3 times of SAF demand!**

[1] European Environment Agency, "Europe's onshore and offshore wind energy potential," 2009
[2] FOREST EUROPE, 2020: State of Europe's Forests 2020

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SAF options: Why Fischer-Tropsch?



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- FT synthesis
  - Large scale, commercial technology
    - Secunda CTL (Sasol): ca. 7 Mio.t/a – since 1980/1984
    - Pearl GTL (Qatar Petroleum + Shell): ca. 6 Mio.t/a – since 2011

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- Fuel
  - Fully synthetic kerosene achievable [3]

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[2] FOREST EUROPE, 2020: State of Europe's Forests 2020
[3] UK Ministry of Defense, „DEF STAN 91-91: Turbine Fuel, Kerosene Type, Jet A-1", UK Defense Standardization, 2011

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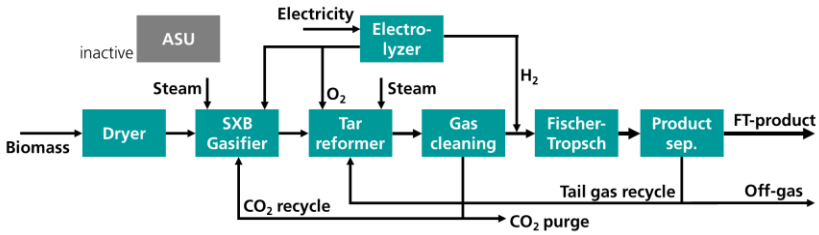
FT-based PBtL conversion pathway
Power&Biomass-to-Liquid technology

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❑ **PBtL** consists of **"fully commercial" (TRL 9)** process units.

- Deployment at commercial scale underway / in planning [1].



[1] IEA Bioenergy Task 39 (2024) Progress in Commercialization of Biojet/ SAF- https://www.ieabioenergy.com/wp-content/uploads/2024/06/IEA-Bioenergy-Task-39-SAF-report.pdf.

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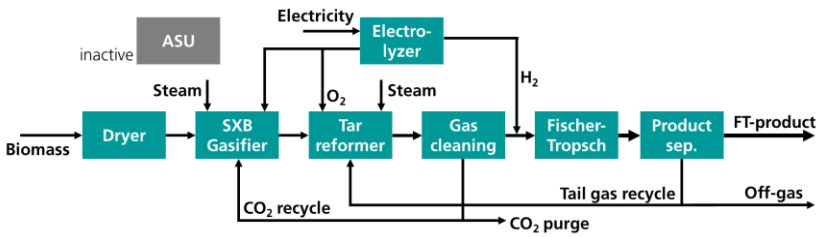
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❑ **Feedstock:** forestry / agricultural residues, waste wood ➔ limited competition

- Product: up to 50 % bio-SAF and 50 % RFNBO
  ➔shows the artificial and missleading distinction between bio/non-bio

[1] IEA Bioenergy Task 39 (2024) Progress in Commercialization of Biojet/ SAF- https://www.ieabioenergy.com/wp-content/uploads/2024/06/IEA-Bioenergy-Task-39-SAF-report.pdf.
[2] The BioTJet project. https://elyse.energy/en/our-projects/biotjet
[3] F. DURAN MARTINEZ (2025) *BioTJet project – The first-of-a-kind industrial e-BtL plant*. Towards Sustainable Aviation Summit - TSAS2025, Toulouse, France

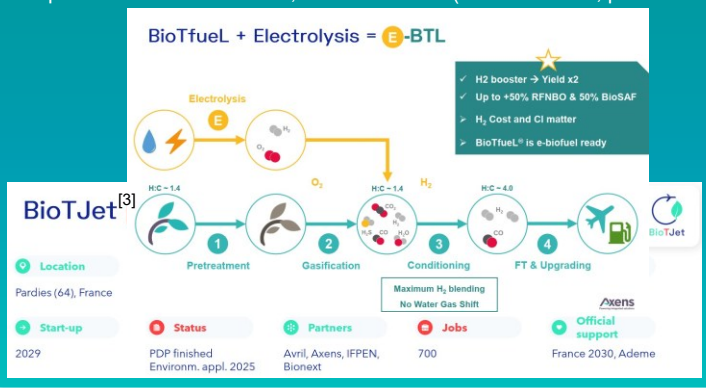
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FT-based PBtL conversion pathway
Power&Biomass-to-Liquid technology

❑ **PBtL** co

- Deploym

- First commercial FT-based production plants under construction [2] / pre FID
- Plant operation risk not technical, but commercial (feedstock cost, product offtake)



❑ **Feedst** ition

- Product:
  ➔shows t

[1] IEA Bioenergy Task 39 (2024) Progress in Commercialization of Biojet/ SAF- https://www.ieabioenergy.com/wp-content/uploads/2024/06/IEA-Bioenergy-Task-39-SAF-report.pdf.
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European FT-based PBtL Feedstock Supply
Feedstock 3a: Forestry waste

Forestry residues are the **leftover materials generated during forest management activities**, such as logging, thinning, and pruning:

- Tree tops and branches
- Bar
- Stumps and roots
- Sawdust and woodchips

Availability (PJ) [1]	Price (€$_{2010}$/GJ) [1]	Climate change impact ($g_{CO_2\text{-eq.}}$/kg) [2]
5601	0–12.7 (Ø 3.3)	8–60

[1] Ruiz et al. (2019): ENSPRESO database (ENS_Med, 2020). http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f
[2] Wernet et. al (2016): The ecoinvent database version 3.11. https://doi.org/10.1007/s11367-016-1087-8

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DLR

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5601	0–12.7 (Ø 3.3)	8–60

Constraints:

- Soil health degradation
- Biodiversity impact
- Erosion risk
- Competing uses

43 [1] Ruiz et al. (2019): ENSPRESO database (ENS_Med, 2020). http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f
[2] Wernet et. al (2016): The ecoinvent database version 3.11. https://doi.org/10.1007/s11367-016-1087-8

European FT-based PBtL Feedstock Supply
Feedstock 3b: Lignin from pulp mill



DLR

Lignin is extracted as a by-product from the pulping process and conventionally burned for electricity generation – easy to use for SAF, but limited amount

Availability (Mt/a) [1]	Price (€$_{2015}$/t) [2]	Climate change impact ($g_{CO_2\text{-eq.}}$/kg) [3]
1.7–2.8	50–750	0–400

- Price strongly dependent on required lignin purity
- Allocation method for pulp mill process is crucial factor for determining lignin's climate change impact

44 [1] Adelung et al. (2022): Deliverable 2.11: Public report on the marketability of the ABC-SALT middle distillates biofuels
[2] Ľudmila et. al (2015): Lignin, potential products and their market value (http://www.woodresearch.sk/wr/201506/13.pdf)
[3] Hermannson et al. (2020): Allocation in life cycle assessment of lignin. https://doi.org/10.1016/j.jcis.2004.08.101

European FT-based PBtL Feedstock Supply
Feedstock 3b: Lignin from pulp mill



DLR

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Availability (Mt/a) [1]	Price (€$_{2015}$/t) [2]	Climate change impact ($g_{CO_2\text{-eq.}}$/kg) [3]
1.7–2.8	50–750	0–400

- Price strongly dependent on required lignin purity
- Allocation method for pulp mill process is crucial factor for determining lignin's climate change impact

Constraints:

- Depolymerisation challenging due to lignin's high natural complexity
- Loss in electricity generation at pulp mill

45

[1] Adelung et al. (2022): Deliverable 2.11: Public report on the marketability of the ABC-SALT middle distillates biofuels
[2] Ľudmila et. al (2015): Lignin, potential products and their market value (http://www.woodresearch.sk/wr/201506/13.pdf)
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European FT-based PBtL Feedstock Supply
Feedstock 3c: Agricultural residues



DLR

Agricultural residues are the **remnants of crops and other plant material left over after harvesting or processing agricultural products:**

- Field residues – Left in the field after harvesting, such as stalks, straw, leaves, and husks.
- Processing residues – Generated during the processing of crops, such as husks, shells, pulp, and bagasse.

Availability (PJ) [1]	Price (€$_{2010}$/GJ) [1]	Climate change impact ($g_{CO_2\text{-eq.}}$/kg) [2]
2637	0–13.7 (Ø 3.4)	14.7–123

46

[1] Ruiz et al. (2019): ENSPRESO database (ENS_Med, 2020). http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f
[2] Wernet et. al (2016): The ecoinvent database version 3.11. https://doi.org/10.1007/s11367-016-1087-8

European FT-based PBtL Feedstock Supply
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Constraints:

- Soil health degradation
- Competing uses
- Seasonal production

47

[1] Ruiz et al. (2019): ENSPRESO database (ENS_Med, 2020). http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f
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FT-BASED PBTL TECHNOLOGY READINESS

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Biomass Gasifier TRL
derived from multiple coal gasification

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Over 100 Gasifiers designed, built and put into successful operation by Uhde since 1941 [1]







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[1] Dr. Alexander Schulz, Green methanol, part of Uhde's green technologies, Aachen, 13.09.2022

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Electrolyser TRL
State-of-the-art / GW installations

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thyssenkrupp is No.1 electrolysis supplier for industr [1]

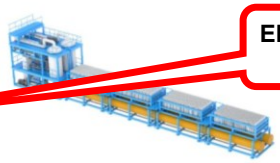
10 Gigawatt
installed Power (Chlor-alkali electrolysis)

50 years
expertise in design, construction and operation

> 1 Gigawatt
of water electrolysis equipment capacity can be manufactured in Germany

> 600
installed capacity worldwide (chlor-alkali electrolysis)

Alkaline water electrolyser module with capacity of 4,000 Nm^3/h H_2



Electrolysis technology: state-of-the-art

50

[1] thyssenkrupp nucera(2026) Success Factors of GW Systems: https://www.new-era-insights.com/article/alkaline-water-electrolysis-enabling-an-industrial-scale-green-energy-transformation

Electrolyser TRL
State-of-the-art / GW installations

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[1]

GW scale electrolysis is common in Chlorine industry

[2]

Location	Country	Operator	Capacity Chlorine (in 1000 t)	Diaphrag.	Membr.	Other	Electrolys. D MW	Electrolys. M MW
		w	1624	1024	600		**2.970**	**1.560**
		ncorn MCP	430		430			**1.118**
					637			**1.656**
		ovestro	480		400	80[5		**1.040**
Lillo	BE	INNOVIN	500		500			**1.300**
Tessenderlo	BE	Inovyn (INEOS)	400		400			**1.040**
Ludwigshafen	GER	BASF	595					**0**
Leverkusen	GER	Covestro	390		390			**1.014**
Lavera	FR	Kem One	341	341			**989**	**0**
Tavaux	FR	INNOVIN	370		370			**962**
Fos	FR	Kem One	333	178	155		**516**	**403**
Kazincbarcika	HUN	BorsodChem	480	384	96		**1.114**	**250**
Uerdingen	GER	Covestro	290		290			**754**
Marl	GER	Vestolit	260		260			**676**
Rafnes (Bamble)	NOR	Inovyn (INEOS)	315		315			**819**
Schkopau	GER	Dow	252		252			**655**
Knapsack	GER	Westlake Vinnolit	250		250			**650**
Rheinberg	GER	Inovyn (INEOS)	220	110	110		**319**	**286**

[1] thyssenkrupp nucera(2026) Success Factors of GW Systems: https://www.new-era-insights.com/article/alkaline-water-electrolysis-enabling-an-industrial-scale-green-energy-transformation

[2] Eurochlor: Chlorine Industry Review 2021-2022, www.chlorineindustryreview.com

Fischer-Tropsch TRL
State-of-the-art / refinery size proven

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[1] https://alfin2300.blogspot.com/2011/11/gas-to-liquids-carbon-sciences-provides.html

TRL discussion summary



DLR

Process De-Risking?

- All necessary units are state-of-the-art (except DAC, but not relevant)
- Chemical engineering can build ANY optimal process for ANY purpose
  - Entire refineries have been built on valid process simulation
  - Clever process engineering / procurement required – failures happen

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TRL discussion summary



DLR

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Business Case Constraints?

- Separate refinery business from oil exploration business
  - Take oil margin for SAF investment?
- Demand risk: Penalty for airlines acceptable? 30 % of flight prices from fuels

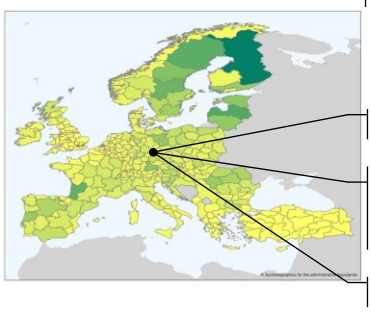


Local PBtL production potential [1]
TEPET linked to Aspen Plus

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For feedstock potential: TEEA for 300 NUTS2 regions



Biomass density[2]:
(⅓ of primary forest residue*)
+Transport distance

Local labour cost[3]

National grid:
- Price[4]
- GHG footprint[5]

Biomass price[2]

Key economic assumptions: see [1]

*Only **primary forest residue** considered

- branches, tops, other parts of trees not used for timber or pulp
  MINBIOFSR1(2030)ENS_LOW[2]:
  990 PJ (62 Mt/a)
- residues from landscape care, to be sustainably collected without adversely affecting soil quality, biodiversity, other ecological functions
  MINBIOFSR1a(2030)ENS_LOW[2]:
  157 PJ (10 Mt/a)
- **secondary residues excludes**, e.g. from the wood processing industry

[1] Habermeyer et. Al (2023) Sustainable aviation fuel from forestry residue and hydrogen. A techno-economic and environmental analysis for an immediate deployment of the PBtL process in Europe. *Sustainable Energy and Fuels*, doi: 10.1039/d3se00358b.
[2] dataset codes **MINBIOFSR1** and **MINBIOFSR1a**, excluding secondary residues from: Ruiz, P., et al. (2019). **ENSPRESO** - an open, EU-28 wide, transparent and coherent **database** of wind, solar and biomass energy potentials *Energy Strategy Reviews*, *26*, 100379.
[3] Eurostat. (2021). Labour cost levels by NACE Rev. 2 activity (Online) https://ec.europa.eu/eurostat/databrowser/product/page/LC_LCI_LEV$DEFAULTVIEW [Accessed 19.01.2022]
[4] Eurostat. (2021). Electricity prices for non-household consumers - bi-annual data (Online) http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do [Accessed 19.01.2022]
[5] European Energy Agency, Greenhouse gas emission intensity of electricity generation by country 2022 [cited 2022 31.1];
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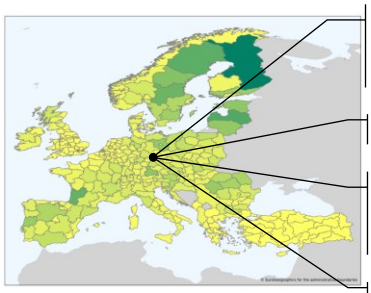
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NUTS2 regions specific results:

Local fuel production cost

Local fuel production GWP

Key economic assumptions: see [1]

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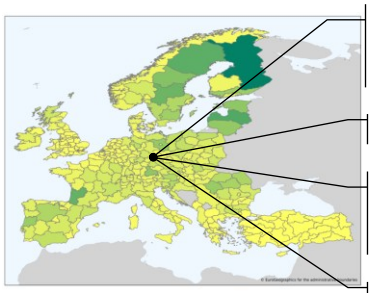
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Local PBtL production potential [1]
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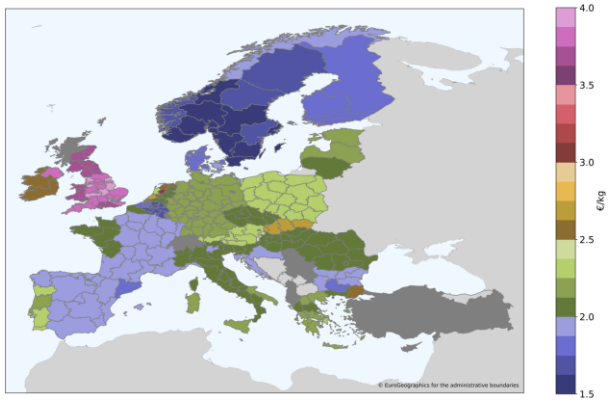
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PBtL potential for Europe [1]
Grid based PBtL: Northern Europe

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Net production cost [€$_{2020}$/kg$_{C5+}$]:



Net Production cost

\+ Abundant cheap woody biomass and low carbon electricity in Scandinavia

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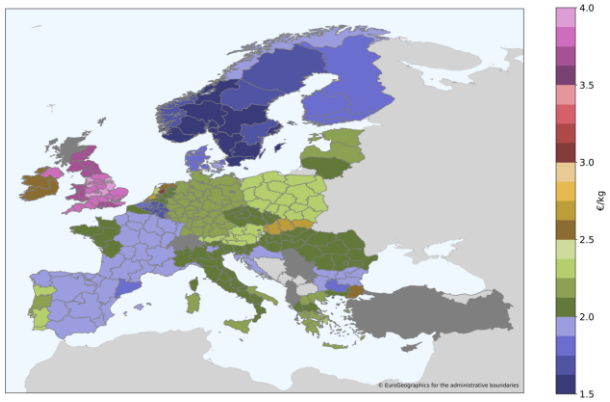
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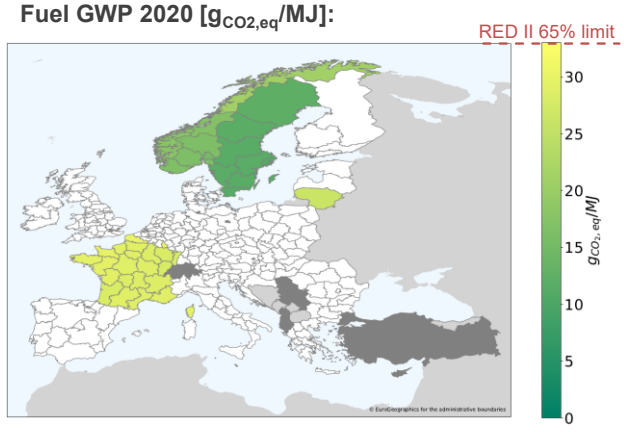
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Net production cost [€$_{2020}$/kg$_{C5+}$]:



Fuel GWP 2020 [g$_{CO2,eq}$/MJ]:



Net Production cost

\+ Abundant cheap woody biomass and low carbon electricity in Scandinavia

Greenhouse Gas Abatement

– High carbon footprint of electricity prevents power-based SAF production in most European countries

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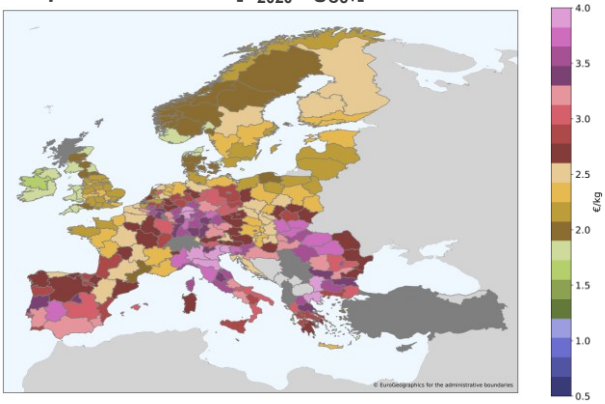
PBtL potential for Europe [1]
On-shore wind PBtL: Costal regions

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Hydrogen storage included:

Net production cost [€$_{2020}$/kg$_{C5+}$]:



Net Production cost

\+ High full load hours of wind power required

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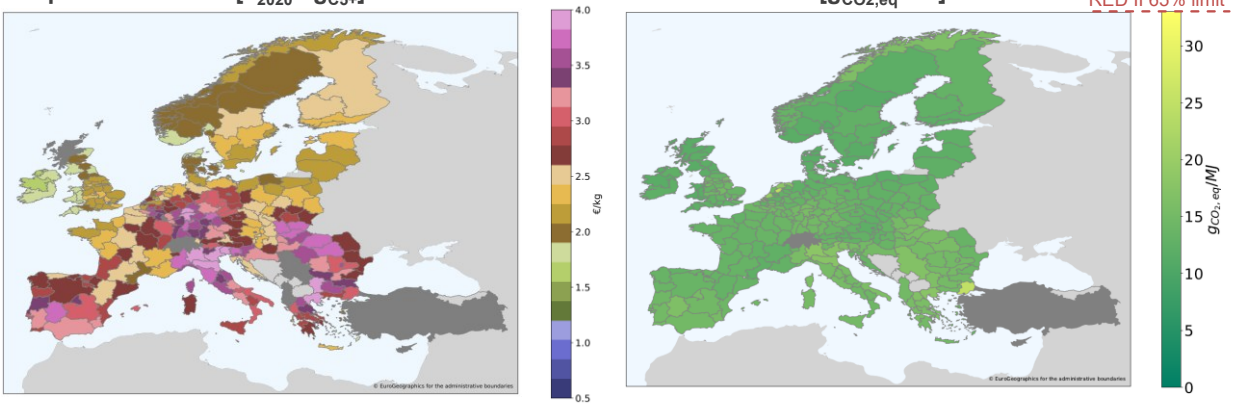
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Hydrogen storage included:

Net production cost [€$_{2020}$/kg$_{C5+}$]:

Fuel GWP 2020 [$g_{CO2,eq}$/MJ]:



Net Production cost

\+ High full load hours of wind power required

Greenhouse Gas Abatement

– No Net Zero SAF anywhere
\+ Wind power based SAF well within RED II

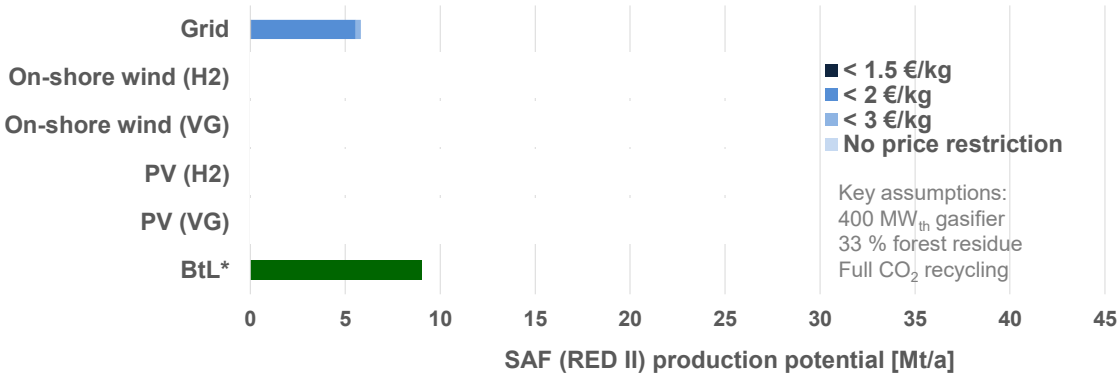
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PBtL potential for Europe
Aggregated SAF potential



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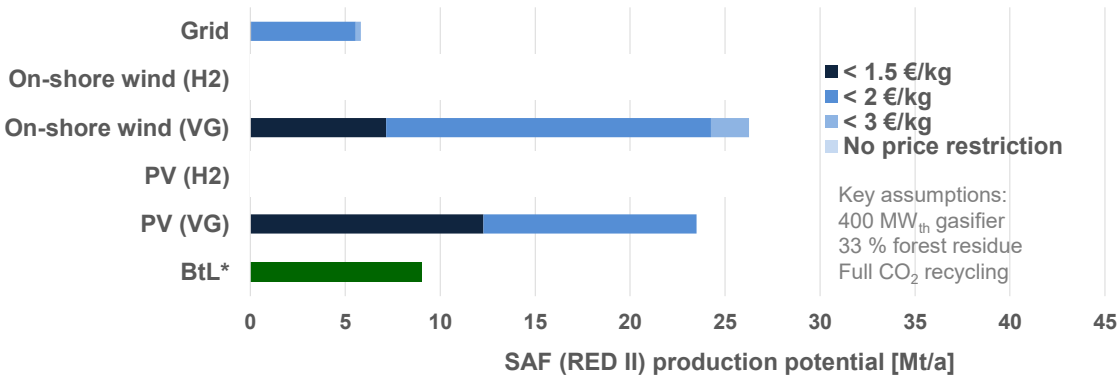
*Assumptions: 19.9 % biomass conversion, entire potential under RED II limit

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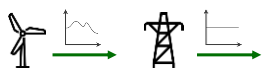
PBtL potential for Europe
Aggregated SAF potential



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Virtual grid (VG)

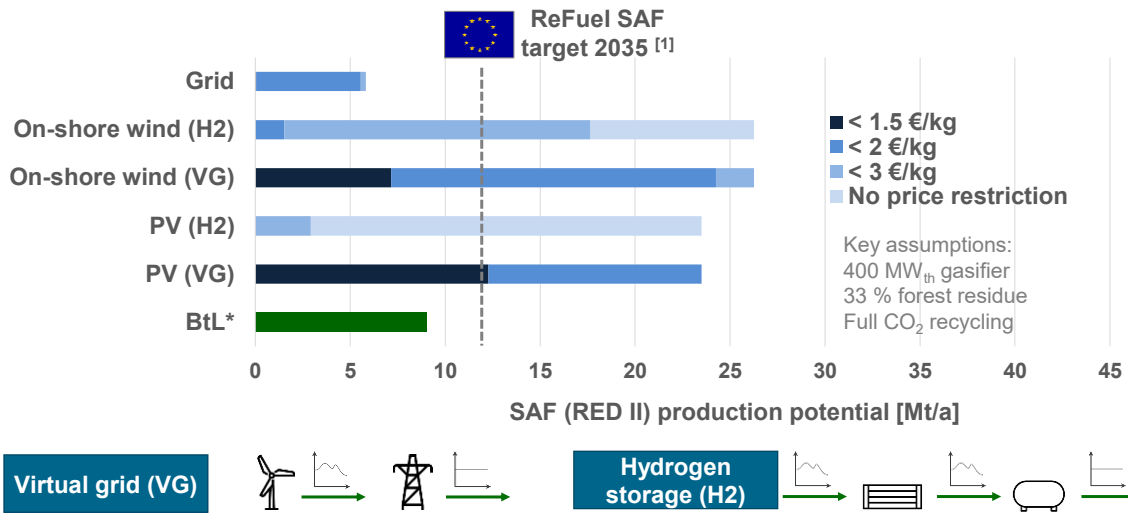


64

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PBtL analysis for Europe
Aggregated SAF potential



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[1] ReFuelEU Aviation. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R2405&qid=1740131530166. From 1 January 2035, a minimum share of 20 % of SAF, of which a minimum share of 5 % of synthetic aviation fuels;

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SAF deployment plan for Europe
ReFuelEU Aviation: too little too late

EUROPEAN COMMISSION

	ReFuelEU Aviation SAF targets [1]	ReFuelEU Aviation Synfuel target [1]
2025	2 % (≈ 1 Mt/a[2])	
2030	6 % (≈ 3.5 Mt/a[2])	1.2 % (≈ 0.7 Mt/a)
2035	20 % (≈ 12 Mt/a[2])	5 % (≈ 3.0 Mt/a)
2050	70 % (≈ 54 Mt/a[2])	35 % (≈ 27 Mt/a)

Compare with 3.4 Mt/a growth since 2020!

66

[1] https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/
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Preference on palm oil (UCO)? Not enough palm oil on earth!

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Paris 1.5 degree commitment intentionally violated!

68

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SAF deployment plan for Europe
Optimistic way forward (personal view)

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EUROPEAN COMMISSION

	ReFuelEU Aviation SAF targets [1]	ReFuelEU Aviation Synfuel target [1]	Ambitious, but realistic, just PBtL SAF
2025	2 % (≈ 1 Mt/a[2])		
2030	6 % (≈ 3.5 Mt/a[2])	1.2 % (≈ 0.7 Mt/a)	**10 Mt/a**
2035	20 % (≈ 12 Mt/a[2])	5 % (≈ 3.0 Mt/a)	**30 Mt/a**
2050	70 % (≈ 54 Mt/a[2])	35 % (≈ 27 Mt/a)	**75+ Mt/a = 100 %! (2045?)**

2025 proposal: Wait even longer?
25 plants across Europe á
- **3.3 GW Wind (5.0 b€) or 6.3 GW PV (5.0 b€) each**
- **FT plant 400 kt_{SAF}/a (1.5 b€) incl. 0.9 GW Electrolyzer**
- **Construction period: 2025 – 2028**
- **Full operation before 2030**

Total Investment?
- **less than 6 months of Europe's crude oil spending**
- **OPEX ➔ CAPEX**

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[1] https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/
[2] growth assumption aviation market 1.5% per annum (according to the International Civil Aviation Organization, ICAO, medium scenario)

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SAF deployment plan for Europe
Optimistic way forward (personal view)

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EUROPEAN COMMISSION

	ReFuelEU Aviation SAF targets [1]	ReFuelEU Aviation Synfuel target [1]	Ambitious, but realistic, just PBtL SAF
2025	2 % (≈ 1 Mt/a[2])		
2030	6 % (≈ 3.5 Mt/a[2])	1.2 % (≈ 0.7 Mt/a)	**10 Mt/a**
2035	20 % (≈ 12 Mt/a[2])	5 % (≈ 3.0 Mt/a)	**30 Mt/a**
2050	70 % (≈ 54 Mt/a[2])	35 % (≈ 27 Mt/a)	**75+ Mt/a = 100 %! (2045?)**

- **About 50 % SAF blending rate achievable with learning curve**
- **100 % SAF certification required for further growth**

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- **Backup, if H_2 aviation won't fly**
- **additional SAF routes / feedstocks from 2035 onwards? Or ➔ Less air traffic?**
- **How about climate neutrality by 2045?**

[1] https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/
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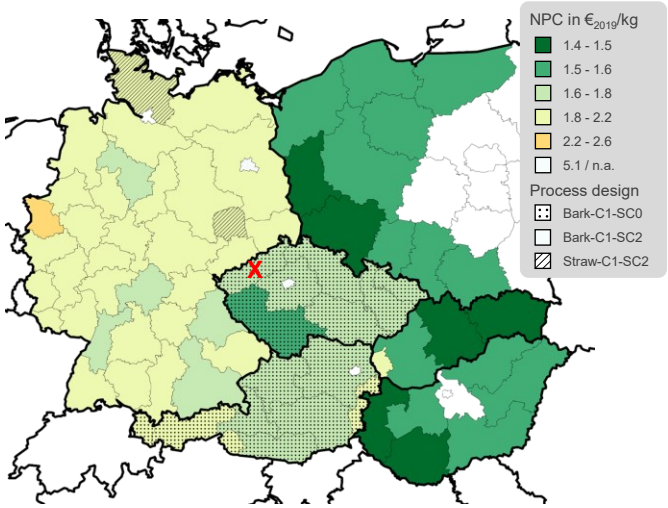
SAF QUICKSTART: EXPLORE THE BIOMASS FROM YOUR NEIGHBORHOOD

BtL from Central Europe [1]
200 MW_{th} DFB Gasifier

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- Assumptions:
  - Bark & straw as biomass feedstock
  - 20 years of plant lifetime
  - 8260 h/a operation
  - 10 persons per shift
  - 10% interest rate
  - Product refining at ORLEN UniPetrol Litvínov – Záluží refinery (**X**)



[1] Maier et al. (2021), Techno-economically-driven identification of ideal plant configurations for a new biomass-to-liquid process – A case study for Central-Europe

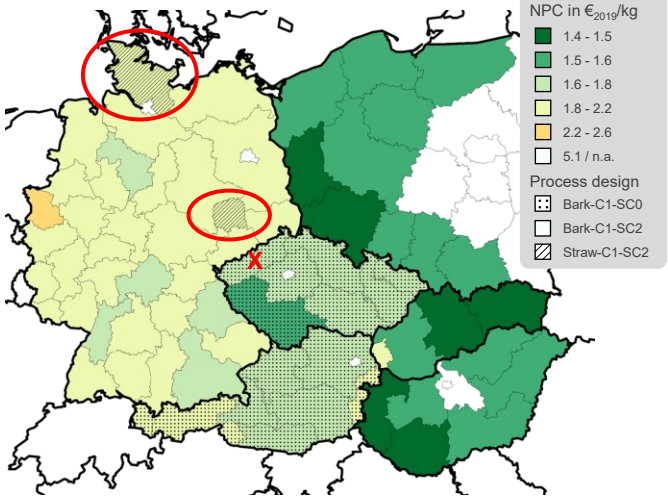
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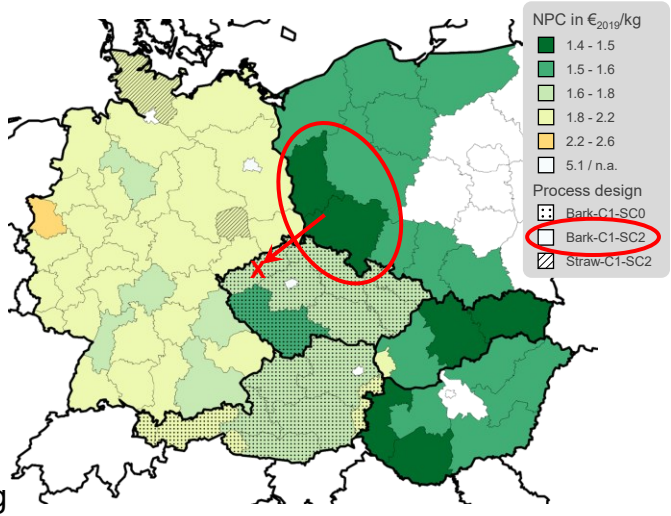
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Preferred:
- West Poland bark
- C1: process configuration “basic”
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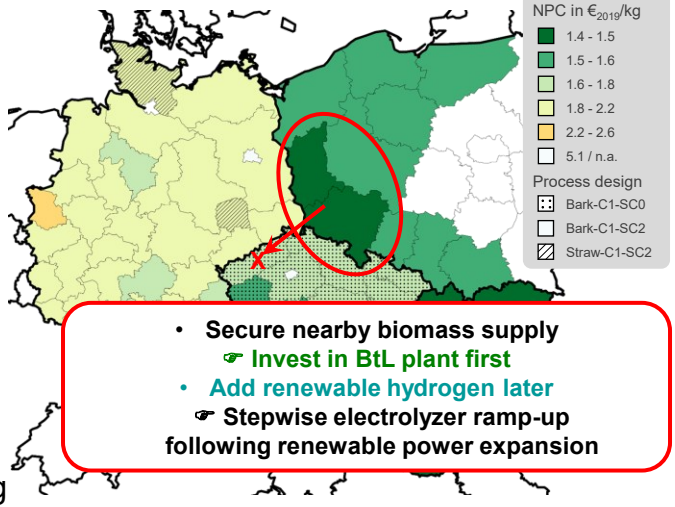
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CONCLUSIONS & OUTLOOK

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Outlook



DLR

- Further stimulate SAF deployment with sticks AND carrots
  - Donate potential SAF overproduction
  - Book&claim mechanism to allow SAF production where economic most viable

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Outlook



DLR

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- Update RefuelEU Aviation towards true GWP abatement
  - Include actual ILUC of crop based feedstocks, sustainability without fraud
  - Ensure equilibrium between carbon uptake and carbon harvesting
  - Prohibit escape routing – fairness to all airlines/airports
  - Include non-CO_2 effects of aviation (soot, PM, NO_x, contrails, …)

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- Ease SAF certification procedure
  - Chemical fuel analysis provides all necessary information for safe usage

Tuesday, 06. October 2026

Workshop 1: Sustainable Aviation Fuel Forum

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THANK YOU FOR YOUR KIND ATTENTION! QUESTIONS?



Techno Economic (TEA) and Environmental Impact Assessment (LCA) of Sustainable Aviation Fuels in Europe

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