Thursday, May 23, 2024
Session 16
Green and Environmental Chemistry

The 2nd World Chemistry Congress 2024
May 22-24, 2024 Osaka, Japan

ASSESSMENT OF EUROPEAN SUSTAINABLE AVIATION FUELS (SAF) PRODUCTION

Innovative biomass based sustainable aviation fuel production
Techno-economic and sustainability assessment

Ralph-Uwe Dietrich, Sandra Adelung, Felix Habermeyer, Simon Maier, Moritz Raab, Yoga Rahmat, Julia Weyand
(DLR e.V., www.DLR.de/tt)

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Towards European SAF production[1]
Agenda

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1. SAF demand and activities
2. Techno-economic and life cycle assessment methodology
3. Techno-economic and life cycle assessment of Power-and-Biomass-to-Liquid
4. Towards a European SAF roadmap
5. Conclusion and outlook

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[1] Dietrich, Dietrich, R.-U., Adelung, S., Habermeyer, F. et al. Technical, economic and ecological assessment of European sustainable aviation fuels (SAF) production. CEAS Aeronaut J 15, 161–174 (2024). https://doi.org/10.1007/s13272-024-00714-0

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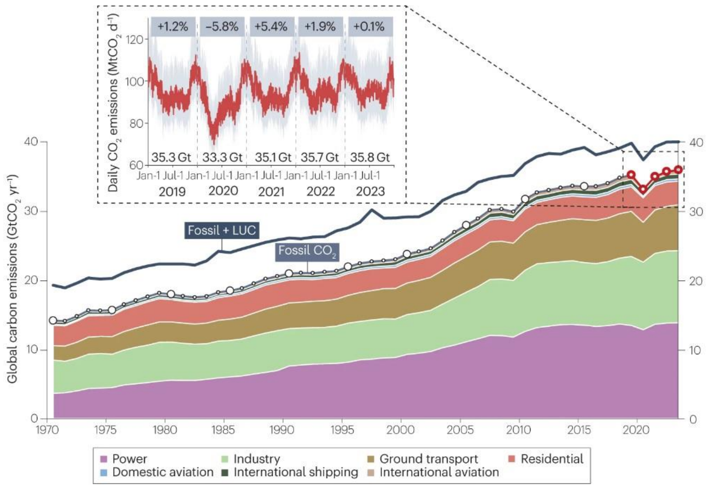
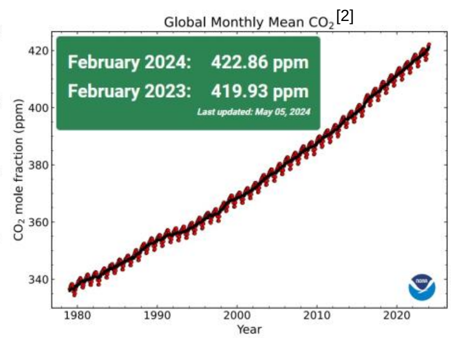
Fig.1: Global CO_2 emissions 1970–2023 [1]



Global Monthly Mean CO_2 [2]



[1] https://www.nature.com/articles/s43017-024-00532-2
[2] https://gml.noaa.gov/webdata/ccgg/trends/co2_trend_all_gl.pdf

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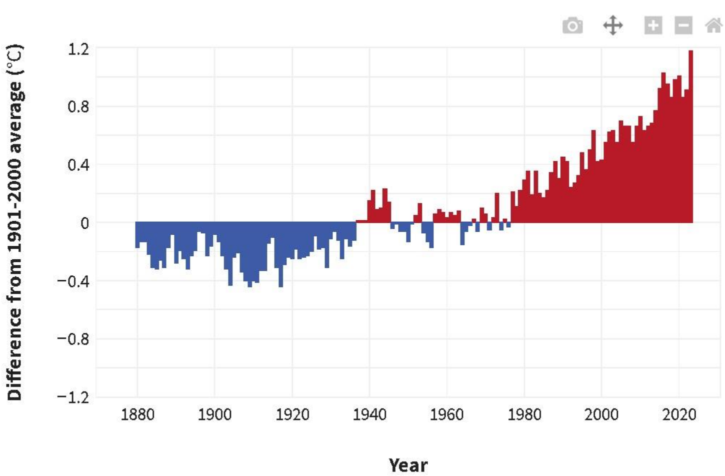
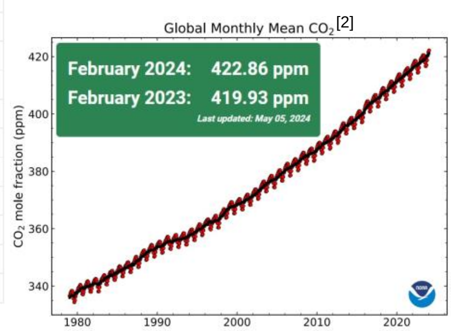
GLOBAL AVERAGE SURFACE TEMPERATURE [3]



Global Monthly Mean CO_2 [2]



[1] https://www.nature.com/articles/s43017-024-00532-2
[2] https://gml.noaa.gov/webdata/ccgg/trends/co2_trend_all_gl.pdf
[3] https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

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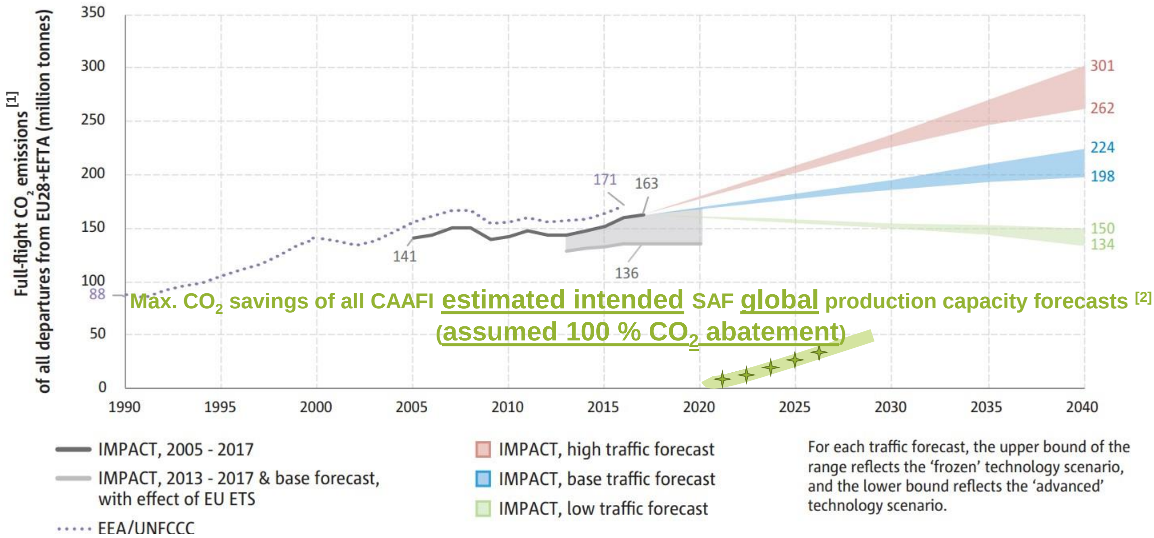
SAF deployment still lagging behind

Too little too late



[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf
[2] calc. from (slide 2) S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf.

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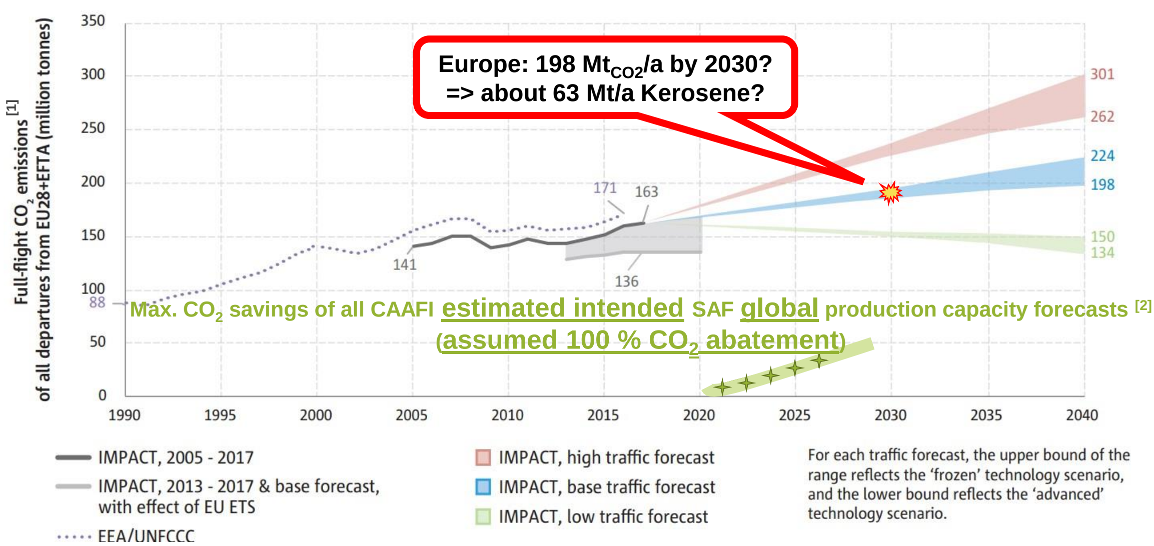

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Assessment of Decarbonization options

Merit Order of GHG emission reduction

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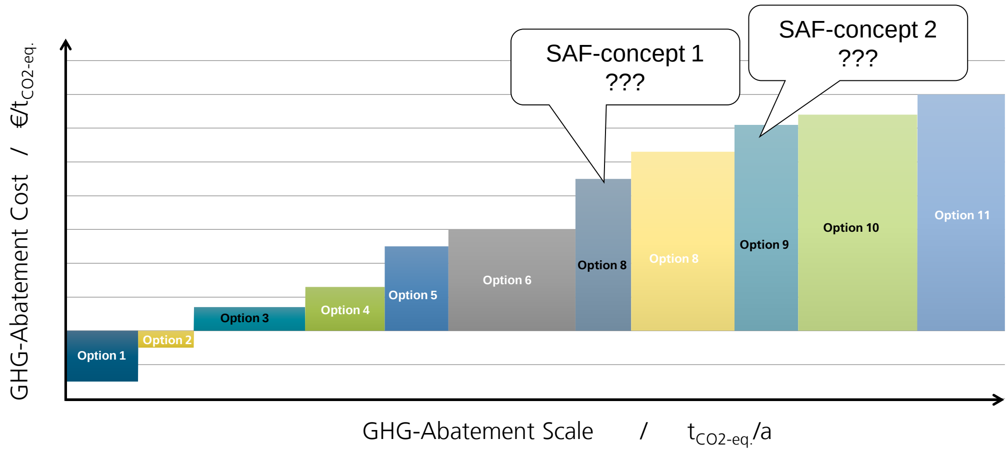

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Assessment of Decarbonization options

Merit Order of GHG emission reduction

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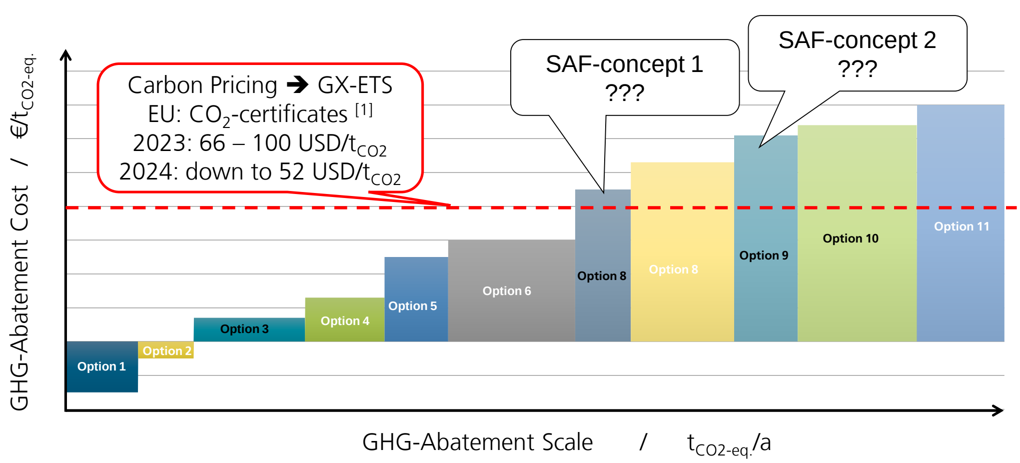

[1] https://www.boerse.de/rohstoffe/Co2-Emissionsrechtepreis/XC000A0C4KJ2

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Assessment of Decarbonization options
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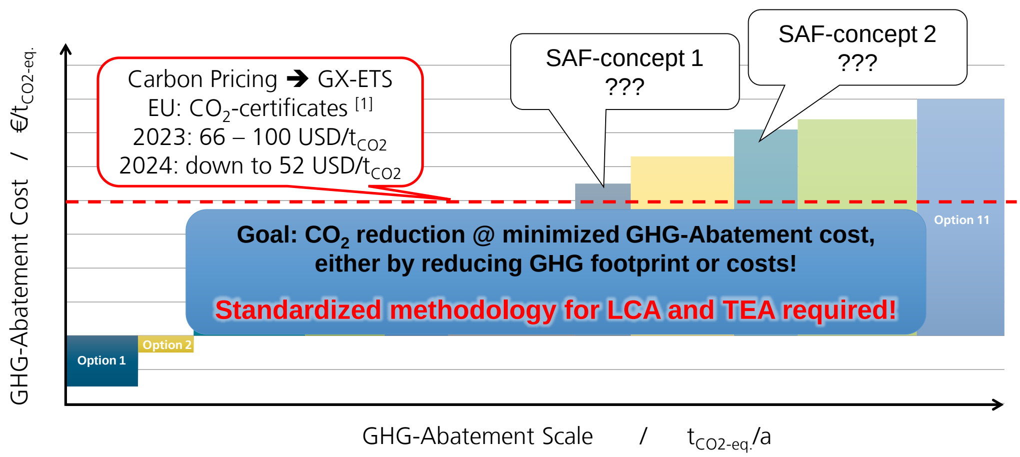

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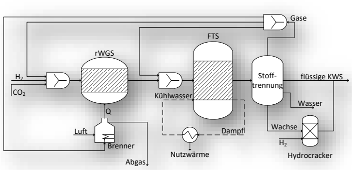
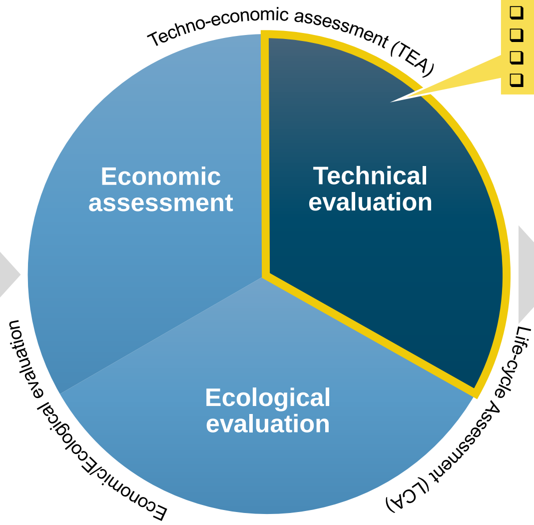
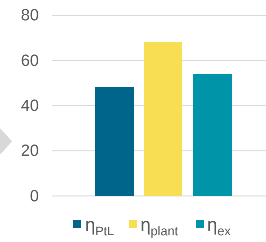
- ❑ Efficiencies (X-to-Liquid, Overall)
- ❑ Carbon conversion
- ❑ Specific feedstock demand
- ❑ Exergy analysis







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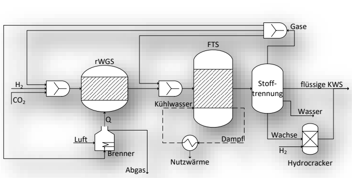

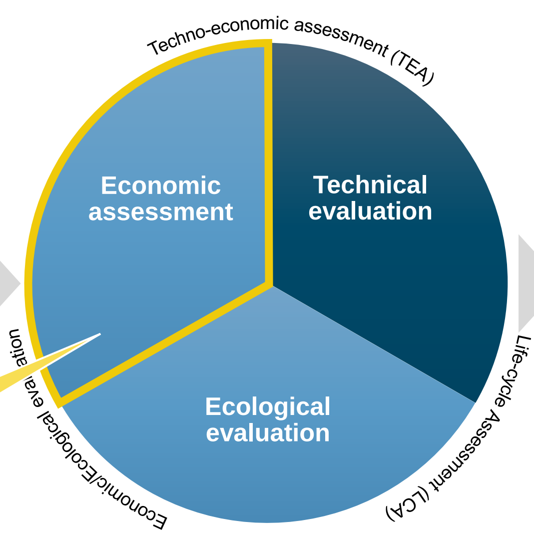

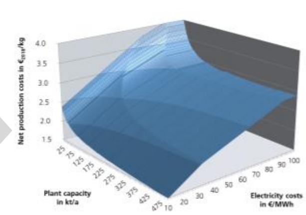

- ❑ CAPEX, OPEX, NPC
- ❑ Sensitivity analysis
- ❑ Identification of most economic feasible process design

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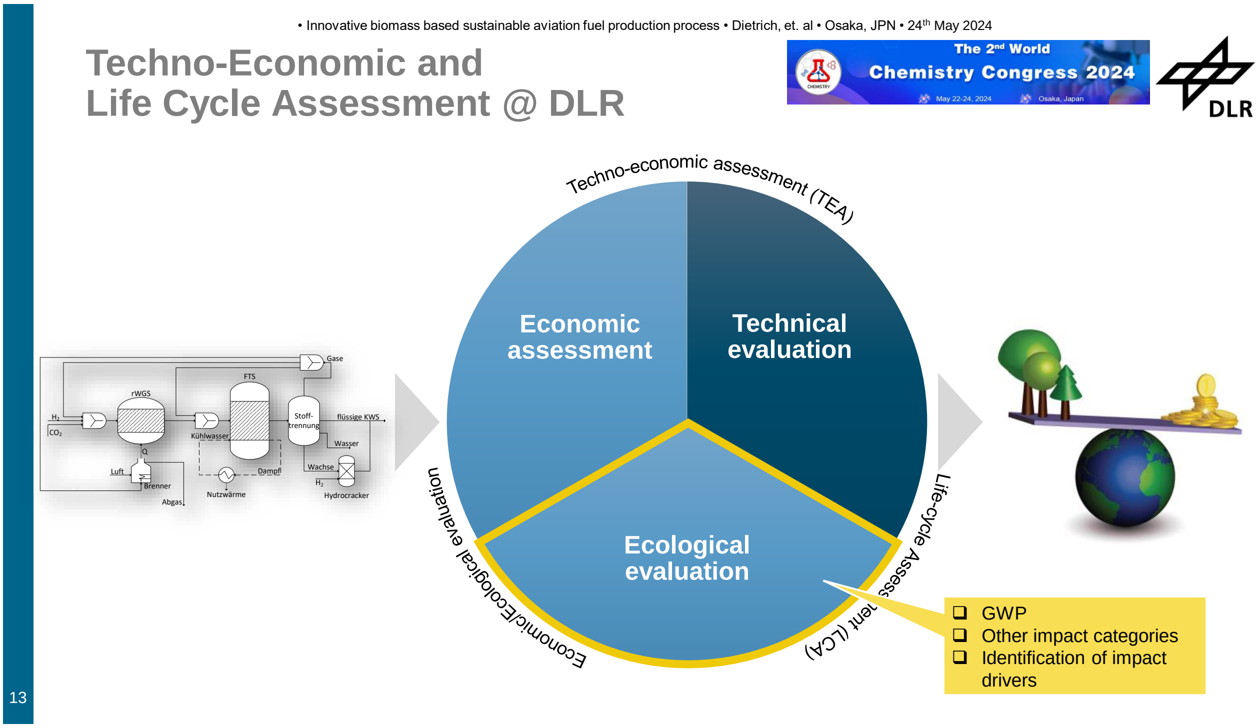
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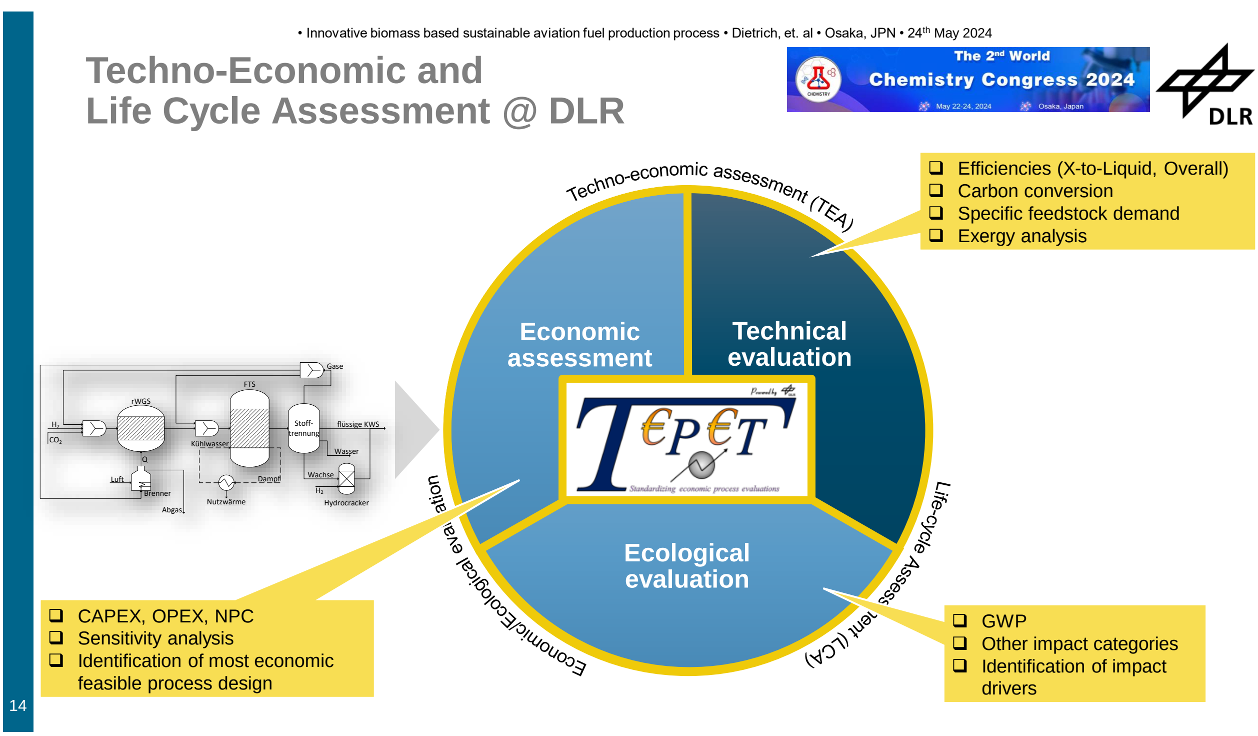
Techno-economic assessment (TEA)
Economic assessment
Technical evaluation
Ecological evaluation
Economic/Ecological evaluation
Life-cycle Assessment (LCA)
GWP
Other impact categories
Identification of impact drivers
13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Techno-economic assessment (TEA)
Efficiencies (X-to-Liquid, Overall)
Carbon conversion
Specific feedstock demand
Exergy analysis
Economic assessment
Technical evaluation
TEPET
Standardizing economic process evaluations
Ecological evaluation
Economic/Ecological evaluation
Life-cycle Assessment (LCA)
CAPEX, OPEX, NPC
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Identification of most economic feasible process design
GWP
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PBtL concept implemented
Experimentally validated Aspen Plus sim.

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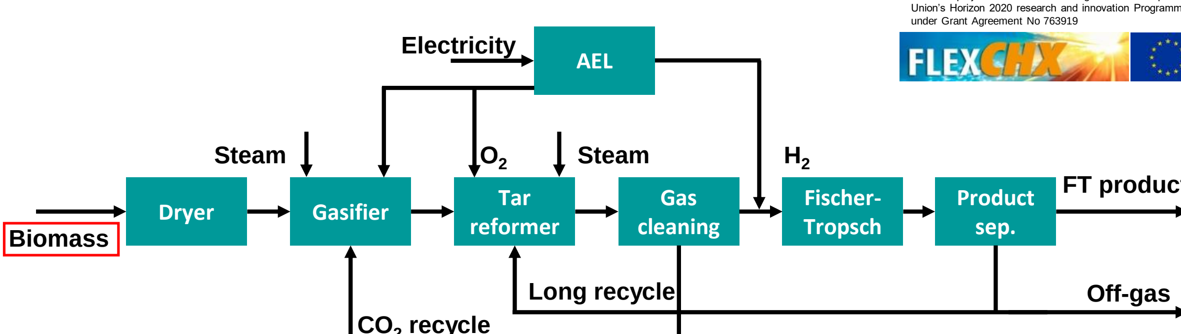

Process details:

- Plant size: biomass input 400 MW_{th} (bark, needles and stem wood from harvesting, industrial wood residues)

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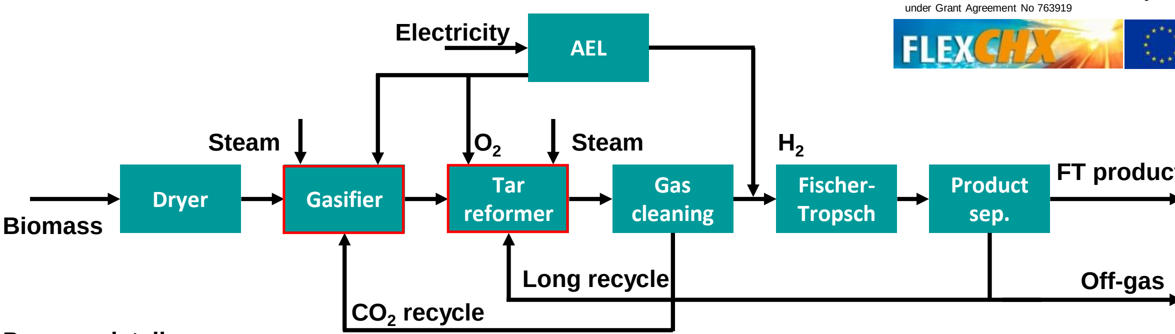

Process details:

- Plant size: biomass input 400 MW_{th} (bark, needles and stem wood from harvesting, industrial wood residues)
- Experimentally validated gasifier and reformer model [1,2]

[1] Hannula, I. (2016). Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. *Energy*, *104*, 199-212.
[2] Kurkela, E., Kurkela, M., & Hiltunen, I. (2021). Pilot-scale development of pressurized fixed-bed gasification for synthesis gas production from biomass residues. *Biomass Conversion and Biorefinery*, 1-22..

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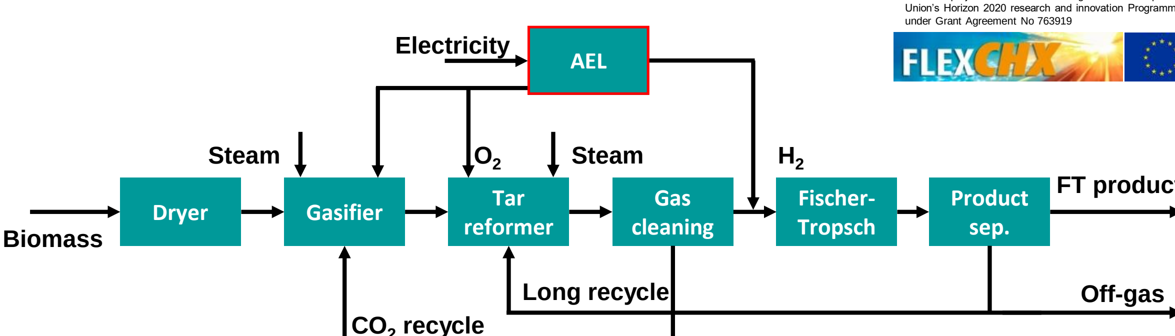

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- AEL electrolyzer (900 MW_{el}) – most mature electrolysis technology [3]

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[3] Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, *82*, 2440-2454.

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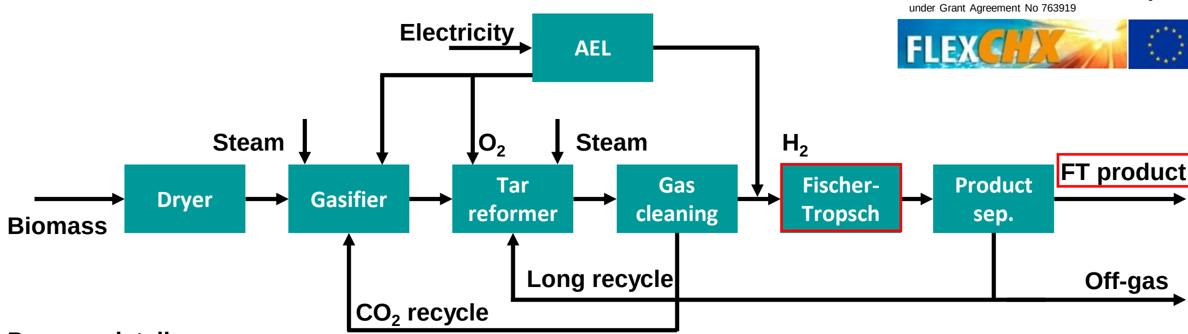

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- Fischer-Tropsch: Slurry bubble column reactor [4], product (0.4 Mt/a C_{5+}) converted in to SAF in central refinery

[1] Hannula, I. (2016). Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. *Energy*, *104*, 199-212.
[2] Kurkela, E., Kurkela, M., & Hiltunen, I. (2021). Pilot-scale development of pressurized fixed-bed gasification for synthesis gas production from biomass residues. *Biomass Conversion and Biorefinery*, 1-22.
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[4] Todic, B., Bhatelia, T., Froment, G. F., Ma, W., Jacobs, G., Davis, B. H., & Bukur, D. B. (2013). Kinetic model of Fischer–Tropsch synthesis in a slurry reactor on Co–Re/Al2O3 catalyst. *Industrial & Engineering Chemistry Research*, *52*(2), 669-679.

Dual configuration for BtL and PBtL [1]

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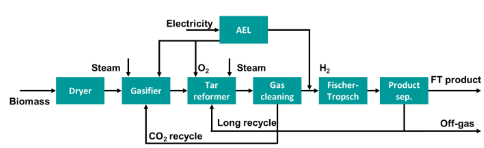
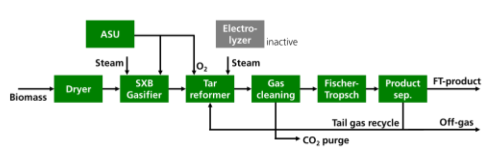
PBtL with electrolyzer:

- no heat demand
- renewable power available



BtL with ASU:

- high heat demand
- low renewable power



[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, 7, p. 4229-4246. doi: 10.1039/d3se00358b.

Techno-Economic Assessment of dual configuration for BtL and PBtL [1]

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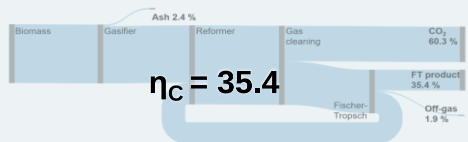
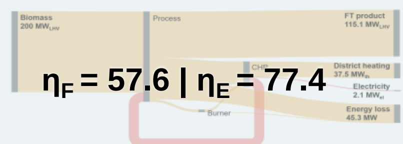
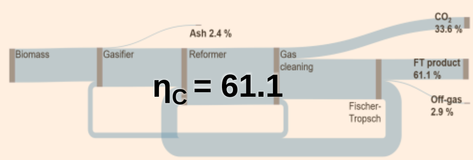
Technical efficiencies [1]

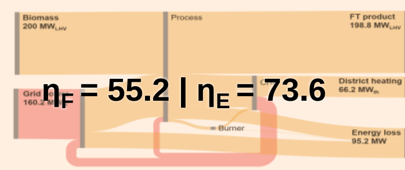
Key technical assumptions:
η_{AEL} = 77.8 $\%_{HHV}$ / H_2/CO = 2.05 / FT-Recycle = 95 %

	Carbon efficiency η_C [%]	Fuel η_F | Energetic efficiency η_E [%]
Winter	$\eta_C = 35.4$	$\eta_F = 57.6$ | $\eta_E = 77.4$
Summer	$\eta_C = 61.1$	$\eta_F = 55.2$ | $\eta_E = 73.6$
50/50	$\eta_{C,av.} = 48.25$	$\eta_{F,av.} = 56.4$ | $\eta_{E,av.} = 75.5$









[1] Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774

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ECONOMIC ASSESSMENT OF FT-SAF (PBTL)

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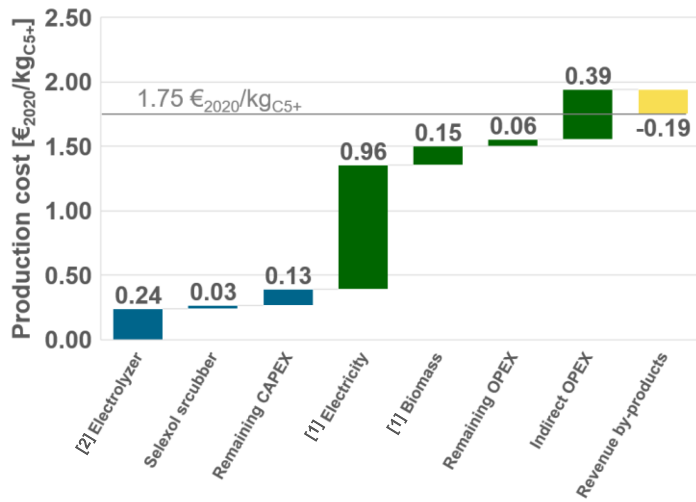
PBtL 2020 Net Production Costs



Key assumptions (Finnish base case):

- 50.4 €/MWh electricity cost [1]
- 42.2 €/t biomass cost [1]
- Alkaline electrolysis 1 M€/MW [2]
- Labor cost 43.1 €/h [3]

[1] Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., ... & Thrän, D. (2019). ENSPRESO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, *26*, 100379.
[2] Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, *82*, 2440-2454.
[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]

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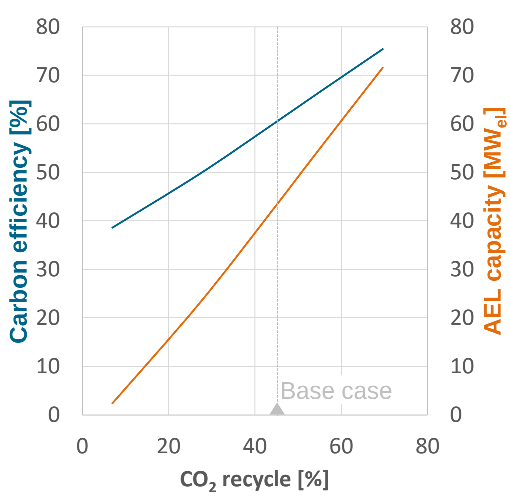
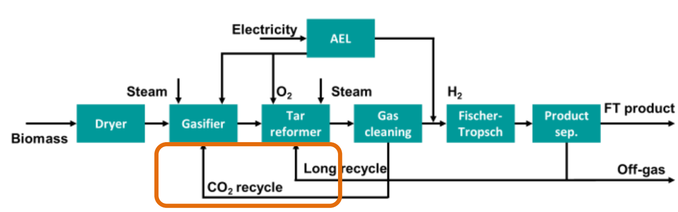
Sensitivity of PBtL CO_2 recycling [1]
Cost reduction @ in-expensive power





More CO_2 recycle to the gasifier:
- \+ Less steam addition to the gasifier, less heat demand
- \+ Increase carbon efficiency, product yield
- – Higher H2 demand, electricity and electrolyzer

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[1] Habermeyer, F.; Weyand, J.; Maier, S.; Kurkela, E.; Dietrich, R.-U. (2023) Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. Biomass Conversion and Biorefinery. doi: 10.1007/s13399-022-03671-y.

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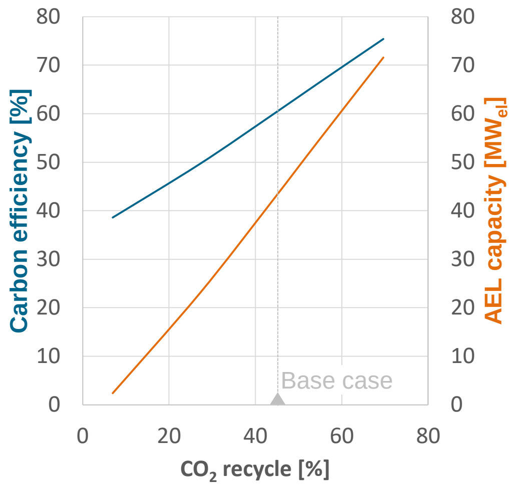

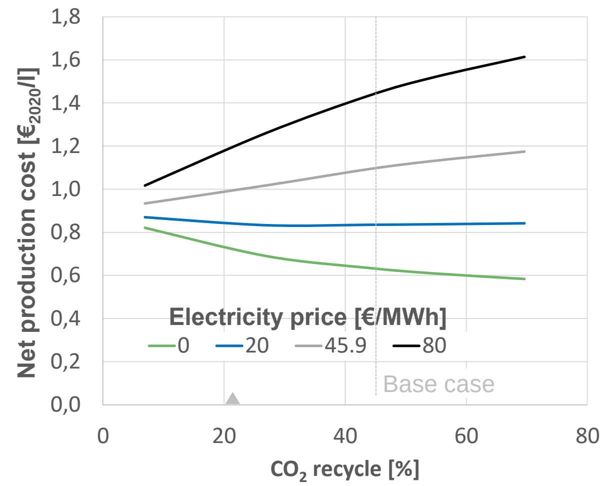

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[1] Habermeyer, F.; Weyand, J.; Maier, S.; Kurkela, E.; Dietrich, R.-U. (2023) Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. Biomass Conversion and Biorefinery. doi: 10.1007/s13399-022-03671-y.

ENVIRONMENTAL ASSESSMENT OF SAF (PBTL)

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Global Warming Potential (GWP) of Dual configuration SAF plant [1]

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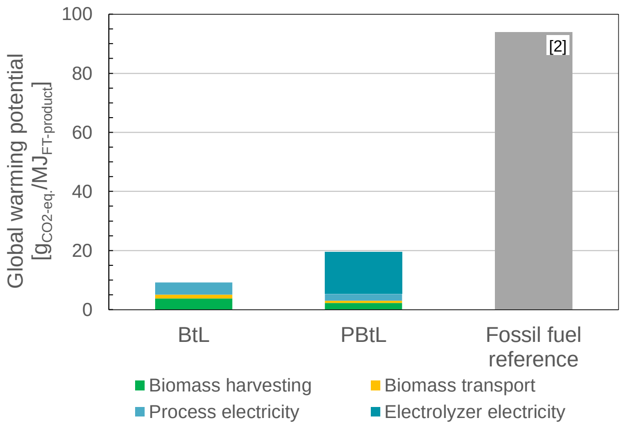
FLEXCHX



- Transportation: 100 km, one-way by truck (69 $g_{CO2-eq.}/(t*km)$)
- Biomass: Forest residues harvesting (19.7 $g_{CO2-eq.}/kg$)
- Electricity: Finnish grid @2020 (68.6 $g_{CO2-eq.}/kWh$)

[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, 7, p. 4229-4246. doi: 10.1039/d3se00358b.
[2] European Union (2018) "Directive 2018/2001 of the European Parliament …on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

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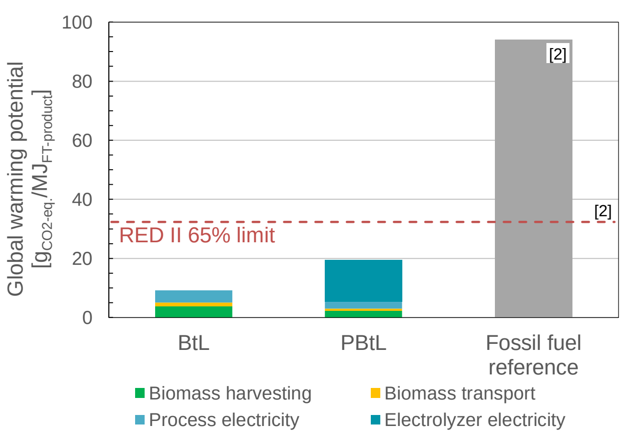

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Conclusion

REDII target accomplished @ FLEXCHX base case

[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, 7, p. 4229-4246. doi: 10.1039/d3se00358b.
[2] European Union (2018) "Directive 2018/2001 of the European Parliament …on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

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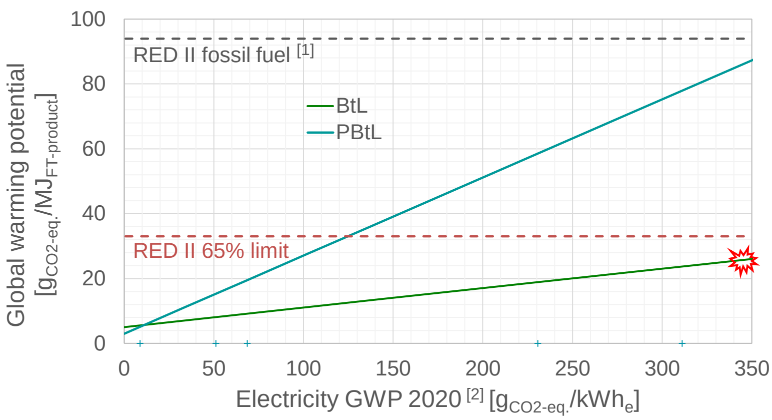
GWP sensitivity of Biomass-to-Liquid / Power&Biomass-to-Liquid

FlexCHX project has received funding from the European Union's Horizon 2020 research and innovation Programme under Grant Agreement No 763919



- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL

[1] European Union (2018) "Directive 2018/2001 of the European Parliament … on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union
[2] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111

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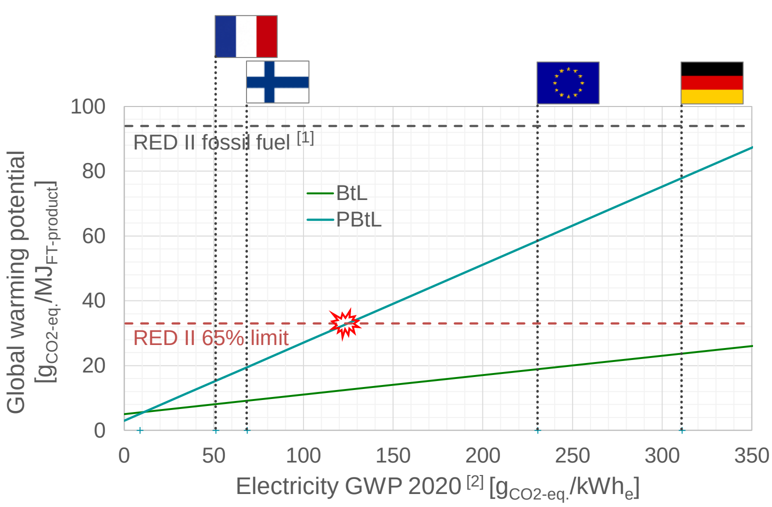

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with GWP <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit

[1] European Union (2018) "Directive 2018/2001 of the European Parliament … on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union
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GWP sensitivity of Biomass-to-Liquid / Power&Biomass-to-Liquid

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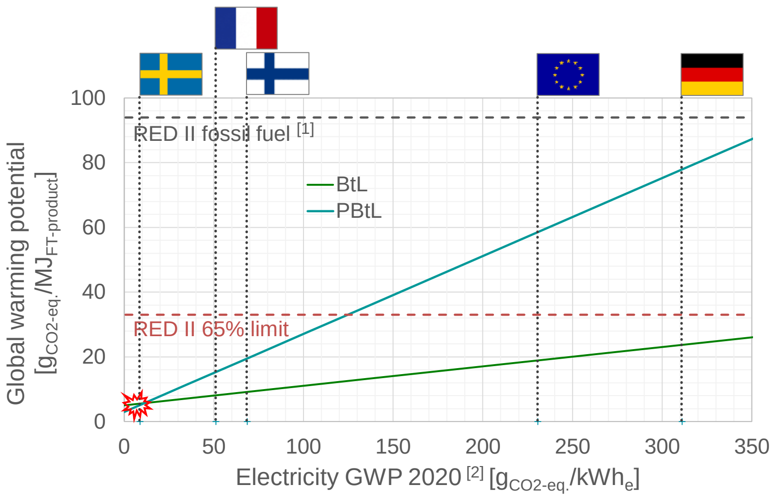

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with GWP <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit
- PBtL could have lower GWP than BtL with Swedish grid mix

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[1] European Union (2018) "Directive 2018/2001 of the European Parliament … on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union
[2] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111

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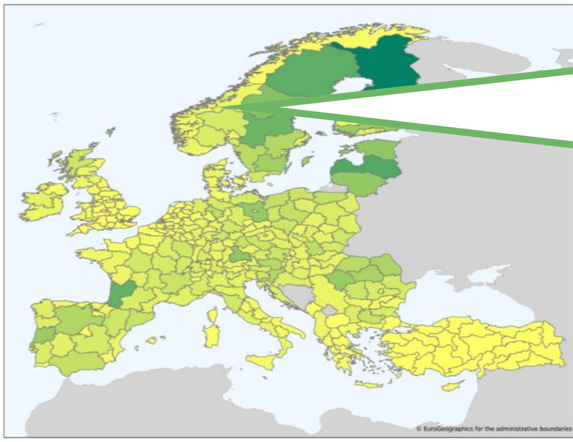
PBtL potential analysis for Europe

Finding the sweet spots



NUTS2 region specific conditions:

Economic
- 2020 National grid electricity prices [1]
- Woody biomass prices & availability [2]
- Transport distance = f(biomass density)
- Nation-specific transport & labor costs

Ecological
- 2020 National grid mix GWP [3]
- Region-specific transport emissions

[1] Eurostat, Electricity prices for non-household consumers - bi-annual data. 2021.
[2] Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., ... & Thrän, D. (2019). ENSPRESSO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, *26*, 100379
[3] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6 [Accessed 14.9.21]

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European PBtL plant (400 kt_{SAF}/a)

Key economic Assumptions

Investment costs:			**Average plant size**
AEL-Electrolyzer	**1**	M€/MW [1]	➔ 900 MW_e Electrolyzer
Fischer-Tropsch SBCR:	**5.9**	k€/m^3 [2]	➔ 400 kt/a SAF product
Selexol:	**5.5**	k€/$kmol_{CO2}$/h [3]	
Fluidized bed gasifier:	**0.5**	M€/($kg_{dry\ biomass}$/s) [4]	➔ 400 MW_{th} gasifier
Raw materials and utility costs			
Selexol:	**4.4**	€/kg [5]	
FT catalyst:	**33**	€/kg [6]	

General economic assumptions:

Year:	2020	*Plant lifetime:*	20 years
Full load hours:	8,100 h/a	*Interest rate:*	7 %

[1] Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renewable and Sustainable Energy Reviews, 82, 2440-2454.
[2] Gasification, B. B. (1998). Aspen Process Flowsheet Simulation Model of a Battelle Biomass-Based Gasification, Fischer-Tropsch Liquefaction and Combined-Cycle Power Plant.
[3] Hamelinck, C. N., & Faaij, A. P. (2002). Future prospects for production of methanol and hydrogen from biomass. *Journal of Power sources*, *111*(1), 1-22.
[4] Hannula, I. (2016). Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. *Energy*, *104*, 199-212.
[5] Albrecht, F. G., König, D. H., Baucks, N., & Dietrich, R. U. (2017). A standardized methodology for the techno-economic evaluation of alternative fuels–A case study. *Fuel*, *194*, 511-526.
[6] Swanson, R. M., Platon, A., Satrio, J. A., & Brown, R. C. (2010). Techno-economic analysis of biomass-to-liquids production based on gasification. *Fuel*, *89*, S11-S19.

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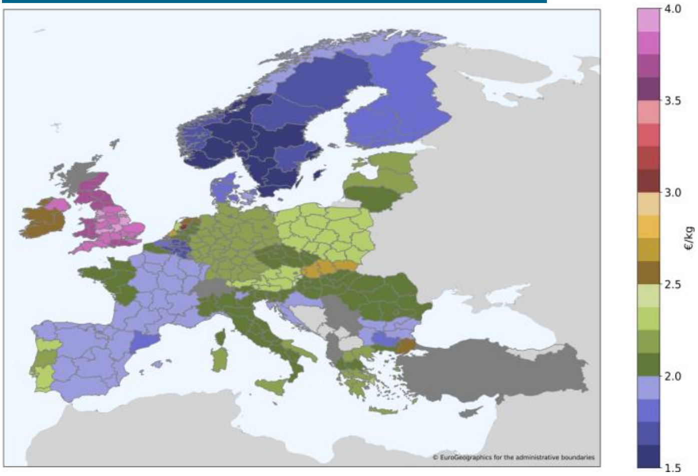
European SAF Roadmap
Local onshore wind power utilization [1]

Net Production Costs of PBtL SAF / €$_{2020}$/kg



Standard **PBtL** plant
- 900 MW_e Electrolyzer
- 400 MW_{th} CFB gasifier
- 400 kt/a SAF output

35

[1] Habermeyer, F., Papantoni, V., Brand-Daniels, U., Dietrich, R.-U. (2023) Sustainable aviation fuel from forestry residue and hydrogen. Sustainable Energy and Fuels(7), p. 4229-4246. Royal Society of Chemistry. doi: 10.1039/d3se00358b.
[2] Eurostat, Electricity prices for non-household consumers - bi-annual data. 2021.
[3] Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., ... & Thrän, D. (2019). ENSPRESSO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, *26*, 100379

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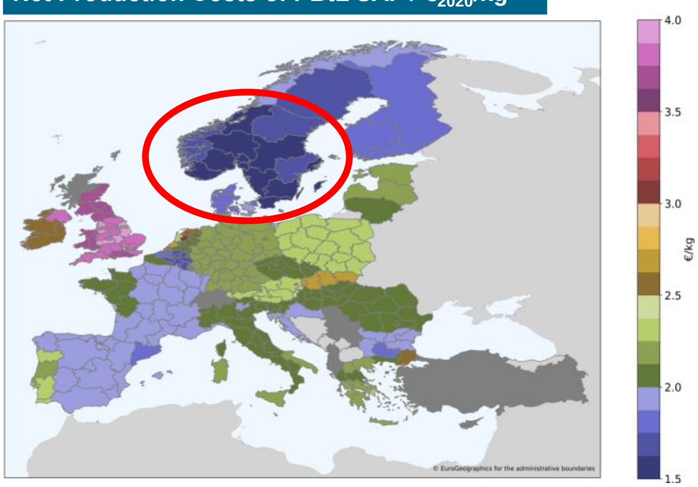

Standard **PBtL** plant
- 900 MW_e Electrolyzer
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➔ Search for cheap biomass residue [3] and inexpensive (renewable) power [2]

1. Norway (57 $PJ_{dry\ biom}$/a)
   @ 50.5 – 51.0 €$_{2020}$/$t_{biom.dry}$
   @ 30.8 €$_{2020}$/kWh grid power
2. Sweden (276 $PJ_{dry\ biom}$/a)
   @ 57.5 – 64.8 €$_{2020}$/$t_{biom.dry}$
   @ 35.6 €$_{2020}$/kWh grid power
3. Finland (201 $PJ_{dry\ biom}$/a)
   @ 61.5 – 61.9 €$_{2020}$/$t_{biom.dry}$
   @ 45.9 € €$_{2020}$/kWh grid power

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[1] Habermeyer, F., Papantoni, V., Brand-Daniels, U., Dietrich, R.-U. (2023) Sustainable aviation fuel from forestry residue and hydrogen. Sustainable Energy and Fuels(7), p. 4229-4246. Royal Society of Chemistry. doi: 10.1039/d3se00358b.
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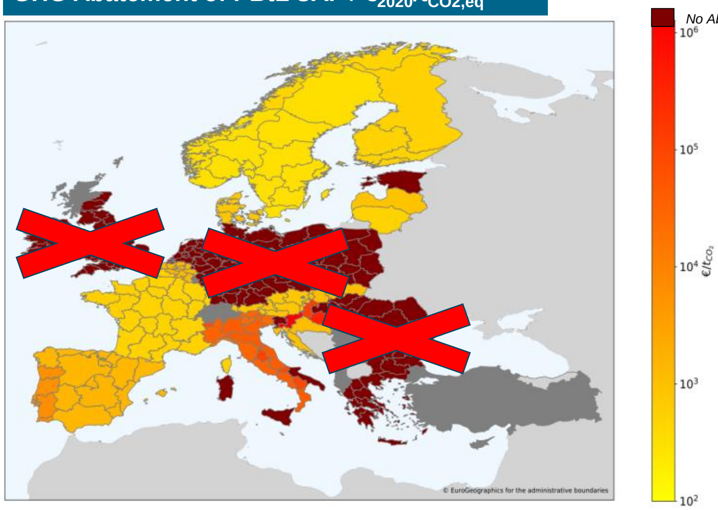
European SAF Roadmap
Local grid-determined sustainability [1]

GHG Abatement of PBtL SAF / $€_{2020}/t_{CO2,eq}$



➔ Decarbonized national grids necessary for effective PBtL roll-out

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[1] Habermeyer, F., Papantoni, V., Brand-Daniels, U., Dietrich, R.-U. (2023) Sustainable aviation fuel from forestry residue and hydrogen. Sustainable Energy and Fuels(7), p. 4229-4246. Royal Society of Chemistry. doi: 10.1039/d3se00358b. 2021.

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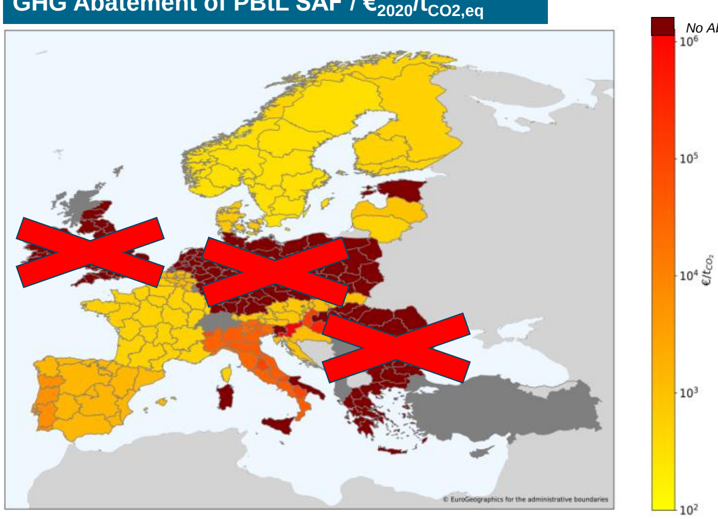

➔ Decarbonized national grids necessary for effective PBtL roll-out

➔ Production volume <1'000 $€/t_{CO2\text{-}eq.}$:
27 Mt_{C5+}/a (all biomass residue to fuel)
@ average NPC of **1.84 $€_{2020}/kg_{C5+}$**

Country	SAF / Mt_{C5+}/a	Av. NPC / $€_{2020}/kg_{C5+}$
	8.3	1,63
	7.3	1.95
	6.1	1.83
	1.7	1.66

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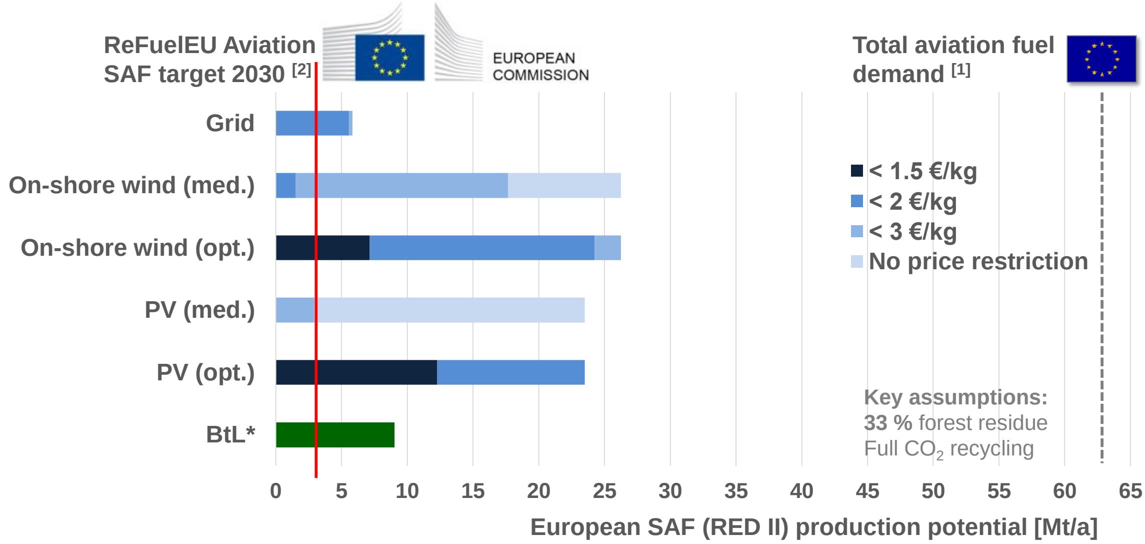
[1] Habermeyer, F., Papantoni, V., Brand-Daniels, U., Dietrich, R.-U. (2023) Sustainable aviation fuel from forestry residue and hydrogen. Sustainable Energy and Fuels(7), p. 4229-4246. Royal Society of Chemistry. doi: 10.1039/d3se00358b. 2021.

Aggregated SAF production potential



[1] S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf. *Assumptions: 19.9 % biomass conversion, entire potential under RED II limit
[2] https://www.easa.europa.eu/en/light/topics/fit-55-and-refueleu-aviation

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)	
2030	6 % (≈ 3.8 Mt/a)	0.7 % (≈ 0.4 Mt/a)
2035	20 % (≈ 13 Mt/a)	5 % (≈ 3.3 Mt/a)
2050	70 % (≈ 54 Mt/a)	35 % (≈ 27 Mt/a)

Compare with 3.4 Mt/a growth[2] 2020-2030!

[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] https://www.concawe.eu/wp-content/uploads/Rpt_21-2.pdf/

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Compare with 3.4 Mt/a growth[2] 2020-2030!

Preference palm oil? Not enough palm oil on earth!

Paris 1.5 degree commitment intentionally violated!

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

EUROPEAN COMMISSION

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2025	≈ 1 Mt/a	
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2035	≈ 13 Mt/a	**30 Mt/a**
2050	≈ 54 Mt/a	**75+ Mt/a = 100 %! (2045?)**

25 plants across Europe á

- 3.3 GW Wind (5.0 b€) or 6.3 GW PV (5.0 b€)
- 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 (OECD) crude oil expenses

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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/

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

EUROPEAN COMMISSION

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- ≈ 50 % SAF blending rate achievable: learning curve
- 100 % SAF certification required for further growth

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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/

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- Backup, if H_2 aviation won't fly
- additional SAF routes / feedstocks from 2035 onwards? or ➔ Less air traffic?
- Climate neutrality by 2045?

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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/

Toward Net Zero Aviation

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Summary

- SAF deployment mandatory towards Paris' goals climate obligations
  - REGULATION will end fossil fuels utilization
  - Extra costs have to be distributed and accepted
- Sustainable carbon and renewable hydrogen need to be explored and utilized large-scale and quickly
  - Technology is available, improvements are always possible (electrolyzer?)
  - SAF cost and GHG emissions need to be minimized together

Transparent, standardized DLR assessment methodology can support

➔ Feedstock search, technology selection and improvement, sweet spot search, regulation adjustment, … !

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Thursday, May 23, 2024
Session 16
Green and Environmental Chemistry

The 2nd World Chemistry Congress 2024
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TOWARD NET-ZERO AVIATION

THANK YOU FOR YOUR ATTENTION !
Questions?

Ralph-Uwe Dietrich, Sandra Adelung, Felix Habermeyer, Simon Maier, Moritz Raab, Yoga Rahmat, Julia Weyand
(DLR e.V., www.DLR.de/tt)

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