Tuesday, 21. January 2025
Session 4D, ROOM M8:
Advanced alternative fuels – From research to practice

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ALTERNATIVE FUELS AND REVOLUTIONARY PROPULSION FOR FUTURE SUSTAINABLE AVIATION

Techno-Economic and Ecological Assessment of Aviation Technologies and Fuels

Ralph-Uwe Dietrich, Rahnuma Bhuiyan Evon, Felix Habermeyer, Simon Maier, Moritz Raab, Julia Weyand (DLR e.V., www.DLR.de/tt)

[redacted]

EU aviation CO_2 emissions

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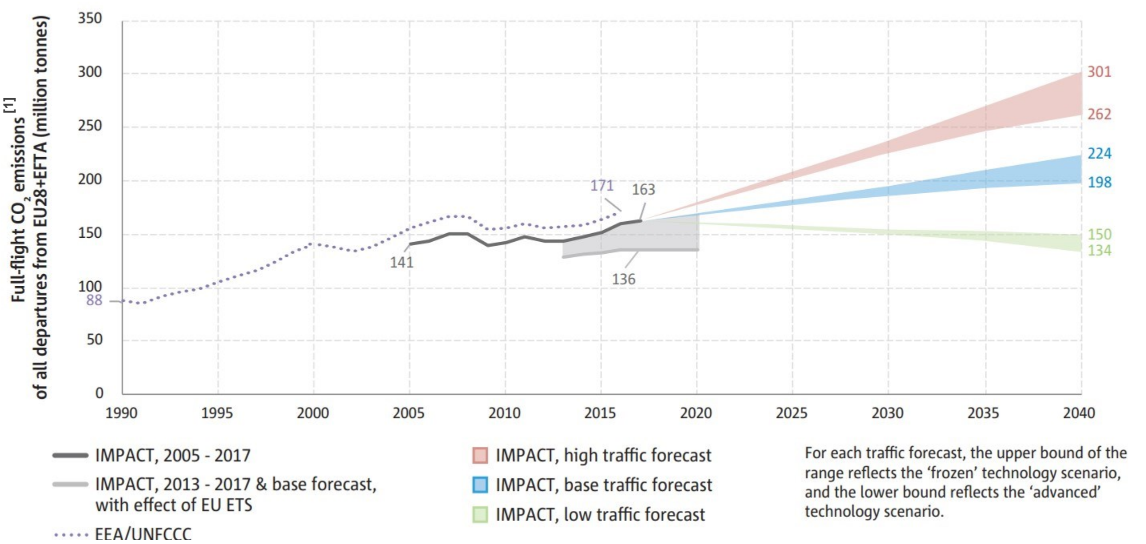

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[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf

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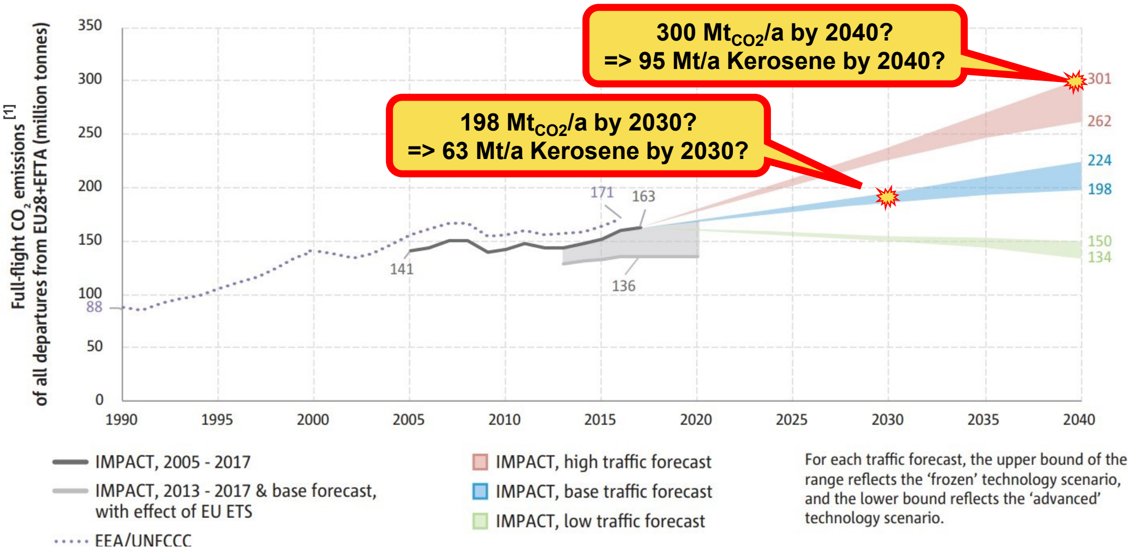
EU aviation CO_2 emissions
Concluded kerosene / SAF demand



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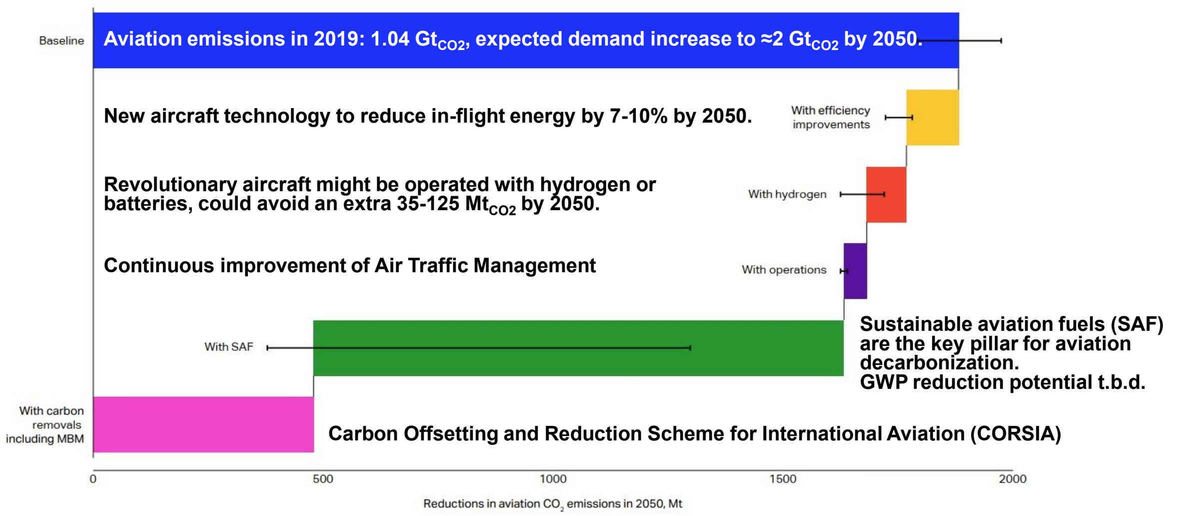
IATA Net Zero Roadmaps [1]
Emission reduction measures



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[1] IATA's Net Zero roadmaps, https://www.iata.org/en/programs/sustainability/roadmaps/

IATA Net Zero Roadmaps [1]

Topics addressed today

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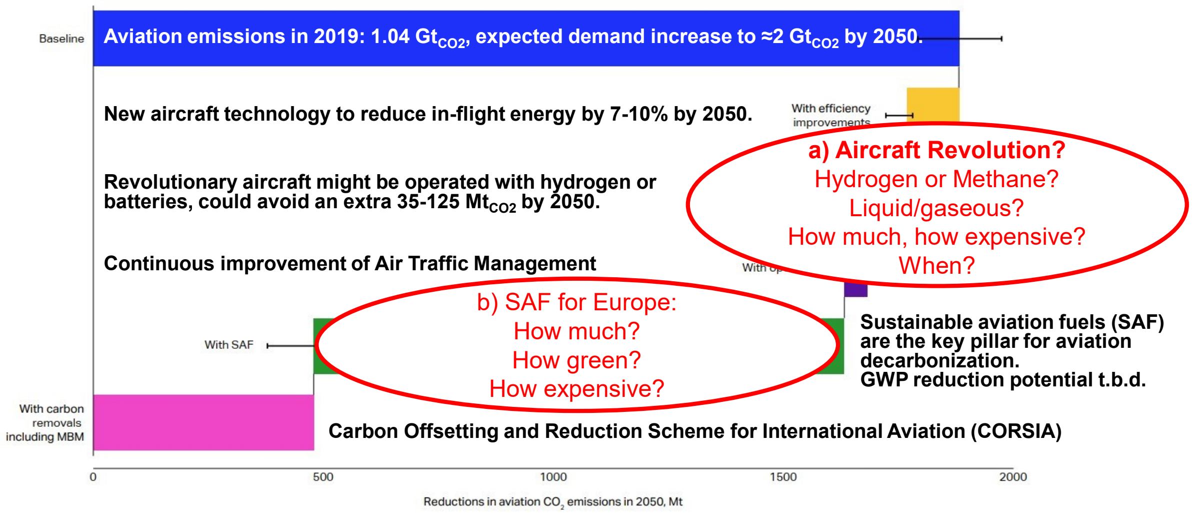

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Civil aviation CO_2 emissions [1]

CO_2 abatement per segments

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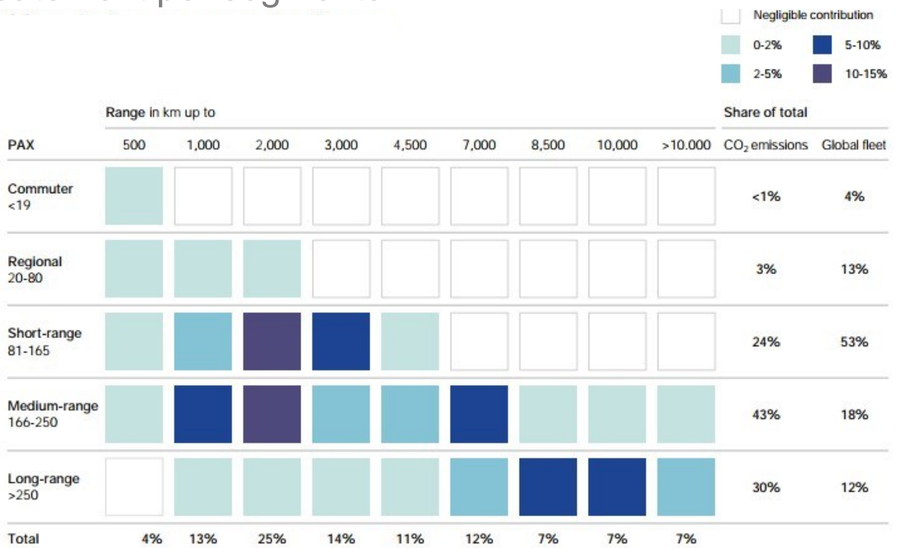

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[1] FCH-JU (2020) Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050. **DOI:** 10.2843/471510

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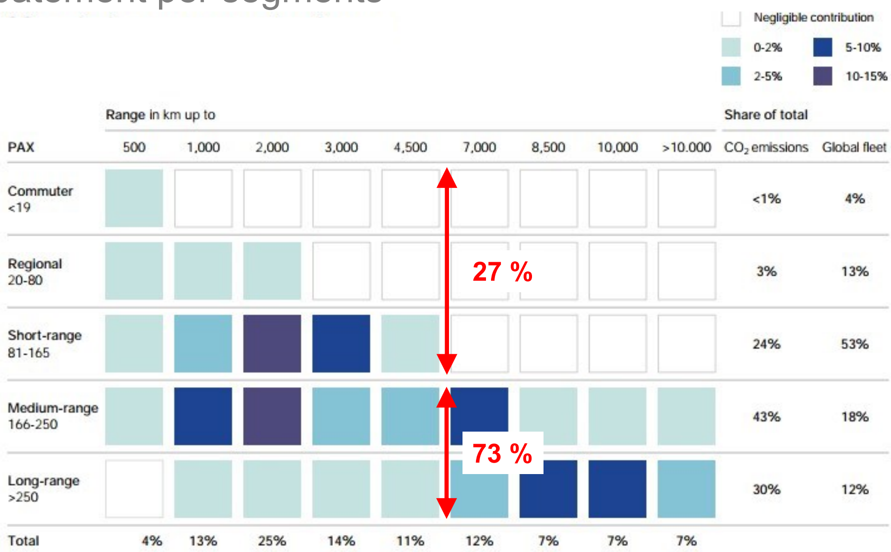

7 [1] FCH-JU (2020) Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050. **DOI:** 10.2843/471510

Aircraft Revolution Roadmap

Based on CO_2 emissions of 2018 [1]

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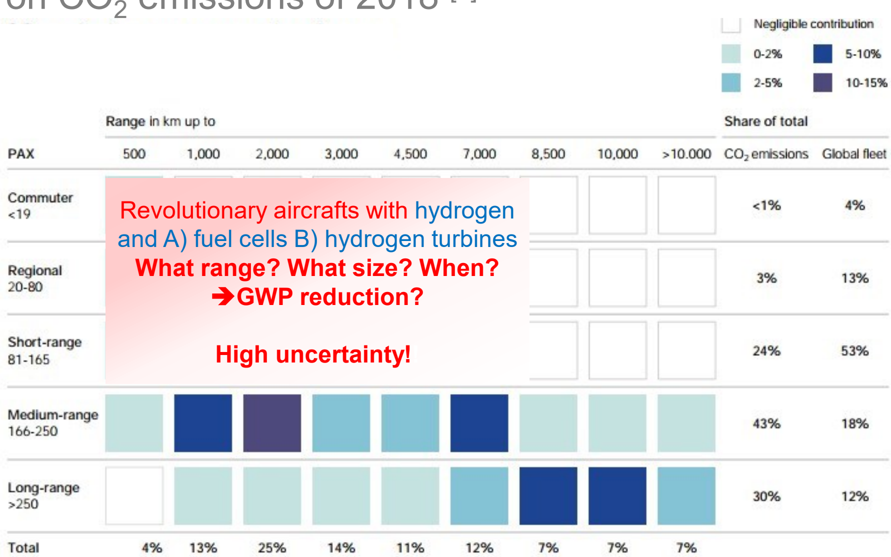

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Negligible contribution
0-2% 5-10%
2-5% 10-15%

PAX	Range in km up to 500	1,000	2,000	3,000	4,500	7,000	8,500	10,000	>10.000	Share of total CO_2 emissions	Share of total Global fleet
Commuter <19										<1%	4%
Regional 20-80										3%	13%
Short-range 81-165										24%	53%
Medium-range 166-250										43%	18%
Long-range >250										30%	12%
Total	4%	13%	25%	14%	11%	12%	7%	7%	7%		

9 [1] FCH-JU (2020) Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050. DOI: 10.2843/471510

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Techno-Economic and Life Cycle Assessment @ DLR

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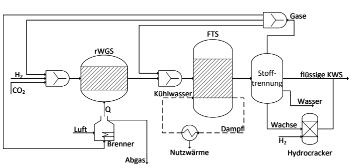
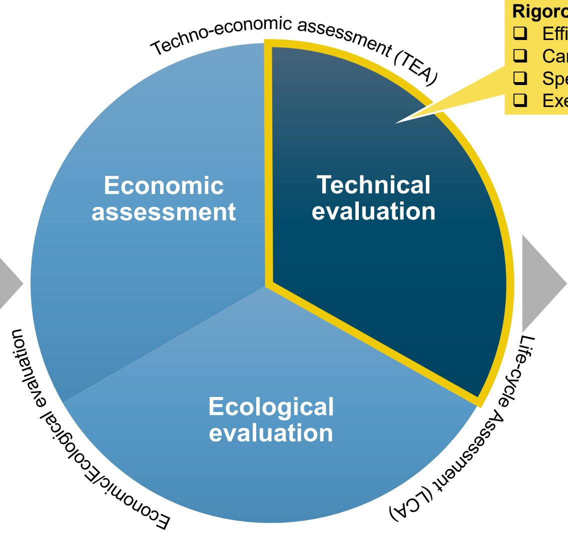
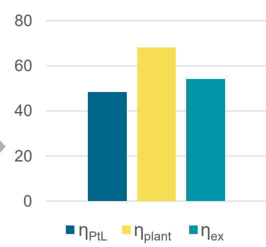




Rigorous process simulation
- ❑ Efficiencies (X-to-Liquid, Overall)
- ❑ Carbon conversion
- ❑ Specific feedstock demand
- ❑ Exergy analysis



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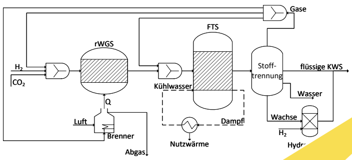

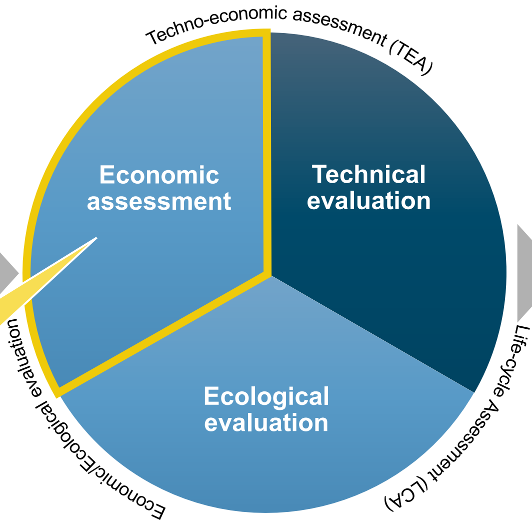

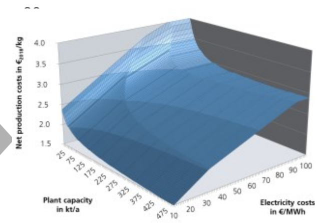

Chemical engineering cost estimation
- Year-specific CAPEX, OPEX, NPC
- Sensitivity analysis
- Identification of most economic feasible process design

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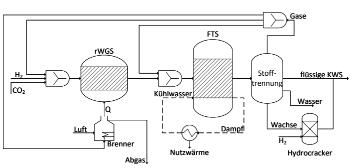

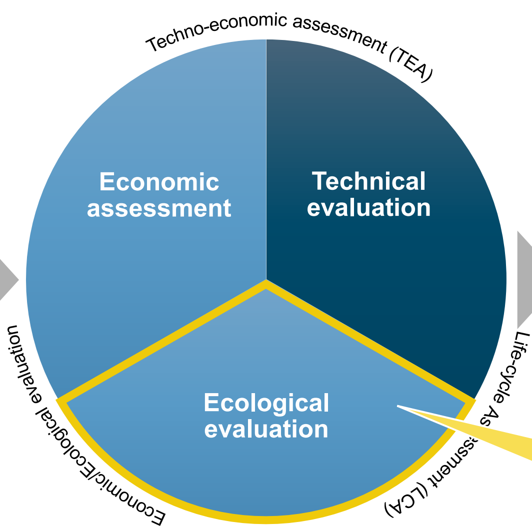

Adapted ISO 14040/14044 LCA
- GWP
- Other impact categories
- Identification of impact drivers

Techno-Economic and Life Cycle Assessment

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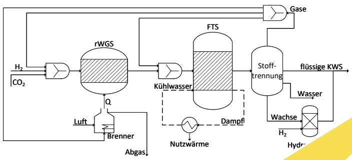

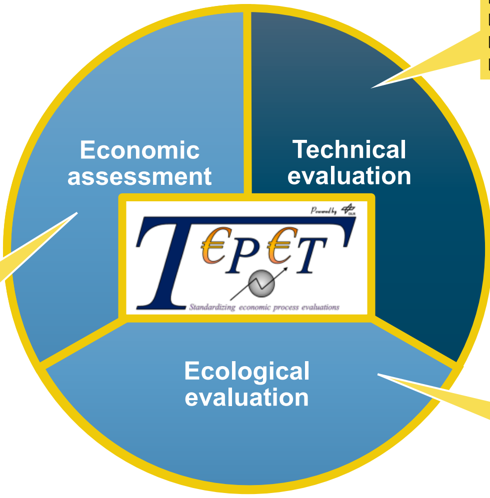

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A) AIRCRAFT REVOLUTION

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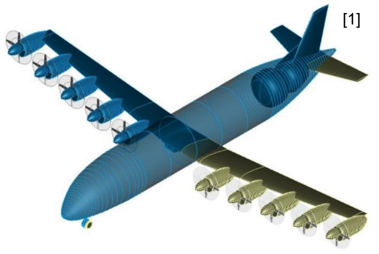
assessment
LCA of H2-FC regional jet (70 PAX)



[1]

Hypothetical DLR aircraft design study
- Power train:10 FCS* á 312 kW [2]

Simplified well-to-wheel LCA:
- German wind power + AEL hydrogen production
- w/o hydrogen leakages / aircraft / inflight emissions

* Fuel Cell System (FCS) includes stacks, hydrogen tank, compressors, humidifier, heat exchangers, pumps

[1] G. Atanasov (2022): Comparison of Sustainable Regional Aircraft Concepts, presented at Deutscher Luft- und Raumfahrtkongress (conference), Dresden, Germany
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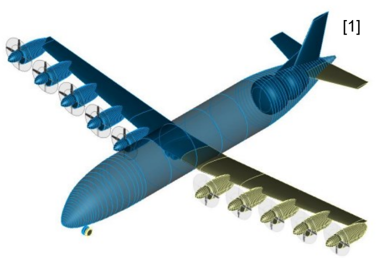
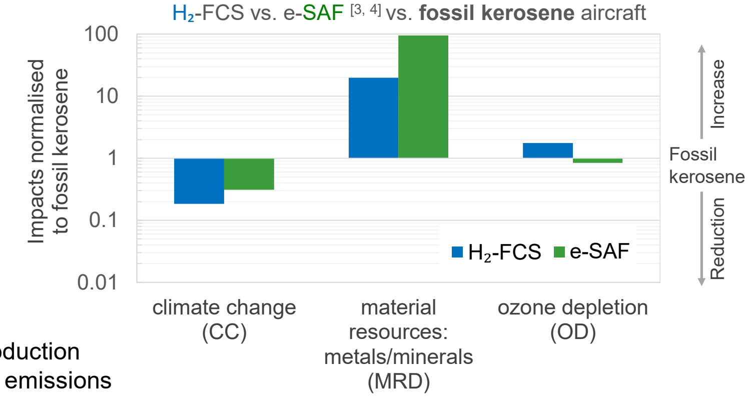


[1]

Simplified environmental impact comparison per 1 PAX*km
H_2-FCS vs. e-SAF [3, 4] vs. **fossil kerosene** aircraft



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- ➢ CC: FCS lower than SAF ☞ lower power consumption during fuel production
- ➢ MRD: FCS and SAF higher than fossil (longer supply chain) → more minerals and metals used
- ➢ OD: FCS highest impact ☞ tetrafluoroethylene for gaskets

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[3] Rojas-Michaga et al. (2023): Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment
[4] Bardow et al. (2021): Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption

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Aircraft revolution option 2
LNG and its potential in aviation [1]

- Despite clear benefits compared to hydrogen aviation, LNG studies from the 1970's and 1980's have not been continued
  - Volumetric energy density of LNG / LH2: 35% / 75% less compared to kerosene

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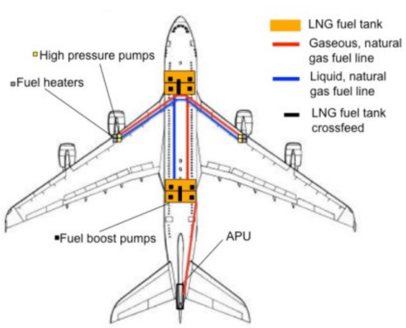
☞ <u>2012(!)</u>: LNG/CNG fuel line at commercial Jet-A airplane (A318, A300, A380) [1]



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[1] J. Gibbs, D. Seigel, and A. Donaldson, A natural gas supplementary fuel system to improve air quality and energy security, in 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2012, American Institute of Aeronautics and Astronautics

Aircraft revolution summary
Comparison of LH2/LNG/e-SAF

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[redacted]

- Simplified e-fuel assessment (far from complete)

	LH2	LNG	e-SAF
propulsion system	H2 turbine / FC to be developed	gas turbine to be adapted to aviation / SOFC to be developed	80 years of turbine improvement
Fuel is global commodity	No	Yes	Yes
Vol. energy density (fuel, excl. system)	24 %	61 %	100 %
Wet wing fuel storage	No	No	Yes
In-flight emissions	Extensive H_2O contrails, combustion: NO_x	H_2O, less: CO_2, NO_x, CH_4 slip	H_2O, CO_2, NO_x, reduced H_2S, soot

Preferred / safe | medium | Worst / risky

19 [1] taken from: M. Raab (2025) A techno-economic "Well-to-wake" evaluation of the aviation fuels LH2, LCH4 and Jet A-1. PhD Univ. Stuttgart

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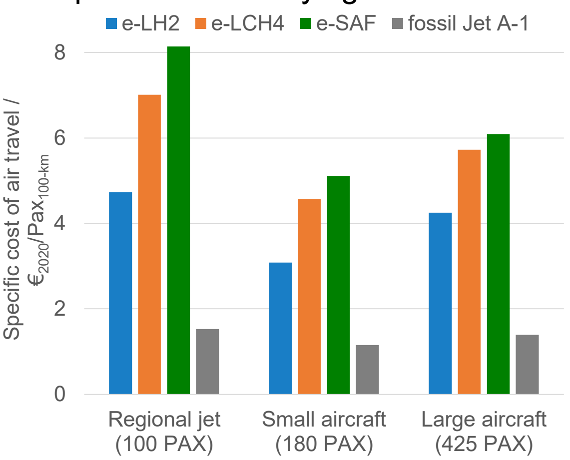
relative eFuel costs	lowest	moderate	highest
Fuel versatility	moderate	high	low

Preferred / safe | medium | Worst / risky

- Specific Cost of flying with e-fuels [1]



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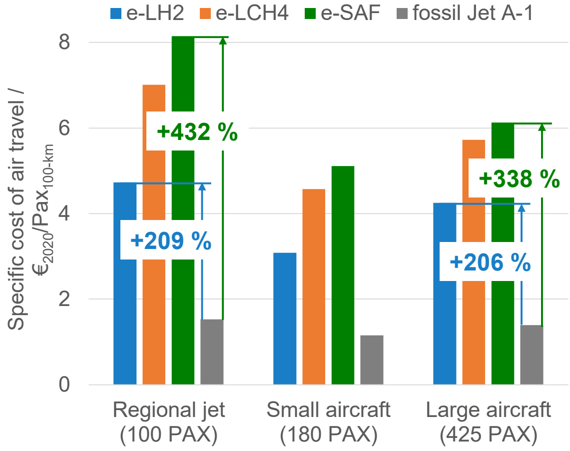

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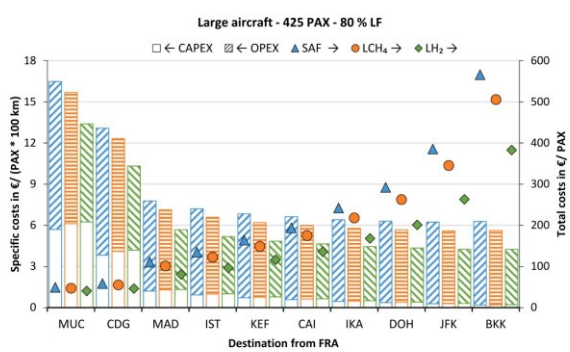
Preferred / safe | medium | Worst / risky

- Specific Cost of flying from FRA [1]
  - High CAPEX for low distance
  - Smaller cost difference at long range



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B) SUSTAINABLE AVIATION FUELS

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FT-based Biomass-to-Liquid and Power&Biomass-to-Liquid SAF [1]

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[redacted]

Challenges for sustainable aviation fuel provision in Europe:

- ReFuel EU[2] : SAF blending rate increase from 2 % (2025) to 70 % (2050)
- Unreliability regarding energy imports ☞ local production required

[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] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561 [Accessed: 31.8.2022]

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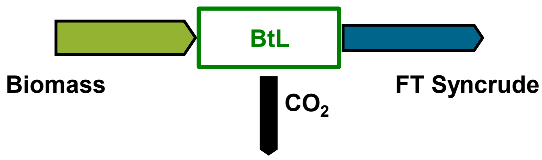

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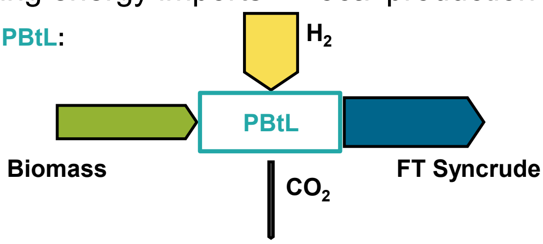
BtL vs. PBtL:



Advantages PBtL	Disadvantages PBtL
+ High conversion of limited biomass feedstock	– Additional cost for electrical power
	– Additional GHG impact due to electricity production

[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] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561 [Accessed: 31.8.2022]

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BtL versus PBtL FT-based SAF Technical Assessment

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Carbon / energy flows [1]

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

	Carbon flow	Energy flow
Winter BtL		
Summer PBtL		
50/50		

[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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[redacted]

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Technical efficiencies [1]

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

	Carbon efficiency η_C [%]	Fuel η_F | Process efficiency η_E [%]
Winter BtL	$\eta_C = 35.4$	$\eta_F = 57.6$ | $\eta_E = 77.4$
Summer PBtL	$\eta_C = 61.1$	$\eta_F = 55.2$ | $\eta_E = 73.6$
50/50	$\eta_{C,av.} = 48.3$	$\eta_{F,av.} = 56.4$ | $\eta_{E,av.} = 75.5$

[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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BtL / PBtL comparison [1]: Net Production Costs

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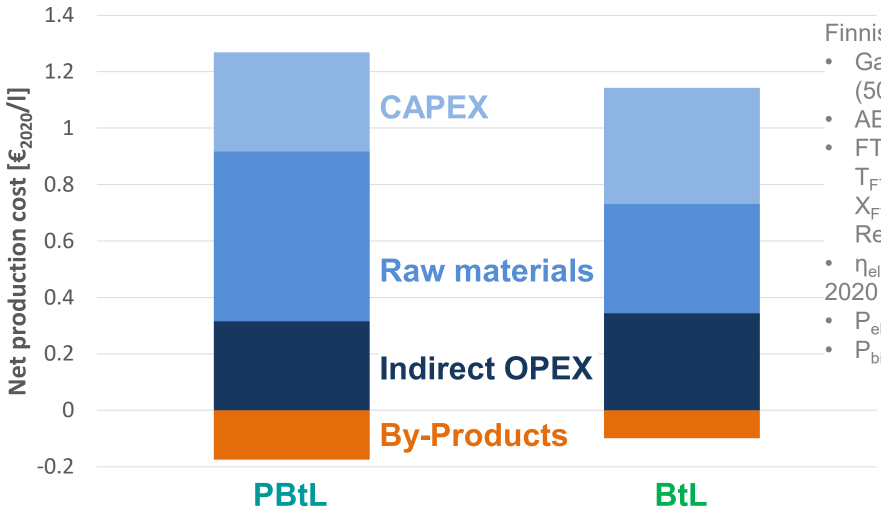
[redacted]



Finnish Base Case:
- Gasifier: small-scale SXB ($50\ MW_{th}$)
- AEL: $42\ MW_{el}$
- FT: $32\ kt_{C5+}/a$
  $T_{FT} = 230$ °C
  $X_{FT} = 55$ %
  $Recycle_{FT} = 95$ %
- $\eta_{el} = 70.8\ \%_{HHV}$

2020 Feedstock cost:
- $P_{el.} = 165$ €/GJ
- $P_{biom.} = 5$ €/GJ

[1] Habermeyer, et. al (2023) Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. Biomass Conversion and Biorefinery. Springer Nature. doi: 10.1007/s13399-022-03671-y. 723774

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Sensitivity of PBtL CO_2 recycle [1]
Carbon efficiency / AEL capacity

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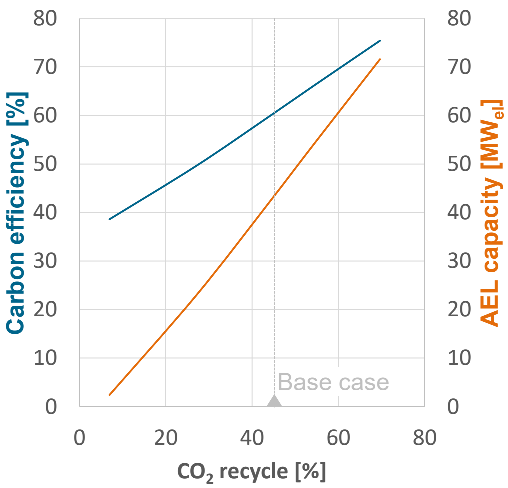

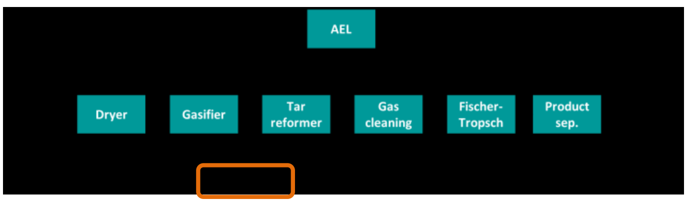

More CO_2 recycle to the gasifier:
\+ Less steam addition to the gasifier, less heat demand
\+ Increase carbon efficiency, product yield
– Higher H2 demand, electricity and electrolyzer

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

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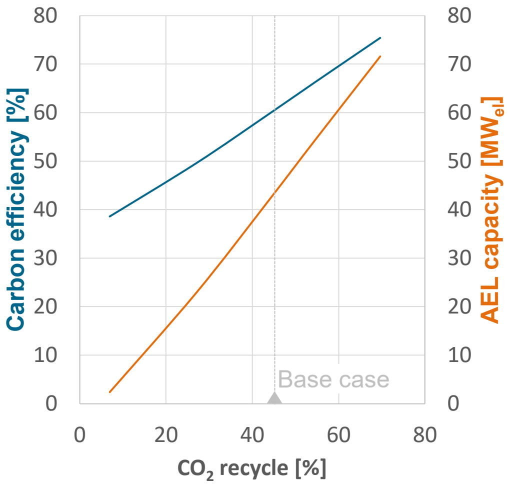

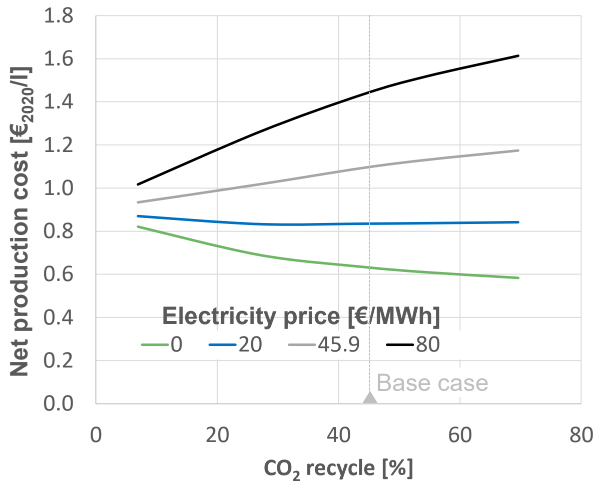

33 [1] Habermeyer, F.; Weyand, J.; Maier, S.; Kurkela, E.; Dietrich, R.-U. (2023) Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. Biomass Conversion and Biorefinery. doi: 10.1007/s13399-022-03671-y.

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Sensitivity of BtL / PBtL SAF net production cost (NPC)

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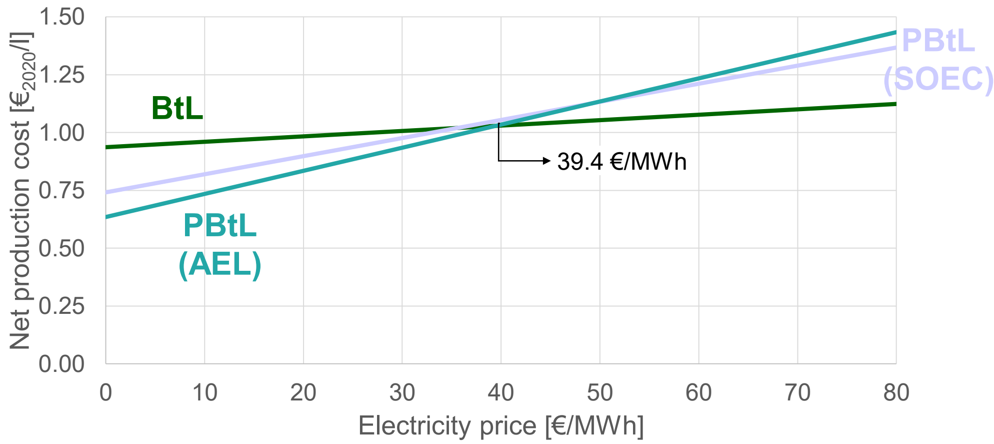
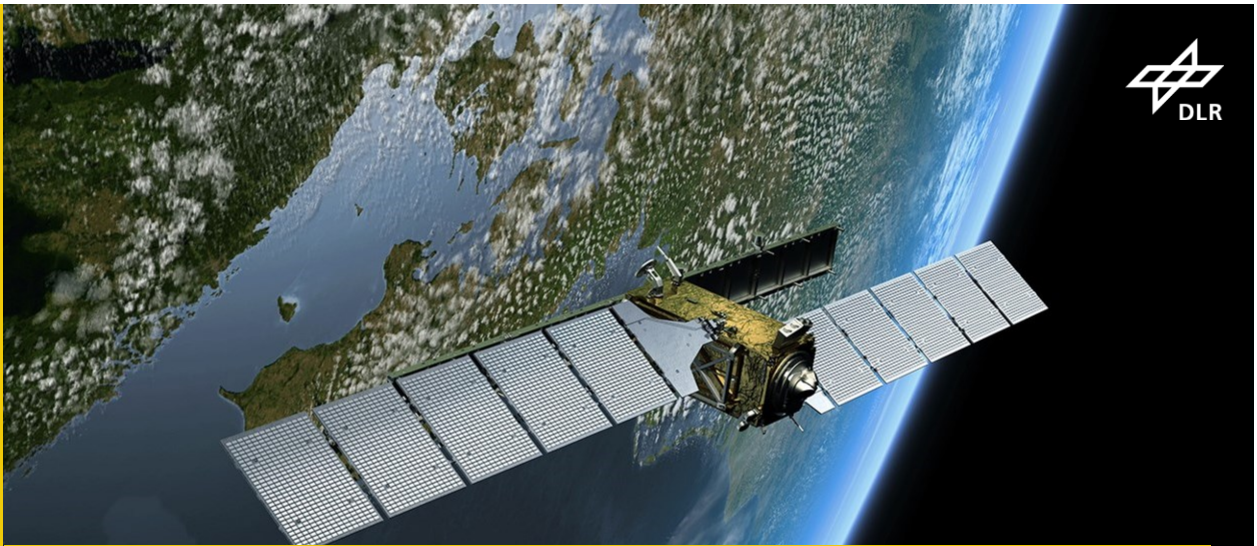
[redacted]

Net production cost sensitivity [1]:



34 [1] Habermeyer, et. al (2023) Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. Biomass Conversion and Biorefinery. Springer Nature. doi: 10.1007/s13399-022-03671-y. 723774



ENVIRONMENTAL ASSESSMENT OF FT-SAF

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

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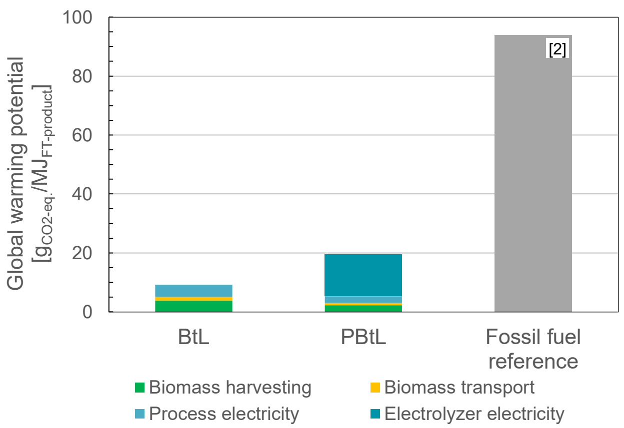

- **Transportation: 100 km, one-way by truck (69 $g_{CO2-eq.}/(t*km)$)**
- **Biomass: Forest residues harvesting (19.7 $g_{CO2-eq.}/kg$)**
- **Electricity: Finnish grid @2020 (68.6 $g_{CO2-eq.}/kWh$)**

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

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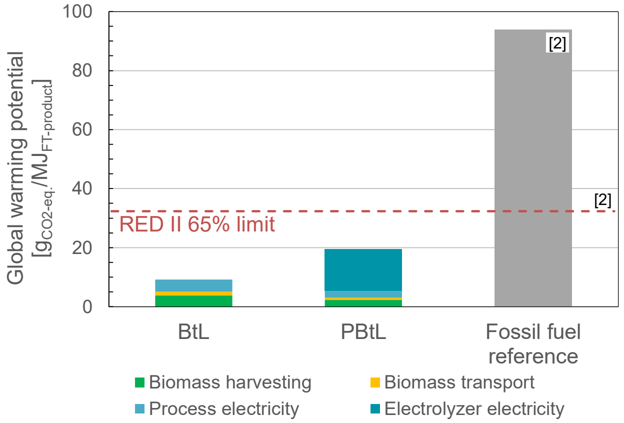

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- **Electricity: Finnish grid @2020 (68.6 $g_{CO2-eq.}$/kWh)**

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.

37 [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

GWP sensitivity of BtL / PBtL

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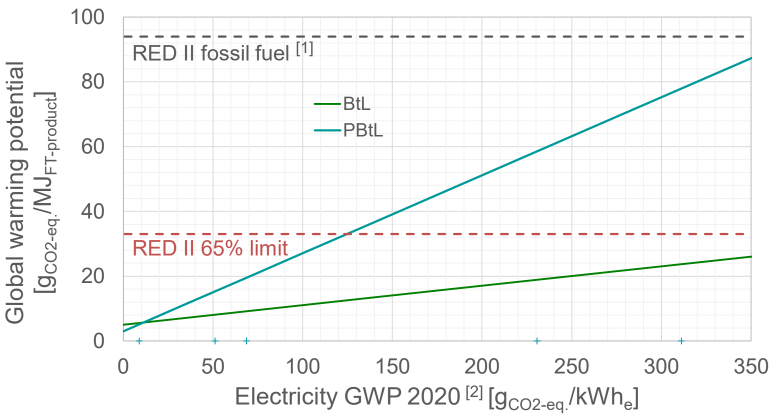

[1] European Union (2018) "Directive 2018/2001 of the European Parliament … on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

38 [2] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111

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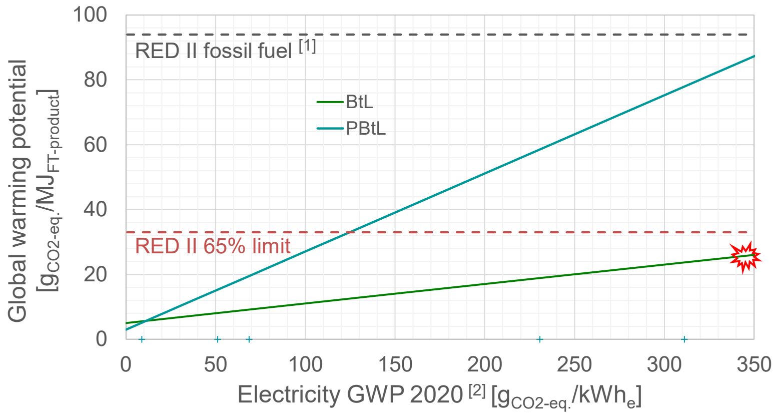

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL

[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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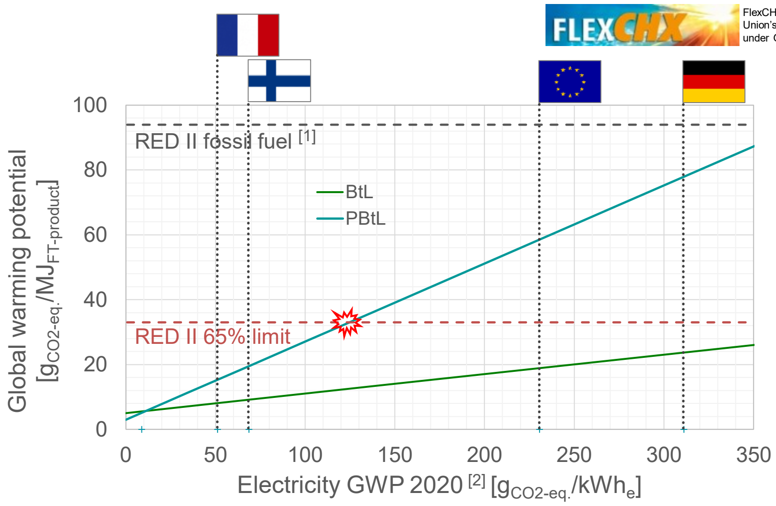

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with GWP <120 $g_{CO2-eq.}/kWh_e$ to reach REDII 65 % limit

[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
[2] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111

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GWP sensitivity of BtL / PBtL

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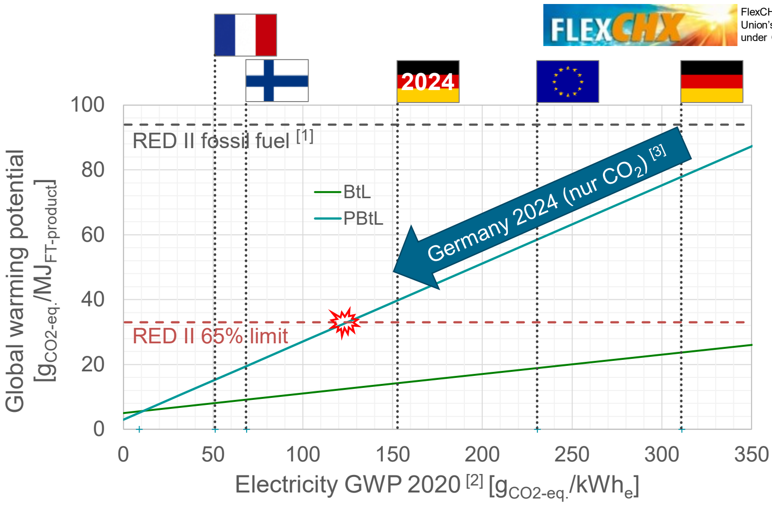

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[2] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111
[3] Fh ISE (2025) Öffentliche Stromerzeugung 2024: Deutscher Strommix so sauber wie nie. https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/2025/oeffentliche-stromerzeugung-2024-deutscher-strommix-so-sauber-wie-nie.html

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GWP sensitivity of BtL / PBtL

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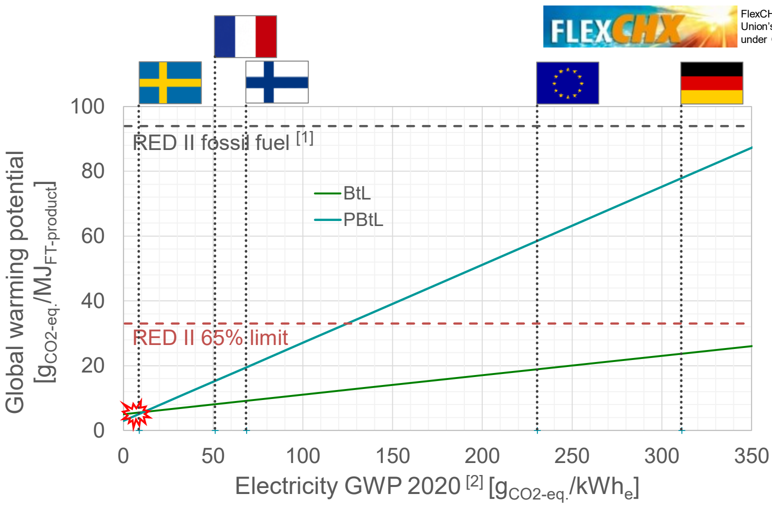

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with GWP <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit
- PBtL could have lower GWP than BtL with Swedish grid mix

[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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TOWARDS A EUROPEAN SAF ROADMAP

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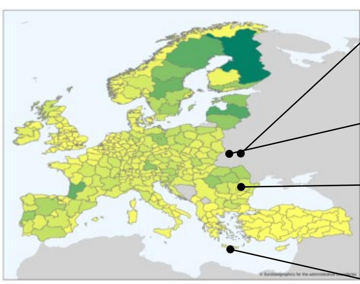
Local **PBtL** production potential
TEPET linked to Aspen Plus

For feedstock potential: TEEA for 300 NUTS2 regions



- Biomass density[2]: (⅓ of forest residue) +Transport distance
- Local labor cost[3]
- National grid:
  - Price[4]
  - GHG footprint[5]
- Biomass price[2]

NUTS2 regions specific results:

- Local fuel production cost
- Local fuel production GWP
- Local fuel potential

Key economic assumptions: see [1]

[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]; Available from: https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tabgooglechartid_googlechartid_googlechart_chart_1111.

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Local PBtL potential
Grid based: Northern Europe

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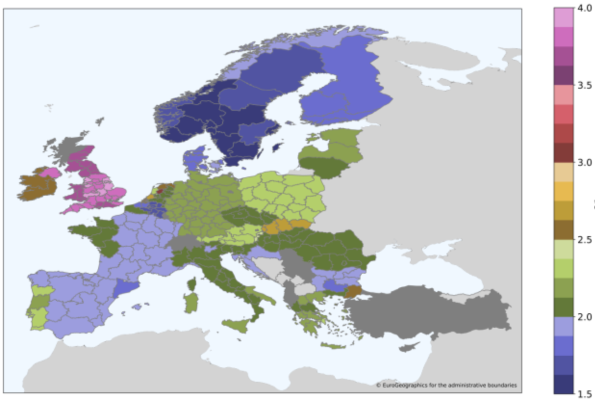
[redacted]

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



Net Production cost

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

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Local PBtL potential
Grid based: Northern Europe

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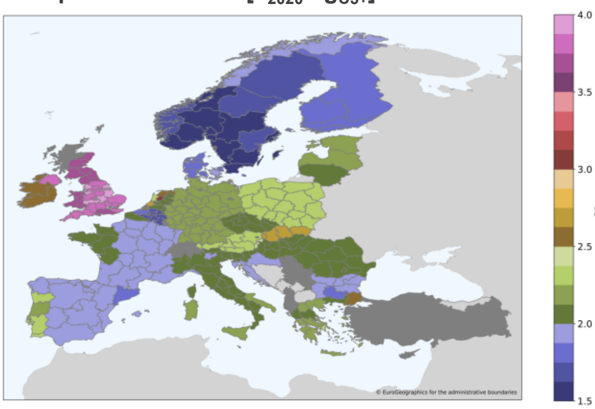
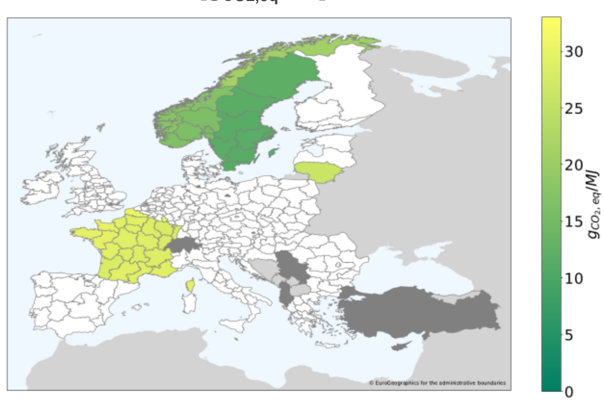
[redacted]

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 power production in most European countries

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Local PBtL potential
On-shore wind: Costal regions

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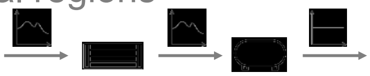
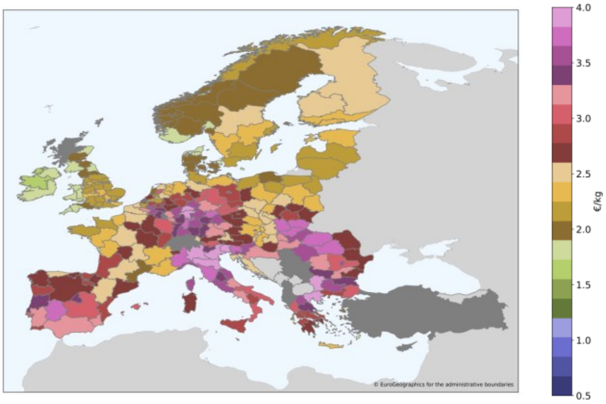
[redacted]

Hydrogen storage included:



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



Net Production cost

+ High full load hours of wind power required

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Local PBtL potential
On-shore wind: Costal regions

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[redacted]

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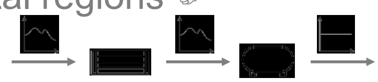
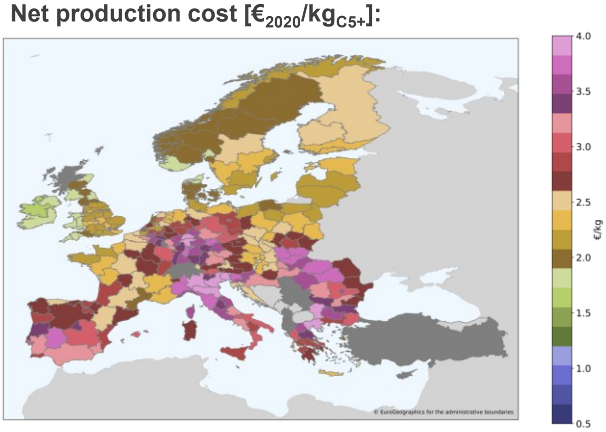
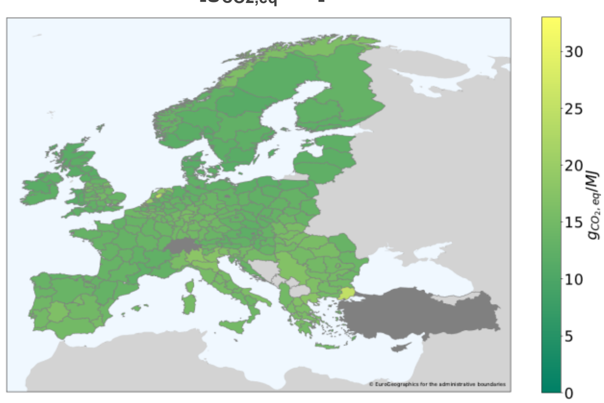


Net production cost [$€_{2020}/kg_{C5+}$]:



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



Net Production cost	Greenhouse Gas Abatement
+ High full load hours of wind power required	– No Net Zero SAF anywhere

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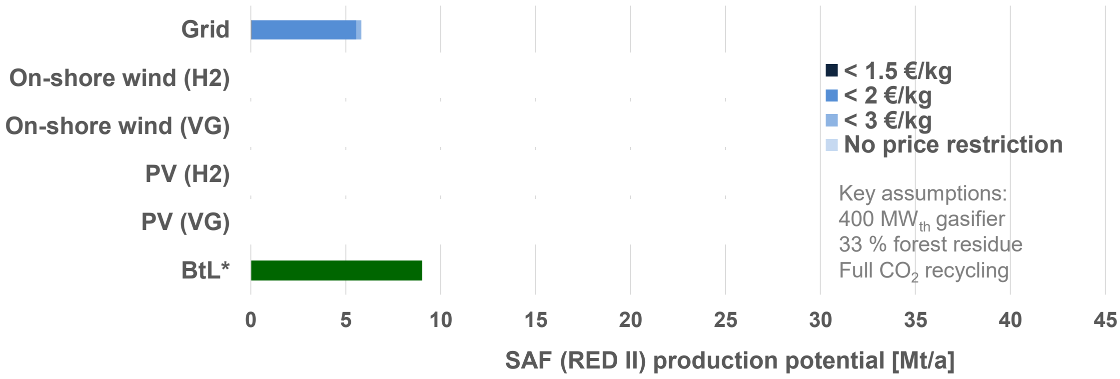
[redacted]

PBtL potential for Europe
Aggregated SAF potential



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

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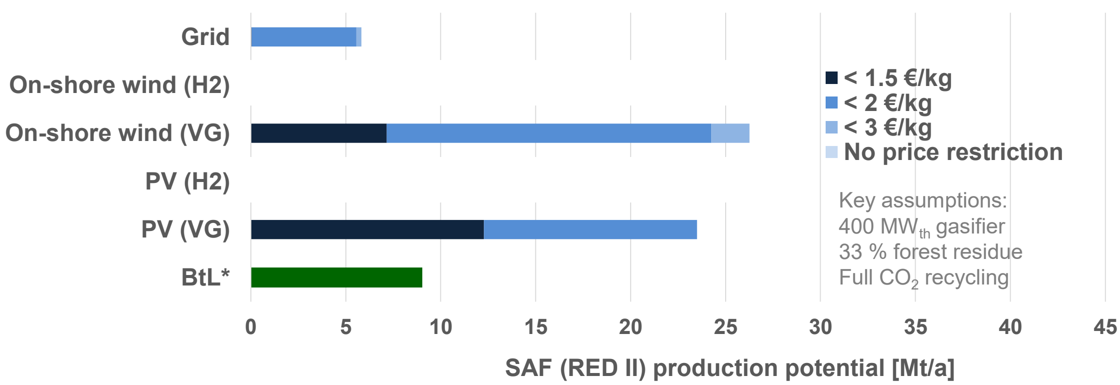
[redacted]

PBtL potential for Europe
Aggregated SAF potential



Virtual grid (VG)

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

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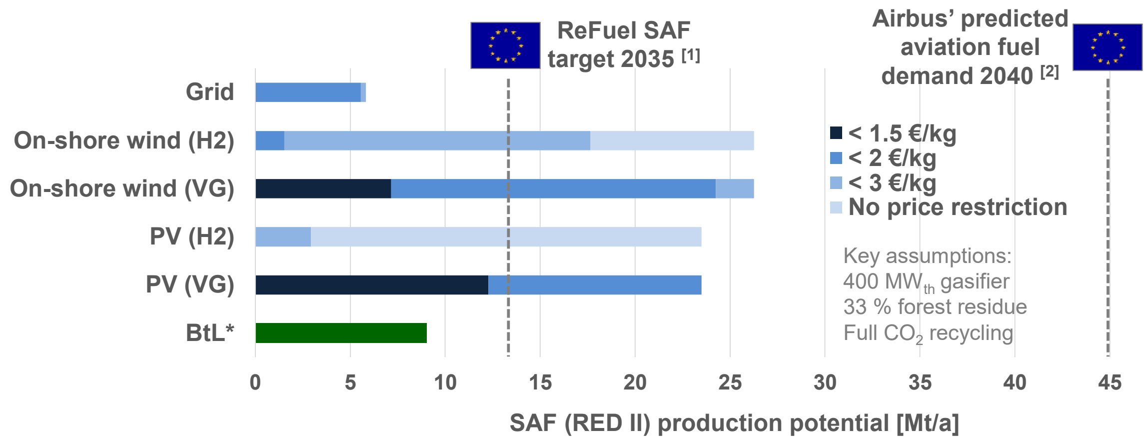
PBtL analysis for Europe
Aggregated SAF potential



Virtual grid (VG)

Hydrogen storage (H2)

[1] … ensuring a level playing field for sustainable air transport [Online] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561. SAF should account for at least 5% of aviation fuels by 2030 and 63% by 2050,
[2] Airbus Global Market forecast 2021 – 2040 [Online] https://www.airbus.com/en/newsroom/press-releases/2021-11-airbus-foresees-demand-for-39000-new-passenger-freighter-aircraft (Accessed 02/2022)
*Assumptions: 19.9 % biomass conversion, entire potential under RED II limit

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Toward Sustainable Aviation in Europe

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20 & 21 January 2025 | CityCube, Messe Berlin
"Into the future - driven by climate protection!"

[redacted]

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Dietrich et. al • Assessment of Technologies and Fuels for Future Sustainable Aviation • Dietrich, et. al • Berlin • 21st January 2025

Toward Sustainable Aviation in Europe

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- DLR provides standardized assessment for any aviation technology, feedstock, location, regulation, … !

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Tuesday, 21. January 2025
Session 4D, ROOM M8:
Advanced alternative fuels – From research to practice

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THANK YOU FOR YOUR KIND ATTENTION!

QUESTIONS?

Techno-Economic and Ecological Assessment of Aviation Technologies and Fuels

Ralph-Uwe Dietrich (ralph-uwe.Dietrich@dlr.de),
Rahnuma Bhuiyan Evon, Felix Habermeyer,
Simon Maier, Moritz Raab, Julia Weyand

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