DAY 3 - Thursday, 17. September 2026

Topic: 13 System Analysis, LCA & Sustainability Assessment

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Science and Industry in Dialogue

SUSTAINABLE AVIATION DREAM AND ROADMAP

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

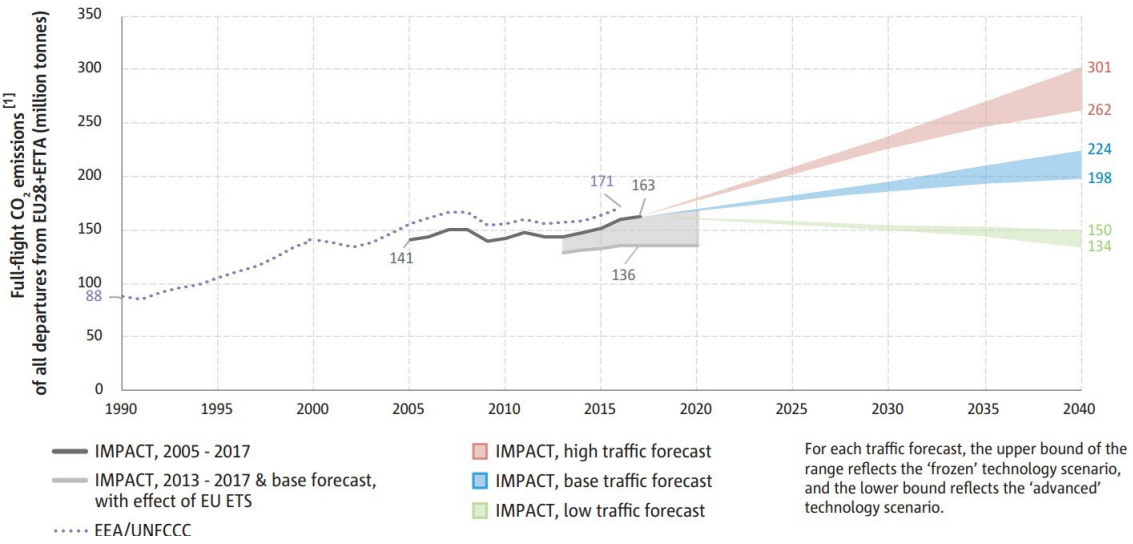
Ralph-Uwe Dietrich, Rahnuma Bhuiyan Evon, Moritz Raab, Janmejai Sharma, Julia Weyand (DLR e.V., www.DLR.de/tt)

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Problem: EU aviation CO_2 emissions

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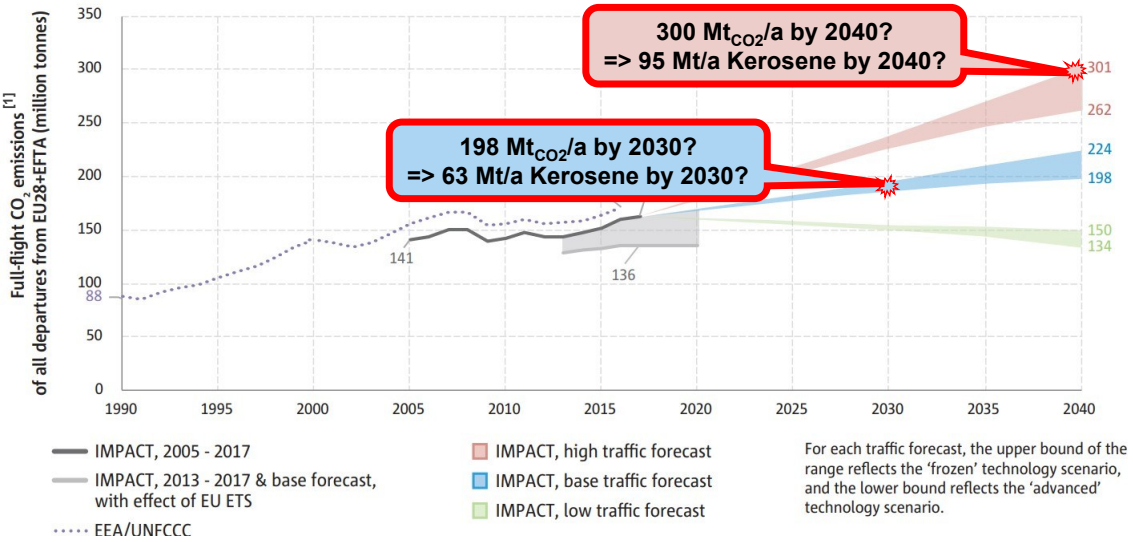
[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf

2

Problem: EU aviation CO_2 emissions
Solution: SAF

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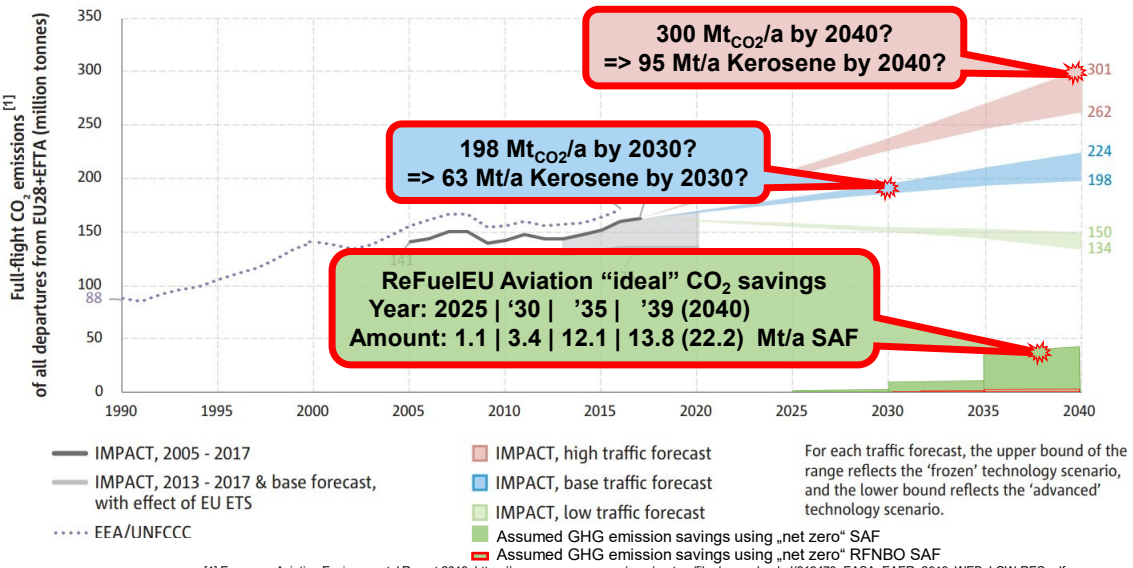
[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf

3

Problem: EU aviation CO_2 emissions
Solution: SAF - ReFuelEU Aviation (a little)

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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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Civil aviation CO_2 emissions [1]
CO_2 abatement per segments

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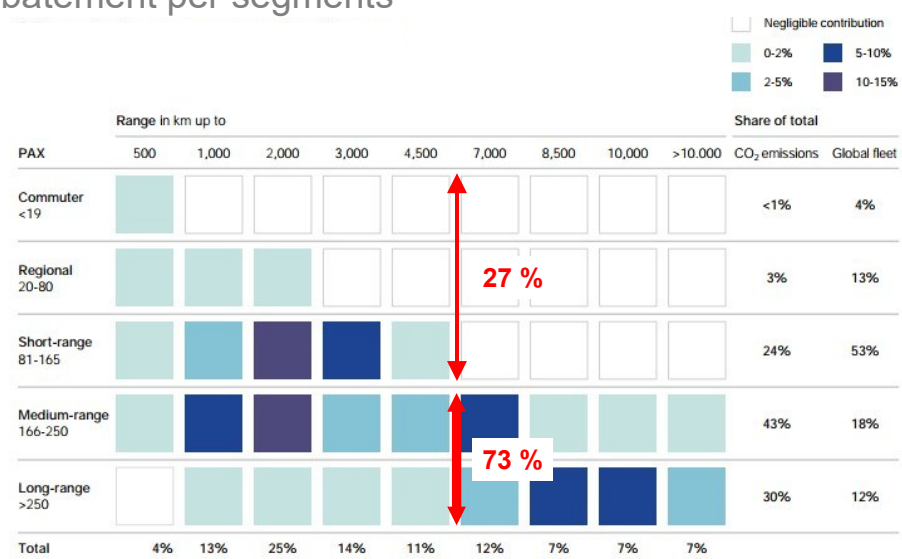
5 [1] FCH-JU (2020) Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050. **DOI:** 10.2843/471510

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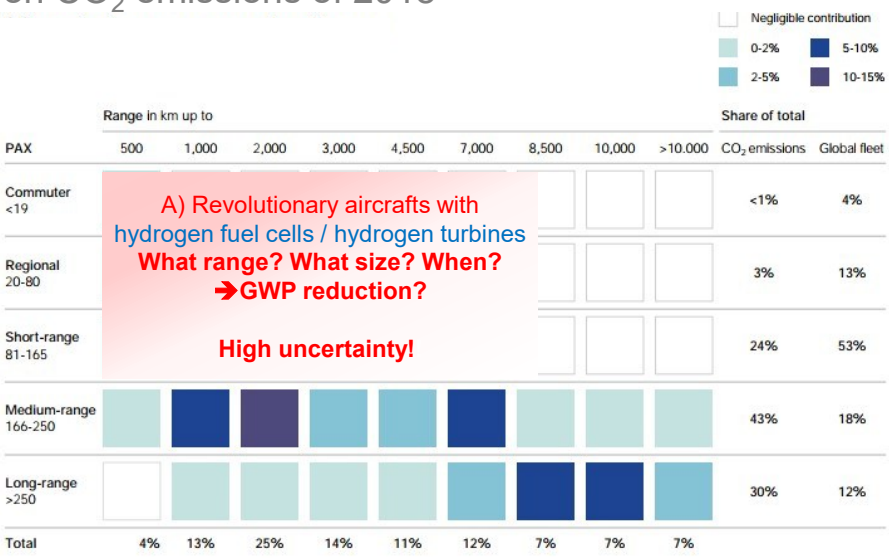


6 [1] FCH-JU (2020) Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050. **DOI:** 10.2843/471510

Aircraft Revolution/Evolution Roadmap
Based on CO_2 emissions of 2018 [1]

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A) Revolutionary aircrafts with hydrogen fuel cells / hydrogen turbines
What range? What size? When?
➔GWP reduction?

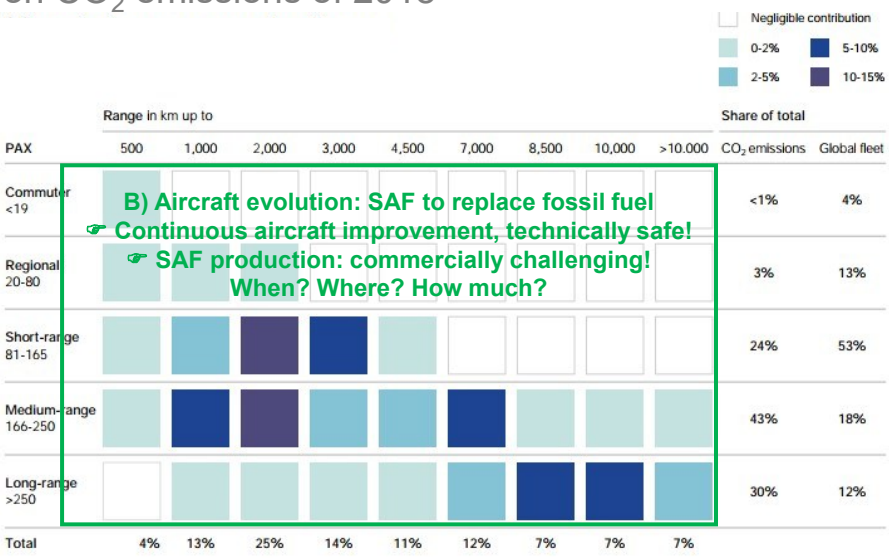
High uncertainty!

[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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B) Aircraft evolution: SAF to replace fossil fuel
☛ Continuous aircraft improvement, technically safe!
☛ SAF production: commercially challenging!
When? Where? How much?

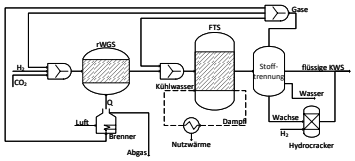
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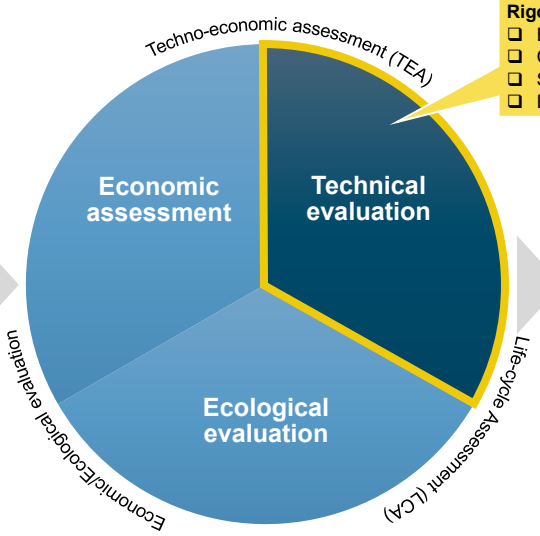
Techno-Economic and Life Cycle Assessment @ DLR

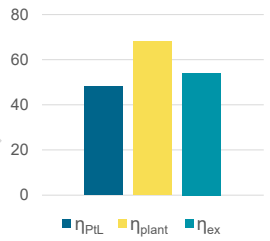
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Rigorous process simulation
- ❑ Efficiencies (X-to-Liquid, Overall)
- ❑ Carbon conversion
- ❑ Specific feedstock demand
- ❑ Exergy analysis







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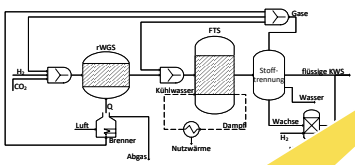
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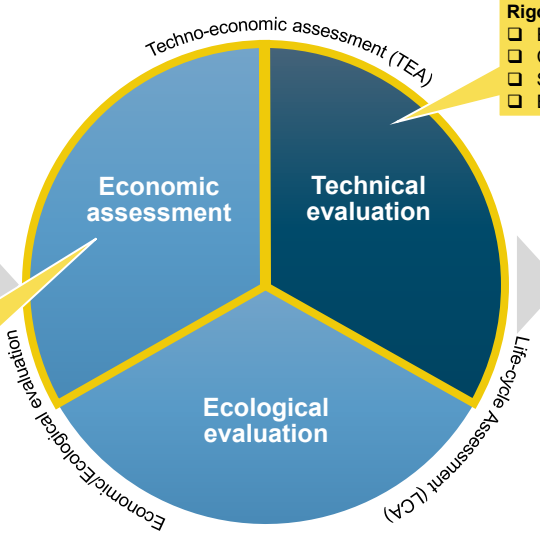
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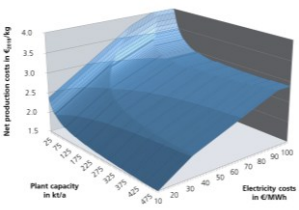
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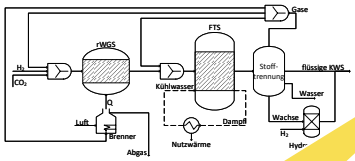
Chemical engineering cost estimation
- ❑ Year-specific CAPEX, OPEX, NPC
- ❑ Sensitivity analysis
- ❑ Identification of most economic feasible process design

10

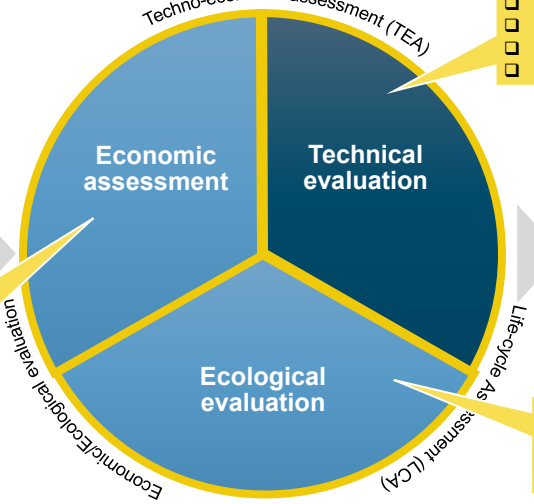
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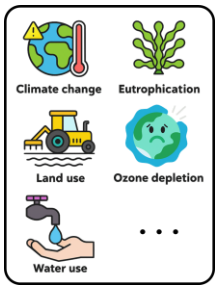
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Adapted ISO 14040/14044 LCA
- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

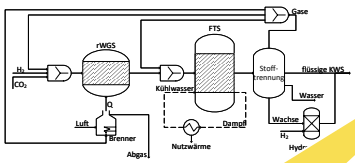
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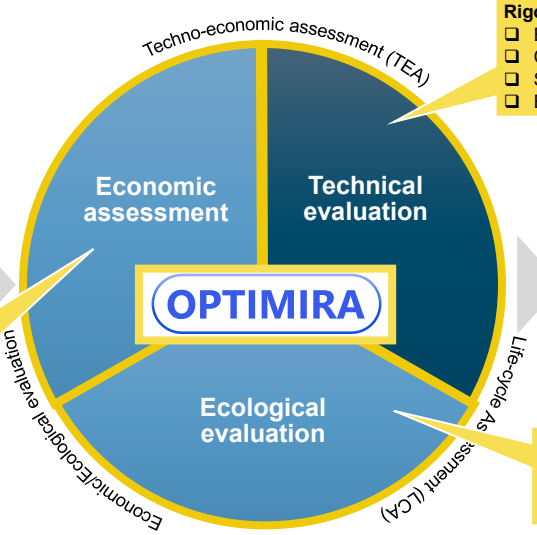
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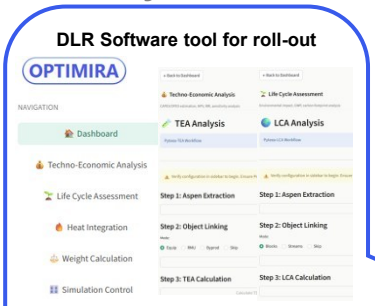
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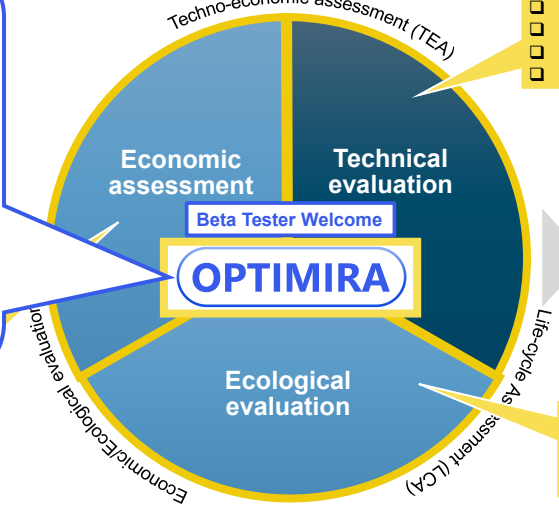
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DLR Software tool for roll-out



- **Seamless Integration**: Connect Aspen flowsheet via OPTIMIRA (NO upload of sensitive data).
- **Automated Assessments**: Execute comprehensive TEA, LCA, Heat Integration (HI), and more.
- **Advanced Optimization**: Transform standard process models into multidimensional analytical tools with simulation control and variation runs.

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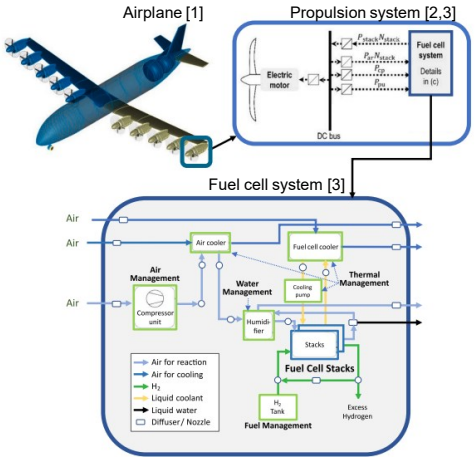
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Aircraft revolution LCA[3]
H2 fuel-cell power train impact

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Hypothetical DLR aircraft design study: D70-Electric
- Regional jet design (70 PAX)
- FL290, Ma = 0.55, L/D = 21
- η_{Prop} = 0.9, η_{Batt} = 0.9
- $m_{Aircraft}$ = 30 t

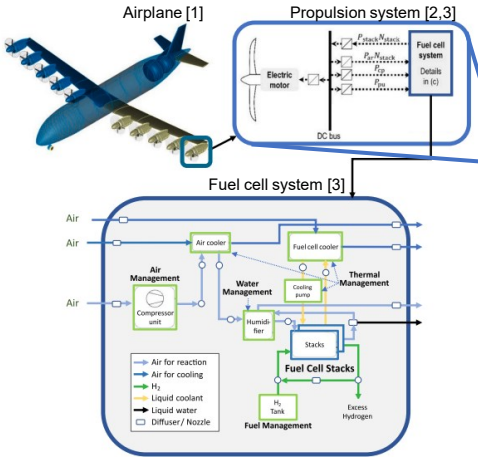
[1] G. Atanasov (2022): Comparison of Sustainable Regional Aircraft Concepts, presented at Deutscher Luft- und Raumfahrtkongress, Dresden, Germany
[2] Schröder et al. (2024): Optimal design of proton exchange membrane fuel cell systems for regional aircraft
[3] Evon, Rahnuma B. und Weyand, Julia und Juschus, Daniel und Schröder, Matthias und Gentner, Christoph und Dietrich, Ralph-Uwe und Ansar, Syed Asif (2026) Life Cycle Assessment of Hydrogen-powered Fuel Cell System for Regional Aviation - Methodology Development and Preliminary Results. International Journal of Hydrogen Energy, doi: 10.1016/j.ijhydene.2025.152527

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Aircraft revolution LCA[3]
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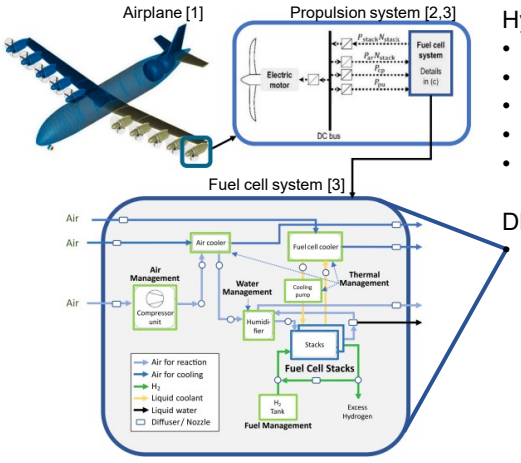
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Aircraft revolution LCA[3]
H2 fuel-cell power train impact

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DLR regional jet design (70 PAX) flight impact
- Detailed H2 fuel-cell **LCA**

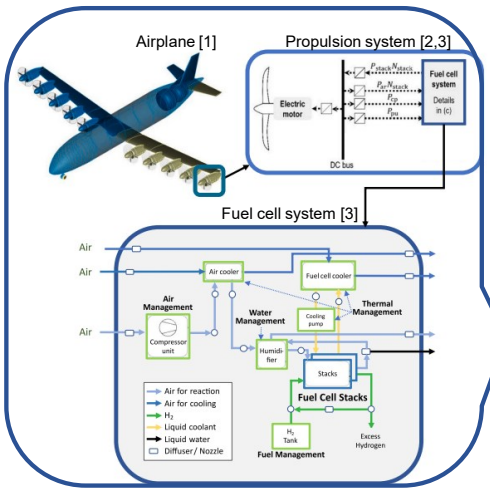
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Aircraft revolution LCA[3]
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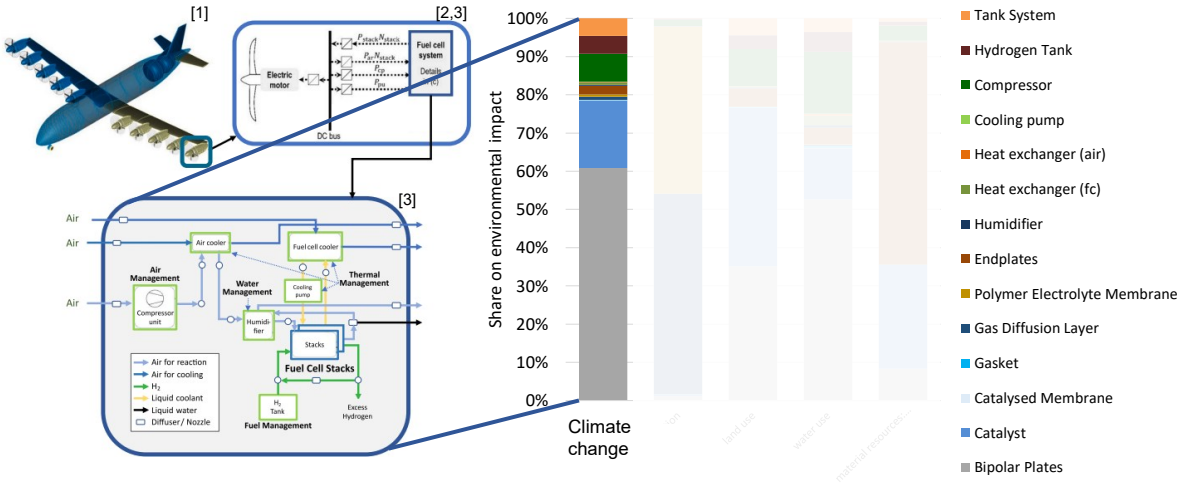
Simplified **flight well-to-wheel LCA**
- German wind power + AEL hydrogen production+liquefaction
- w/o hydrogen leakages / aircraft / inflight emissions

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Aircraft revolution LCA[3]
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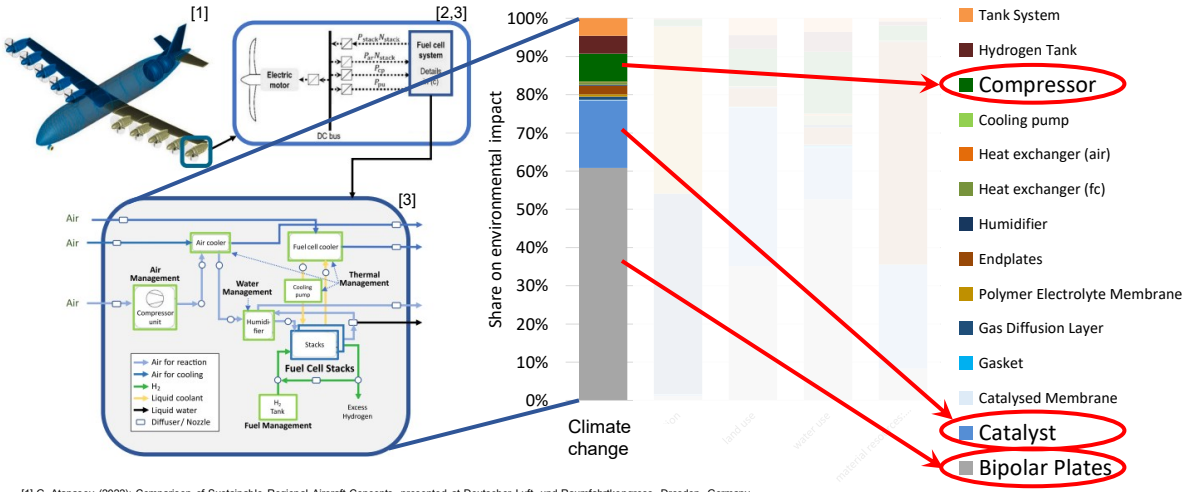
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Aircraft revolution LCA[3]
H2 fuel-cell power train impact

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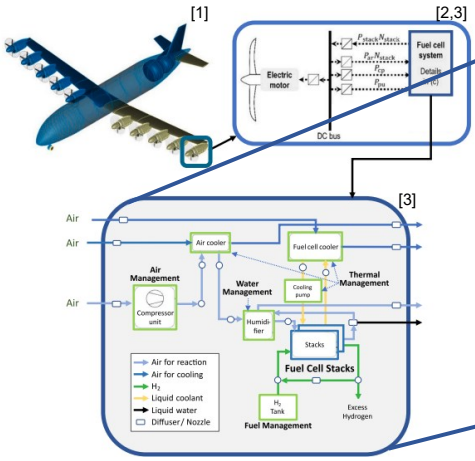


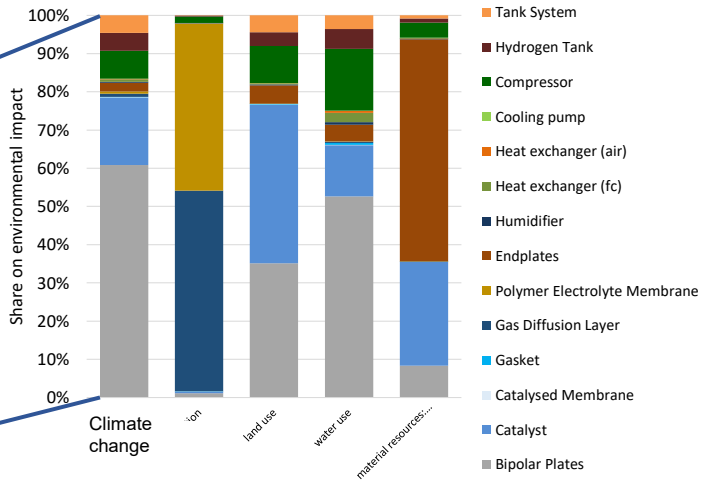
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Aircraft revolution LCA[3]
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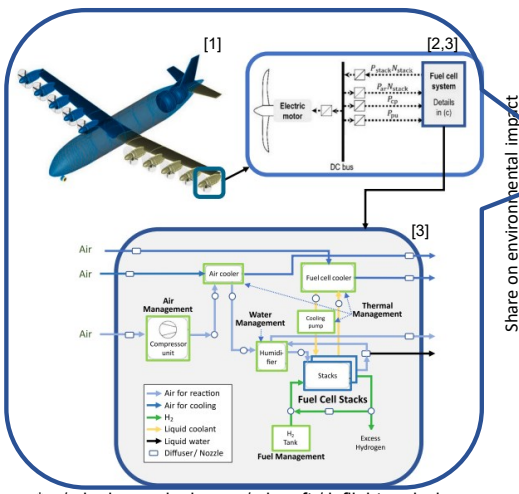


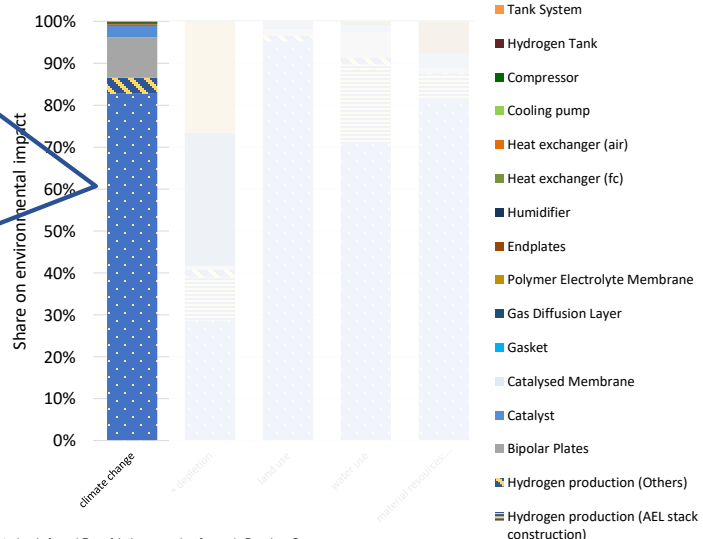
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Aircraft revolution LCA[3]
H2 fuel-cell jet design (70 PAX) flight impact*

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* w/o hydrogen leakages / aircraft / inflight emissions

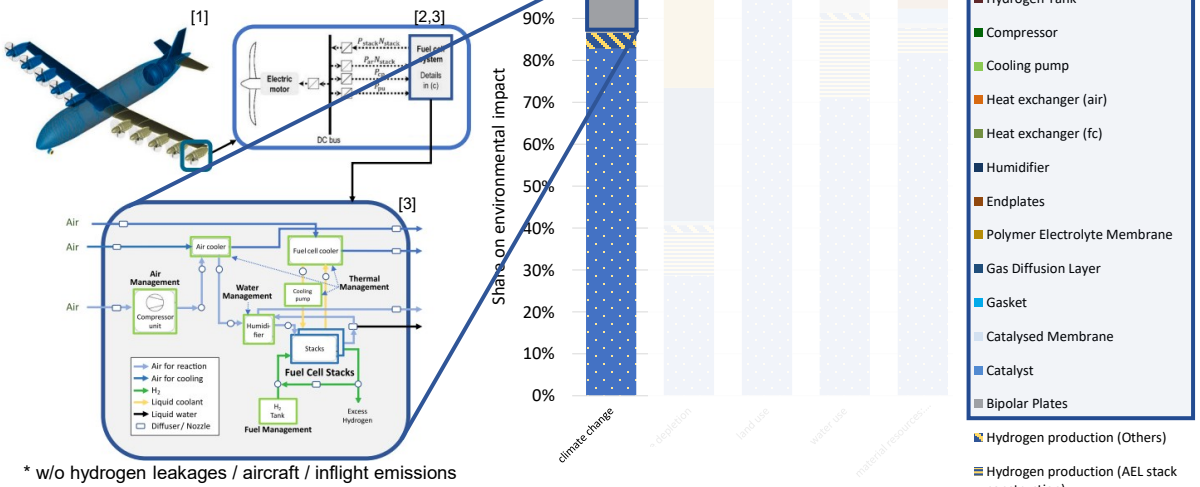
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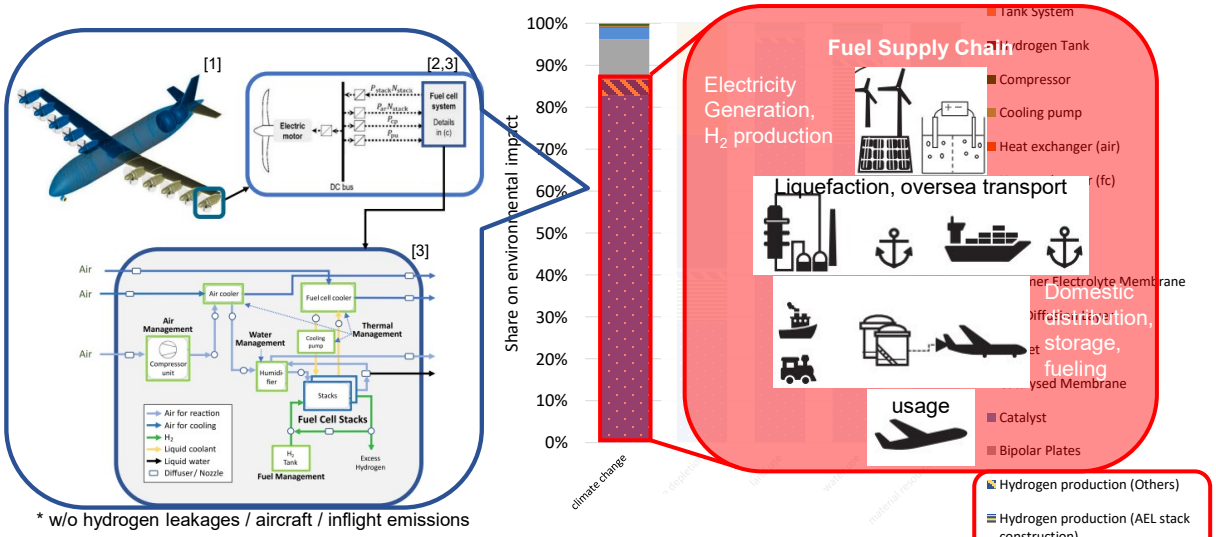
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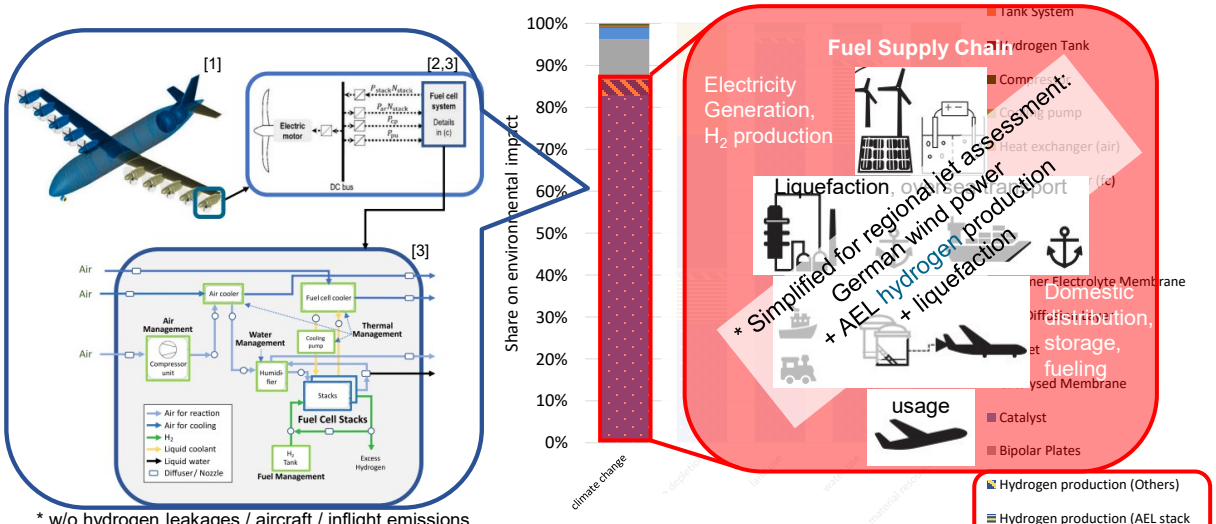


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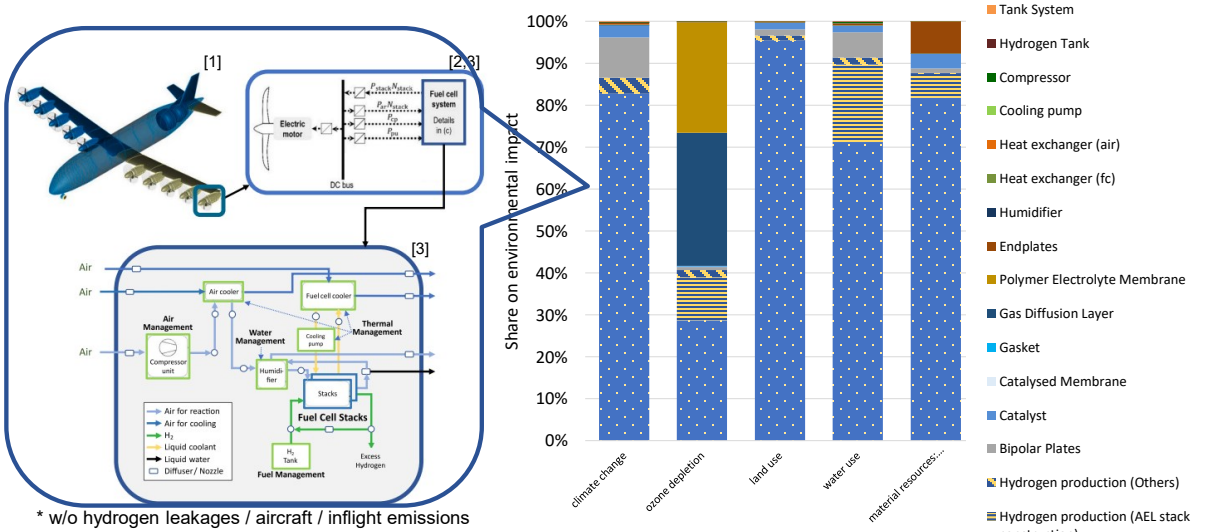
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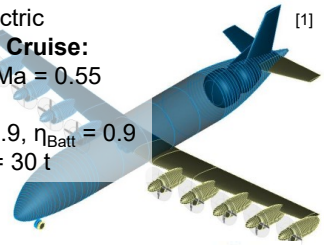
26

Aircraft revolution LCA [3]
H2 fuel-cell versus SAF flight impact*

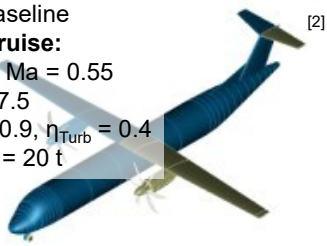
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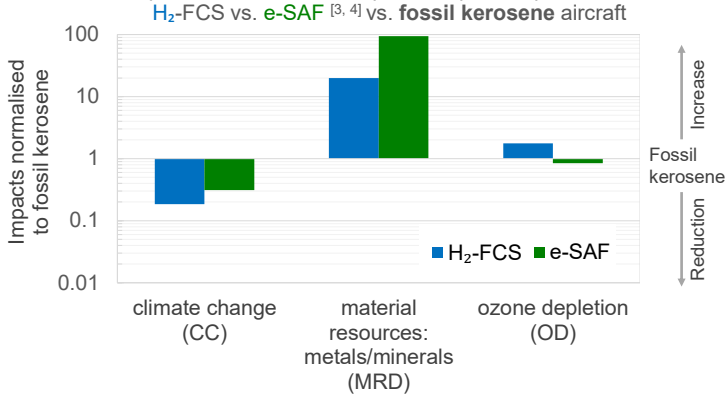
D70-Electric [1]
Electric Cruise:
FL290, Ma = 0.55
L/D = 21
η_{Prop} = 0.9, η_{Batt} = 0.9
$m_{Aircraft}$ = 30 t



D70-Baseline [2]
SAF Cruise:
FL290, Ma = 0.55
L/D =17.5
η_{Prop} = 0.9, η_{Turb} = 0.4
$m_{Aircraft}$ = 20 t



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



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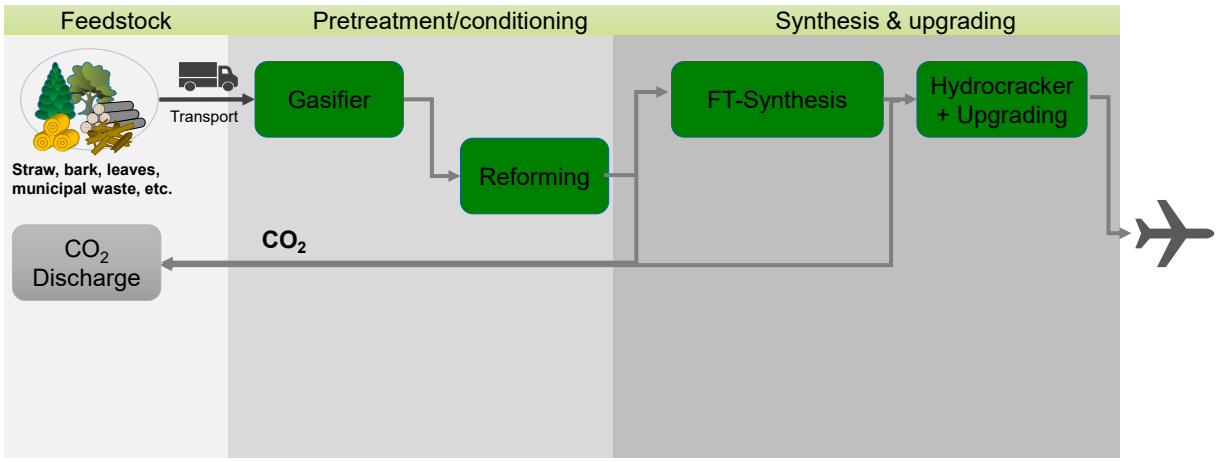
27



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Fischer-Tropsch based SAF concepts

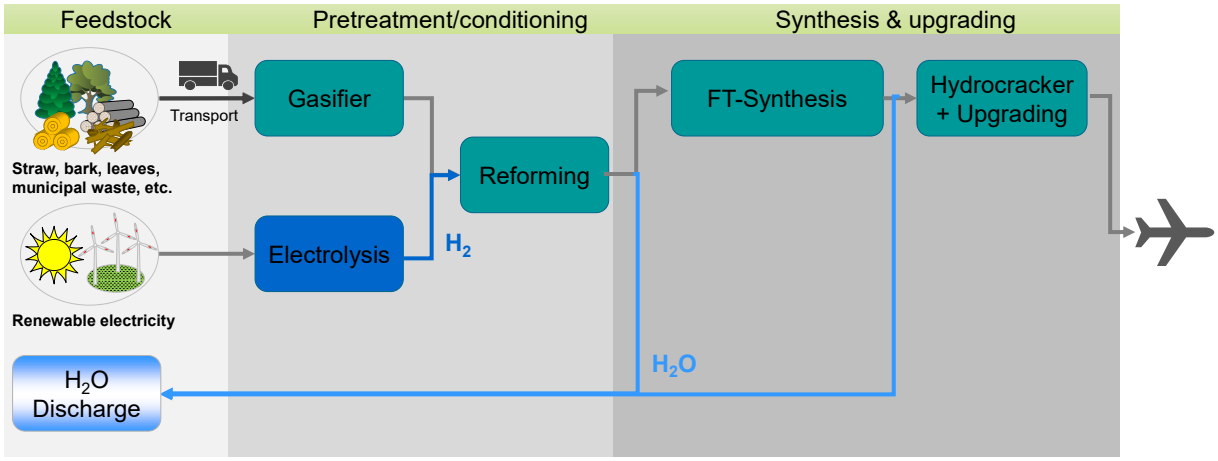
Biomass-to-FT-jet (FT-BtL)



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Fischer-Tropsch based SAF concepts

Power&Biomass-to-FT-jet (FT-PBtL)



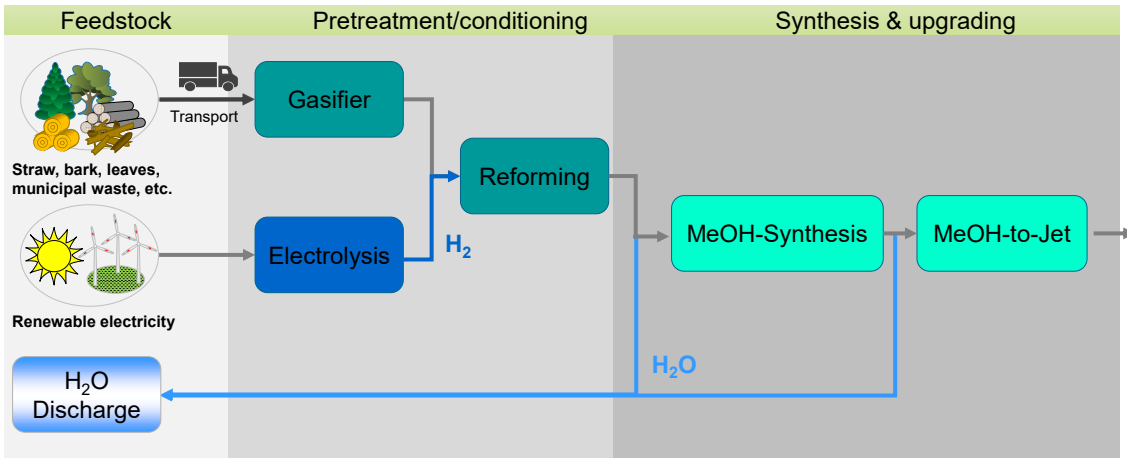
30

Methanol-to-Jet SAF concepts

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Power&Biomass-Methanol-to-jet (MeOH-PBtL)

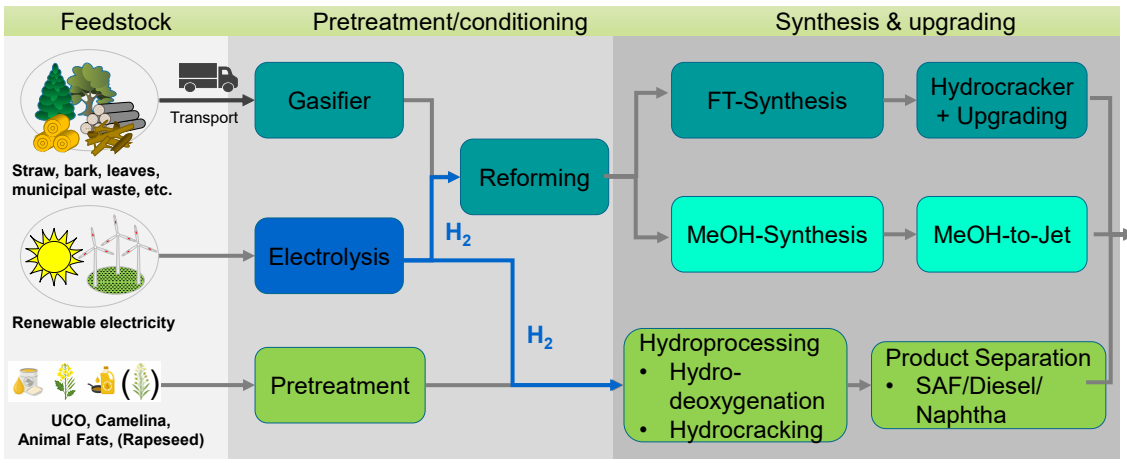


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European feedstock based SAF concepts

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FT based SAF concepts compered to HEFA
Stochiometric preference

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Power-to-Liquid (PtL)

$$\Delta H^0_{F,byproduct} = -484\ kJ \rightarrow -484\ \frac{kJ}{(CH_2)}$$

$$CO_2 + 3\ H_2 \rightarrow -CH_2- + 2\ H_2O$$

Biomass-to-Liquid (BtL)

$$\Delta H^0_{F,byproduct} = -394\ kJ \rightarrow -131\ \frac{kJ}{(CH_2)}$$

$$2\ C_2H_3O^* \rightarrow 3\ -CH_2- + CO_2$$

Power&Biomass-to-Liquid (PBtL)

$$\Delta H^0_{F,byproduct} = -484\ kJ \rightarrow -121\ \frac{kJ}{(CH_2)}$$

$$2\ C_2H_3O^* + 6\ H_2 \rightarrow 4\ -CH_2- + 2\ H_2O$$

Palm-oil-to-HEFA

$$\Delta H^0_{F,byproduct} = -484\ kJ \rightarrow -30\ \frac{kJ}{(CH_2)}$$

$$C_{16}H_{32}O_2{}^{**} + 2\ H_2 \rightarrow 16\ -CH_2- + 2\ H_2O$$

* Example: woody biomass elemental mass composition: $C_{52.1}H_{6.1}O_{38.5}X_{2.9}$
** Example: palmitic acid elemental molar composition: $C_{16}H_{32}O_2$

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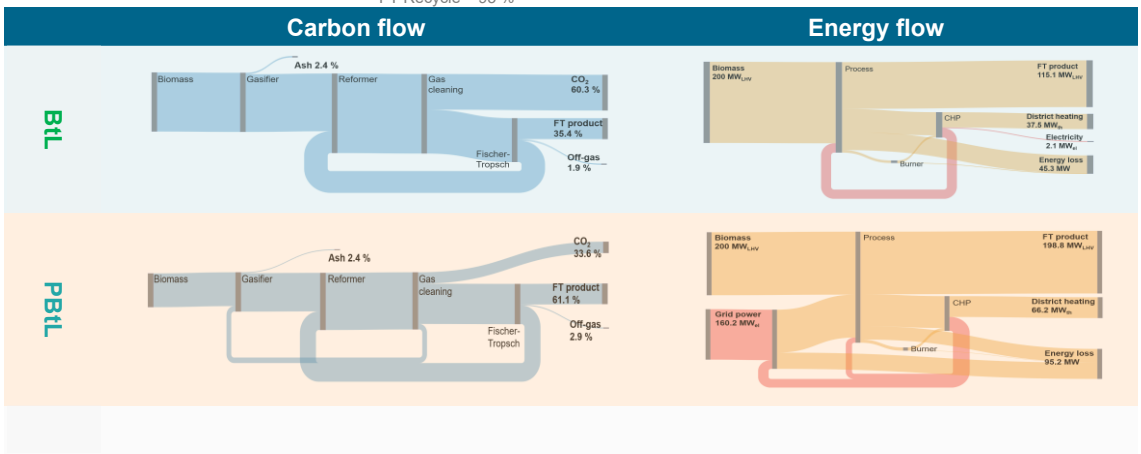
FT based SAF concepts
Technical assessment of BtL / PBtL PFD

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Carbon / energy flows [1]

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



[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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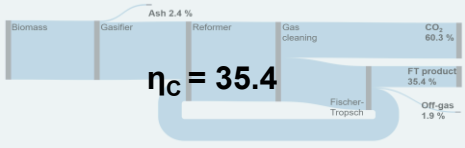
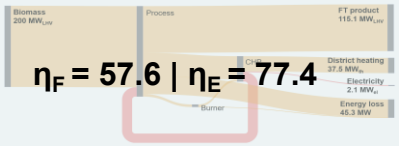
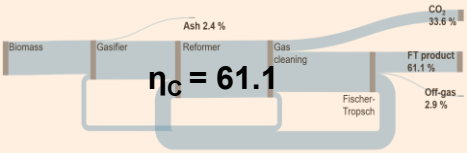
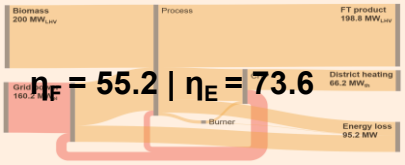
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Technical efficiencies [1]

Key assumptions:
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H_2/CO = 2.05
FT-Recycle = 95 %

	Carbon efficiency η_C [%]	Fuel η_F | Process efficiency η_E [%]
BtL	 η_C = 35.4	 η_F = 57.6 | η_E = 77.4
PBtL	 η_C = 61.1	 η_F = 55.2 | η_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

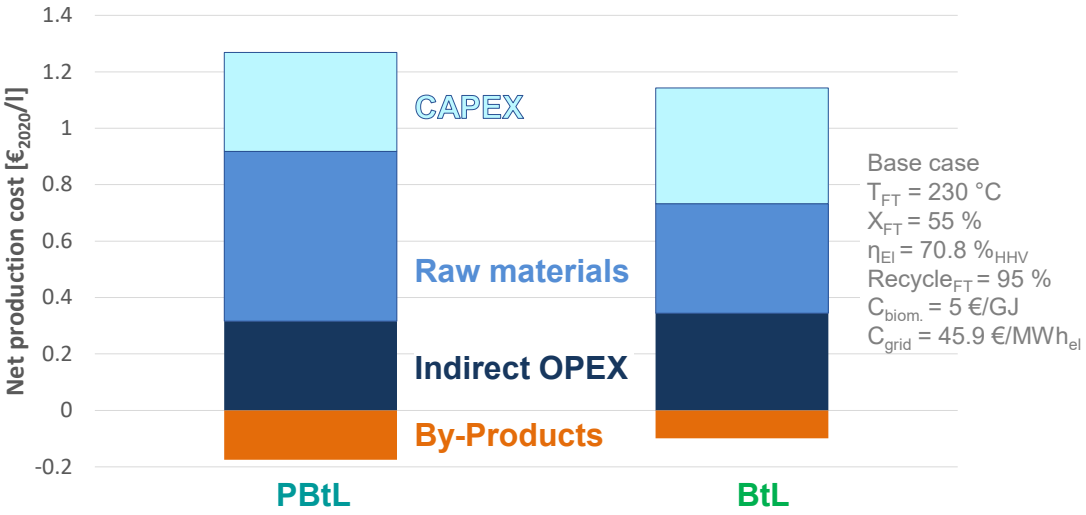
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BtL / PBtL comparison [1]: Net Production Costs

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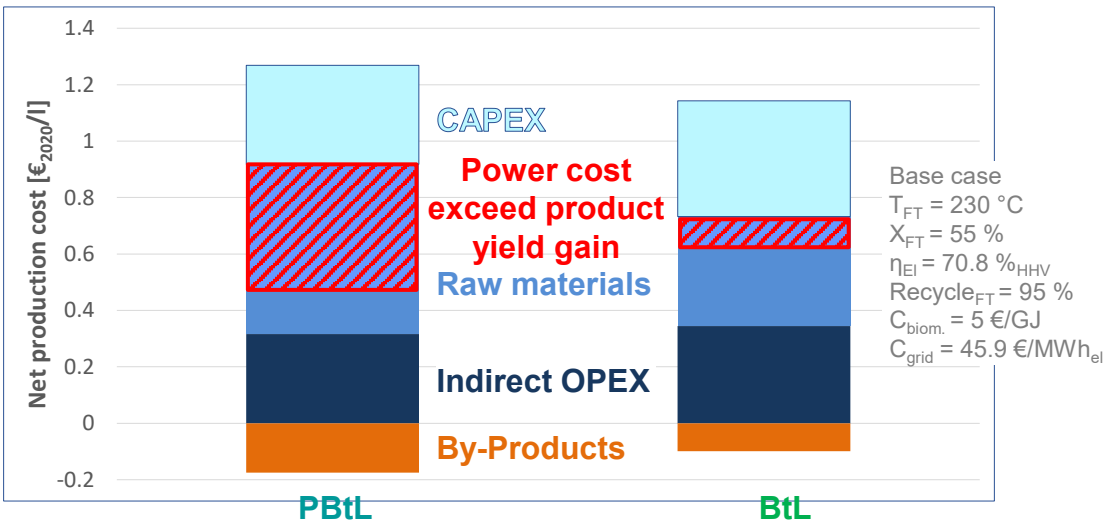
[1] Habermeyer, et. al (2023) Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production. Biomass Conversion and Biorefinery. Springer Nature. doi: 10.1007/s13399-022-03671-y. 723774

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BtL / PBtL comparison [1]: Net Production Costs

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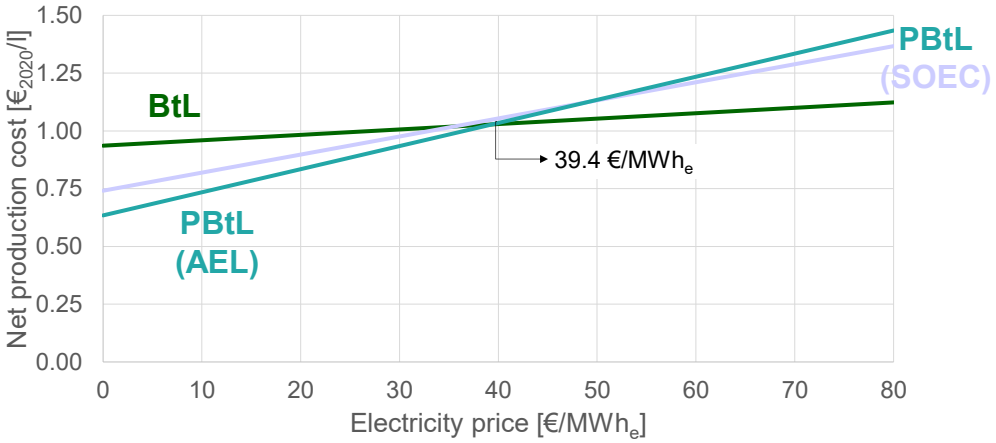
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Assessment of BtL / PBtL SAF net production cost (NPC)

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Net production cost sensitivity [1]:



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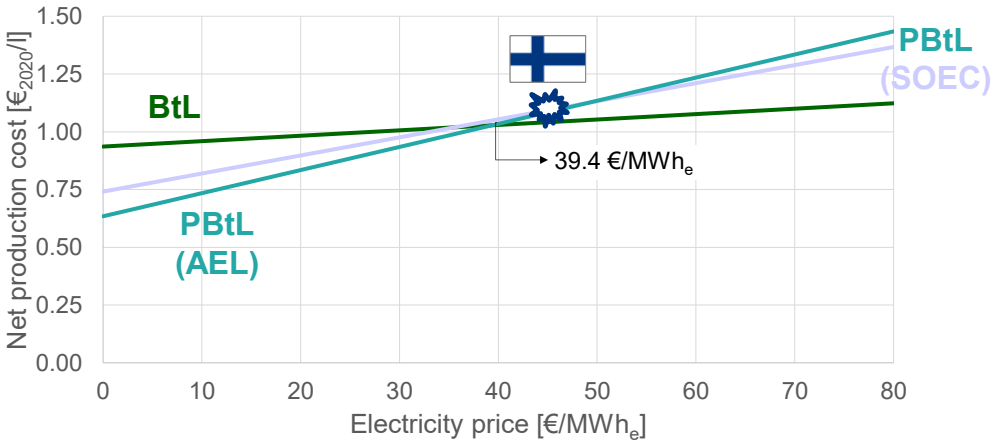
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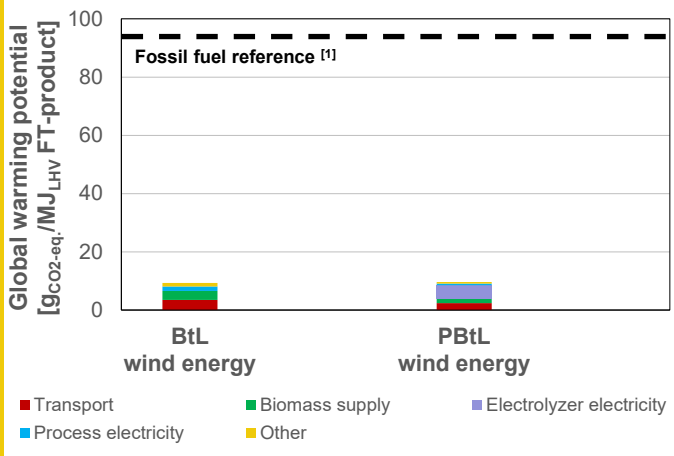


Life Cycle Assessment Example Results
Global warming potential in FLEXCHX cases

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- **Transportation: truck** (size: >32t / 16-32t)
  - **100 km biomass** (90.9 $g_{CO2-eq.}$/(t*km) [2])
  - **200 km FT-products** (166.8 $g_{CO2-eq.}$/(t*km) [2])
- **Biomass: Harvesting woody residues (bark, saw dust, wood chips)** (13.8 $g_{CO2-eq.}$/kg [2])
- **Electricity: Finnish onshore wind energy** (17.2 $g_{CO2-eq.}$/kWh [2])

[1] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union
[2] Wernet, G et al. (2016) – The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9): 1218–1230.

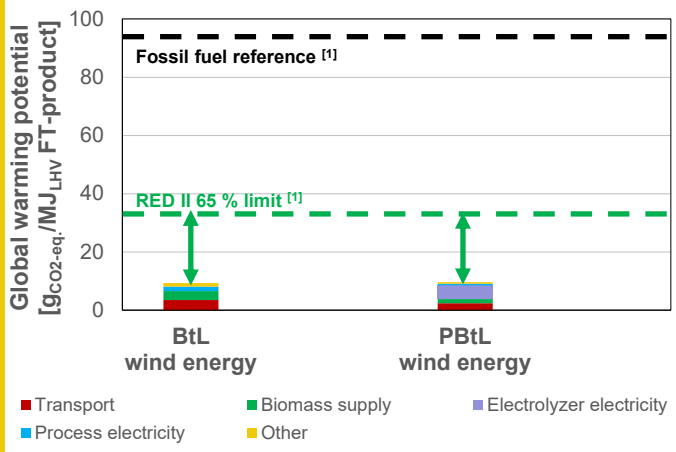
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Global warming potential in FLEXCHX cases

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Conclusion

- REDII target accomplished @ Finnish FLEXCHX base case assumptions (no benefit for undercut)

[1] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union
[2] Wernet, G et al. (2016) – The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9): 1218–1230.

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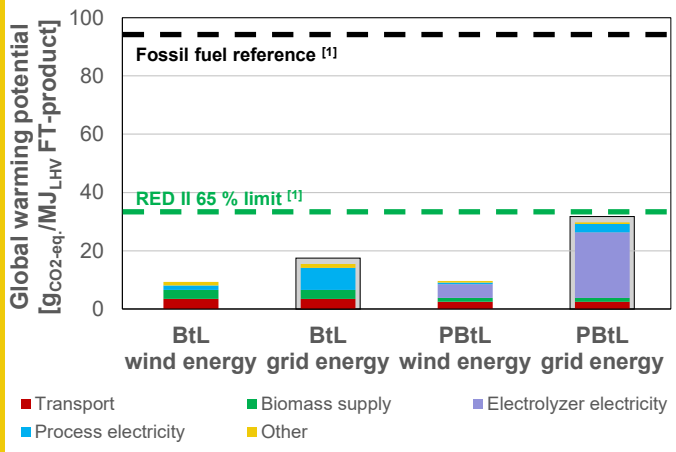
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Life Cycle Assessment Example Results
Global warming potential in FLEXCHX cases

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- **Electricity: Finnish onshore wind energy** (17.2 $g_{CO2\text{-}eq.}$/kWh [2])
- **Electricity: Finnish grid mix** (86 $g_{CO2\text{-}eq.}$/kWh [3])

Conclusion

- REDII target accomplished @ Finnish FLEXCHX base case assumptions
- REDII target **still slightly** accomplished for PBtL @ 2020 Finnish grid mix electricity

[1] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union
[2] Wernet, G et al. (2016) – The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9): 1218–1230.
[3] Online https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6 [Accessed 14.9.21]

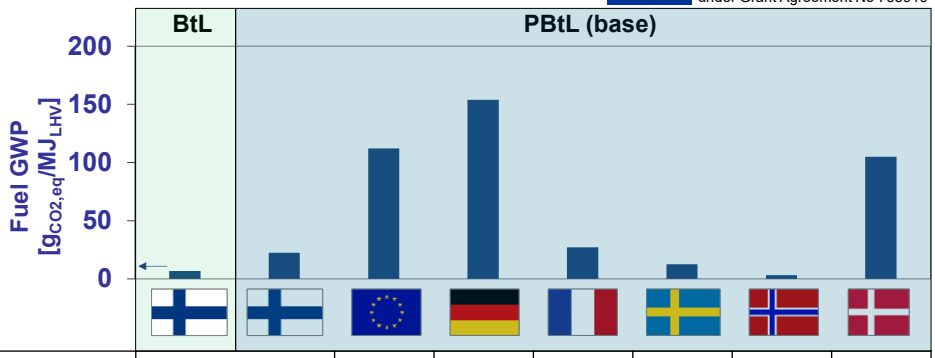
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Life Cycle Assessment Example Results
Global warming potential in FLEXCHX cases

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Grid power price [€2017/MWhe] [1]	61	101	132	79	58	72	235
Grid power emission [kgCO2,eq/MWhe] [2]	86	447	615	105	47	9	377

[1] Hannula, I., & Reiner, D. M. (2019). Near-term potential of biofuels, electrofuels, and battery electric vehicles in decarbonizing road transport. *Joule*, *3*(10), 2390-2402.
[2] Online https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6 [Accessed 14.9.21]

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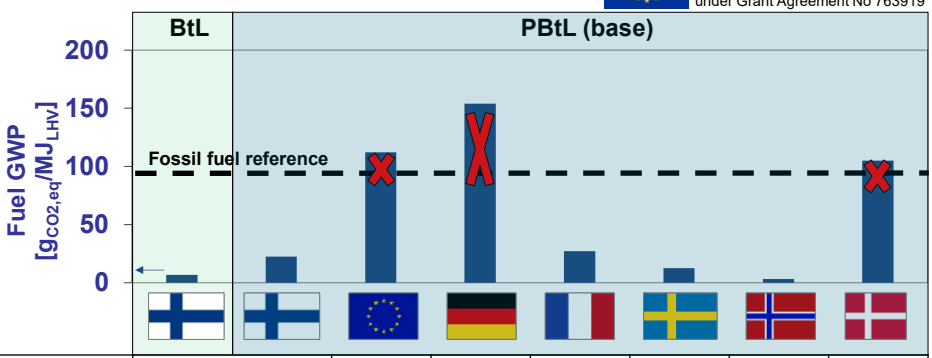
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Life Cycle Assessment Example Results
Global warming potential in FLEXCHX cases

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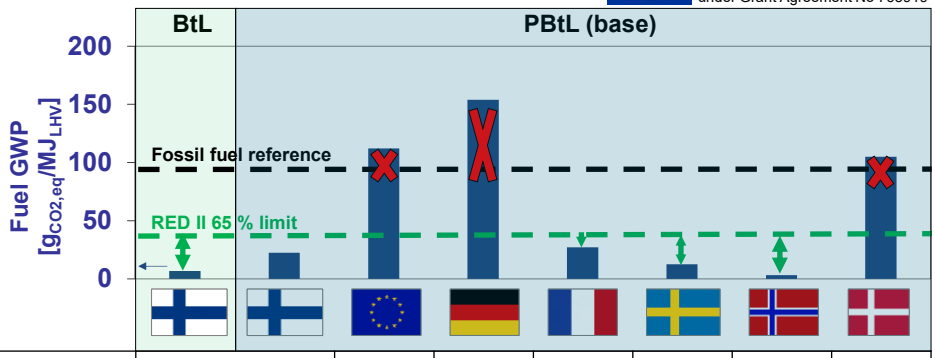
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Life Cycle Assessment Example Results
Global warming potential in FLEXCHX cases

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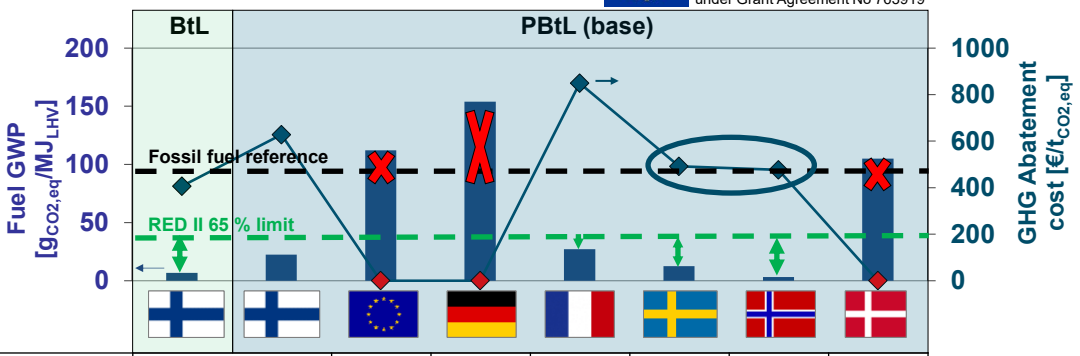
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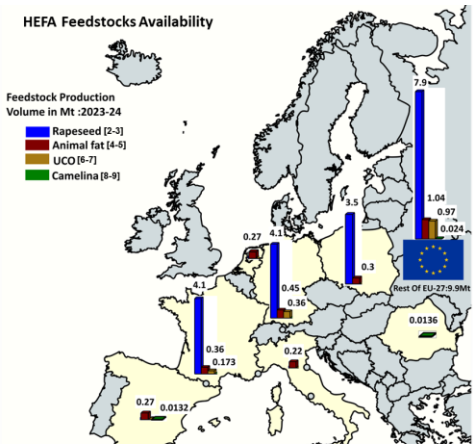


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HEFA Feedstock[1] Availability

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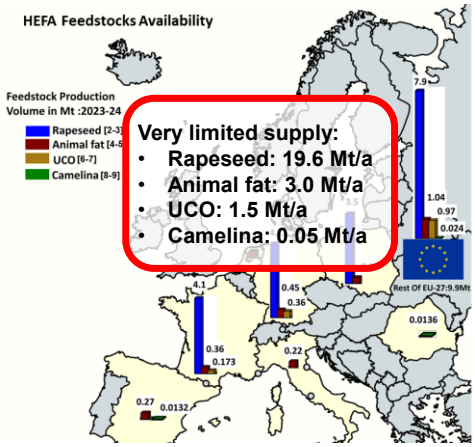
[1] Sharma J., et al. (2026). "The Status of HEFA Kerosene in Europe: Technoeconomic and Environmental Assessment" (*Under Submission*)
[2] F. A. S. U.S. Department of Agriculture. Rapeseed: Global production data, U.S. Department of Agriculture, Foreign Agricultural Service.https://www.fas.usda.gov/data/production/2226000
[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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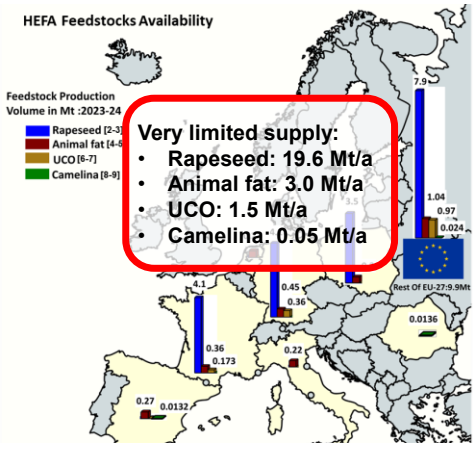


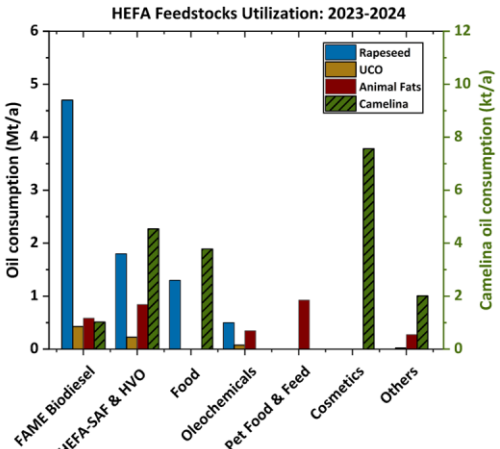
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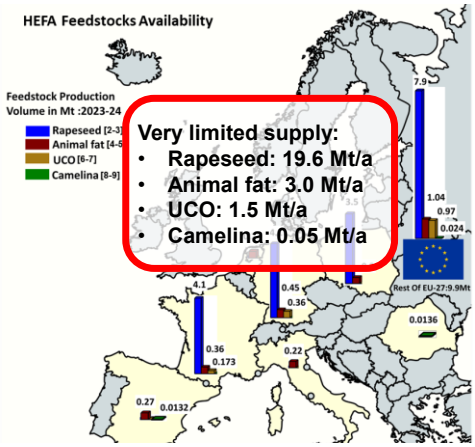


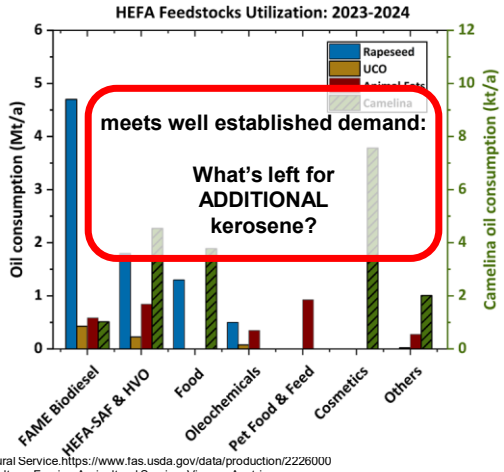
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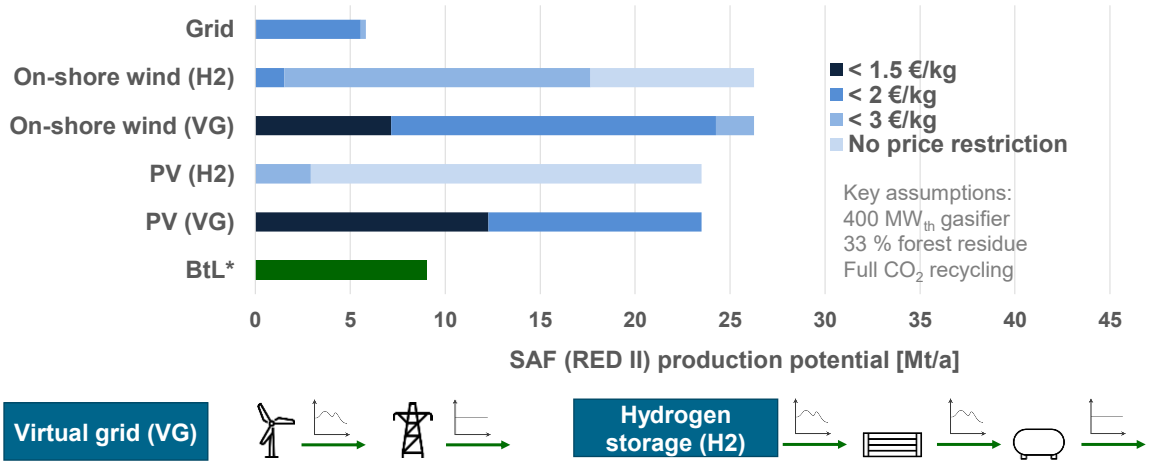


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BtL / PBtL Feedstock Availability
Aggregated SAF potential

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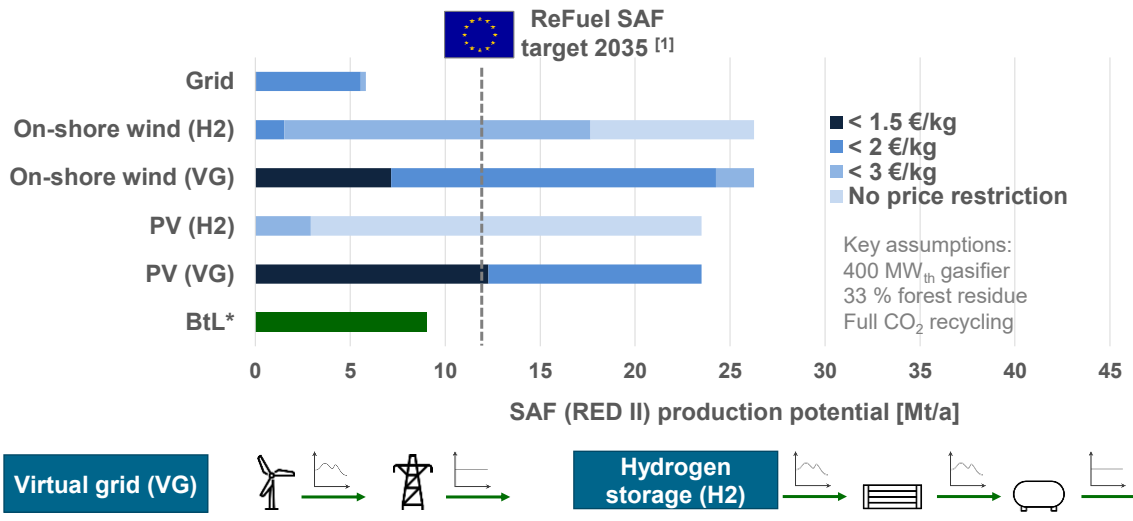


Virtual grid (VG)

Hydrogen storage (H2)

BtL / PBtL Feedstock Availability
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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Toward Sustainable Aviation in Europe

- B) Aircraft evolution using RE-supported SAF is technically feasible, economically challenging, regulation driven, ready to go
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  - New PBtL-SAF industry needs to be established – competing with fossil kerosene supply

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Toward Sustainable Aviation in Europe

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- DLR provides standardized assessment for any airplane design, fuel supply technology, feedstock, location, regulation, … !

TRY ☞ OPTIMIRA

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DAY 3 - Thursday, 17. September 2026

Topic: 13 System Analysis, LCA & Sustainability Assessment

THANK YOU FOR YOUR KIND ATTENTION! QUESTIONS?



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

Ralph-Uwe Dietrich, Rahnuma Bhuiyan Evon, Moritz Raab, Janmejai Sharma, Julia Weyand (DLR e.V., www.DLR.de/tt)