Tuesday, 06. May 2025

SAF intelligence & Masterclass day

Getting SAF to Market

SUSTAINABLE AVIATION FUTURES CONGRESS

6 - 8 May 2025
Beurs van Berlage
Amsterdam

The World's Largest SAF & Aviation Decarbonisation Event

DECARBONISING EUROPE'S AVIATION SECTOR AT SCALE

Techno Economic and Environmental Assessment of SAF production

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

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Decarbonising Europe’s Aviation
Agenda

1. Motivation and goals
2. Techno economic and environmental assessment
    1. Technical
    2. Economic
    3. Environmental
3. Feedstock supply
4. Technological readiness
5. European SAF roadmap
6. Conclusion and outlook

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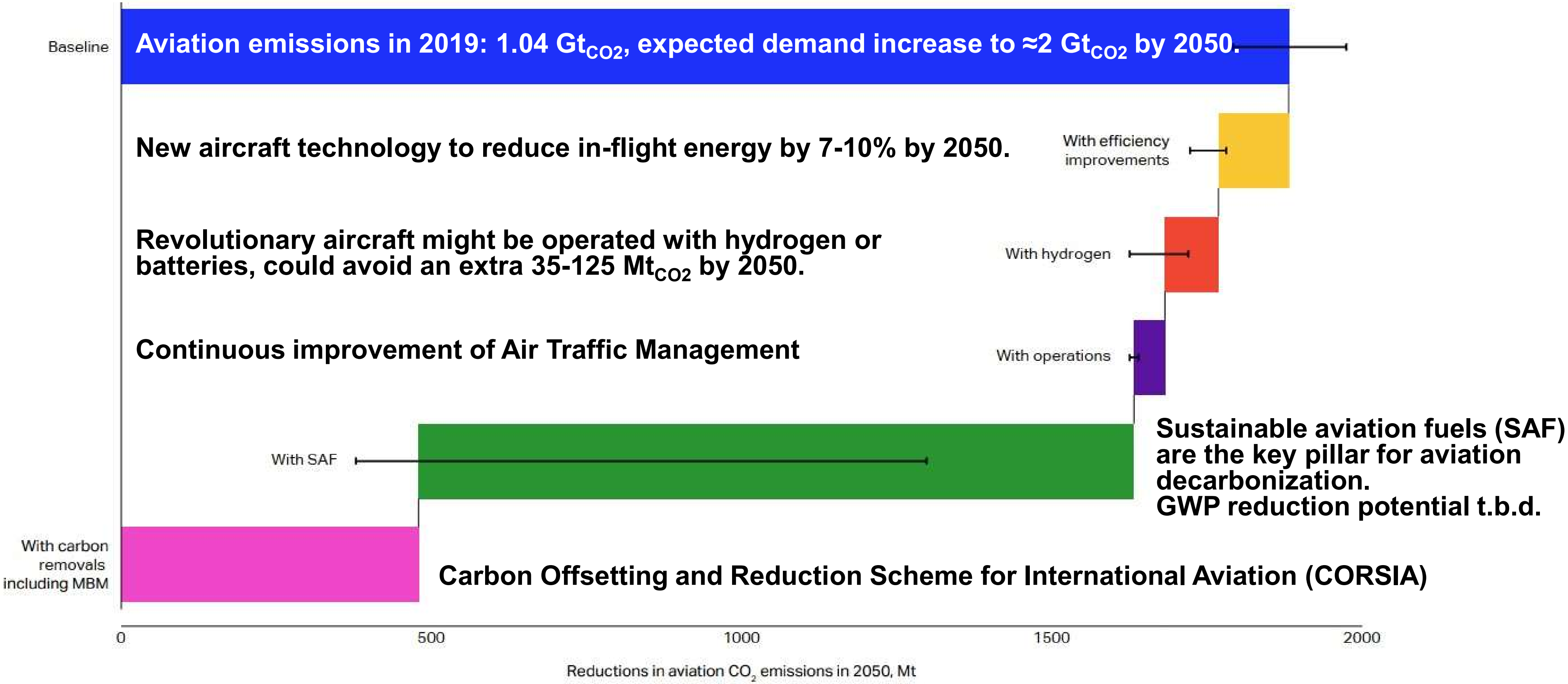
IATA Net Zero Roadmaps [1]
International Aviation Contribution



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

IATA Net Zero Roadmaps [1]

International Aviation Contribution

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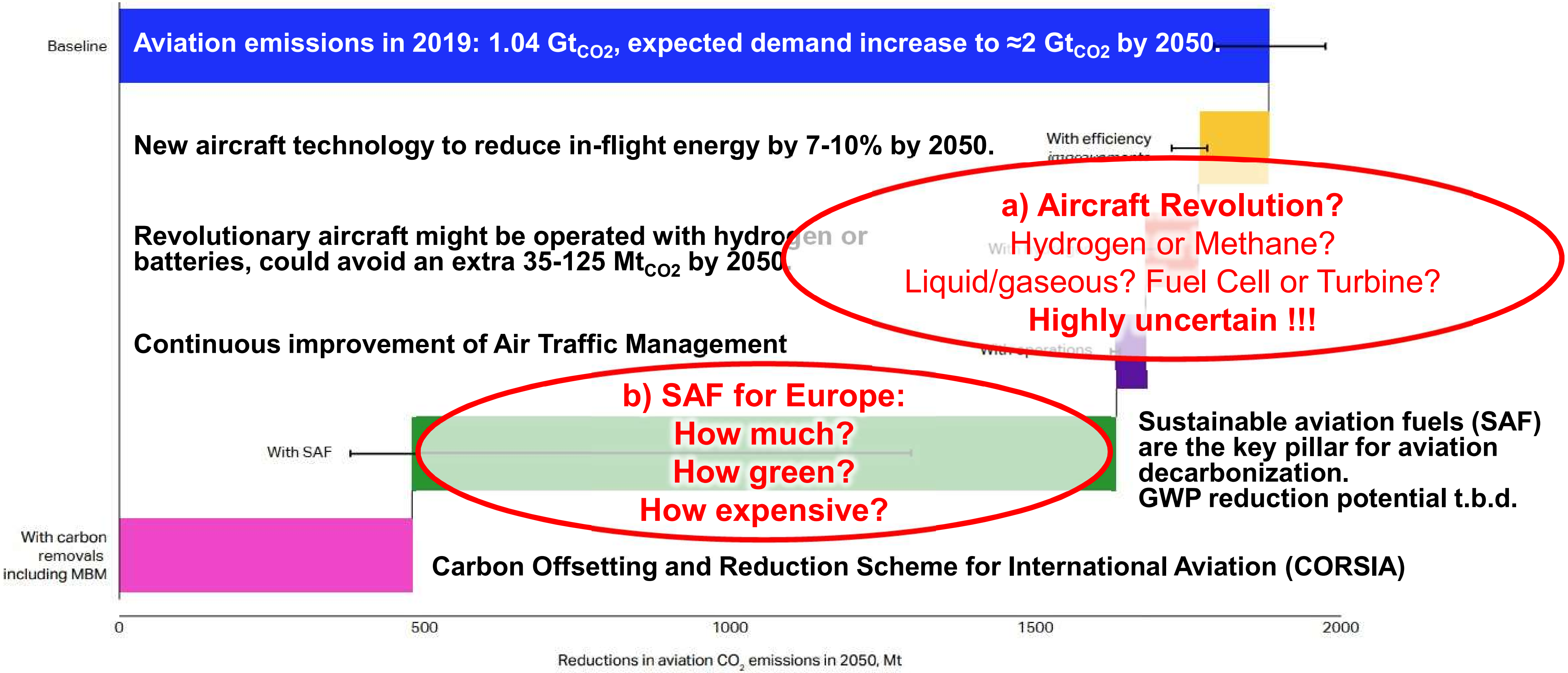

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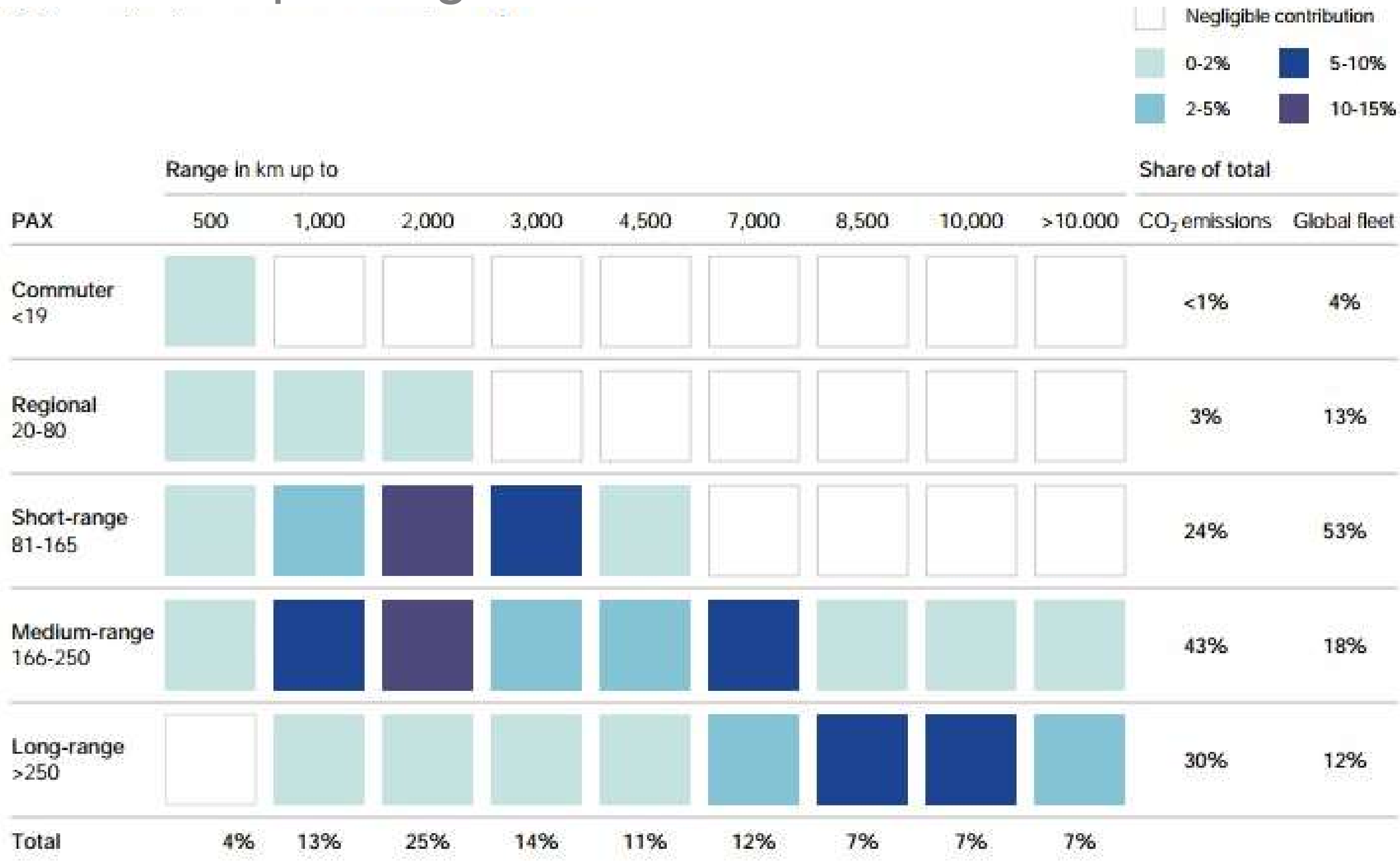
Civil aviation CO_2 emissions

CO_2 contribution per segment 2018 [1]



[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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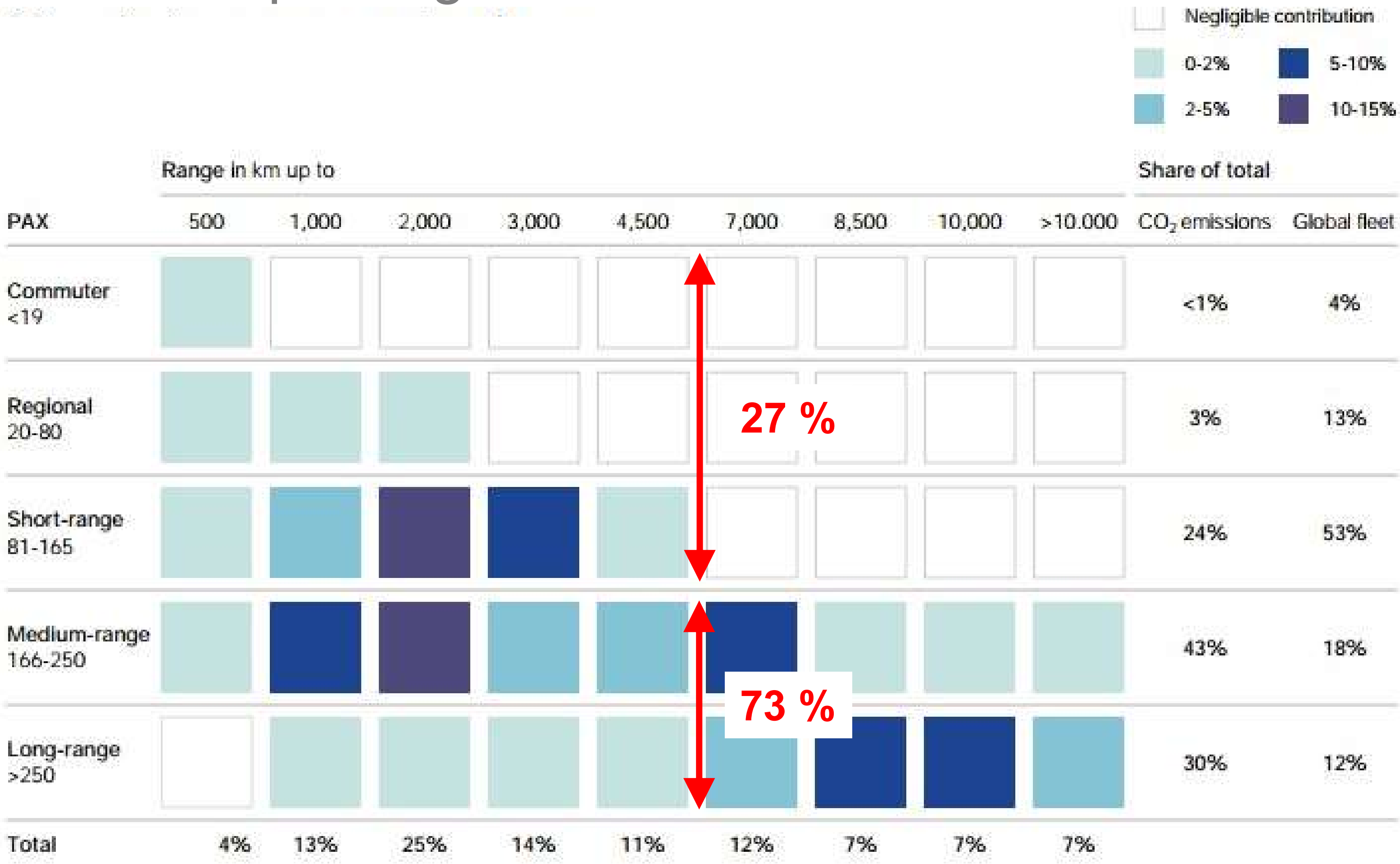

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Aircraft (R)evolution Roadmap

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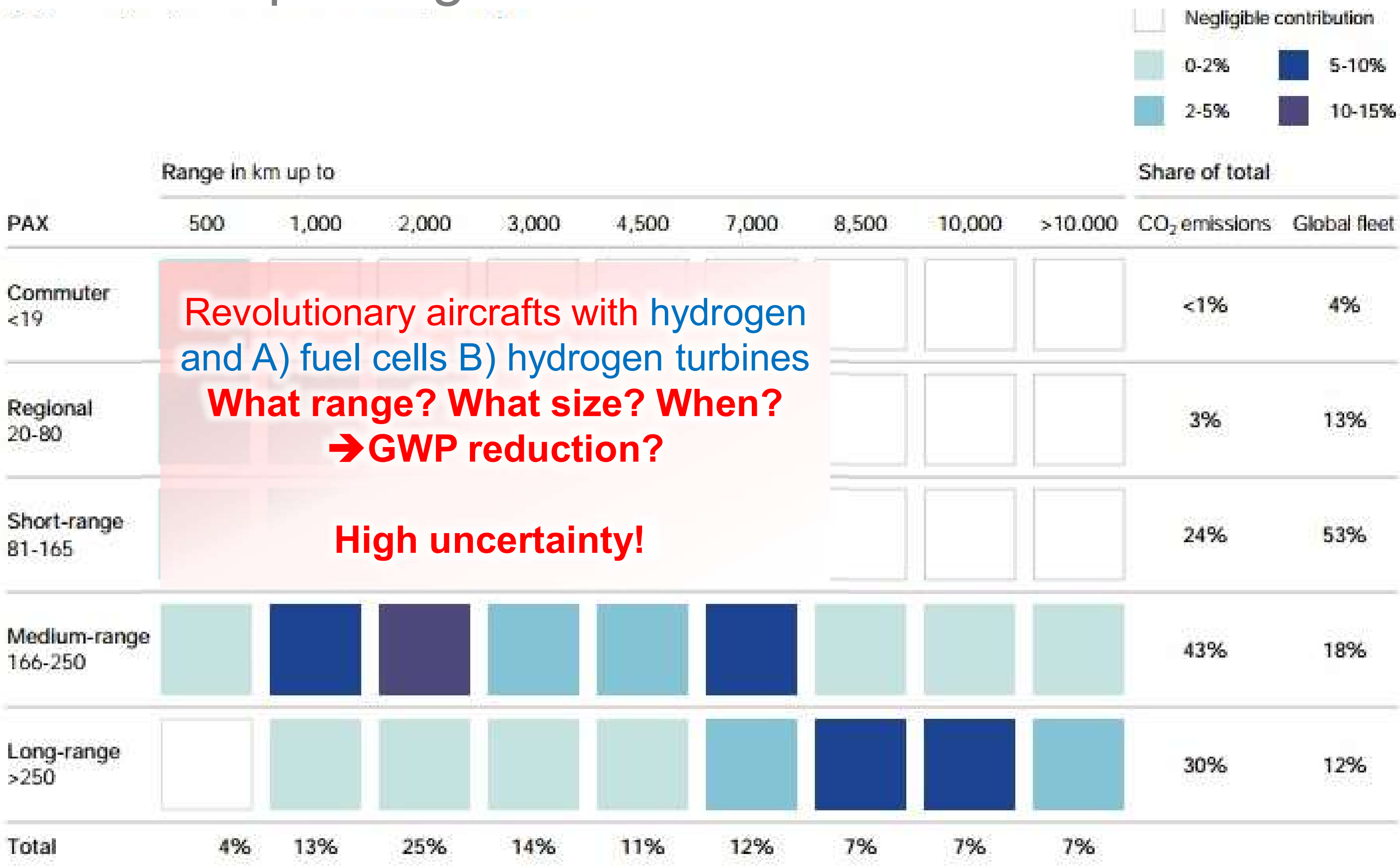

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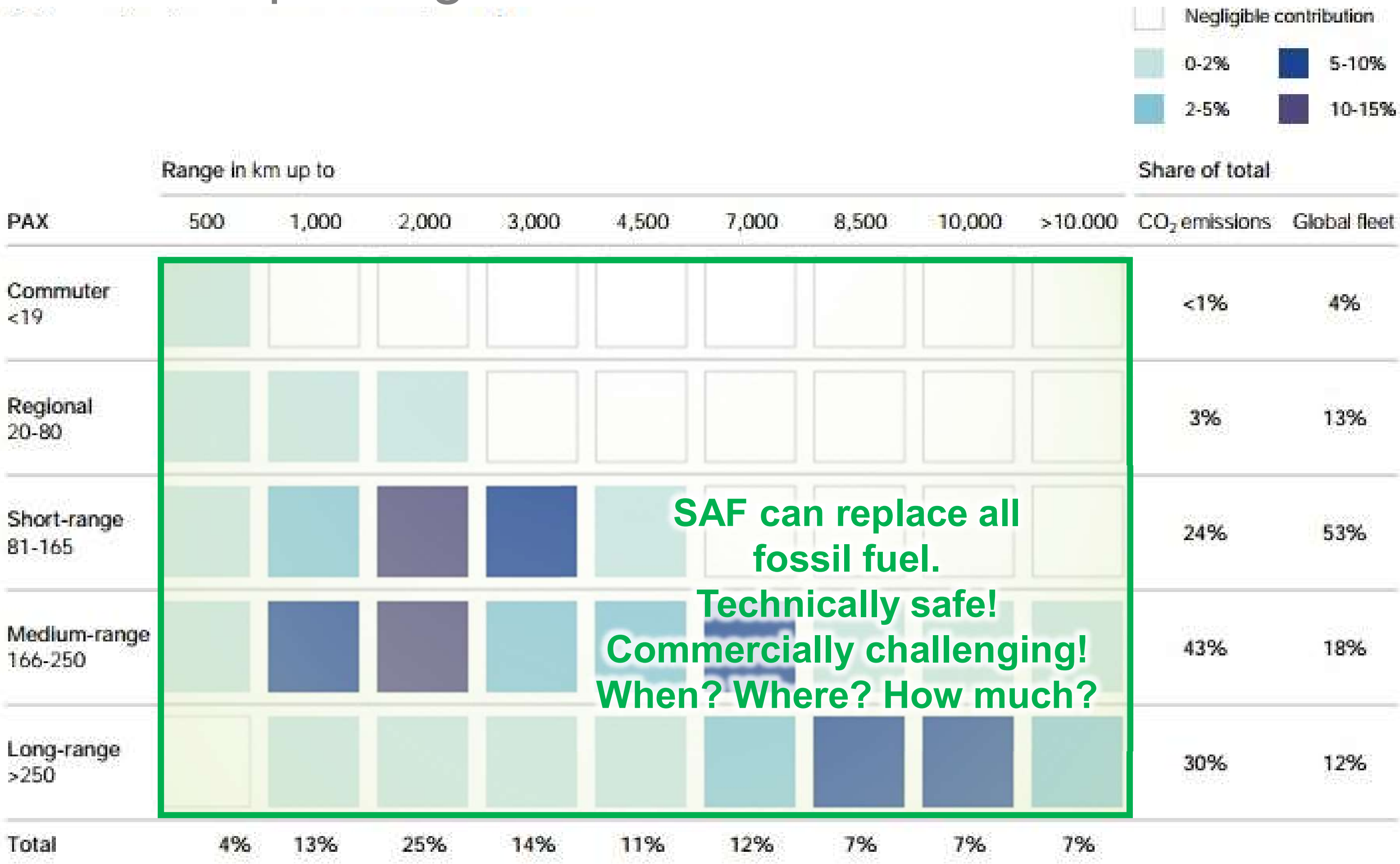

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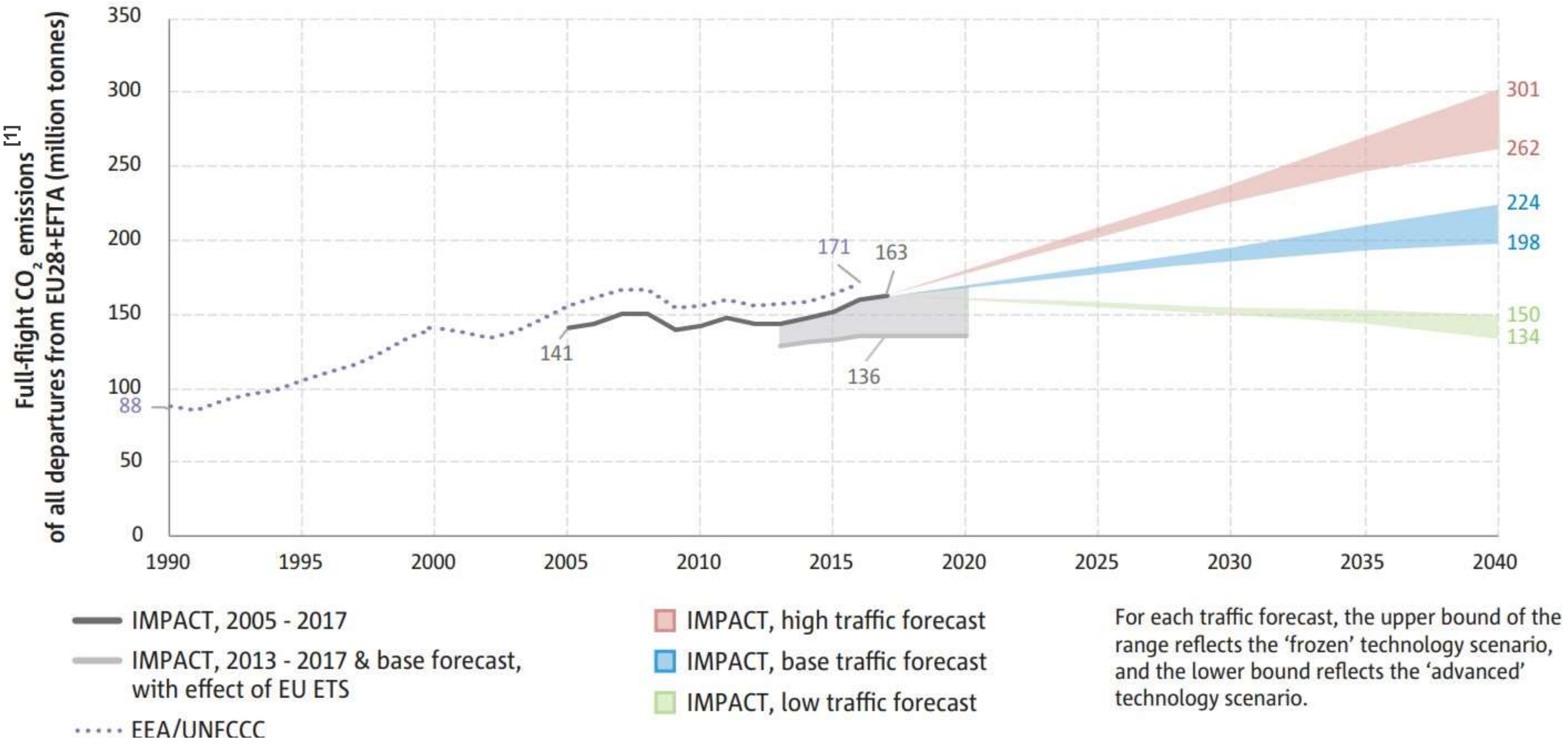
EU aviation CO_2 emissions
SAF demand and ReFuelEU Aviation



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

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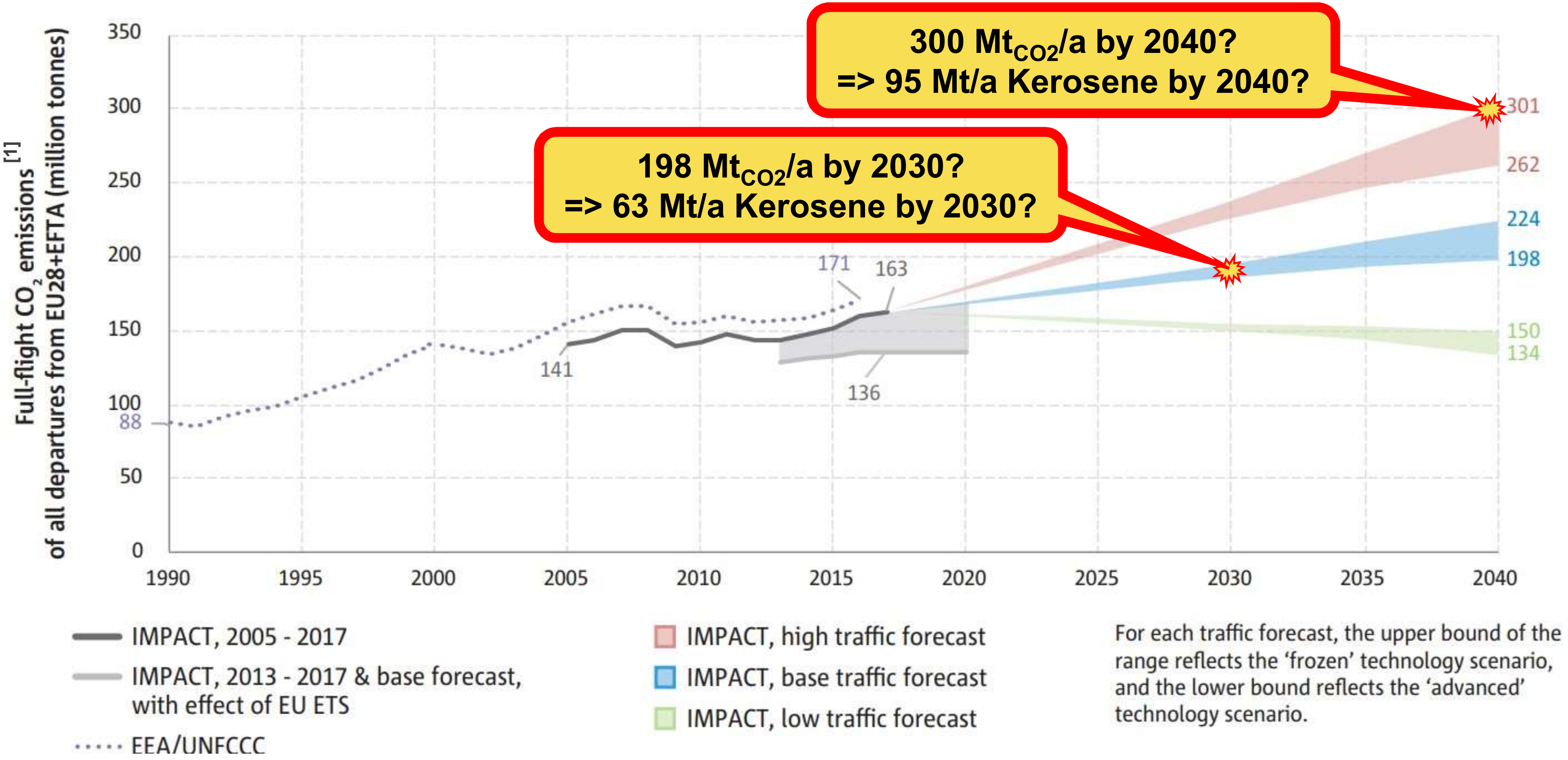

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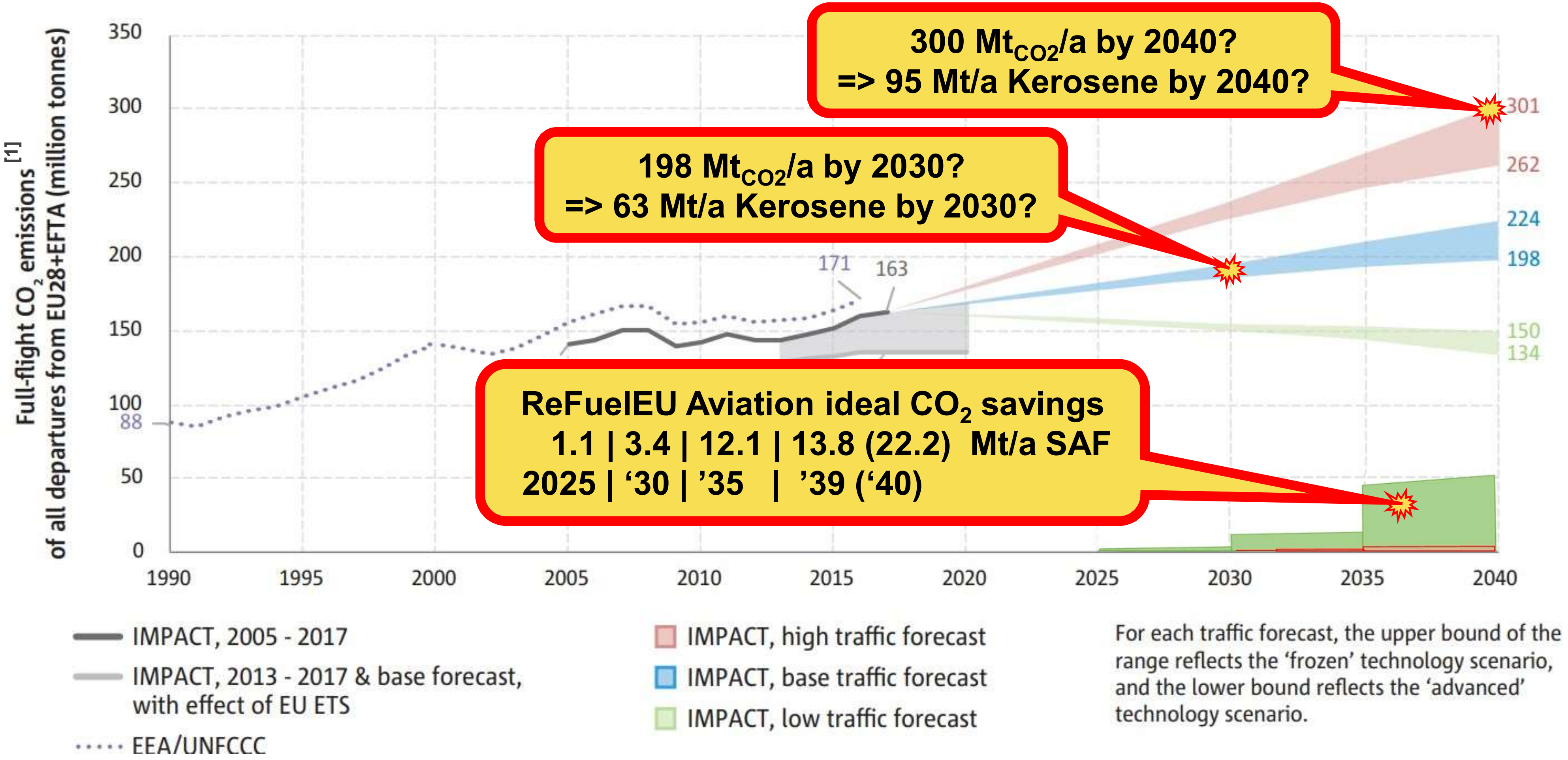

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Dietrich, et. al • Decarbonising Europe's Aviation Sector at Scale • 06. May 2025 • Amsterdam, NL

Techno-Economic and Life Cycle Assessment @ DLR

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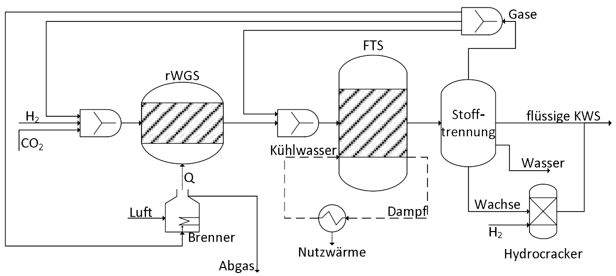
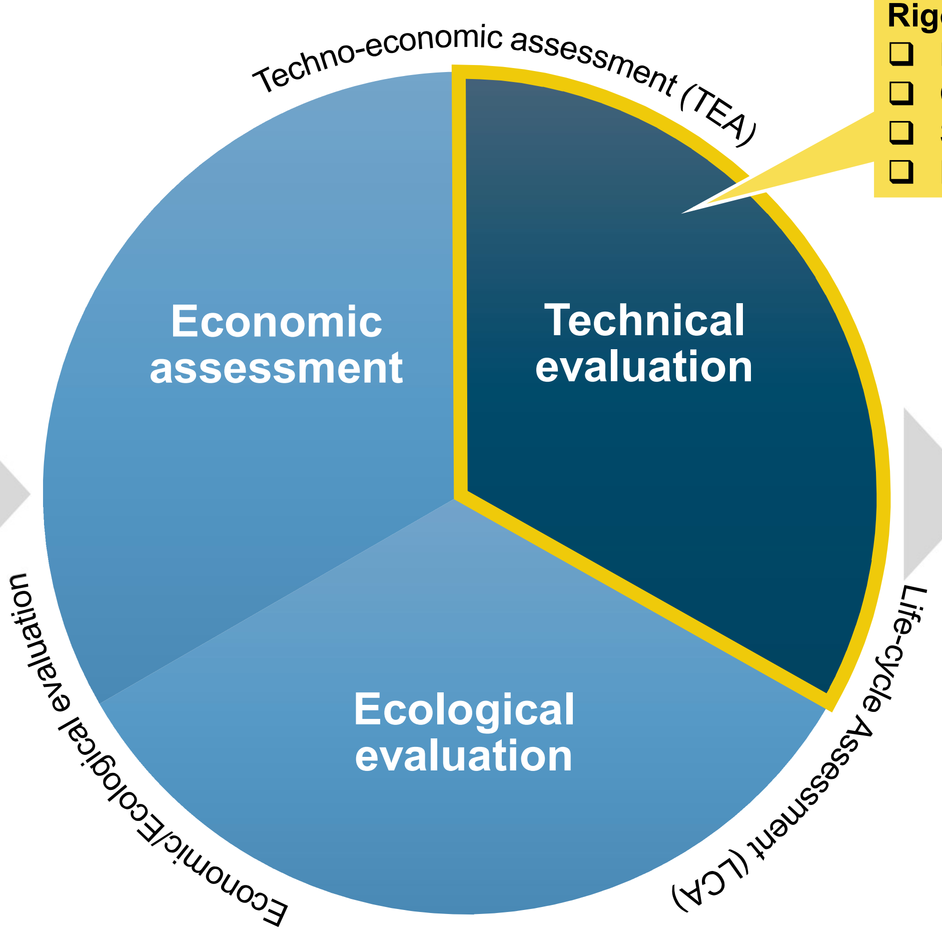
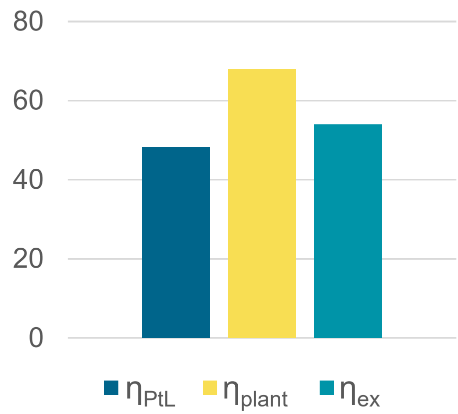
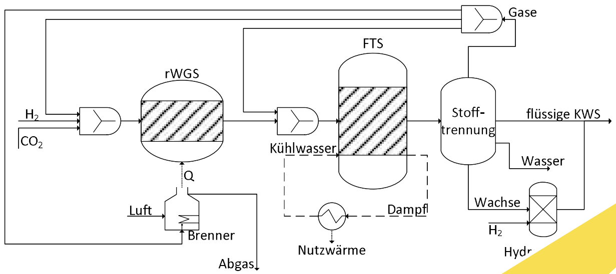


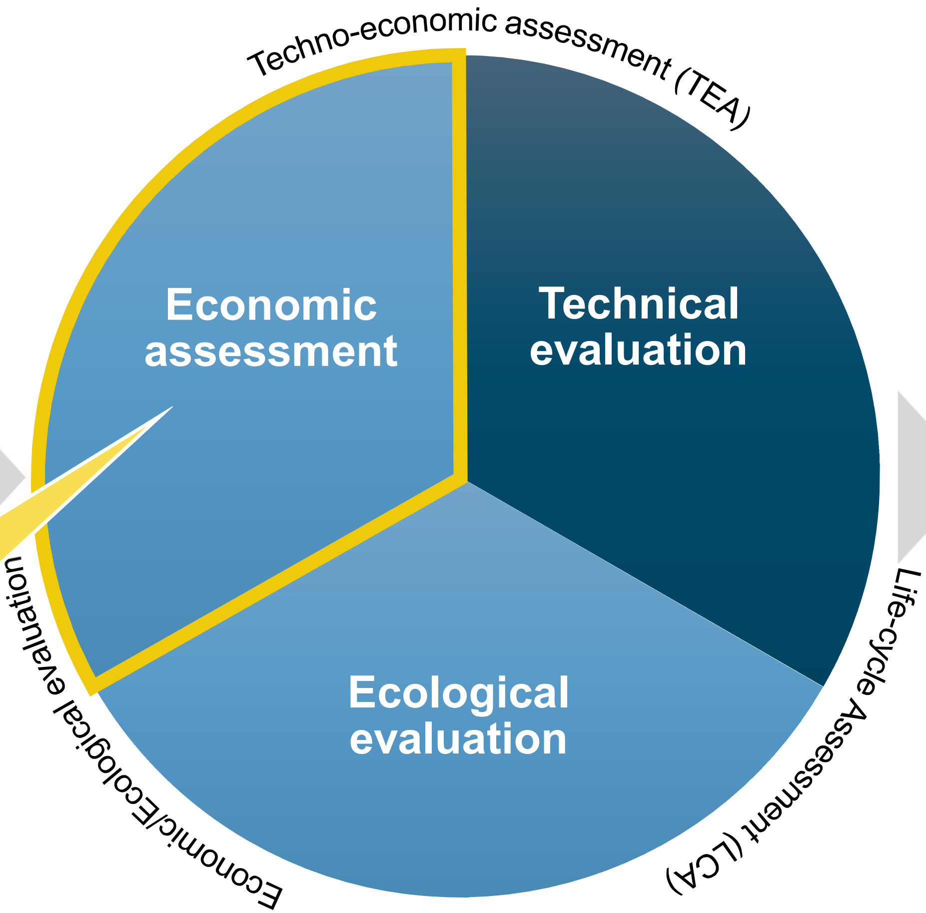


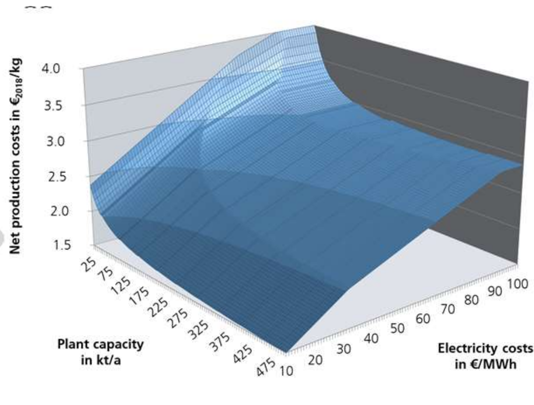
Rigorous process simulation
- ❑ Efficiencies (X-to-Liquid, Overall)
- ❑ Carbon conversion
- ❑ Specific feedstock demand
- ❑ Exergy analysis



Techno-Economic and Life Cycle Assessment @ DLR



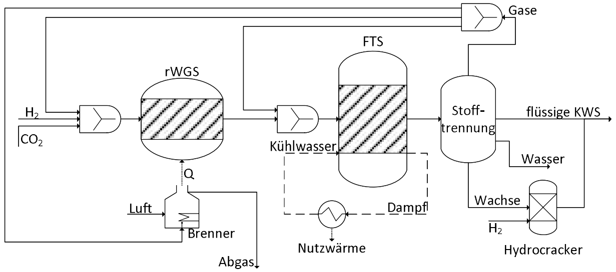


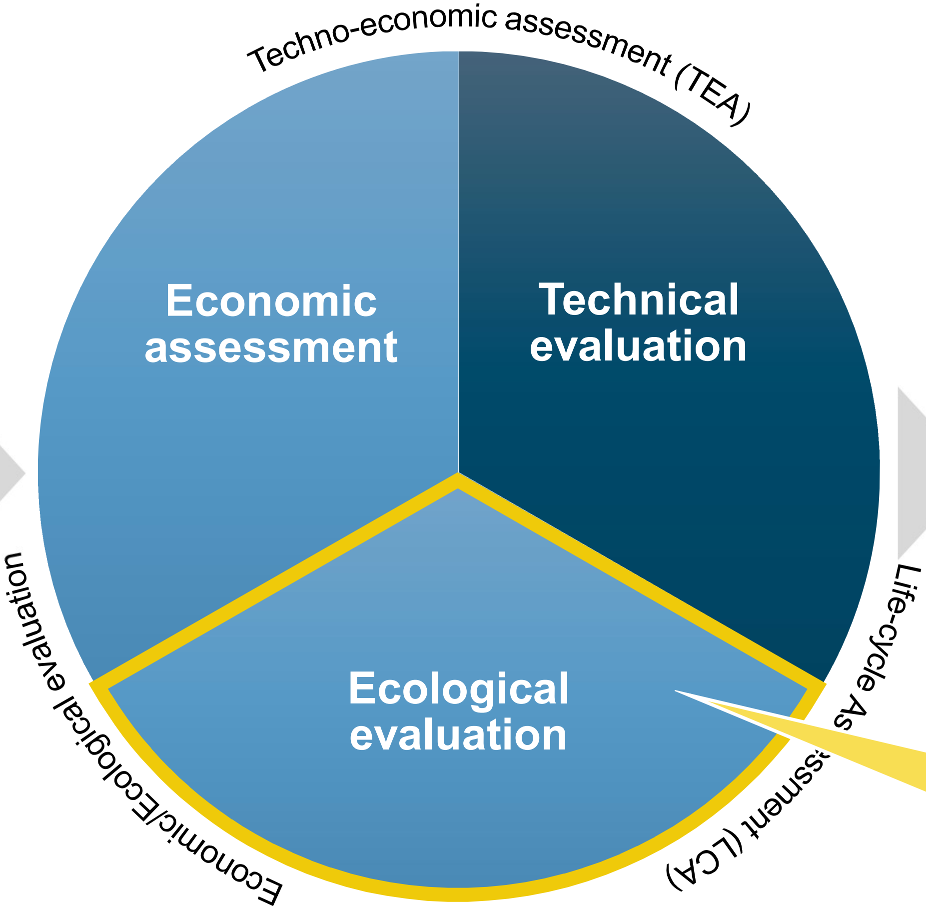


Chemical engineering cost estimation

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

Techno-Economic and Life Cycle Assessment @ DLR





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

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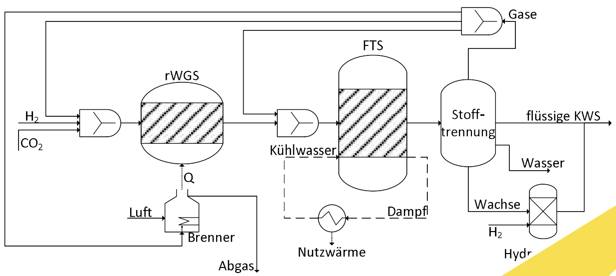

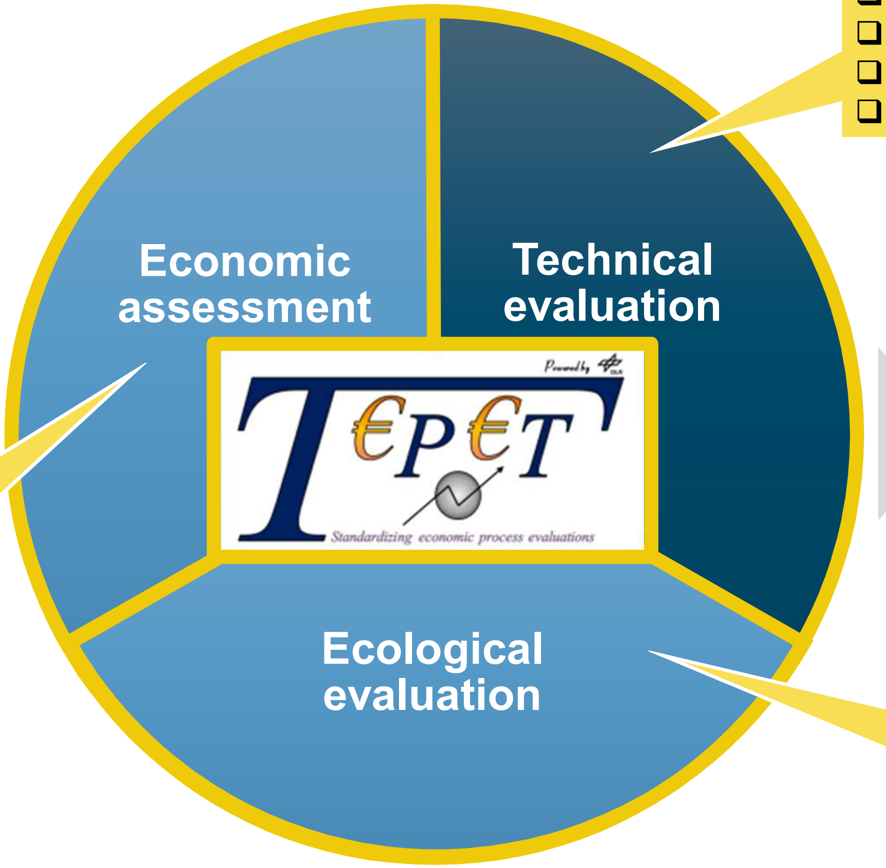

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Adapted ISO 14040/14044 LCA
- ❑ GWP
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TECHNICAL ASSESSMENT OF SAF CONCEPTS

Technical Assessment
Methodology

- Definition of KPIs such as:

$$\eta_{\mathrm{C}} = \frac{\dot{n}_{\mathrm{C,C5+}}}{\dot{n}_{\mathrm{C,feedstock}}} \qquad \eta_{\mathrm{H}} = \frac{\dot{n}_{\mathrm{H,C5+}}}{\dot{n}_{\mathrm{H,elektrolysis}}} \qquad \eta_{\mathrm{PtL}} = \frac{\dot{m}_{\mathrm{C5+}} LHV_{\mathrm{C5+}}}{P_{\mathrm{elektrolysis}} + P_{\mathrm{MEA}} + P_{\mathrm{compressor}}}$$

- Rigorous steady-state process simulation + validation
  - Validated process models of most processes from research projects available
  - Adaptable to any new configuration / feedstock / …
- Automated parameter variation and grid search via DLR in-house tools
  - Sensitivity of each process parameter on each KPI
  - Automated heat integration – flexibility towards configuration changes

Technical Assessment Example
Power-to-Liquid process simulation

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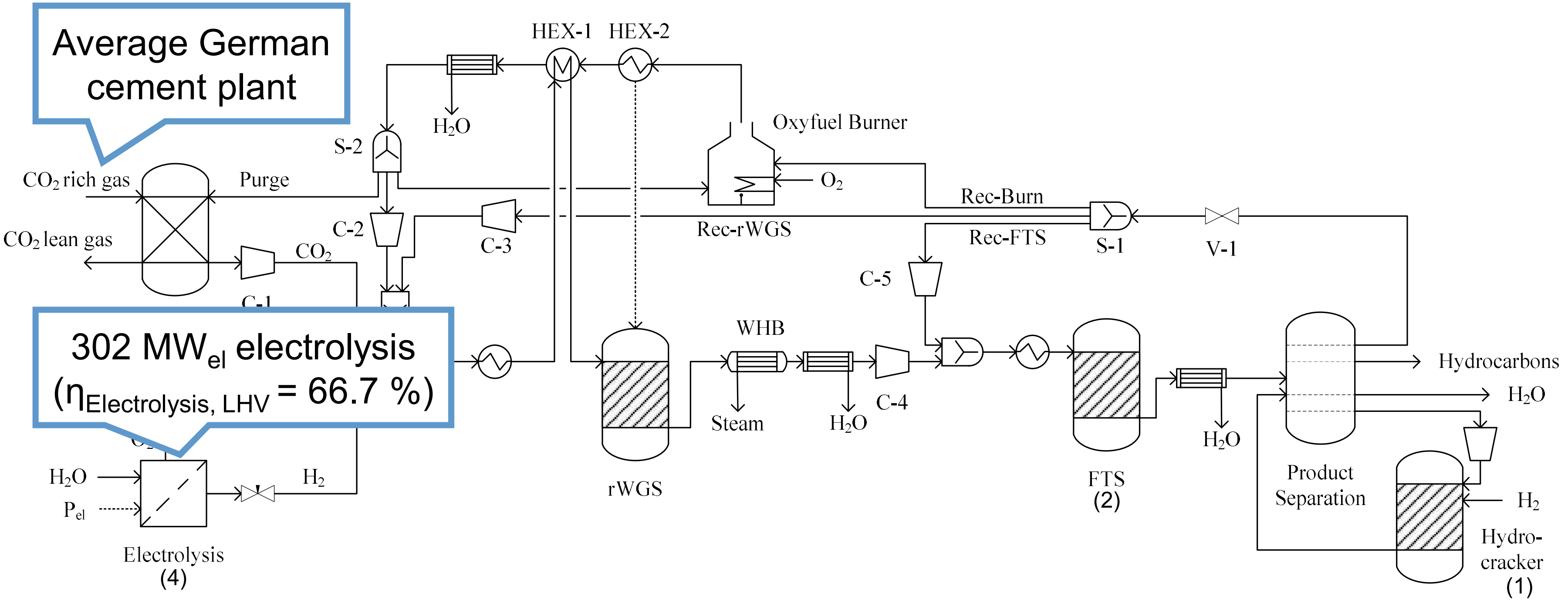
Methodology: Experimentally validated flowsheet [5]



(1) D. Leckel, M. Liwanga-Ehumbu (2006): Diesel-Selective Hydrocracking of an Iron-Based Fischer−Tropsch Wax Fraction (C 15 −C 45) Using a MoO 3 -Modified Noble Metal Catalyst
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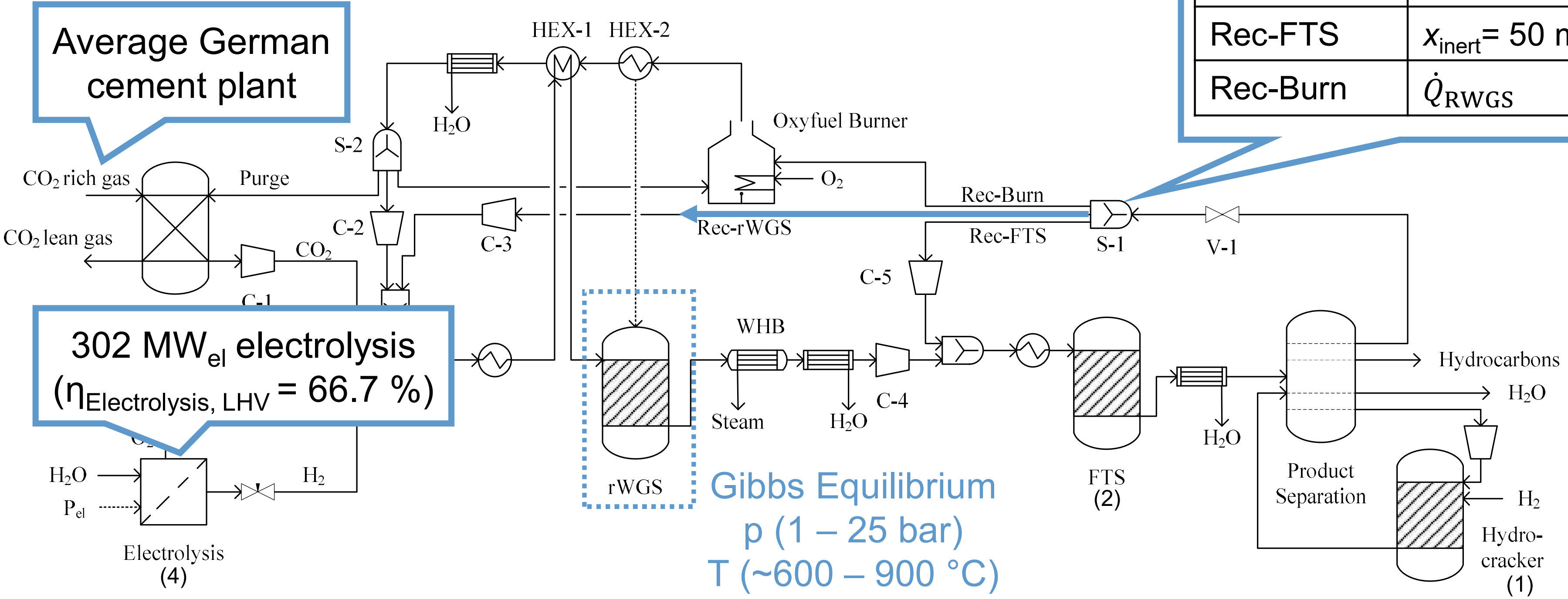
(4) Schmidt et al. (2017): Future cost and performance of water electrolysis:: An expert elicitation study
(5) Adelung and Dietrich, R.-U. (2022). Impact of the reverse water-gas shift operating conditions on the Power-to-Liquid process efficiency

Technical Assessment Example
Power-to-Liquid process simulation

Methodology: Experimentally validated flowsheet [5]

Recycle	Specification
Rec-FTS	x_{inert}= 50 mol %
Rec-Burn	$\dot{Q}_{RWGS}$



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Technical Assessment Example

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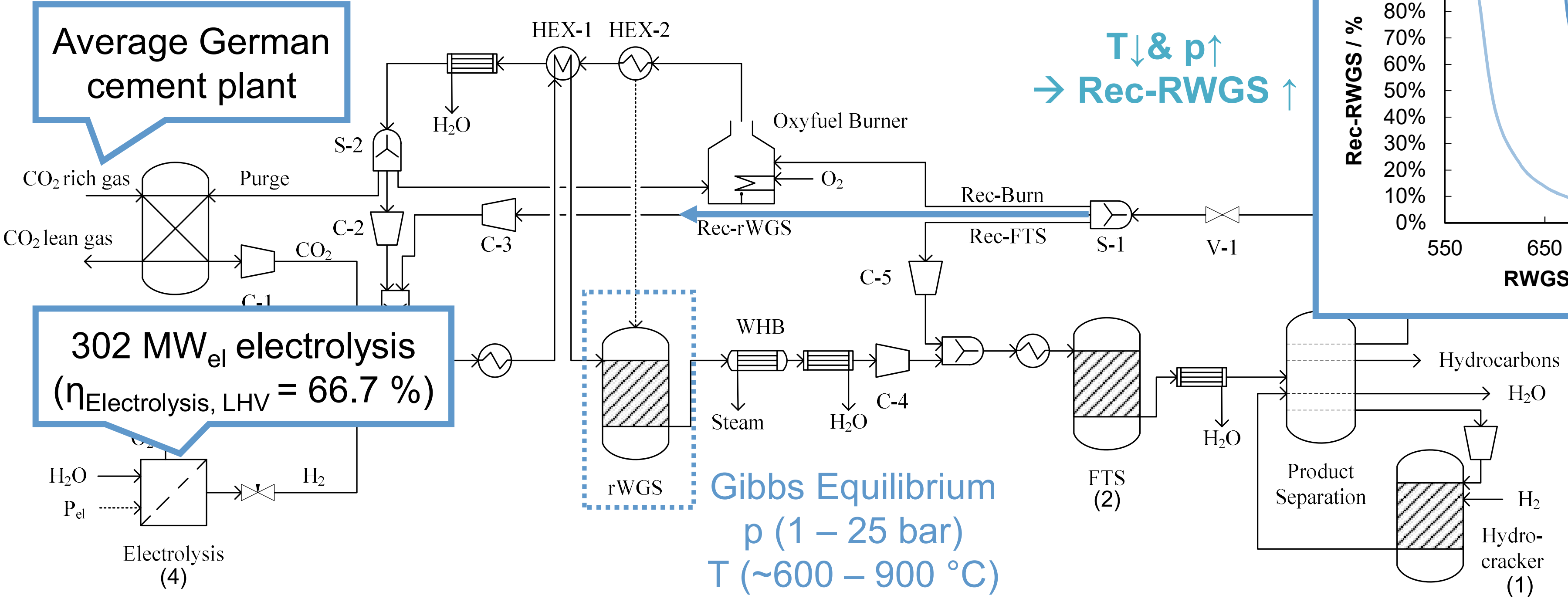

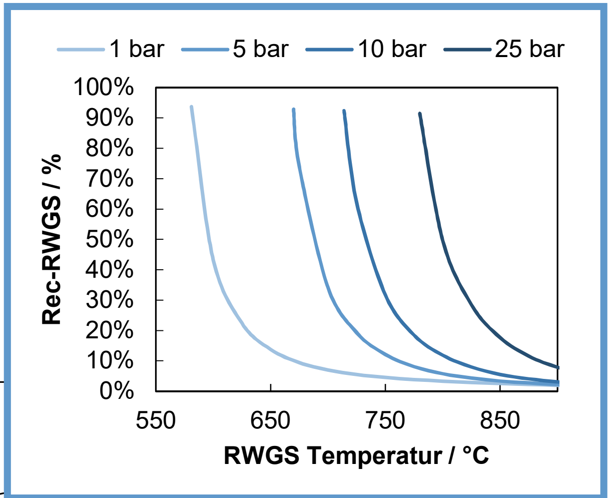

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Technical Assessment Example
Power-to-Liquid efficiency

Process Parameter dependent Material / Energy Efficiency (5)

■ = Highest efficiency

$$\eta_{\mathrm{C}} = \frac{\dot{n}_{\mathrm{C,C5+}}}{\dot{n}_{\mathrm{C,feedstock}}}$$

RWGS Temperatur / °C	1	5	10	25
900	82.2%	82.2%	82.4%	83.7%
875	82.3%	82.4%	82.8%	84.5%
850	82.4%	82.6%	83.1%	85.1%
825	82.5%	82.8%	83.7%	85.8%
800	82.5%	83.1%	84.3%	86.7%
775	82.8%	83.7%	85.1%	
750	82.9%	84.3%	85.9%	
725	83.2%	85.1%	86.7%	
700	83.4%	86.0%		
675	83.9%	86.8%		
650	84.5%			
625	85.3%			
600	86.3%			

RWGS press. / bar

Higher recycle rate to RWGS increases C efficiency

$$\eta_{\mathrm{H}} = \frac{\dot{n}_{\mathrm{H,C5+}}}{\dot{n}_{\mathrm{H,elektrolysi}}}$$

RWGS Temperatur / °C	1	5	10	25
900	23.6%	23.6%	23.6%	23.1%
875	23.8%	23.7%	23.6%	22.8%
850	23.9%	23.9%	23.7%	22.2%
825	24.0%	23.9%	23.6%	21.1%
800	24.2%	24.0%	23.4%	19.0%
775	24.3%	24.0%	22.8%	
750	24.4%	23.8%	21.6%	
725	24.5%	23.3%	19.0%	
700	24.6%	22.0%		
675	24.6%	18.8%		
650	24.5%			
625	24.0%			
600	22.5%			

RWGS press. / bar

Less water formation increases H efficiency

$$\eta_{\mathrm{PtL}} = \frac{\dot{m}_{\mathrm{C5+}} LHV_{\mathrm{C5+}}}{P_{\mathrm{elektrolys}} + P_{\mathrm{MEA}} + P_{\mathrm{compressor}}}$$

RWGS Temperatur / °C	1	5	10	25
900	35.3%	36.1%	36.2%	35.8%
875	35.5%	36.2%	36.3%	35.5%
850	35.7%	36.4%	36.4%	34.6%
825	35.8%	36.5%	36.3%	32.8%
800	36.0%	36.6%	36.0%	29.7%
775	36.2%	36.5%	35.0%	
750	36.3%	36.2%	33.1%	
725	36.4%	35.2%	29.0%	
700	36.4%	33.1%		
675	36.3%	28.0%		
650	36.0%			
625	34.9%			
600	32.0%			

RWGS press. / bar

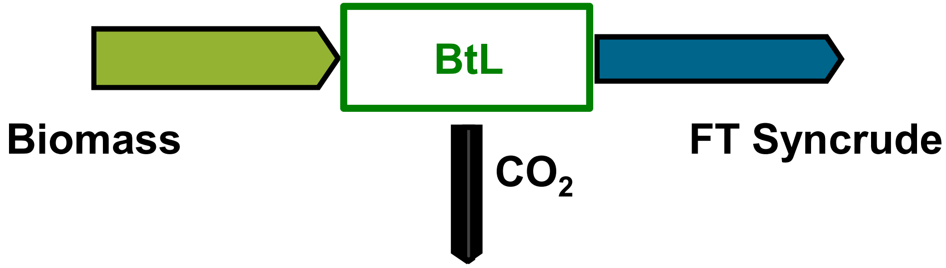
High H efficiency plus low compression demand maximizes PtL efficiency

[1] Adelung, S. and Dietrich, R.-U. (2022). *Impact of the reverse water-gas shift operating conditions on the Power-to-Liquid fuel production cost*. Fuel. Vol. 317, 2022, 123440, doi: 10.1016/j.fuel.2022.123440

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

Utilizing European waste wood: Cheap green, easy to harvest carbon!

Biomass-to-Liquid (BtL)



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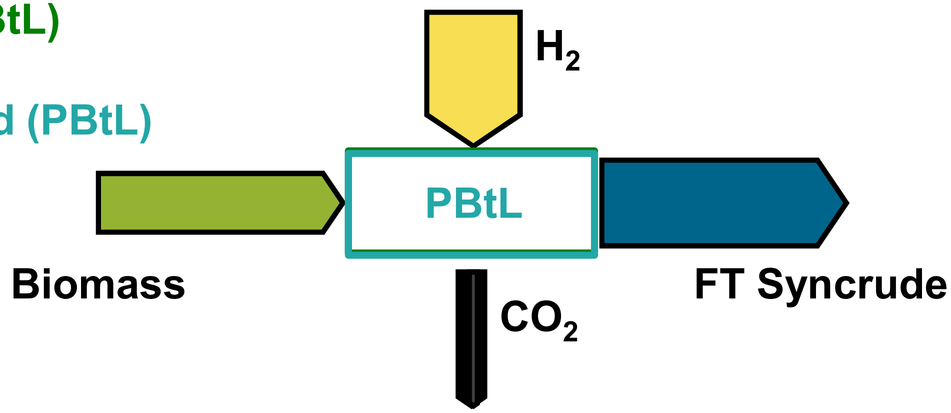
Biomass-to-Liquid (BtL)
vs.
Power&Biomass-to-Liquid (PBtL)



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.

Assessment of BtL and PBtL SAF

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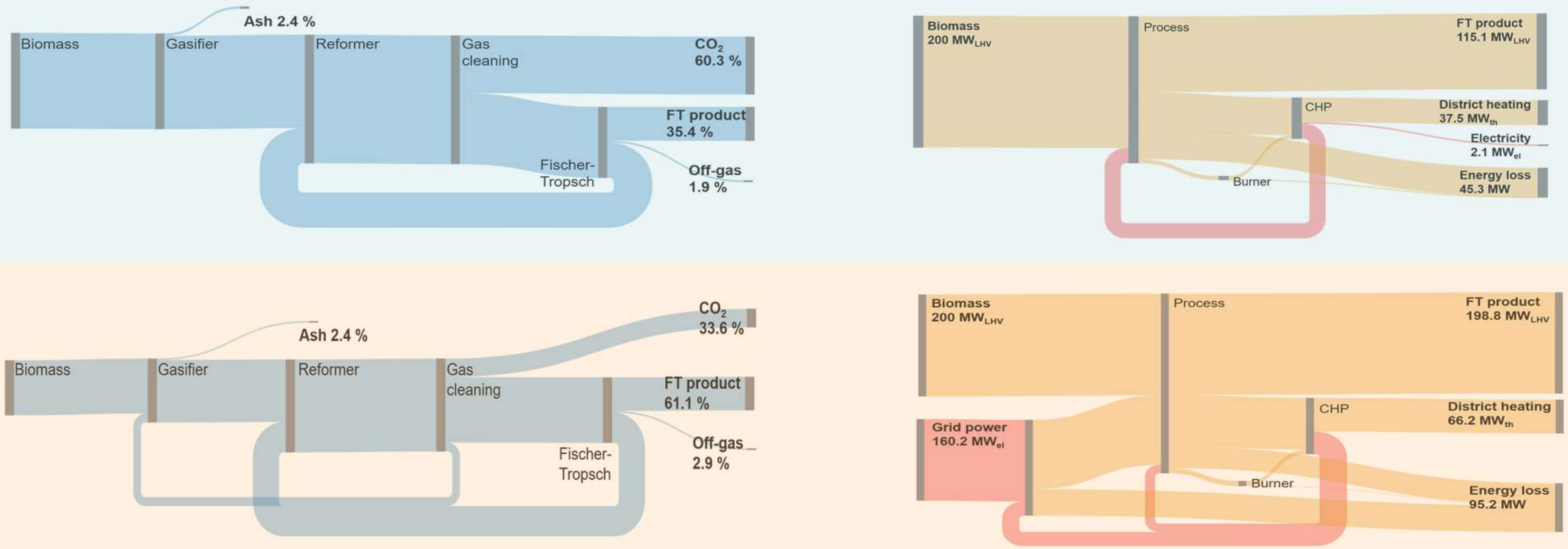
Carbon / energy flows [1]

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

	Carbon flow	Energy flow
BtL		
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

Technical Assessment Example

BtL / PBtL efficiency

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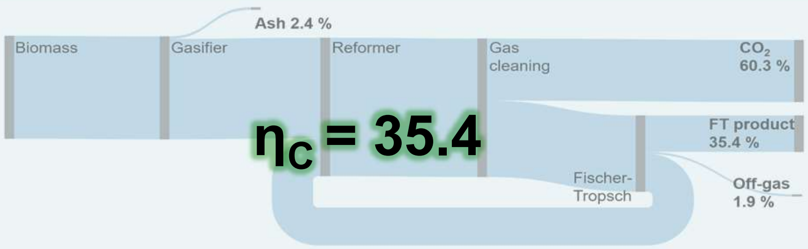
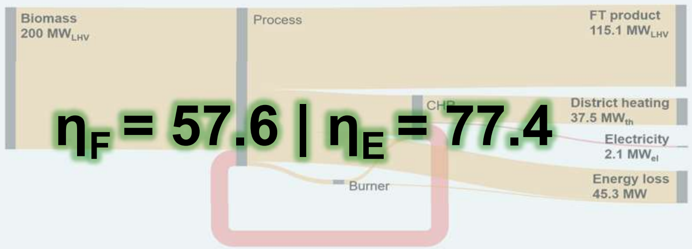
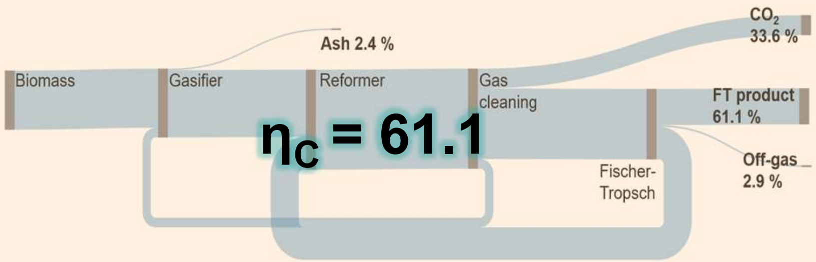
Technical efficiencies [1]

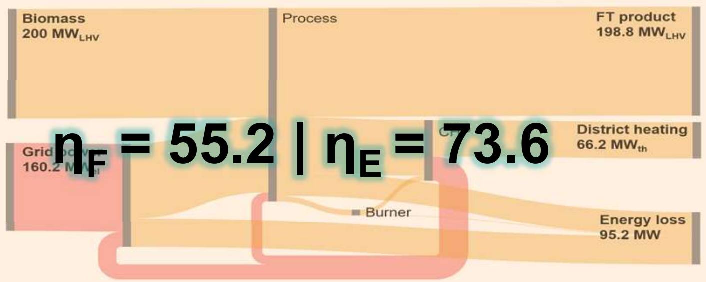
Key assumptions:
$\eta_{AEL} = 77.8\ \%_{HHV}$
$H_2/CO = 2.05$
FT-Recycle = 95 %

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









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ECONOMICAL ASSESSMENT OF SAF CONCEPTS

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Economic Assessment
Methodology

- All cost are highly dependent on multiple factors (location, year, feedstock, …)
- Standard chemical cost estimation are based on validated basic design
  - All chemical standard equipment cost available
  - New equipment via analogies, exchange with technology suppliers
  - Summarizing annualized CAPEX and OPEX in the following Equation:

$$\mathrm{NPC}\left(\frac{€/\$}{\mathrm{kg_{fuel}}}\right) = \frac{ACC + \sum OPEX_{\mathrm{dir}} + \sum OPEX_{\mathrm{ind}} + (h_{\mathrm{labor}} \cdot c_{\mathrm{labor}})}{\dot{m}_{\mathrm{fuel}}}$$

- Fully automated economic cost estimation using DLR in-house tools

Economic Assessment Example
Power-to-Liquid cost & sensitivity

Process Parameter dependent Net Production Costs [1] / NPC in $€_{2019}/kg_{C5+}$

■ = lower NPC

H_2-Input: 4.1 €/kg_{H2}

RWGS Temperature / °C	1	5	10	25
900	3.16	3.09	3.09	3.18
875	3.15	3.08	3.08	3.19
850	3.14	3.07	3.07	3.26
825	3.13	3.06	3.08	3.41
800	3.12	3.06	3.12	3.71
775	3.11	3.07	3.19	
750	3.10	3.10	3.36	
725	3.10	3.18	3.78	
700	3.10	3.37		
675	3.11	3.91		
650	3.15			
625	3.24			
600	3.52			

RWGS pressure / bar

Minimum

[1] Adelung, S. and Dietrich, R.-U. (2022). *Impact of the reverse water-gas shift operating conditions on the Power-to-Liquid fuel production cost.* Fuel. Vol. 317, 2022, 123440, doi: 10.1016/j.fuel.2022.123440

Economic Assessment Example
Power-to-Liquid cost & sensitivity

Process Parameter dependent Net Production Costs [1] / NPC in $€_{2019}/kg_{C5+}$

= lower NPC

H_2-Input: 2.3 €/kg_{H2}

RWGS Temperature / °C \ RWGS pressure / bar	1	5	10	25
900	1.90	1.82	1.82	1.89
875	1.90	1.82	1.81	1.89
850	1.89	1.81	1.81	1.91
825	1.89	1.81	1.82	1.99
800	1.88	1.81	1.84	2.15
775	1.88	1.82	1.88	
750	1.88	1.85	1.98	
725	1.88	1.90	2.22	
700	1.88	2.01		
675	1.90	2.33		
650	1.93			
625	2.00			
600	2.19			

H_2-Input: 4.1 €/kg_{H2}

RWGS Temperature / °C \ RWGS pressure / bar	1	5	10	25
900	3.16	3.09	3.09	3.18
875	3.15	3.08	3.08	3.19
850	3.14	3.07	3.07	3.26
825	3.13	3.06	3.08	3.41
800	3.12	3.06	3.12	3.71
775	3.11	3.07	3.19	
750	3.10	3.10	3.36	
725	3.10	3.18	3.78	
700	3.10	3.37		
675	3.11	3.91		
650	3.15			
625	3.24			
600	3.52			

H_2-Input: 7.6 €/kg_{H2}

RWGS Temperature / °C \ RWGS pressure / bar	1	5	10	25
900	5.63	5.55	5.56	5.7
875	5.60	5.53	5.54	5.74
850	5.57	5.50	5.53	5.87
825	5.55	5.49	5.54	6.16
800	5.53	5.48	5.6	6.76
775	5.5	5.49	5.73	
750	5.49	5.54	6.05	
725	5.47	5.68	6.83	
700	5.47	6.01		
675	5.47	6.98		
650	5.52			
625	5.66			
600	6.09			

Minimum

[1] Adelung, S. and Dietrich, R.-U. (2022). *Impact of the reverse water-gas shift operating conditions on the Power-to-Liquid fuel production cost*. Fuel. Vol. 317, 2022, 123440, doi: 10.1016/j.fuel.2022.123440

Economic Assessment Example
Power-to-Liquid cost & sensitivity

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DLR

Process Parameter dependent Net Production Costs [1] / NPC in $€_{2019}/kg_{C5+}$

(darker green) = lower NPC

H_2-Input: 2.3 €/kg_{H2}

RWGS Temperature / °C	1	5	10	25
900	1.90	1.82	1.82	1.89
875	1.90	1.82	1.81	1.89
850	1.89	1.81	1.81	1.91
825	1.89	1.81	1.82	1.99
800	1.88	1.81	1.84	2.15
775	1.88	1.82	1.88	
750	1.88	1.85	1.98	
725	1.88	1.90	2.22	
700	1.88	2.01		
675	1.90	2.33		
650	1.93			
625	2.00			
600	2.19			

RWGS pressure / bar

H_2-Input: 4.1€/kg_{H2}

RWGS Temperature / °C	1	5	10	25
900	3.16	3.09	3.09	3.18
875	3.15	3.08	3.08	3.19
850	3.14	3.07	3.07	3.26
825	3.13	3.06	3.08	3.41
800	3.12	3.06	3.12	3.71
775	3.11	3.07	3.19	
750	3.10	3.10	3.36	
725	3.10	3.18	3.78	
700	3.10	3.37		
675	3.11	3.91		
650	3.15			
625	3.24			
600	3.52			

RWGS pressure / bar

H_2-Input: 7.6 €/kg_{H2}

RWGS Temperature / °C	1	5	10	25
900	5.63	5.55	5.56	5.7
875	5.60	5.53	5.54	5.74
850	5.57	5.50	5.53	5.87
825	5.55	5.49	5.54	6.16
800	5.53	5.48	5.6	6.76
775	5.5	5.49	5.73	
750	5.49	5.54	6.05	
725	5.47	5.68	6.83	
700	5.47	6.01		
675	5.47	6.98		
650	5.52			
625	5.66			
600	6.09			

RWGS pressure / bar

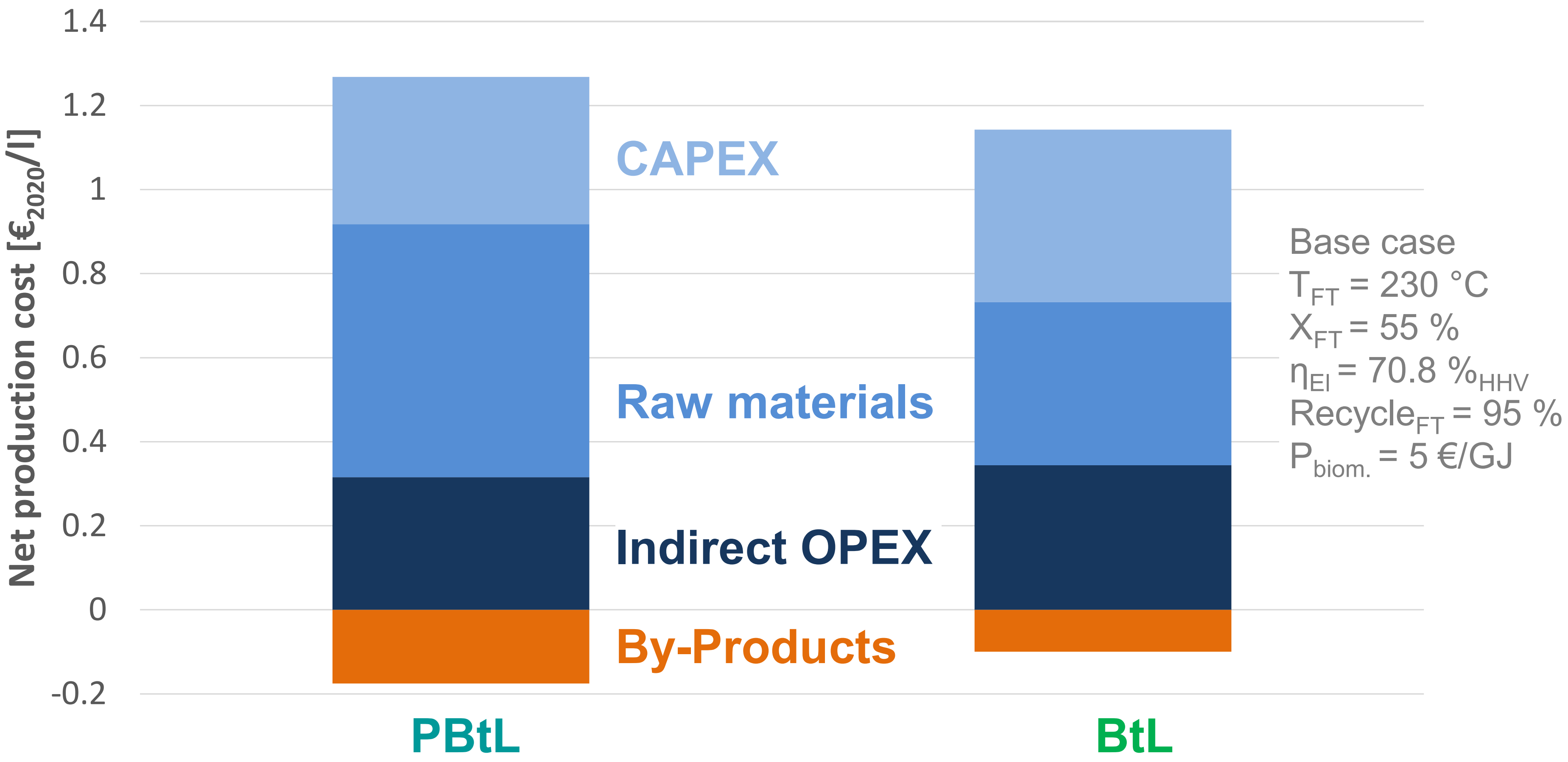
Minimum

5 bar and 800 °C: low cost, robust NPC optimum for all H_2 feedstock costs

[1] Adelung, S. and Dietrich, R.-U. (2022). *Impact of the reverse water-gas shift operating conditions on the Power-to-Liquid fuel production cost.* Fuel. Vol. 317, 2022, 123440, doi: 10.1016/j.fuel.2022.123440

Economic Assessment Example

BtL / PBtL cost [1]



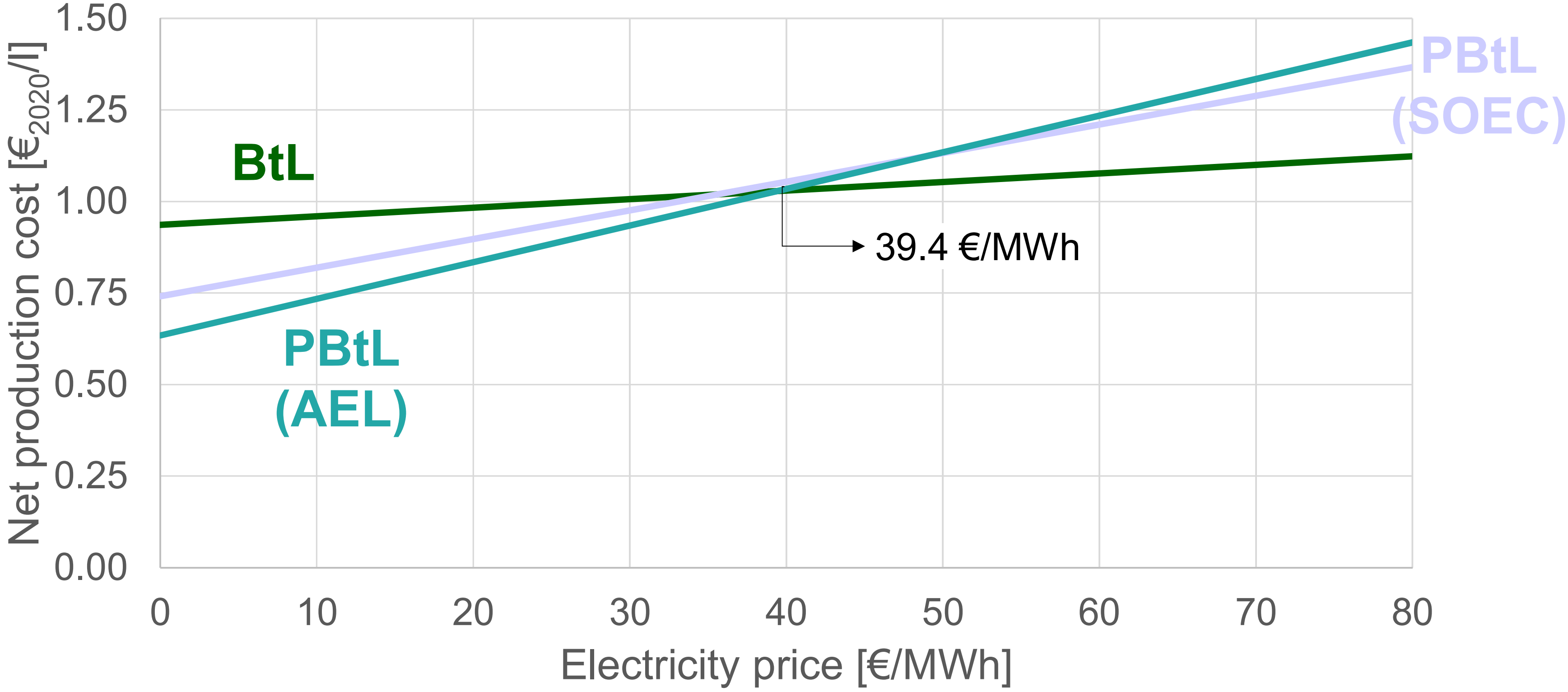
[1] Habermeyer, et. al (2023) *Power Biomass to Liquid — an option for Europe's sustainable and independent aviation fuel production*. Biomass Conversion and Biorefinery. Springer Nature. doi: 10.1007/s13399-022-03671-y. 723774

Economic Assessment Example

BtL / PBtL cost sensitivity [1]

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

Net production cost sensitivity [1] :



[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

ENVIRON. ASSESSMENT OF SAF CONCEPTS

Environmental Assessment
Methodology

- KPI's of LCA ➔ more than only climate change
  - Water use versus water scarcity
  - Land use competition?
  - High minerals and metals resource depletion in SAF process chain (compared to crude oil)

- Comply with regulation: Renewable Energy Directive (RED III)
  ➔ 65(70)% climate change reduction – due to change: RED IV, V, VI?
  - No consideration of impacts from cultivation phase
  - Full feedstock sustainability questionable (carbon harvested = carbon regrowth)
  - No credit for higher climate change reduction potential above 70%
    - ➢ No incentive for minimising climate change below threshold

Environmental Assessment
Methodology

- ISO 14040/14044 for standard life cycle assessment (LCA) procedure
- Simplified PBtL climate change calculation example:

Harvesting

Fertilizer

CO_2 **DAC**

Electricity production

•
•
•

- Fully automated environmental impact estimation using DLR in-house tools

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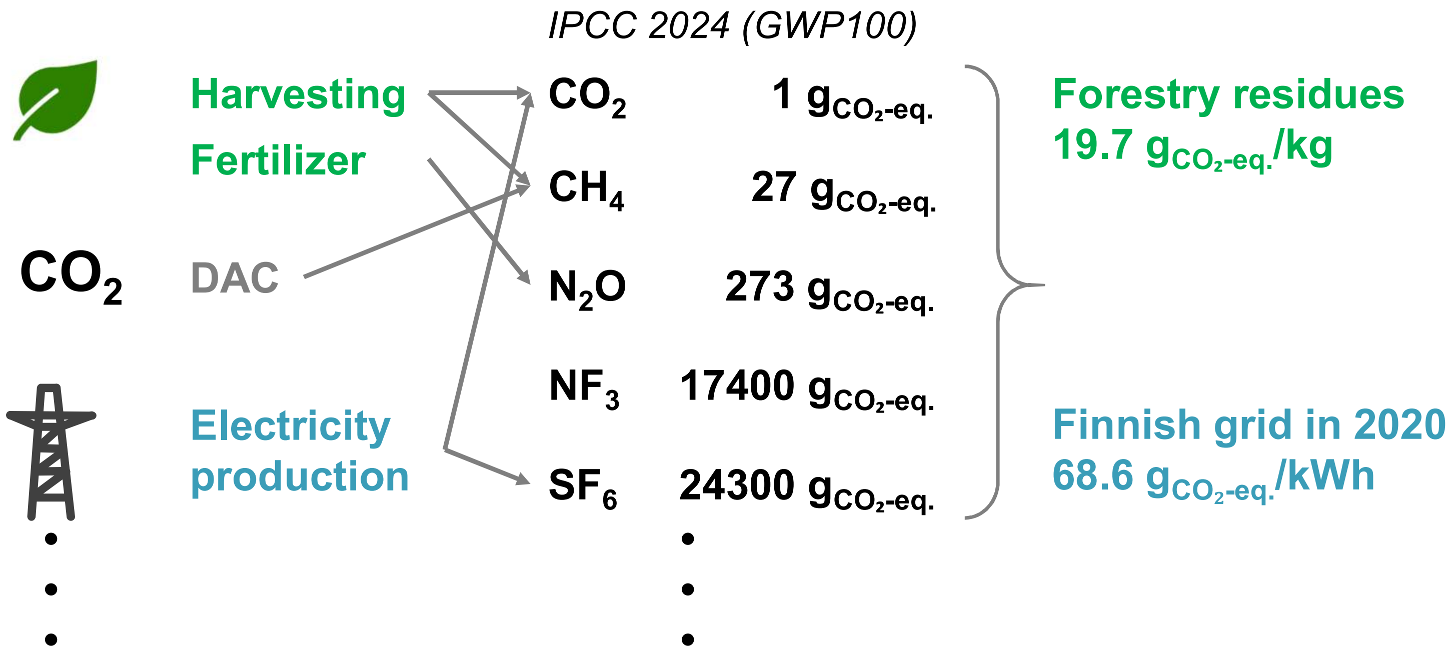
Environmental Assessment
Methodology

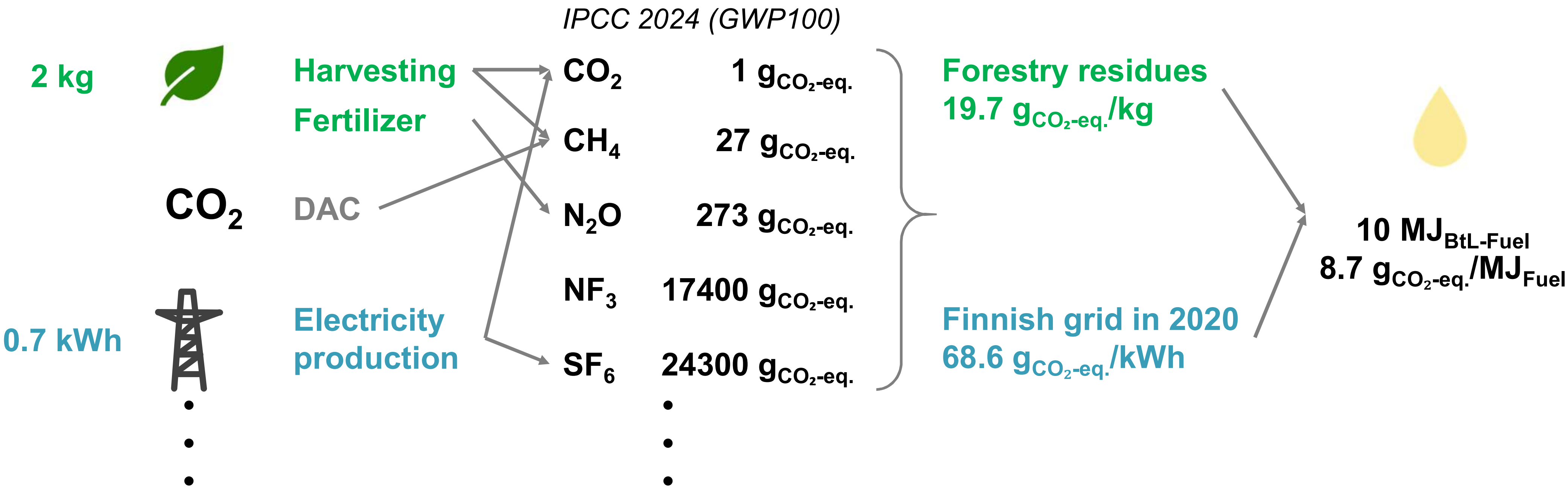
- ISO 14040/14044 for standard life cycle assessment (LCA) procedure
- Simplified PBtL climate change calculation example:



- Fully automated environmental impact estimation using DLR in-house tools

Environmental Assessment
Methodology

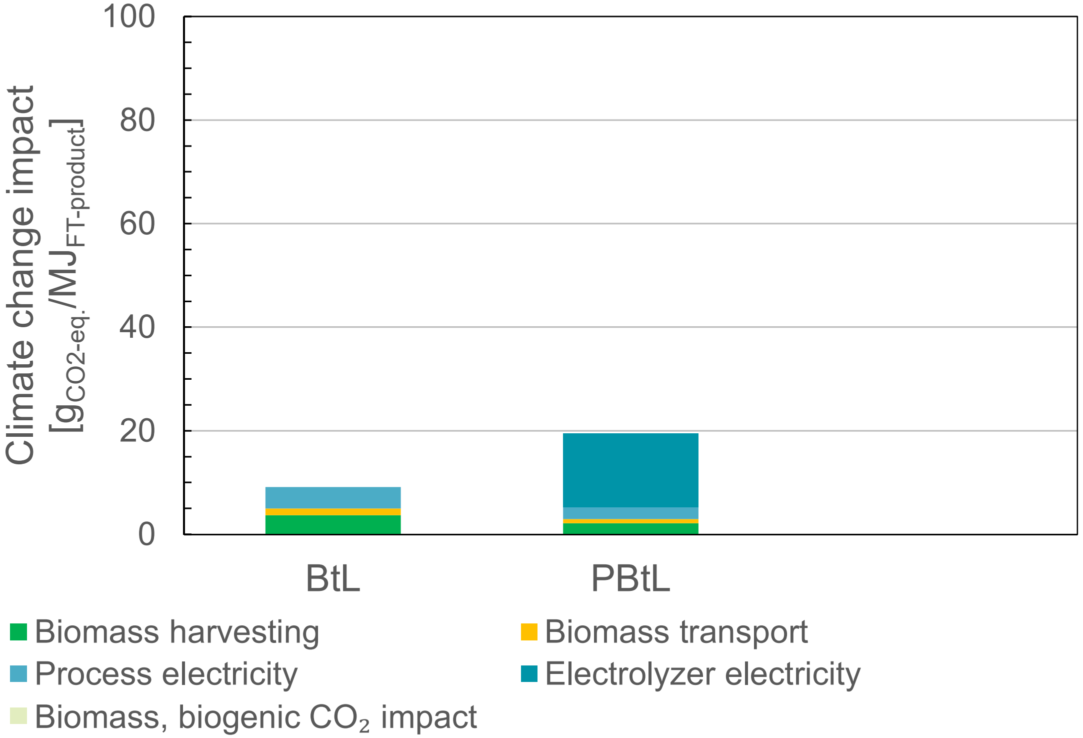
- ISO 14040/14044 for standard life cycle assessment (LCA) procedure
- Simplified PBtL climate change calculation example:



- Fully automated environmental impact estimation using DLR in-house tools

Economic Assessment Example
BtL / PBtL comparison [1]

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



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

[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
[3] Cherubini et al. (2011). CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming

Economic Assessment Example
BtL / PBtL comparison [1]

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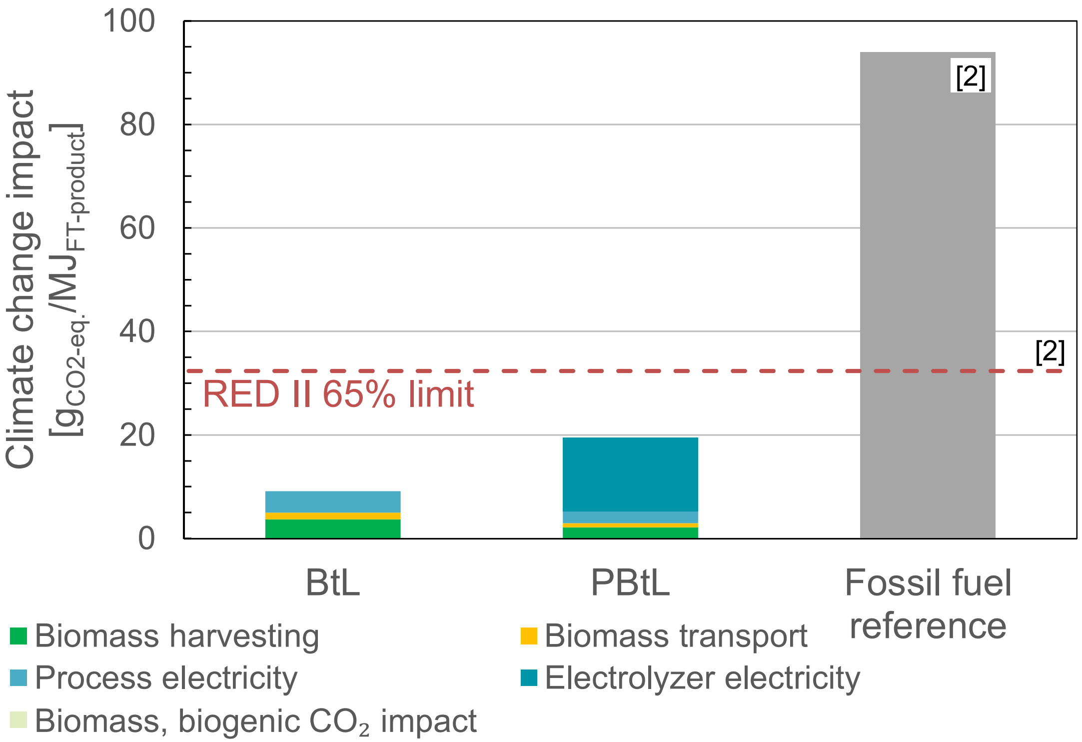

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Economic Assessment Example

BtL / PBtL comparison [1]

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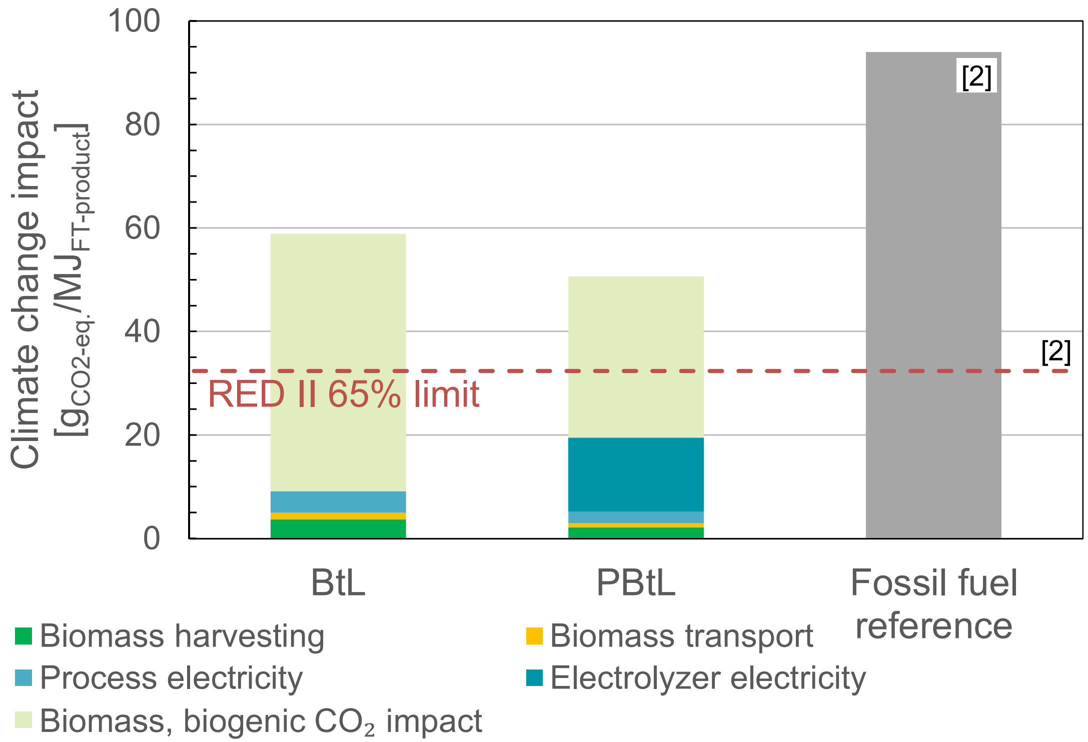

- **Electricity: Finnish grid (68.6 $g_{CO2\text{-}eq.}$/kWh in 2020)**
- **Transportation: 100 km, one-way by truck (69 $g_{CO2\text{-}eq.}$/(t*km))**
- **Biomass: Forest residues harvesting (19.7 $g_{CO2\text{-}eq.}$/kg)**
- **Biogenic C [3]: 60 a old softwood (32 $\%_{wt.}$) (not in RED III) 80 a hardwood (68 $\%_{wt.}$) (1.1 $kg_{CO2\text{-}eq.}$/kg_C)**

[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.
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Economic Assessment Example
BtL / PBtL comparison [1]

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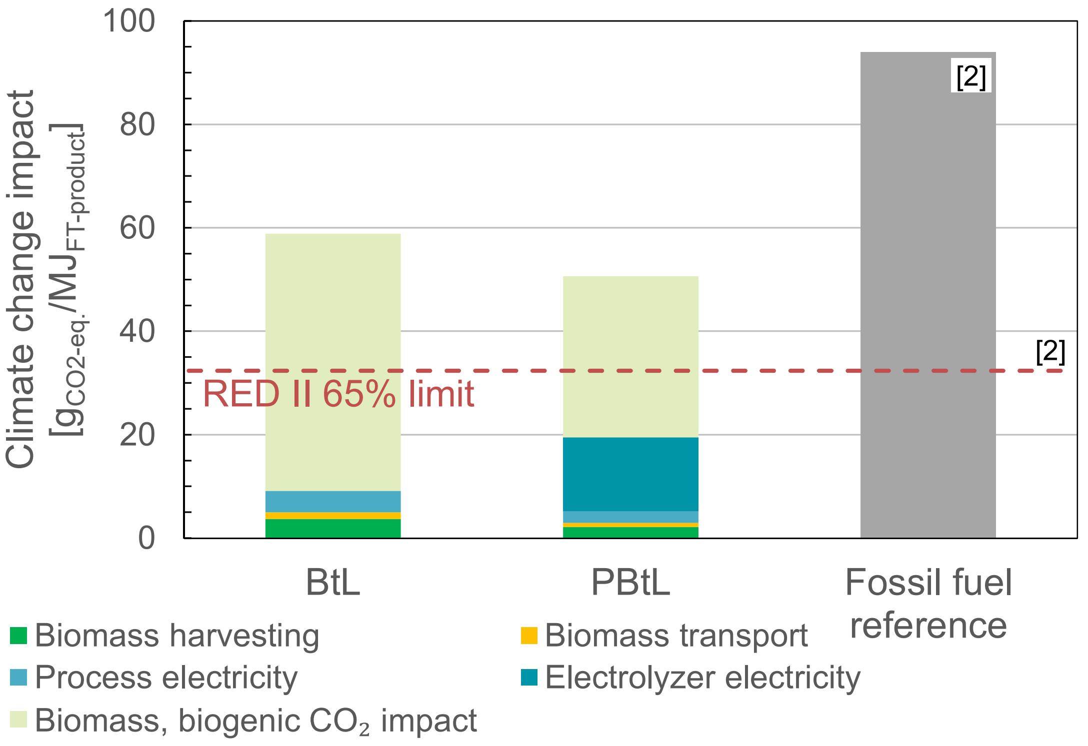

- **Electricity: Finnish grid (68.6 $g_{CO2\text{-}eq.}$/kWh in 2020)**
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Conclusion

REDII target accomplished @ FLEXCHX case without biogenic CO_2 impact

[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.
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[3] Cherubini et al. (2011). CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming

Climate change sensitivity
BtL / PBtL based on power source

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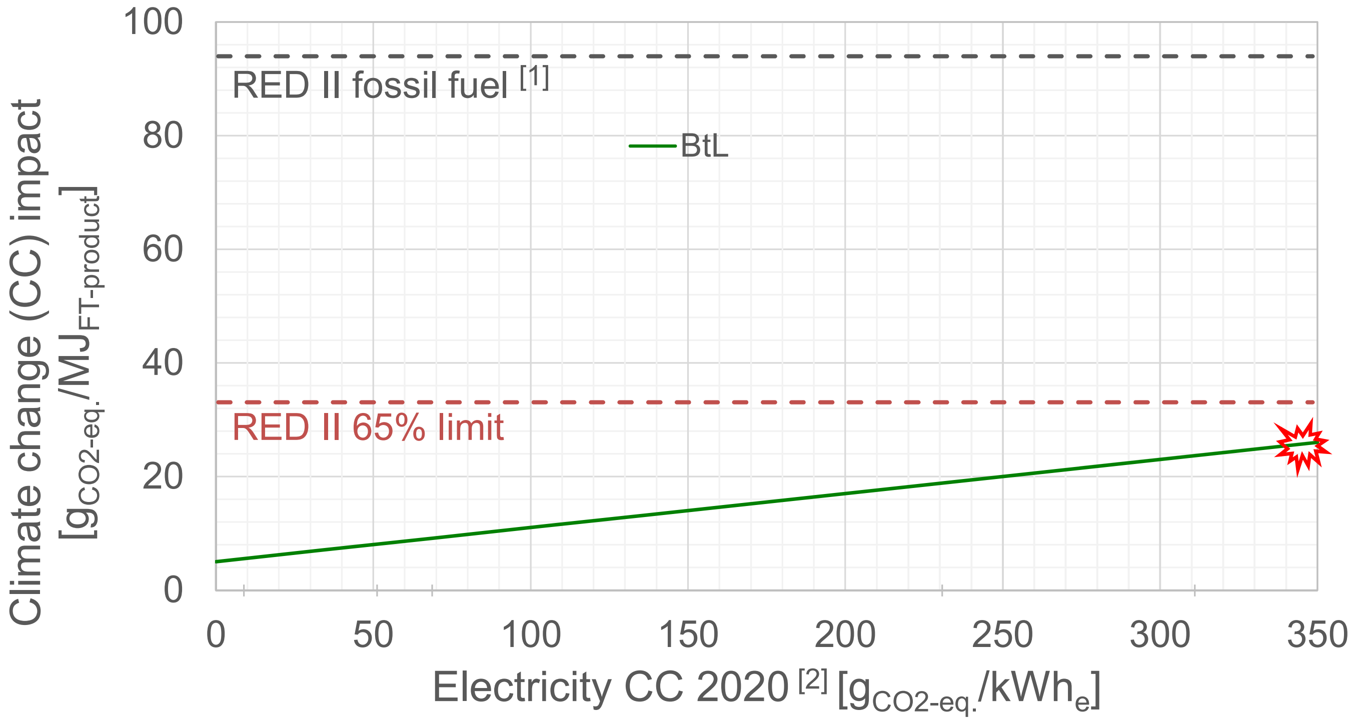
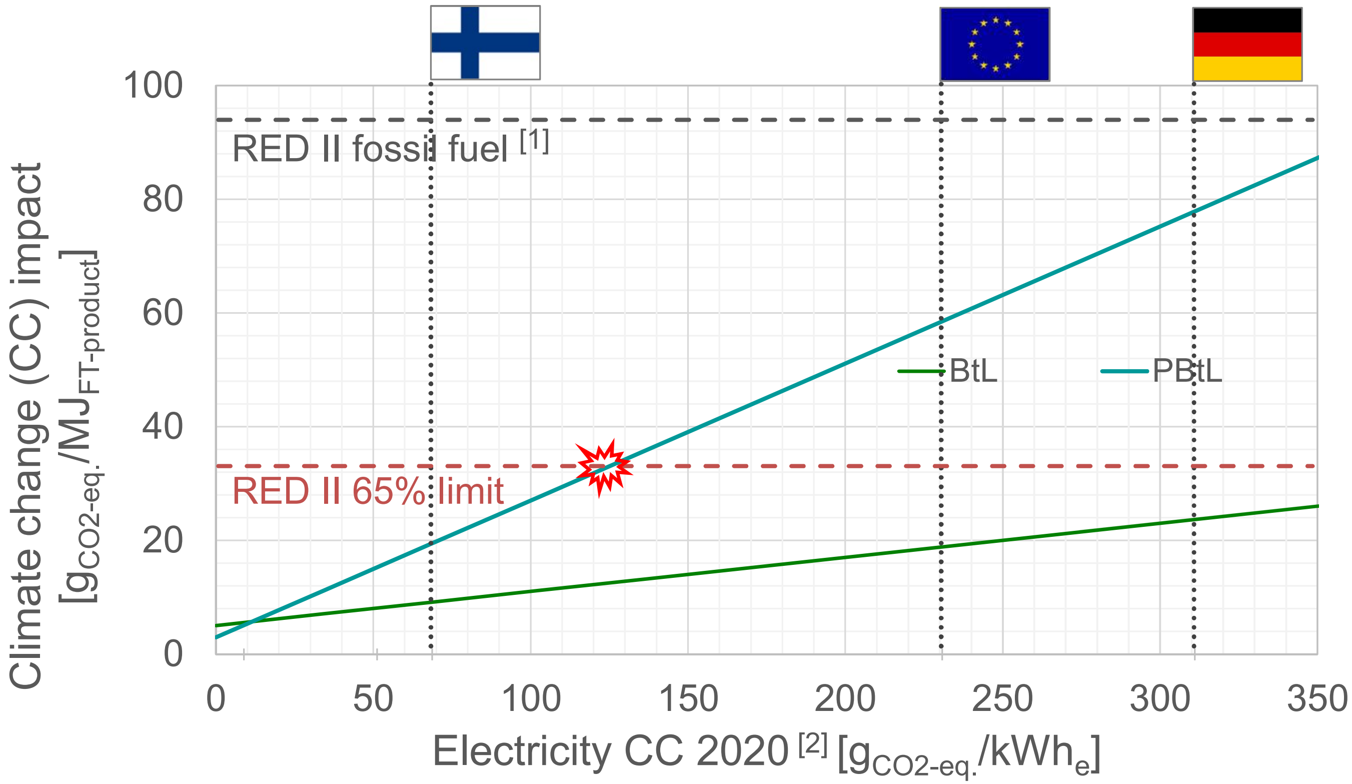


- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL

[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

Climate change sensitivity
BtL / PBtL based on power source

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
- PBtL requires electricity with CC impact <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
[2] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111

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Climate change sensitivity
BtL / PBtL based on power source

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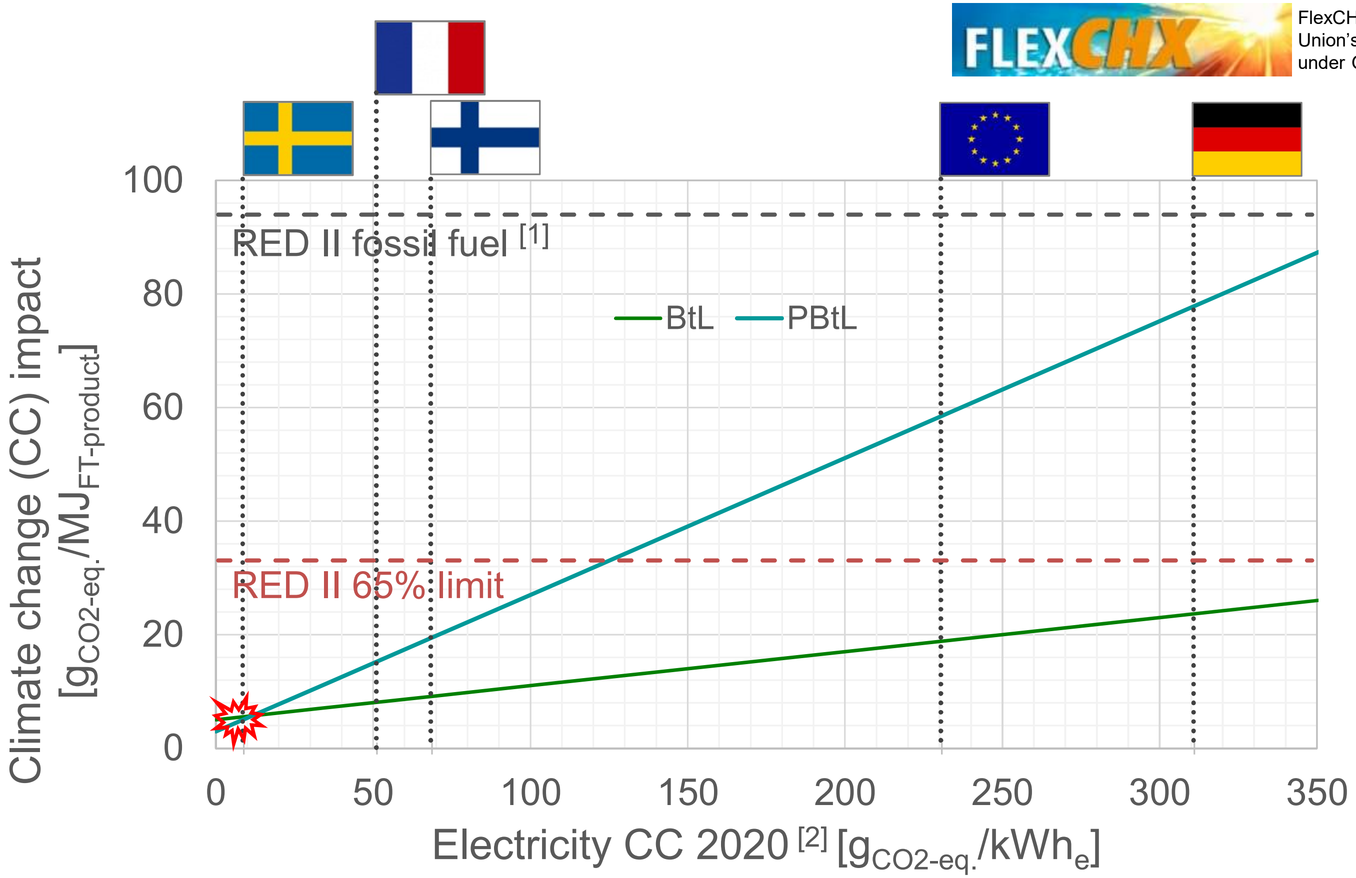

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with CC impact <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit
- PBtL could have lower CC impact than BtL with Swedish grid mix

[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
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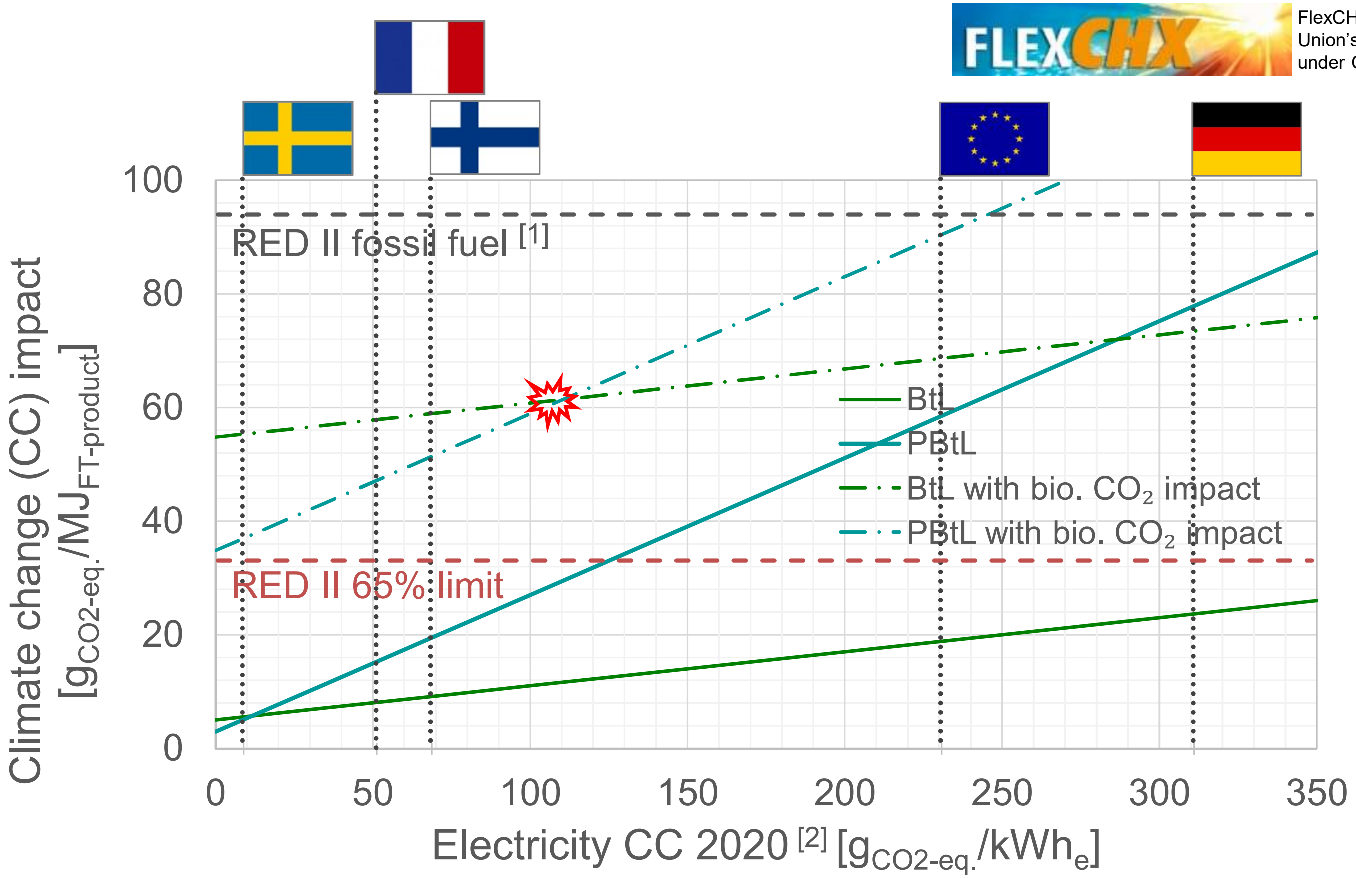
Climate change sensitivity
BtL / PBtL based on power source

FLEXCHX
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
- PBtL requires electricity with CC impact <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit
- PBtL could have lower CC impact than BtL with Swedish grid mix
- With biogenic CO_2 impact PBtL could reach lower CC impact than BtL if electricity CC impact <115 $g_{CO2\text{-}eq.}/kWh_e$

[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

EUROPEAN SAF FEEDSTOCK SUPPLY

Certified Alternative Jet Fuels
ASTM D7566 – 21 [1]

Feedstock	Synthesis technology	Fuel
~~Coal, natural gas~~, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis using Fe or Co catalyst,	Synthetic paraffinic kerosene (FT-SPK)
Non-petroleum derived light aromatics (primarily benzene)	Blend aromatics produced by alkylation to FT-SPK	FT-SPK plus Aromatics (SPK/A)
Biogenic lipids (e.g. algae, soya, palm oil, jatropha)	Hydrogenation and deoxygenation of fatty acids and esters (HEFA) + subsequent hydrocracking, hydroisomerization, isomerization, …	Synthetic paraffinic kerosene (HEFA-SPK)
Additional algae produced oil containing a high percentage of unsaturated hydrocarbons known as botryococcenes,	Blend botryococcenes hydrocarbons prior to hydroprocessing Esters and Fatty Acids (HC-HEFA)	SPK from Hydroprocessed Hydrocarbons, Esters and Fatty Acids (HC-HEFA)
Biogenic lipids (e.g. algae, soya, palm oil, jatropha)	Catalytic hydrothermal conversion of fatty acids and esters	Catalytic hydrothermolysis Jet (CHJ)
Sugar from Biomass	Direct Sugars to Hydrocarbons (DSHC)	Synthetic iso-paraffins (SIP) / Farnesane
Bio-isobutanol (-methanol, -ethanol, -propanol, …)	dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AD-SPK
Any C2-C5 alcohols (individually or combined)	Dehydration+oligomerization+hydrogenation Aromatic / nonaromatic components produced separately	Alcohol to Jet with Aromatics (ATJ-SKA)

[1] ASTM International, „ASTM D7566-21 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2021

Certified Alternative Jet Fuels

ASTM D7566 – 21 [1]

Feedstock	Synthesis technology	Fuel
~~Coal, natural gas~~, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis using Fe or Co catalyst,	Synthetic paraffinic kerosene (FT-SPK)
Non-petroleum derived light aromatics (primarily benzene)	Blend aromatics produced by alkylation to FT-SPK	FT-SPK plus Aromatics (SPK/A)
Biogenic lipids (e.g. algae, soya, palm oil, jatropha)	Hydrogenation and deoxygenation of fatty acids and esters (HEFA) + subsequent hydrocracking, hydroisomerization, isomerization, …	Synthetic paraffinic kerosene (HEFA-SPK)
Additional algae produced oil containing a high percentage of unsaturated hydrocarbons known as botryococcenes,	Blend botryococcenes hydrocarbons prior to hydroprocessing Esters and Fatty Acids (HC-HEFA)	SPK from Hydroprocessed Hydrocarbons, Esters and Fatty Acids (HC-HEFA)
Biogenic lipids (e.g. algae, soya, palm oil, jatropha)	Catalytic hydrothermal conversion of fatty acids and esters	Catalytic hydrothermolysis Jet (CHJ)
Sugar from Biomass	Direct Sugars to Hydrocarbons (DSHC)	Synthetic iso-paraffins (SIP) / Farnesane
Bio-isobutanol (-methanol, -ethanol, -propanol, …)	dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AD-SPK

[1] ASTM International, „ASTM D7566-21 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2021

Certified Alternative Jet Fuels

ASTM D7566 – 21 [1]

Feedstock	Synthesis technology	Fuel
~~Coal, natural gas~~, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis using Fe or Co catalyst,	Synthetic paraffinic kerosene (FT-SPK)
Non-petroleum derived light aromatics (primarily benzene)	Blend aromatics produced by alkylation to FT-SPK	FT-SPK plus Aromatics (SPK/A)
Biogenic lipids (e.g. algae, soya, palm oil, jatropha)	Hydrogenation and deoxygenation of fatty acids and esters (HEFA) + subsequent hydrocracking, hydroisomerization, isomerization, …	Synthetic paraffinic kerosene (HEFA-SPK)
Additional alg… percentage o… botryococce…		…ons, …HEFA)
Biogenic lipi…		Jet
Sugar from E…		…IP)
Bio-isobutano…	(Alcohol-to-Jet, AtJ)	

Future role of 1st generation jet fuels within the aviation sector questionable due to:

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

➔ **How / Where / When to deploy 2nd generation SAF?**

[1] ASTM International, „ASTM D7566-21 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2021

Assessment of SAF options
/ configurations / locations / …

Feedstock availability towards 63 Mt/a

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

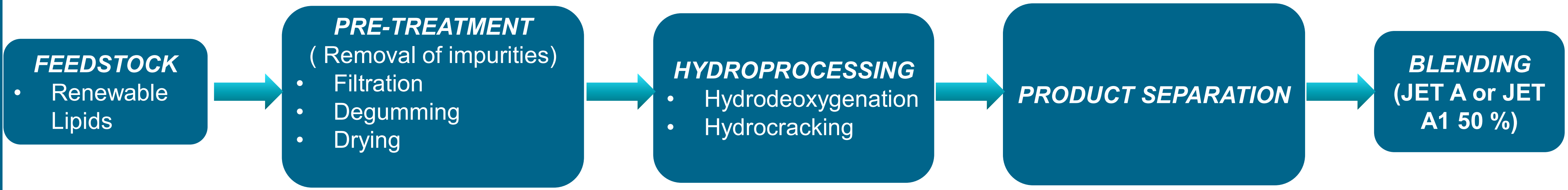
- Feedstock
  - Synthesis gas available from almost any carbon and hydrogen source ➔ Sustainability?
    - European wind power potential[1] for **sustainable H**: 12,200 – 30,400 TWh_e **≈ 10 - 20 times of SAF demand!**
    - Annual sequestration of carbon in European forest biomass[2] for **sustainable C**: 155 Mt/a **≈ 3 times of SAF demand!**
- FT synthesis
  - Large scale, commercial technology
    - Secunda CTL (Sasol): ca. 7 Mio.t/a – since 1980/1984
    - Pearl GTL (Qatar Petroleum + Shell): ca. 6 Mio.t/a – since 2011
- Fuel
  - Fully synthetic kerosene achievable [3]

[1] European Environment Agency, "Europe's onshore and offshore wind energy potential," 2009
[2] FOREST EUROPE, 2020: State of Europe's Forests 2020
[3] UK Ministry of Defense, „DEF STAN 91-91: Turbine Fuel, Kerosene Type, Jet A-1", UK Defense Standardization, 2011

Assessment of SAF options

HEFA certified ASTM D7566 – 24d [1]

Feedstock	Synthesis technology	Fuel
Biogenic lipids (e.g. algae, soya, palm oil, jatropha)	Hydrogenation and deoxygenation of fatty acids and esters (HEFA) + subsequent hydrocracking, hydroisomerization, isomerization, …	Synthetic paraffinic kerosene (HEFA-SPK)
Additional algae produced oil containing a high percentage of unsaturated hydrocarbons known as botryococcenes,	Blend botryococcenes hydrocarbons prior to hydroprocessing Esters and Fatty Acids (HC-HEFA)	SPK from Hydroprocessed Hydrocarbons, Esters and Fatty Acids (HC-HEFA)



[1] ASTM International, „ASTM D7566-24d Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2024

HEFA feedstock assessment
Multiple sources – multiple issues

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

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

[1] ASTM International, „ASTM D7566-24d Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2024

HEFA feedstock assessment
Multiple sources – multiple issues

- Despite a long feedstock list:
  product quality, reliabil

1. European rapeseed oil:
Germany > France > Poland > Romania > Bulgaria

PROS:
- High oil yield per hectare
- Low free fatty acid content suitable for Hydro-processing.
- Rich in Oleic acid

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

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

2. *European camelina oil: Italy > France > Germany > Spain*

PROS:
- **High lipid content** (~35–40%)
- **Good proportion of C16 and C18 fatty acids** – ideal for jet/diesel fuel chains
- **Low sulfur and aromatic content** – cleaner burn
- **Non-edible** – avoids food supply conflicts
- Supports **RED II**
- Drought resistant and sustainable as it aids in crop rotation.

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

[1] ASTM International, „ASTM D7566-24d Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2024

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HEFA feedstock assessment
Multiple sources – multiple issues

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

Category	Feedstock		
Vegetable Oils	Soybean Oil Rapeseed (Canola Oil) Camelina Oil Palm Oil Jatropha Oil		
Animal Fats	Tallow (Beef/Pork) Poultry Fat Lard		
Used Cooking Oils (UCO)	Used Cooking Oils		
Algal Oils	Algae Oils	Algae species (Eg.Chlorella ,Nannochlropsis etc.)	Omega-3 fatty acids (EPA/DHA), Oleic acid

3. *European soybean oil : Netherlands > Spain > Germany*

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

<u>CONS:</u>
- Land use concerns as it affects food prices and deforestation.
- Food vs Fuel Debate hence limited scalability.
- Large amount of hydrogen needed for processing.

[1] ASTM International, „ASTM D7566-24d Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2024

HEFA feedstock assessment
Multiple sources – multiple issues

- Despite a long feedstock list:
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Category	Feedstock		
Vegetable Oils	Soybean O Rapeseed (Canola Oi Camelina (Palm Oil Jatropha (		
Animal Fats	Tallow (Beef/F		
Used Cooking Oils (UCO)	Used Cooking		
Algal Oils	Algae Oils	(Eg.Chlorella ,Nannochlropsis etc.)	Oleic acid

4. *European animal fats:*
Germany > Spain > Netherlands > Poland > Denmark,…

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

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

[1] ASTM International, „ASTM D7566-24d Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2024

HEFA feedstock assessment
Multiple sources – multiple issues

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	Rapeseed (Canola O		
	Camelina		
	Palm O		
	Jatropha		
Animal Fats	Tallow (Beef		
	Poultry F		
	L		
Used Cooking Oils (UCO)			
Algal Oils	Algae O		

5. *European Used Cooking Oil (UCO):*
Italy > Netherlands > Germany > Spain > France > Ireland > Portugal

<u>PROS:</u>
- **Sustainable:** Uses **waste oil**
- **Low GHG**, 60-90% lower than fossil fuels
- **Drop-in fuel** compatibility.
- Circular economy

- **<u>CONS:</u>**
- **Limited Supply:** UCO availability is finite and region-dependent.
- **Collection Logistics:** Requires efficient infrastructure for sourcing.
- **Feedstock Quality:** Variability in UCO quality affects processing efficiency.

[1] ASTM International, „ASTM D7566-24d Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2024

HEFA feedstock assessment

Multiple sources – multiple issues

- Despite a long feedstock list:
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Vegetable Oils	Soybean Oil Rapeseed (Canola Oil) Camelina Oil Palm Oil Jatropha Oil		
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Algal Oils	Algae Oils	Algae species (Eg.Chlorella ,Nannochlropsis etc.)	Omega-3 fatty acids (EPA/DHA), Oleic acid

6. ***Micro Algae: Norway > Germany > Italy > Portugal***

PROS:

- High lipid yield (up to 50% dry weight).
- Rapid growth (up to double the volume in 24 hours)
- Avoids food vs. fuel conflict
- Utilizes wastewater or CO_2 :Helps in environmental remediation
- Can be grown on non-arable land.

CONS:

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

[1] ASTM International, „ASTM D7566-24d Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2024

HEFA feedstock assessment
Multiple sources – multiple issues

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

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	Camelin…		
	Palm…		
	Jatroph…		
Animal Fats	Tallow (Be…		
	Poultr…		
	La…		
Used Cooking Oils (UCO)	U…		
Algal Oils	Alg…		

7. *Macro Algae: Norway > France > Ireland > Spain > Portugal*

<u>PROS:</u>
- High lipid content yields high quality SAFs.
- Non-food source hence sustainble
- High growth rate in coastal regions thus need less land, water and fertilizer
- Beneficial to environment as it absorbs CO_2.

<u>CONS:</u>
- Needs efficient oil extarction in terms of harvest, cost and scalability
- Lower yield than terrestial feedstocks

[1] AS…

HEFA Feedstock assessment
- not completed jet -

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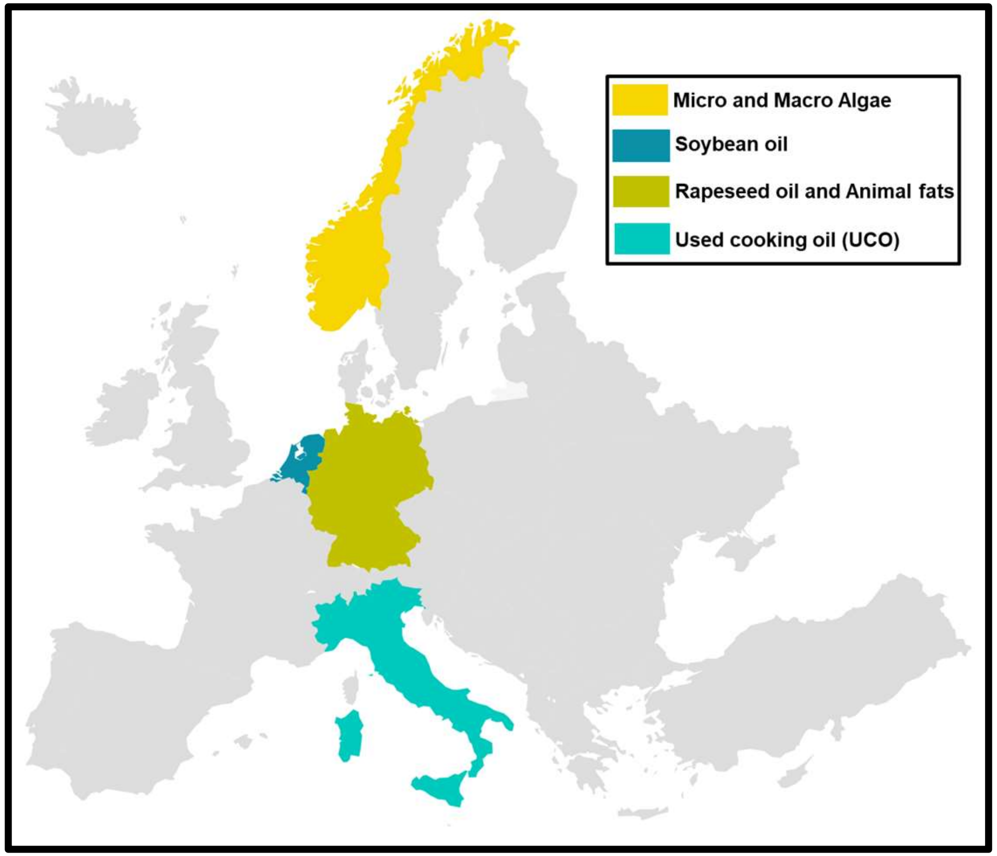
Possible European HEFA Feedstock favorites



Status quo:

- HEFA is a promising SAF
  - Low conversion costs
  - Inexpensive feedstocks

Open socio-economical questions:

- Food vs. fuel vs. road transport
- Reliability / sustainability of import
- Cost vs. environmental impact
- EU-wide feedstock collection mechanism?

Alcohol-to-Jet
Using MeOH under development

Bio-isobutanol (-methanol, -ethanol, -propanol, …)	dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AD-SPK
Any C2-C5 alcohols (individually or combined)	Dehydration+oligomerization+hydrogenation Aromatic / nonaromatic components produced separately	Alcohol to Jet with Aromatics (ATJ-SKA)

- Methanol as educt with versatile use cases
  → Lower investment risk
- Process configuration allows jet fuel-like product composition (aromatics)
- High product efficiency (> 70% SAF from MeOH)
- New MeOH-to-SAF certification procedure in progress

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European SAF Feedstock Supply
Renewable electricity

- Renewable electricity (RE) generation in Europe in 2024: 1160 TWh [1] (≙ 60 Mt/a PBtL)
- LCOE of RE in Europe: ~ 71 $€_{2023}$/MWh
- Climate change impact of RE in Europe: ~ 33 $g_{CO_2\text{-eq.}}$/kWh

Energy Source	**Estimated Output 2024 (TWh)** [2]	**Levelized Cost of Electricity 2023 (€/MWh)** [3]	**Climate change impact ($g_{CO_2\text{-eq.}}$/kWh)** [4,5]
Wind	39.1% (~450)	30–100	7–56
Hydropower	29.9% (~350)	25–250	1–2200
Solar	22.4% (~260)	40–150	7–180
Bioenergy	8.1% (~94)	50–215	0–420
Geothermal	0.5% (~6)	50–85	6–79

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

European SAF Feedstock Supply
Forestry residues

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

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

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

Constraints:

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

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

European SAF Feedstock Supply
Lignin from pulp mill

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

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

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

Constraints:

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

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

European SAF Feedstock Supply
Agricultural residues

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

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

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

Constraints:

- Soil health degradation
- Competing uses
- Seasonal production

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

European SAF Feedstock Supply
Industrial CO_2 & DAC

Industrial CO_2

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

Constraints:

- Industrial CO_2 is about to decrease in the future with the EU's goals for decarbonisation

Atmospheric CO_2 (DAC)

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

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

* With RE CC impact from previous slide

European SAF Feedstock Supply
Water for electrolysis

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

EU renewable hydrogen target (by 2030) [1]: 10 Mt H_2

- ~90 million m³/a deionized water

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

Constraints:

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

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

* With RE CC impact from previous slide

LARGE SCALE SAF PRODUCTION TRL

Biomass gasification TRL?

- typically at temperatures 700 - 1200 °C
- Air, oxygen, steam or their mixtures as gasifying agent
- Reaction pathway understood in detail[1]
- Wide range of reactor configurations: fixed bed (updraft and downdraft), fluidized bed, entrained flow, spouted beds, rotary kiln, plasma reactors

[1] Biomass steam gasification reactions and steps involved. From Arregi et al., *Evaluation of thermochemical routes for hydrogen production from biomass: A review*, Energy Conversion and Management, 2018 (v.165), doi.org/10.1016/j.enconman.2018.03.089

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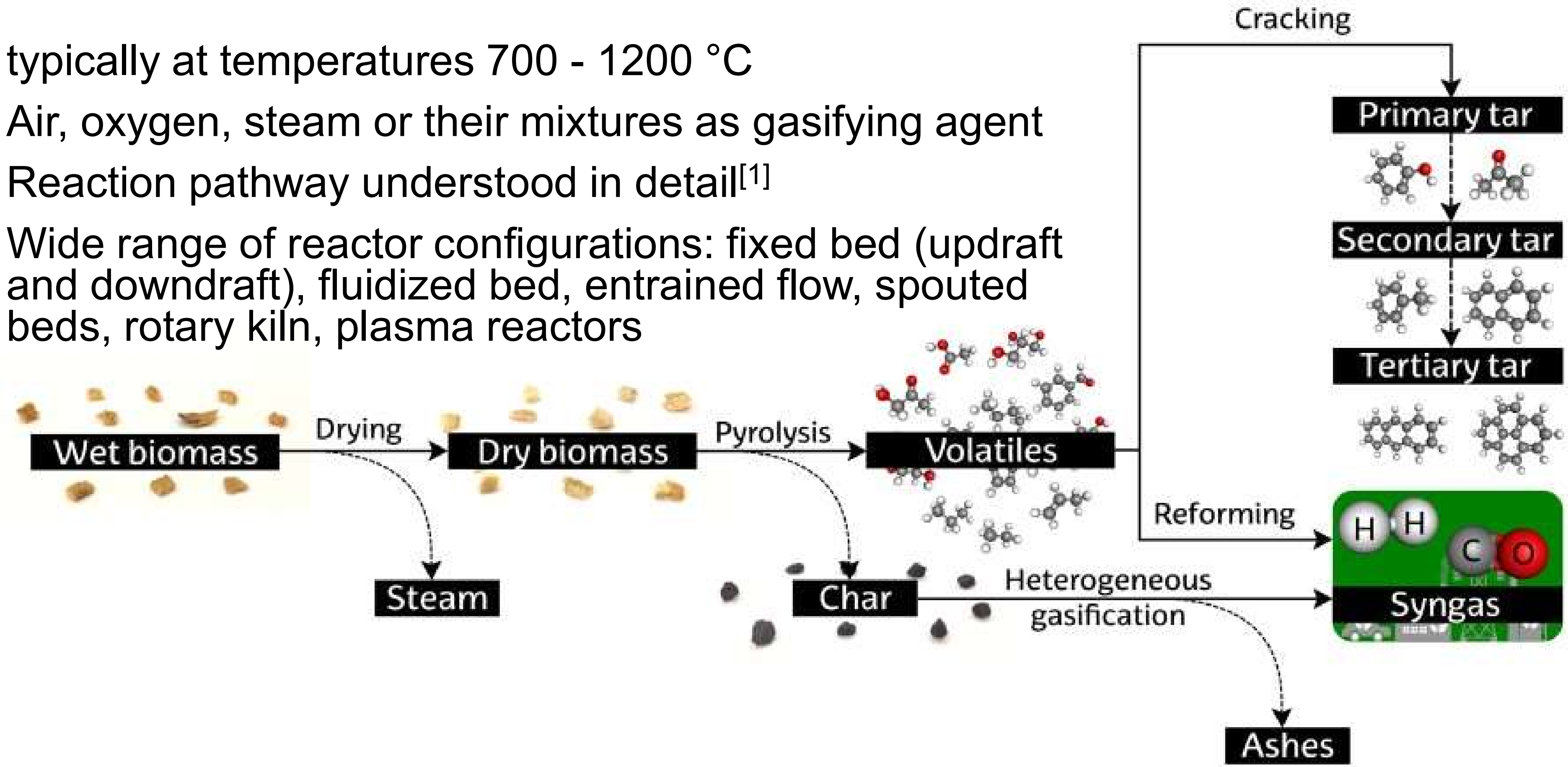
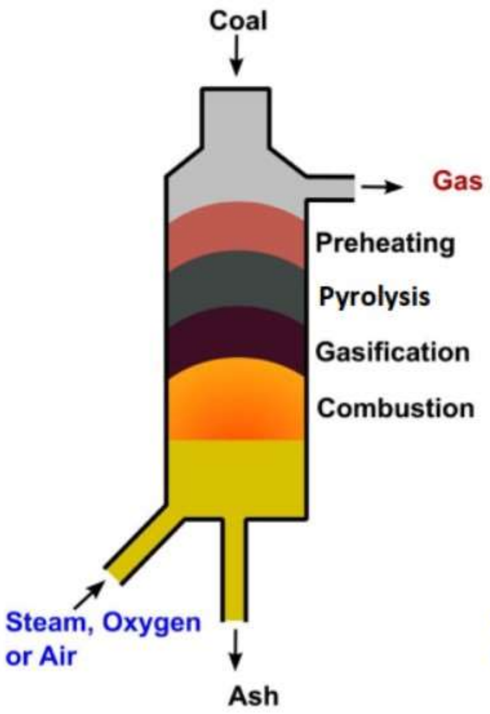


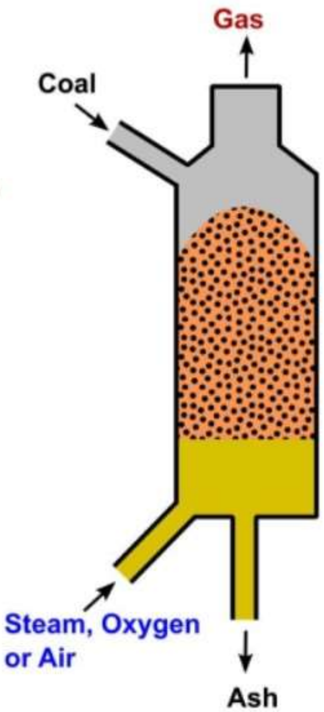
[1] Biomass steam gasification reactions and steps involved. From Arregi et al., *Evaluation of thermochemical routes for hydrogen production from biomass: A review*, Energy Conversion and Management, 2018 (v.165), doi.org/10.1016/j.enconman.2018.03.089

Gasifier TRL?

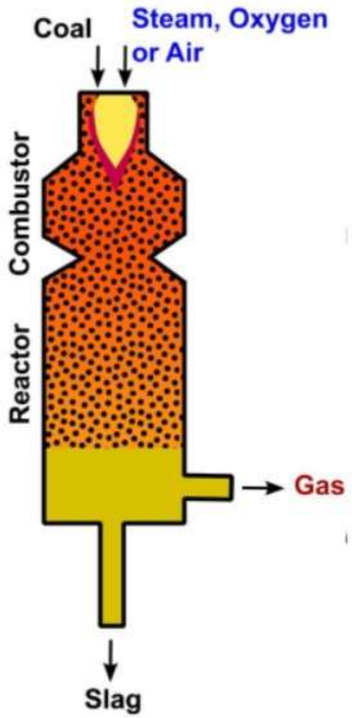
State-of-the-art coal technology



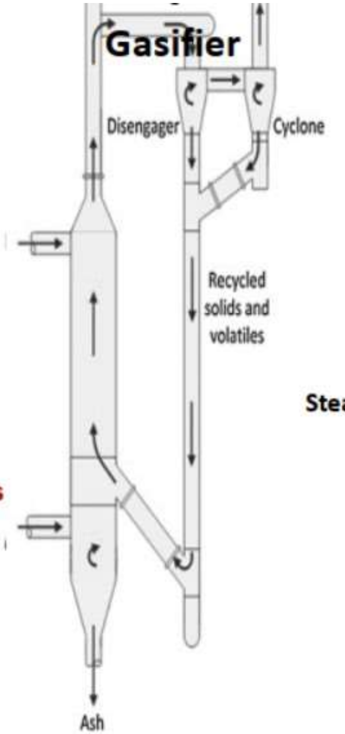
Fixed (moving) bed



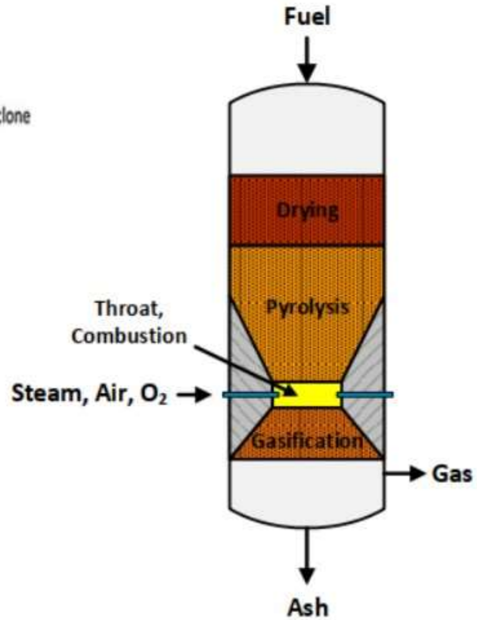
Fluidized bed



Entrianed flow



Transport
Integrated



Downdraft

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Gasifier TRL?
Multiple installations (incl. biomass)

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

Electrolyser TRL?

Ready despite ongoing research

Table 2. Summary of parameters of state-of-the-art water electrolysis.

Technology	AEL	PEM	SOEC
Electrolyte	20–40 wt % KOH	water	steam
Operating temperature [°C]	60–90	50–80	700–900
Typical operating pressure [bar]	10–30	20–50	1–15
Current density [$A\,cm^{-2}$]	0.2–0.4 / 1.2[b)]	0.6–2.0	0.3–2.0
Cell area [m^2]	<4	<0.3	<0.01
Specific energy consumption (stack) [$kWh_{el}\,Nm^{-3}\,H_2$]	4.2–4.8	4.4–5.0	>3.0
Specific energy consumption (system) [$kWh_{el}\,Nm^{-3}\,H_2$]	5.0–5.9	5.0–6.5	3.7–3.9 (4.7 $kWh\,Nm^{-3}\,H_2$)
Lower dynamic range [%][a)]	10–40 / <10 [c)]	0–10	>30
Gas purity [%]	> 99.5 / > 99.95[b)]	99.99	99.90
System response	seconds	milliseconds	seconds
Cold time start [min]	<60 / <1–50 %[b)]	<20	<60
Stack lifetime [h]	60 000–90 000	20 000–60 000	<10 000
Maturity	mature	commercial	demonstration
Investments costs [$€\,kW^{-1}$]	800–1500	1400–2100	>2000

a) Minimum operable hydrogen production rate relative to maximum specified production rate; b) thyssenkrupp system installed at Carbon2Chem®; c) Lüke and Zschocke [14].

[1] Tenhumberg, *Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies*, Chem. Ing. Tech. 2020, 92, No. 10, 1586–1595

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

[1]

Electrolysis technology is state-of-the-art

[1] Source: tkUCE/tkis

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

[1] [2]

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

[1] Source: tkUCE/tkis

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

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Electrolyser TRL?

State-of-the-art / GW installations

[1]

GW scale electrolysis is common in Chlorine industry

Electrolysis technology is state-of-the-art

[2]

Location	Country	Operator	Capacity Chlorine (in 1000 t)	Diaphrag.	Membr.	Other	Electrolys. D MW	Electrolys. M MW
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		**2.970**	**1.560**
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Dormagen	GER	Covestro	480		400	80[5		**1.040**
Lillo	BE	INNOVIN	500		500			**1.300**
Tessenderlo	BE	Inovyn (INEOS)	400		400			**1.040**
[illegible]	[illegible]	[illegible]	[illegible]					**0**
[illegible]	[illegible]	[illegible]	[illegible]		390			**1.014**
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			**989**	**0**
[illegible]	[illegible]	[illegible]	[illegible]		370			**962**
Fos	FR	Kem One	[illegible]	178	155		**516**	**403**
Kazincbarcika	HUN	BorsodChem	480	384	96		**1.114**	**250**
Uerdingen	GER	Covestro	290		290			**754**
Marl	GER	Vestolit	260		260			**676**
Rafnes (Bamble)	NOR	Inovyn (INEOS)	315		315			**819**
Schkopau	GER	Dow	252		252			**655**
Knapsack	GER	Westlake Vinnolit	250		250			**650**
Rheinberg	GER	Inovyn (INEOS)	220	110	110		**319**	**286**

[1] Source: tkUCE/tkis

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

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

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

PBtL TRL?

Already towards FEED [1]

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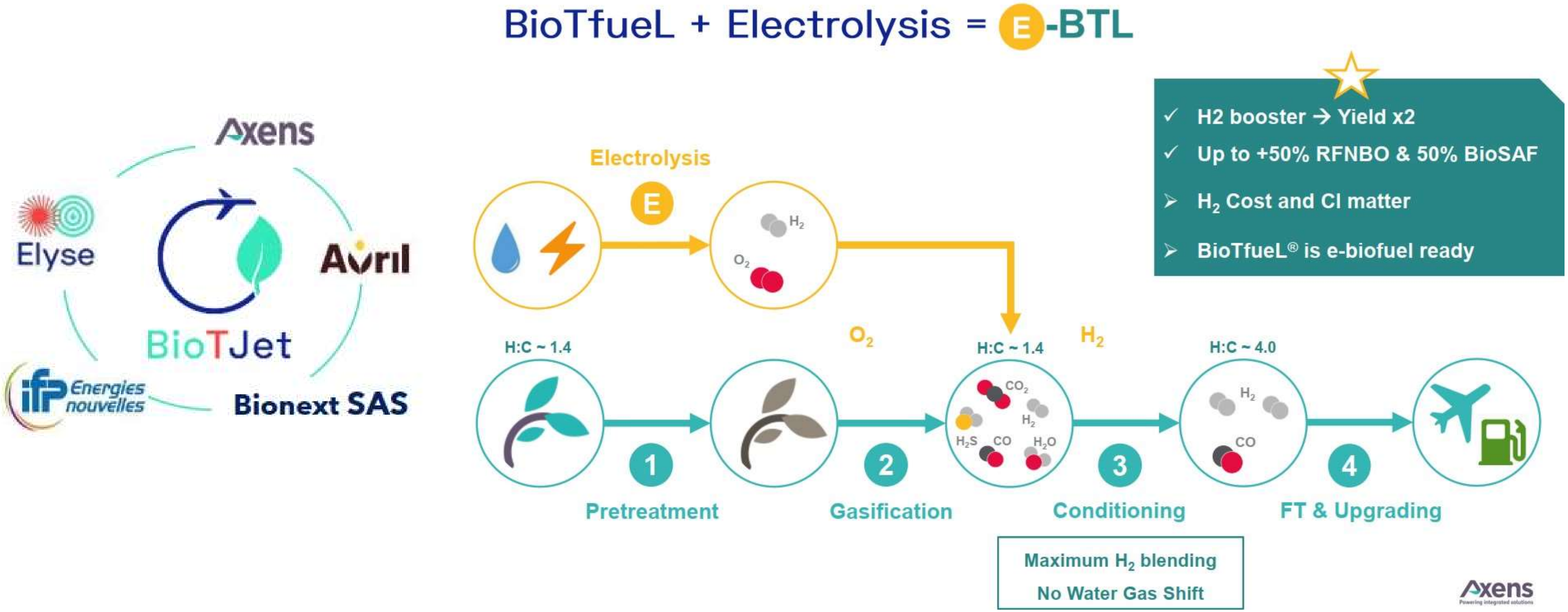
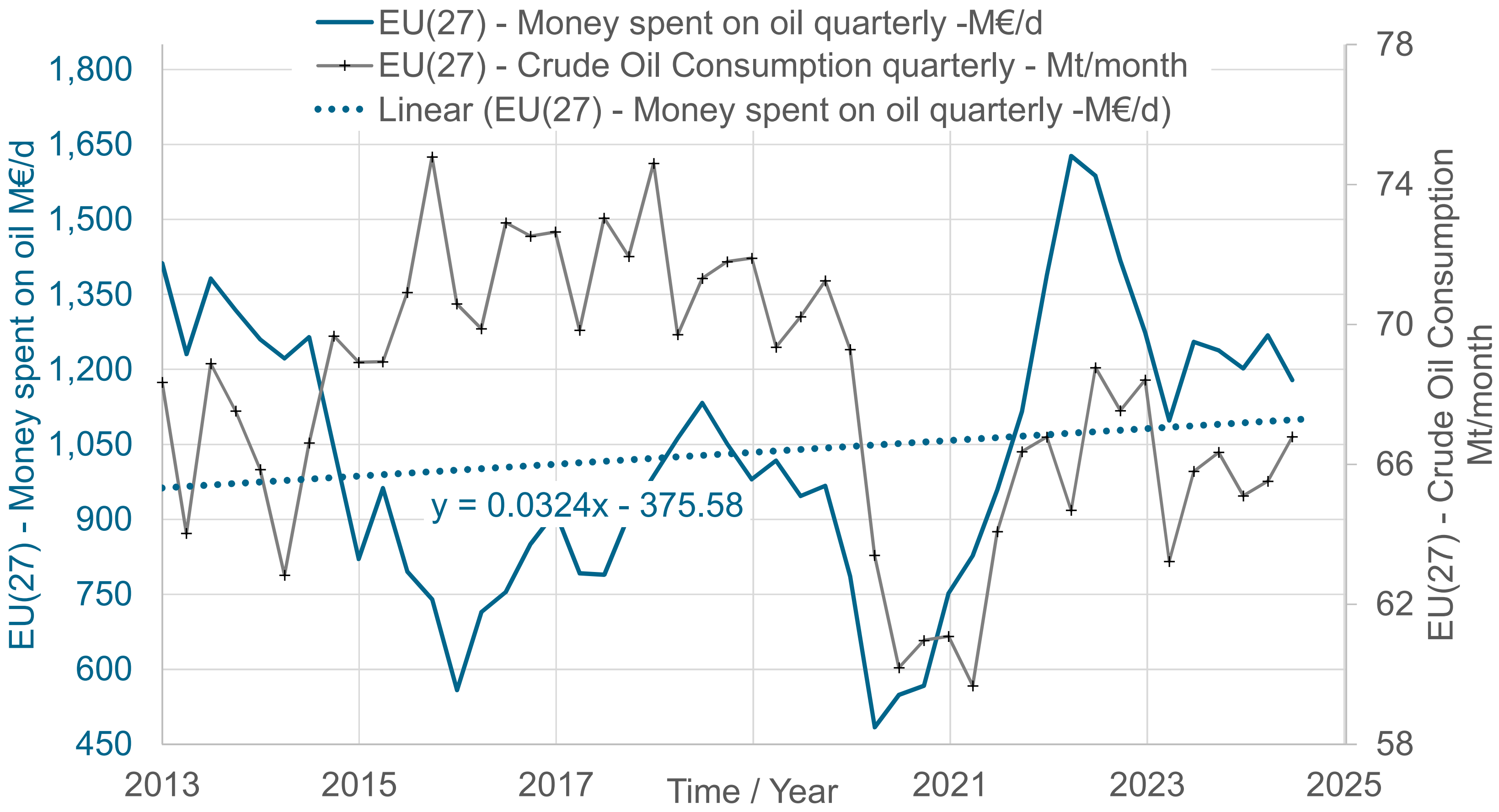
- e-BioTfueL®: 300 kt/a feedstock, 240 MW electrolysis, 110 kt/a fuels.



[1] F. DURAN MARTINEZ (2025) *BioTJet project – The first-of-a-kind industrial e-BtL plant*. Towards Sustainable Aviation Summit - TSAS2025, Toulouse, France

Aviation: part of fossil oil business
Replacing 1.000 M€/d business?



[1] Eurostat. Imports of oil and petroleum products by partner country - monthly data [nrg_ti_oilm__custom_15511616], https://ec.europa.eu/eurostat/databrowser/view/NRG_TI_OIL/default/table?lang=en

TRL discussion summary

Process De-Risking?

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

TRL discussion summary

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- Chemical engineering can build ANY optimal process for ANY purpose
  - Entire refineries have been built on valid process simulation
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Business Case Constraints?

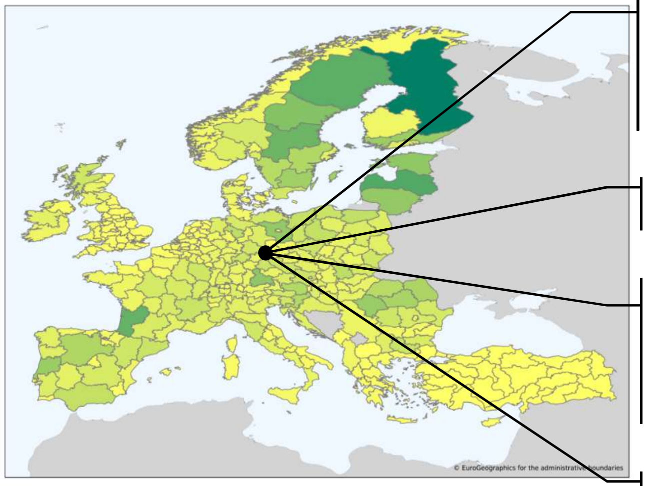
- Separate refinery business from oil exploration business
  - Take oil margin for SAF investment?

- Demand risk: Penalty for airlines acceptable? 30 % of flight prices from fuels

TOWARDS A EUROPEAN PBTL SAF ROADMAP

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

For feedstock potential: TEEA for 300 NUTS2 regions



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

Local labour cost[3]

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

Biomass price[2]

*Only **primary forest residue** considered

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

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_googlechartid_chart_1111.

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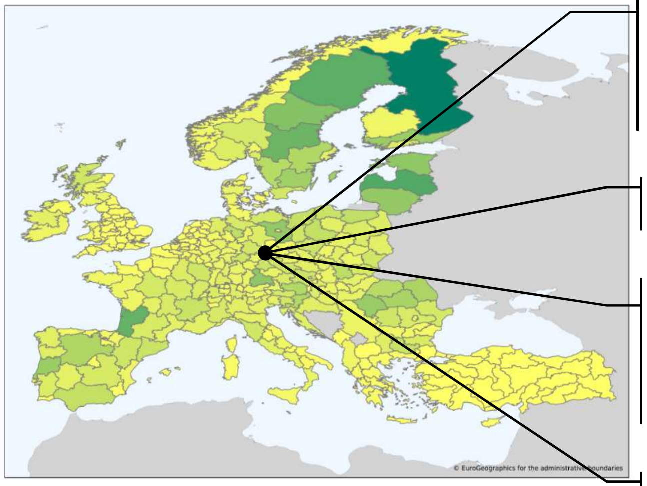

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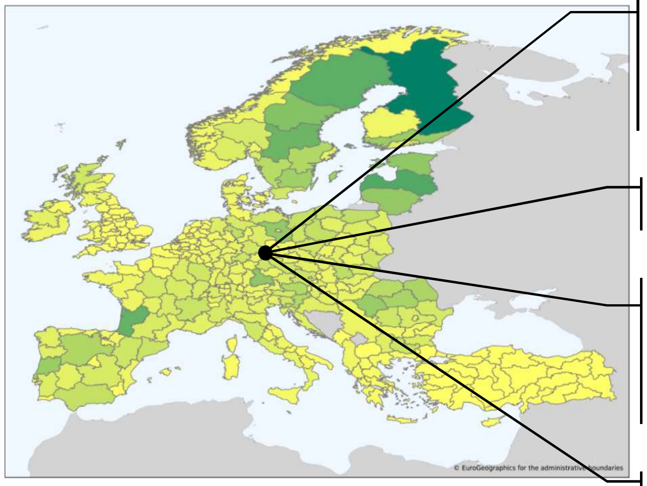

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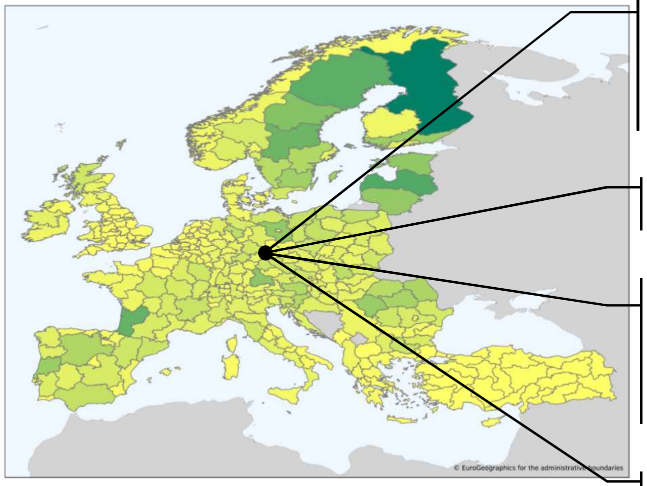

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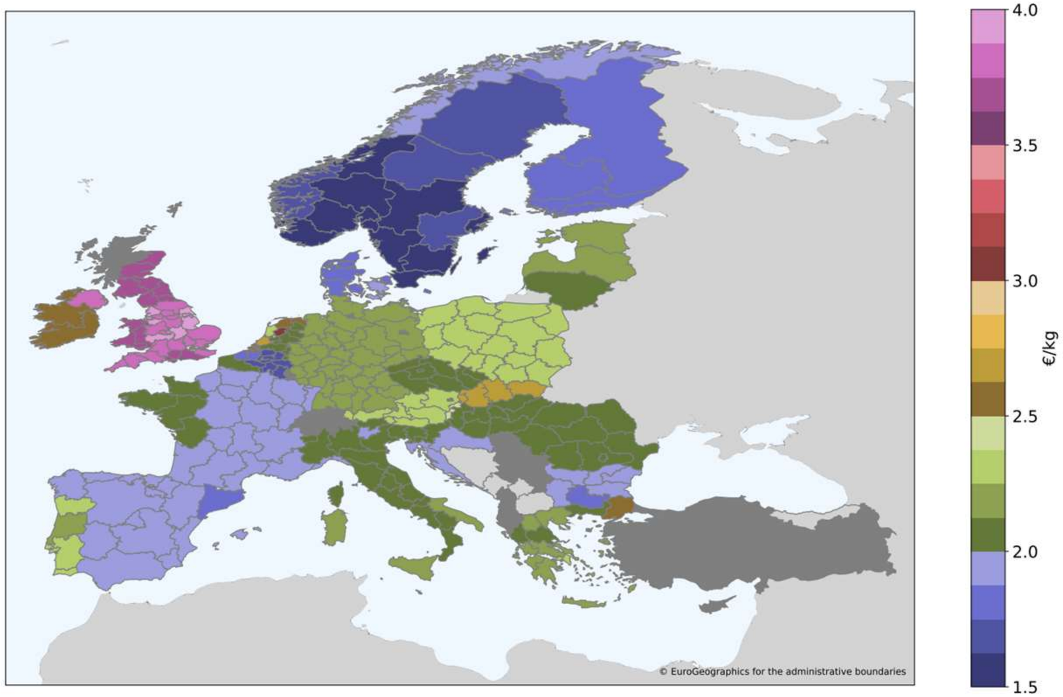
PBtL potential for Europe [1]

Grid based PBtL: Northern Europe 👍

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



Net Production cost

+ Abundant cheap woody biomass and low carbon electricity in Scandinavia

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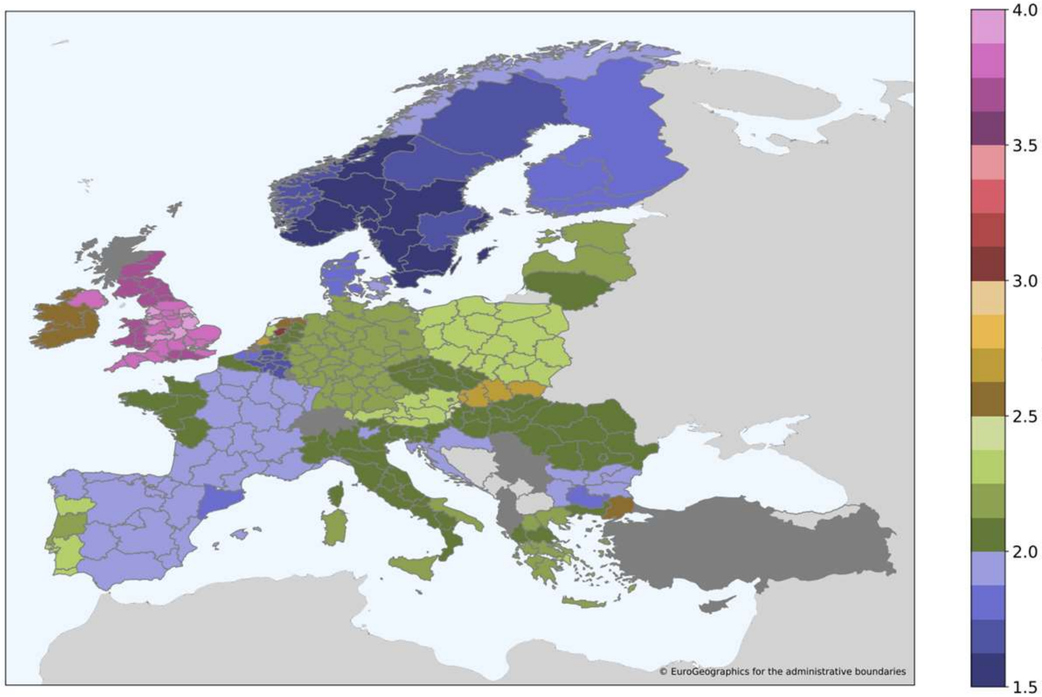
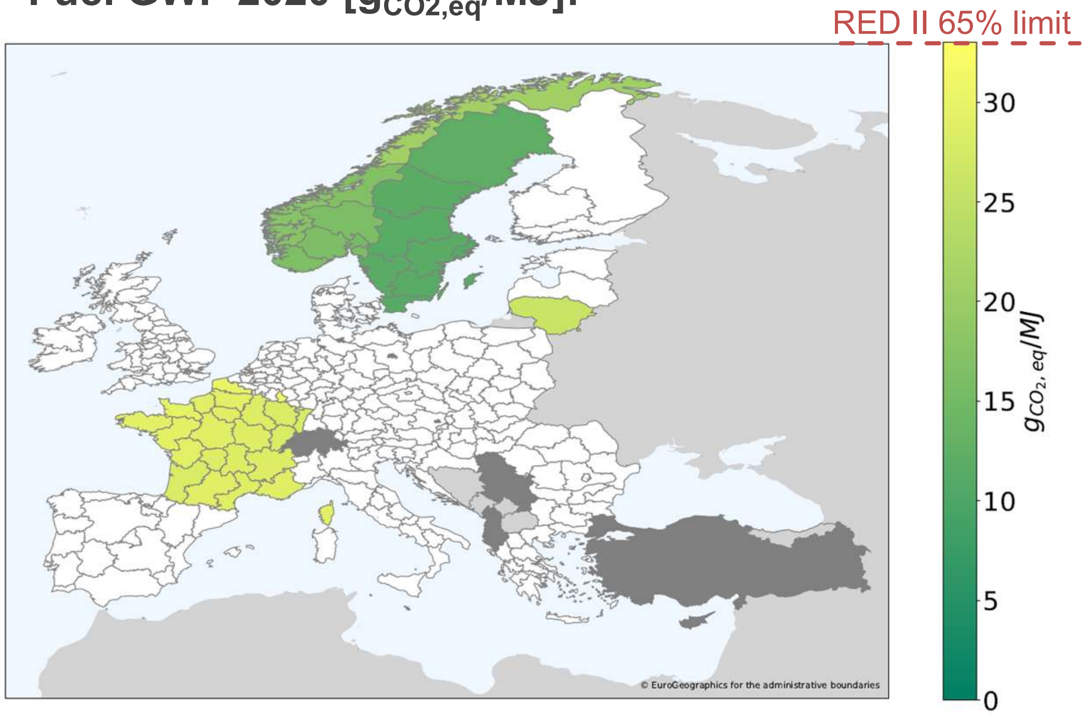


Fuel GWP 2020 [$g_{CO2,eq}/MJ$]:

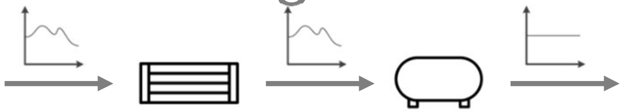


Net Production cost	Greenhouse Gas Abatement
+ Abundant cheap woody biomass and low carbon electricity in Scandinavia	– High carbon footprint of electricity prevents power-based SAF production in most European countries

PBtL potential for Europe [1]

On-shore wind PBtL: Costal regions

Hydrogen storage included:



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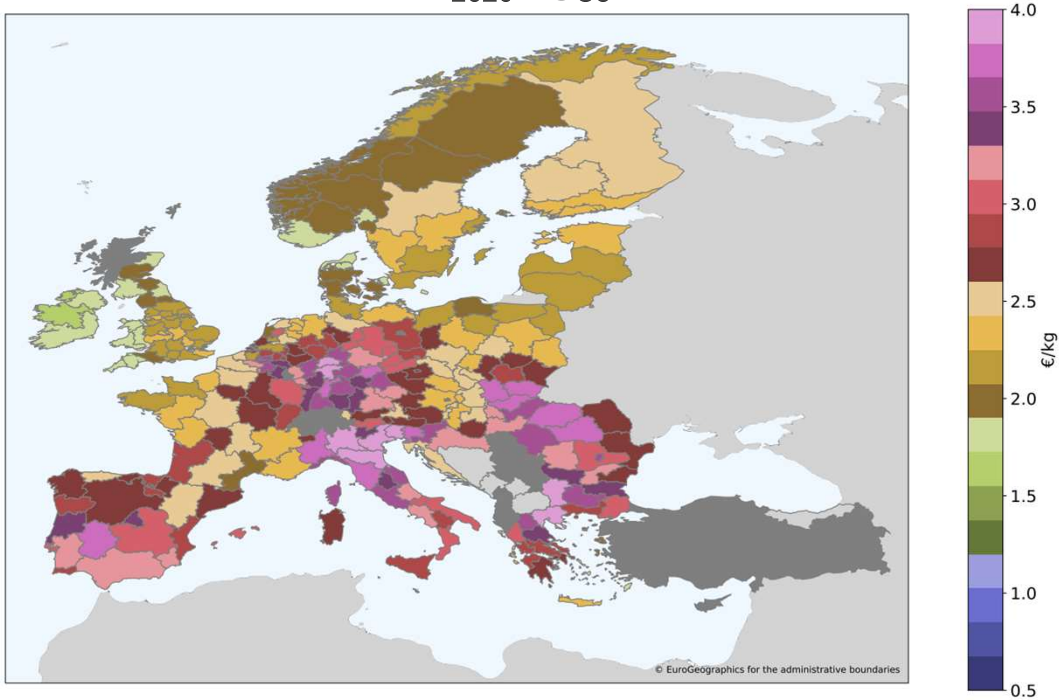

Net Production cost

+ High full load hours of wind power required

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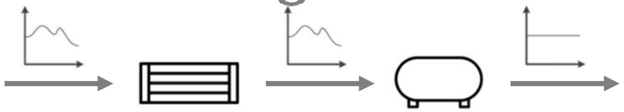

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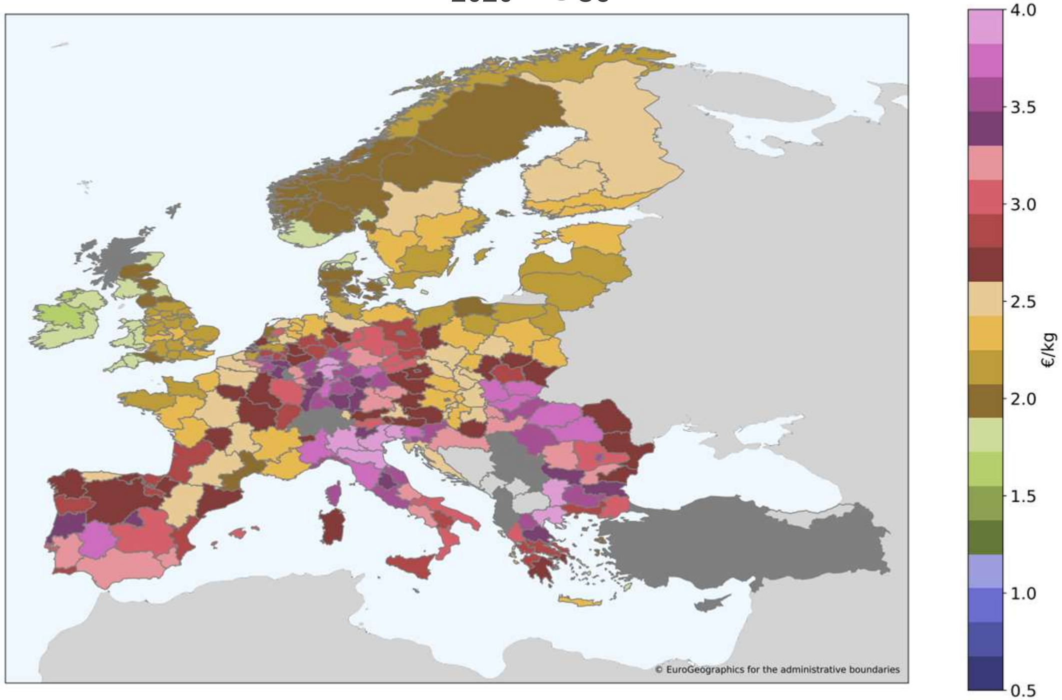

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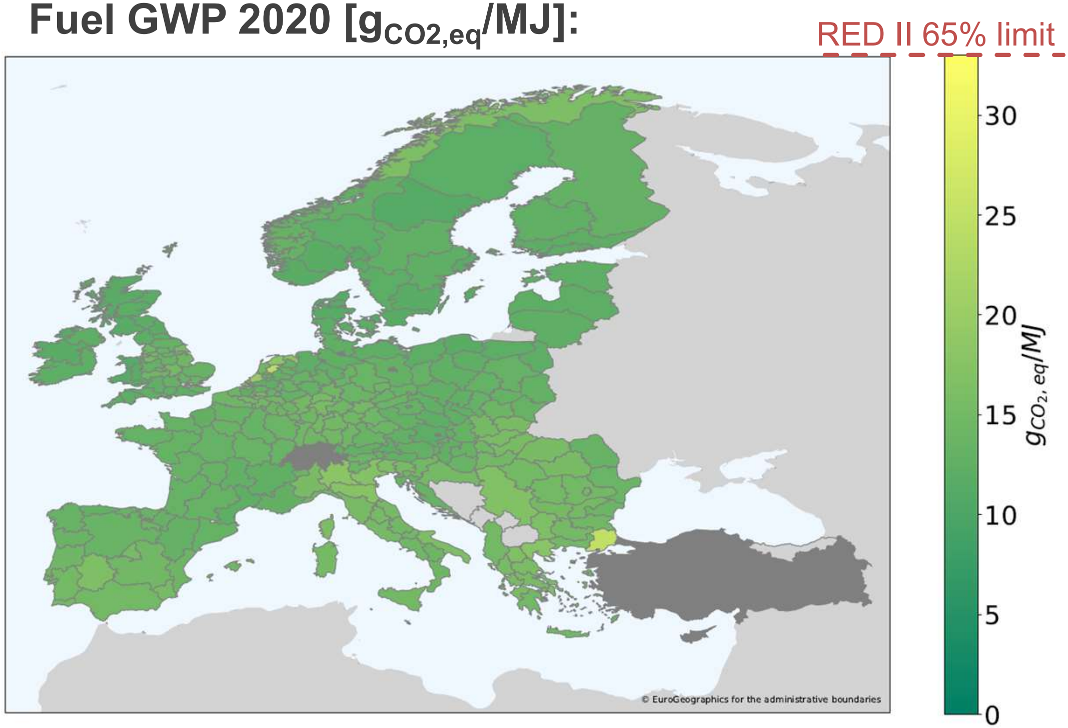
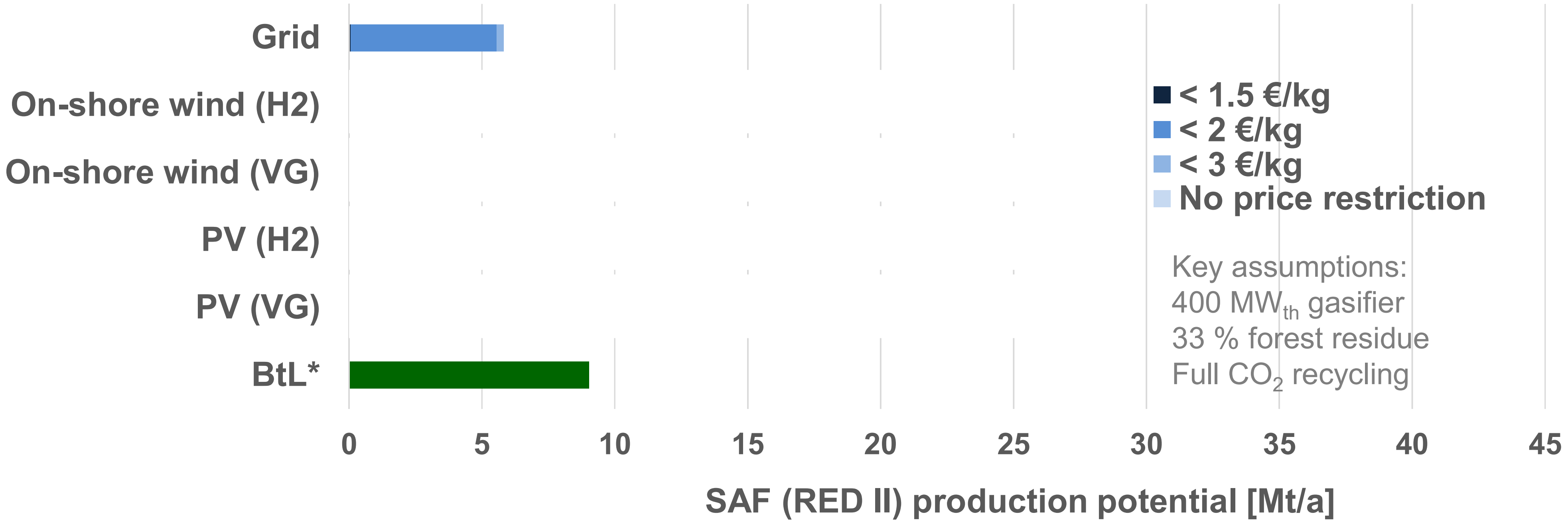


Net Production cost	Greenhouse Gas Abatement
+ High full load hours of wind power required	– No Net Zero SAF anywhere + Wind power based SAF well within RED II

PBtL potential for Europe
Aggregated SAF potential



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

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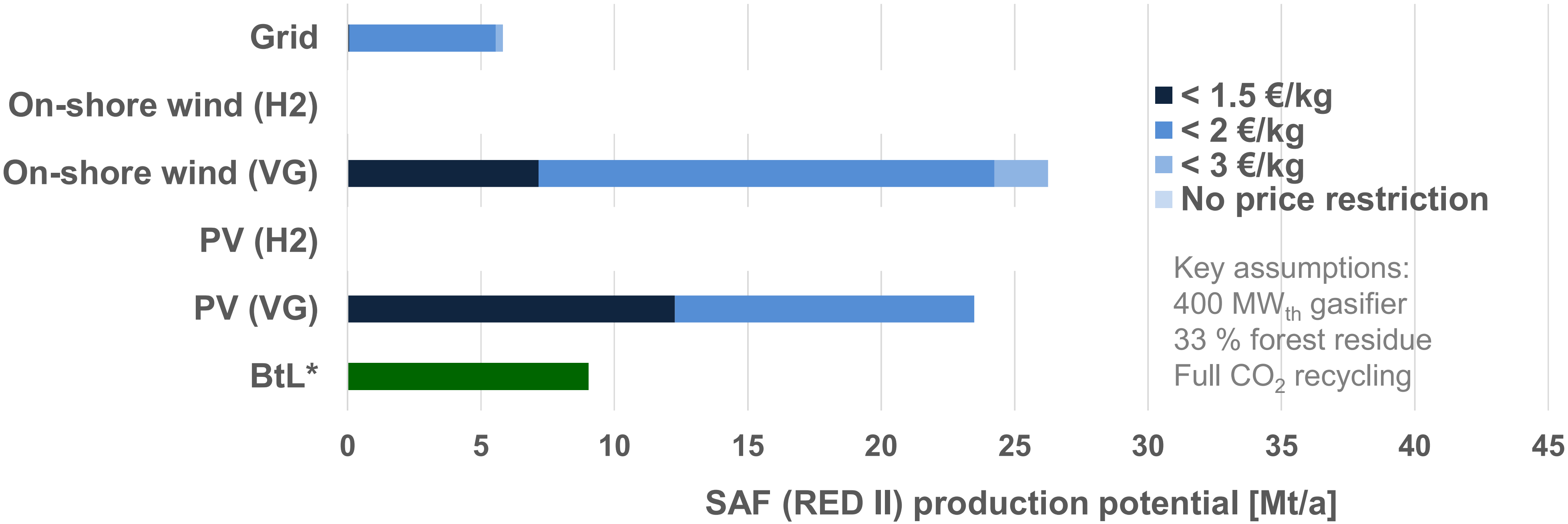
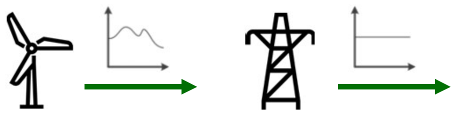


Virtual grid (VG)



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PBtL analysis for Europe
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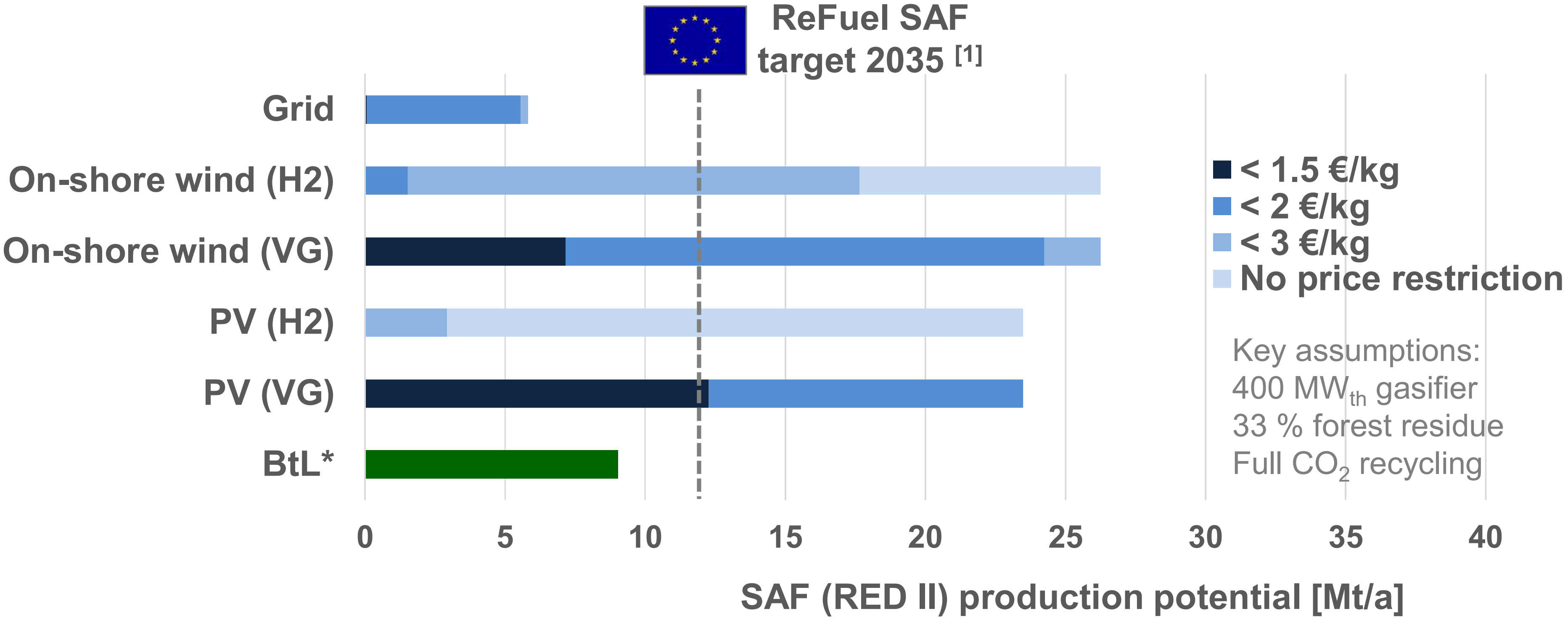

Key assumptions:
400 MW_{th} gasifier
33 % forest residue
Full CO_2 recycling

[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;

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

EUROPEAN COMMISSION

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2025	2 % (≈ 1 Mt/a[2])	
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Compare with 3.4 Mt/a growth since 2020!

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Not enough palm oil on earth!

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Paris 1.5 degree commitment intentionally violated!

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SAF deployment plan for Europe

Optimistic way forward (personal view)

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25 plants across Europe á

- **3.3 GW Wind (5.0 b€) or 6.3 GW PV (5.0 b€) each**
- **FT plant 400 kt$_{SAF}$/a (1.5 b€) incl. 0.9 GW Electrolyzer**
- **Construction period: 2025 – 2028**
- **Full operation before 2030**

Total Investment?

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

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

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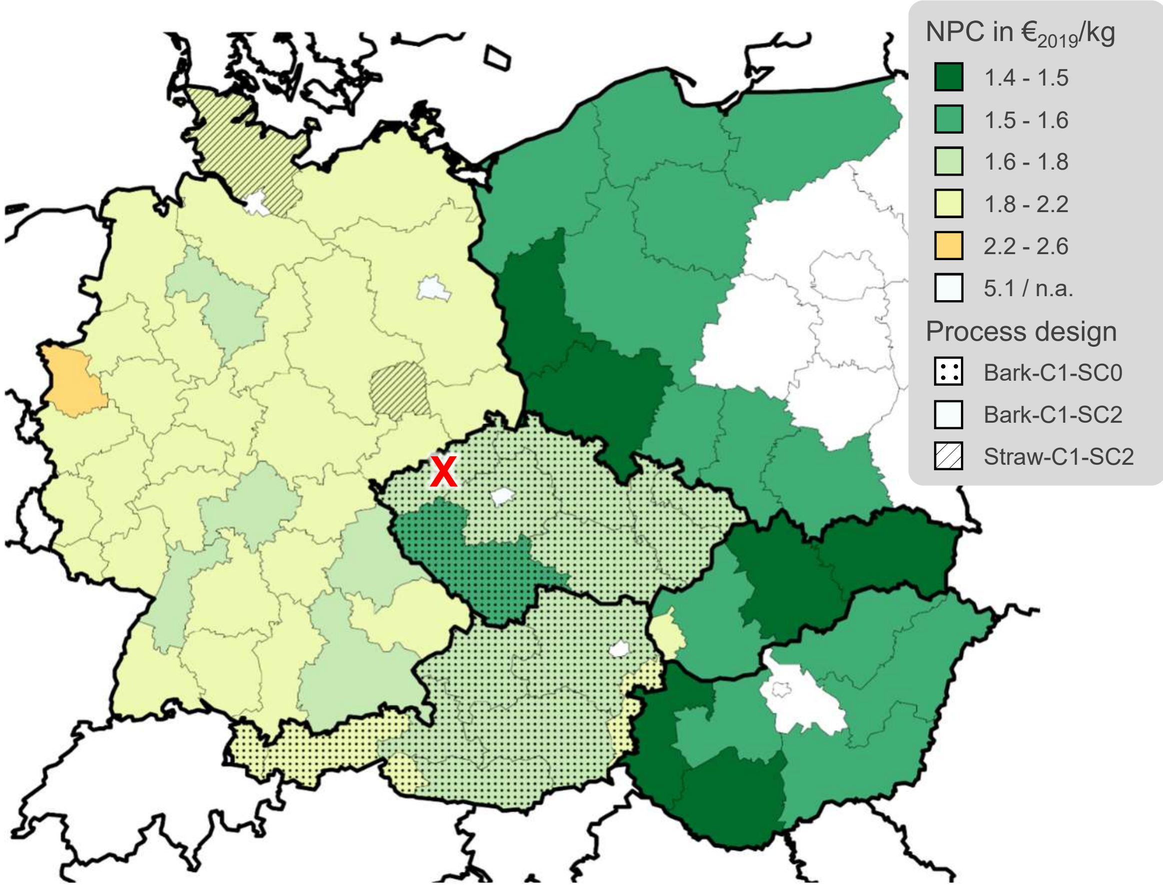
- **Backup, if H_2 aviation won't fly**
- **additional SAF routes / feedstocks from 2035 onwards?**
  Or ➔ Less air traffic?
- **How about climate neutrality by 2045?**

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

SAF QUICKSTART: EXPLORE THE BIOMASS FROM YOUR NEIGHBORHOOD

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

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



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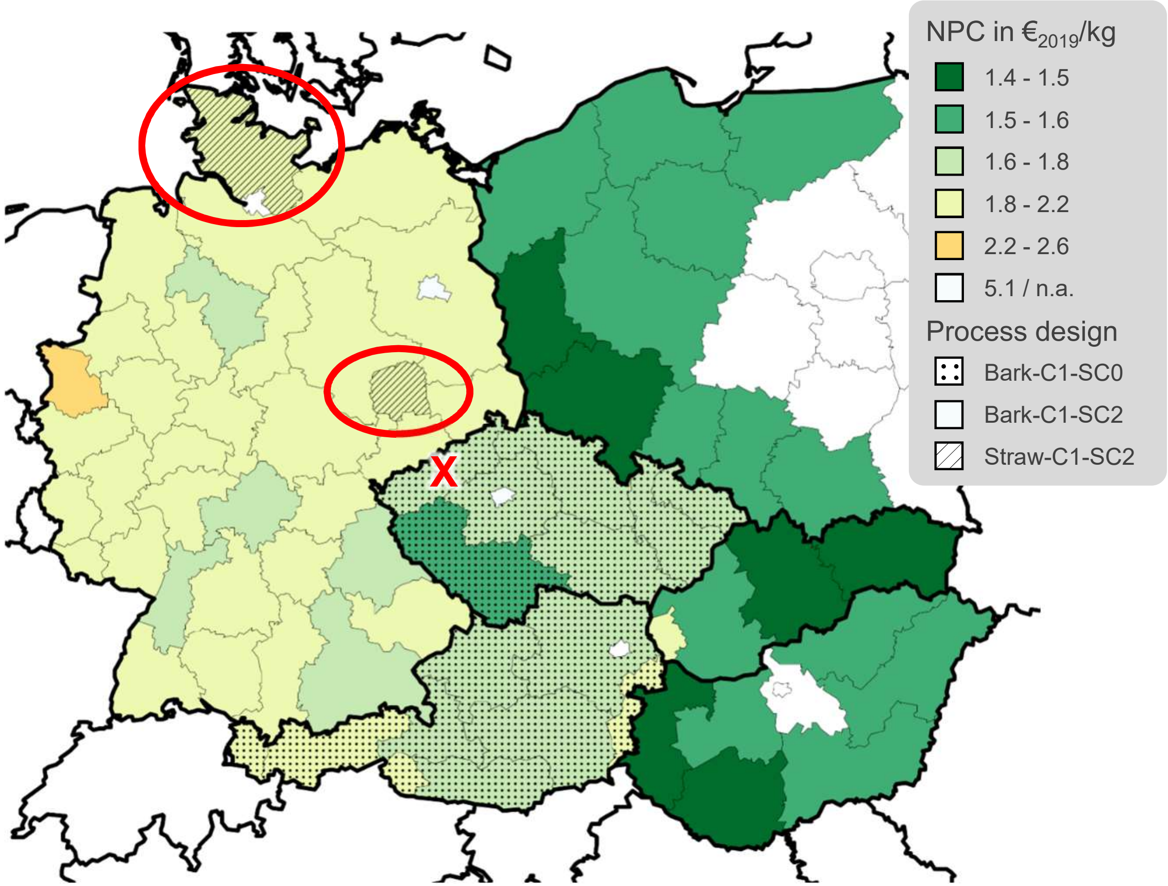

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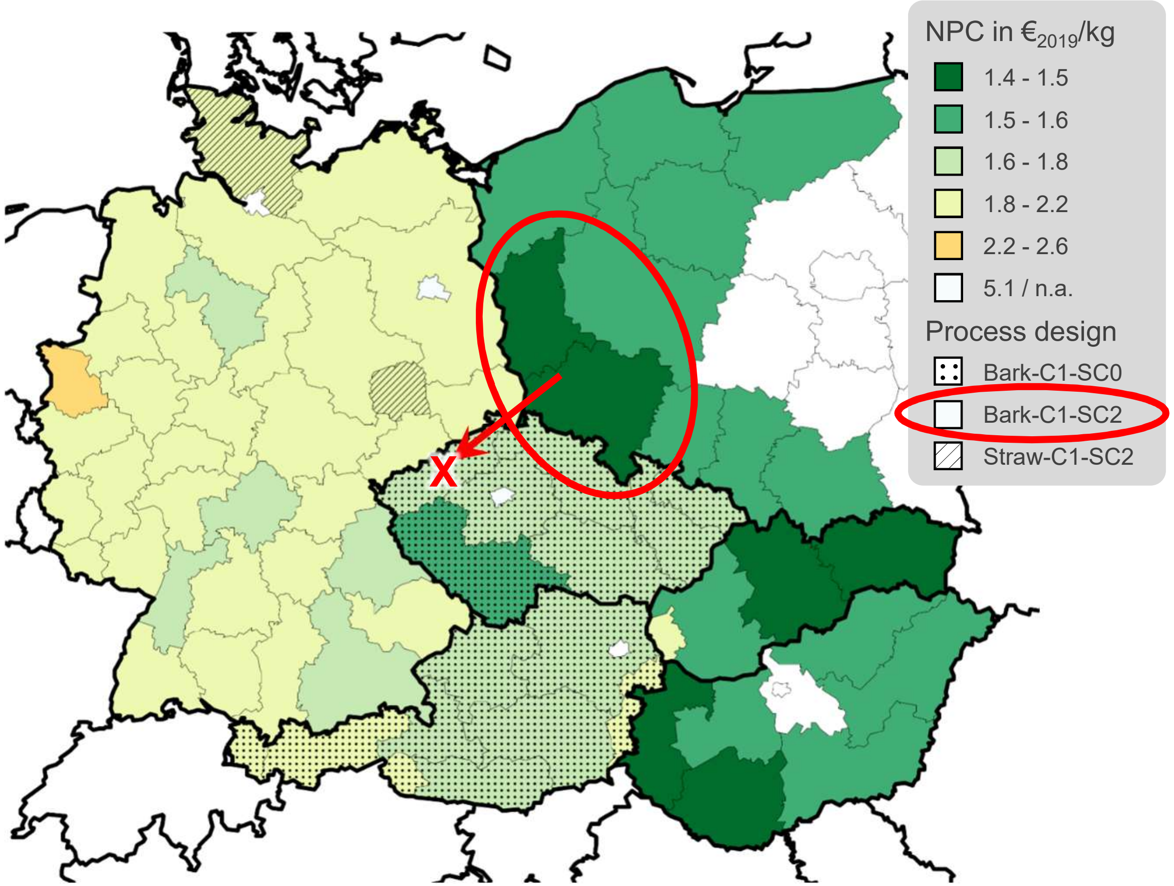
- West Poland bark
- C1: process configuration "basic"
- SC2: steam cycle & district heating



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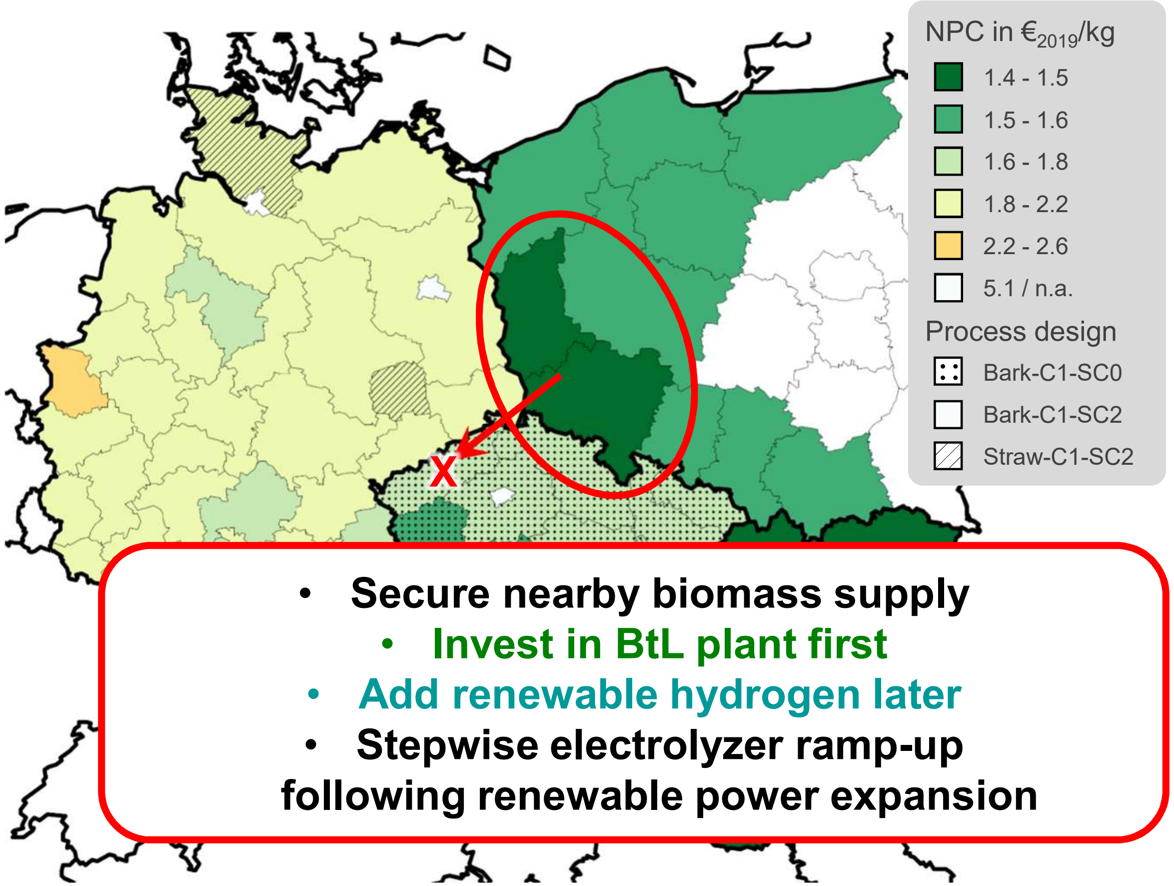

- **Secure nearby biomass supply**
- **Invest in BtL plant first**
- **Add renewable hydrogen later**
- **Stepwise electrolyzer ramp-up following renewable power expansion**

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CONCLUSION & OUTLOOK

Toward Sustainable Aviation in Europe

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- European SAF regulation should reflect real climate protection demand
  - 2050 climate neutrality currently out of reach
  - True accounting for aviation climate impact and mitigation measures required

Toward Sustainable Aviation in Europe

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- Large-scale decarbonization of aviation using RE-supported SAF is technically feasible, economically challenging, ready to go
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  - New SAF industry to be established – competing with fossil kerosene supply

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

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

Tuesday, 06. May 2025

SAF intelligence & Masterclass day

Getting SAF to Market

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THANKS TO THE TEAM!
FOR YOUR KIND ATTENTION!
QUESTIONS?

Techno Economic and Environmental Assessment of SAF production

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

DLR