Tuesday, 23. January 2024

Session 6C:

Biofuels and renewable fuels in aviation

Assessment of technologies and import options for sustainable aviation fuels (SAF)

Sandra Adelung, Ralph-Uwe Dietrich, Felix Habermeyer, Simon Maier, Moritz Raab, Yoga Rahmat, Julia Weyand

(DLR e.V., www.DLR.de/tt)

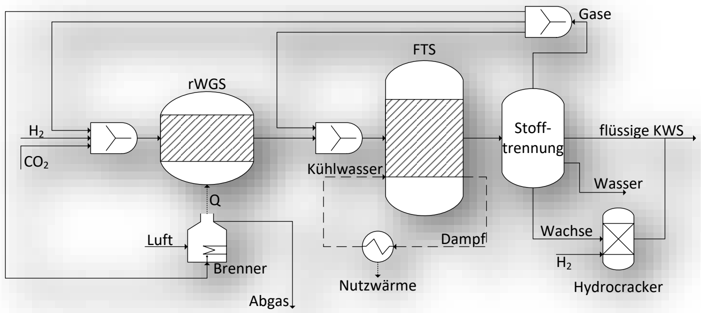
Assessment of technologies and import options for sustainable aviation fuels

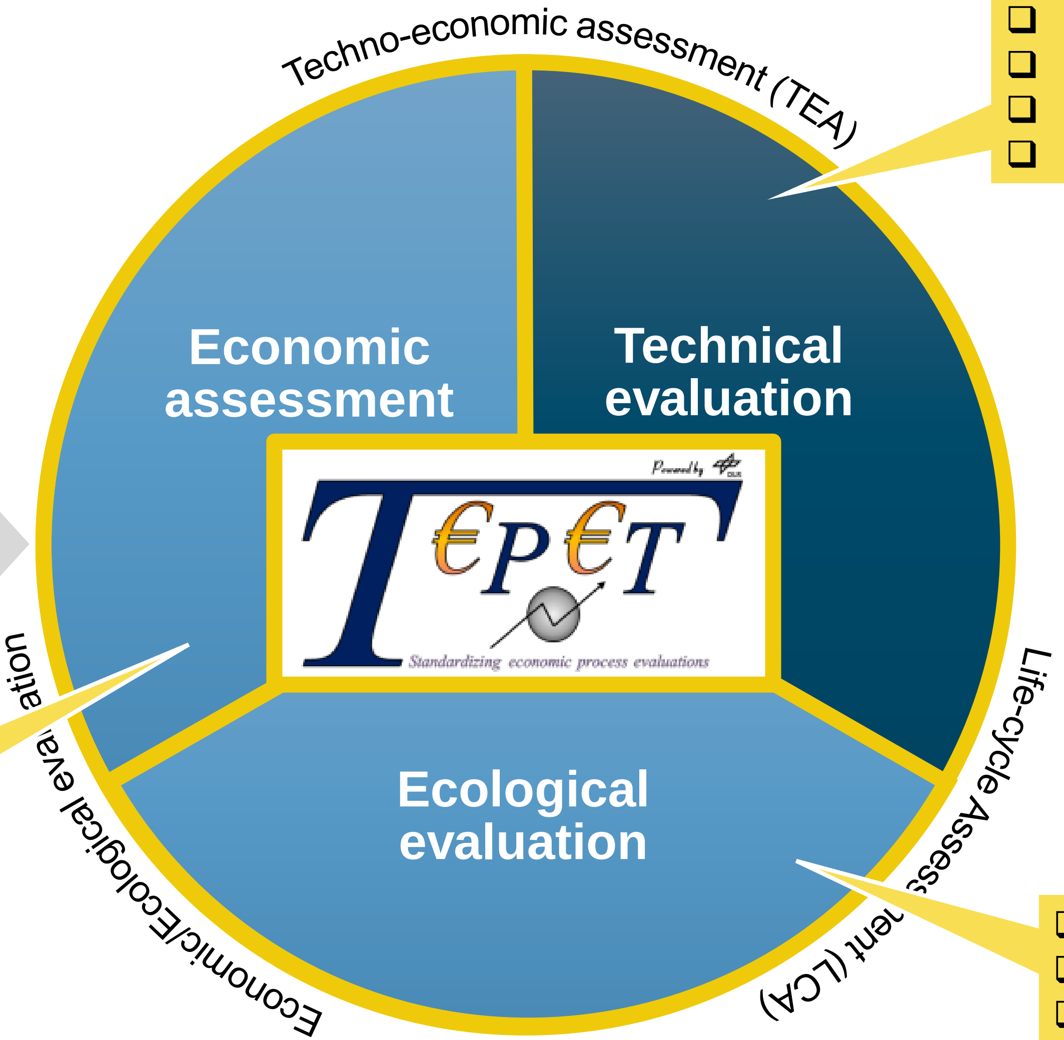
1. Techno-economic and life cycle analysis
2. Technological readiness
3. Towards a European SAF roadmap
4. SAF deployment plan
5. Conclusion and outlook

Techno-Economic and Life Cycle Assessment @ DLR

FUELS OF THE FUTURE

DLR





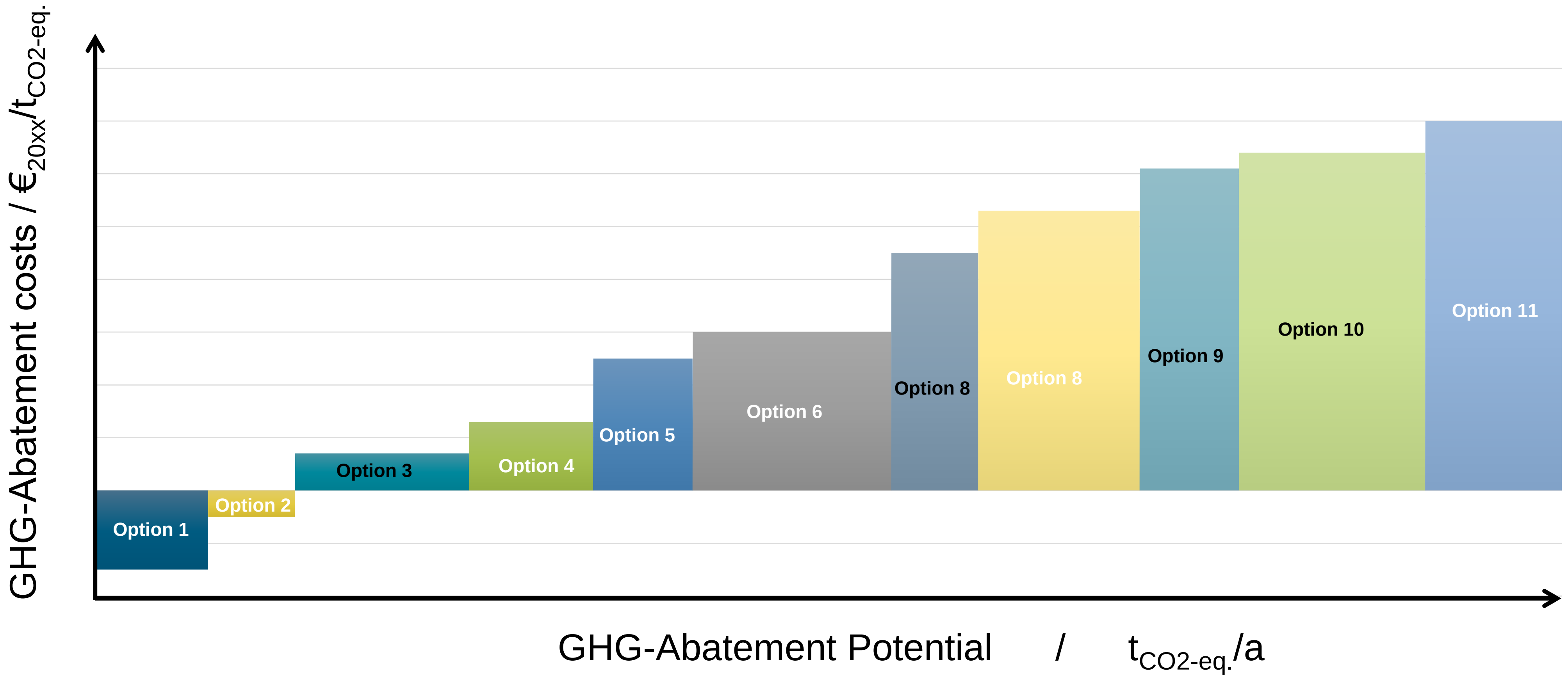
- Efficiencies (X-to-Liquid, Overall)
- Carbon conversion
- Specific feedstock demand
- Exergy analysis

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

- GWP
- Other impact categories
- Identification of impact drivers

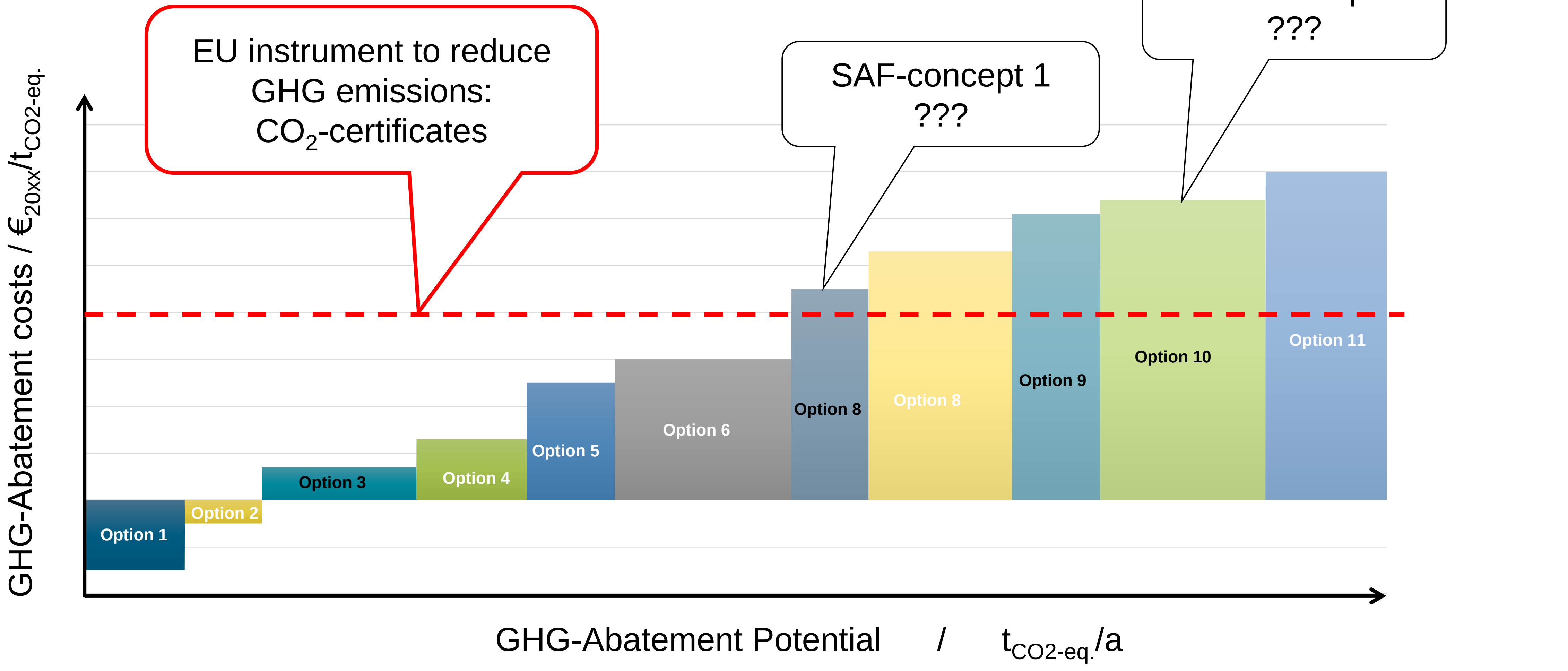
Assessment of SAF concepts / options / configurations / locations / …

Merit-Order of GHG reduction technologies



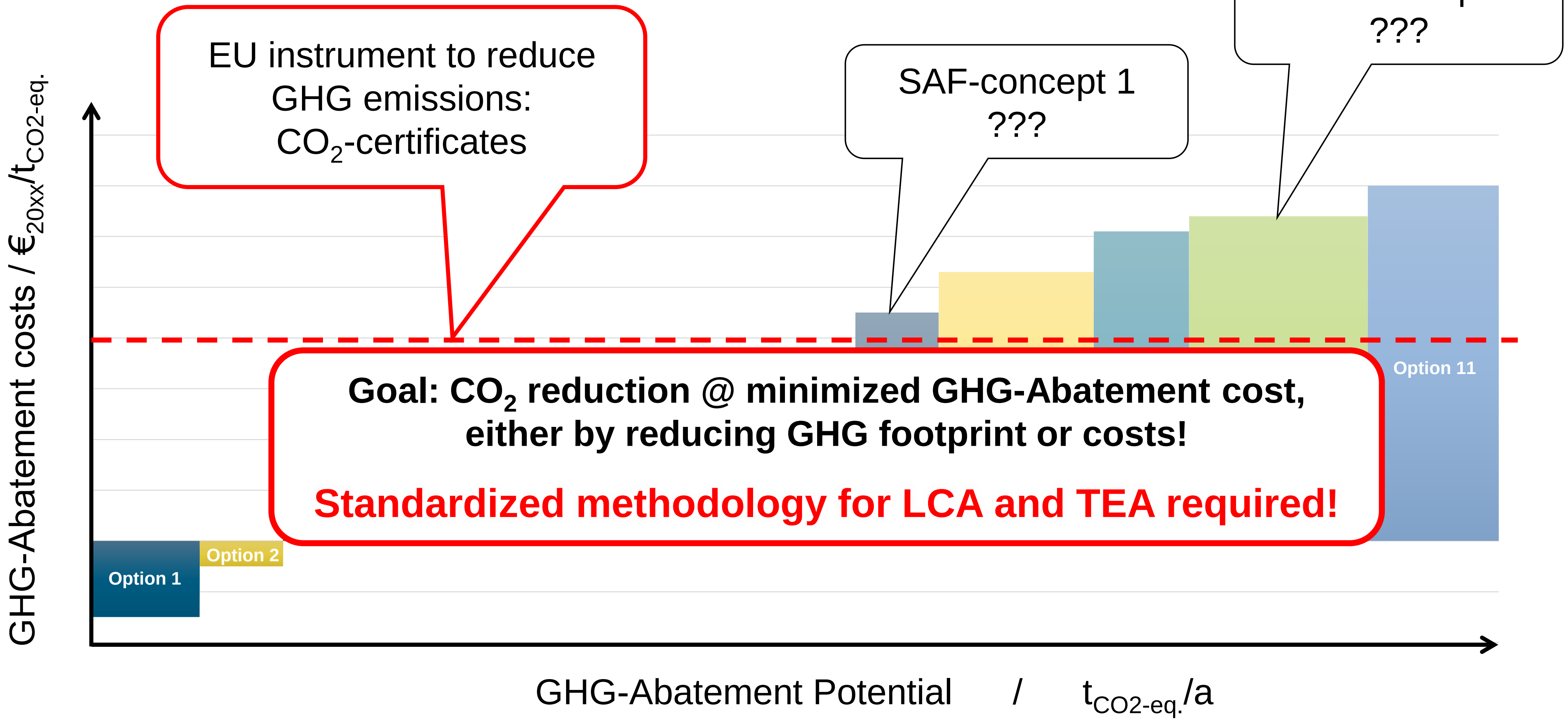
Assessment of SAF concepts / options / configurations / locations / …

Merit-Order of GHG reduction technologies



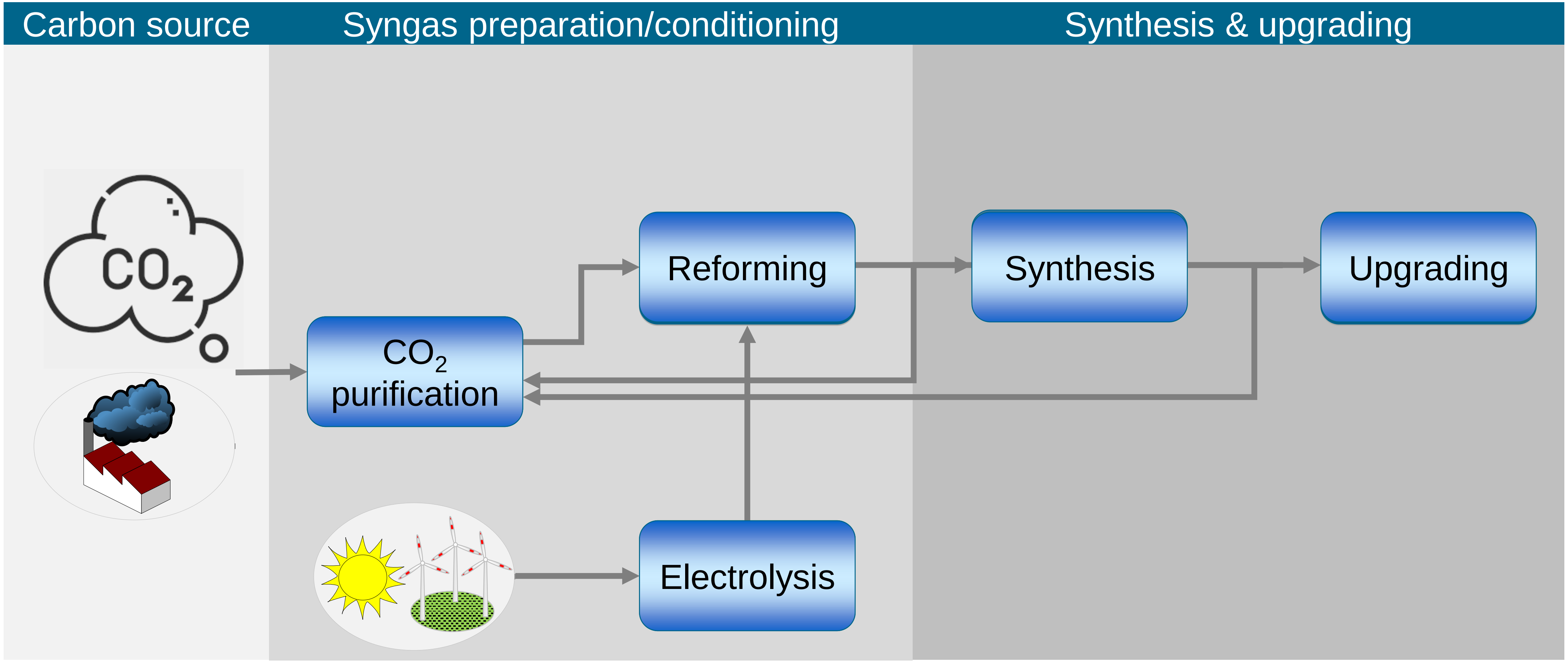
Assessment of SAF concepts / options / configurations / locations / …

Merit-Order of GHG reduction technologies



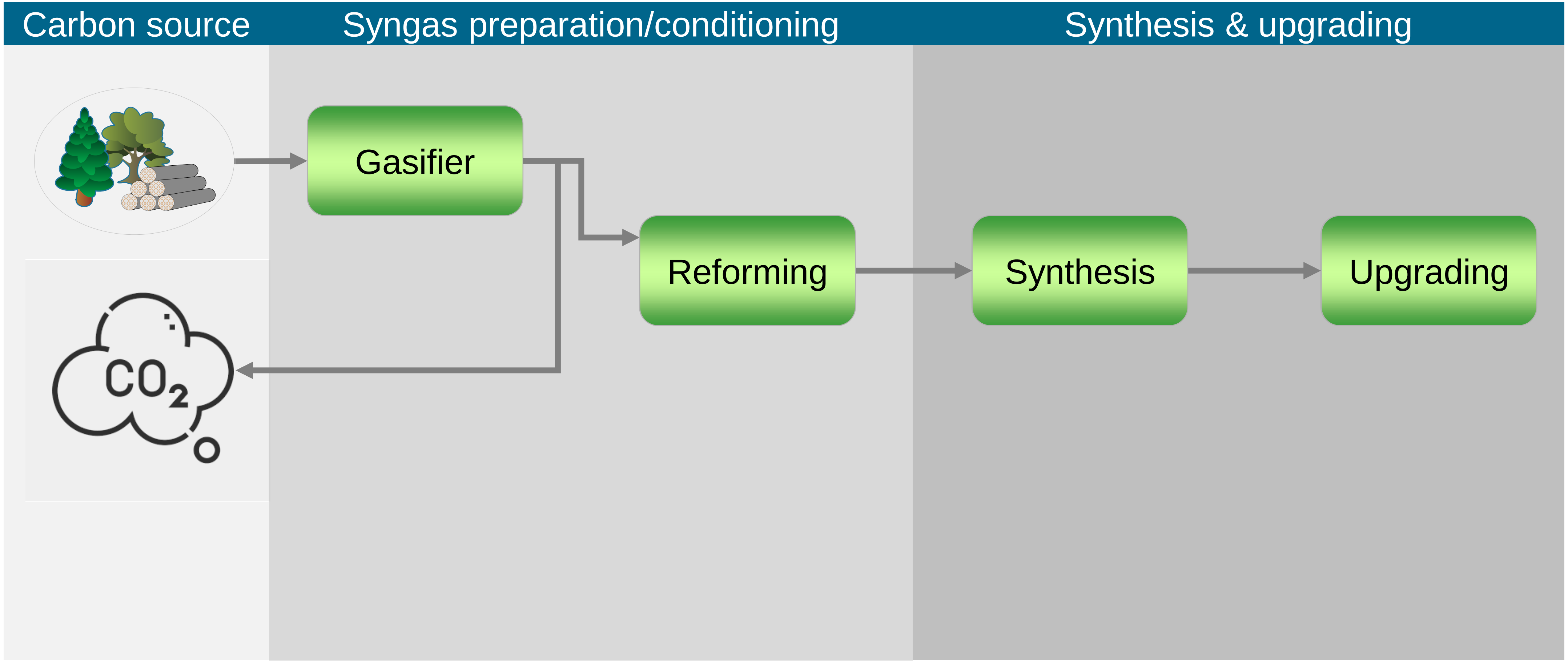
3 generic FT-based SAF concepts

Power-to-Liquid



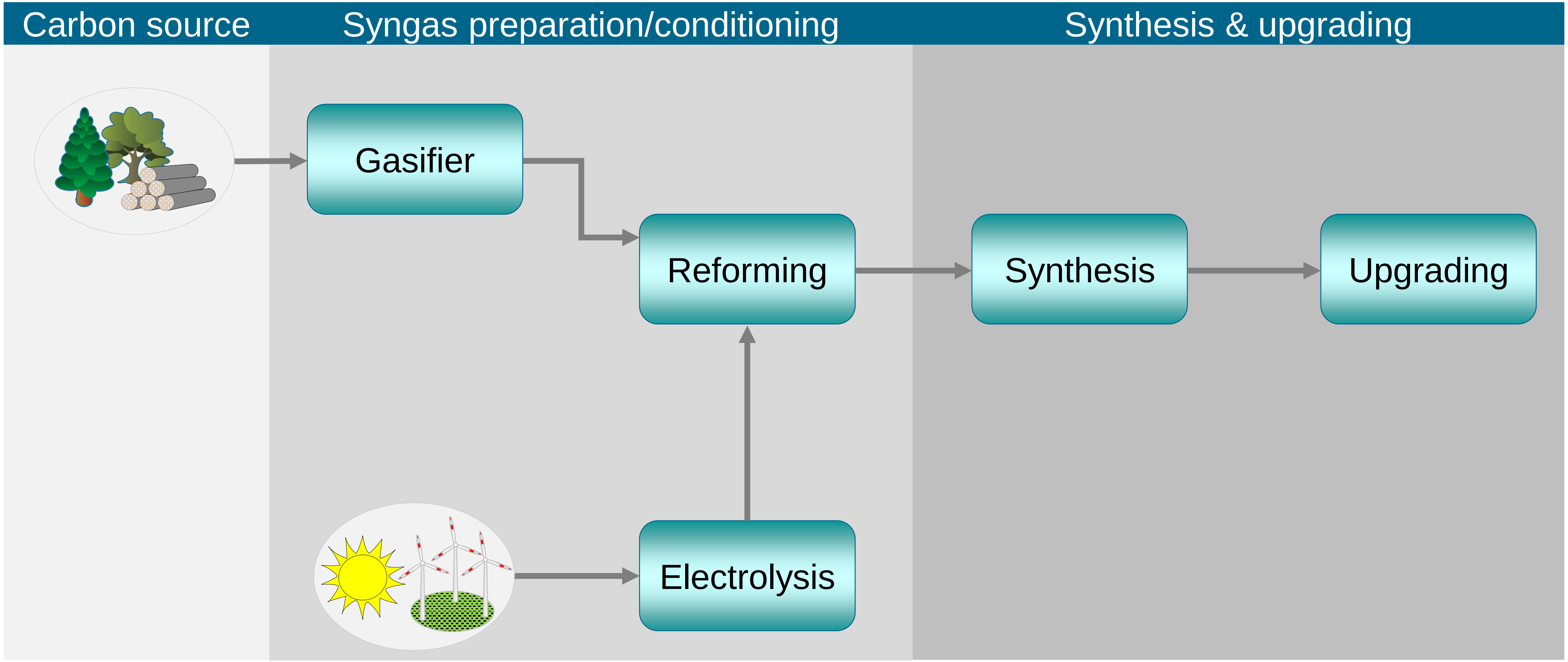
3 generic FT-based SAF concepts

Biomass-to-Liquid



3 generic FT-based SAF concepts

Power&Biomass-to-Liquid



Fischer-Tropsch based SAF concepts
Stochiometric preference

Power-to-Liquid

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

$$\mathbf{CO_2 + 3\ H_2 \rightarrow -CH_2- + 2\ H_2O}$$

Fischer-Tropsch based SAF concepts
Stochiometric preference

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

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

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

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

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

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

* Woody biomass elemental mass composition: $C_{52.1}H_{6.1}O_{38.5}X_{2.9}$

Fischer-Tropsch based SAF concepts
Stochiometric preference

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

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

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

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

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

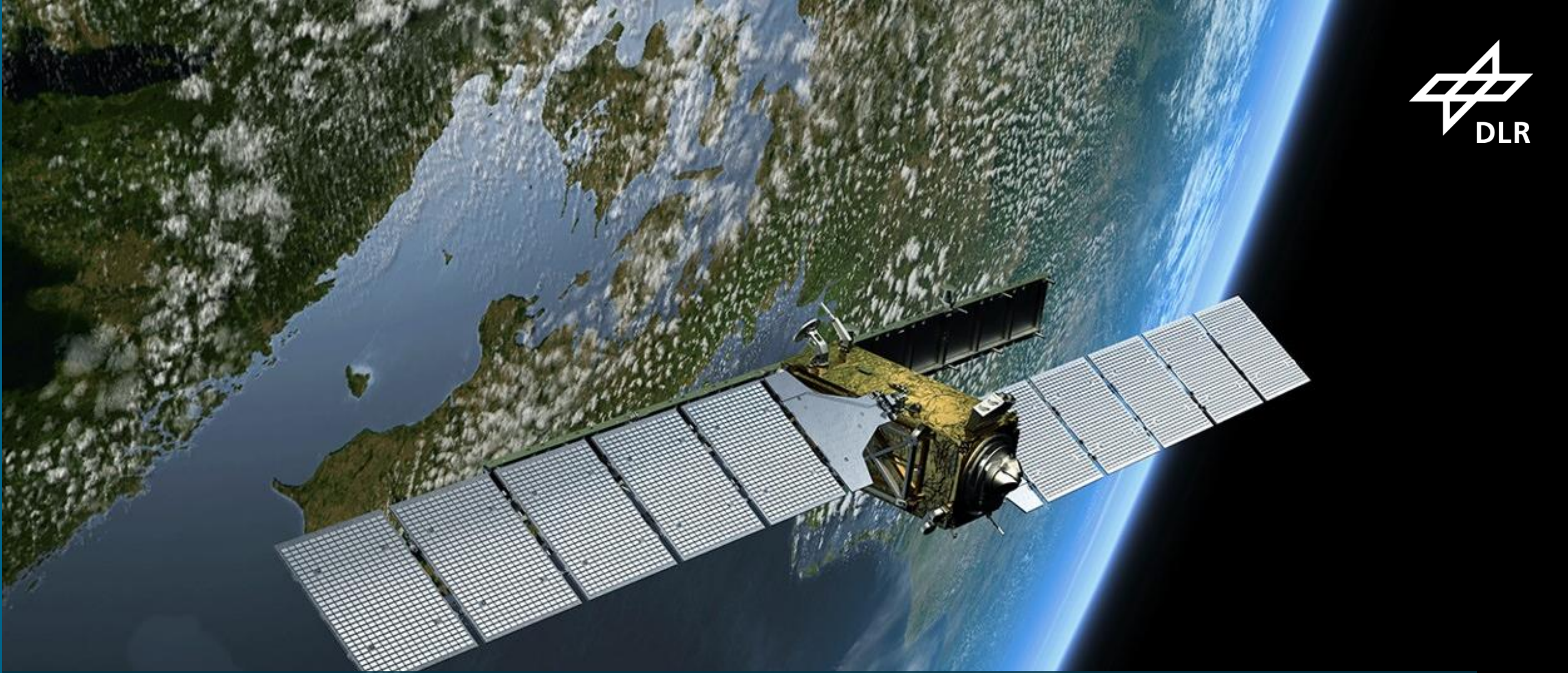
$$2\ C_2H_3O^* + 6\ H_2 \rightarrow 4\ -CH_2- + 2\ H_2O$$

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

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

* Woody biomass elemental mass composition: $C_{52.1}H_{6.1}O_{38.5}X_{2.9}$

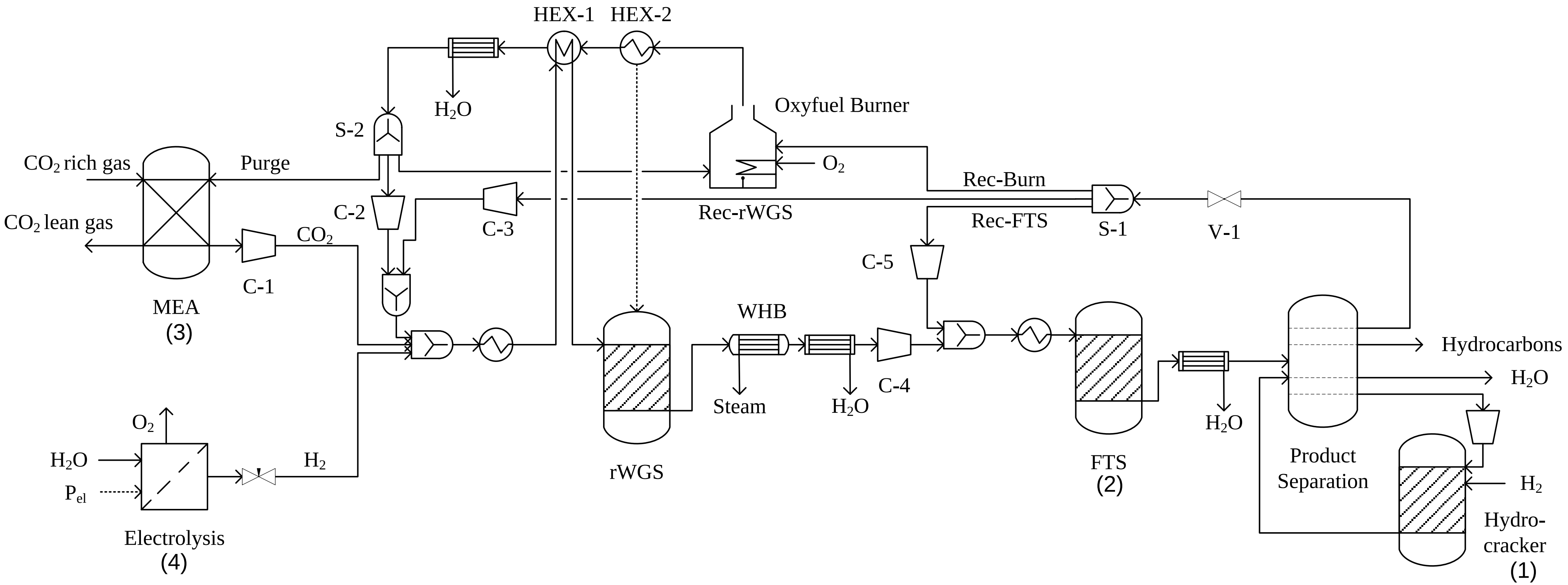
** Example: palmitic acid elemental molar composition: $C_{16}H_{32}O_2$



TECHNICAL ASSESSMENT OF SAF (PTL)

Technical Assessment: Power-to-Liquid

Methodology: Experimentally validated flowsheet (5)



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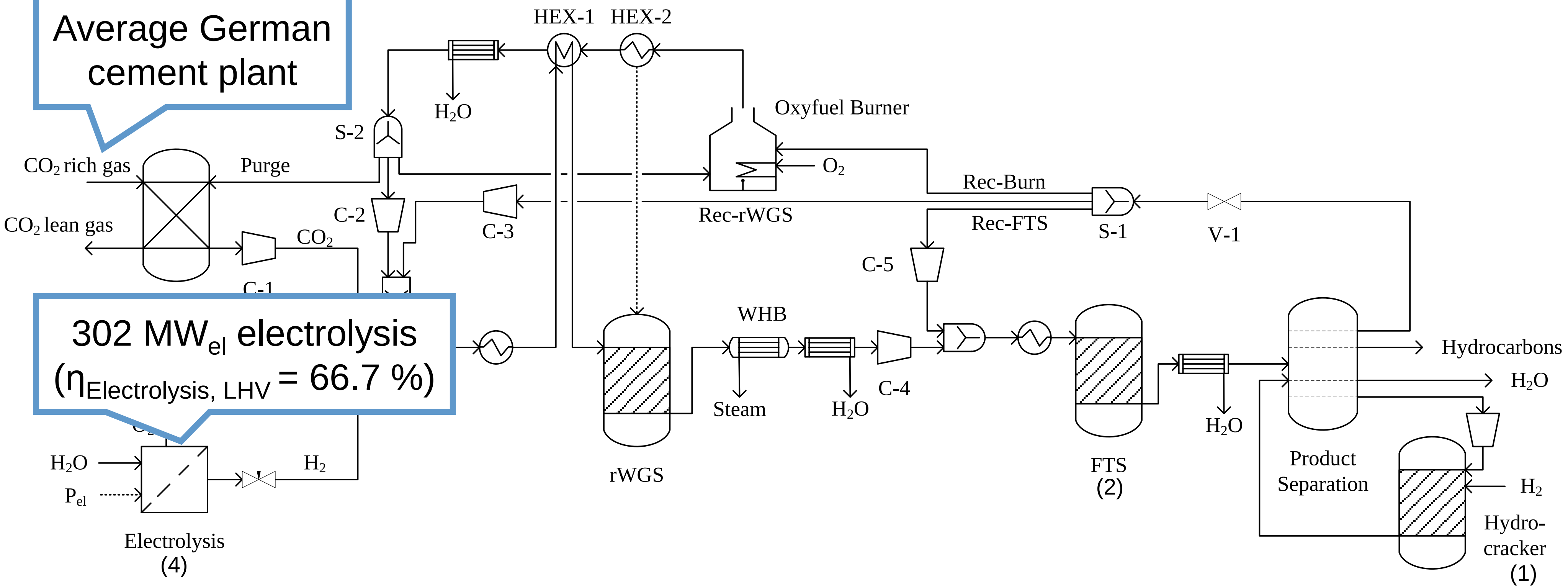
Technical Assessment: Power-to-Liquid

Methodology: Experimentally validated flowsheet (5)

Average German cement plant

302 MW_{el} electrolysis ($\eta_{Electrolysis, LHV}$ = 66.7 %)



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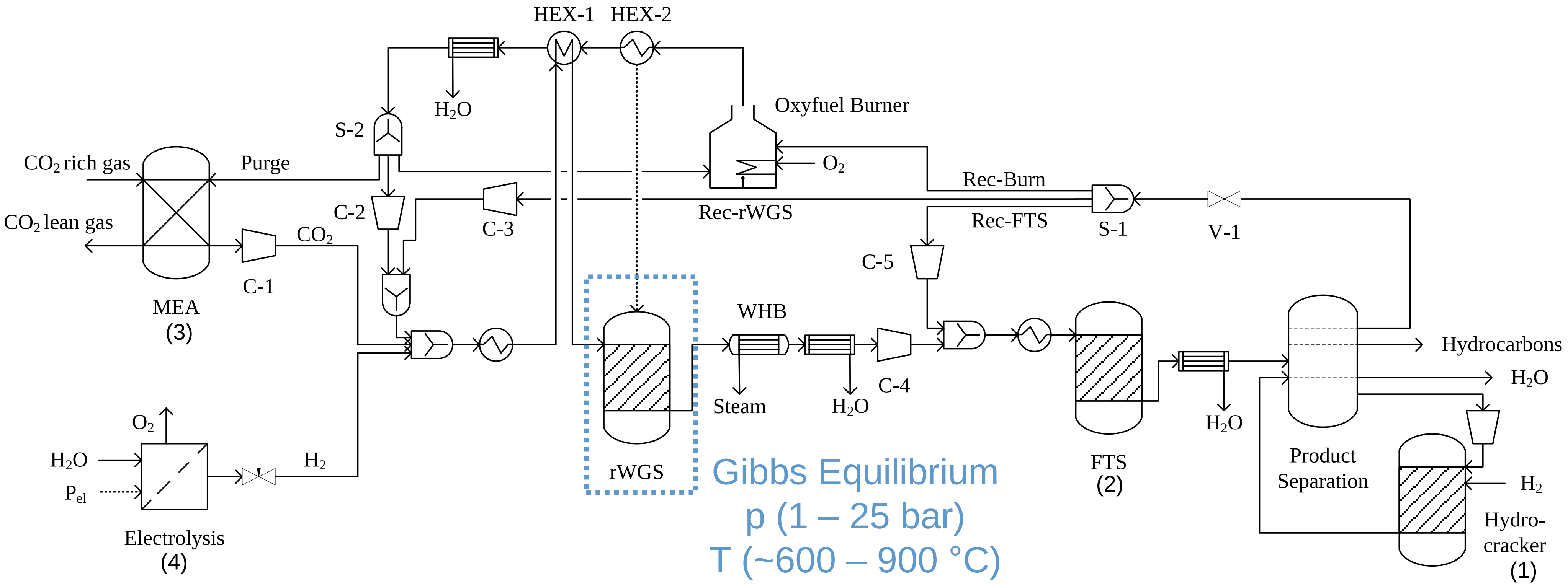
Technical Assessment: Power-to-Liquid

Methodology: Experimentally validated flowsheet (5)



Gibbs Equilibrium
p (1 – 25 bar)
T (~600 – 900 °C)

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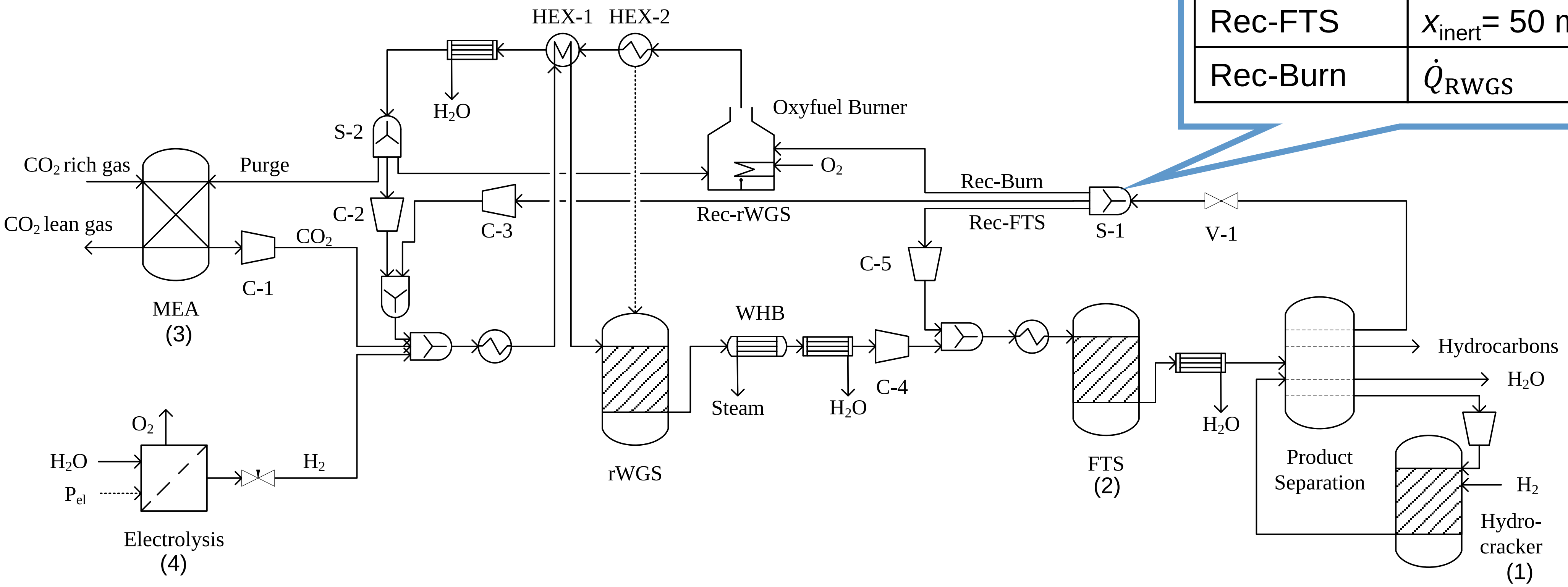

Recycle	Specification
Rec-FTS	x_{inert}= 50 mol %
Rec-Burn	$\dot{Q}_{RWGS}$

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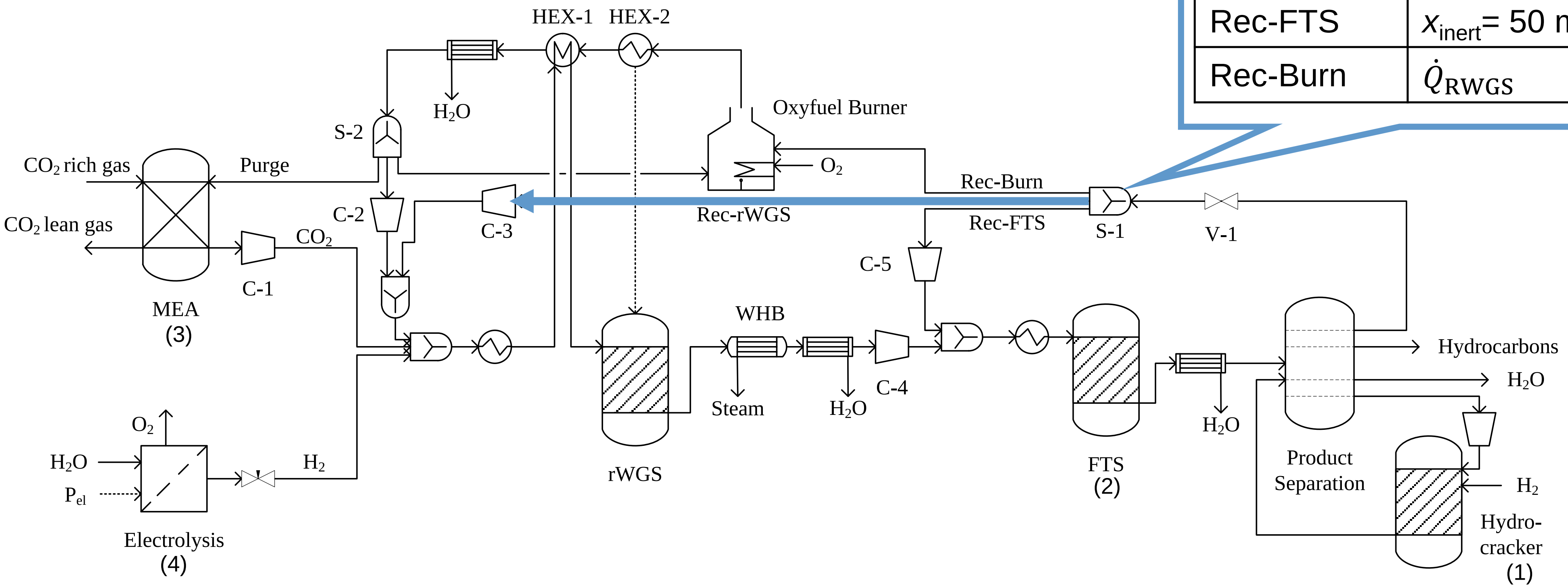
Technical Assessment: Power-to-Liquid

FUELS OF THE FUTURE

DLR

Methodology: Experimentally validated flowsheet (5)



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Technical Assessment: Power-to-Liquid

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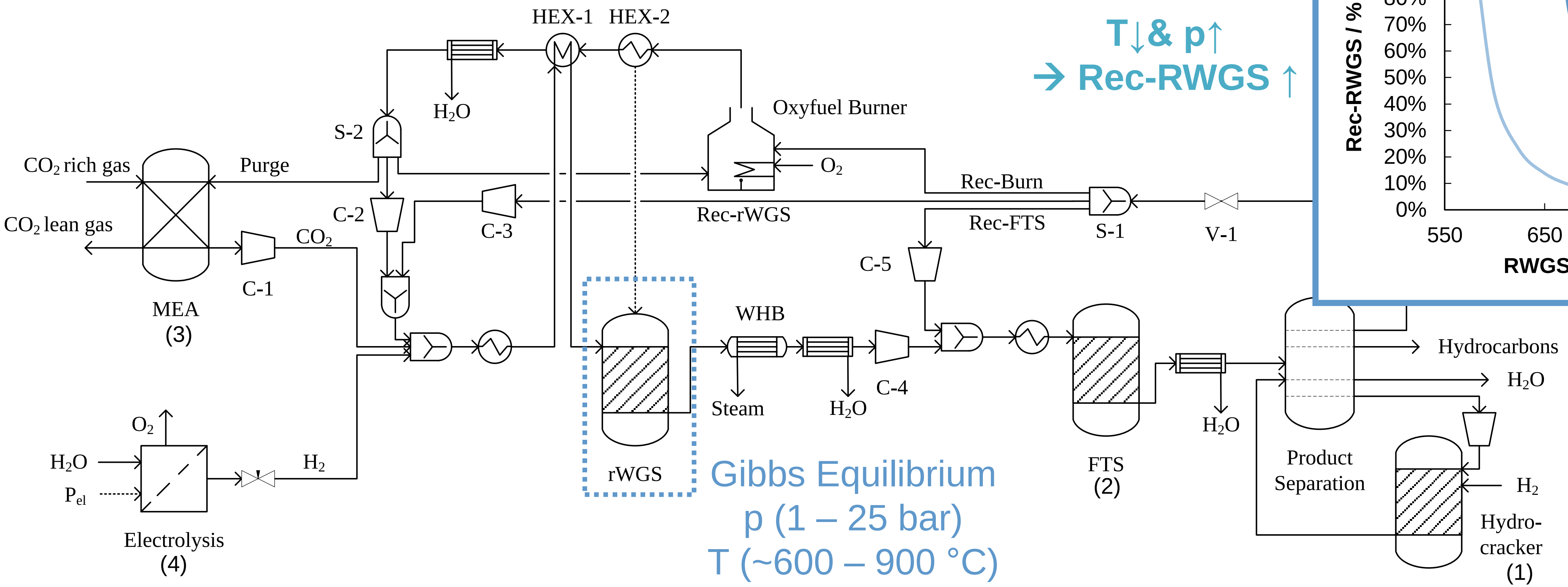
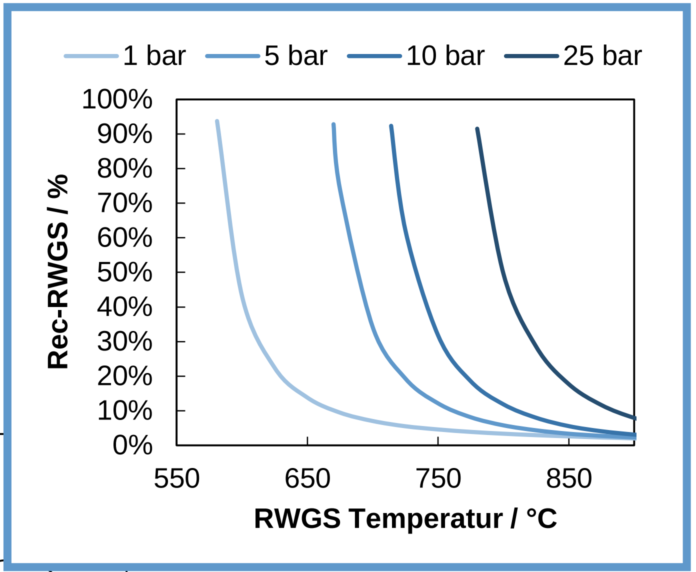


T↓& p↑
→ Rec-RWGS ↑



Gibbs Equilibrium
p (1 – 25 bar)
T (~600 – 900 °C)

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Technical Assessment: Power-to-Liquid

= Highest efficiency

Process Parameter dependent Material / Energy Efficiency (5)

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

RWGS Temperatur / °C \ RWGS press. / bar	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%			

[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.*

Technical Assessment: Power-to-Liquid

FUELS OF THE FUTURE

DLR

Process Parameter dependent Material / Energy Efficiency (5)

[Dark blue colour] = Highest efficiency

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

RWGS Temperatur / °C ↓ \ RWGS press. / bar →	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%			

Higher recycle rate to RWGS increases C 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.*

Technical Assessment: Power-to-Liquid

FUELS OF THE FUTURE

DLR

Process Parameter dependent Material / Energy Efficiency (5)

= Highest efficiency

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

RWGS Temperatur / °C	RWGS press. 1 bar	5 bar	10 bar	25 bar
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%
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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

$$\eta_H = \frac{\dot{n}_{H,C5+}}{\dot{n}_{H,electrolysis}}$$

RWGS Temperatur / °C	RWGS press. 1 bar	5 bar	10 bar	25 bar
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

Higher recycle rate to RWGS increases C 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.*

Technical Assessment: Power-to-Liquid

🟦 = Highest efficiency

Process Parameter dependent Material / Energy Efficiency (5)

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

RWGS Temperatur / °C \ RWGS press. / bar	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%
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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%			

Higher recycle rate to RWGS increases C efficiency

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

RWGS Temperatur / °C \ RWGS press. / bar	1	5	10	25
900	23.6%	23.6%	23.6%	23.1%
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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%			

Less water formation increases H 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.*

Technical Assessment: Power-to-Liquid

Process Parameter dependent Material / Energy Efficiency (5)

(Dark blue shading = Highest efficiency)

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

RWGS Temperatur / °C \ RWGS press. / bar	1	5	10	25
900	82.2%	82.2%	82.4%	83.7%
875	82.3%	82.4%	82.8%	84.5%
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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%			

Higher recycle rate to RWGS increases C efficiency

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

RWGS Temperatur / °C \ RWGS press. / bar	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%			

Less water formation increases H efficiency

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

RWGS Temperatur / °C \ RWGS press. / bar	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%			

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.*

ECONOMICAL ASSESSMENT OF SAF (PTL)

Economical Assessment: Power-to-Liquid

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.*

Economical Assessment: Power-to-Liquid

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			

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.*

Economical Assessment: Power-to-Liquid

FUELS OF THE FUTURE

DLR

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

= 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
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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

[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.*

Economical Assessment: Power-to-Liquid

FUELS OF THE FUTURE

DLR

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

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850	1.89	1.81	1.81	1.91
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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		
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600	2.19			

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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

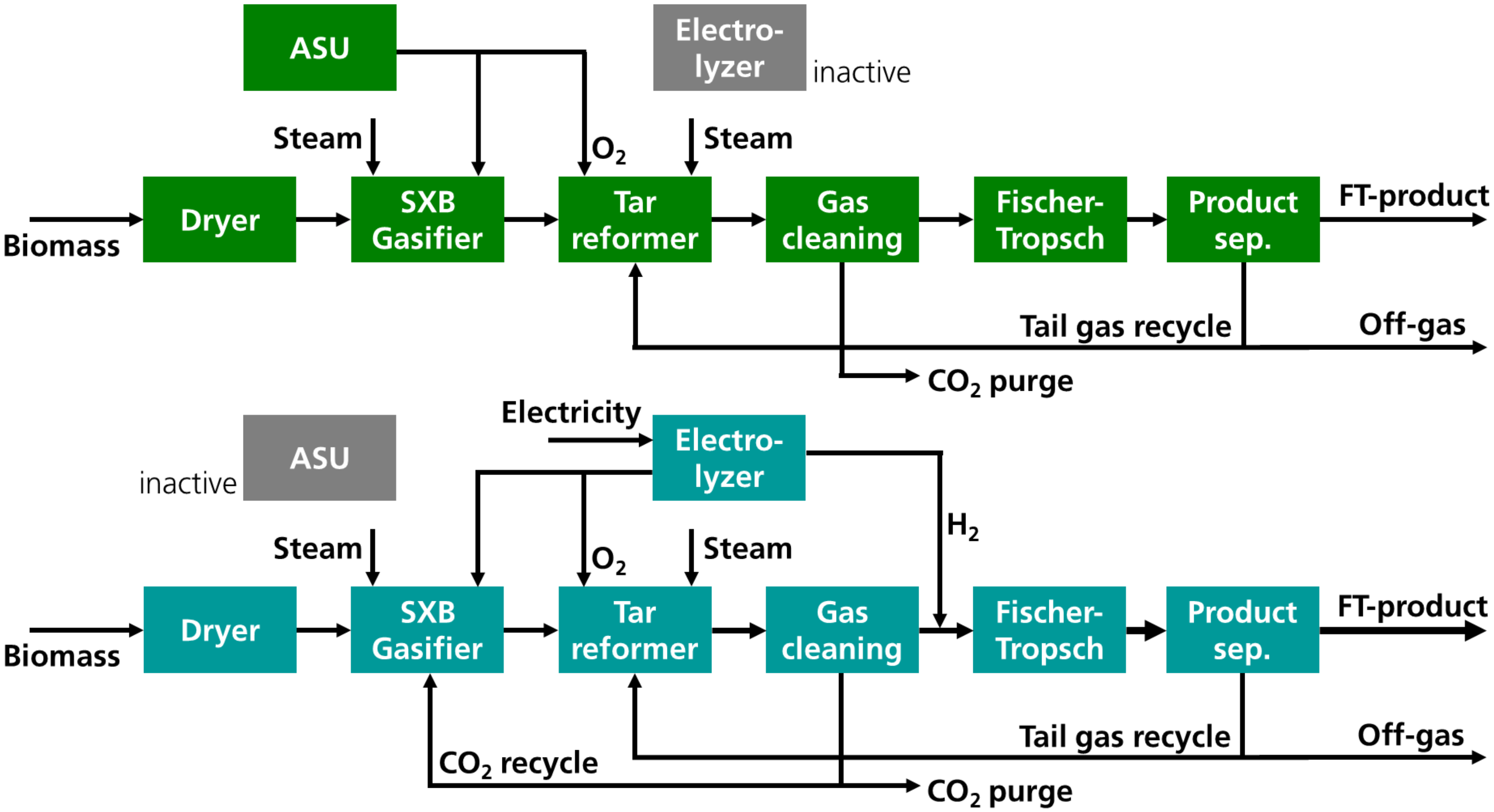
5 bar and 800 °C: low cost, robust NPC optimum for all H_2 feedstock costs

[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.*

ENVIRONMENTAL ASSESSMENT OF SAF (PBTL)

Dual configuration for Biomass-to-Liquid and Power&Biomass-to-Liquid SAF [1]

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



BtL with ASU:

- high heat demand
- low renewable power

PBtL with electrolyzer :

- no heat demand
- renewable power available

[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.

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

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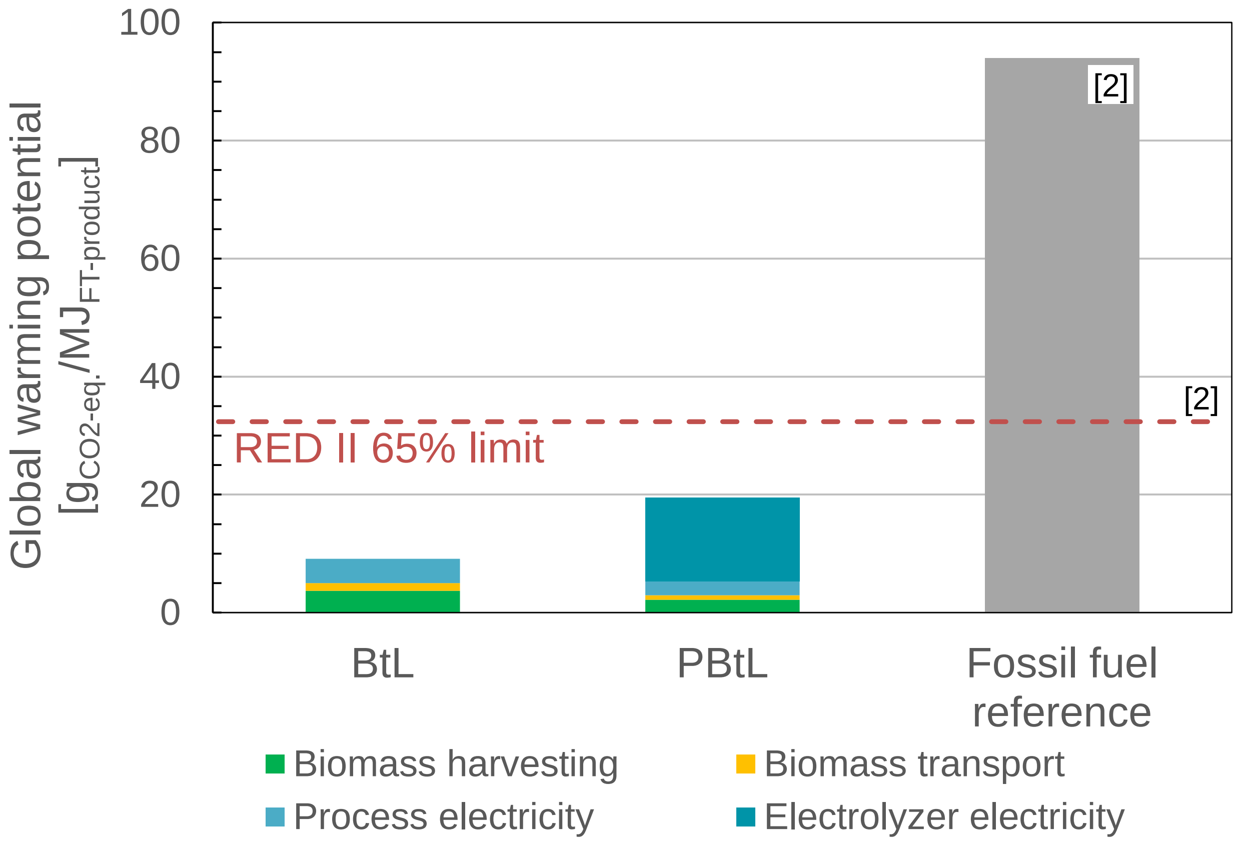

- **Transportation: 100 km, one-way by truck (69 $g_{CO2\text{-}eq.}$/(t*km))**
- **Biomass: Forest residues harvesting (19.7 $g_{CO2\text{-}eq.}$/kg)**
- **Electricity: Finnish grid @2020 (68.6 $g_{CO2\text{-}eq.}$/kWh)**

[1] Habermeyer et. al (2023) Sustainable aviation fuel from forestry residue and hydrogen. A techno-economic and environmental analysis for an immediate deployment of the PBtL process in Europe. Sustainable Energy and Fuels, 7, p. 4229-4246. doi: 10.1039/d3se00358b.
[2] European Union (2018) "Directive 2018/2001 of the European Parliament …on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

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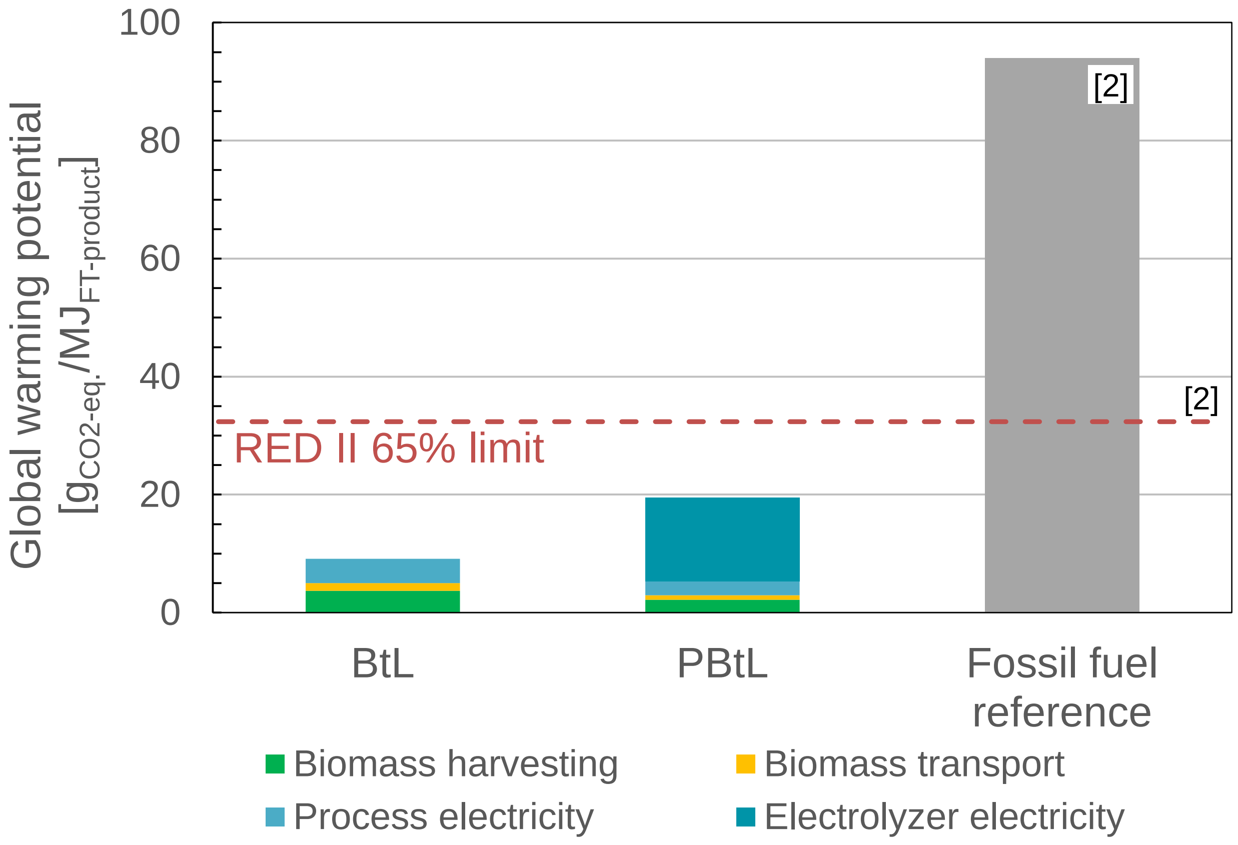


- **Transportation: 100 km, one-way by truck (69 $g_{CO2\text{-}eq.}$/(t*km))**
- **Biomass: Forest residues harvesting (19.7 $g_{CO2\text{-}eq.}$/kg)**
- **Electricity: Finnish grid @2020 (68.6 $g_{CO2\text{-}eq.}$/kWh)**

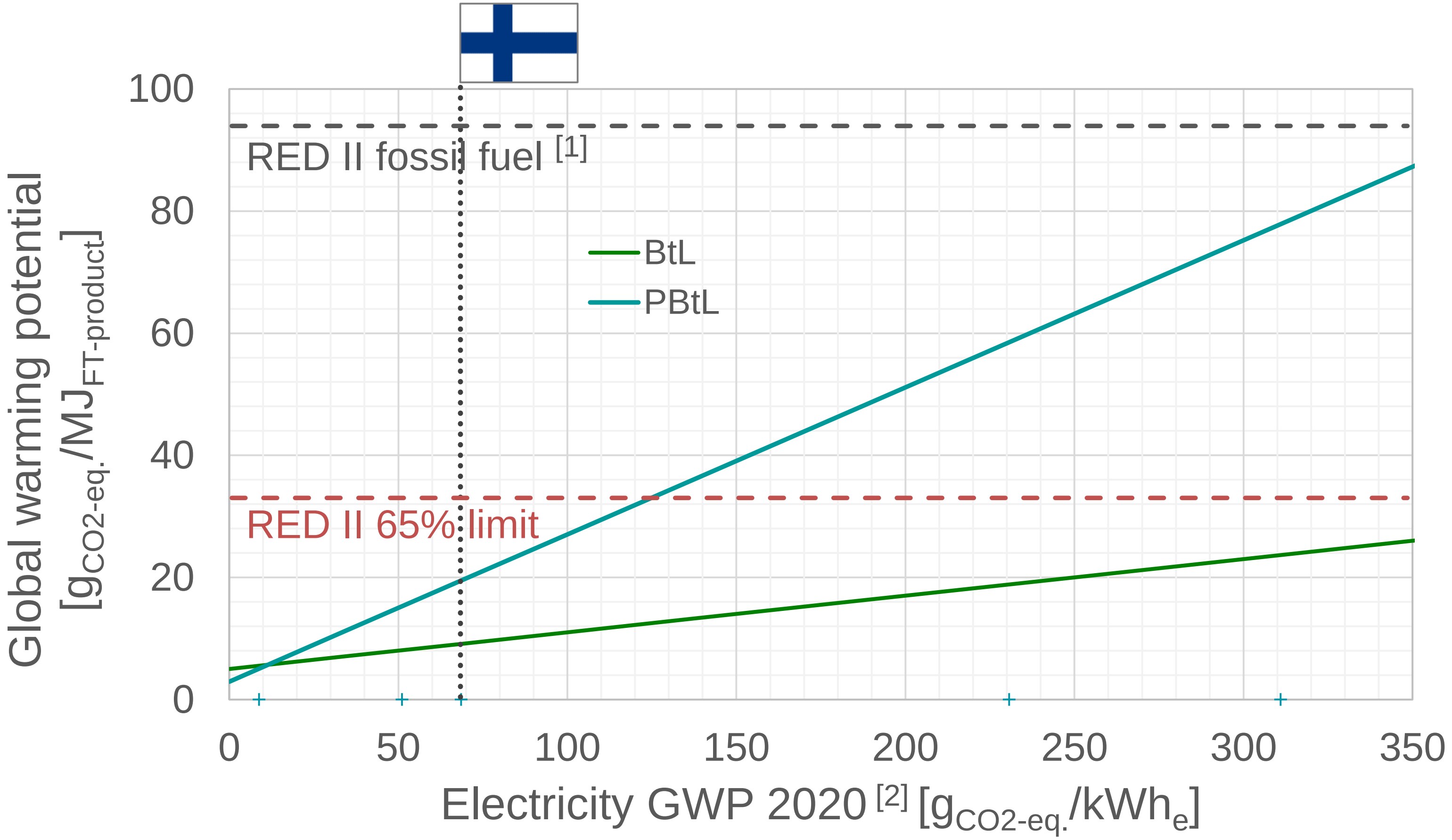
Conclusion

REDII target accomplished @ FLEXCHX base case

[1] Habermeyer et. al (2023) Sustainable aviation fuel from forestry residue and hydrogen. A techno-economic and environmental analysis for an immediate deployment of the PBtL process in Europe. Sustainable Energy and Fuels, 7, p. 4229-4246. doi: 10.1039/d3se00358b.
[2] European Union (2018) "Directive 2018/2001 of the European Parliament …on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

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

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



- GWP of grid electricity determines GWP of power-based SAF

[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

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

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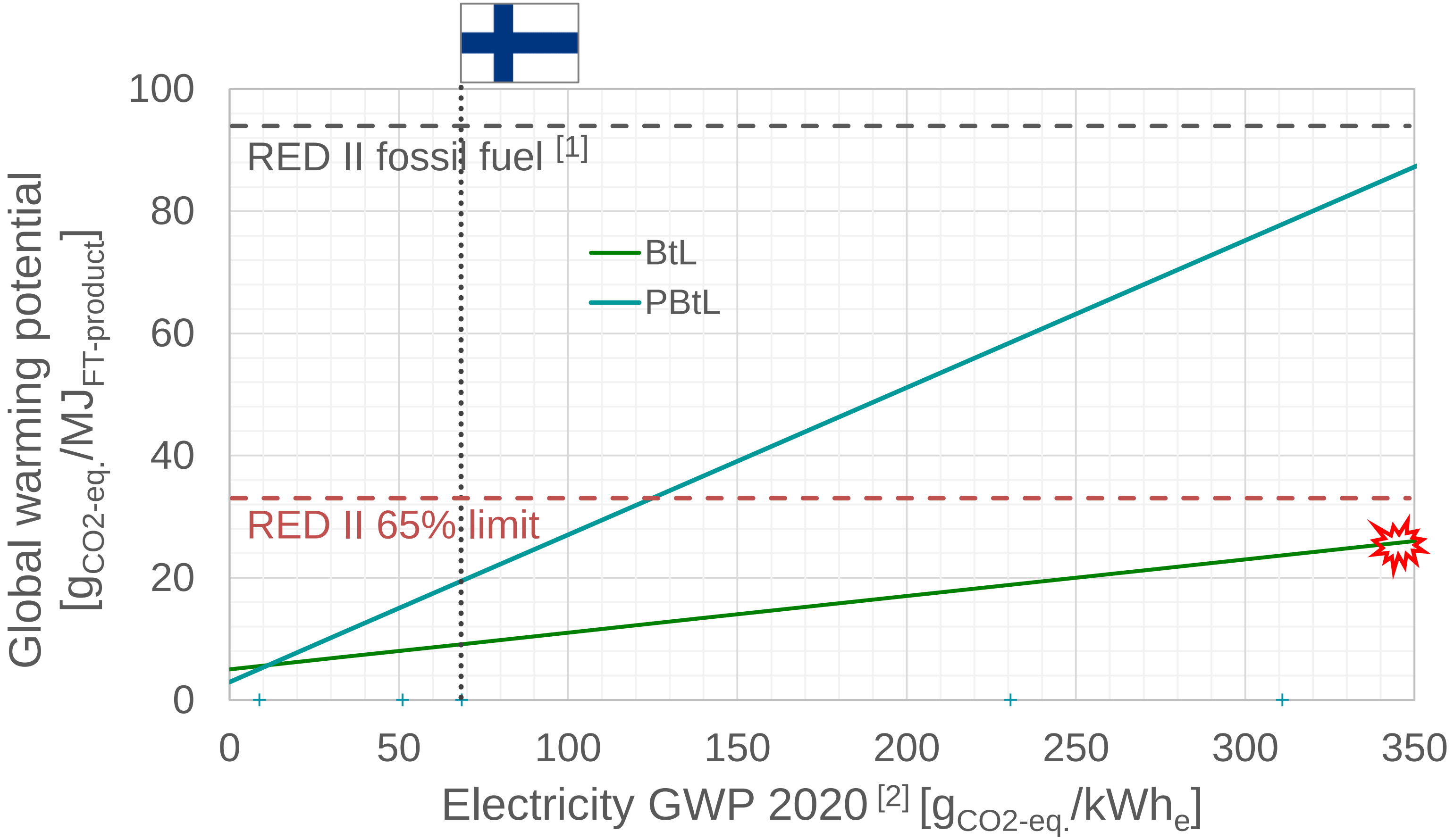

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL

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

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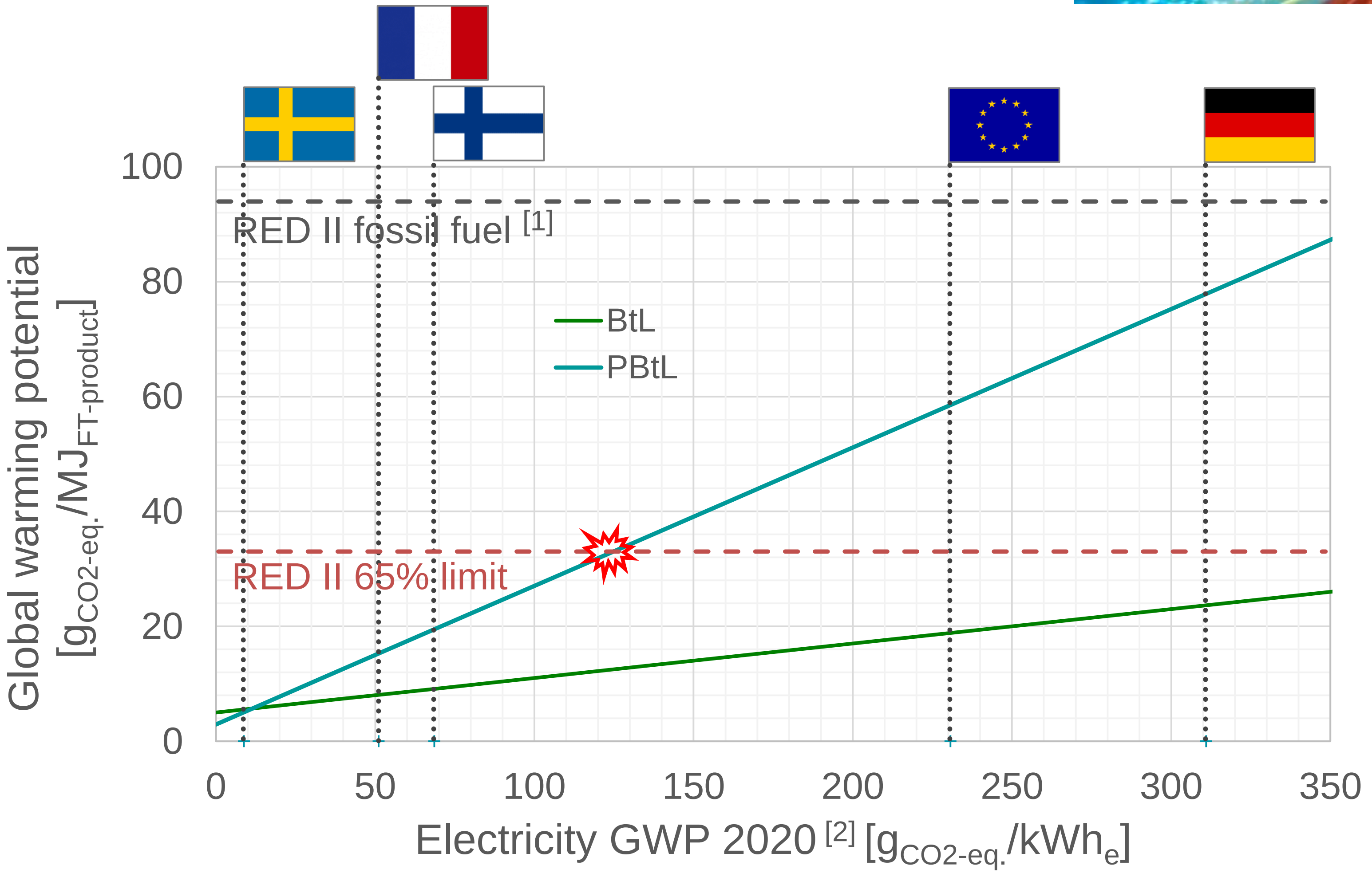

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with GWP <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit

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

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

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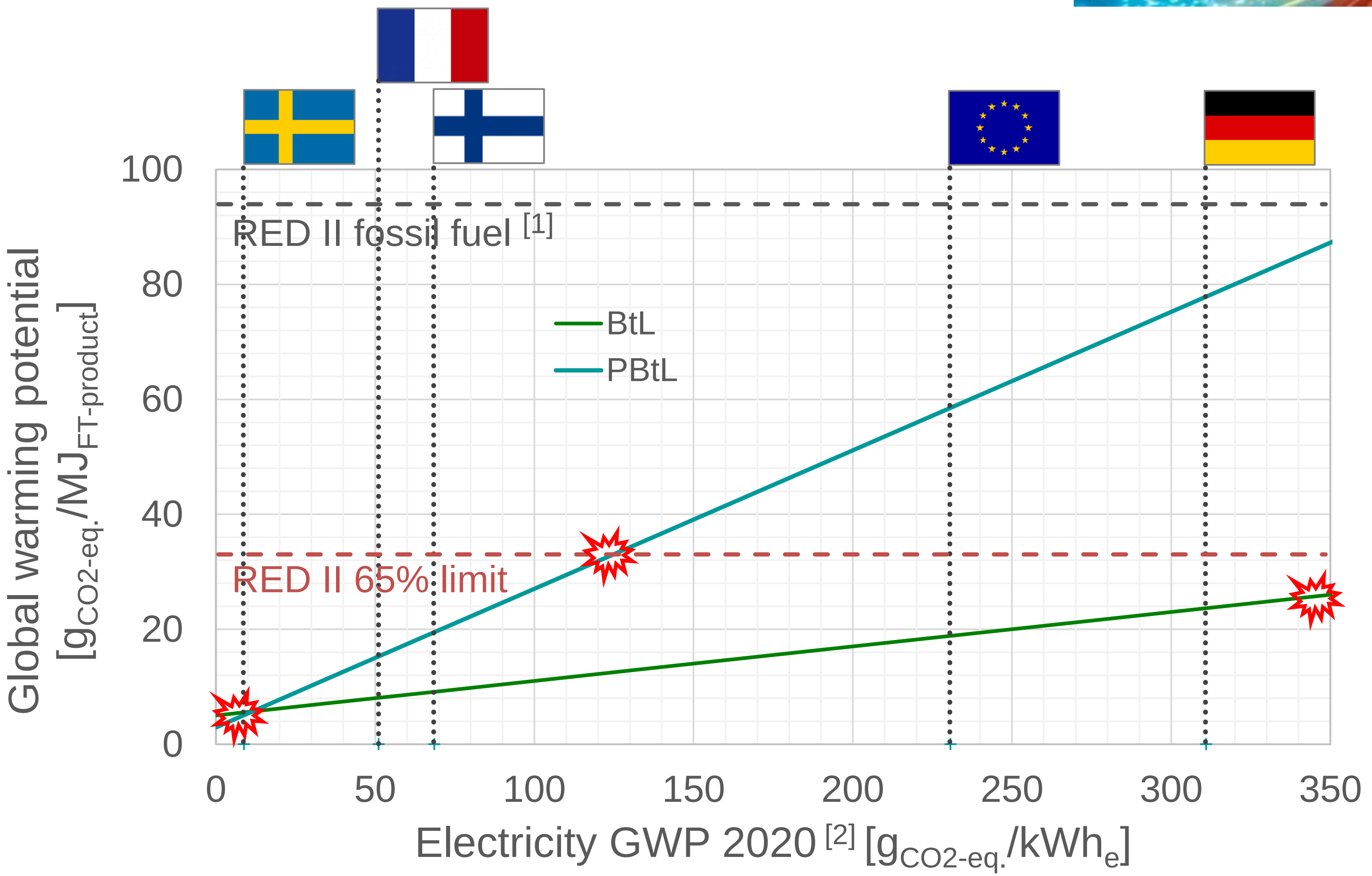
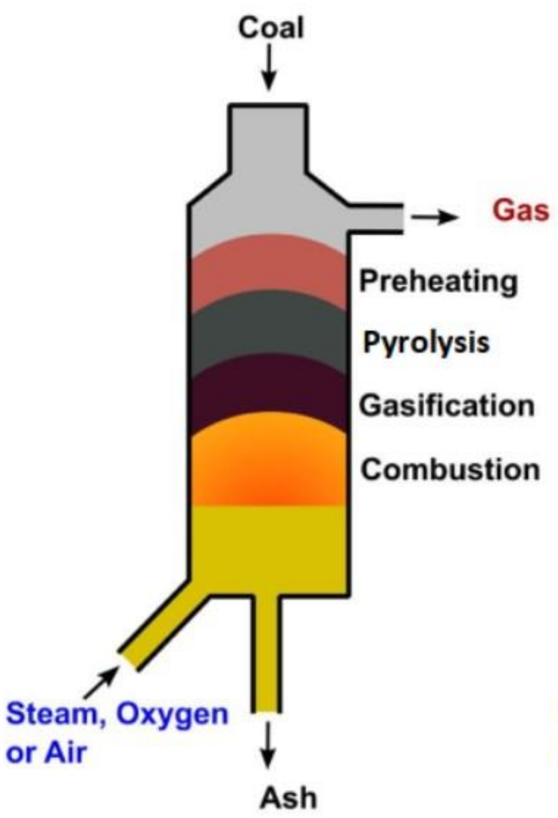


- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with GWP <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit
- PBtL could have lower GWP than BtL with Swedish grid mix

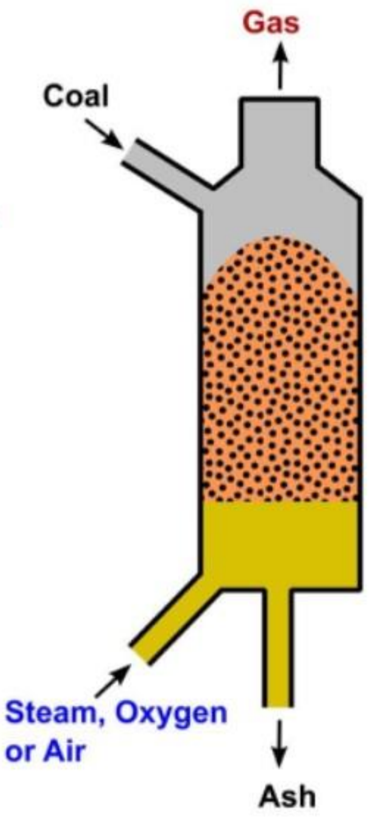
[1] European Union (2018) "Directive 2018/2001 of the European Parliament … on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union
[2] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111

TECHNOLOGY READINESS OF PBTL SAF

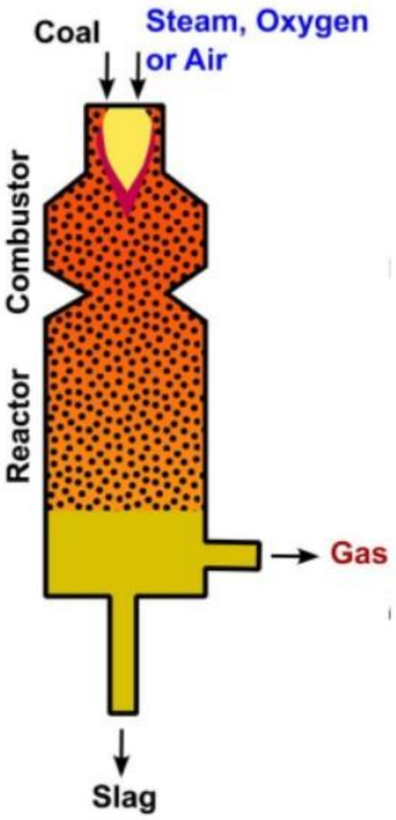
Gasifier: state-of-the-art coal technology[1,2,3]



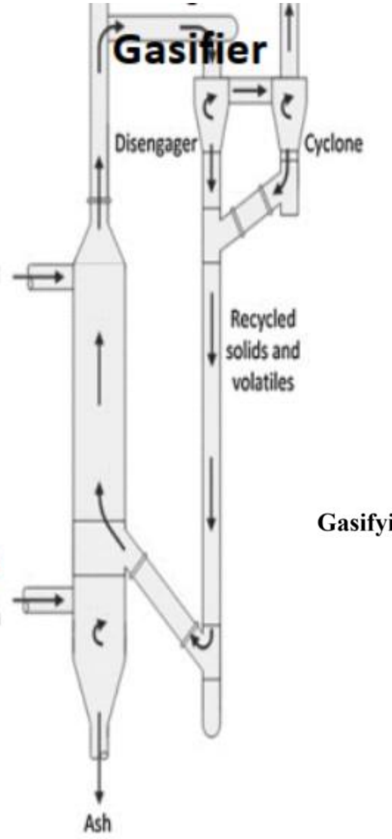
Fixed (moving) bed



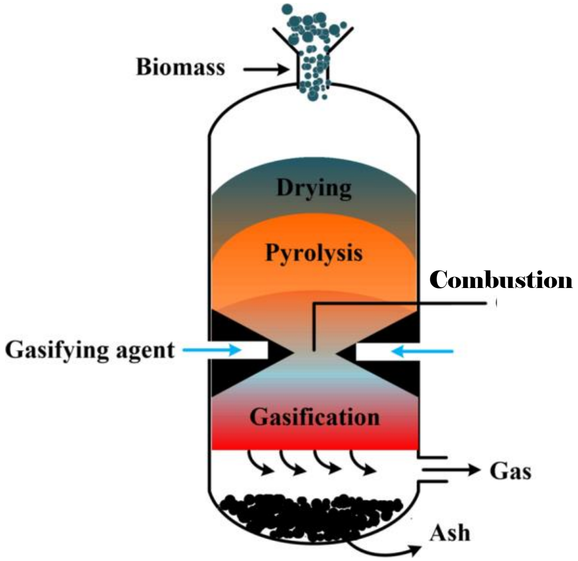
Fluidized bed



Entriained flow



Transport Integrated



Downdraft

[1] Kaneko, Shozo. (2015) Integrated Coal Gasification Combined Cycle: A Reality, Not a Dream. Journal of Energy Engineering. 142. E4015018.
[2] Jeffrey Phillips (2006) Different types of gasifiers and their integration with gas turbines, https://www.researchgate.net/publication/300432219_Different_types_of_gasifiers_and_their_integration_with_gas_turbines/figures?lo=1
[3] Marzoughi, Tayebeh, Samimi, Fereshteh and Rahimpour, Mohammad Reza. "Environmental and thermodynamic performance assessment of biomass gasification process for hydrogen production in a downdraft gasifier" Chemical Product and Process Modeling, vol. 17, no. 6, 2022, pp. 637-654.

Gasifier: multiple installations,
➔ biomass applications proven

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

Gasifier: multiple installations,
➔ biomass applications proven

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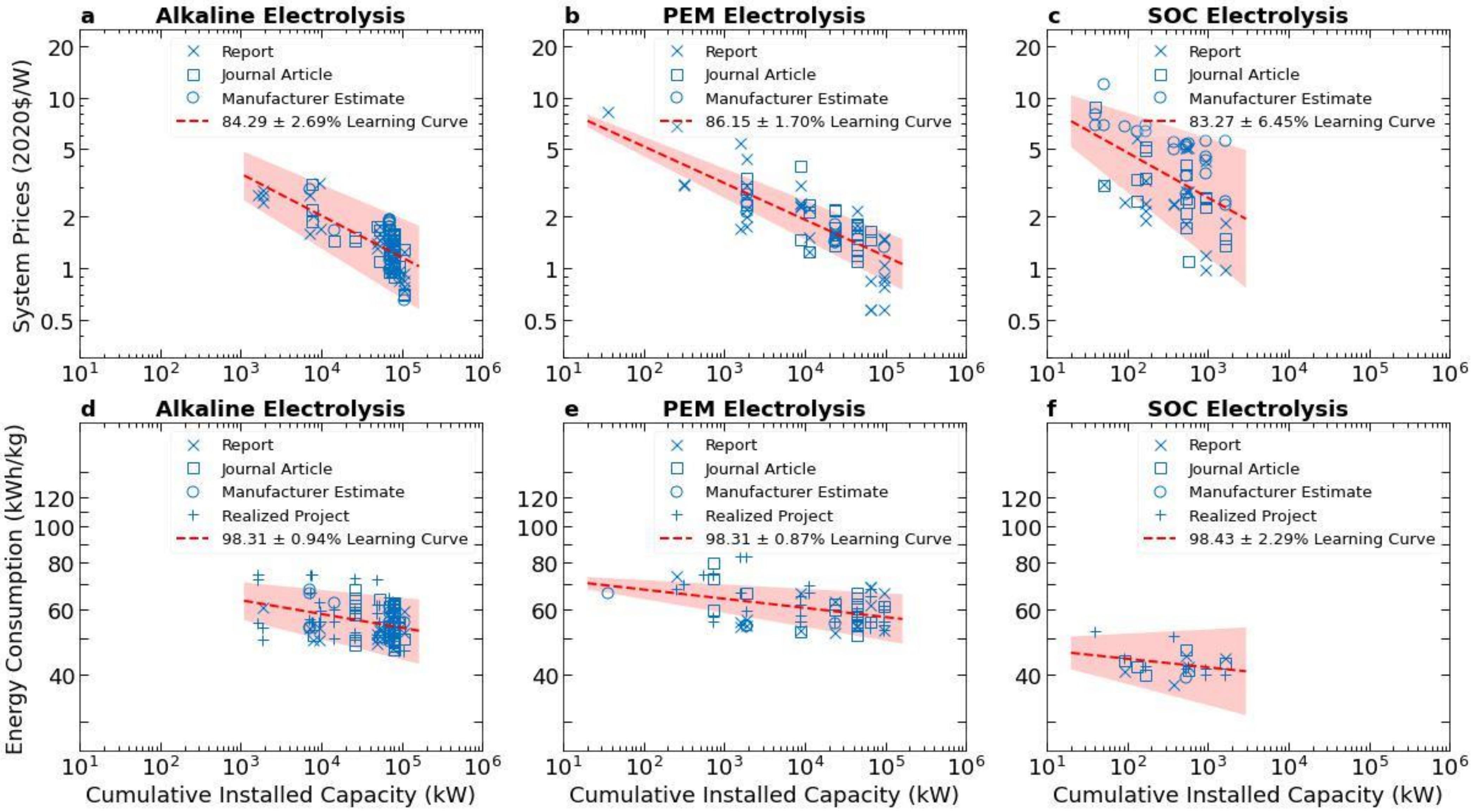
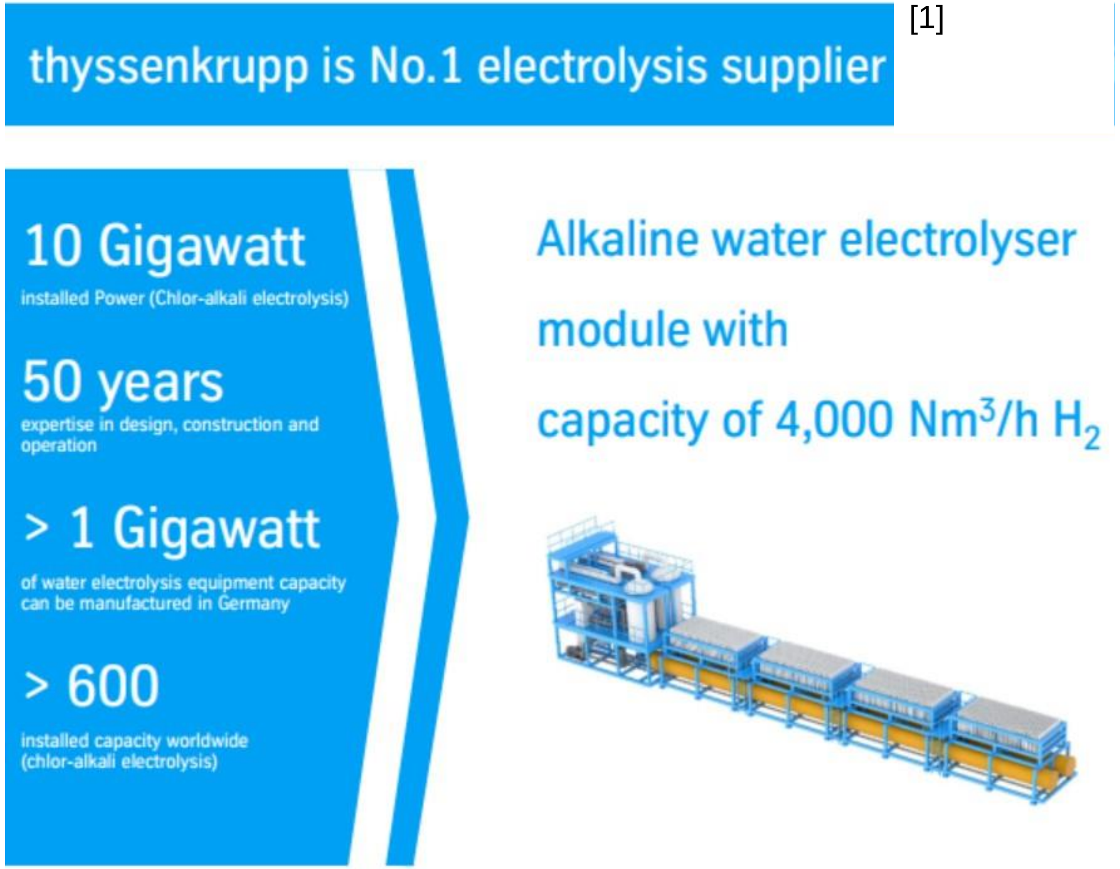
Electrolysis: WELL-KNOWN technology[1]



[1] Glenk, G., Holler, P., Reichelstein, S., Advances in Power-to-Gas Technologies: Cost and Conversion Efficiency. TRR 266 Working Paper Series No. 109, Available at http://dx.doi.org/10.2139/ssrn.4300331

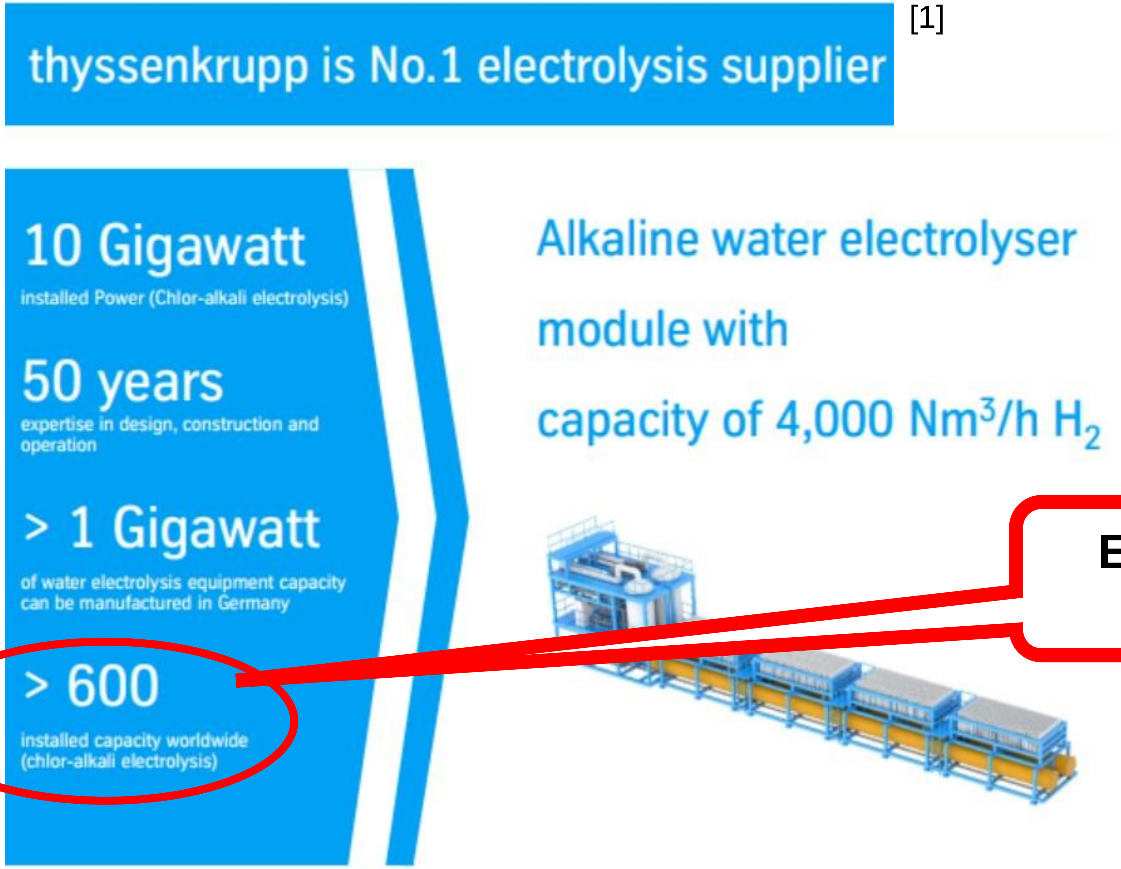
Electrolysis
State-of-the-art technology



[1]

[1] Source: tkUCE/tkis

Electrolysis
State-of-the-art technology



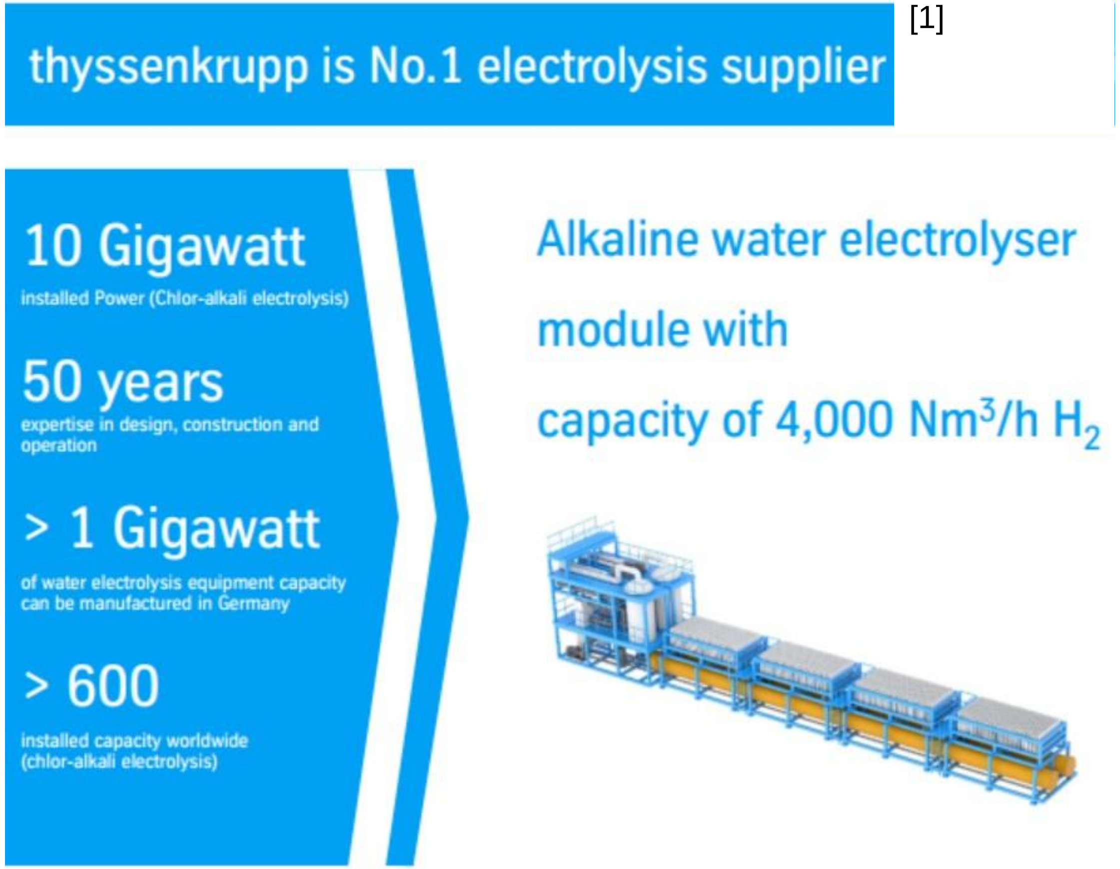
[1]

Electrolysis technology is state-of-the-art

[1] Source: tkUCE/tkis

Electrolysis
State-of-the-art / GW installations in Europe

[1]



[2]

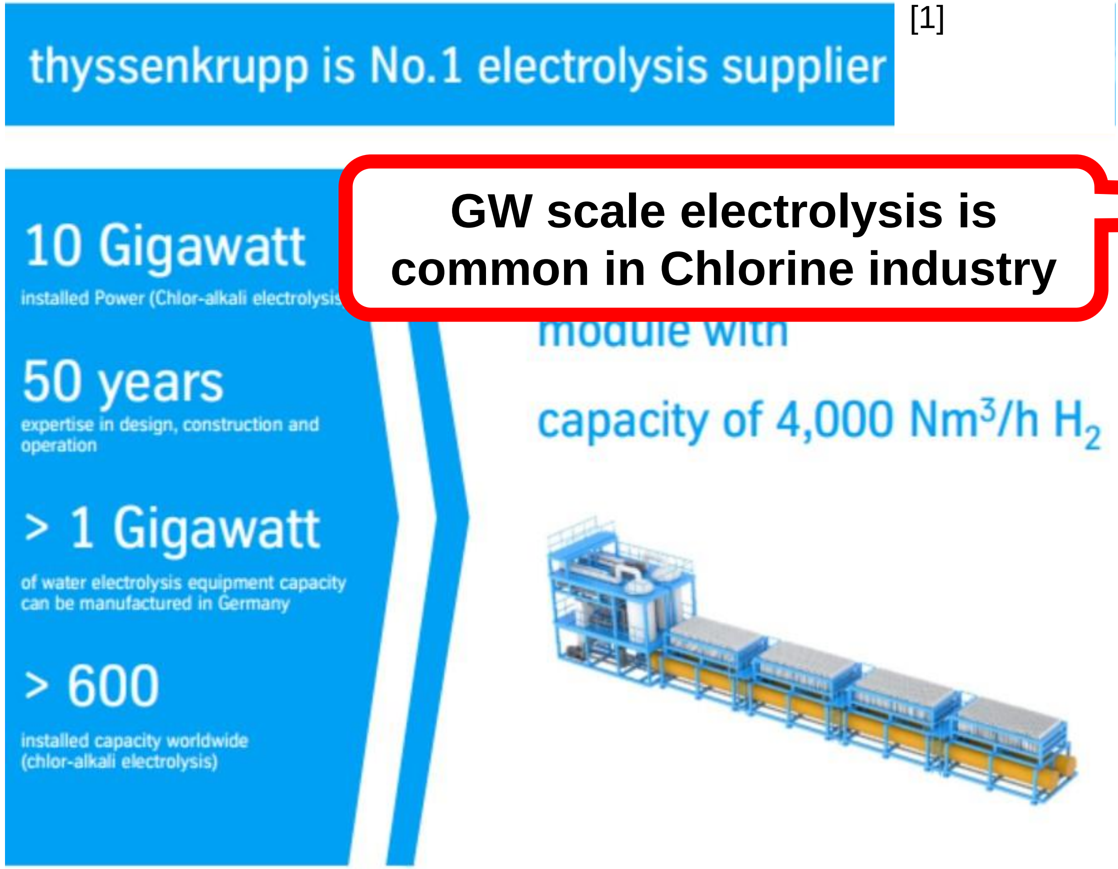
Location	Country	Operator	Capacity Chlorine (in 1000 t)	Diaphrag.	Membr.	Other	Electrolys. D MW	Electrolys. M MW
Stade	GER	Dow	1624	1024	600		**2.970**	**1.560**
Runcorn	UK	Runcorn MCP	430		430			**1.118**
Rotterdam-Botlek	NL	Nobian	637		637			**1.656**
Dormagen	GER	Covestro	480		400	80[5]		**1.040**
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

Electrolysis
State-of-the-art / GW installations in Europe

[1]



GW scale electrolysis is common in Chlorine industry

[2]

Location	Country	Operator	Capacity Chlorine (in 1000 t)	Diaphrag.	Membr.	Other	Electrolys. D MW	Electrolys. M MW
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		**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[illegible]		**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**
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[1] Source: tkUCE/tkis

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

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

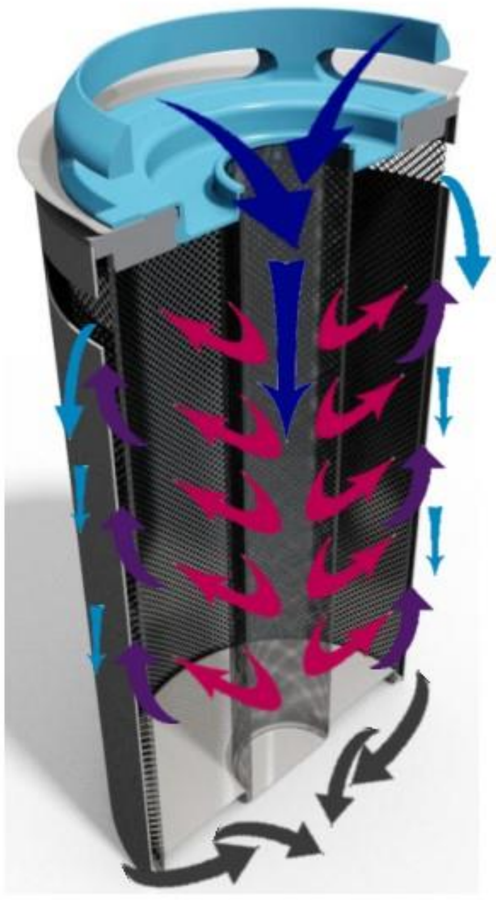
7 Mt/a FT production "commercial" enough?

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

New FT-Technology – but No Game Changer

Benefits of FT **CANS** technology compared to conventional Fixed-Bed FT Technology[1]

Increased Productivity	• 3 fold increase in production for same size reactor
Easier to Manufacture Reactor	• Larger tubes, low weight • Tube numbers reduced by 95%
Large Cost Savings	• FT Unit cost reduced by ~50%
Improved Catalyst Performance	• Volumes reduced by >50% • 3 years life without regen. expected
No catalyst handling in life cycle	• Prefilled in factory • Spent catalyst returned in **CANS** carriers for metals recovery
Improved Efficiency	• >90% overall CO conversion in single stage recycle loop which can operate with >50% inerts

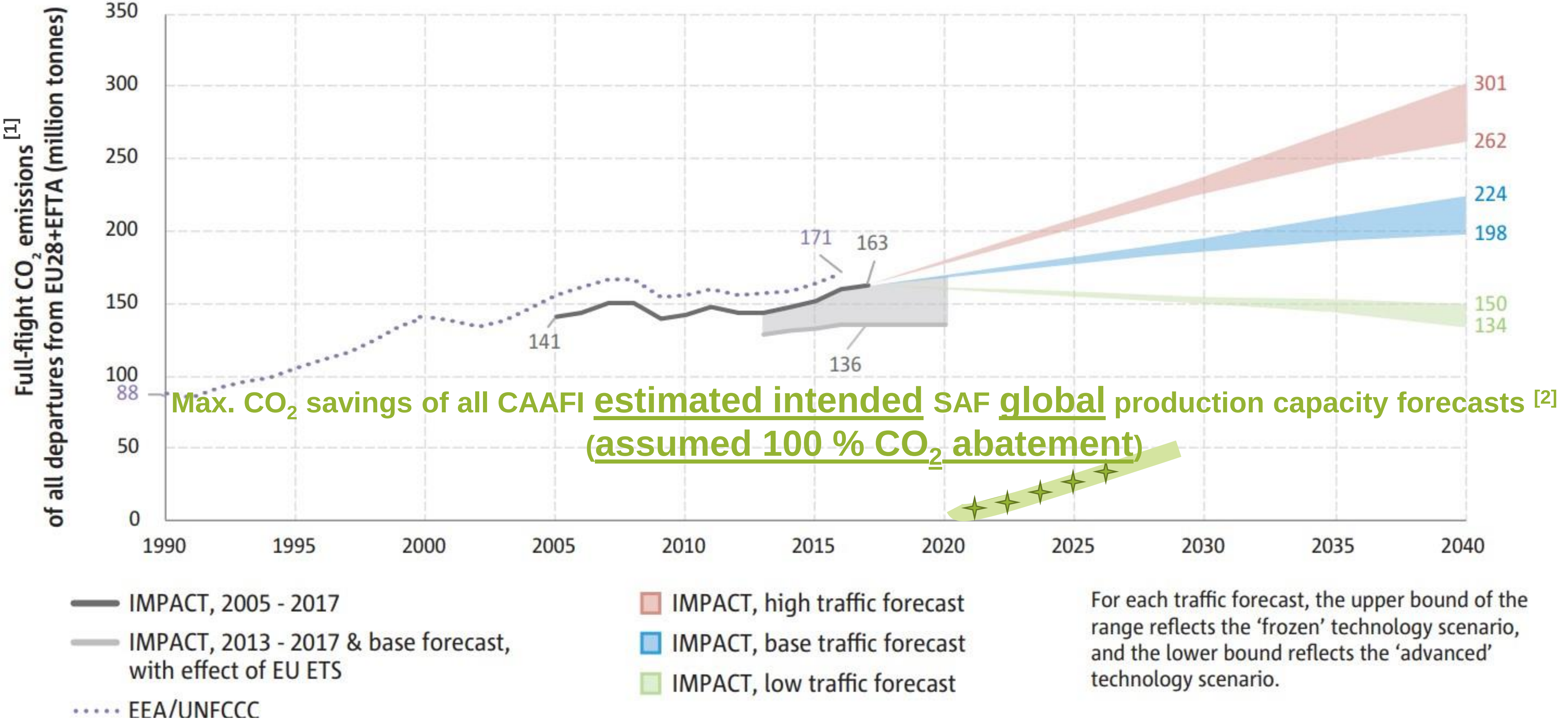


JM

[1] https://globalsyngas.org/wp-content/conference-presentations/2020/2020-w2-d1-m2-JM-BP-Presentation.pdf

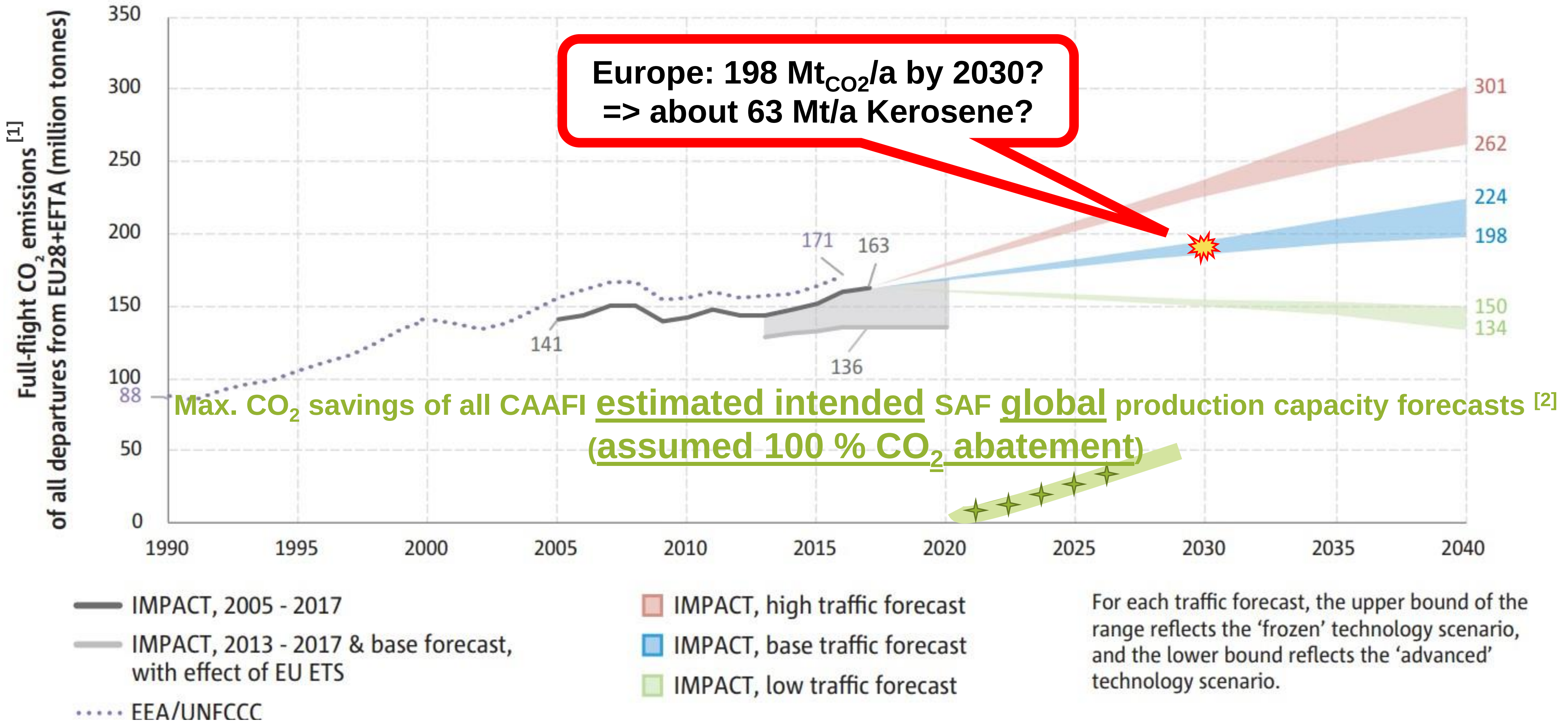
TOWARDS A EUROPEAN SAF ROADMAP

SAF deployment still lagging behind
Too little too late



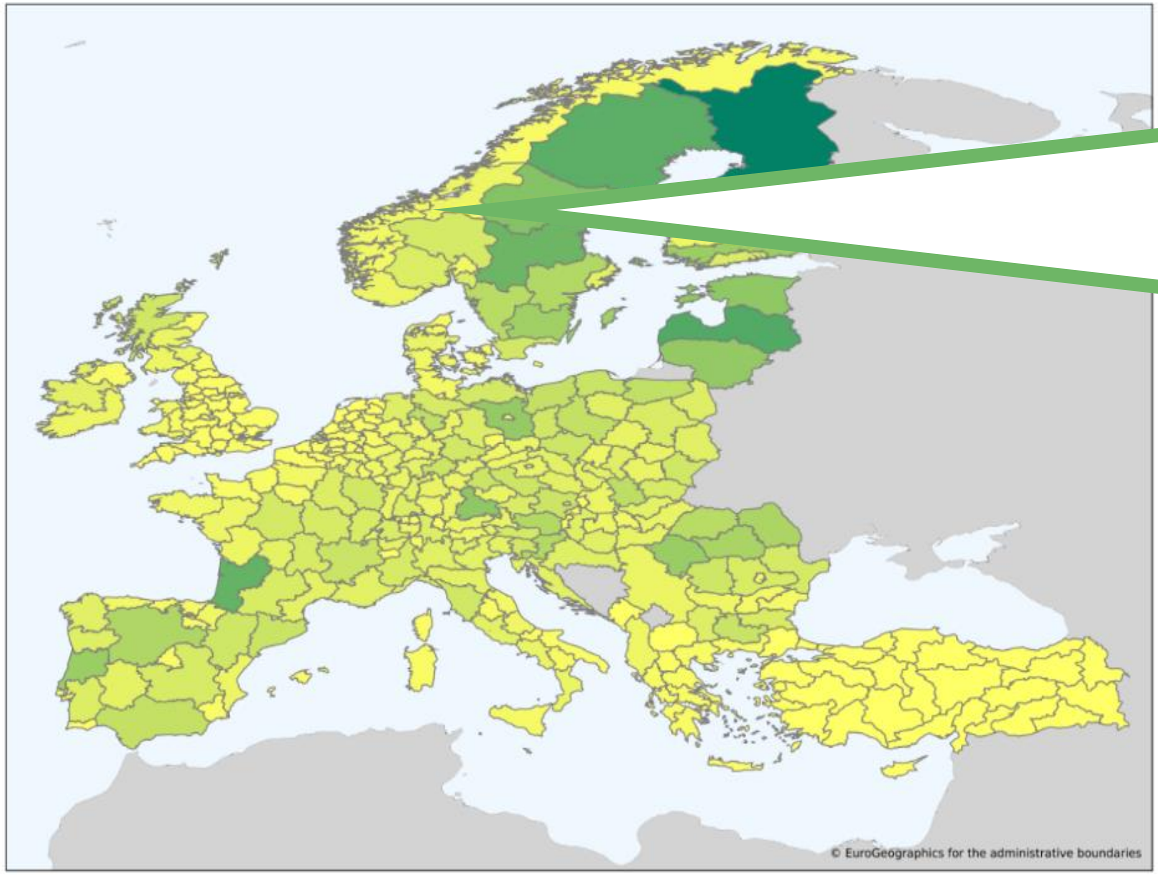
[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf
[2] calc. from (slide 2) S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf.

SAF deployment still lagging behind
Too little too late



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

PBtL potential analysis for Europe
Finding the sweet spots



NUTS2 region specific conditions:

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

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

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

Large scale PBtL SAF plant: 400 kt_{SAF}/a incl. 900 MW_e Electrolyzer / 400 MW_{th} CFB gasifier

Key economic Assumptions

Investment costs:		
AEL-Electrolyzer	**1**	$M€_{2020}/MW$ [1]
Fischer-Tropsch SBCR:	**5.9**	$k€_{2020}/m^3$ [2]
Selexol:	**5.5**	$k€_{2020}/kmol_{CO2}/h$ [3]
Fluidized bed gasifier:	**0.5**	$M€_{2020}/(kg_{dry\ biomass}/s)$ [4]
Raw materials and utility costs		
Selexol:	**4.4**	$€_{2020}/kg$ [5]
FT catalyst:	**33**	$€_{2020}/kg$ [6]

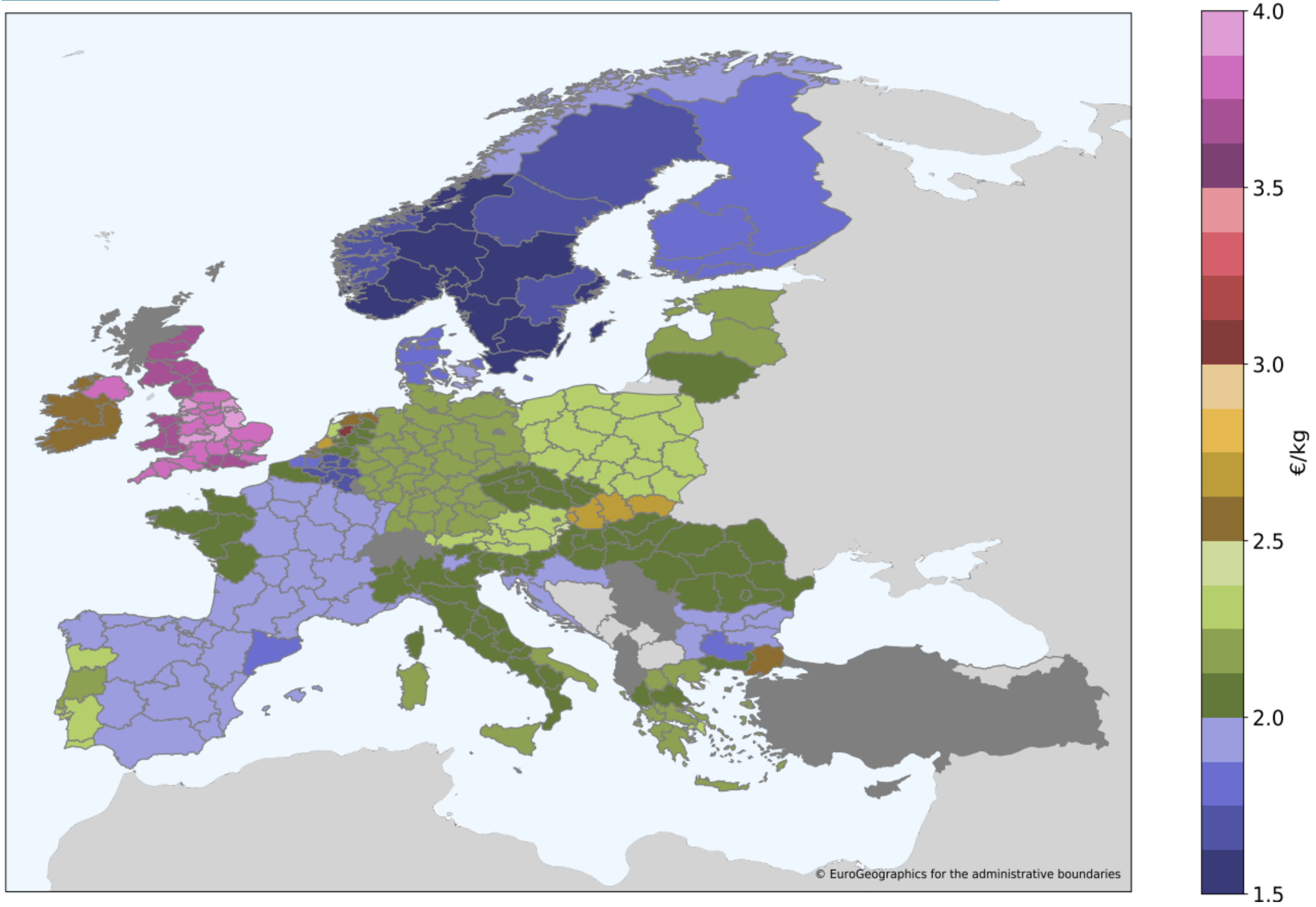
General economic assumptions:

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

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

European SAF Roadmap
Scandinavia ➔ Lowest NPC (electricity price)

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



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

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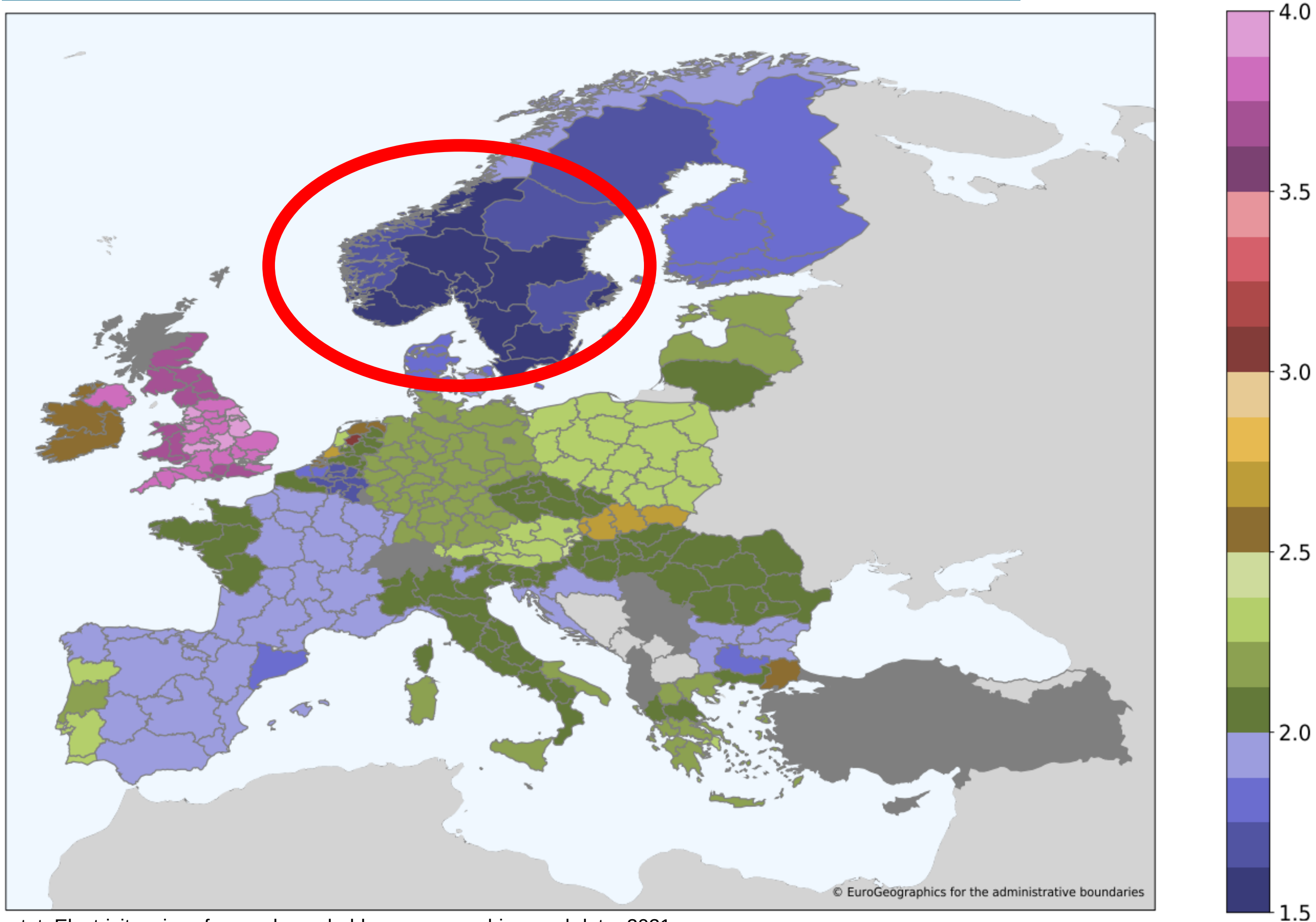

Standard **PBtL** plant

- 900 MW_e Electrolyzer
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- 400 kt/a SAF output

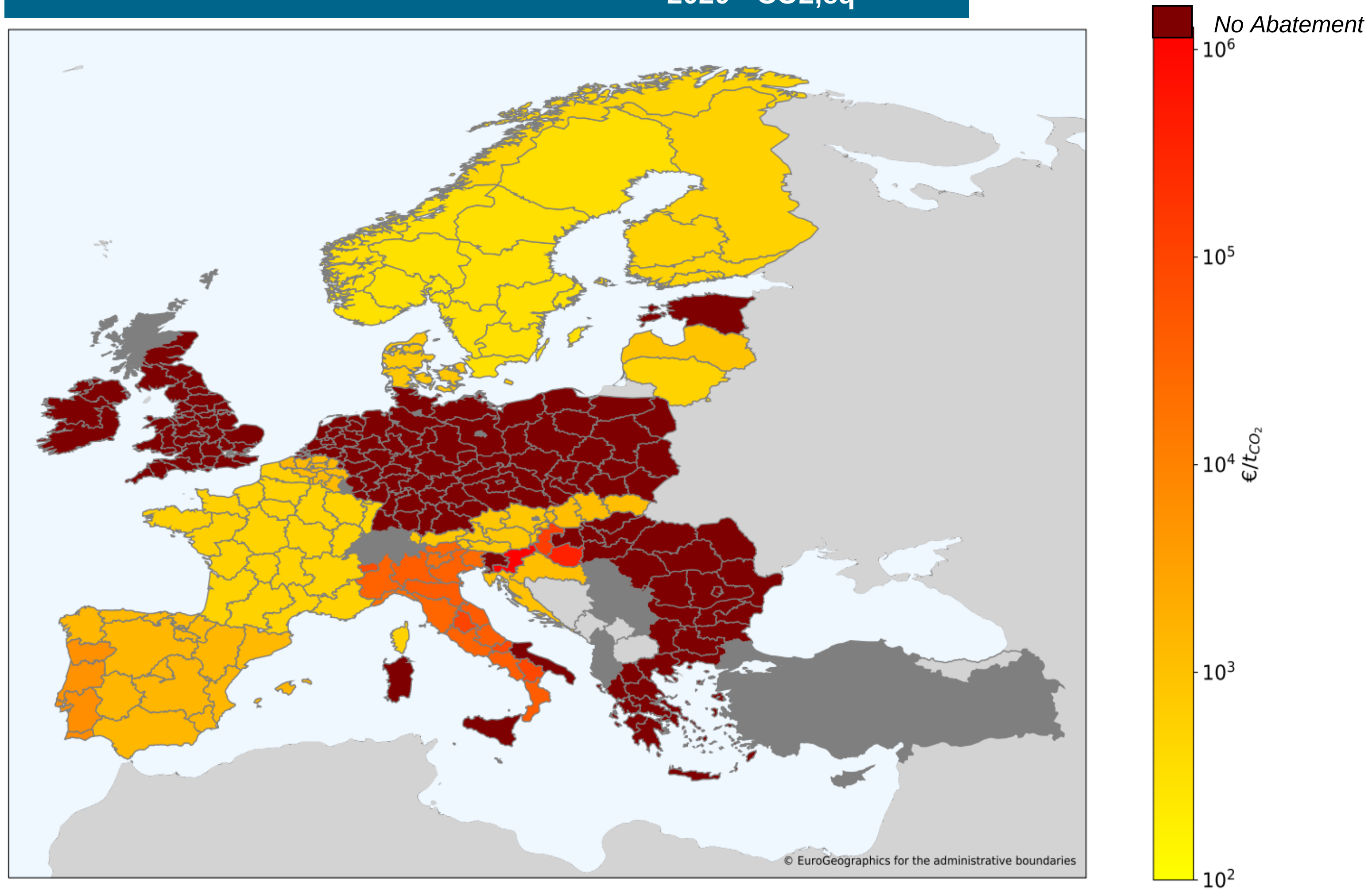
➔ Search for cheap biomass residue and inexpensive (renewable) power [1,2]

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

[1] Eurostat, Electricity prices for non-household consumers - bi-annual data. 2021.
[2] Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., ... & Thrän, D. (2019). ENSPRESSO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, *26*, 100379

European SAF Roadmap
No GHG abatement for high GWP grid

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



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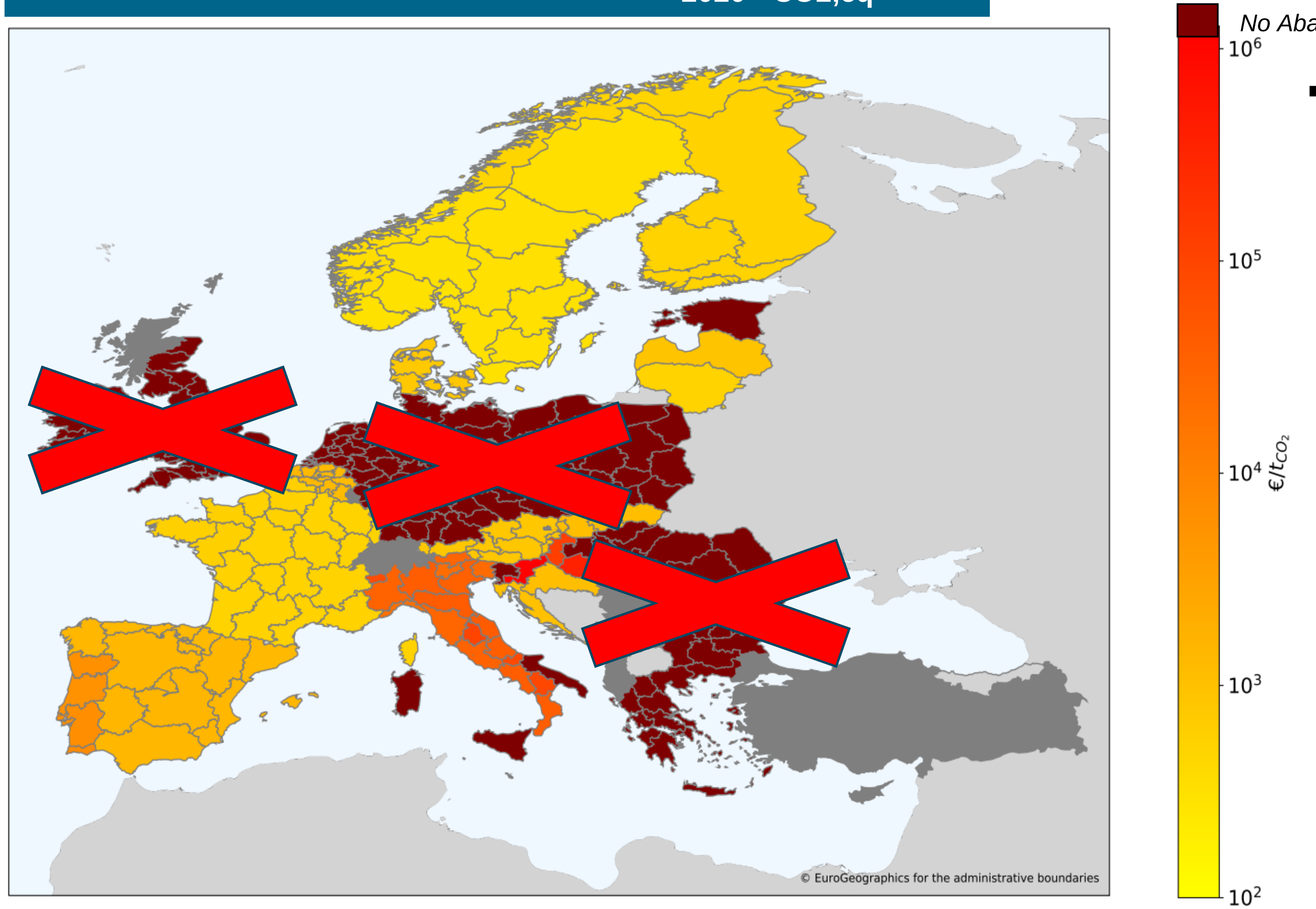

➔ Decarbonized national grids necessary for effective PBtL roll-out

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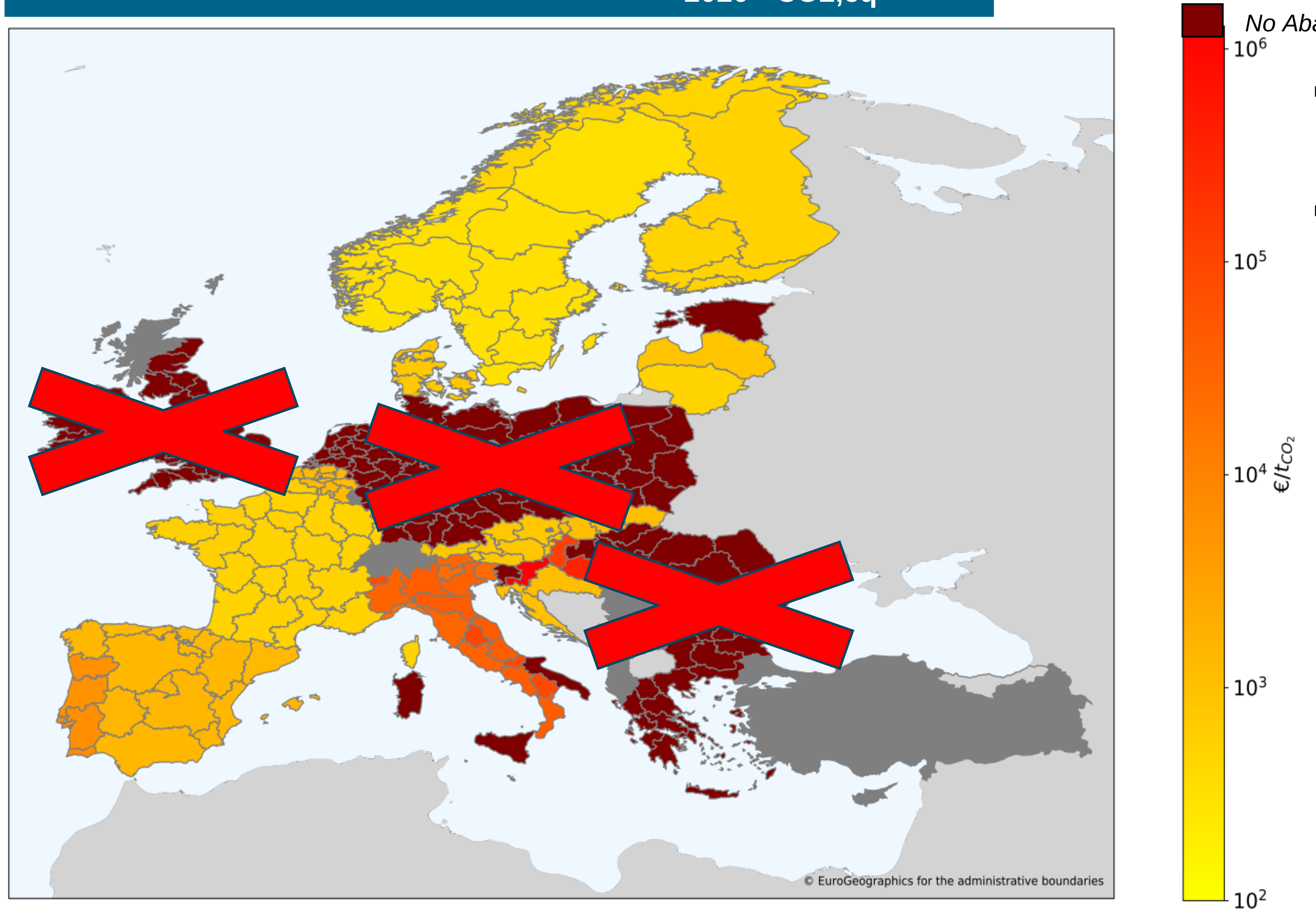
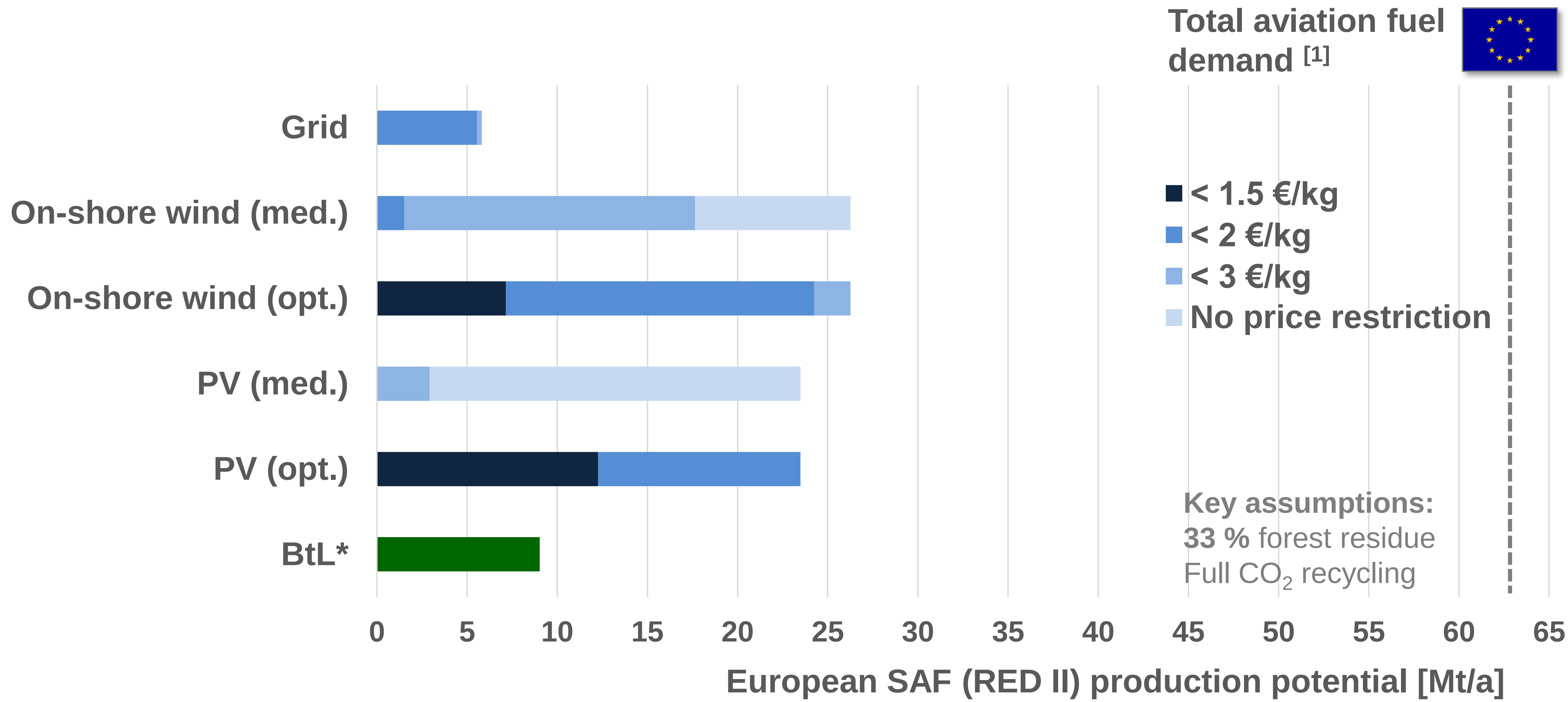


➔ Decarbonized national grids necessary for effective PBtL roll-out

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

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

Aggregated SAF production potential



[1] S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf. *Assumptions: 19.9 % biomass conversion, entire potential under RED II limit

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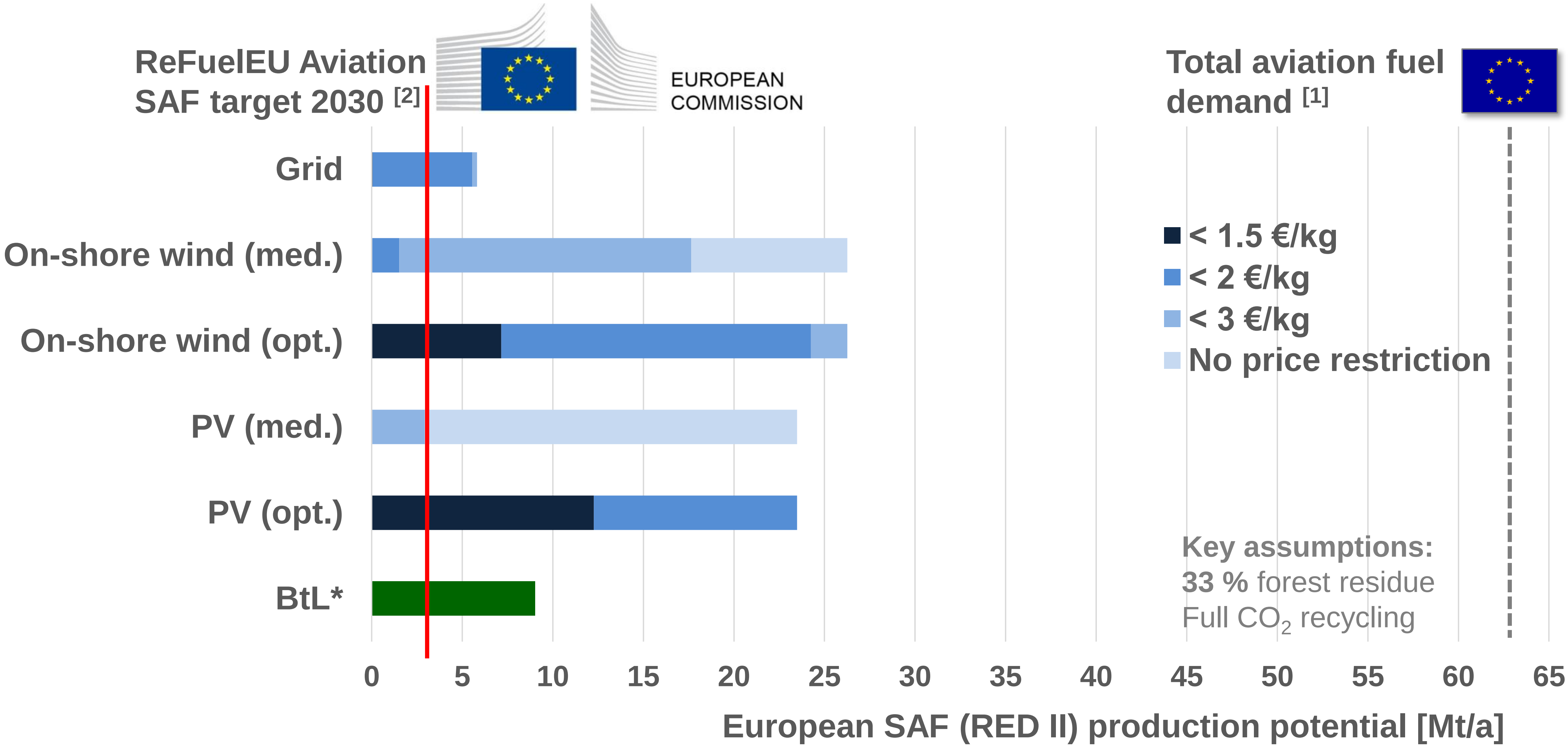

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[2] https://www.easa.europa.eu/en/light/topics/fit-55-and-refueleu-aviation

AN AMBITIOUS SAF DEPLOYMENT PLAN

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

EUROPEAN COMMISSION

	ReFuelEU Aviation SAF targets [1]	ReFuelEU Aviation Synfuel target [1]
2025	2 % (≈ 1 Mt/a)	
2030	6 % (≈ 3.8 Mt/a)	0.7 % (≈ 0.4 Mt/a)
2035	20 % (≈ 13 Mt/a)	5 % (≈ 3.3 Mt/a)
2050	70 % (≈ 54 Mt/a)	35 % (≈ 27 Mt/a)

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

[1] https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector
[2] https://www.concawe.eu/wp-content/uploads/Rpt_21-2.pdf/

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Preference palm oil?
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)

EUROPEAN COMMISSION

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

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

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CONCLUSION & OUTLOOK

Assessment of technologies and import options for SAF

Summary

- SAF feasible today and required for Europe's climate obligations
  - REGULATION will end fossil fuels utilization
- European refineries can largely produce SAF locally
  - utilizing biomass residues ➔ BtL quick start
  - & investing in renewable power ➔ PBtL large scale rollout
- Expose any excuses for SAF deployment delay
  - PtX research, development, demonstration: reinventing the wheel?
  - All technologies mature and available

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FUELS OF THE FUTURE

DLR

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Transparent, standardized DLR assessment methodology offers

➔Site specific feedstock search, technology selection, refinery integration, …!

➔Policy support: JUST DO IT!

Tuesday, 23. January 2024

Session 6C:

Biofuels and renewable fuels in aviation

FUELS OF THE FUTURE

THANK YOU FOR YOUR ATTENTION !

QUESTIONS?

Assessment of technologies and import options for sustainable aviation fuels (SAF)

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

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