Thursday, 26. October 2023

Session FOUR PART ONE: Alternative fuels; CCU and E-Fuels

European Carbon Dioxide Utilisation Summit 2023

Hamburg, Germany

25th–26th October 2023

OPPORTUNITIES AND CHALLENGES FOR ELECTRO-FUELS IN FUTURE AVIATION

Technical, economic and ecological assessment
of European sustainable aviation fuels (SAF) production

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

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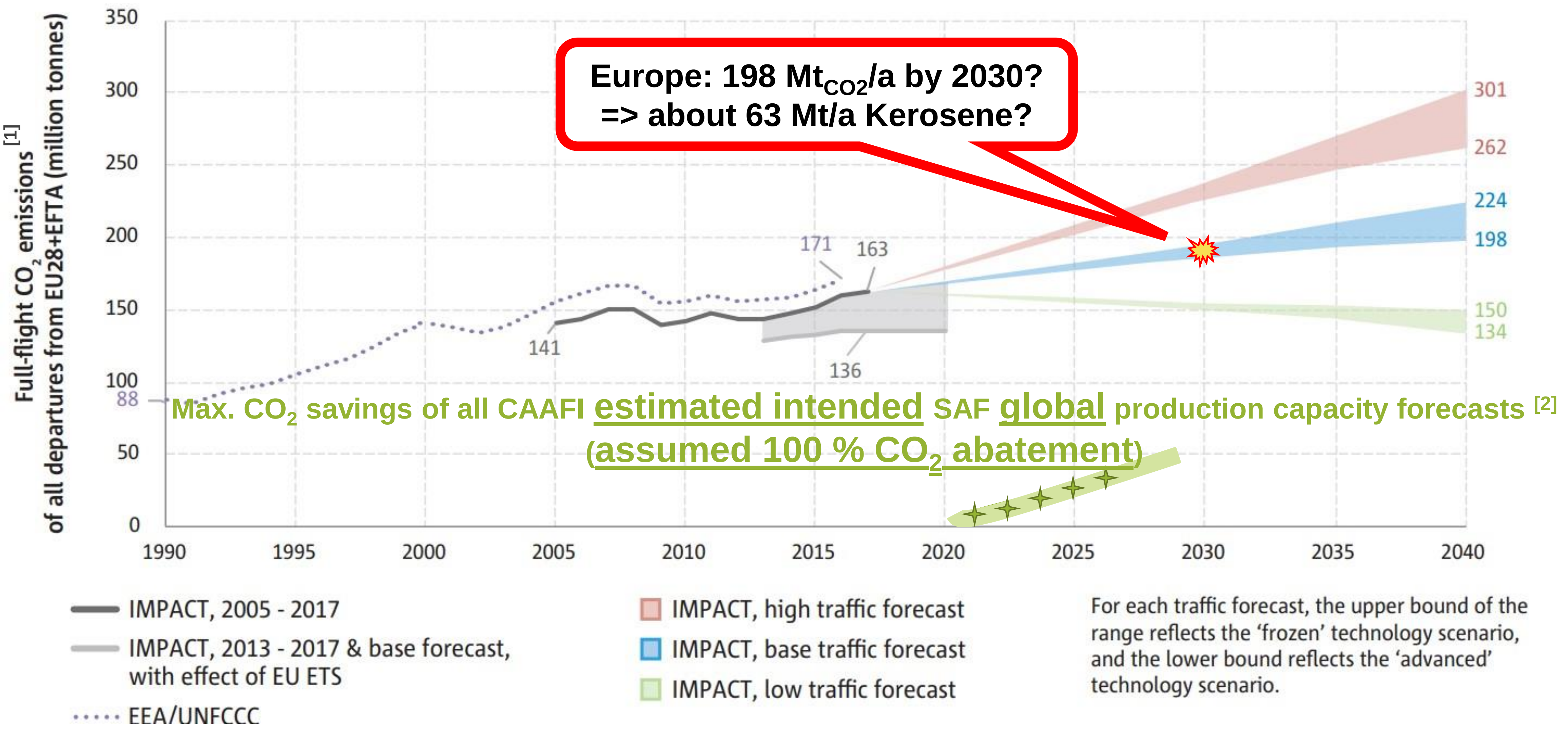
Opportunities and challenges for electro-fuels in future aviation - Agenda

1. SAF options and activities
2. Need for techno-economic assessment and life cycle analysis
3. Examples of
   1. Technical assessment
   2. Economical assessment
   3. Ecological assessment
4. Towards a European SAF roadmap
5. Proof of technological readiness
6. The Ambitious SAF deployment plan (Optimistic way forward, personal view)
7. Conclusion and outlook

SAF deployment too slow for significant CO_2 abatement



[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.

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

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Additional alg… percentage c… botryococcen…		…ons, …HEFA)
Biogenic lipi…		… Jet
Sugar from E…		…IP)
Bio-isobutanol (+methanol, +ethanol, +propanol, …)	…dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AtJ-SPK

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 concepts / options / configurations / locations / …

Feedstock availability towards 63 Mt/a

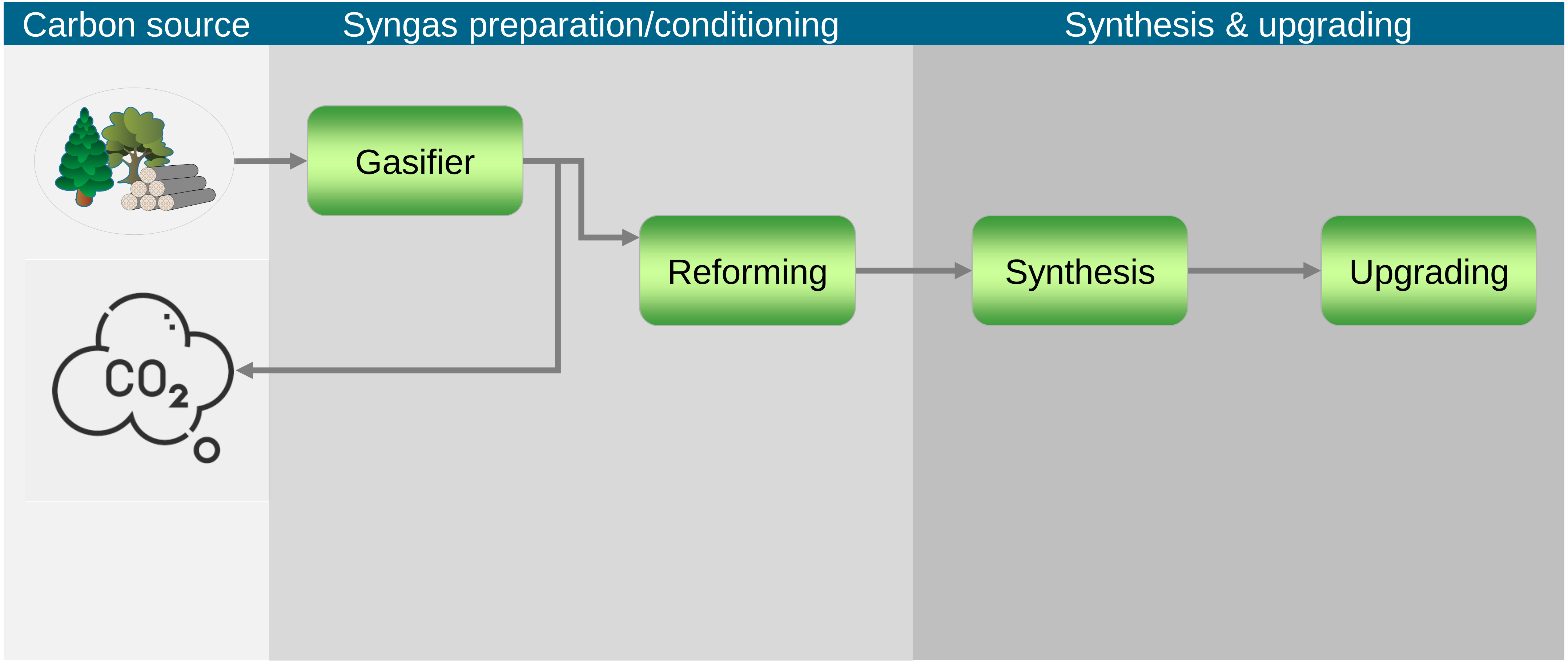
Feedstock	Synthesis technology	Fuel
~~Coal, natural gas~~, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis using Fe or Co catalyst,	Synthetic paraffinic kerosene (FT-SPK)

- Feedstock
  - SAF via the Fischer-Tropsch pathway not restricted to certain feedstocks
  - Synthesis gas available from almost any carbon and hydrogen source ➔ Sustainability?
    - Sustainable Hydrogen via RE: European wind power potential[1]: 12,200 – 30,400 TWh_e ≈ 10 - 20 times of SAF demand!
    - Sustainable Carbon: carbon sequestration in European forest biomass[2]: 155 Mt/a ≈ 3 times of SAF demand!
- Fischer-Tropsch 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 [2]

[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

3 generic Fischer-Tropsch based Sustainable Aviation Fuels (SAF) concepts

Biomass-to-Liquid



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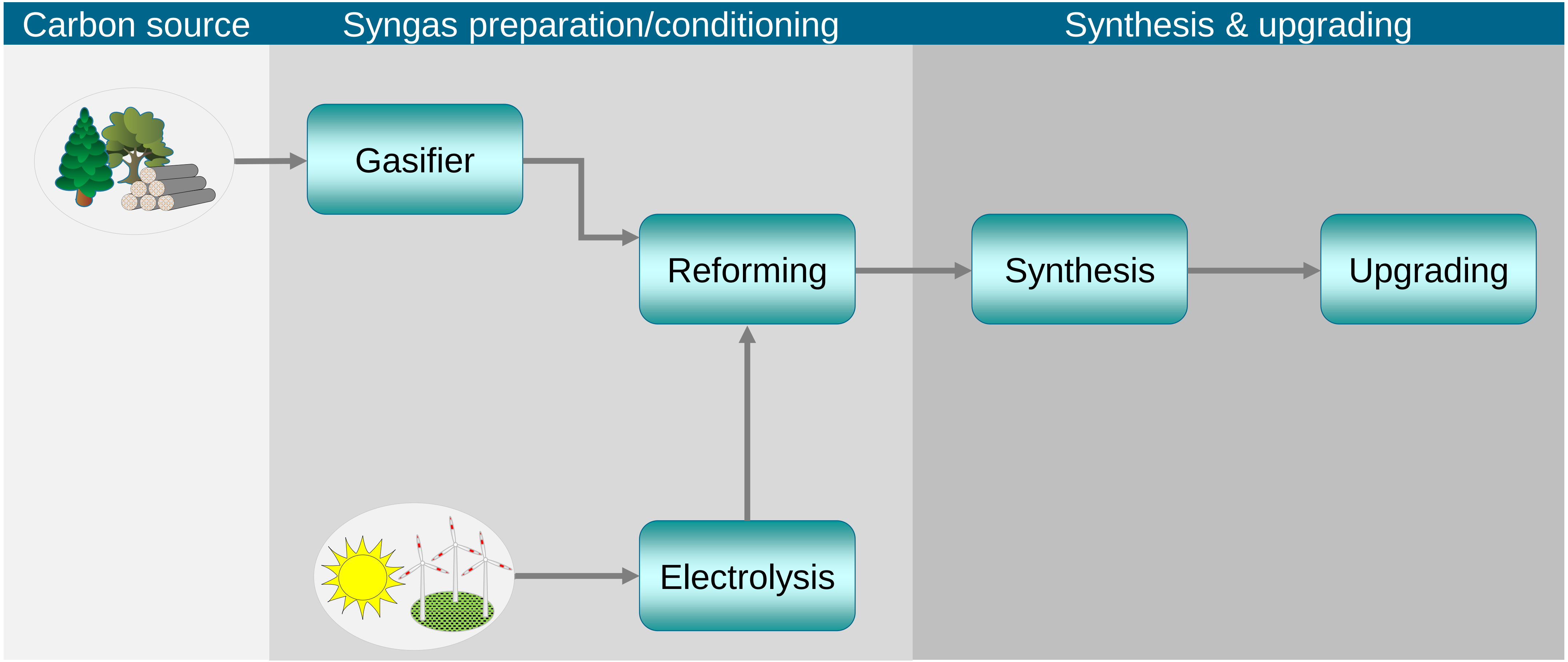
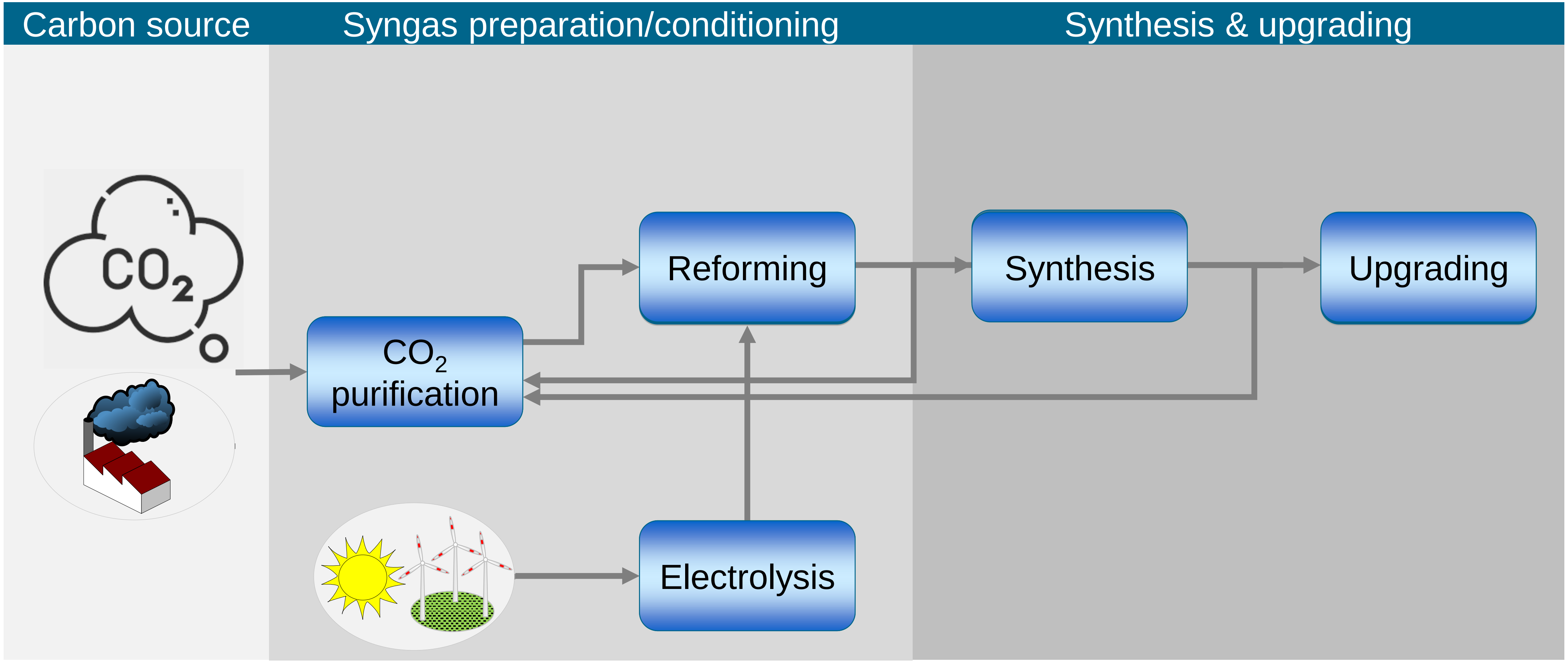
Power&Biomass-to-Liquid



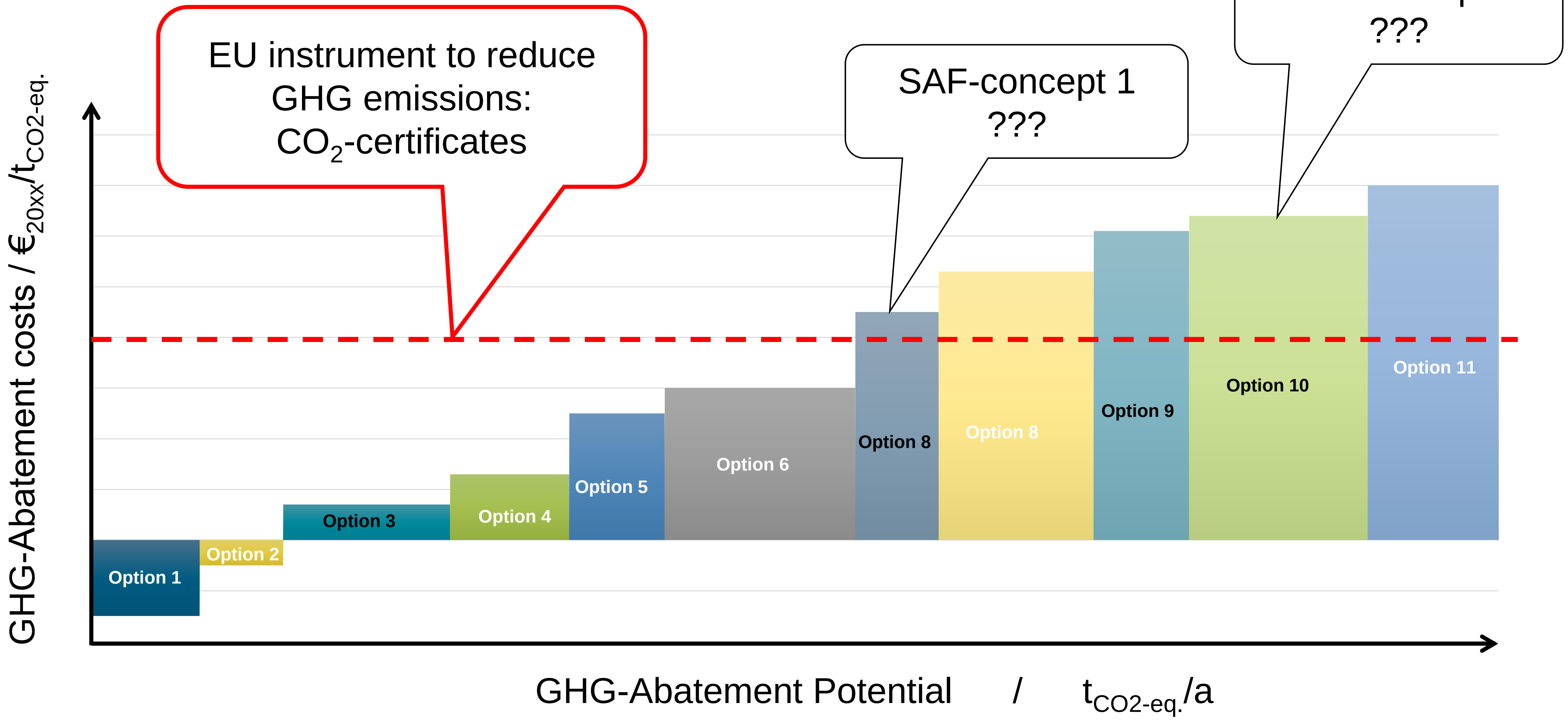
3 generic Fischer-Tropsch based Sustainable Aviation Fuels (SAF) concepts

Power-to-Liquid



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

Merit-Order of GHG reduction technologies



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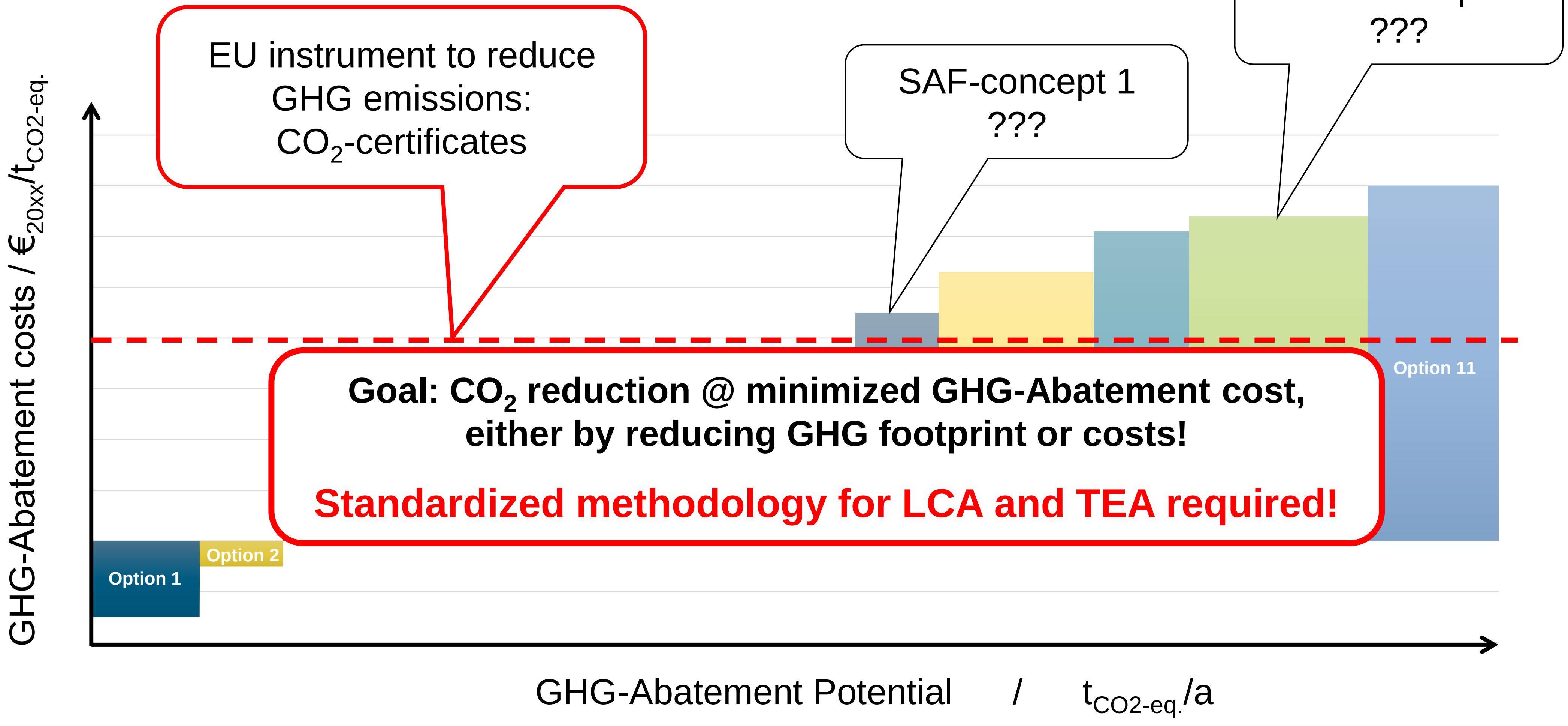
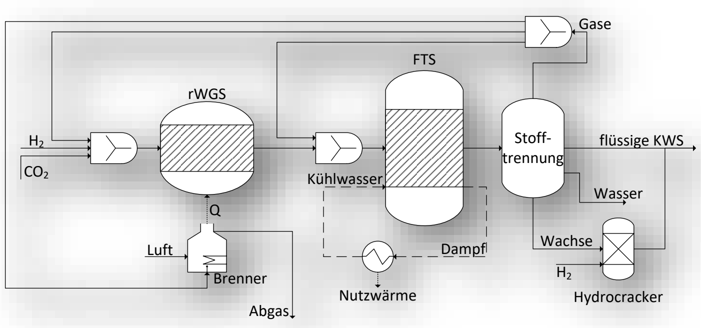
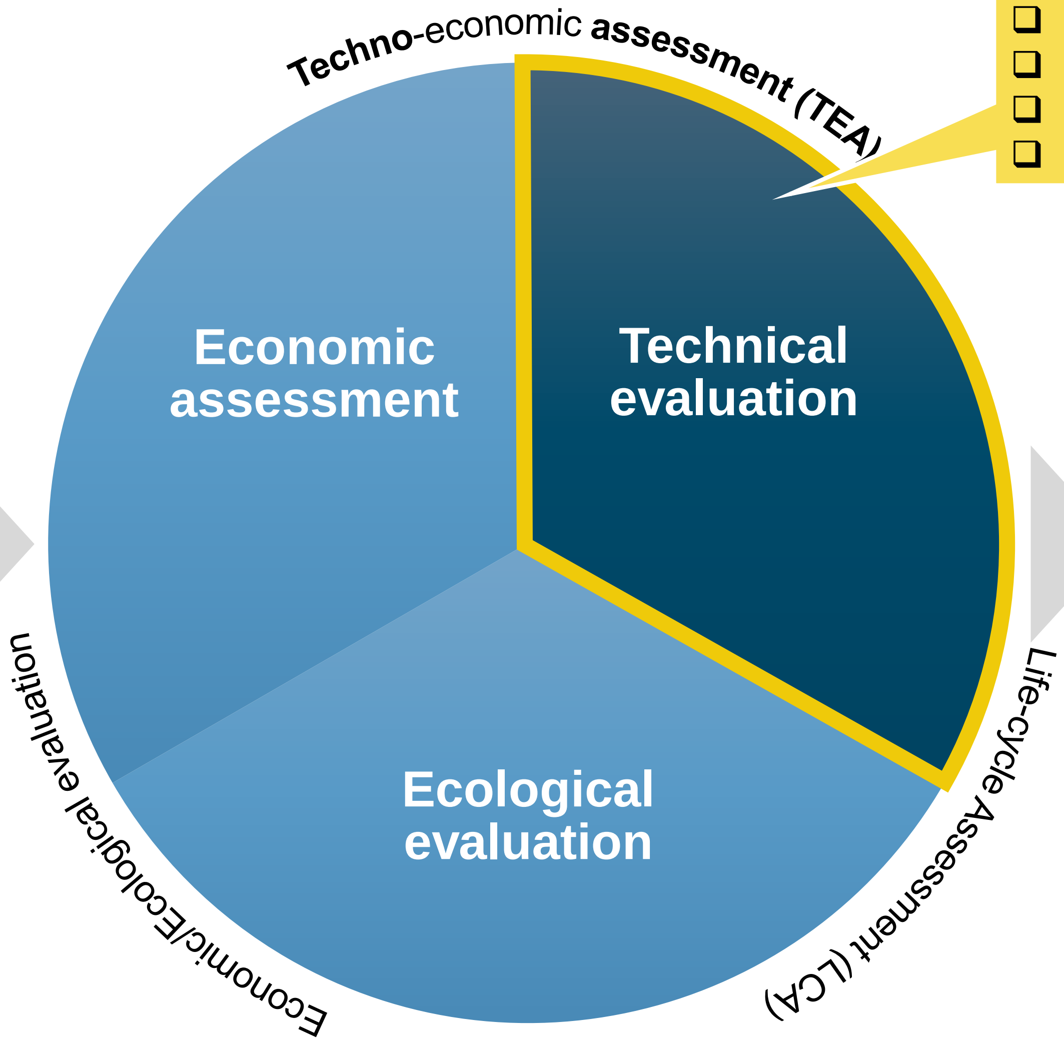
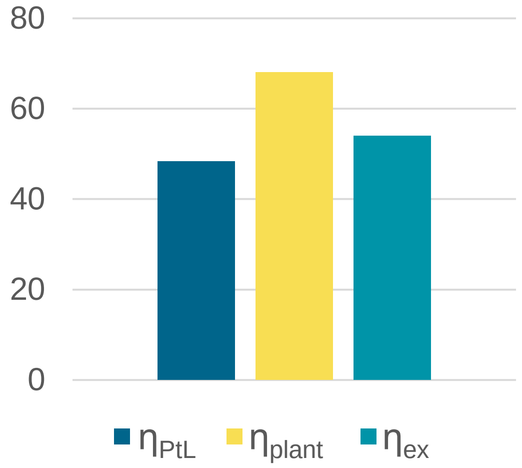


Techno-Economic and Ecological Assessment
TEEA





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



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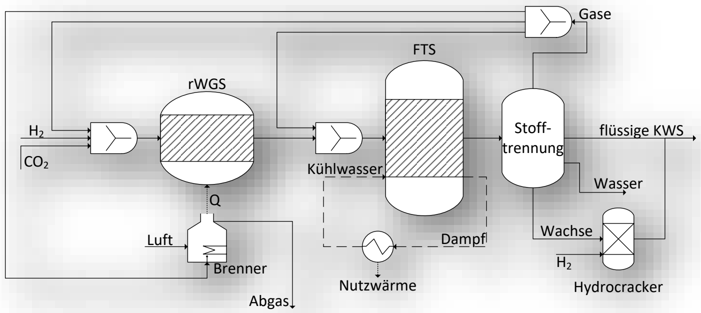

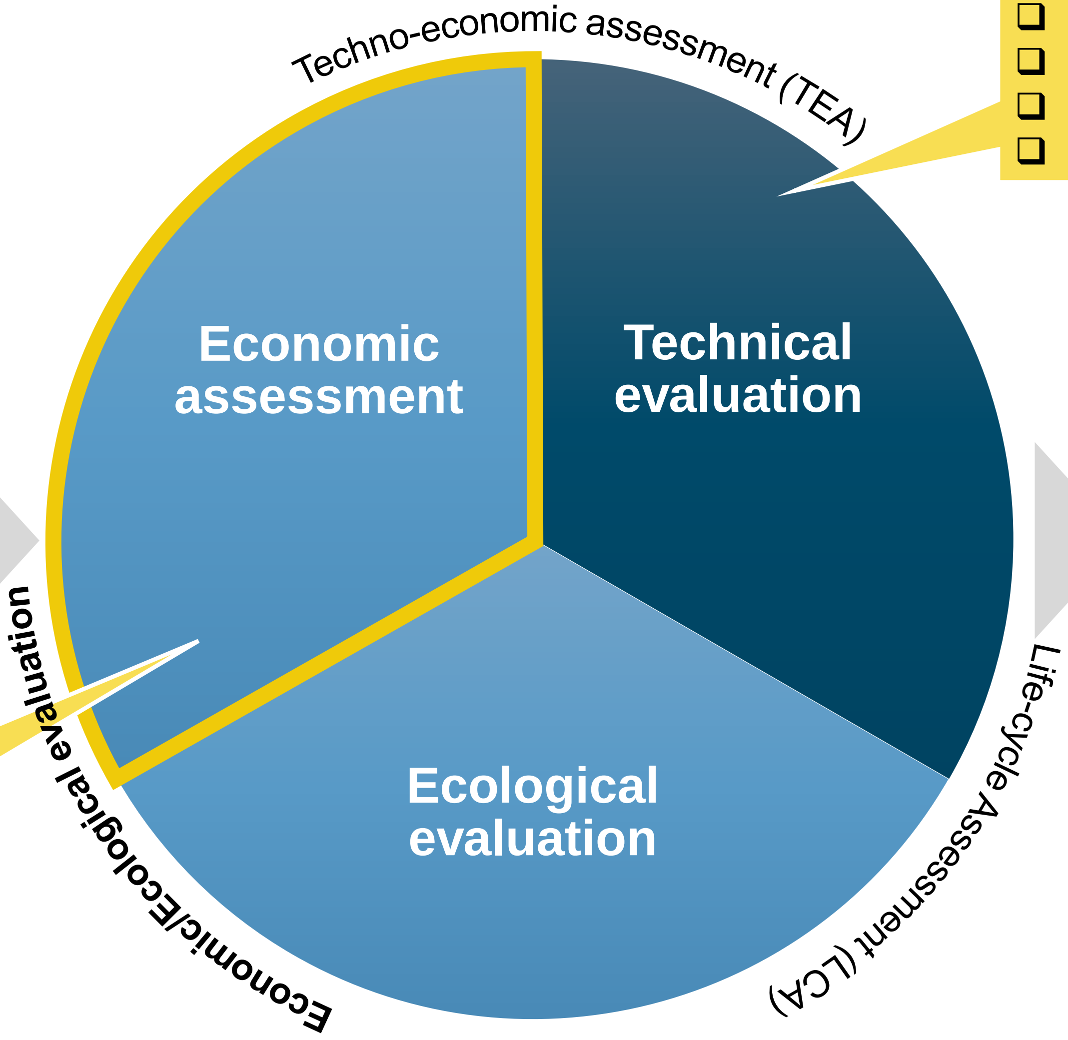

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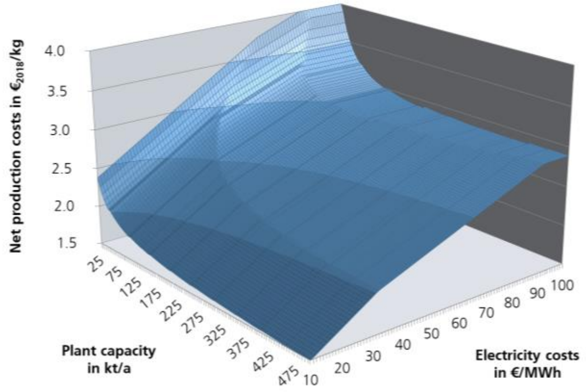

- ❑ CAPEX, OPEX, NPC
- ❑ Sensitivity analysis
- ❑ Identification of most economic feasible process design

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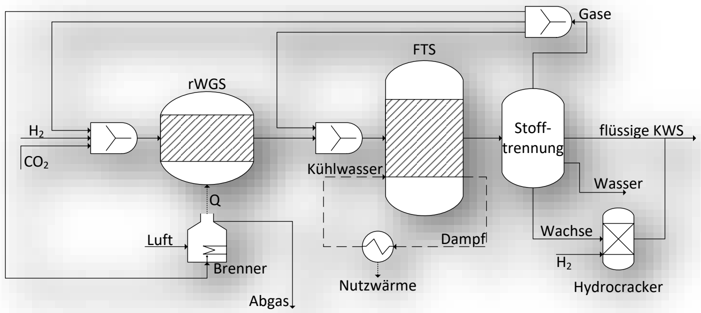

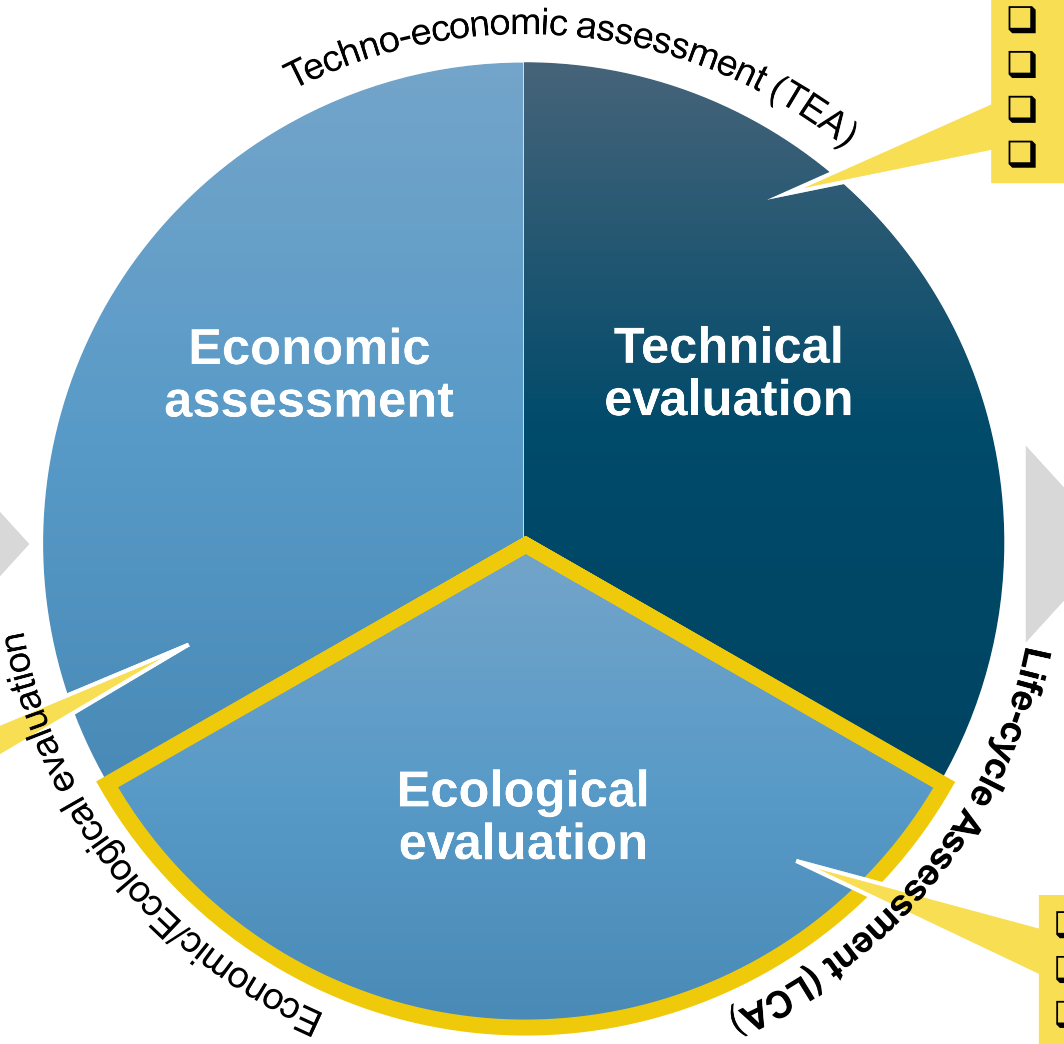

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- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

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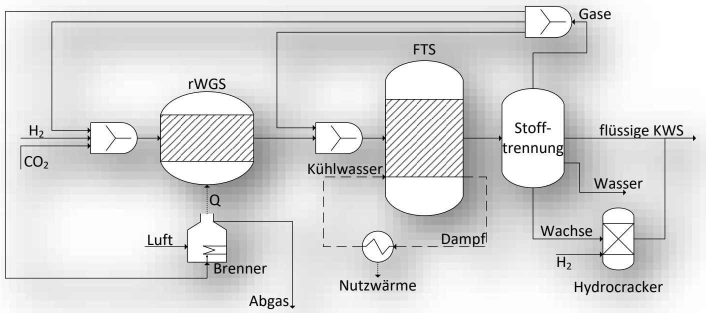

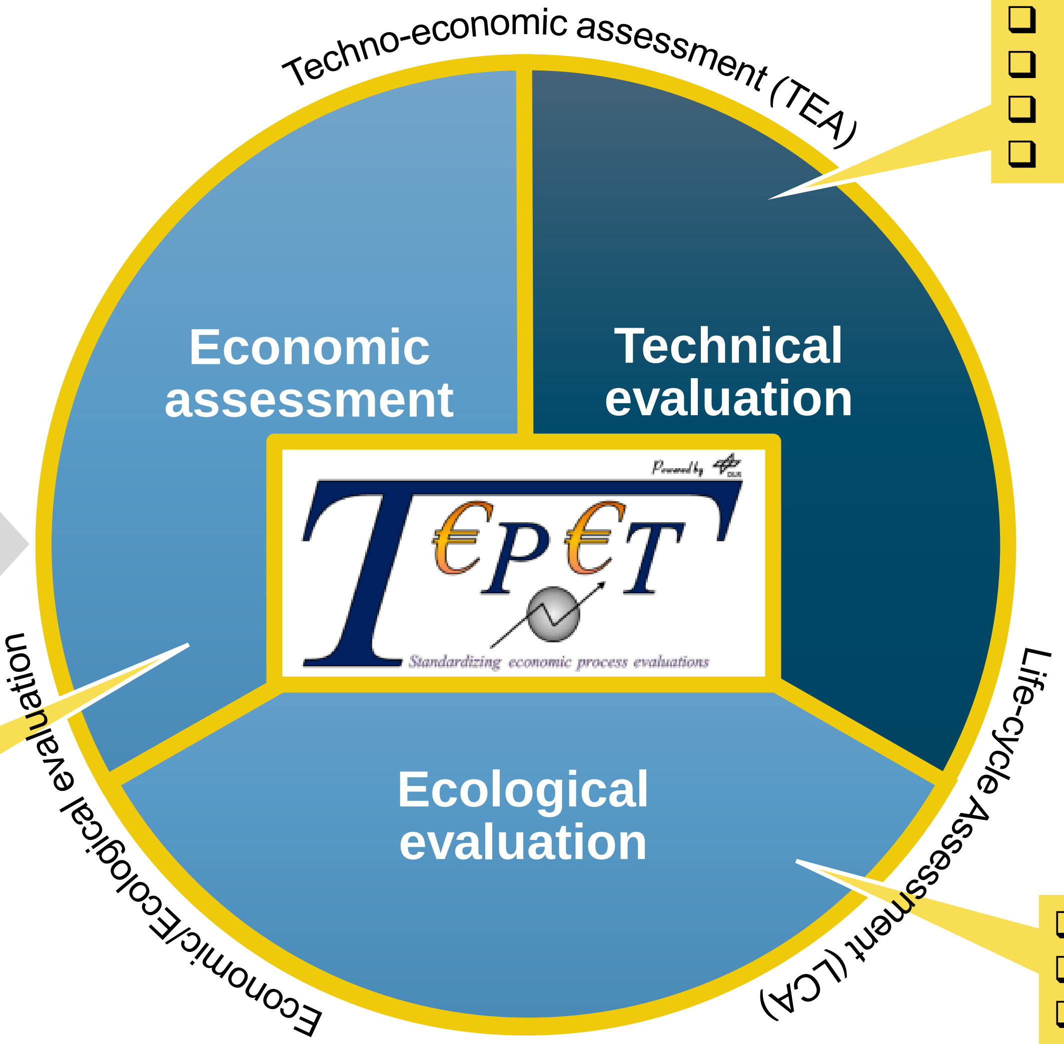

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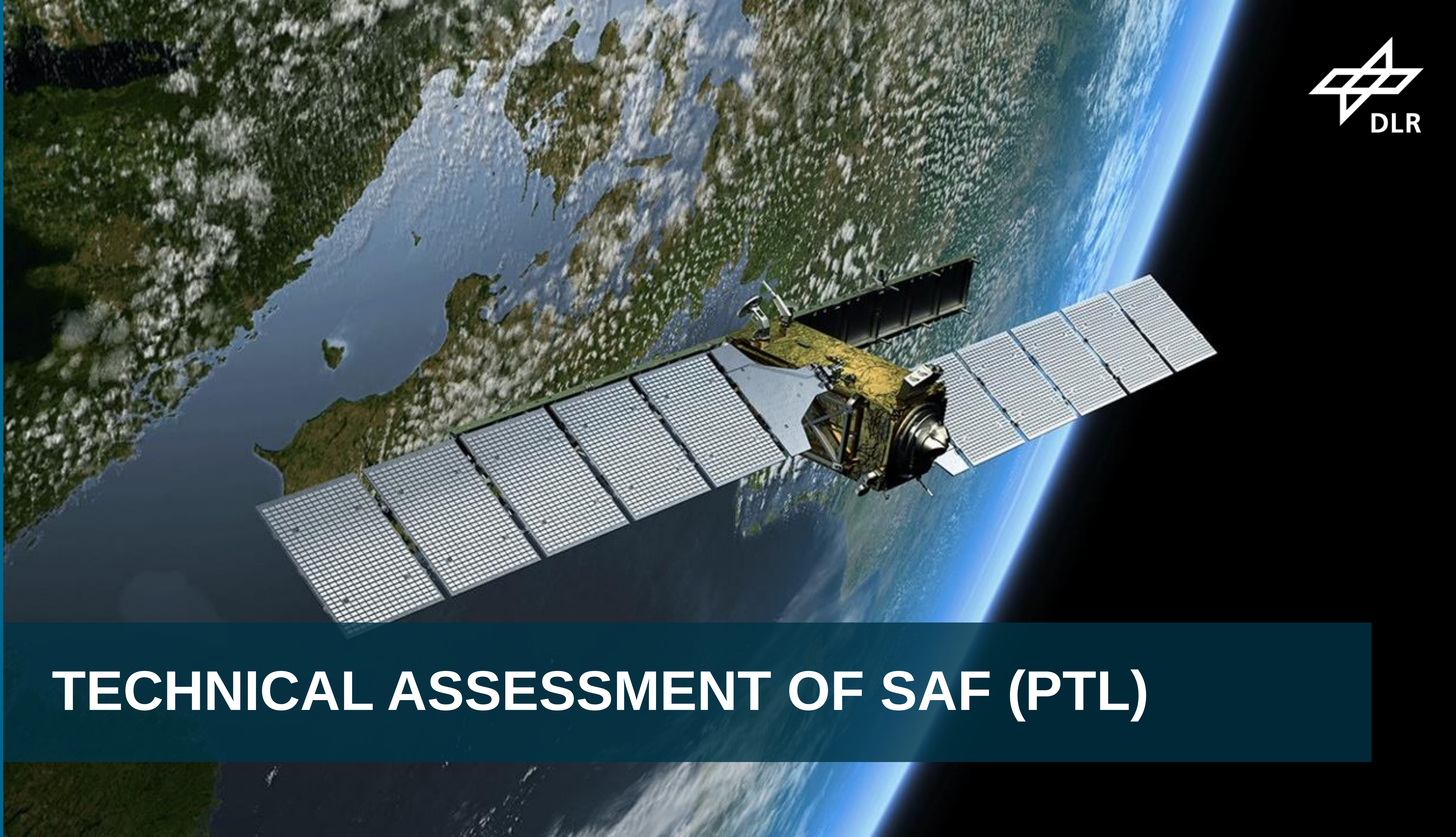
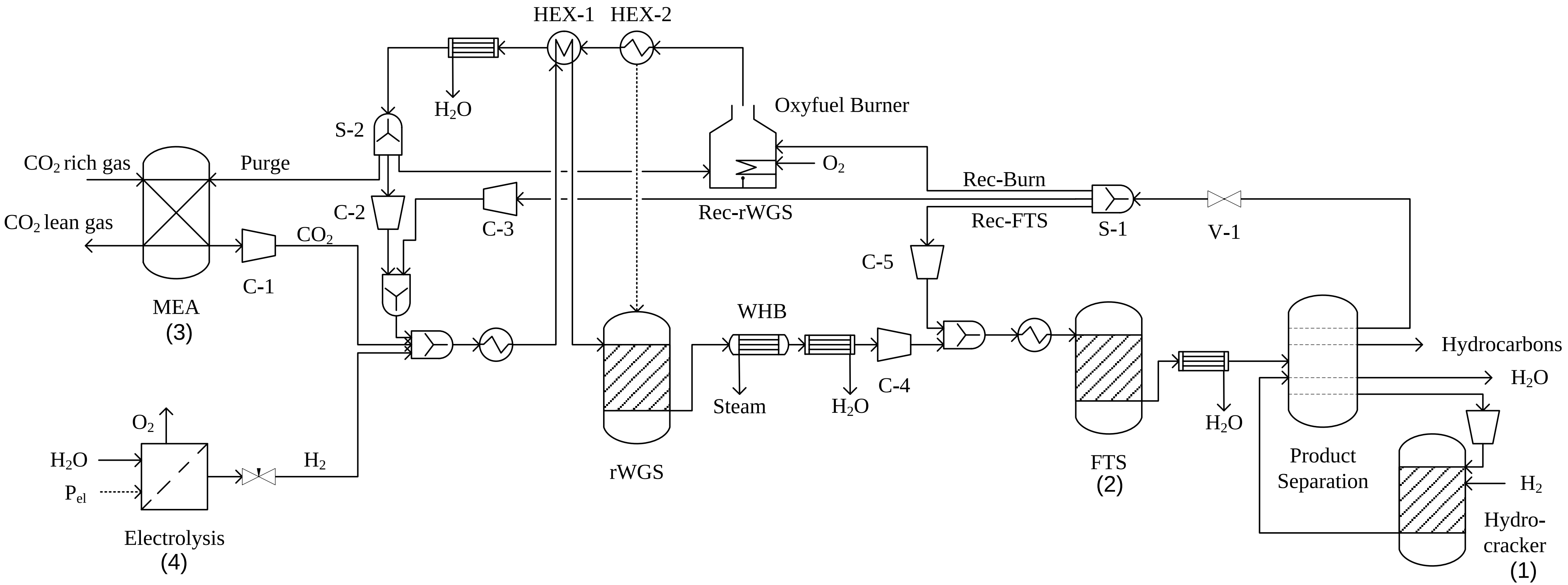


TECHNICAL ASSESSMENT OF SAF (PTL)

Technical Assessment: Power-to-Liquid

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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(5) Adelung and Dietrich, R.-U. (2022). Impact of the reverse water-gas shift operating conditions on the Power-to-Liquid process efficiency

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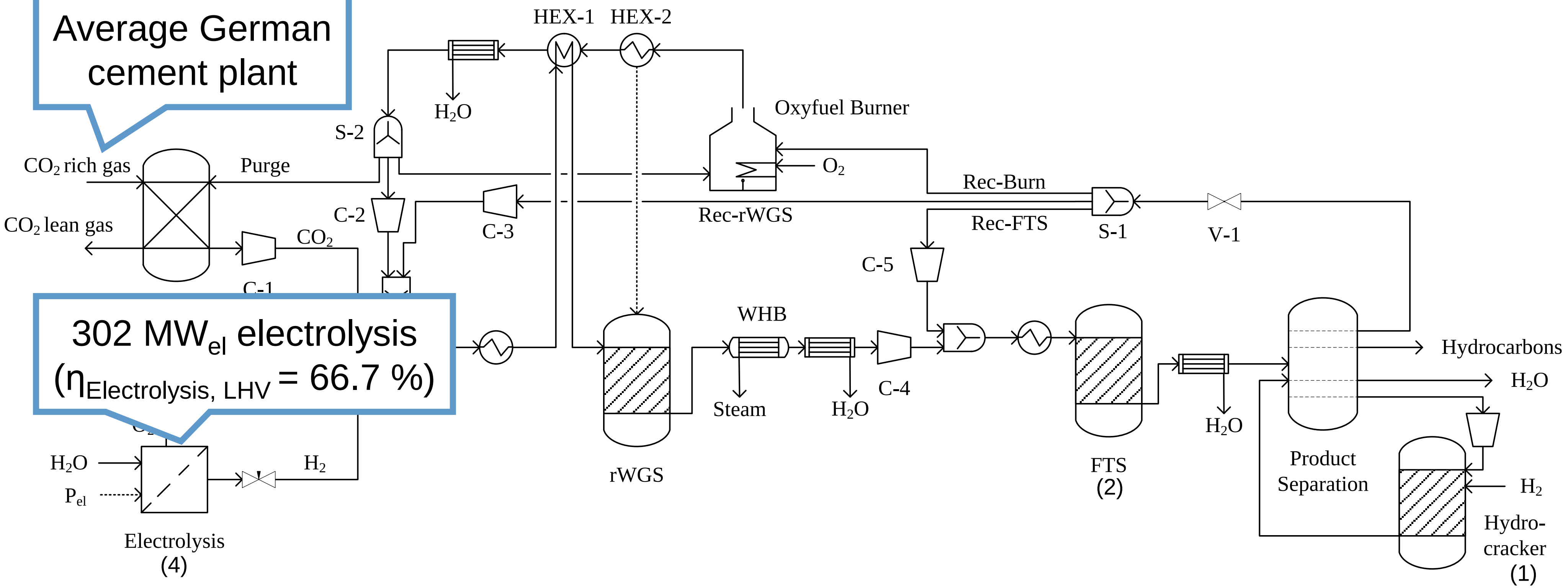
Technical Assessment: Power-to-Liquid

Methodology: Experimentally validated flowsheet [5]

Average German cement plant

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



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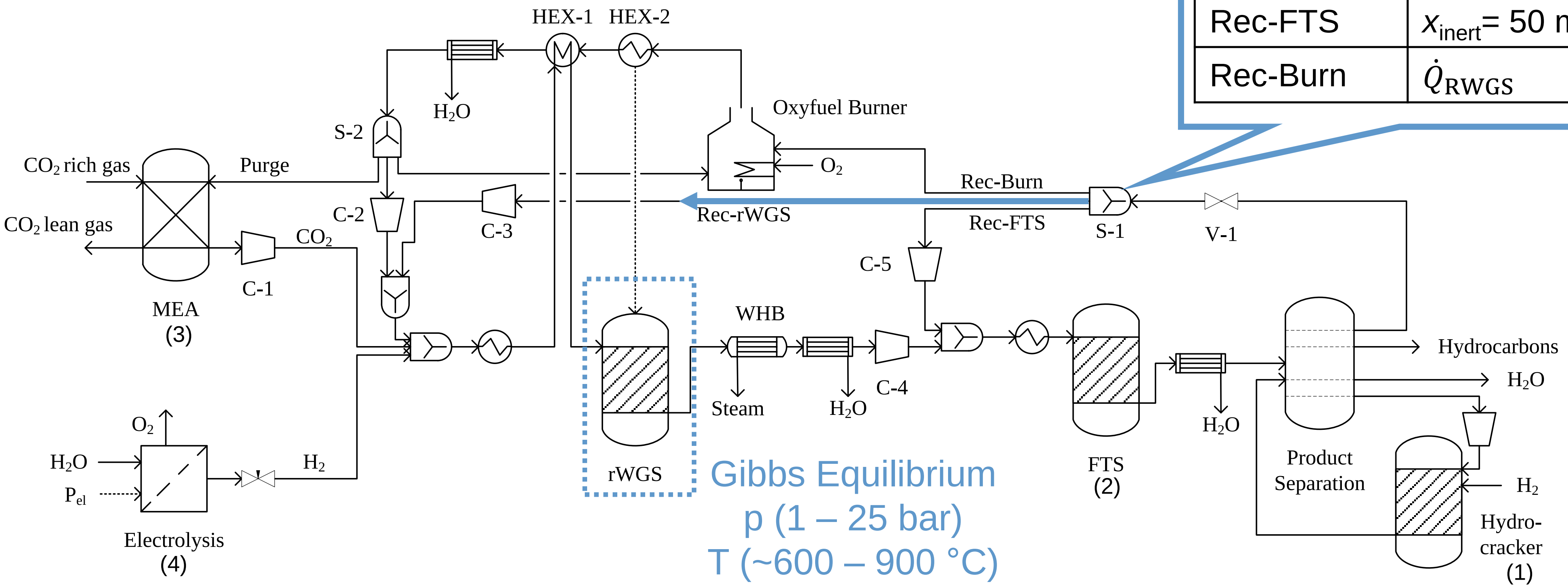
Technical Assessment: Power-to-Liquid

Methodology: Experimentally validated flowsheet [5]

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



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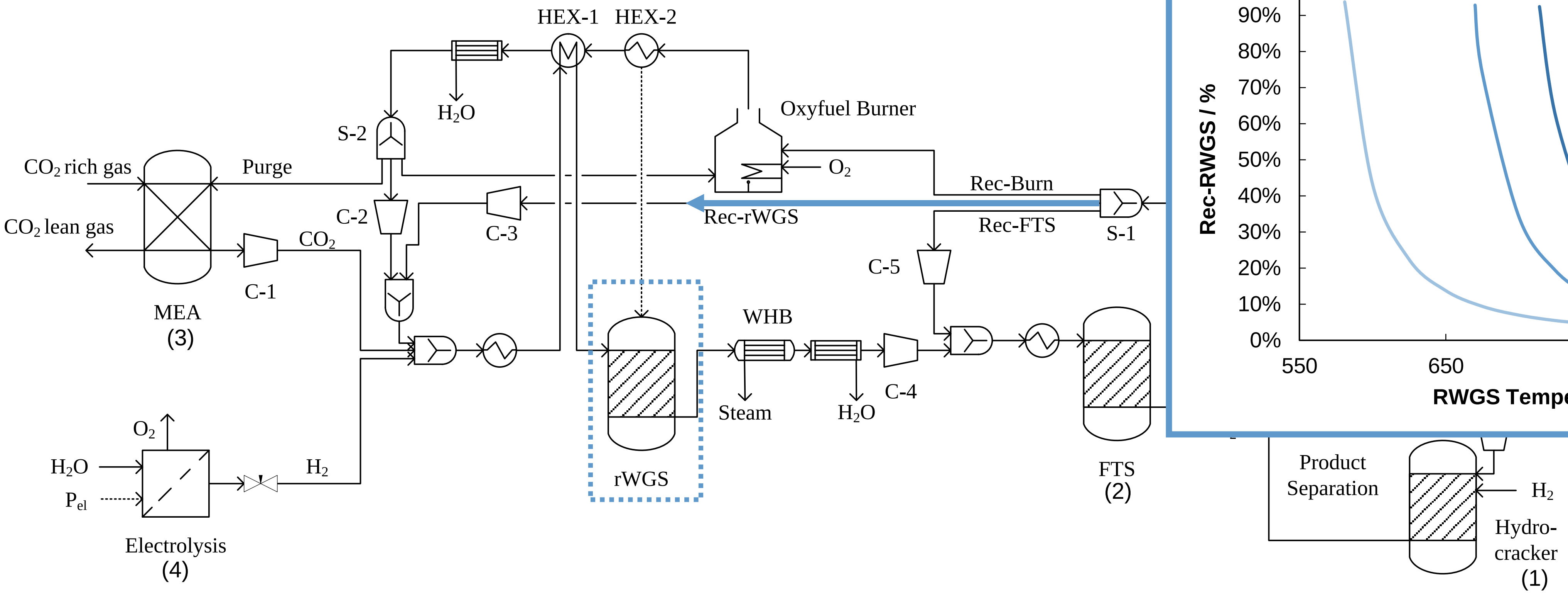

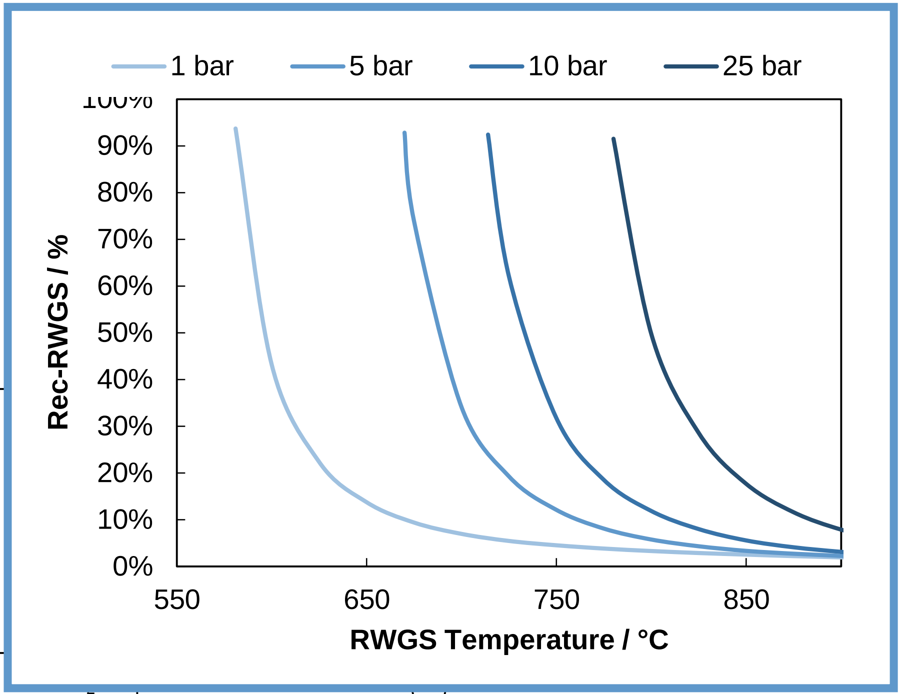

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Technical Assessment: Power-to-Liquid

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Process Parameter dependent Material / Energy Efficiency (5)

■ = Highest efficiency

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

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

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

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

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

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.*

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 \ 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

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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

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Economical Assessment: Power-to-Liquid

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= lower NPC

H_2-Input: 2.3 €/kg$_{H2}$

RWGS Temperature / °C	RWGS pressure 1 bar	5 bar	10 bar	25 bar
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 1 bar	5 bar	10 bar	25 bar
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 1 bar	5 bar	10 bar	25 bar
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

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

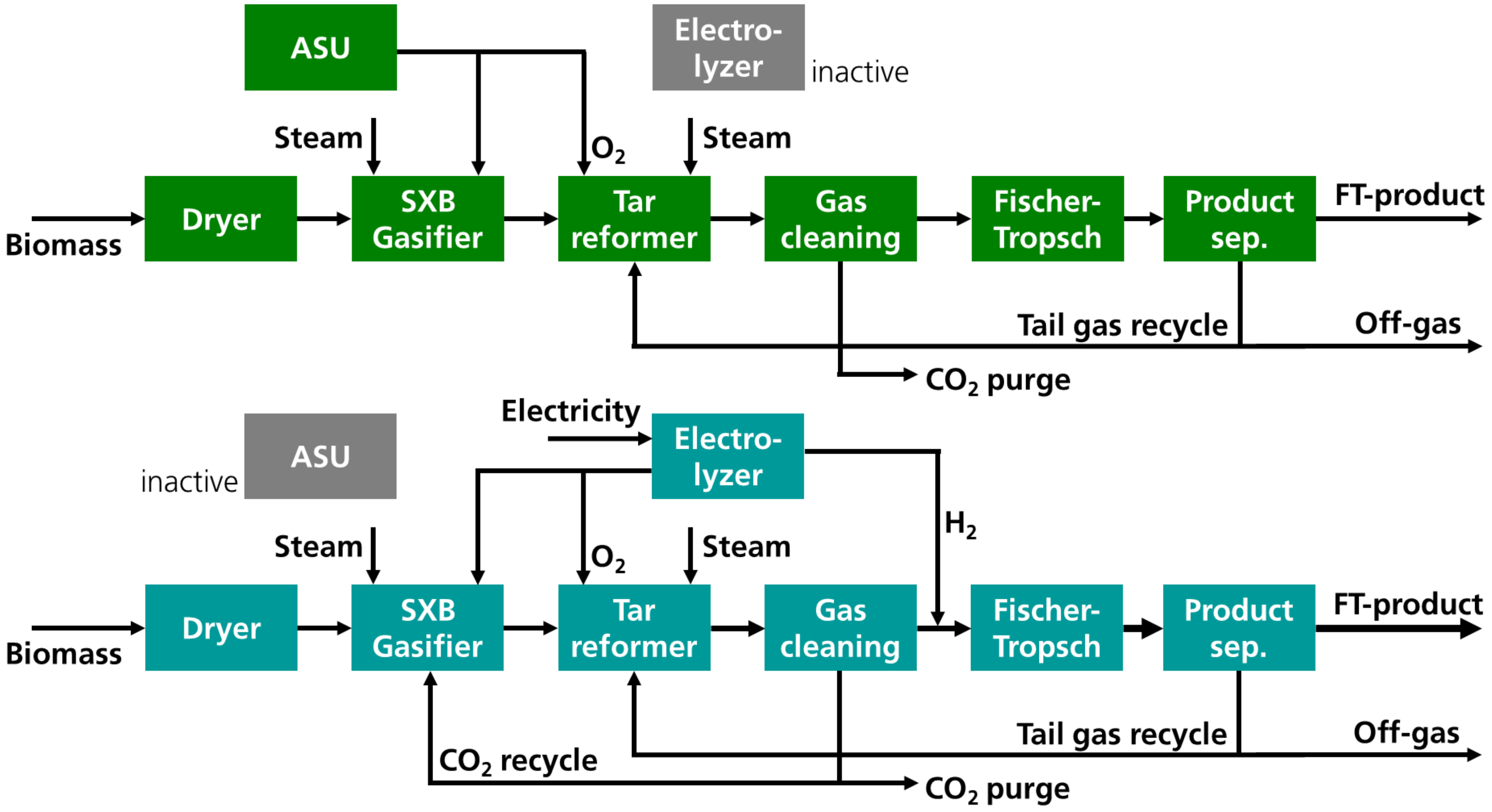
[1]Adelung, S. and Dietrich, R.-U. (2022). Impact of the reverse water-gas shift operating conditions on the Power-to-Liquid fuel production cost. *Fuel.*

ENVIRONMENTAL ASSESSMENT OF SAF (PBTL)

Environmental Assessment of Biomass-to-Liquid versus Power&Biomass-to-Liquid Application

Dual configuration concept [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 (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

Environmental Assessment of Biomass-to-Liquid versus Power&Biomass-to-Liquid Application

Global Warming Potential (GWP) [1]

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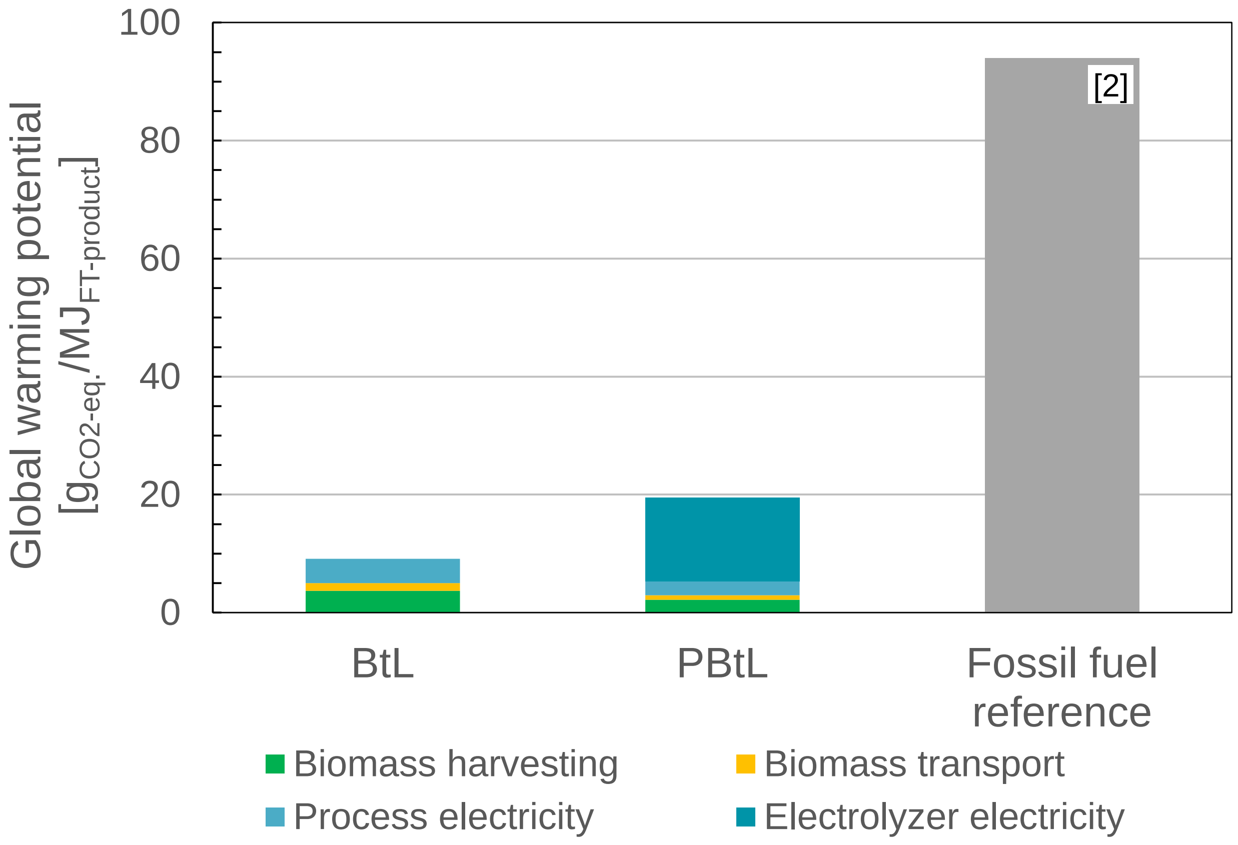

- **Transportation: 100 km (one-way) by truck (69 $g_{CO2\text{-}eq.}$/(t*km))**
- **Biomass: Harvesting forest residues (19.7 $g_{CO2\text{-}eq.}$/kg)**
- **Electricity: Finnish wind energy (68.6 $g_{CO2\text{-}eq.}$/kWh)**

[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
[2] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

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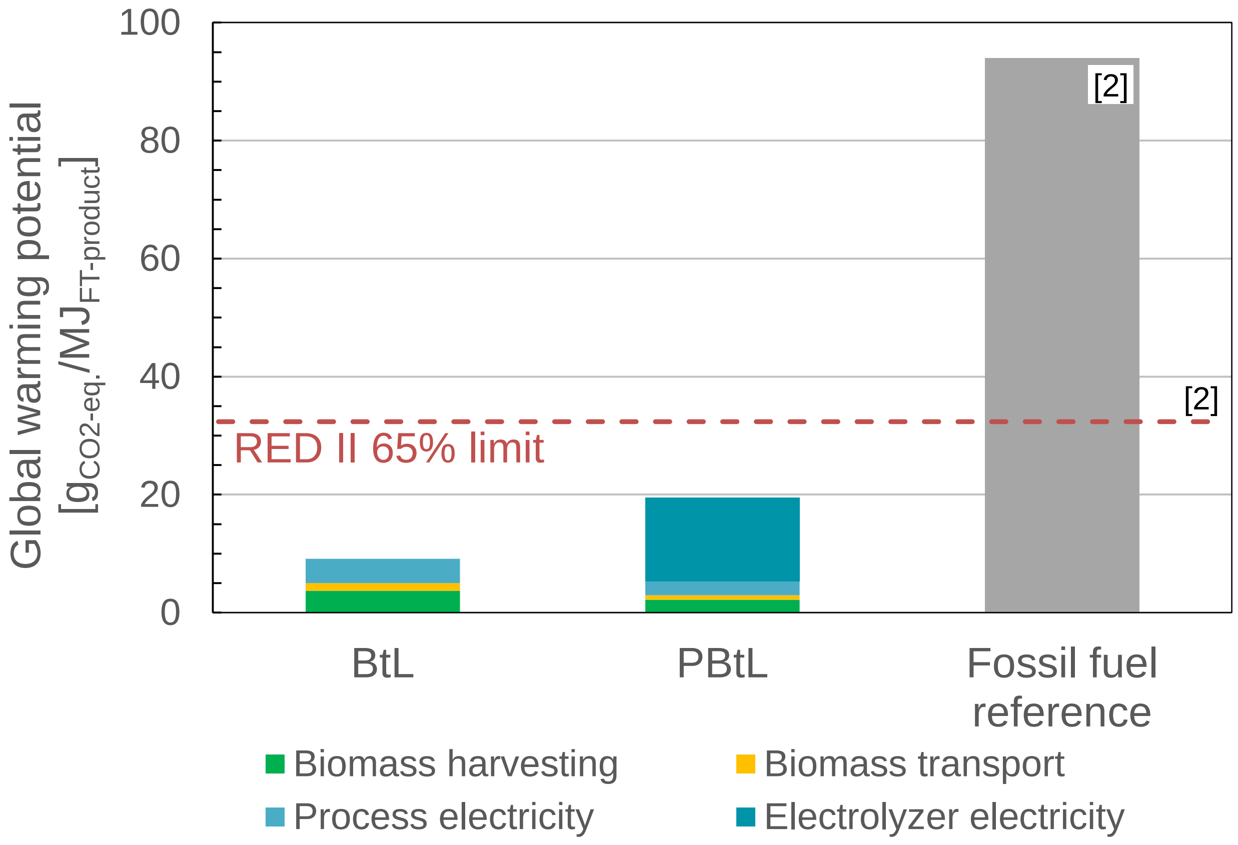

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- **Biomass: Harvesting forest residues (19.7 $g_{CO2\text{-}eq.}$/kg)**
- **Electricity: Finnish wind energy (68.6 $g_{CO2\text{-}eq.}$/kWh)**

Conclusion

REDII target accomplished @ FLEXCHX base case

[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
[2] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

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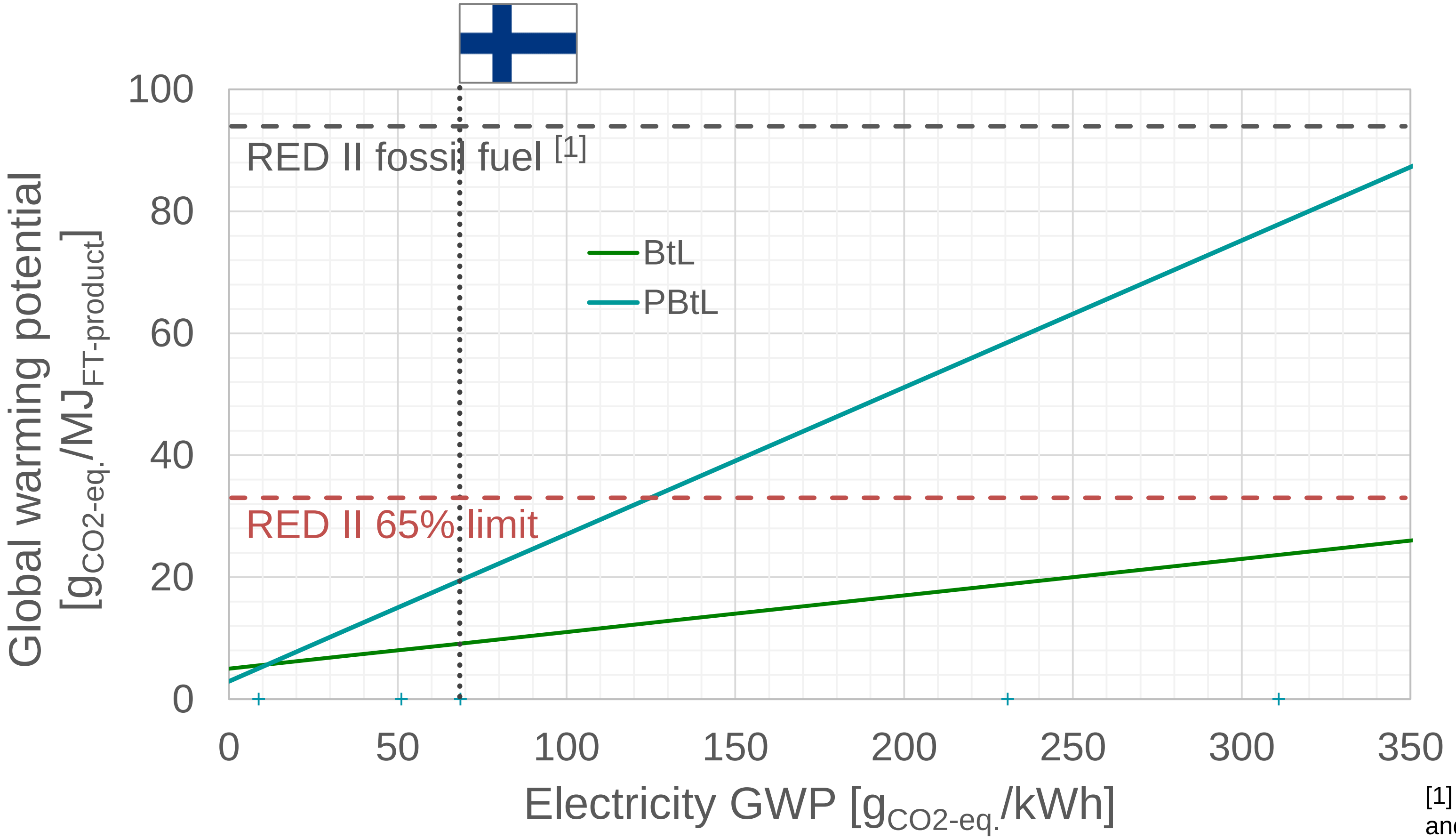

- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL

[1] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union

Environmental Assessment of Biomass-to-Liquid versus Power&Biomass-to-Liquid Application

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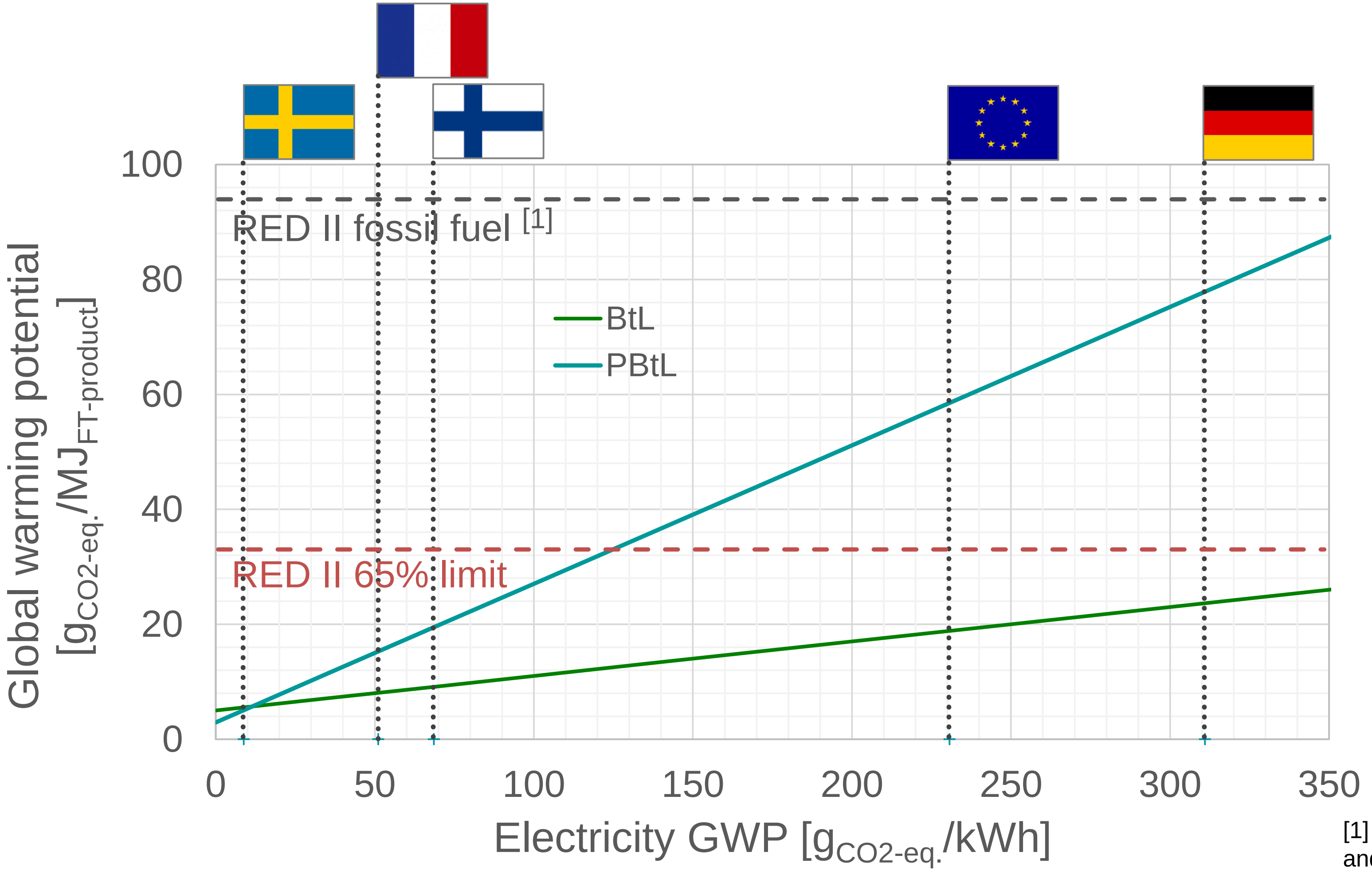
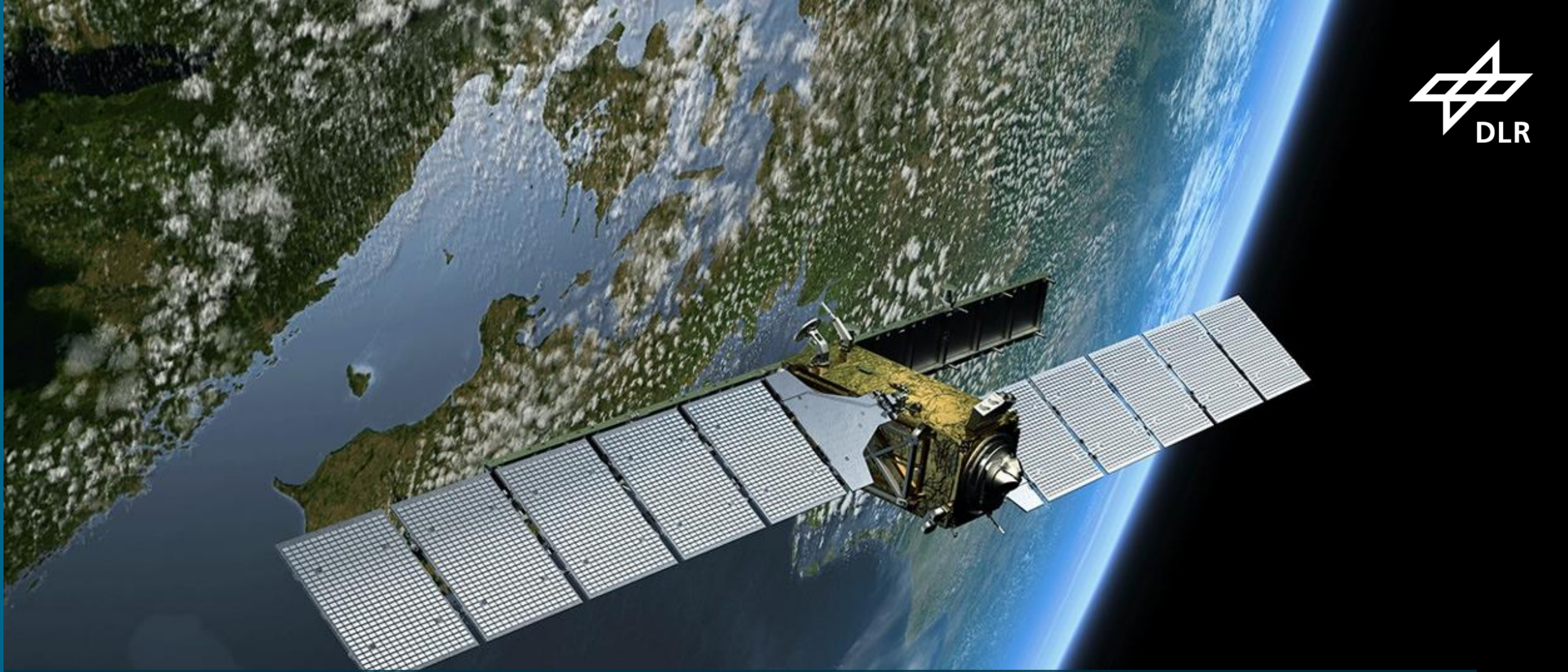


- REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- PBtL requires electricity with GWP <120 $g_{CO2\text{-}eq.}$/kWh to reach REDII 65 % limit
- PBtL could have lower GWP than BtL with Swedish grid mix

[1] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union



TOWARDS A EUROPEAN SAF ROADMAP

Fischer-Tropsch based SAF concepts
Stochiometric preference

Power-to-Liquid

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

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

Biomass-to-Liquid

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

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

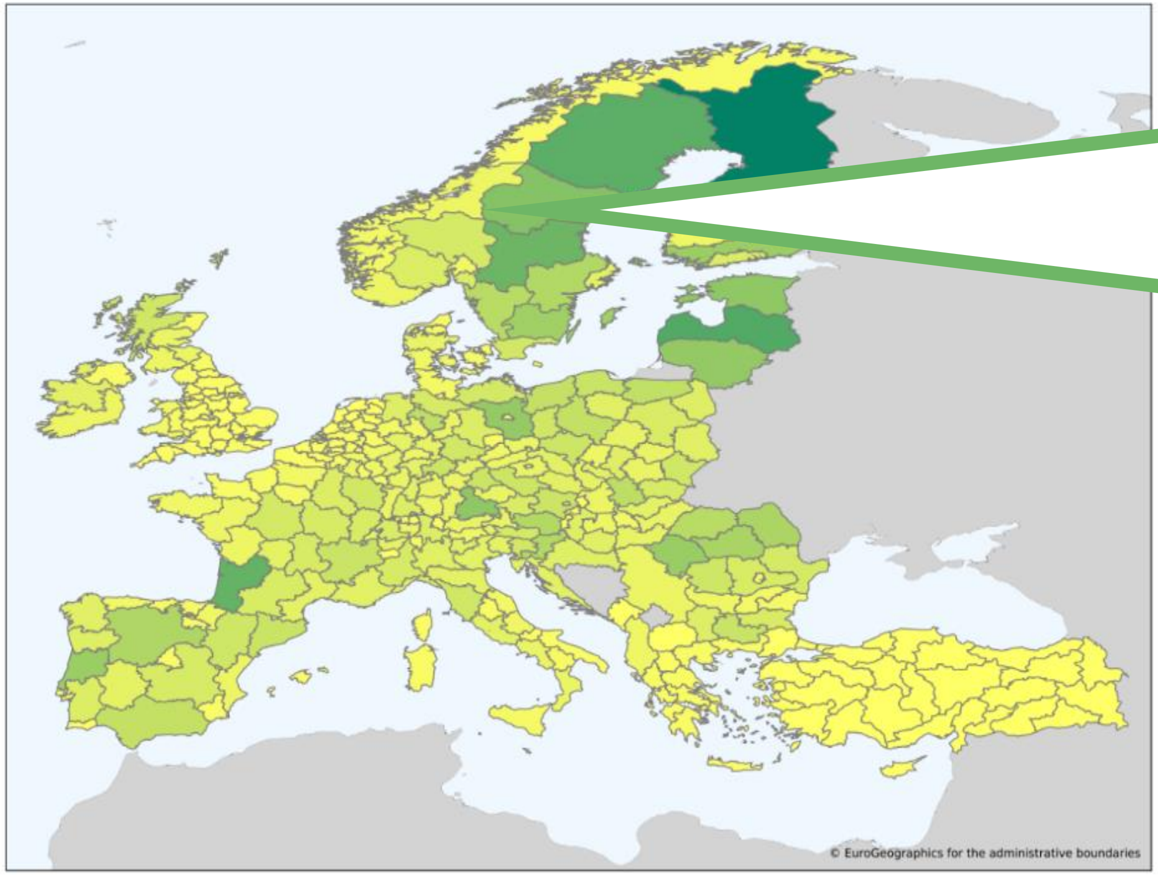
Power&Biomass-to-Liquid

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

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

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

PBtL potential analysis for Europe
Finding the sweet spots



NUTS2 region specific conditions:

Economic

- National electricity prices [1]
- Biomass prices [2]
- Transport distance = f(biomass density)
- Nation-specific transport, labor costs

Ecological

- 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]
.

Average PBtL plant for European SAF

Key economic Assumptions

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

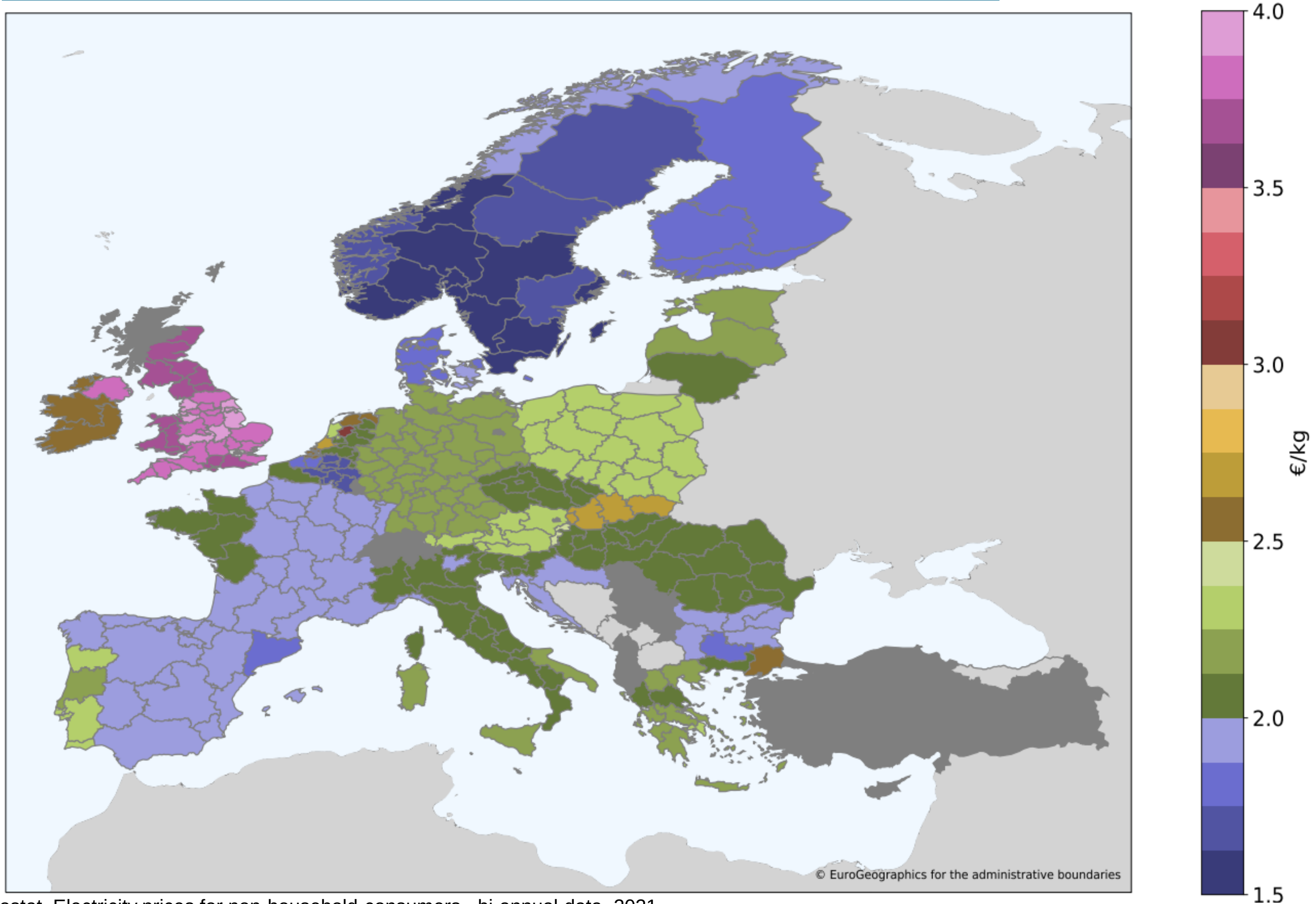
General economic assumptions:

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

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

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 fuel

[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). ENSPRESO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, *26*, 100379.

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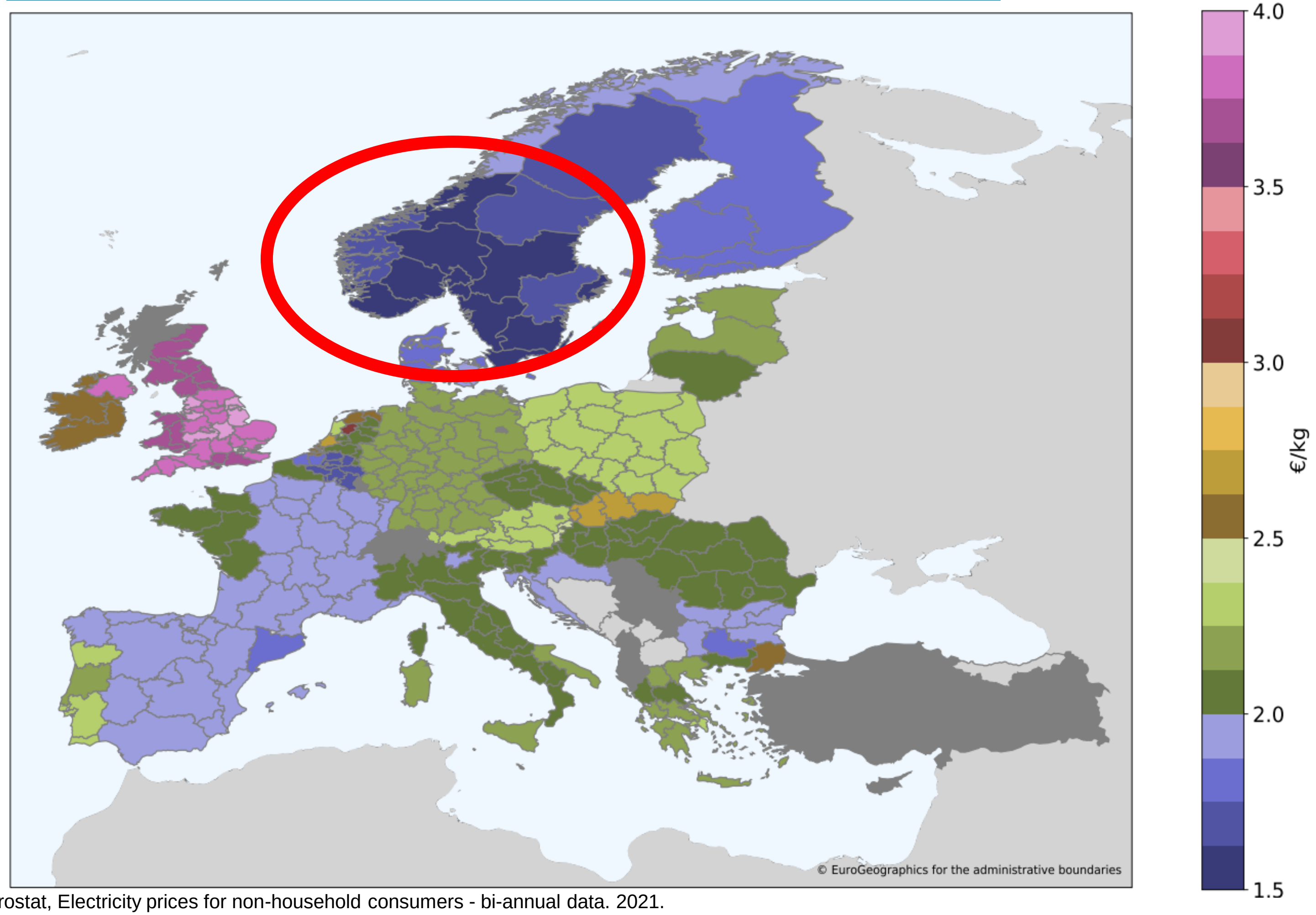


Standard PBtL plant

- 900 MW_e Electrolyzer
- 400 MW_{th} CFB gasifier
- 400 kt/a fuel

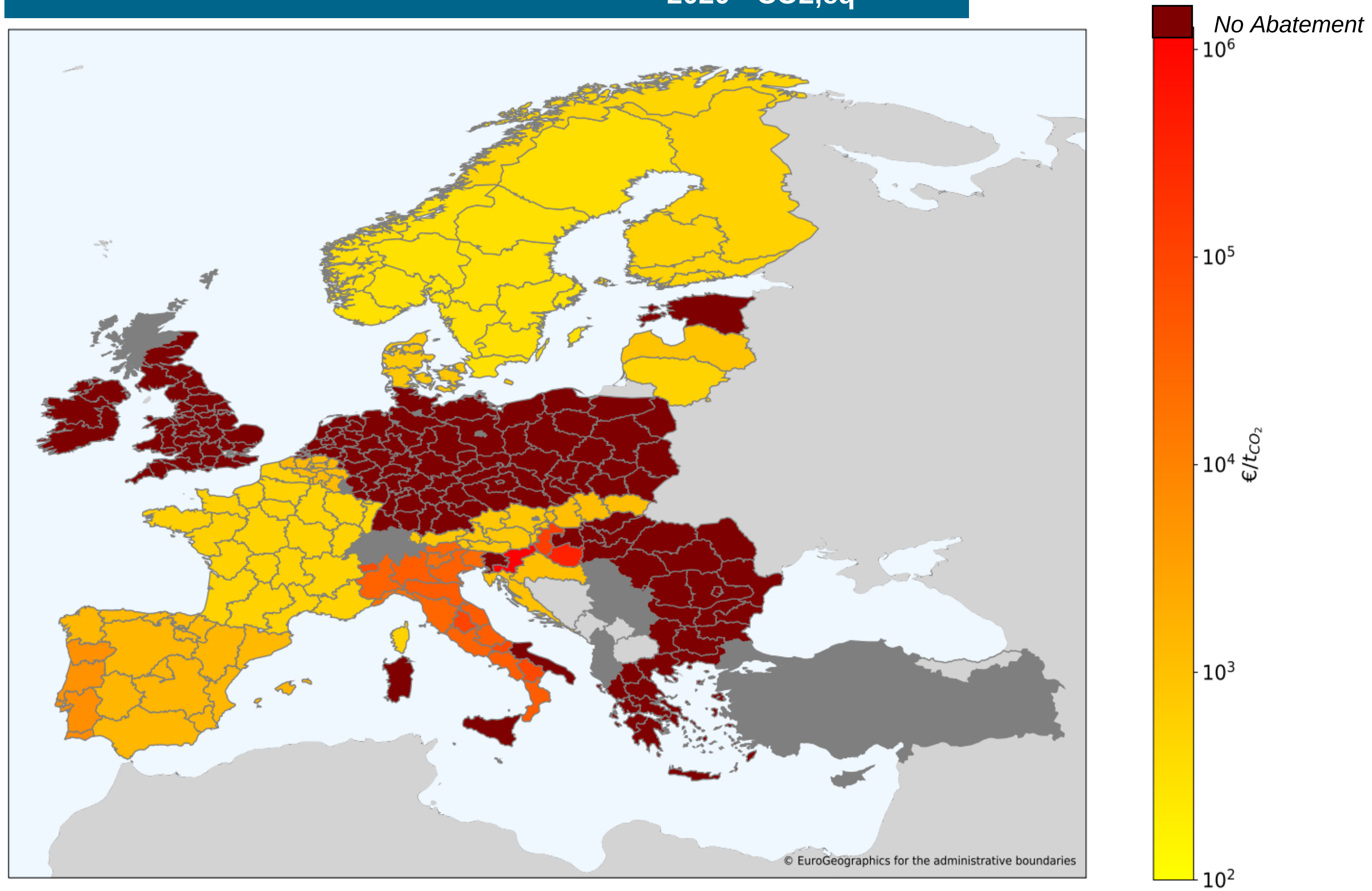
➔ Search for cheap biomass residue and inexpensive renewable power

1. Norway (57 $PJ_{dry\ biom}$/a) @ 50.5 – 51.0 €$_{2022}$/t
2. Sweden (276 $PJ_{dry\ biom}$/a) @ 57.5 – 64.8 €$_{2022}$/t
3. Finland (201 $PJ_{dry\ biom}$/a) @ 61.5 – 61.9 €$_{2022}$/t

[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). ENSPRESO-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 half of Europe ➔ grid GHG

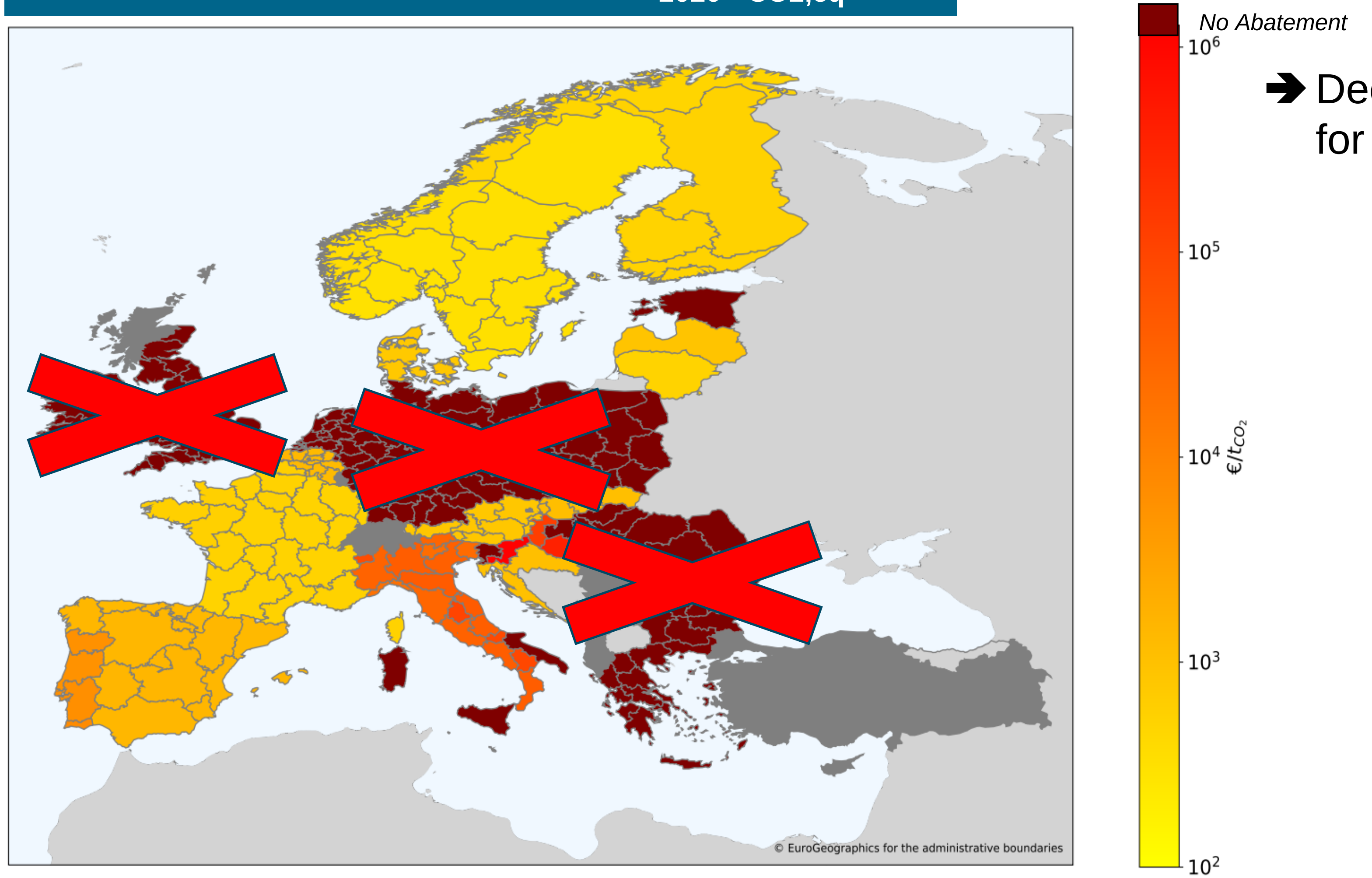
GHG Abatement of PBtL SAF / €$_{2020}$/t$_{CO2,eq}$



European SAF Roadmap

No GHG abatement for half of Europe ➔ grid GHG

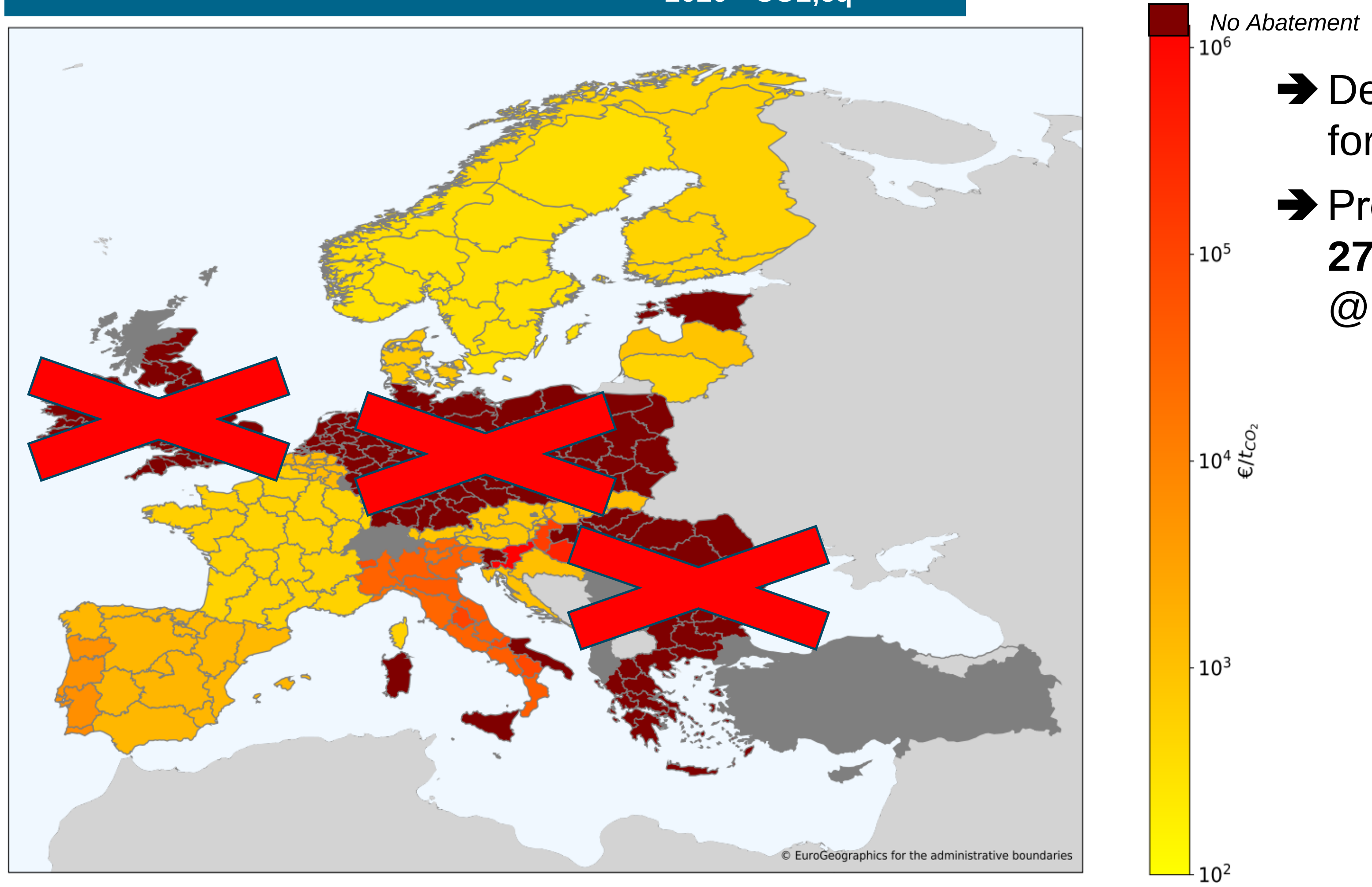
GHG Abatement of PBtL SAF / $€_{2020}/t_{CO2,eq}$



➔ Decarbonized national grids necessary for effective PBtL roll-out

European SAF Roadmap
No GHG abatement for half of Europe ➔ grid GHG

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

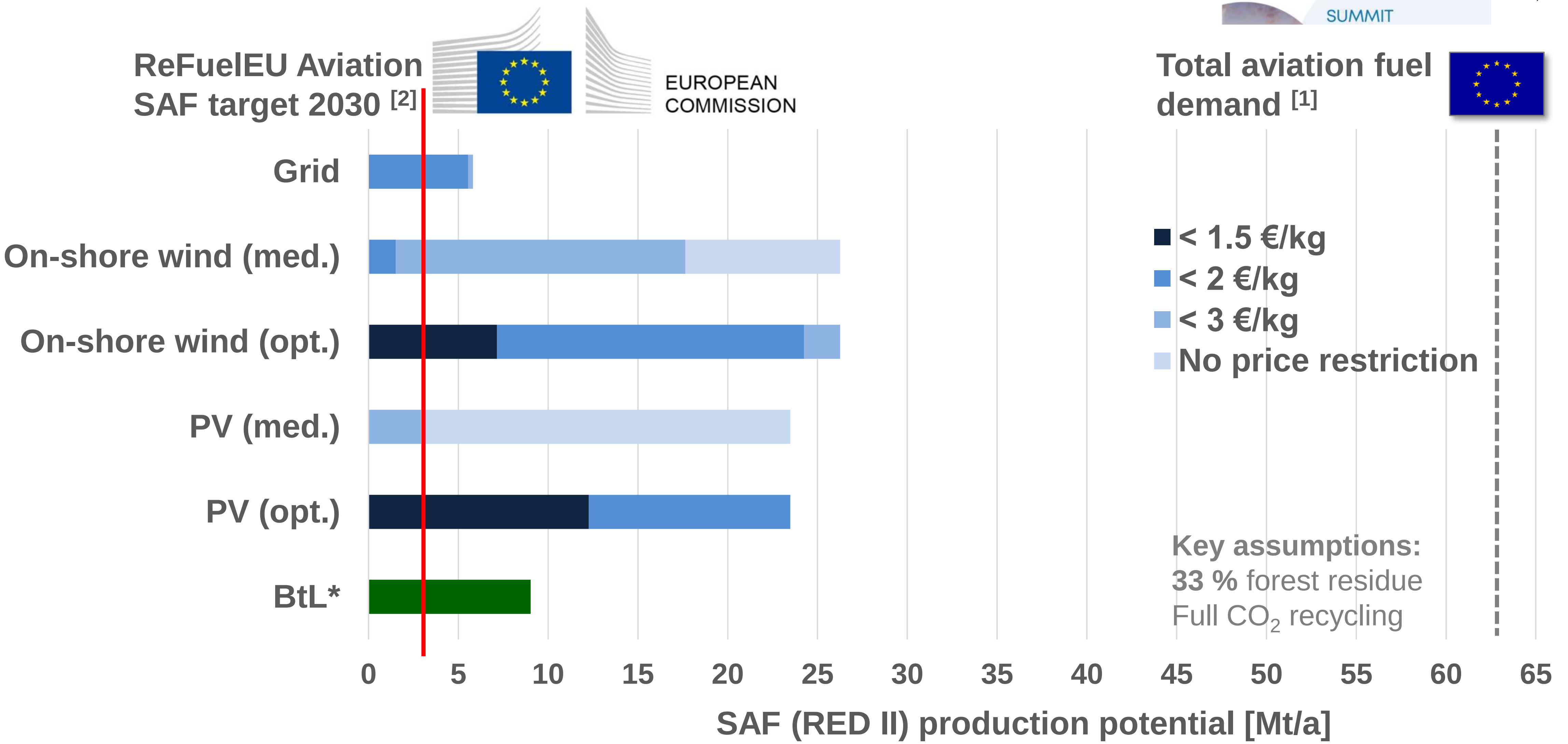


➔ Decarbonized national grids necessary for effective PBtL roll-out

➔ Production volume under 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 / $€_{2020}/kg_{C5+}$
(Sweden flag)	8.3	1,63
(France flag)	7.3	1.95
(Finland flag)	6.1	1.83
(Norway flag)	1.7	1.66

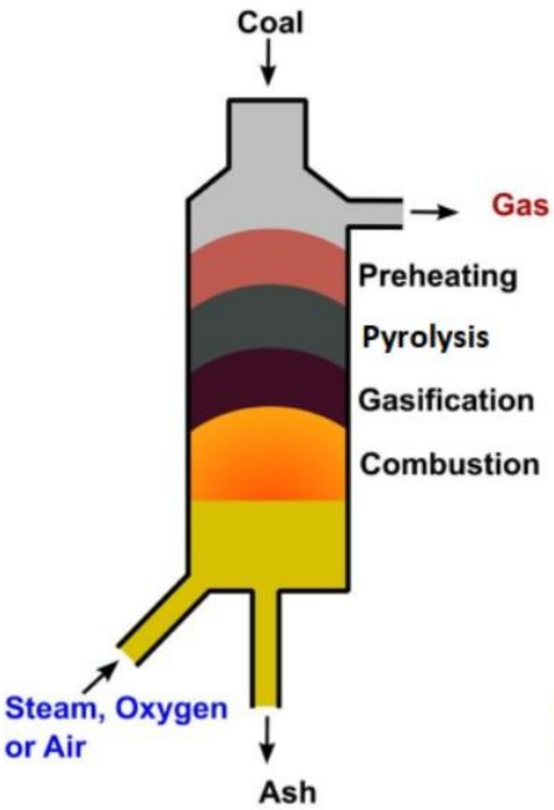
Aggregated European SAF production potential



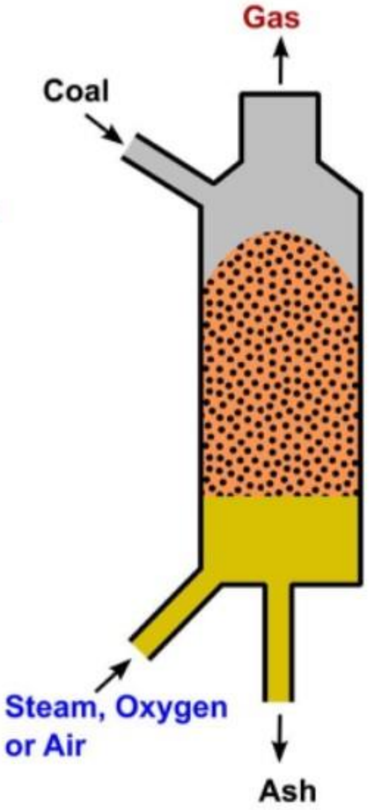
[1] S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf. *Assumptions: 19.9 % biomass conversion, entire potential under RED II limit
[2] https://www.easa.europa.eu/en/light/topics/fit-55-and-refueleu-aviation

SAF ROADMAP: TECHNOLOGY READINESS

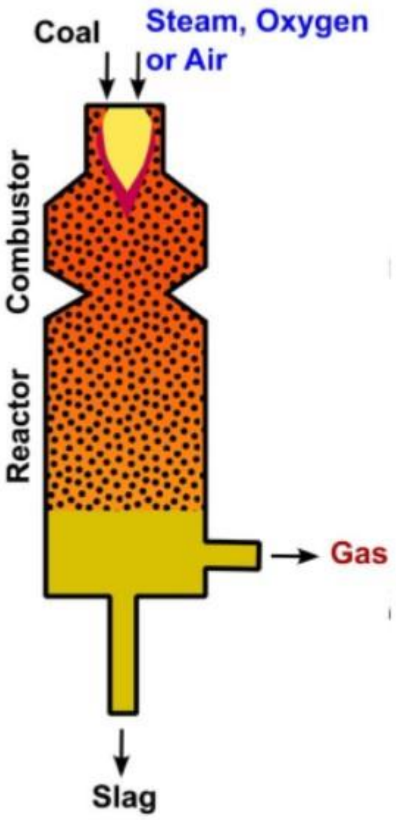
Gasifier: state-of-the-art coal technology



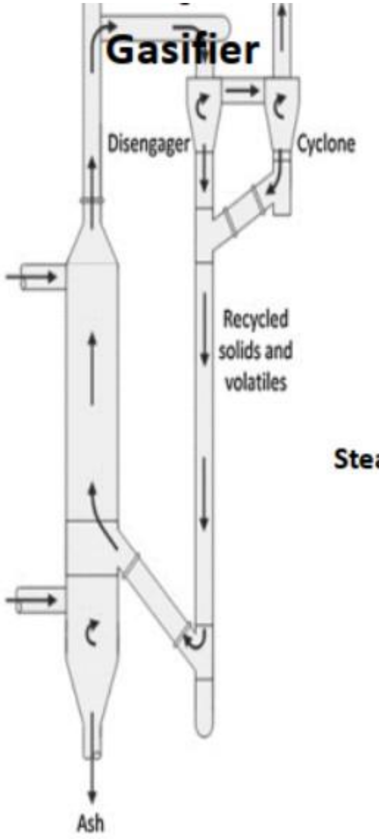
Fixed (moving) bed



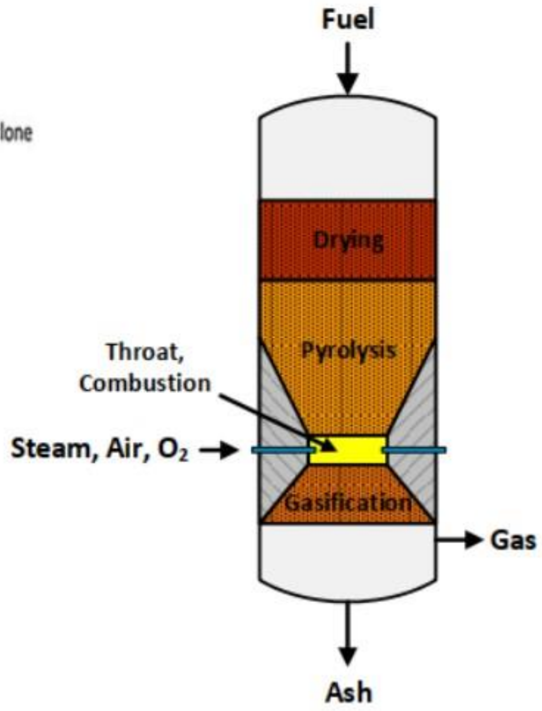
Fluidized bed



Entrianed flow



Transport Integrated



Downdraft

Gasifier: multiple installations,
➔ biomass applications proven

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

Electrolysis
Ongoing research

ACI 25th - 26 October - Hamburg The European CARBON DIOXIDE UTILIZATION SUMMIT

DLR

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

Electrolysis
State-of-the-art

[1]

[2]

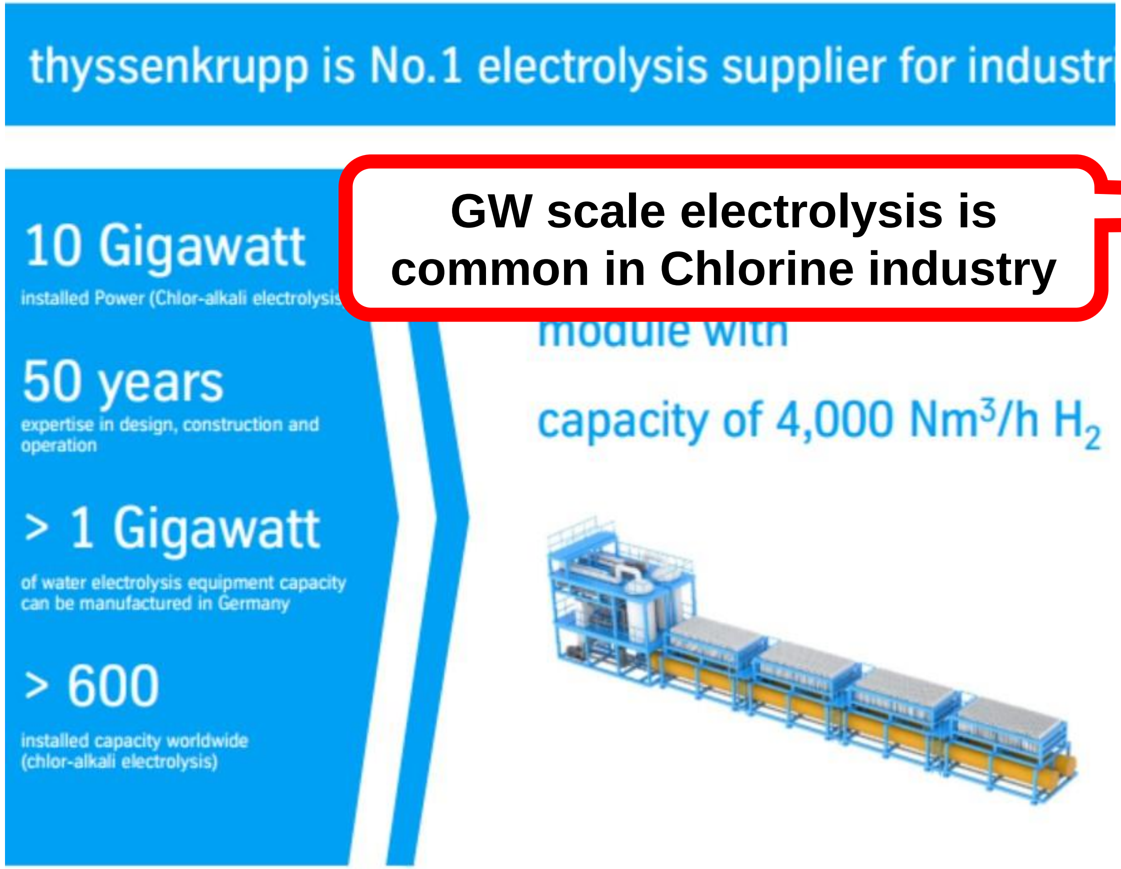
Electrolysis technology is state-of-the-art

[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
							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

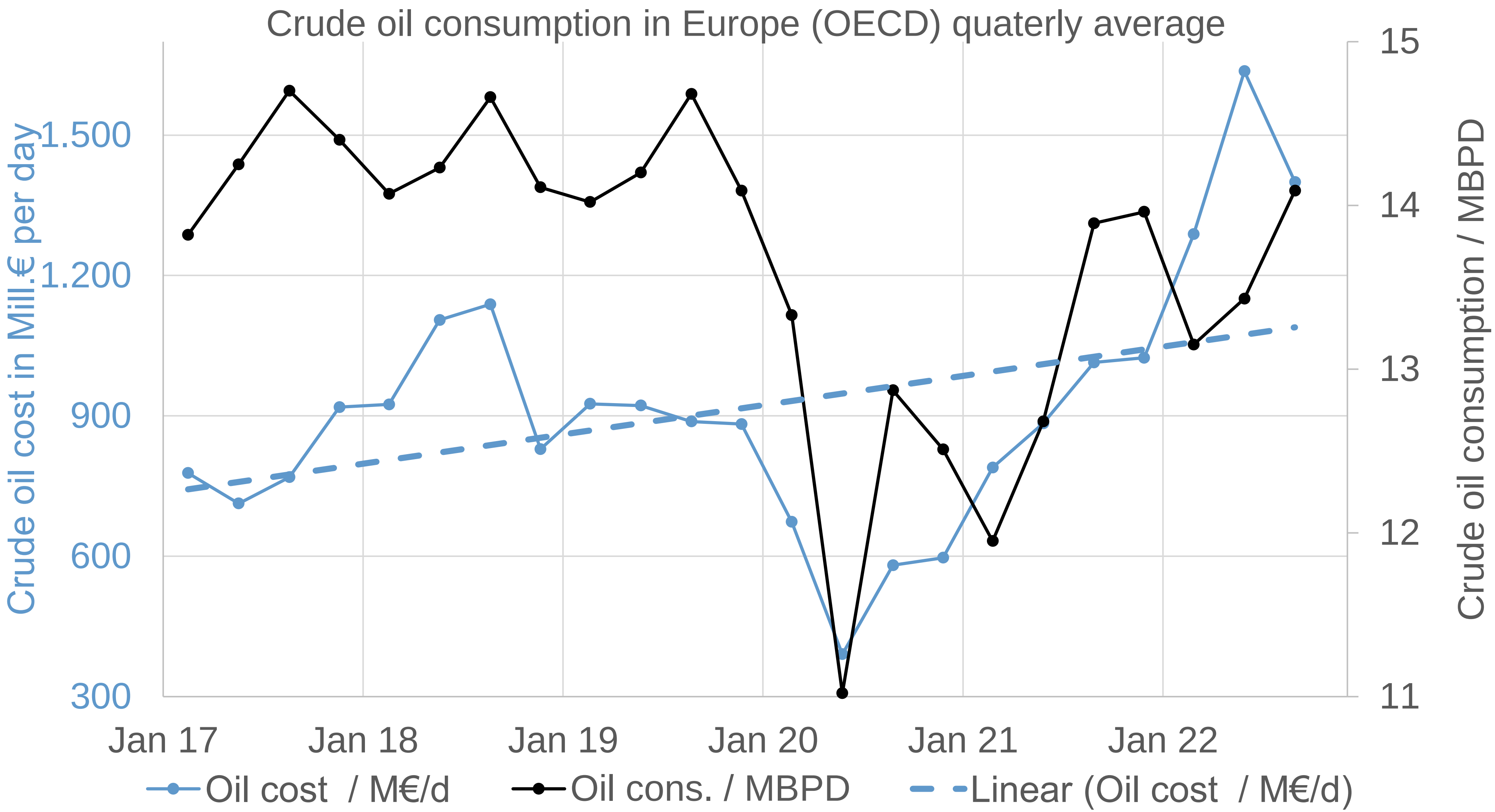
[2] Eurochlor: Chlorine Industry Review 2021-2022, www.chlorineindustryreview.com

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

Shell Qatar GTL facility, built in 2012, produces 140,000 barrels a day

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

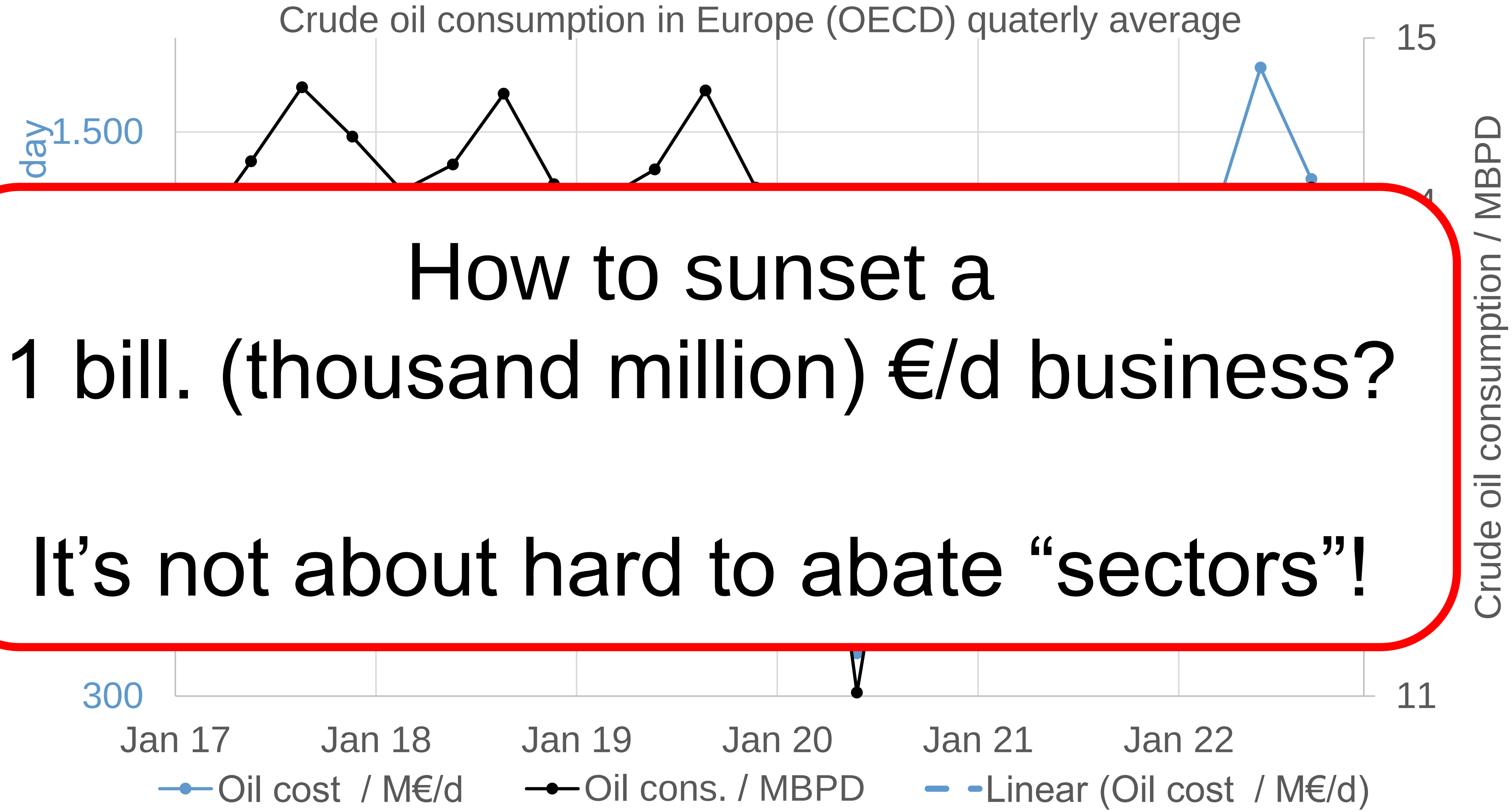
Aviation remains part of fossil oil business
“Money makes the world go round”



[1] Bukold (EnergyComment), Ölverbrauch in Deutschland und Europa, Chem. Ing. Tech. 2020, 92, No. 10, 1586–1595

Aviation remains part of fossil oil business

“Money makes the world go round”



How to sunset a
1 bill. (thousand million) €/d business?

It’s not about hard to abate “sectors”!

[1] Bukold (EnergyComment), Ölverbrauch in Deutschland und Europa, Chem. Ing. Tech. 2020, 92, No. 10, 1586–1595

AN AMBITIOUS SAF DEPLOYMENT PLAN

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

	ReFuelEU Aviation SAF targets [1]	ReFuelEU Aviation Synfuel target [1]
2025	2 % (≈ 1 Mt/a)	
2030	~~5~~6 % (≈ 3.8 Mt/a)	0.7 % (≈ 0.4 Mt/a)
2035	20 % (≈ 13 Mt/a)	5 % (≈ 3.3 Mt/a)
2050	~~63~~70 % (≈ 54 Mt/a)	~~28~~35 % (≈ 27 Mt/a)

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

SAF deployment plan for Europe
Regulation

	ReFuelEU Aviation SAF targets [1]	ReFuelEU Aviation Synfuel target [1]
2025	2 % (≈ 1 Mt/a)	
2030	~~5~~6 % (≈ 3.8 Mt/a)	0.7 % (≈ 0.4 Mt/a)
2035	20 % (≈ 13 Mt/a)	5 % (≈ 3.3 Mt/a)
2050	~~63~~70 % (≈ 54 Mt/a)	~~28~~35 % (≈ 27 Mt/a)

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

Preference palm oil?
Not enough palm oil on earth!

Paris 1.5 degree commitment intentionally violated!

[1] https://www.easa.europa.eu/en/light/topics/fit-55-and-refueleu-aviation
[2] https://www.concawe.eu/wp-content/uploads/Rpt_21-2.pdf

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

	ReFuelEU Aviation SAF targets [1]	ReFuelEU Aviation Synfuel target [1]	**Ambitious, but realistic, just** PBtL SAF
2025	2 % (≈ 1 Mt/a)		
2030	~~5~~6 % (≈ 3.8 Mt/a)	0.7 % (≈ 0.4 Mt/a)	**10 Mt/a**
2035	20 % (≈ 13 Mt/a)	5 % (≈ 3.3 Mt/a)	**30 Mt/a**
2050	~~63~~70 % (≈ 54 Mt/a)	~~28~~35 % (≈ 27 Mt/a)	**75+ Mt/a = 100 %! (2045?)**

25 plants across Europe á

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

Investment:
less than 6 months of Europe's crude oil spending

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

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

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- **Backup, if H_2 aviation won't fly**
- **additional SAF routes from 2035 onwards required, or**
  ➔ Less air traffic?

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

CONCLUSION & OUTLOOK

Reject missleading PtX hoax‘

If defossilization is the real goal …

- Don’t wait for research progress to meet climate obligations
  - “Too little too late” is not researchers malfunction
- Market won’t solve, ONLY REGULATION will end fossil fuels utilization
  - SAF blending mandate can be set far more ambitious
- Expose any excuses for SAF deployment delay
  - PtX research, development, demonstration demand
  - Technology readiness
- Make sure, PtX research is not just “reinventing the wheel”
  - Millions research funding won’t fulfill climate obligations

Opportunities and challenges for electro-fuels in future aviation

Summary

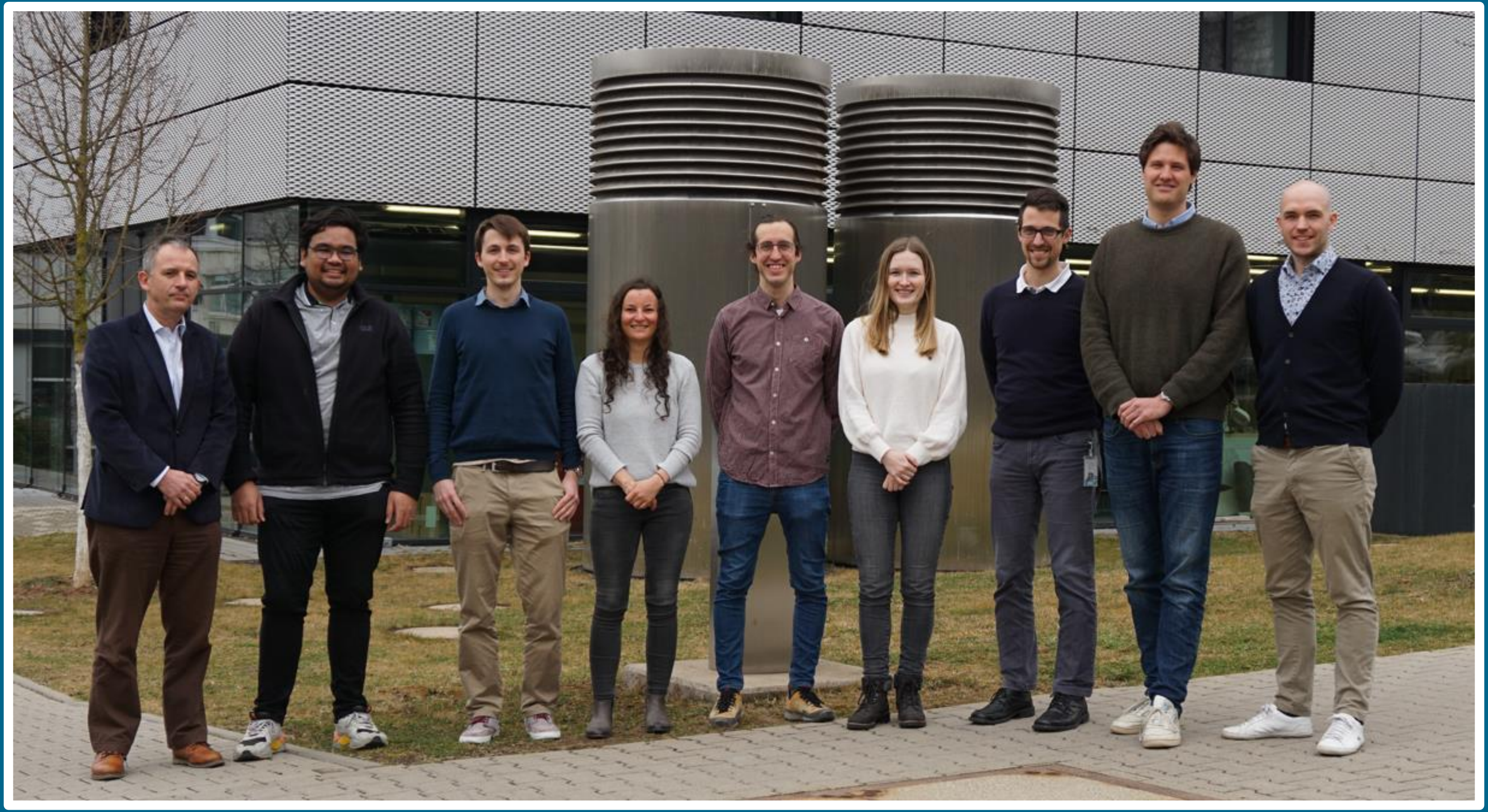
- Sustainable fuels are required to meet the aviation contribution towards Europe's climate obligations
- GHG abatement costs shall be the key decision criteria for large scale SAF deployment ➔ PBtL: < 1.000 €/$t_{CO2\text{-}eq.}$ achievable
- Europe can largely decarbonize its aviation, utilizing biomass residues, investing in renewable power
- PtX will only cover a minor portion of current crude oil consumption
  ➔ Preventing + Shifting + Replacing of transport by **REGULATION**

Transparent, standardized DLR assessment methodology can help for reasonableness

THANK YOU FOR YOUR ATTENTION !
Questions?

25th - 26 October - Hamburg

The European CARBON DIOXIDE UTILIZATION



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