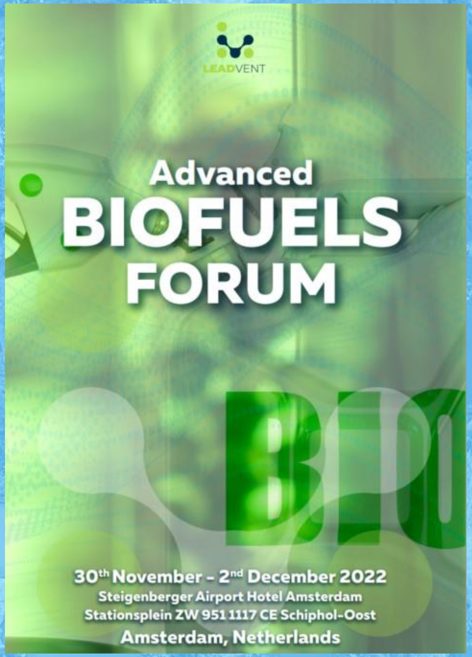
ADVANTAGES AND CHALLENGES IN RENEWABLE POWER ASSISTED BIOFUELS PRODUCTION

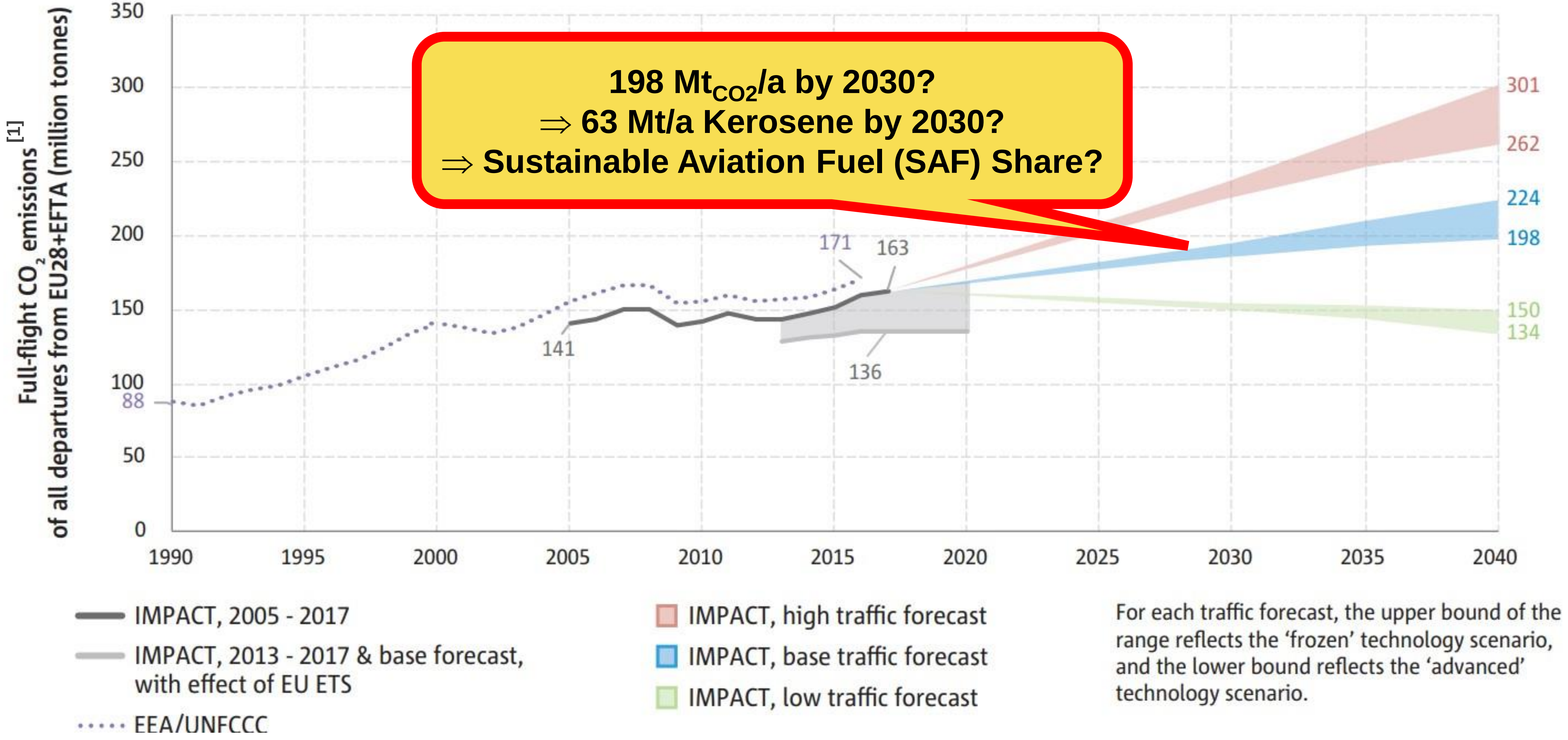


Techno-economic & environmental assessment

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

DLR

Future European aviation fuel demand



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

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

Feedstock availability => 63 Mt/a

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Total technical potential of 1st generation European sustainable jet fuel [2-6]:

Feedstock	Kerosene yield from total EU crop production [Mt/a]	Share of total cultivation area in EU [%]
Wheat	23.0 – 32.9	30.2
Sugar	3.9	1.8
Rapeseed	7.3	13.3
Σ	**34.3 – 44.2**	**45.2**

[2] Eurostat „Crop statistics“ 2014
[3] Specialist agency renewable raw materials e. V., „Introduction of fuel ethanol”, 2016
[4] NREL, „Review of Biojet Fuel Conversion Technologies”, Golden, 2016
[5] UFOP “Rapeseed the Power Plant“ 2017
[6] DBFZ, „Abschlussbericht Projekt BurnFAIR”, 2014

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

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Total technical potential of 1st generation European sustainable jet fuel [2-6]:

Feedstock
Wheat
Sugar
Rapeseed
Σ

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
- supplier's reliability
- Low technical development potential

➔ **2nd generation SAF?**

[2] Eurostat „Crop statistics“ 2014
[3] Specialist agency renewable raw materials e. V., „Introduction of fuel ethanol”, 2016
[4] NREL, „Review of Biojet Fuel Conversion Technologies”, Golden, 2016
[5] UFOP “Rapeseed the Power Plant“ 2017
[6] DBFZ, „Abschlussbericht Projekt BurnFAIR”, 2014

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

Advanced BIOFUELS FORUM

DLR

Feedstock availability towards 63 Mt/a

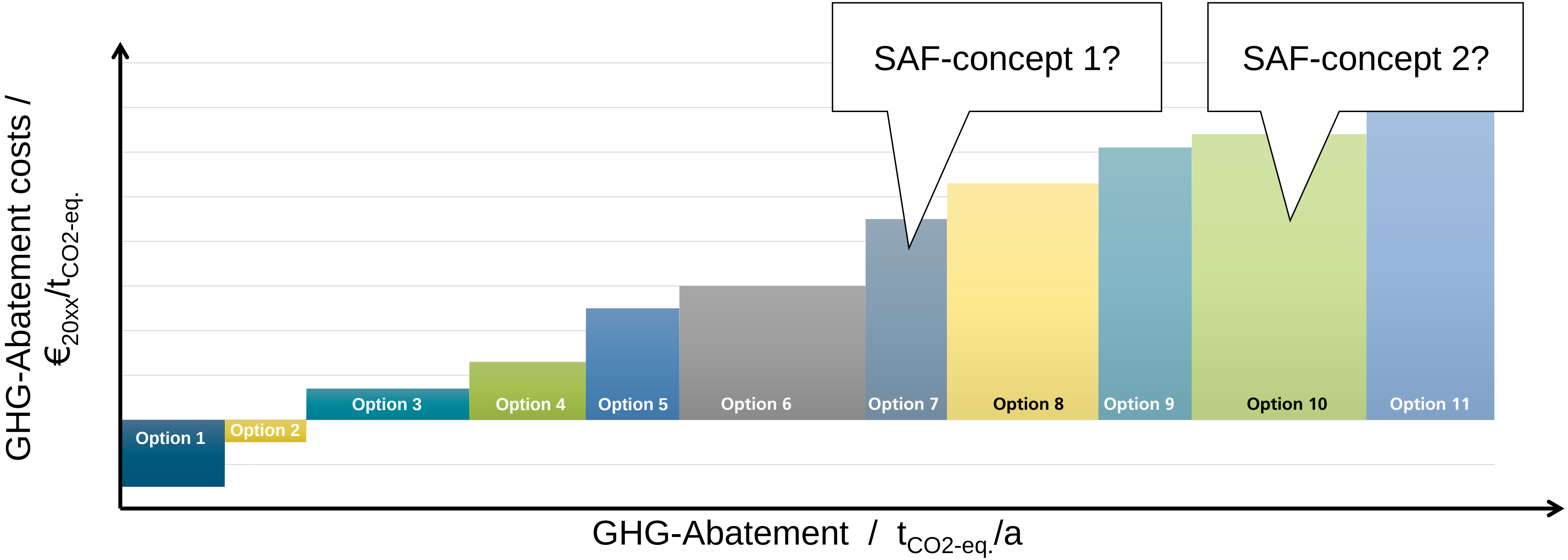
Feedstock	Synthesis technology	Fuel
~~Coal, natural gas~~, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis using Fe or Co catalyst,	Synthetic paraffinic kerosene (FT-SPK)

- 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]

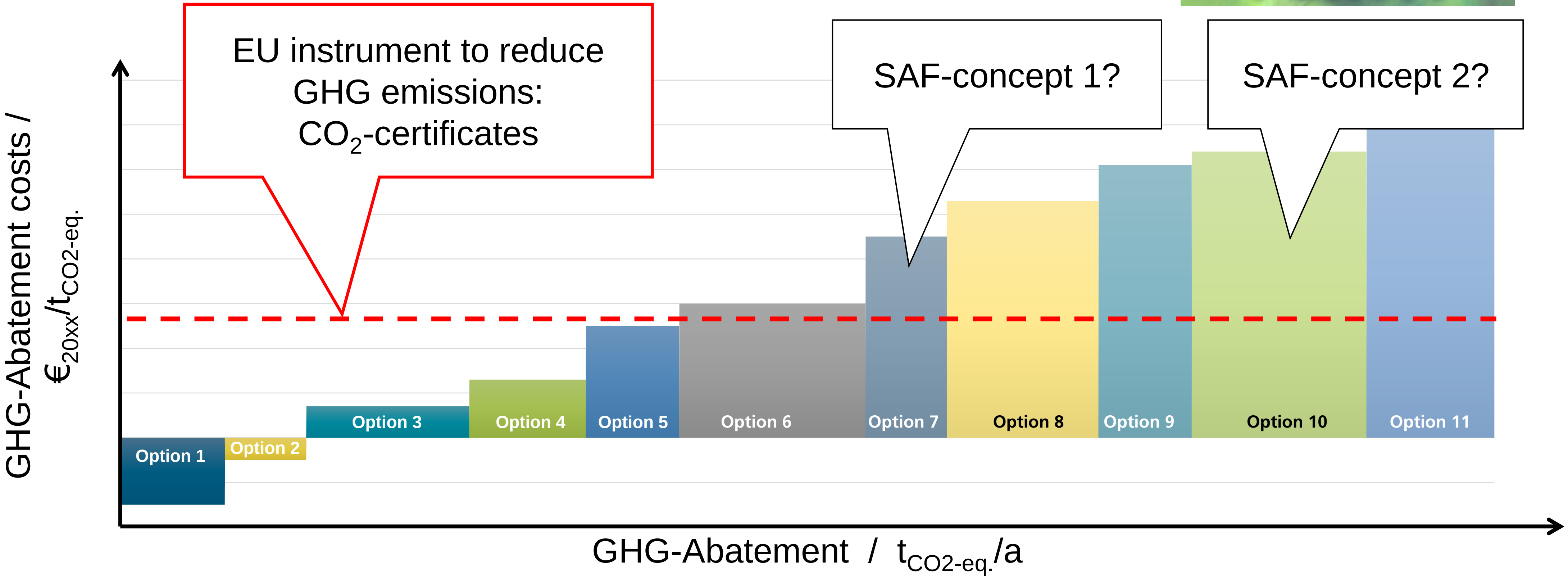
[1] European Environment Agency, "Europe's onshore and offshore wind energy potential," 2009
[2] FOREST EUROPE, 2020: State of Europe's Forests 2020
[3] UK Ministry of Defense, „DEF STAN 91-91: Turbine Fuel, Kerosene Type, Jet A-1", UK Defense Standardization, 2011

Assessment of SAF concepts

Merit-Order of GHG reduction technologies

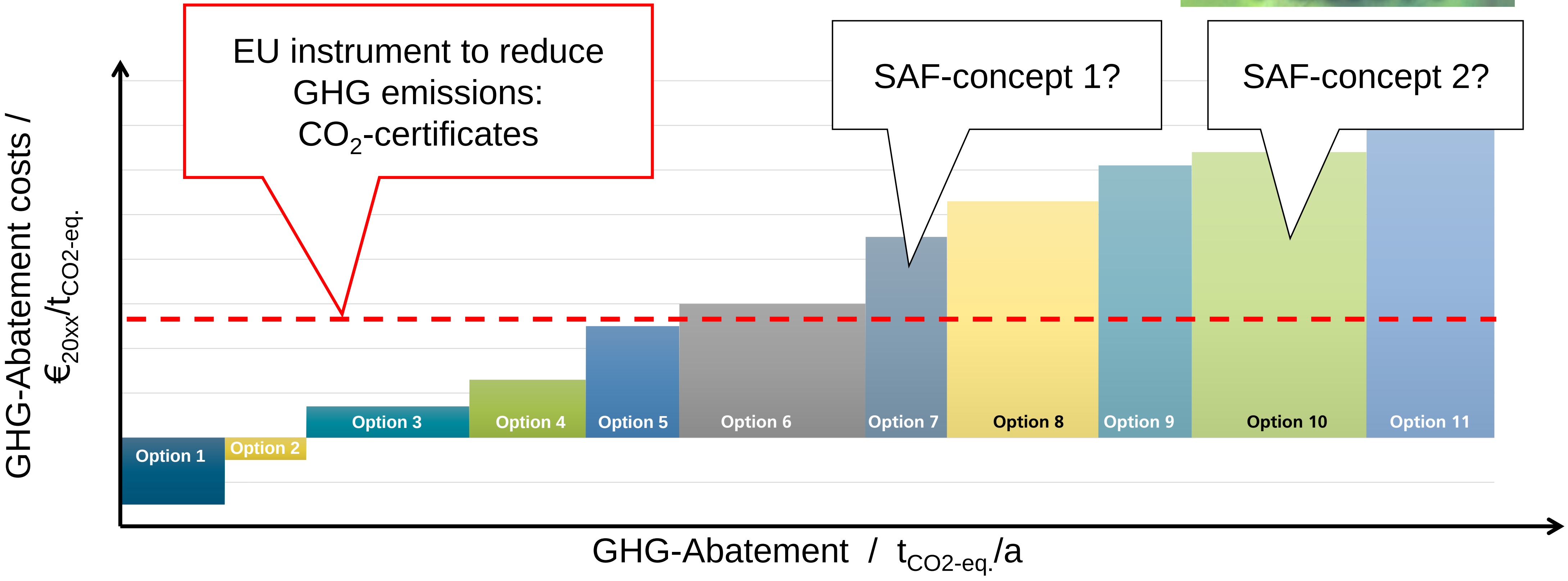


Assessment of SAF concepts
Merit-Order of GHG reduction technologies



Goal: Maximal CO_2 reduction @ minimized GHG-Abatement cost, either by reducing GHG footprint or costs!

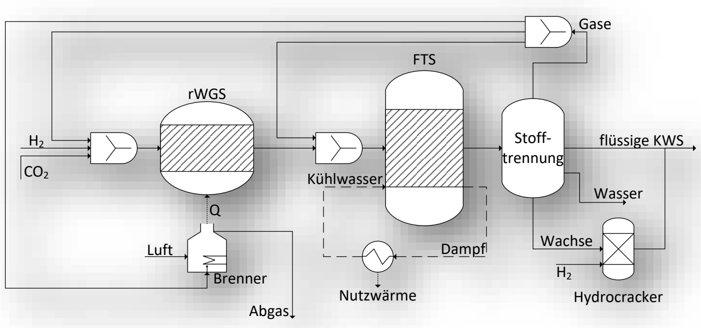
Assessment of SAF concepts
Merit-Order of GHG reduction technologies

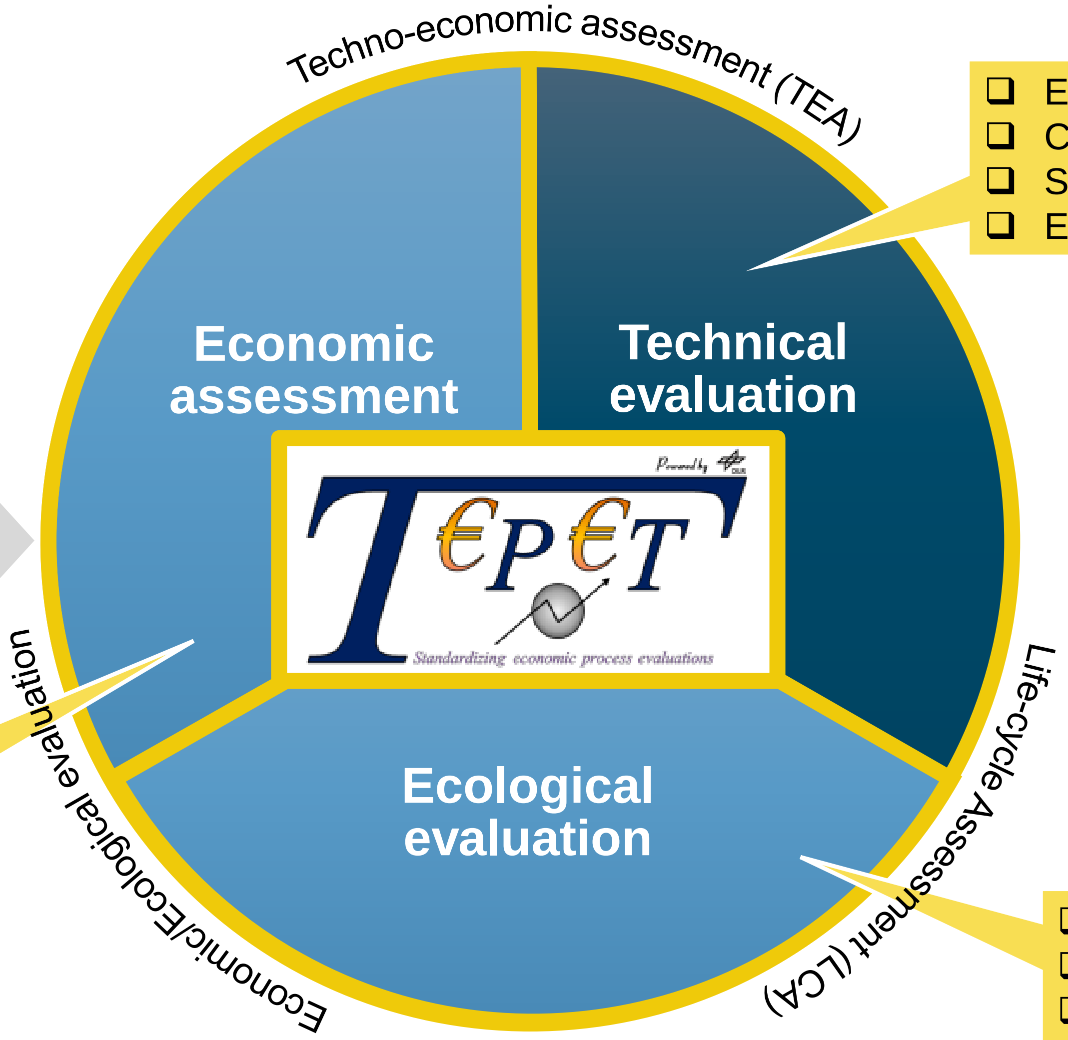


Goal: Maximal CO_2 reduction @ minimized GHG-Abatement cost, either by reducing GHG footprint or costs!

→ Standardized methodology for LCA and TEA

Techno-Economic & ecological assessment





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

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

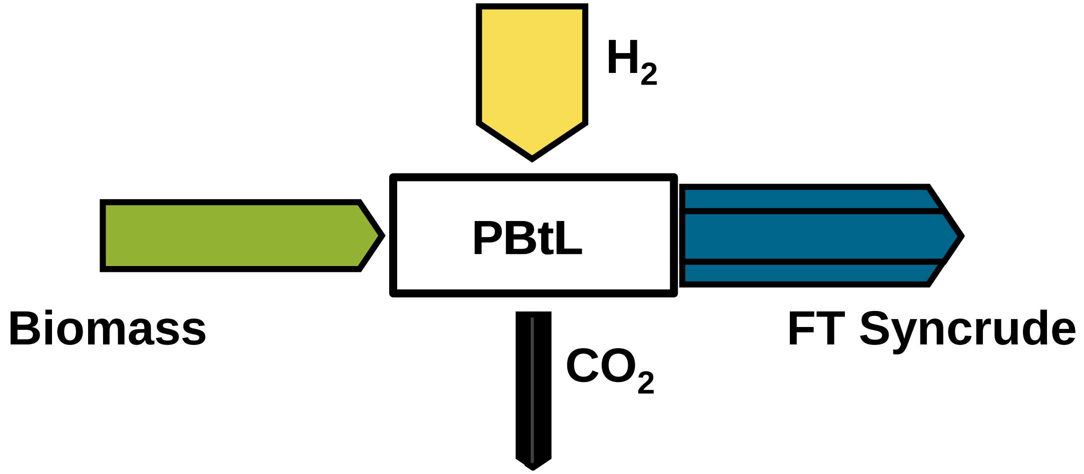
- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

Assessment of SAF concepts
BtL versus PBtL

Challenges for aviation fuel provision in Europe:

- ReFuel EU[1] aims for a rapid SAF blending rate increase from 2 % in 2025 to 63 % in 2050
- Unreliability regarding energy imports

☛ **Local production of low-carbon fuel from waste biomass, boosted by renewable power/H_2?**



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

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

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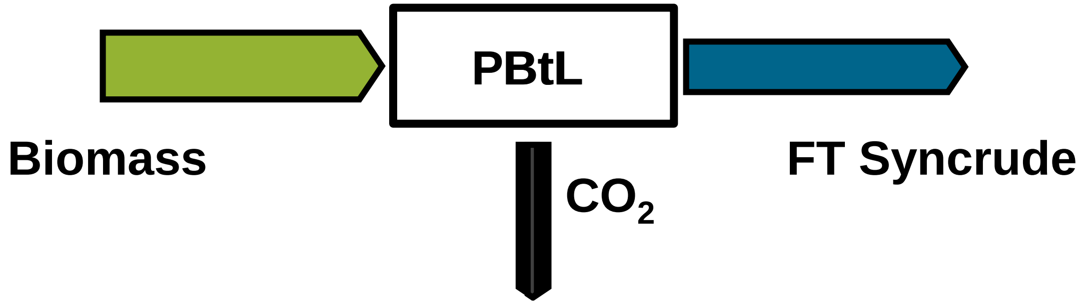

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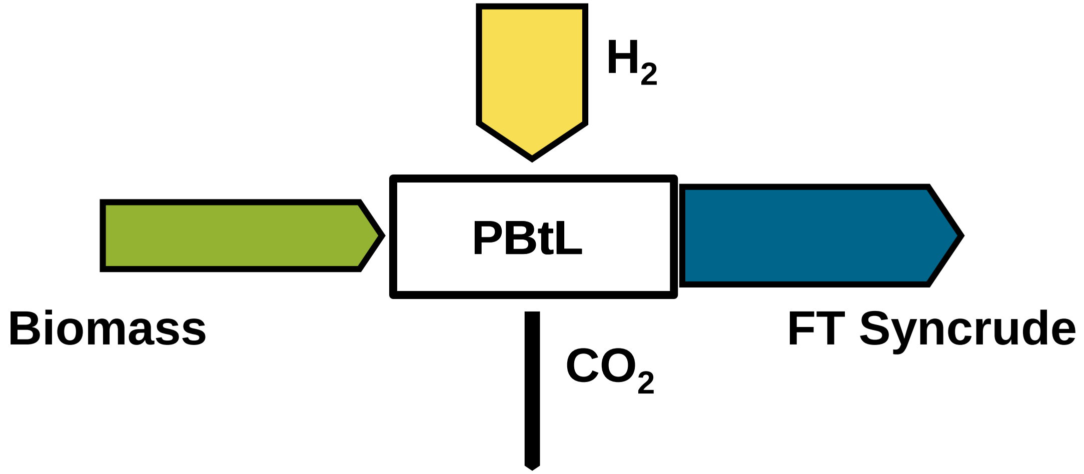

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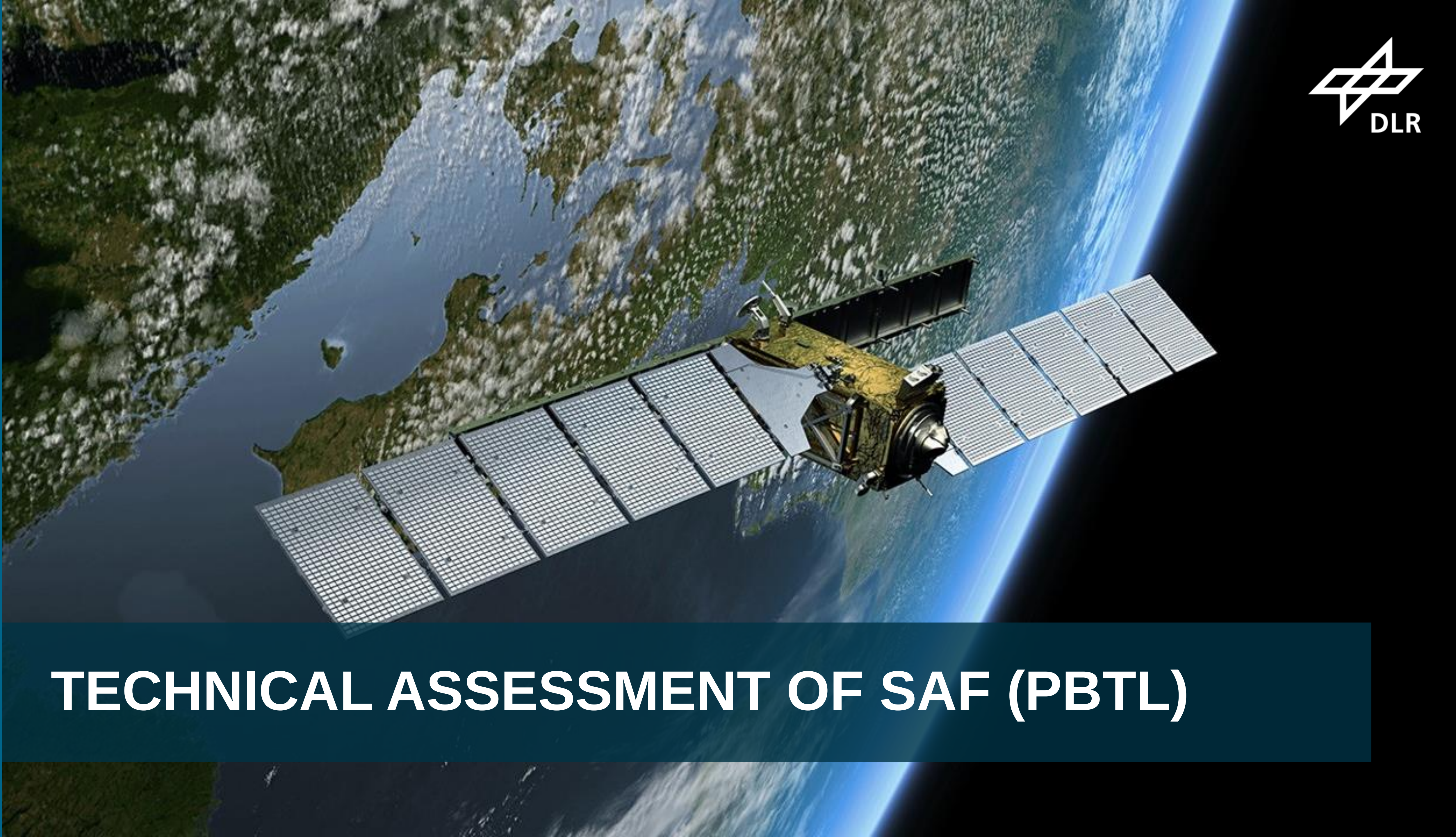
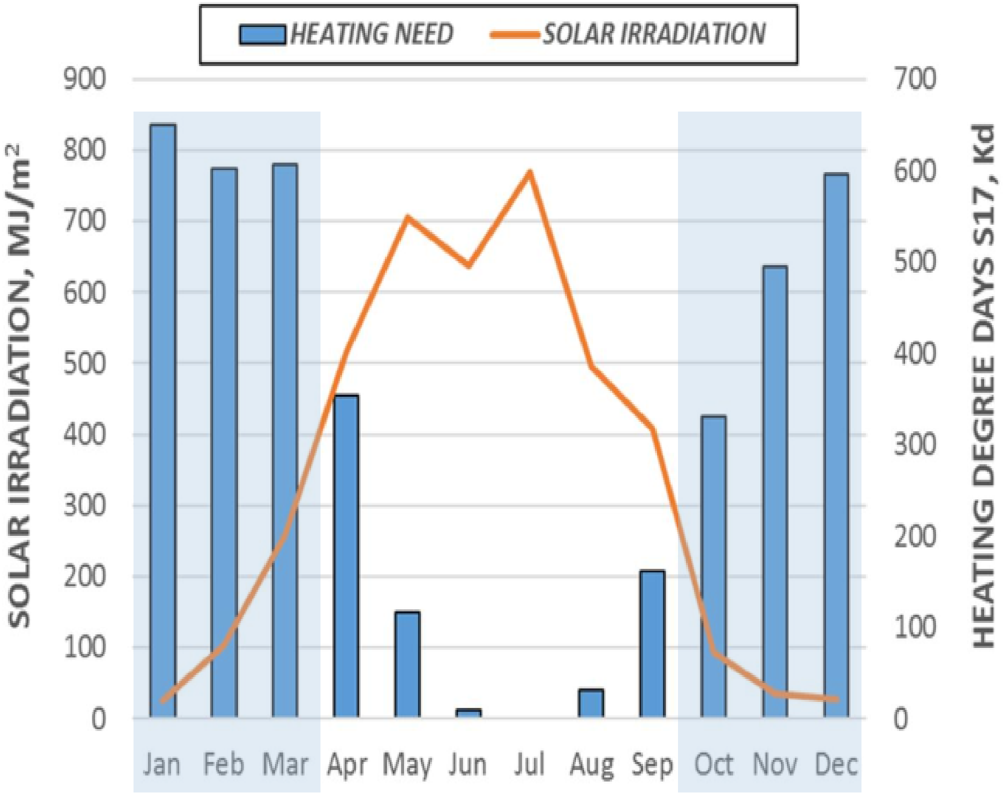


TECHNICAL ASSESSMENT OF SAF (PBTL)

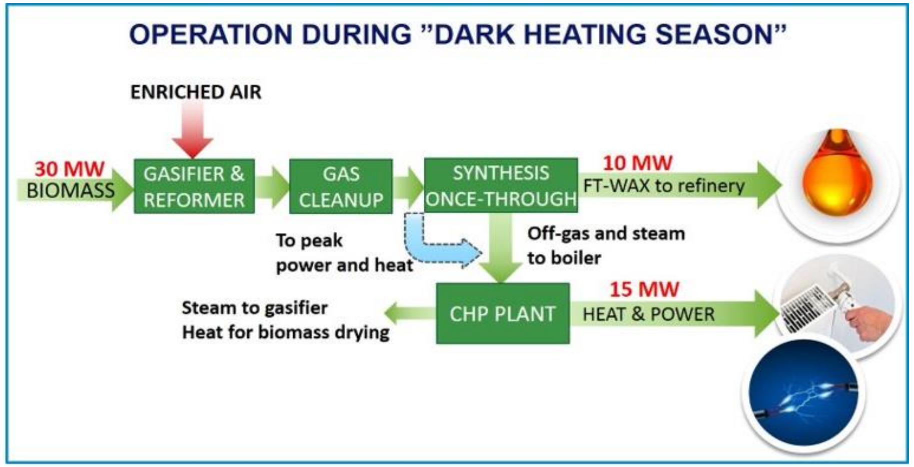
Techno-Economic Assessment of Power&Biomass-to-Liquid SAF

Seasonal market response approach:

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



High heat demand & Low renewable electricity availability



Techno-Economic Assessment of Power&Biomass-to-Liquid SAF

Seasonal market response approach:

FLEXCHX

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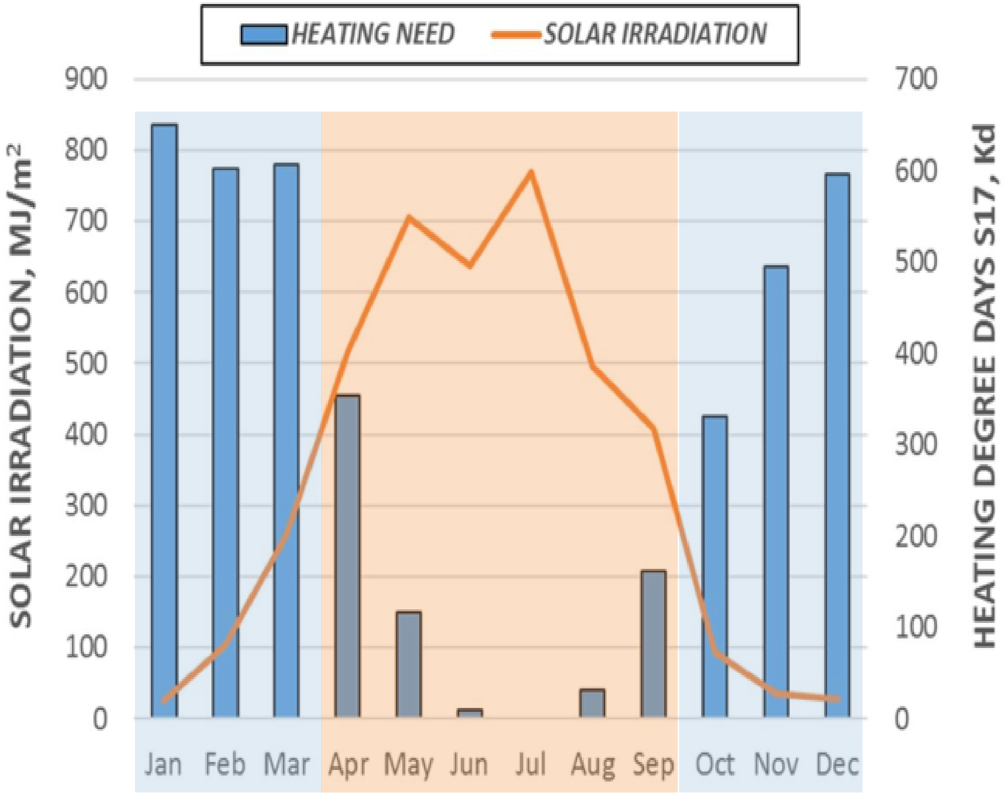

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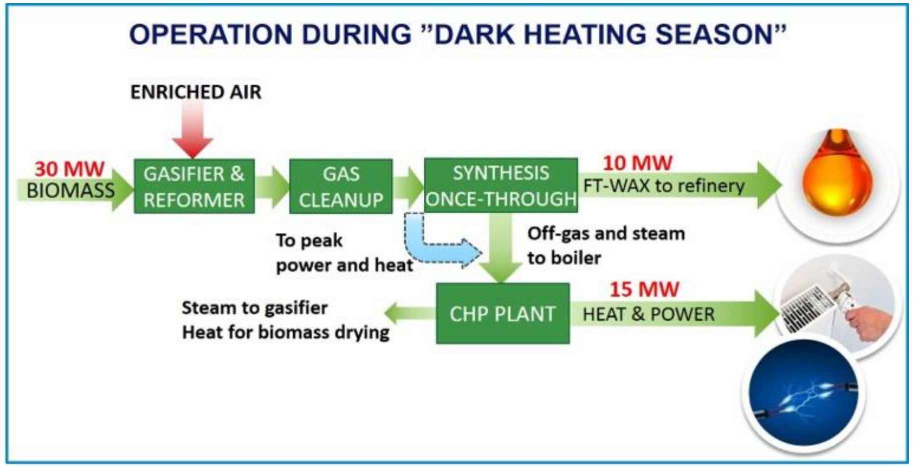
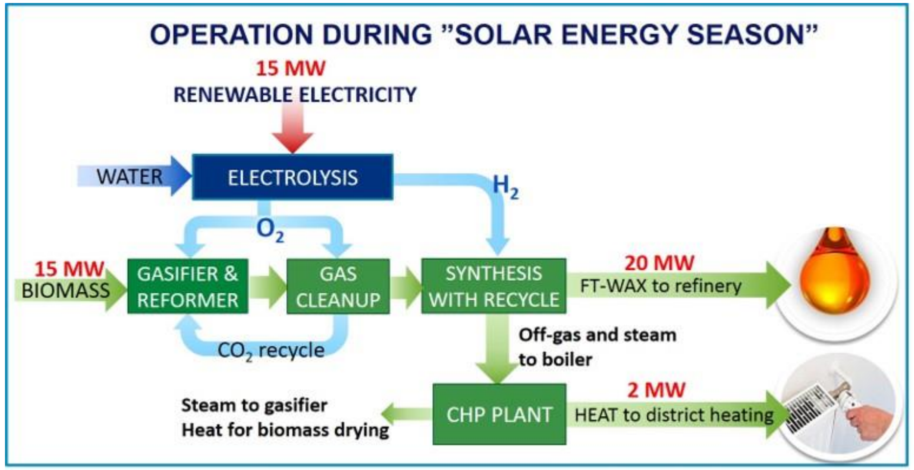


Low heat demand & High renewable electricity availability



Techno-Economic Assessment of Power&Biomass-to-Liquid SAF[1]

Dual configuration concept [1] :

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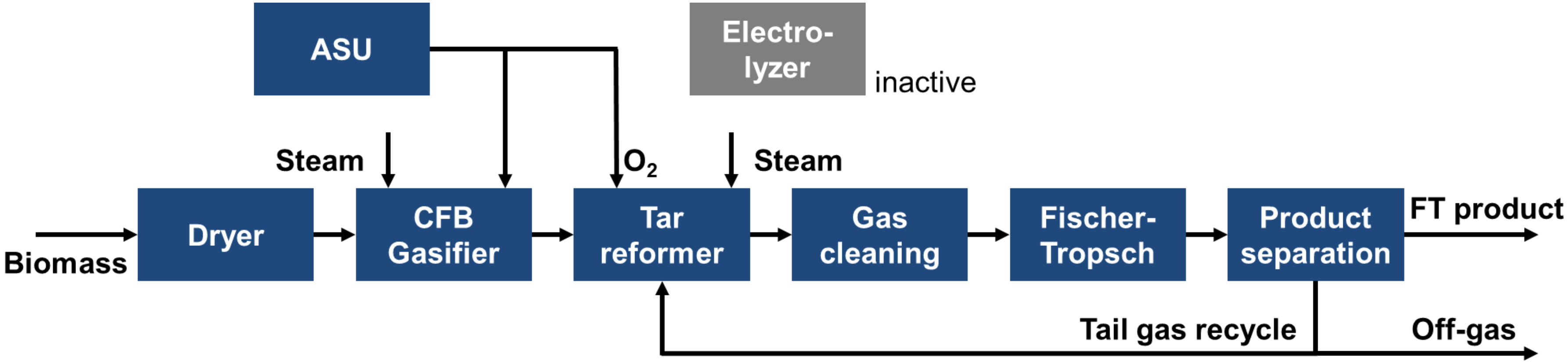

Winter mode:

- high heat demand
- low renewable power

Solution: BtL with ASU

[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

Techno-Economic Assessment of Power&Biomass-to-Liquid SAF[1]

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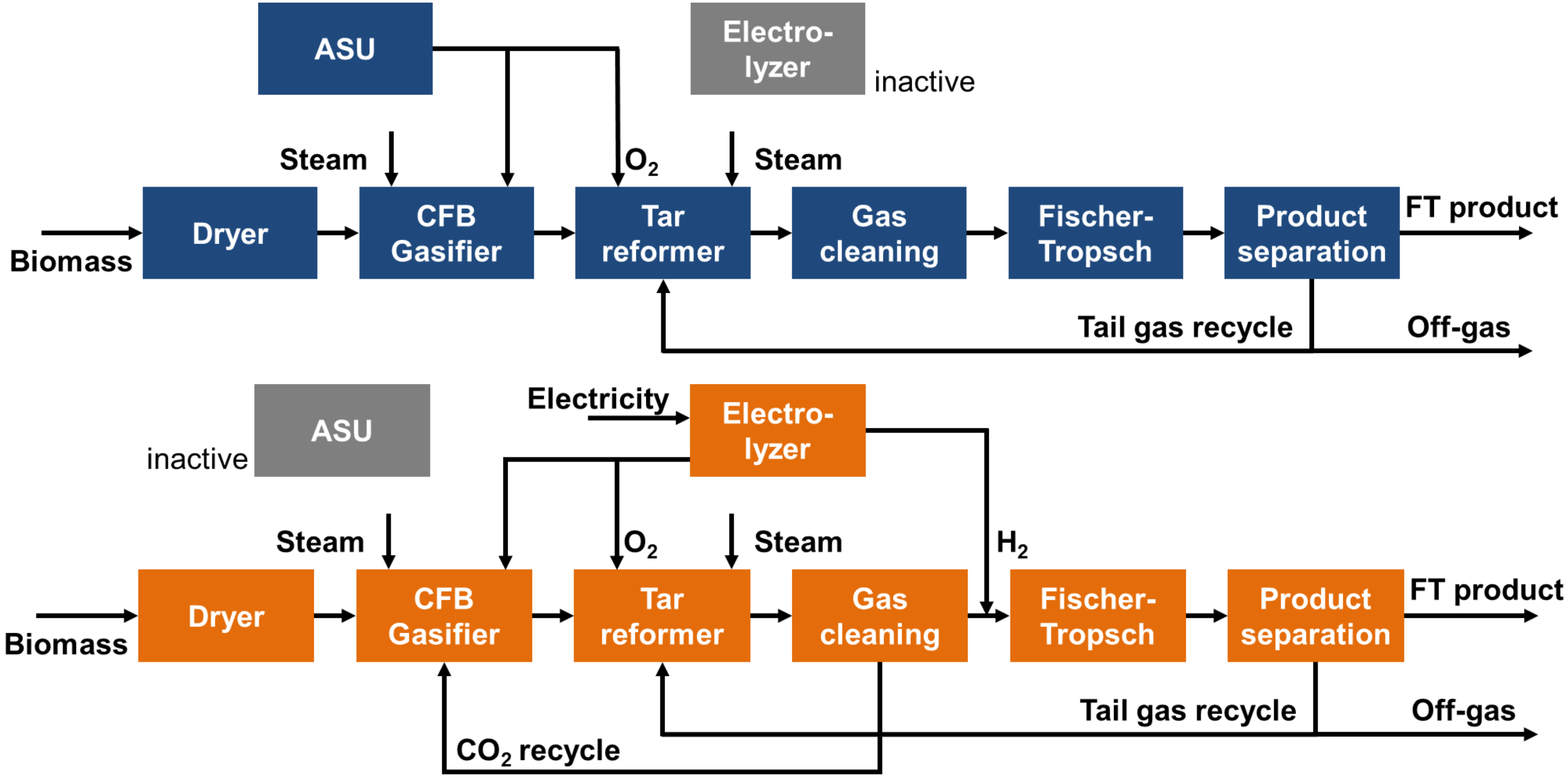


Winter mode:

- high heat demand
- low renewable power

Solution: BtL with ASU

Summer mode:

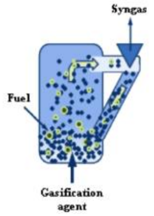
- no heat demand
- PV power available

Solution: electrolyzer assisted PBtL

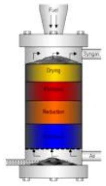
[1]Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774

Technology options for the PBtL processes

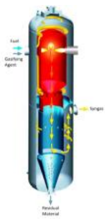
Gasifier [1]



Fluidized bed
+ Fuel flexibility
- Difficult control



Fixed bed
+ Proven for small-scale applications
- Limited scale-up

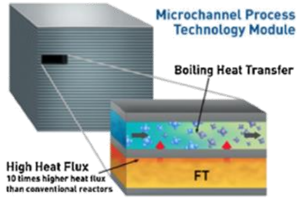


Entrained flow
+ High conversion efficiency
- High fuel specificity

Fischer-Tropsch reactor [2]

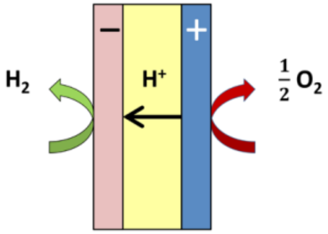
SBCR
+ Simple thermo management
- Difficult product separation

Fixed-bed
+ Easy product separation
- Heat transfer limitations

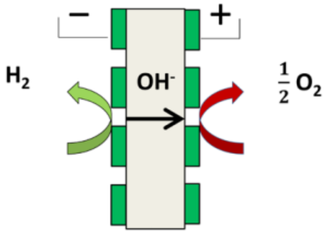


Microreactor
+ High once-through conversion
- High capital cost

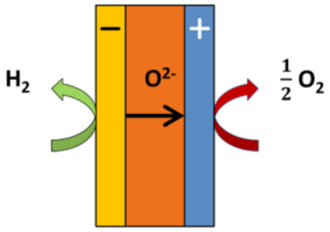
Electrolysis [3]



PEM
+ Load flexibility (0-100 %)
- Low heat integration potential



AEL
+ Lowest investment cost
- Limited system efficiency (< 60 $\%_{LHV}$)



SOEC
+ High electric efficiency
- Low technology readiness level (largest SOEC plant 225 kW)

[1] Puig-Arnavat, M., Bruno, J. C., & Coronas, A. (2010). Review and analysis of biomass gasification models. *Renewable and sustainable energy reviews*, *14*(9), 2841-2851.
[2]] LeViness, S., Deshmukh, S. R., Richard, L. A., & Robota, H. J. (2014). Velocys Fischer–Tropsch synthesis technology—new advances on state-of-the-art. Topics in Catalysis, 57(6-9), 518-525.
[3] 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.

Techno-Economic Assessment of Power&Biomass-to-Liquid SAF

Technical efficiencies [1]

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

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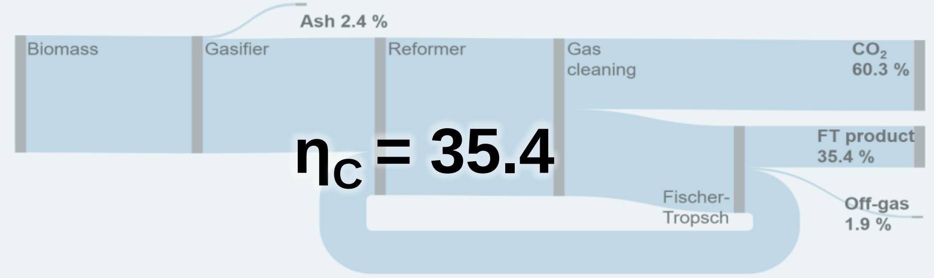
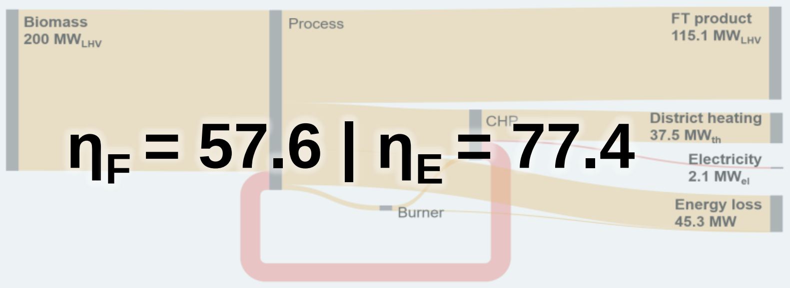
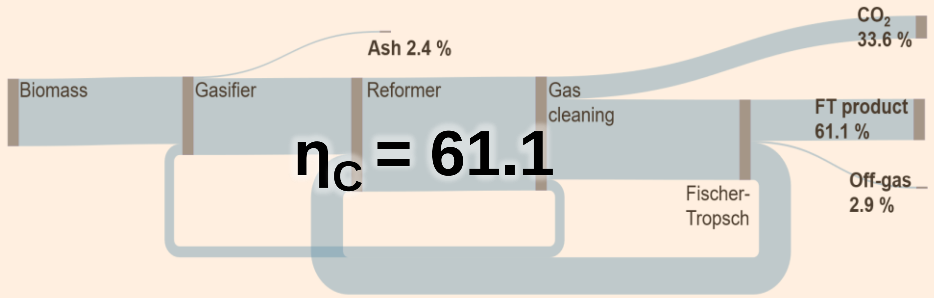
	Carbon efficiency η_C [%]	Fuel η_F | Process efficiency η_E [%]
Winter	$\eta_C = 35.4$	$\eta_F = 57.6$ | $\eta_E = 77.4$
Summer	$\eta_C = 61.1$	$\eta_F = 55.2$ | $\eta_E = 73.6$
50-50	$\eta_{C,av.} = 48.25$	$\eta_{F,av.} = 56.4$ | $\eta_{E,av.} = 75.5$

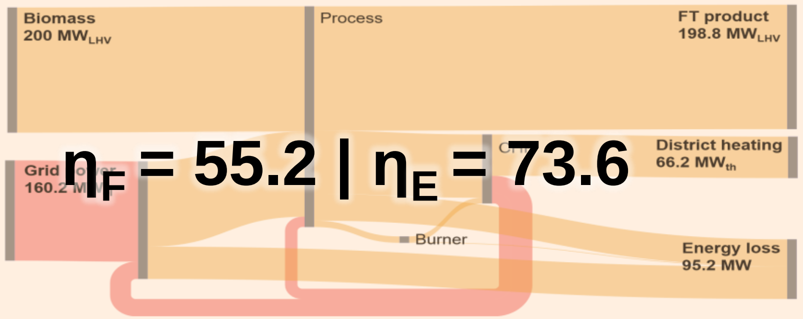
Winter:





Summer:





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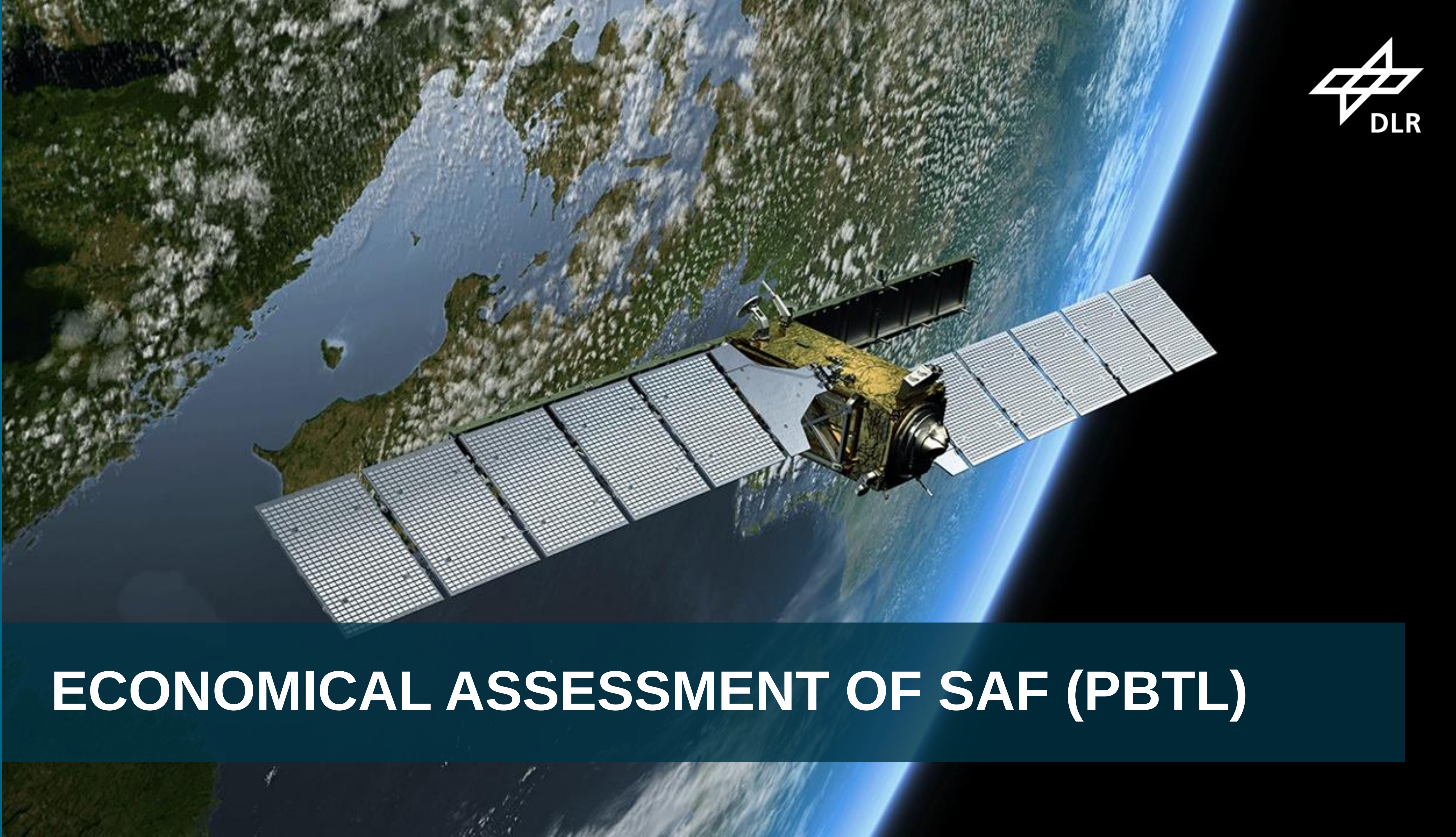
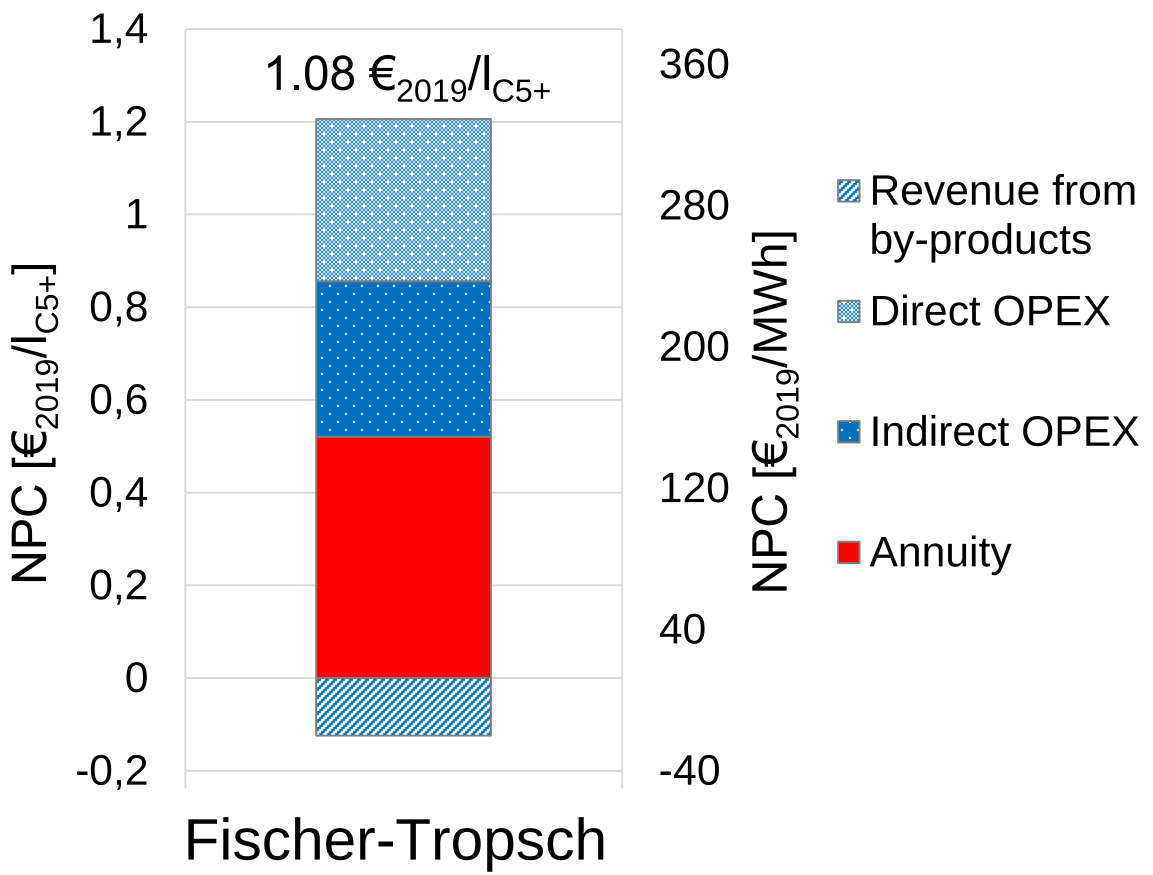


ECONOMICAL ASSESSMENT OF SAF (PBTL)

FLEXCHX Cost breakdown – Winter mode

NPC Breakdown for 76 kt/a SAF



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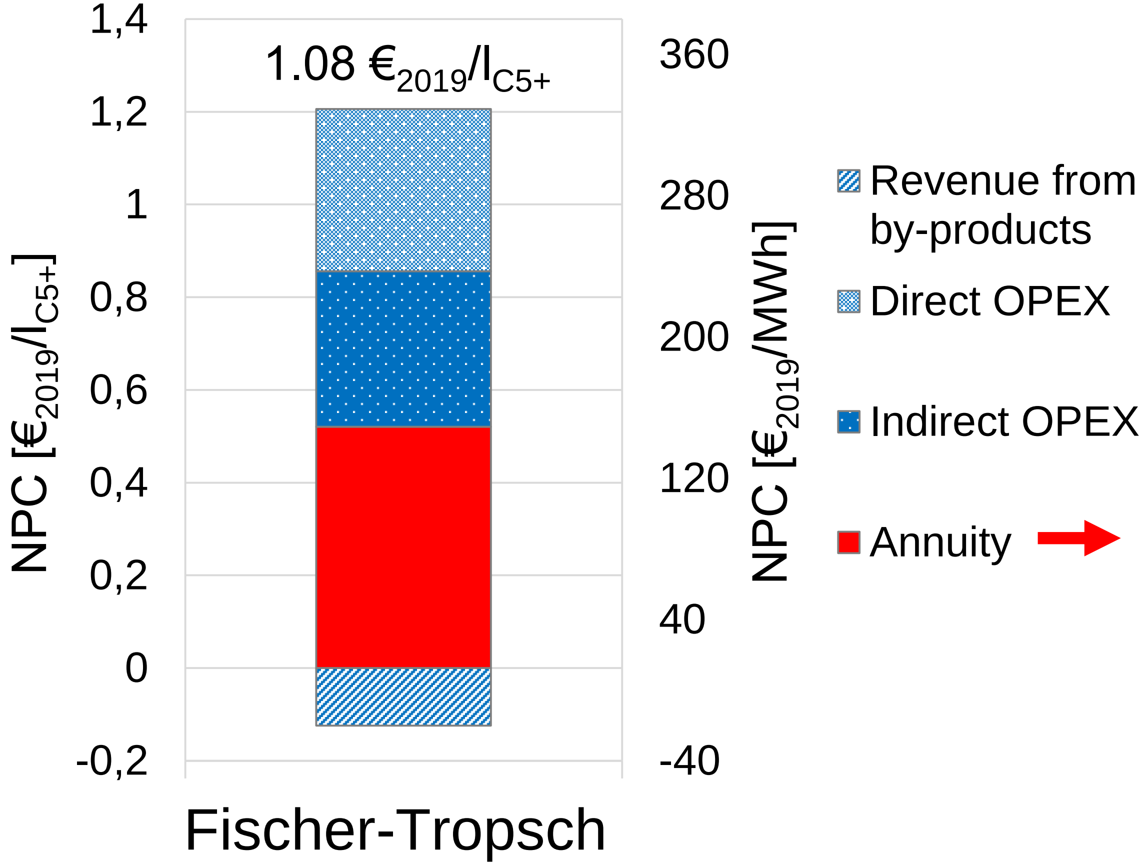
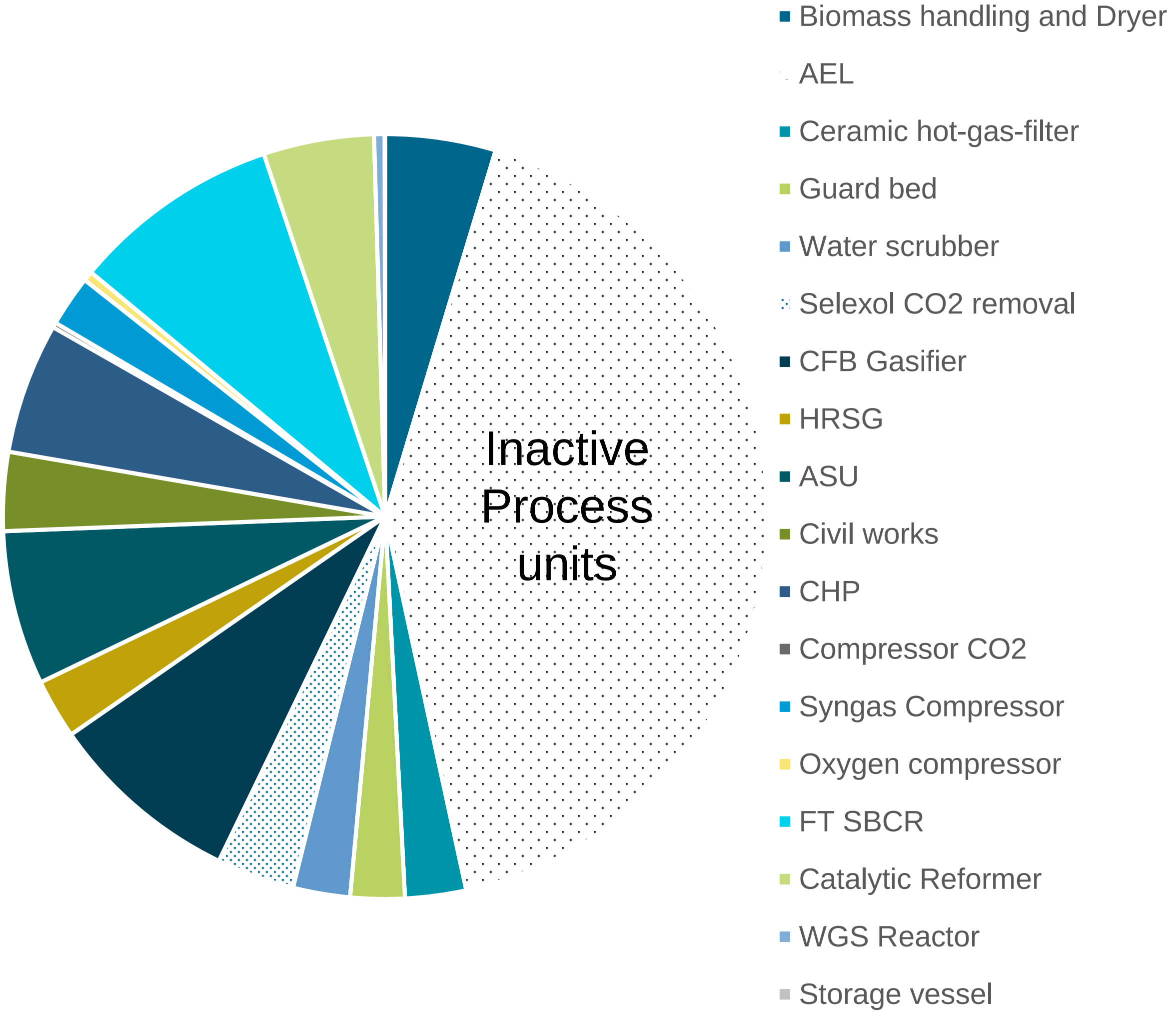
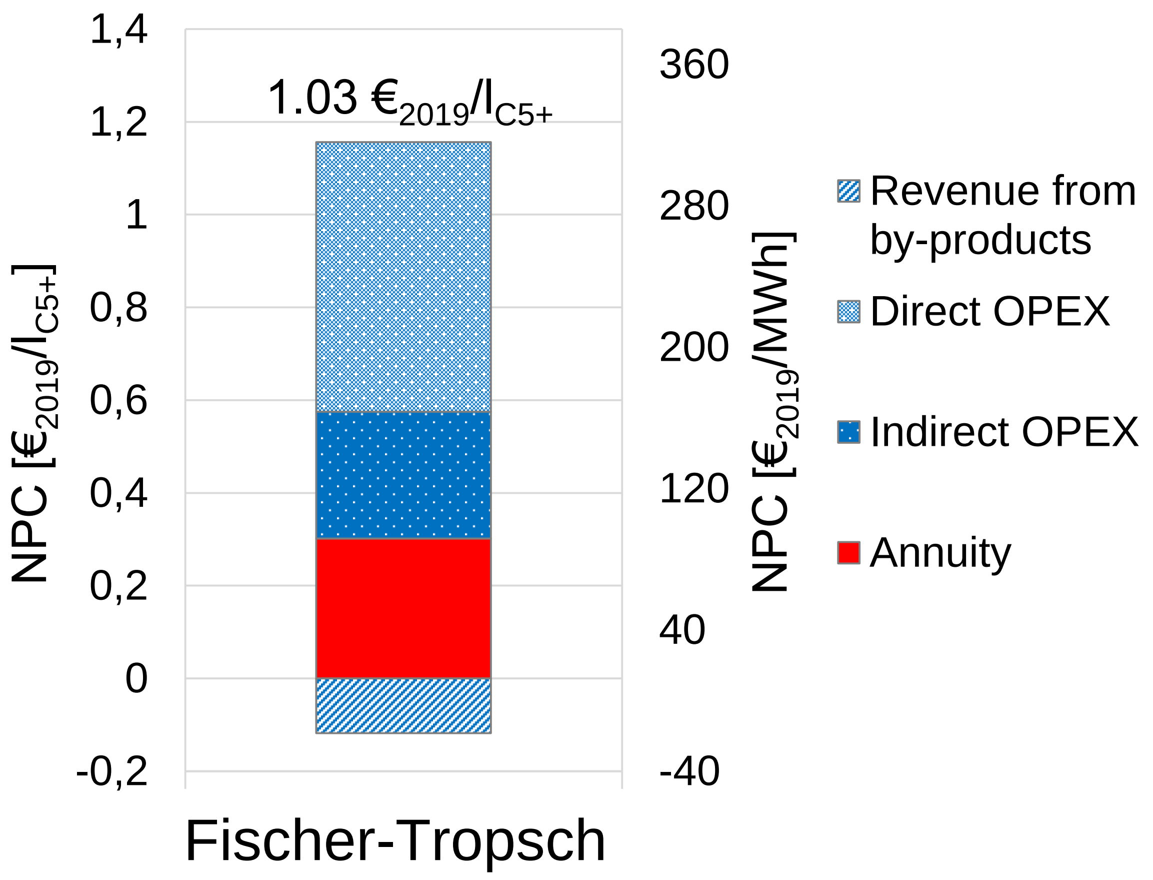


CAPEX



FLEXCHX Cost breakdown – Summer mode

NPC Breakdown for 132 kt/a SAF



FLEXCHX Cost breakdown – Summer mode

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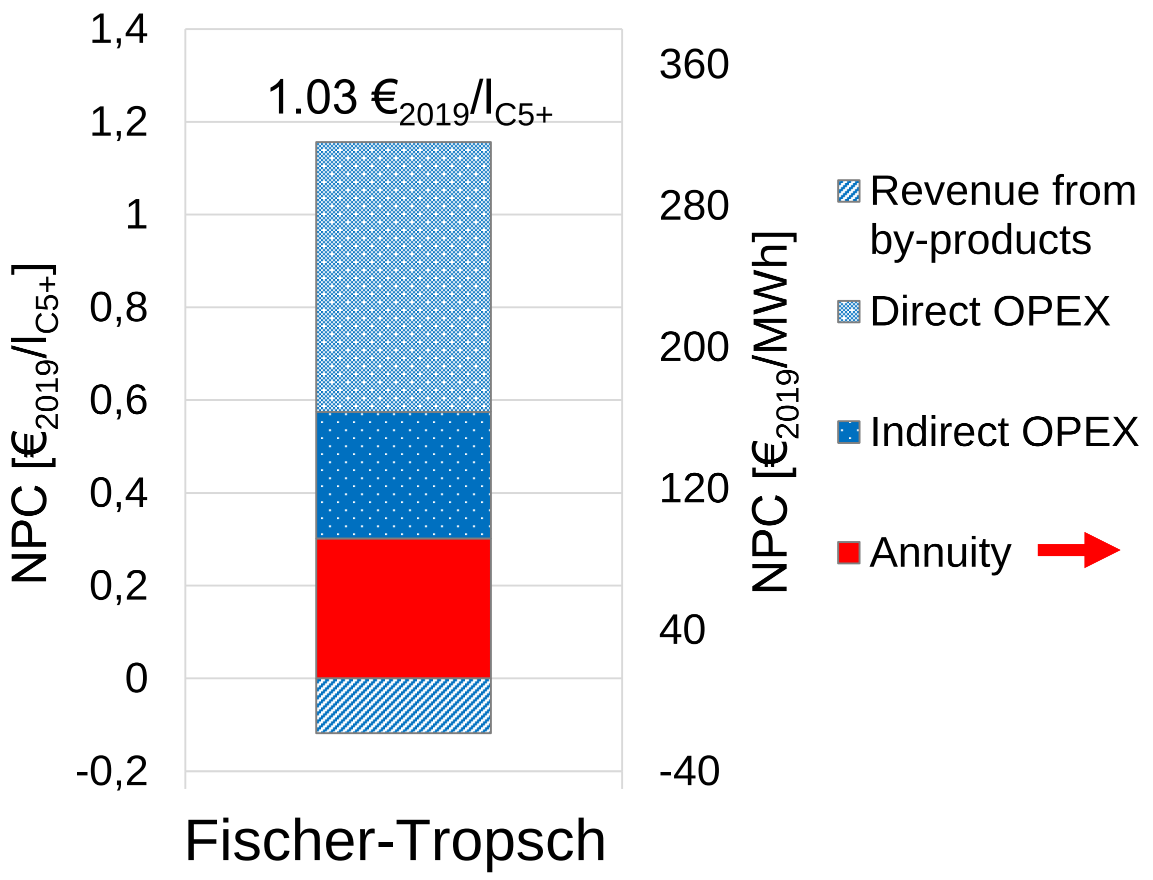

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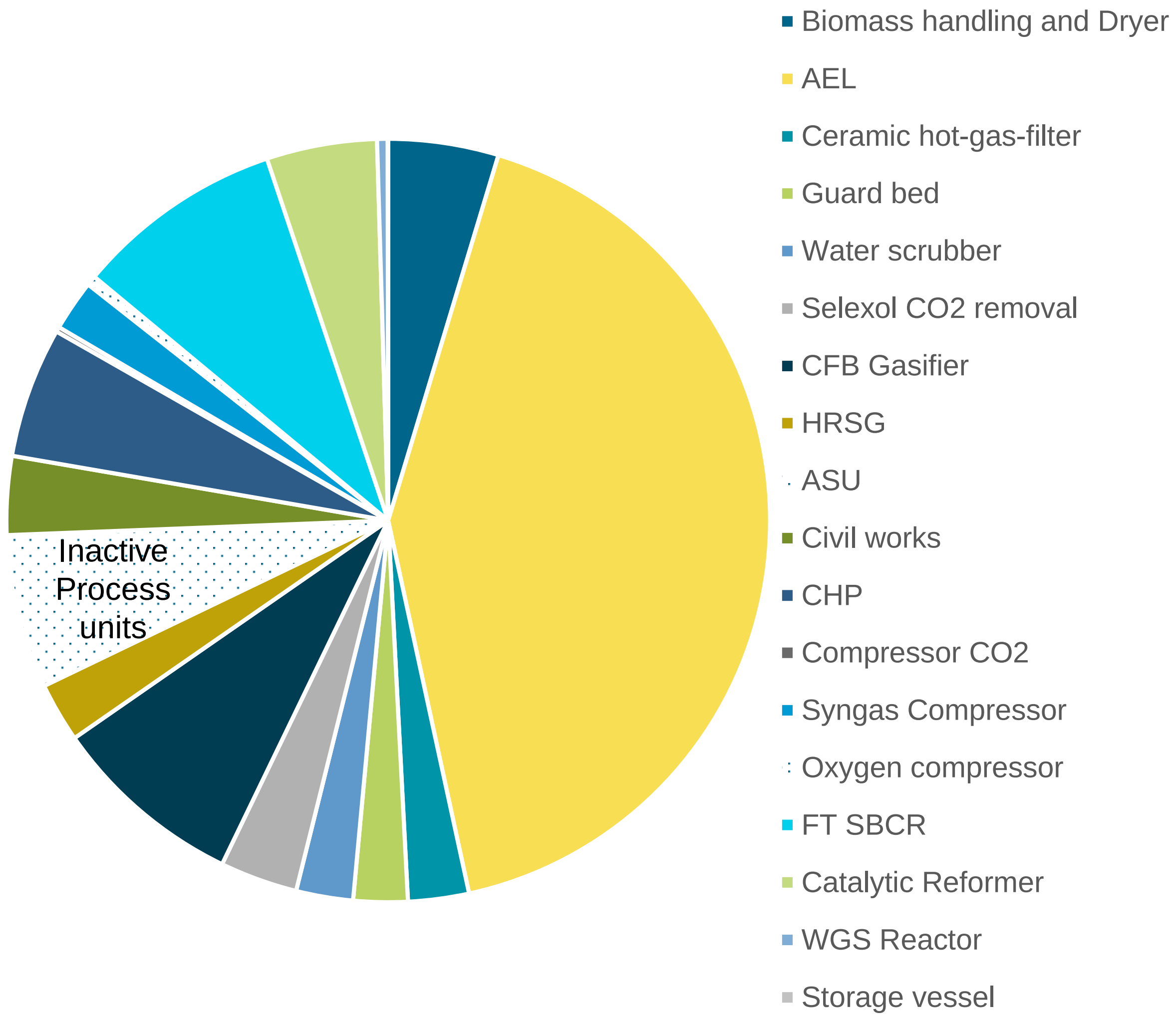

Techno-Economic Assessment of Power&Biomass-to-Liquid SAF

Net production cost sensitivity [1] :

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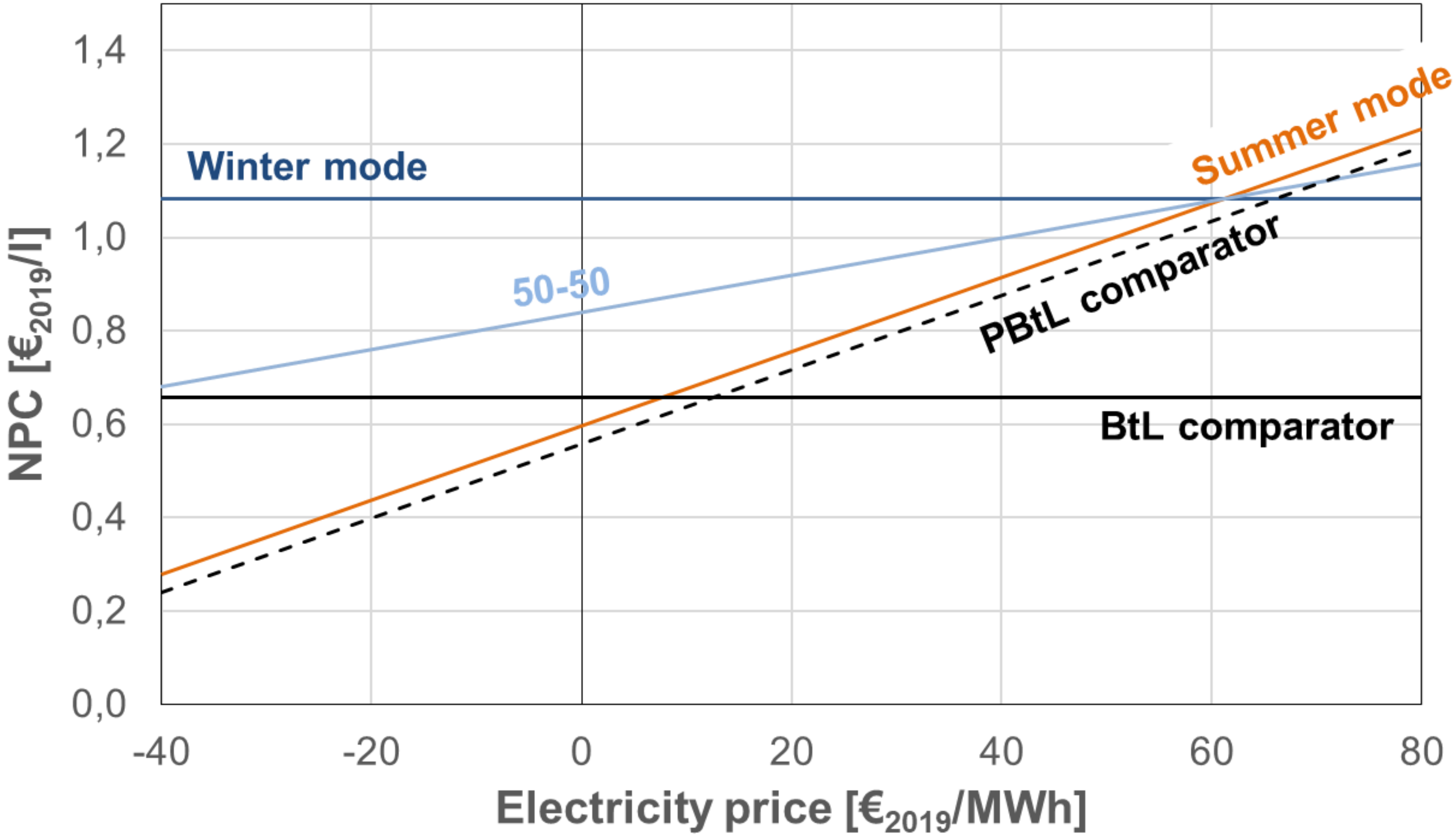

[1]Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774

ENVIRONMENTAL ASSESSMENT OF SAF (PBTL)

Environmental Assessment of Power&Biomass-to-Liquid SAF

Global Warming Potential (GWP)

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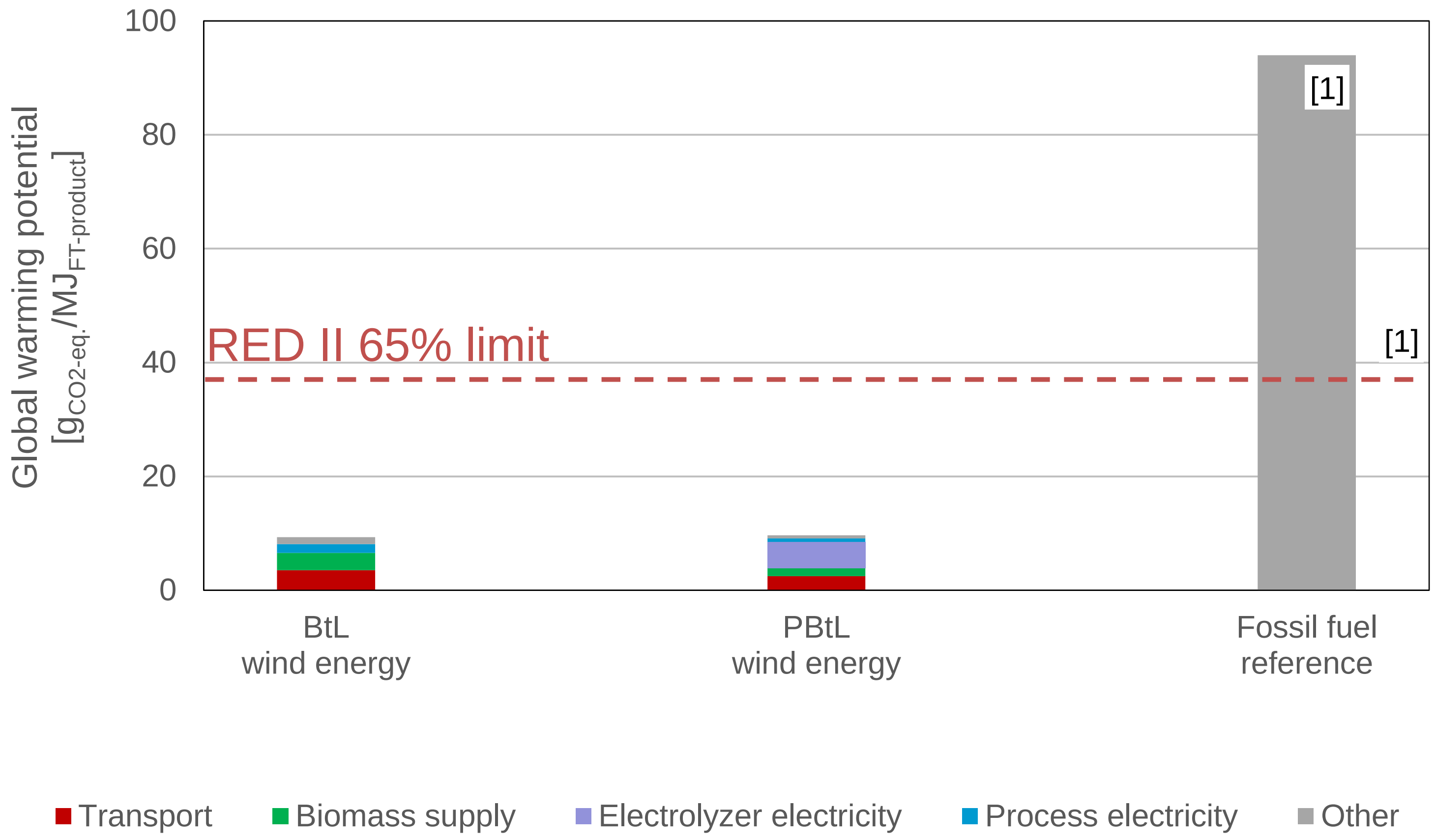

- **Transportation: truck (one-way)**
  - 100 km biomass
  - 200 km FT-products
- **Biomass: Harvesting woody residues (bark, saw dust, wood chips)**
- **Electricity: Finnish wind energy**

Conclusion

REDII target accomplished under FLEXCHX base case assumptions

[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 Power&Biomass-to-Liquid SAF

Global Warming Potential (GWP)

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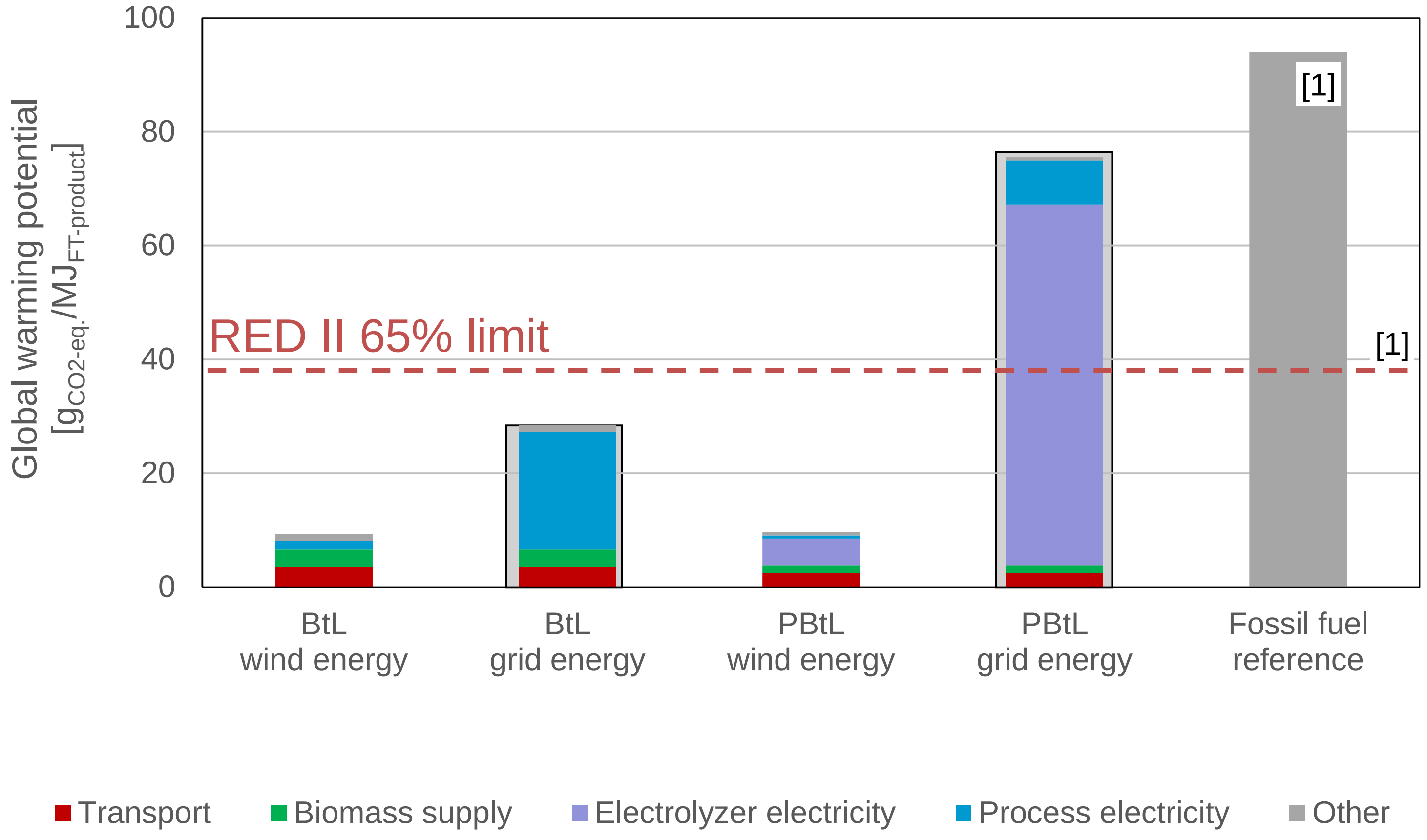

- Transportation: truck (one-way)
  - 100 km biomass
  - 200 km FT-products
- Biomass: Harvesting woody residues (bark, saw dust, wood chips)
- Electricity: Finnish wind energy
  Finnish grid mix

Conclusion

REDII accomplishment doubtful using Finnish grid power

[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 Power&Biomass-to-Liquid SAF

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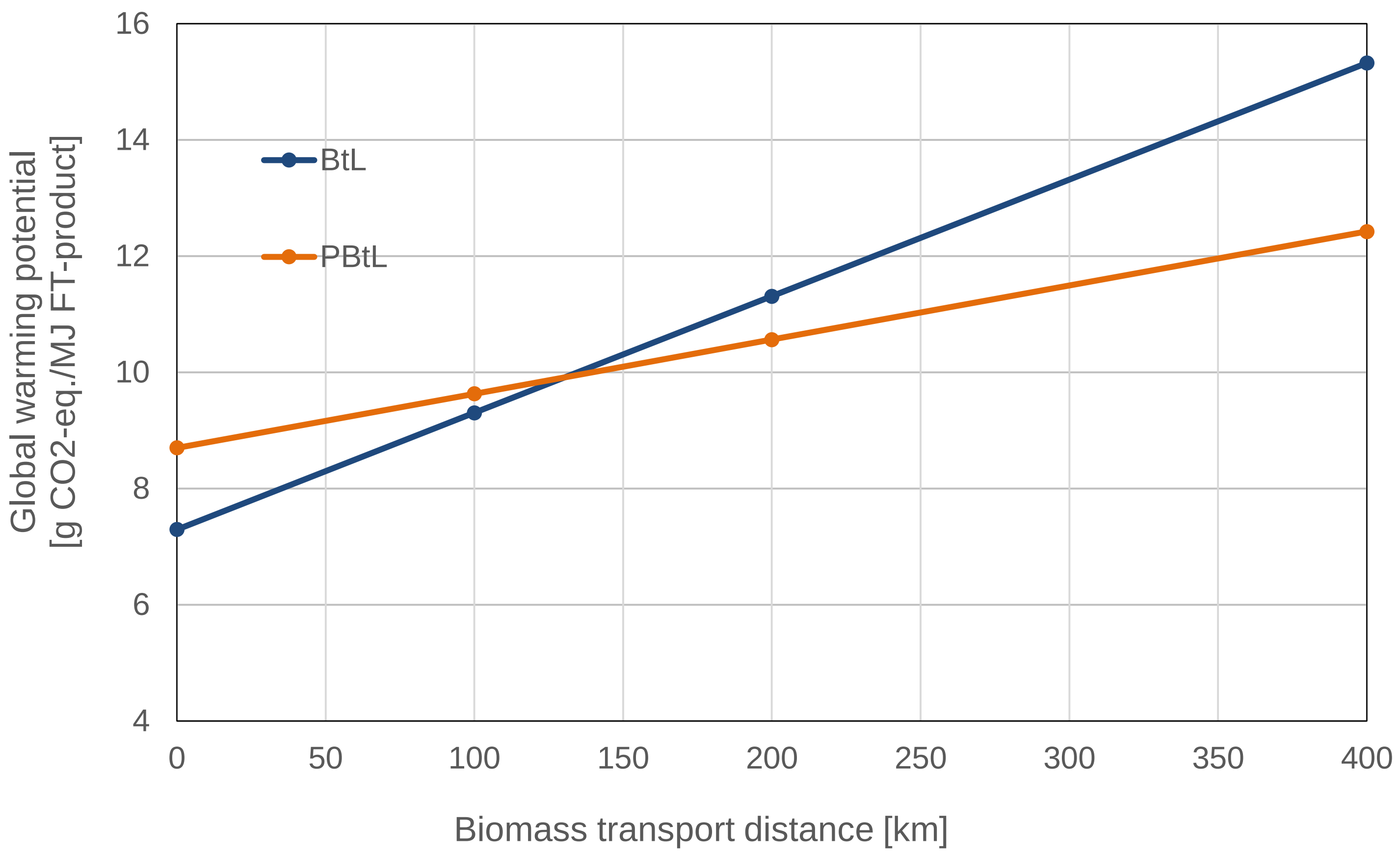


- **Transportation: truck (one-way)**
  - longer biomass transport
  = higher feedstock availability
  - 200 km FT-products
- **Biomass: Harvesting woody residues (bark, saw dust, wood chips)**
- **Electricity: Finnish wind energy (electrolyzer excluded)**

Conclusion

- Biomass transport distance effects GWP of SAF
- Lower effect on PBtL GWP
- BtL requires short distance preferred < 130 km

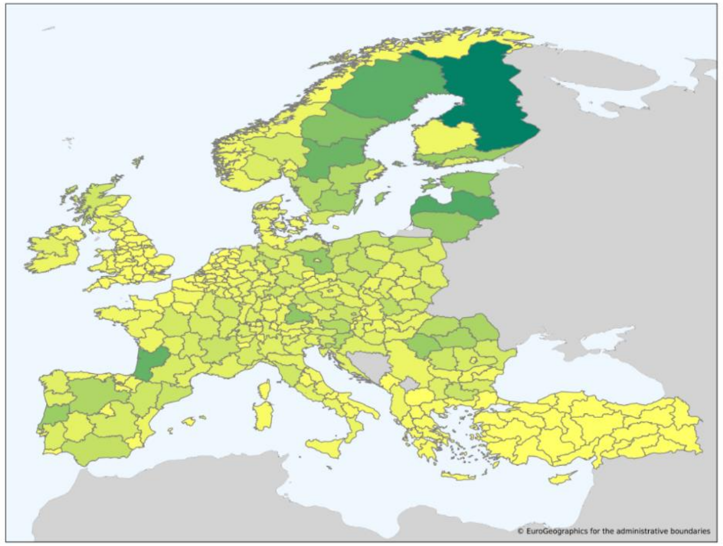
[1] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union,

POTENTIAL EUROPEAN SAF ROADMAP

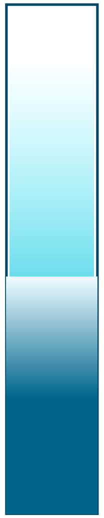
PBtL techno-economic-ecologic analysis for European SAF

PBtL as a suitable SAF production route for Europe?

- Significant contribution to future European aviation fuel demand[1]
- Fuel production GHG below 32.9 $g_{CO2,eq}$/MJ (RED II) [2]
- Low production cost



63 Mt/a (2030?)



[1] S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf.
[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG (Accessed 09/2022)

European SAF Roadmap key economic assumptions

Key Assumptions of multiple 400 MW_{th} biomass plants (400 kt_{SAF}/a)

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]

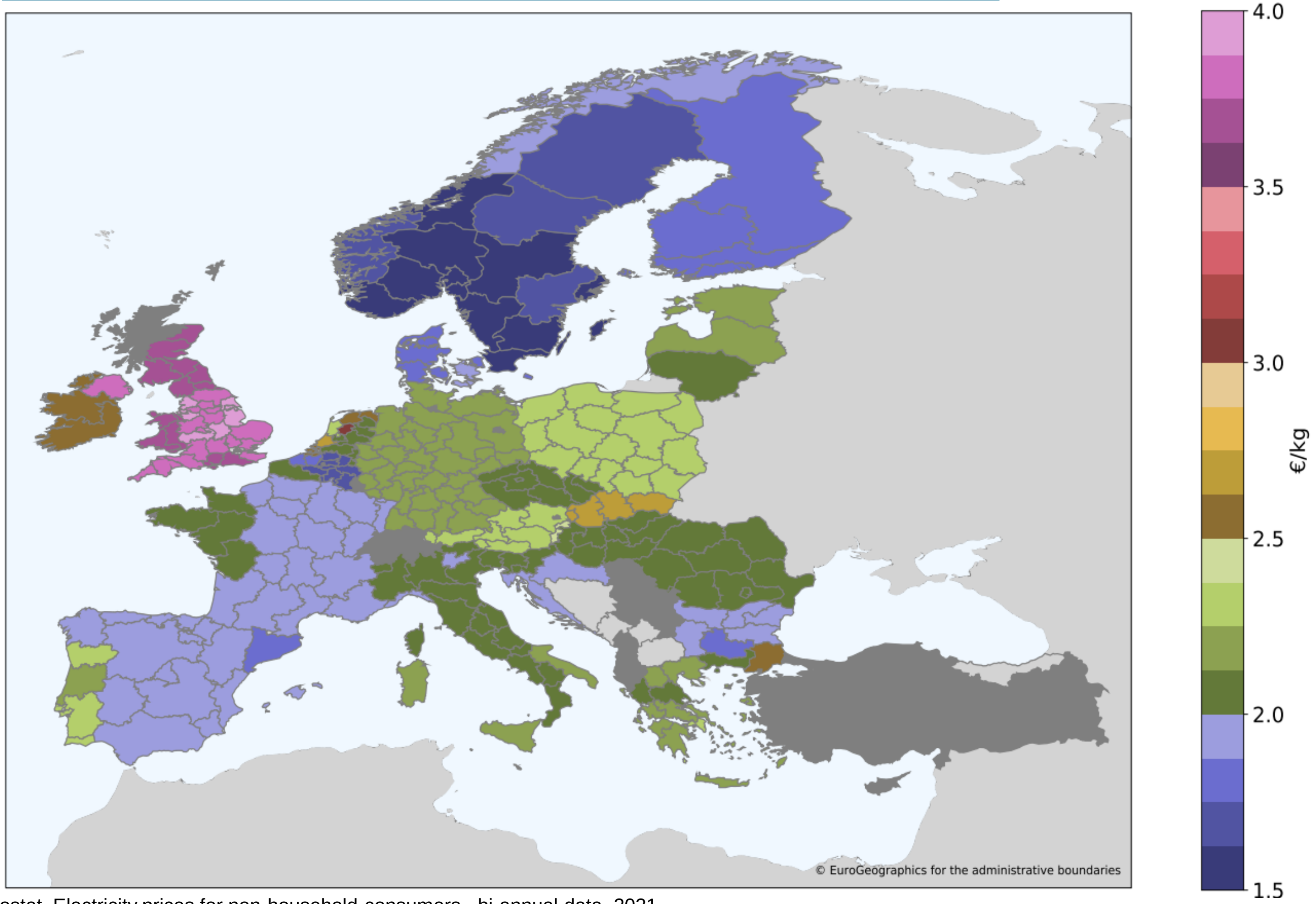
General economic assumptions:

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.

Northern EU's inexpensive electricity: Lowest NPC

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



NUTS 2 region specific conditions:

- National electricity prices from [1]
- Biomass prices from [2]
- Transport distance as a function of biomass density
- Nation-specific transport and labor costs

[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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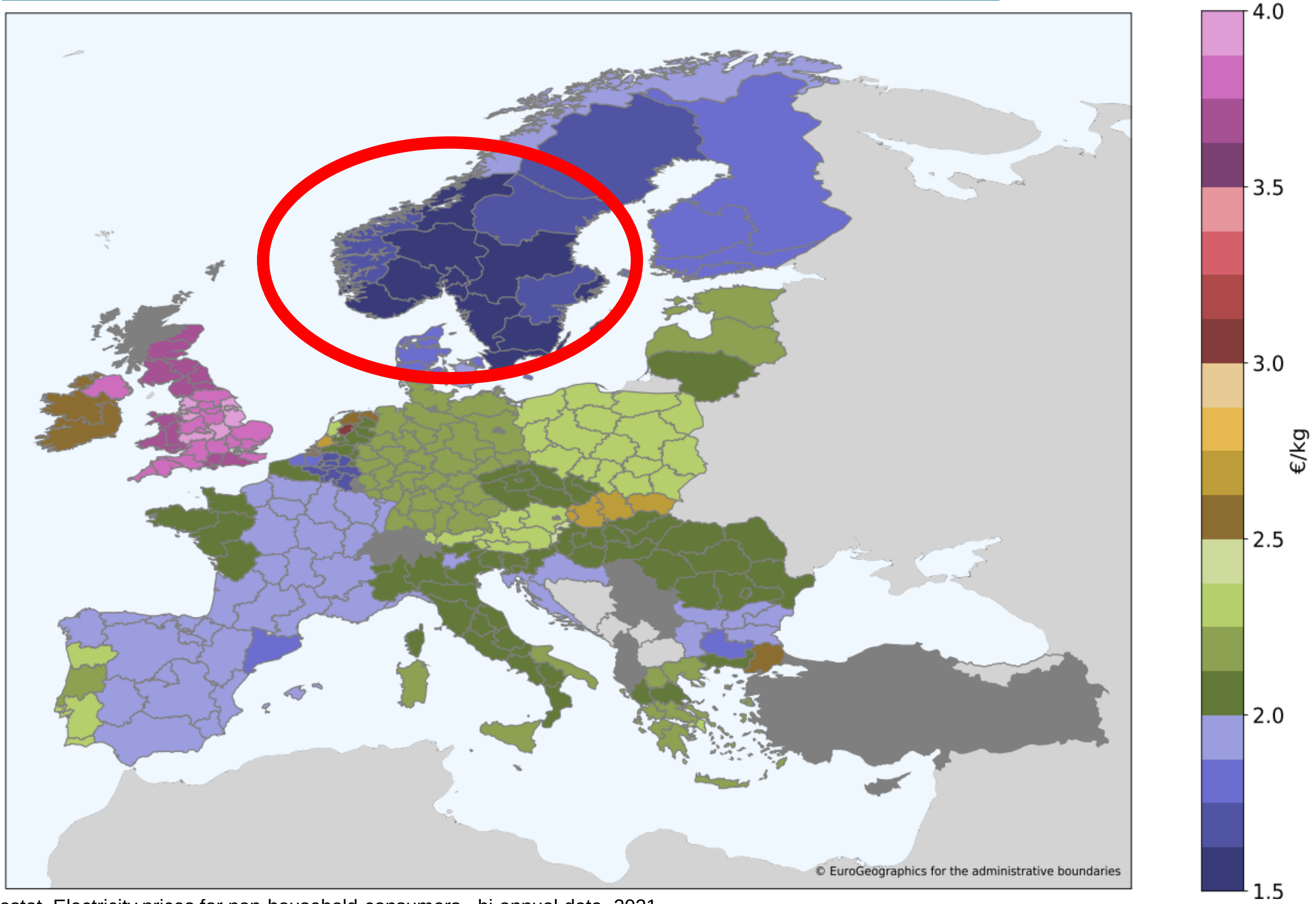


NUTS 2 region specific conditions:

- National electricity prices from [1]
- Biomass prices from [2]
- Transport distance as a function of biomass density
- Nation-specific transport and labor costs

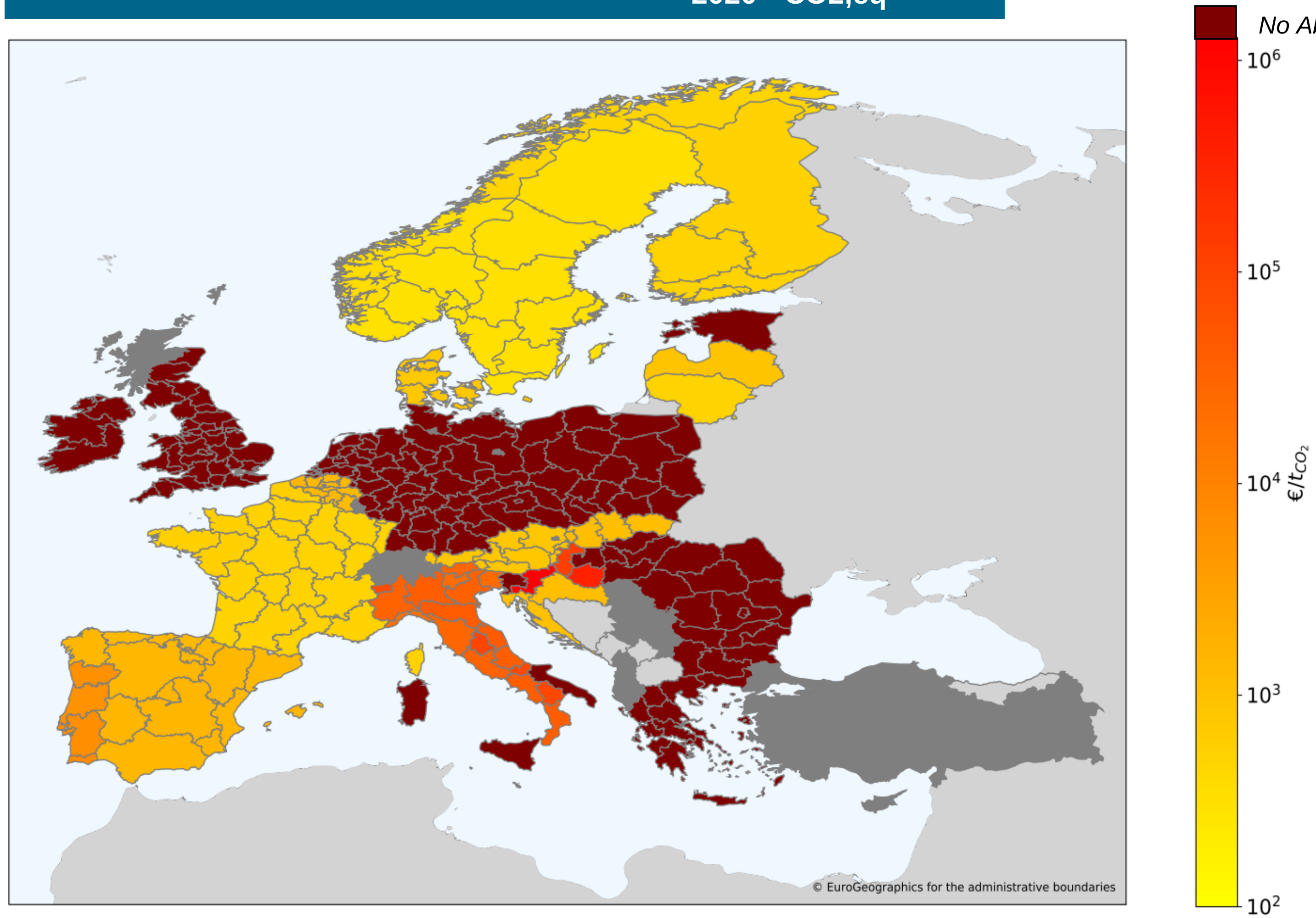
➔ Search for cheap biomass residue and inexpensive renewable power

1. Norway (57 $MJ_{dry\ biom}$/a)
2. Sweden (276 $MJ_{dry\ biom}$/a)
3. Finland (201 $MJ_{dry\ biom}$/a)

[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.

High GHG emissions in national grid: No GHG abatement for half of Europe

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



NUTS 2 region specific conditions:

- National grid mix GWP [1]
- Region-specific transport emissions
- No GHG abatement for countries with high GHG power grid

[1] Online https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6 [Accessed 14.9.21]

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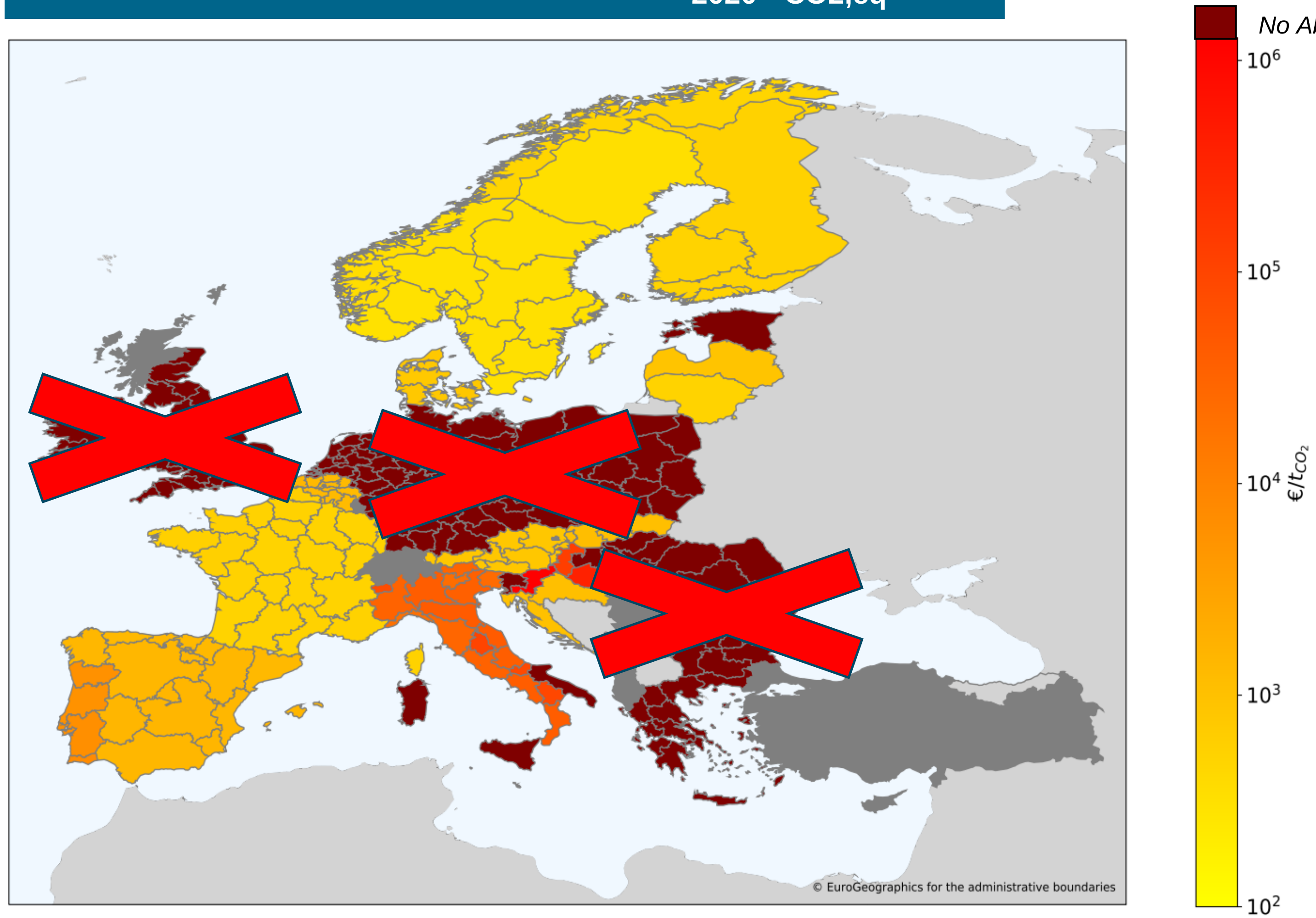
GHG Abatement of PBtL SAF / $€_{2020}/t_{CO2,eq}$



NUTS 2 region specific conditions:

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➔ Decarbonized national grids necessary for effective PBtL roll-out

[1] Online https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6 [Accessed 14.9.21]

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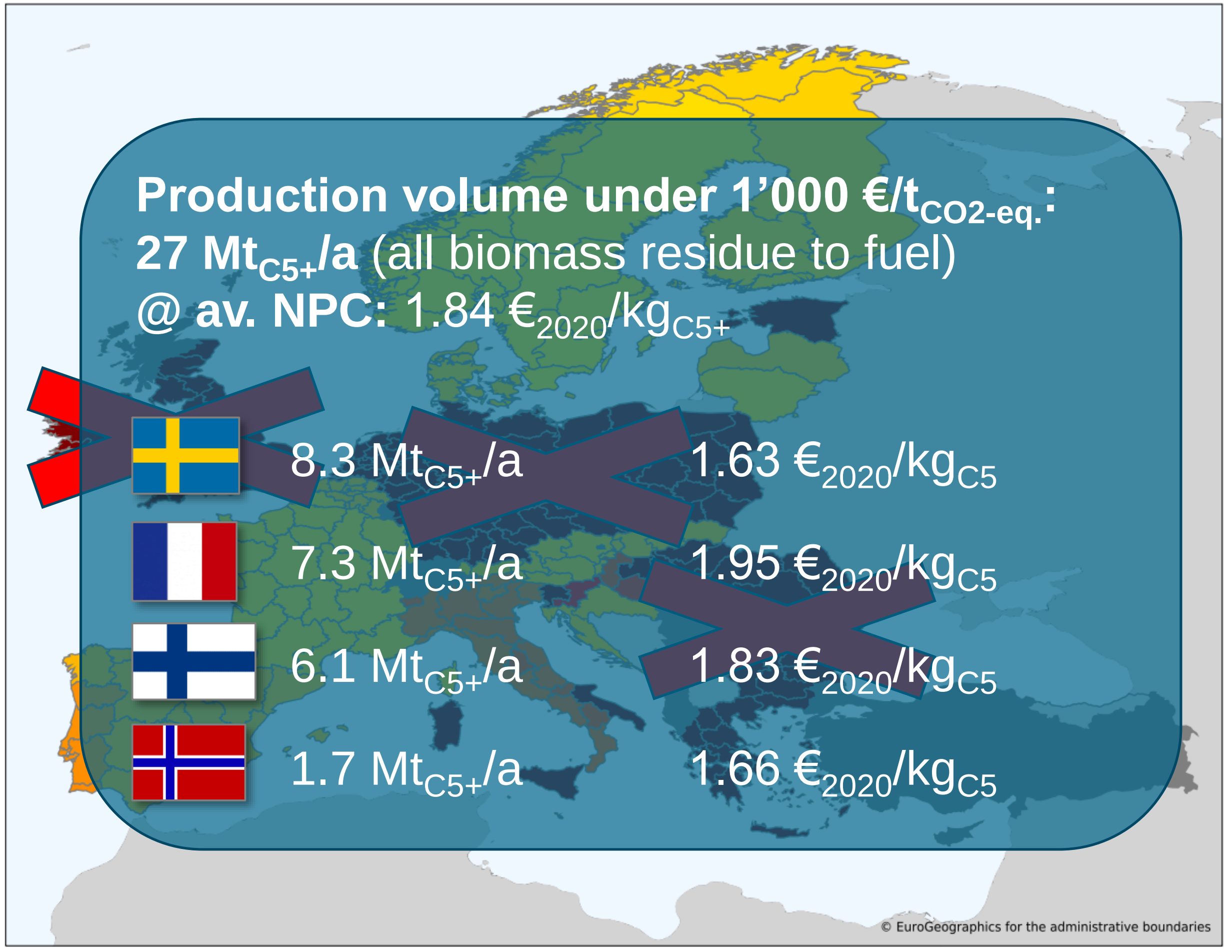

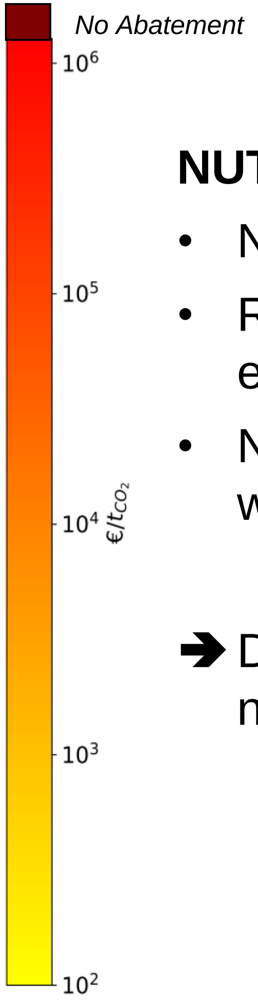

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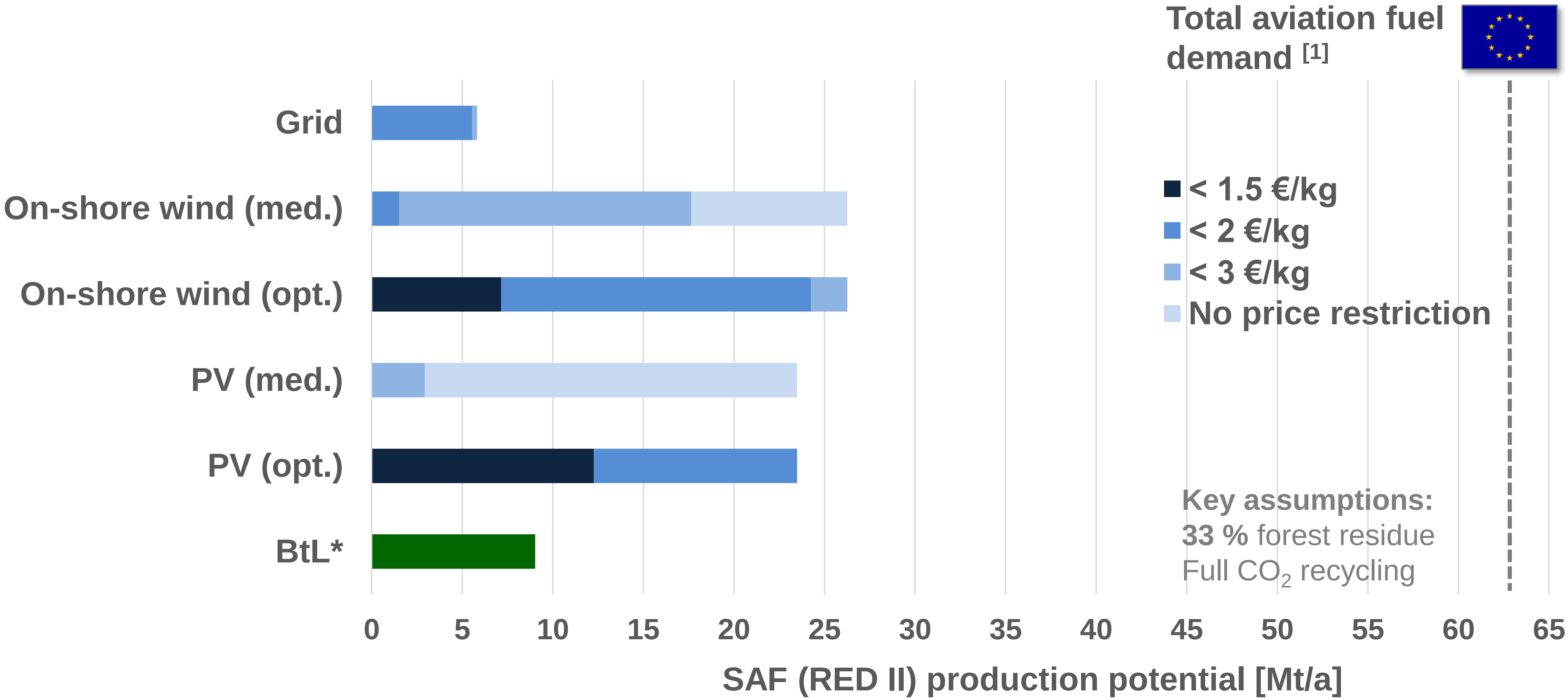
Aggregated European SAF production potential



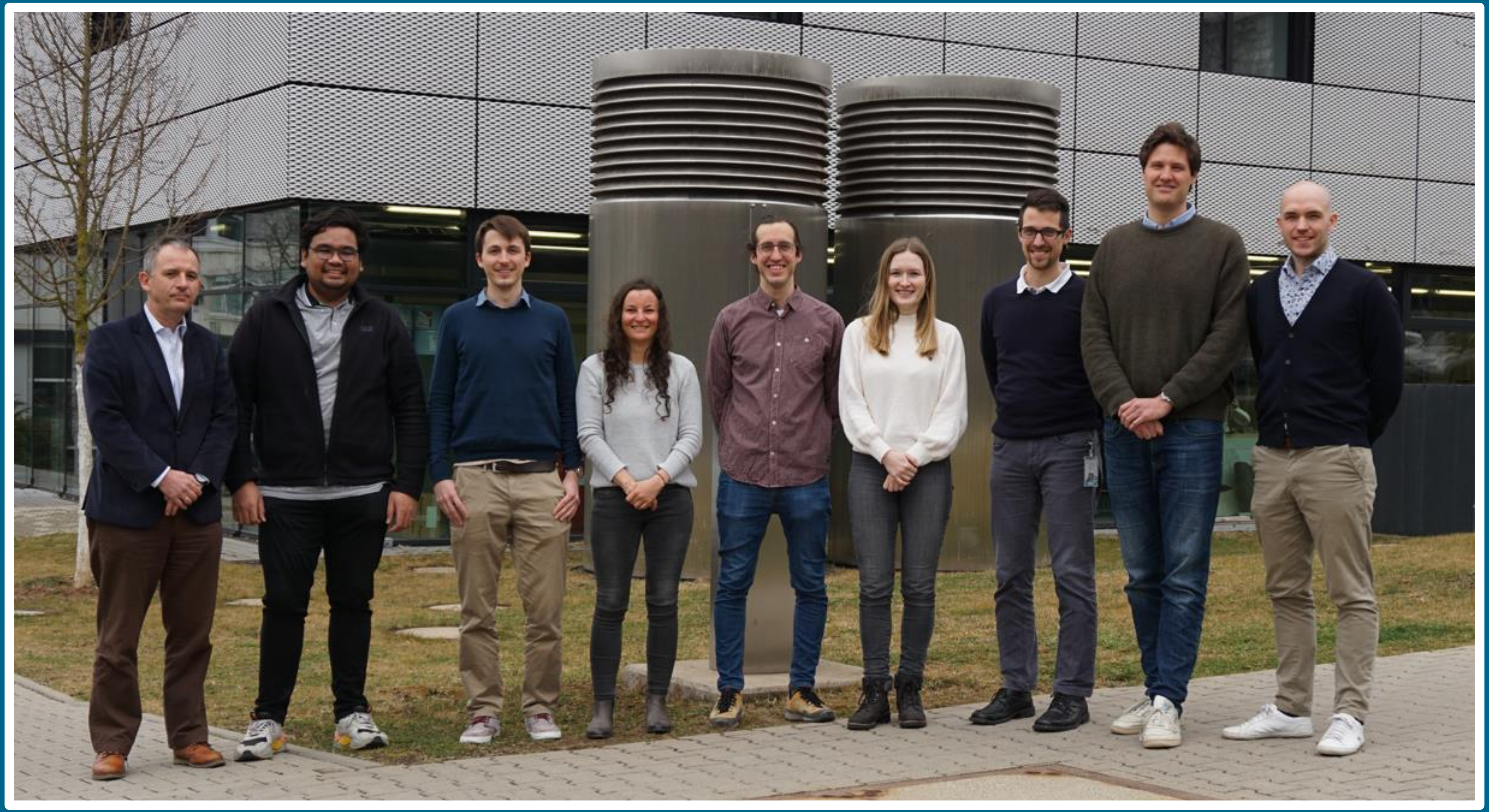
[1] S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf.
*Assumptions: 19.9 % biomass conversion, entire potential under RED II limit

Technical, economic and ecological assessment of European SAF production

Summary

- Renewable fuels are required to meet the aviation contribution towards European climate change mitigation
- PBtL uses affordable renewable carbon and electricity ➔ max. yield
- Renewable Carbon (biomass)
  - Local availability, competing demand, sustainability?
- Renewable Power
  - European ramp up to be accelerated
  - Integration of fluctuating renewable power at large scale?
- Transparent, standardized DLR assessment methodology
  - each technology option, roadmap creation, tracking of progress

THANK YOU FOR YOUR ATTENTION !
Questions?



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