Wednesday, 2024/11/08

Session VI: SAF commercial technologies

Sustainable Aviation Fuels
time for take-off
7-8 November 2024
Athens, Divani Palace Acropolis

TECHNO-ECONOMIC AND (ECOLOGICAL) ASSESSMENT

Large-scale economic production of sustainable aviation fuels in Europe

Ralph-Uwe Dietrich, Felix Habermeyer, Nathanael Heimann,
Simon Maier, Yoga Rahmat, Julia Weyand

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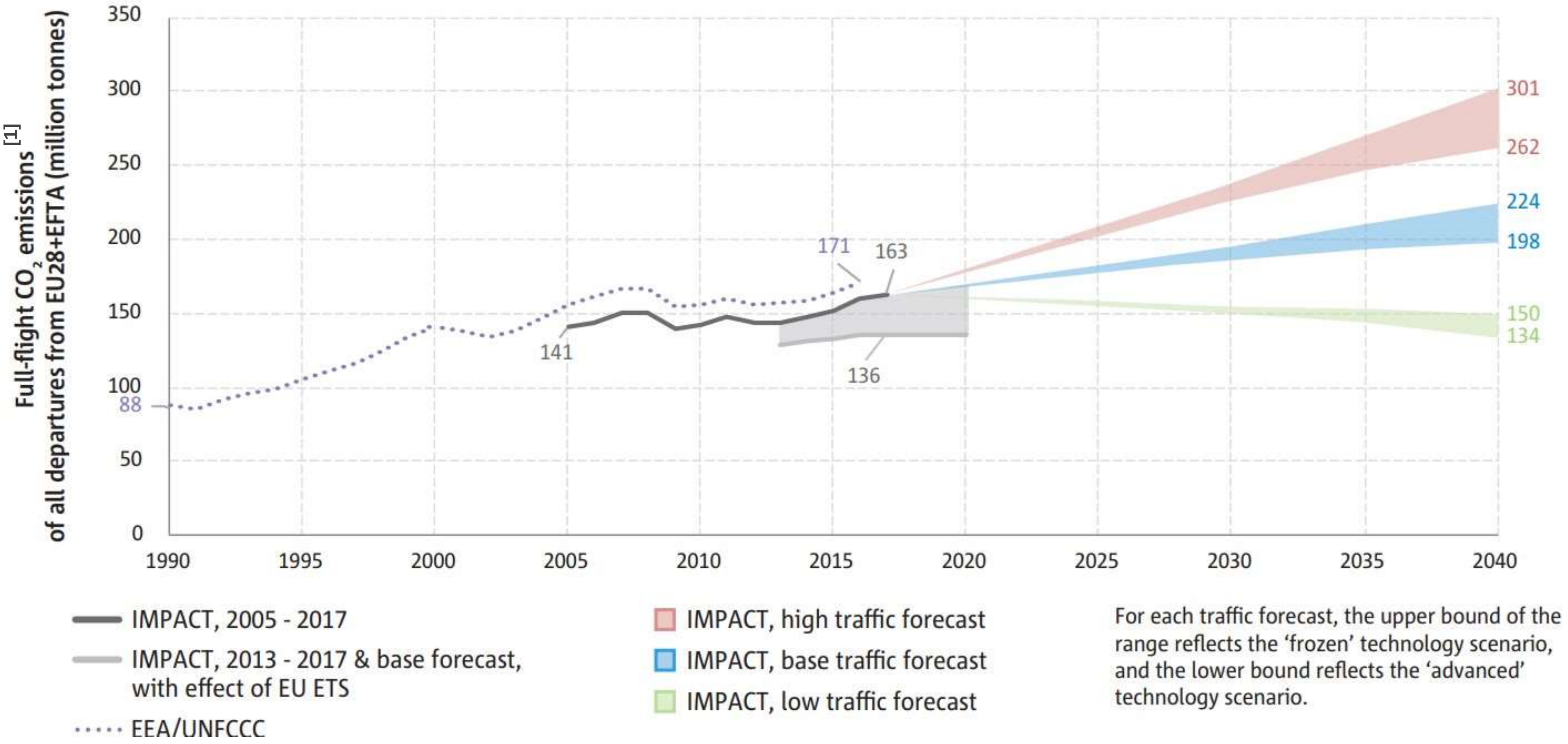
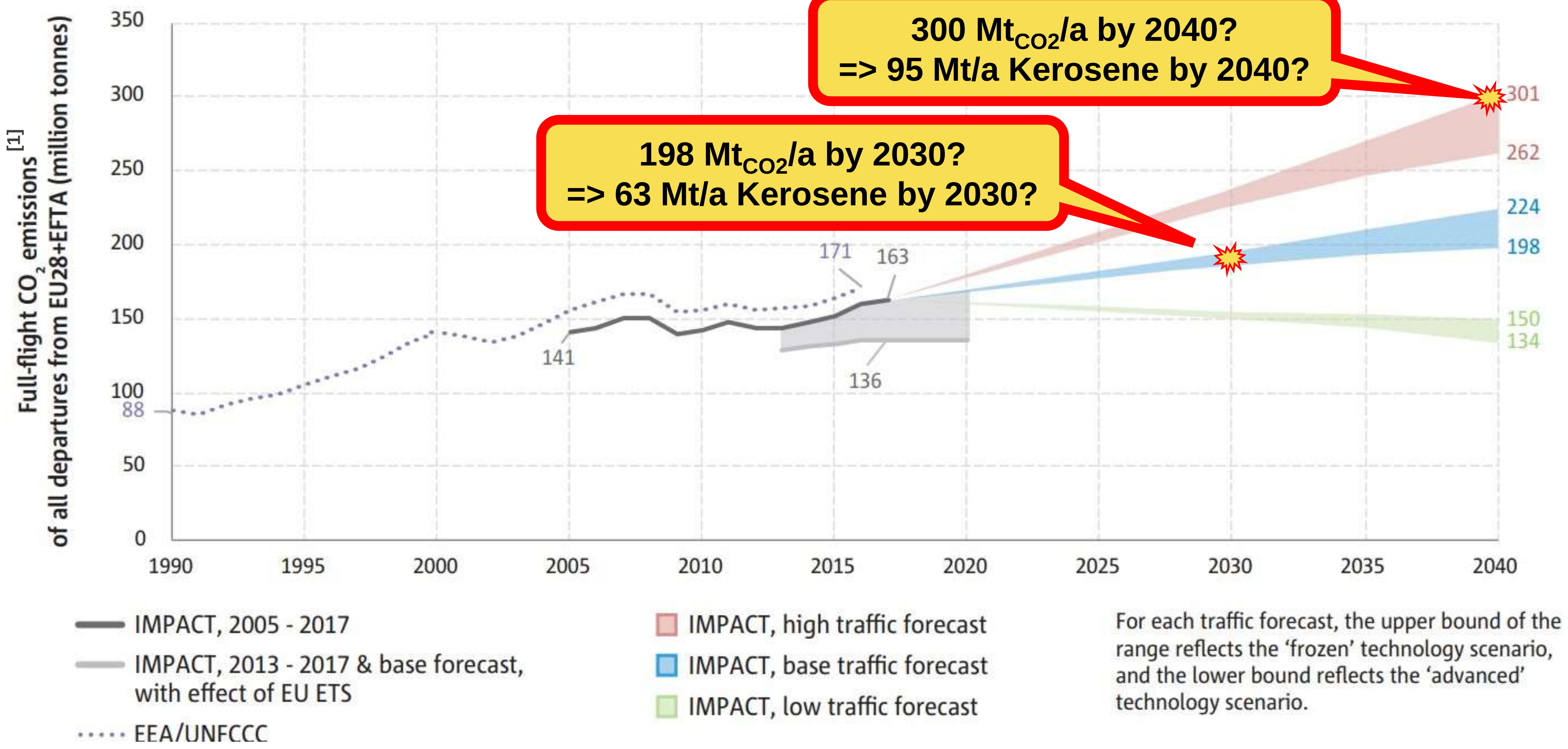
EU aviation CO_2 emissions forecast



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

EU aviation CO_2 emissions forecast
EU aviation CO_2 abatement 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

TECHNO-ECONOMIC AND LIFE CYCLE ANALYSIS

Techno-Economic and Life Cycle Assessment @ DLR

Sustainable Aviation Fuels time for take-off
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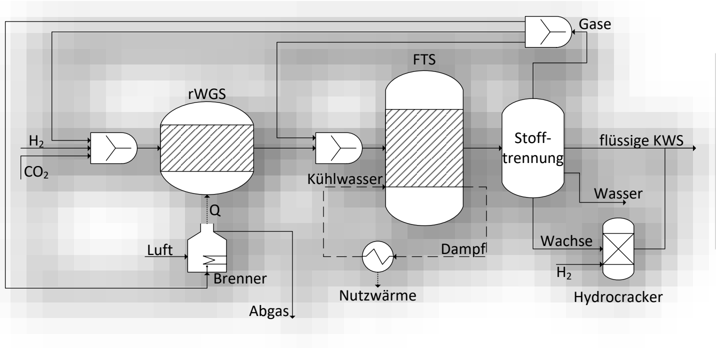
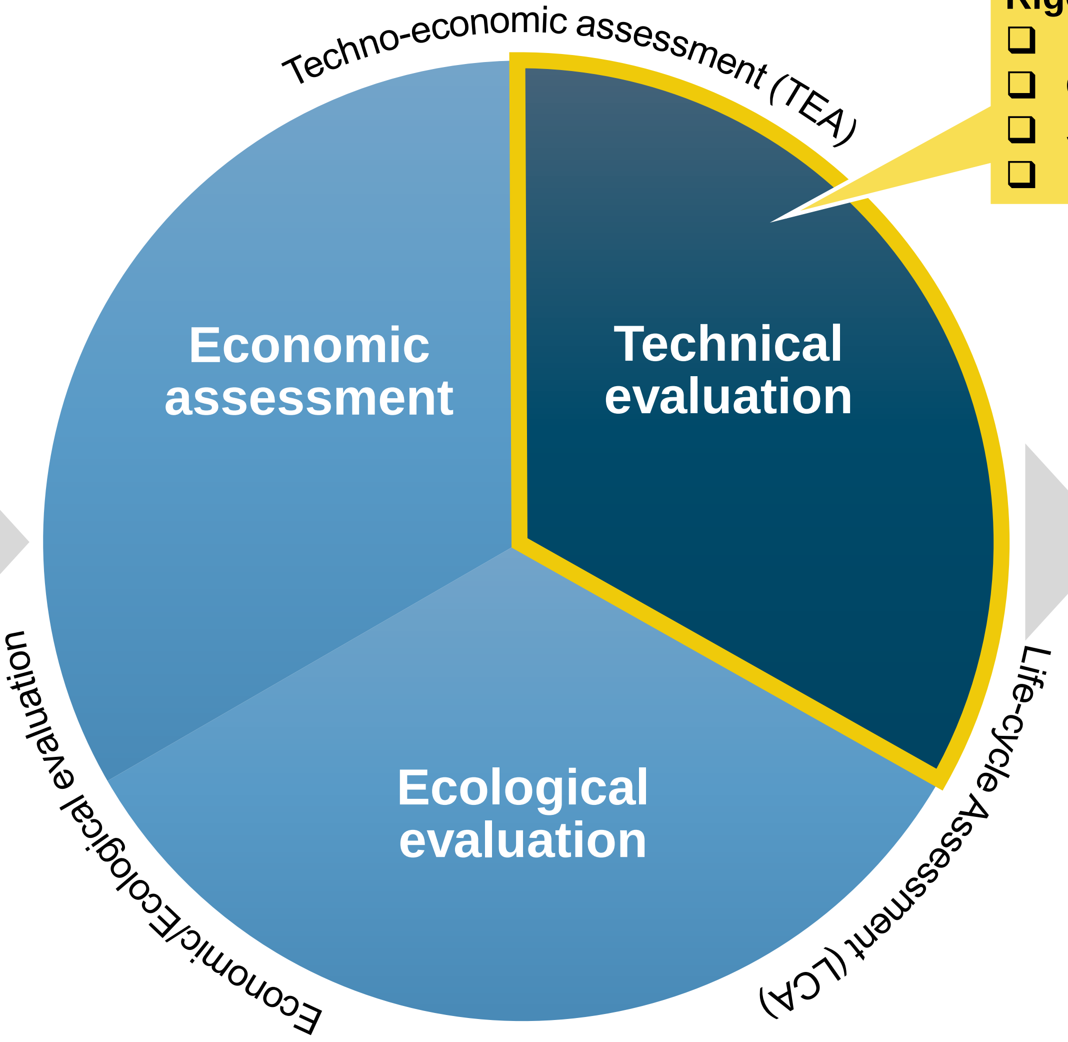
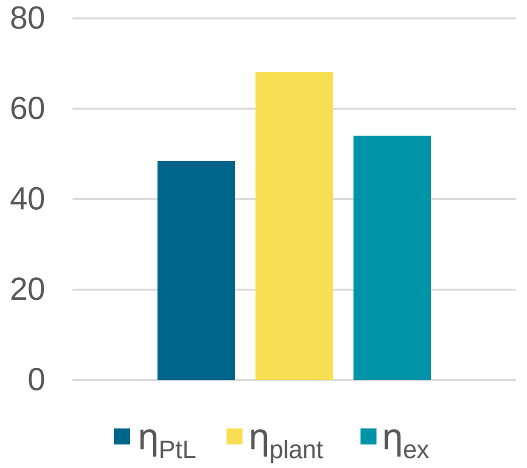
Rigorous process simulation
- ❑ Efficiencies (X-to-Liquid, Overall)
- ❑ Carbon conversion
- ❑ Specific feedstock demand
- ❑ Exergy analysis







Techno-Economic and Life Cycle Assessment @ DLR

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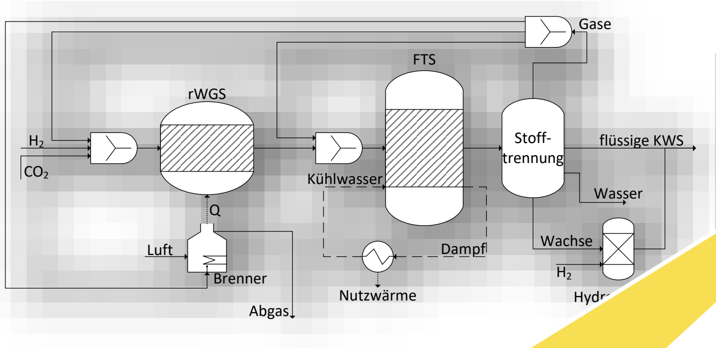

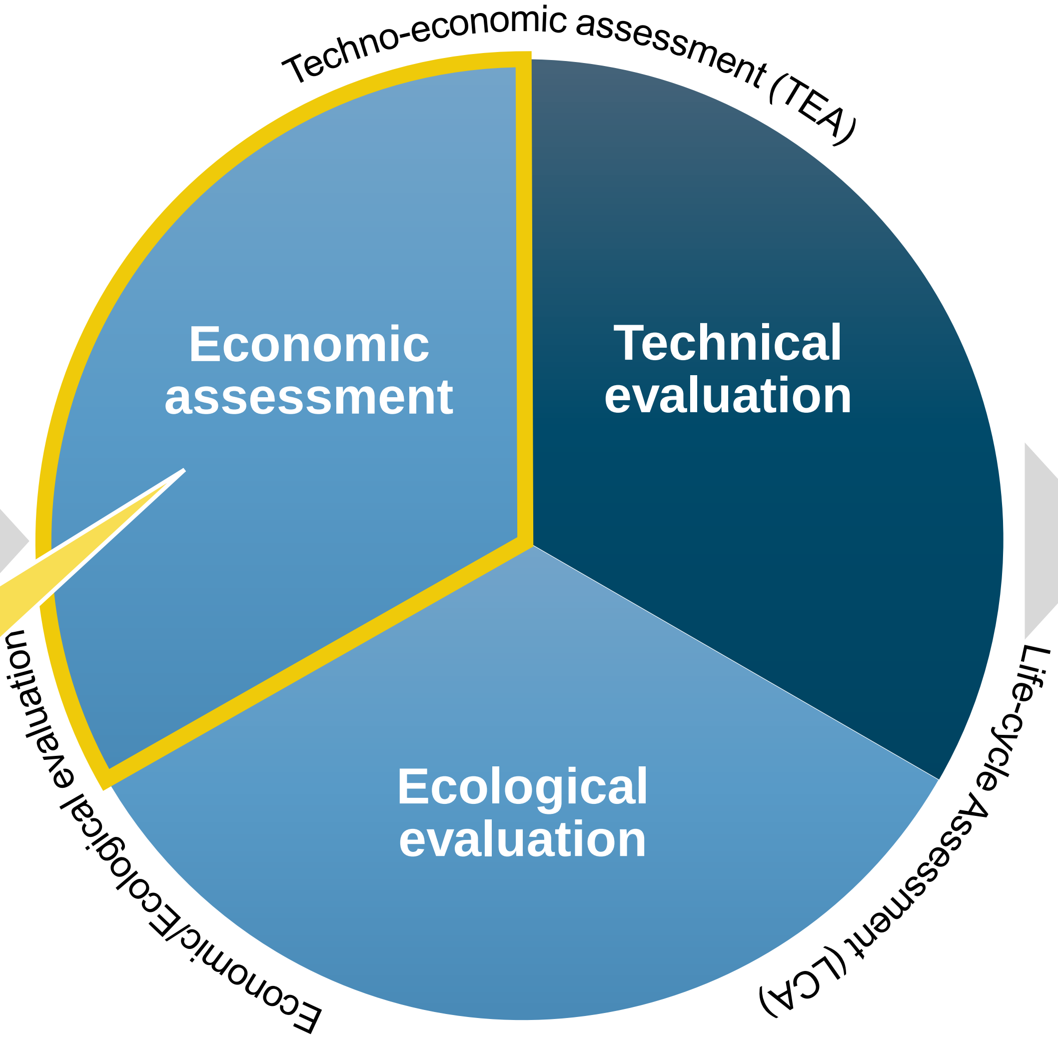

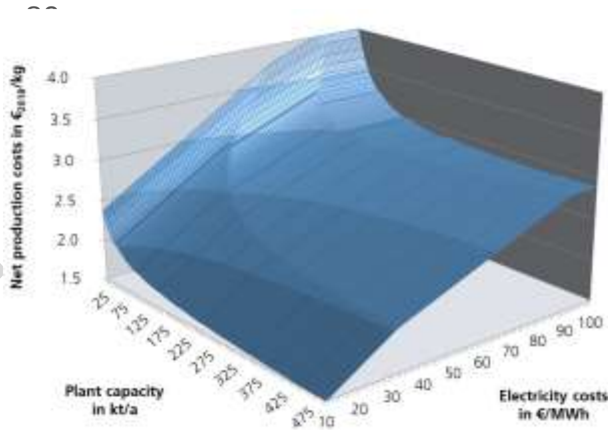

Chemical engineering cost estimation
- ❑ Year-specific CAPEX, OPEX, NPC
- ❑ Sensitivity analysis
- ❑ Identification of most economic feasible process design

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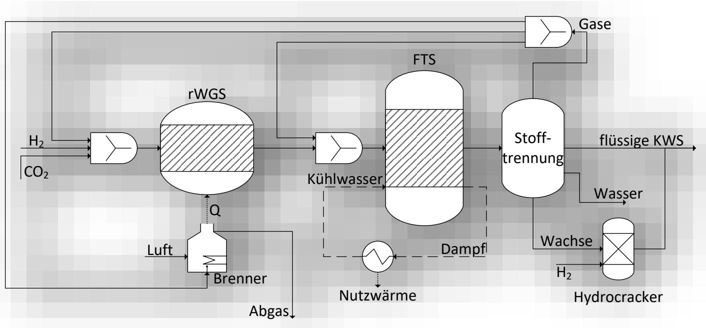

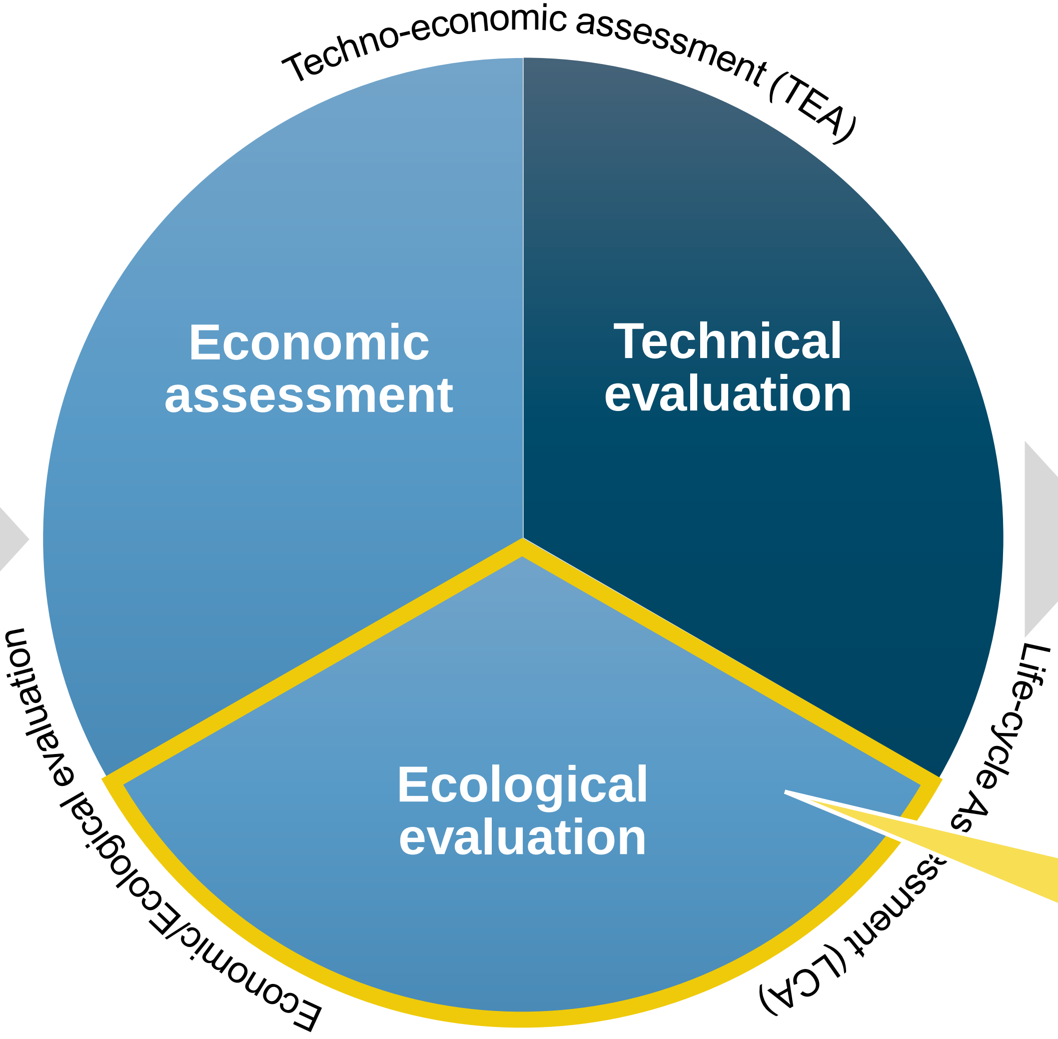

Adapted ISO 14040/14044 LCA
- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

Techno-Economic and Life Cycle Assessment

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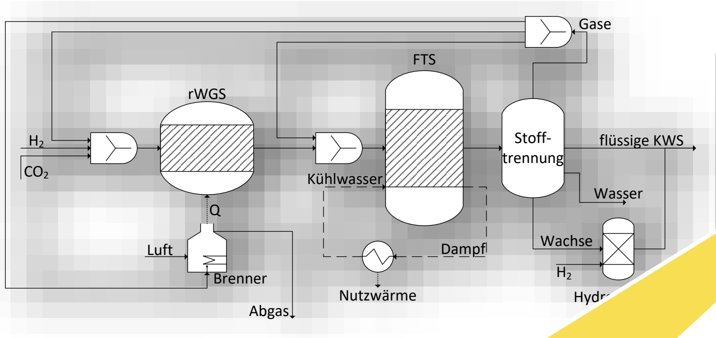

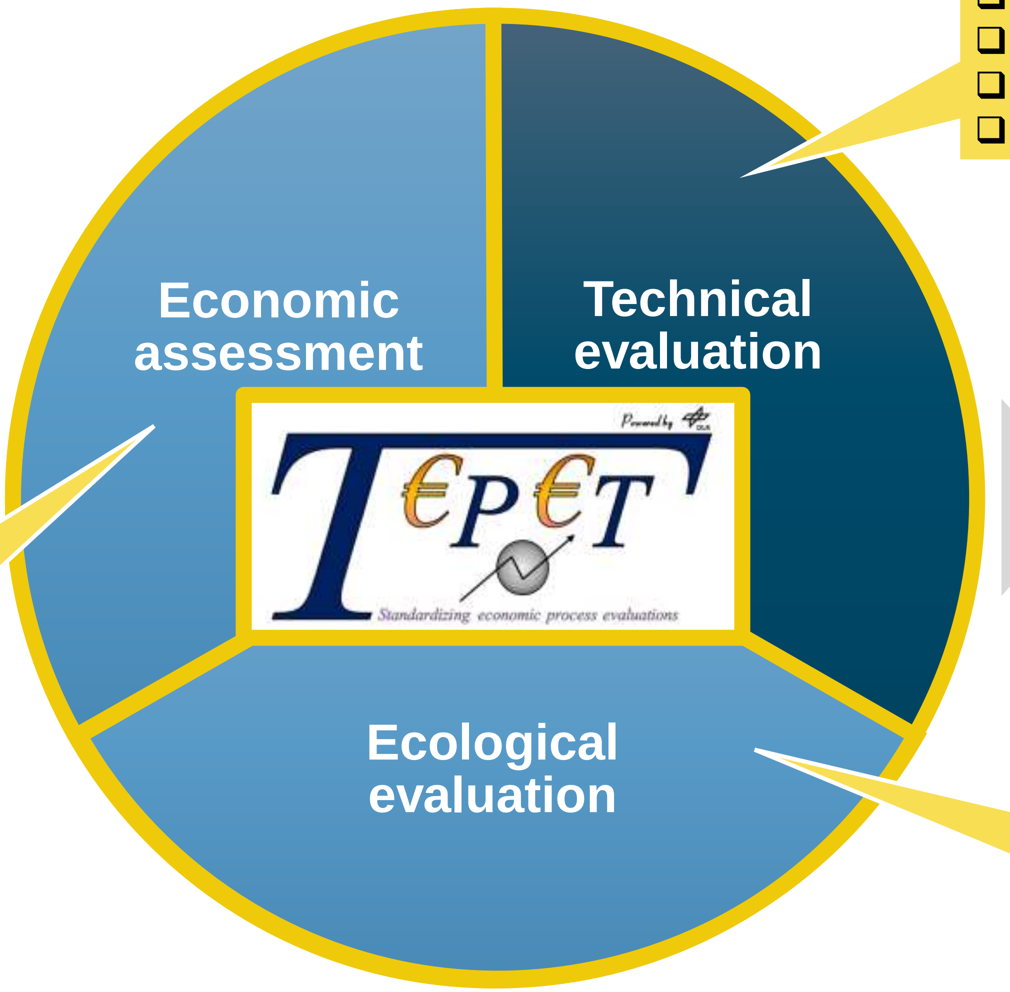

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Adapted ISO 14040/14044 LCA
- ❑ GWP
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ASSESSMENT BASICS FOR UNDERGRADUATES

Fischer-Tropsch based SAF concepts
Stochiometric comparison with HEFA

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

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

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

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

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

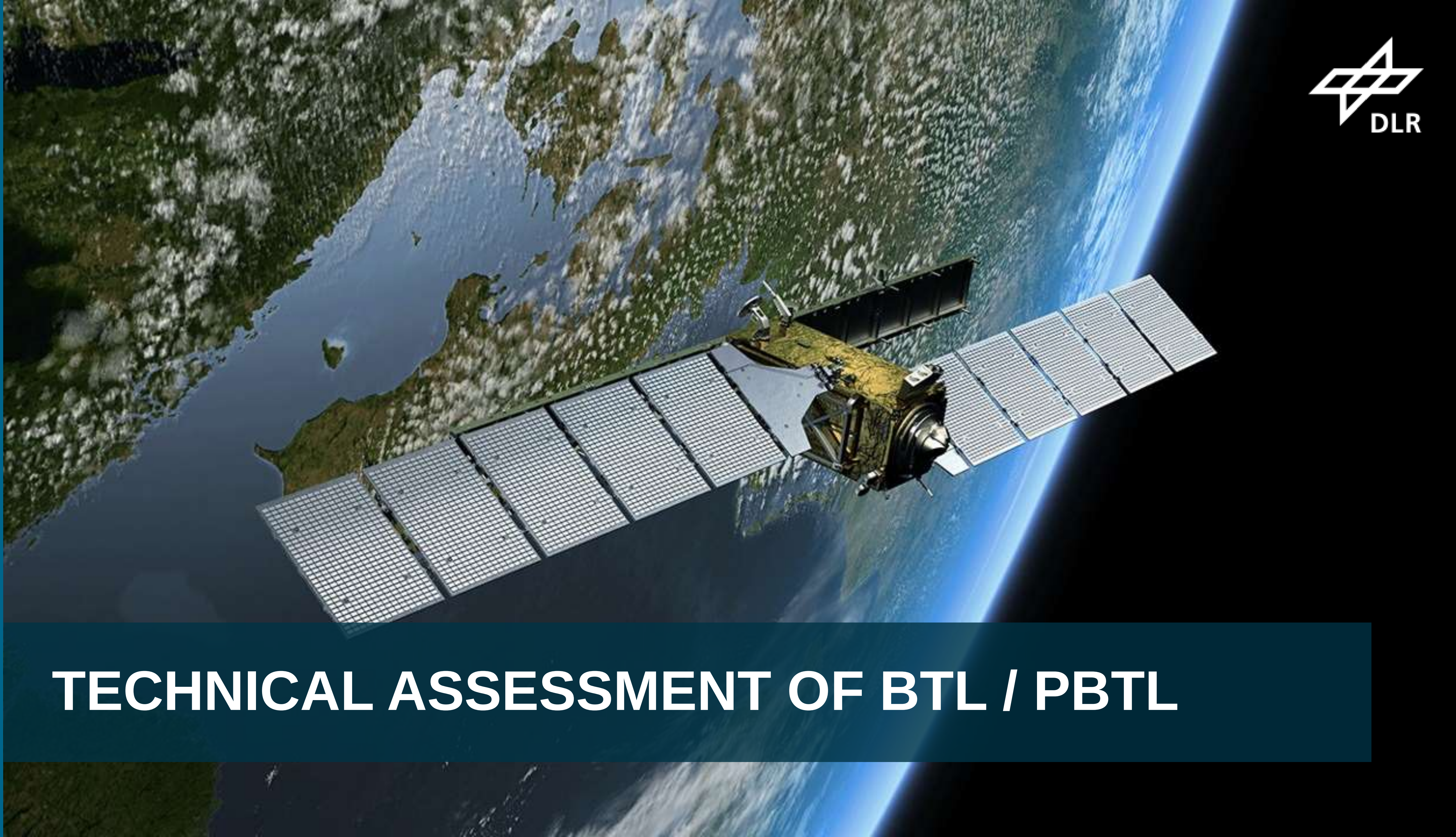
$$2\ C_2H_3O^* + 6\ H_2 \rightarrow 4\ -CH_2- + 2\ H_2O$$

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

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

* 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 BTL / PBTL

Assessment of Biomass-to-Liquid / Power&Biomass-to-Liquid SAF

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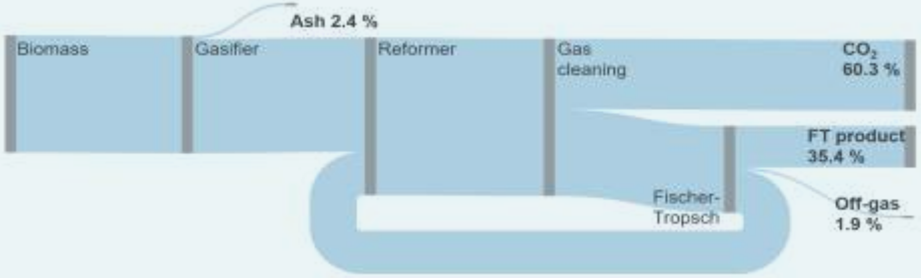
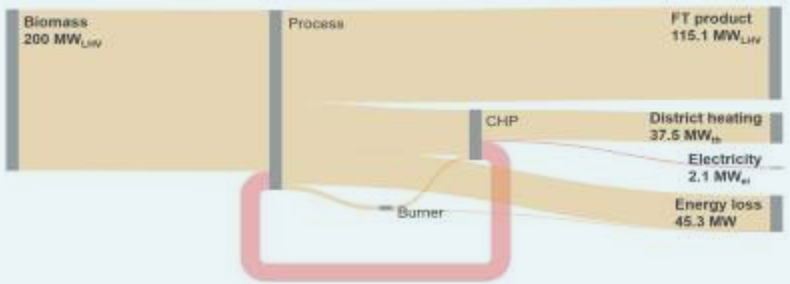
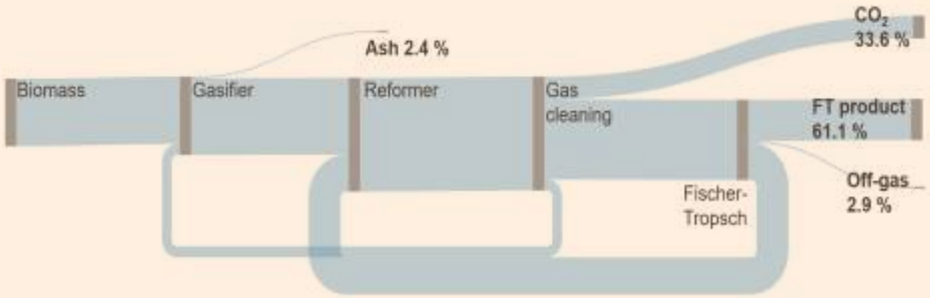
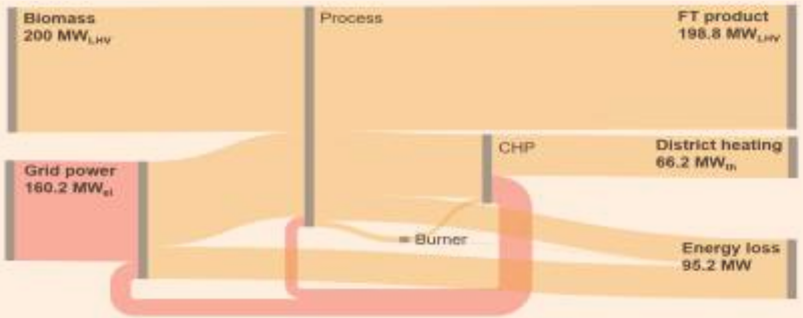
Technical efficiencies [1]

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

FLEXCHX

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

	Carbon efficiency η_C [%]	Fuel η_F | Process efficiency η_E [%]
Winter		
Summer		
50/50		

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

Assessment of Biomass-to-Liquid / Power&Biomass-to-Liquid SAF

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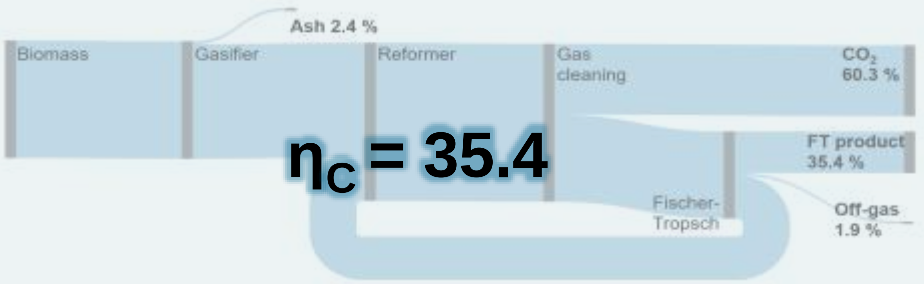
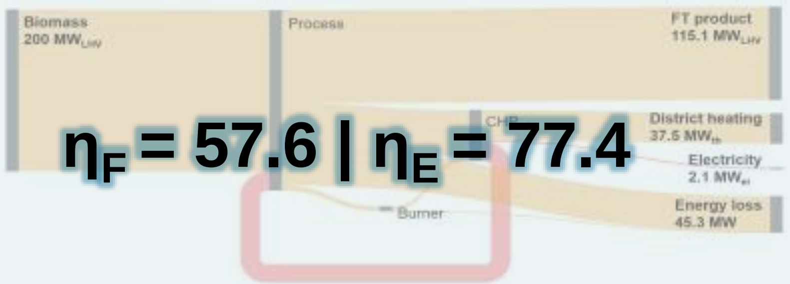
Carbon efficiency η_C [%] | Fuel η_F | Process efficiency η_E [%]

Winter

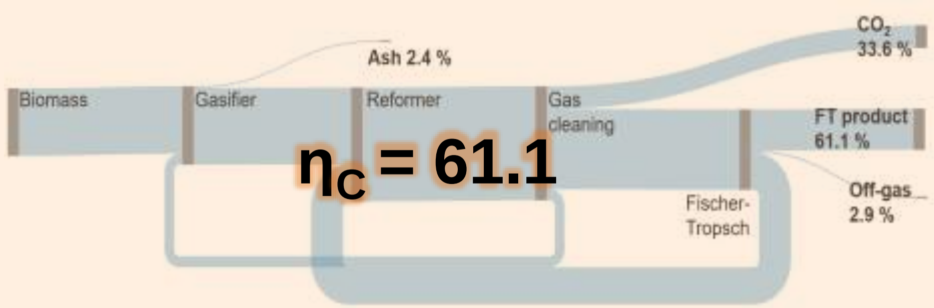


η_C = 35.4

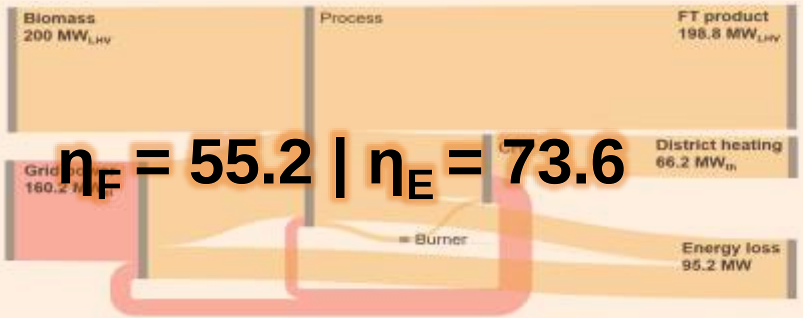


η_F = 57.6 | η_E = 77.4

Summer



η_C = 61.1



η_F = 55.2 | η_E = 73.6

50/50

$\eta_{C,av.}$ = 48.3

$\eta_{F,av.}$ = 56.4 | $\eta_{E,av.}$ = 75.5

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

ECONOMIC ASSESSMENT OF PBTL

PBtL 2020 Net Production Costs

Finnish Base Case: small-scale SXB gasifier (50 MW_{th}), 42 MW_{el} AEL ➔ 32 $kt_{FT\text{-}C5+}$/a

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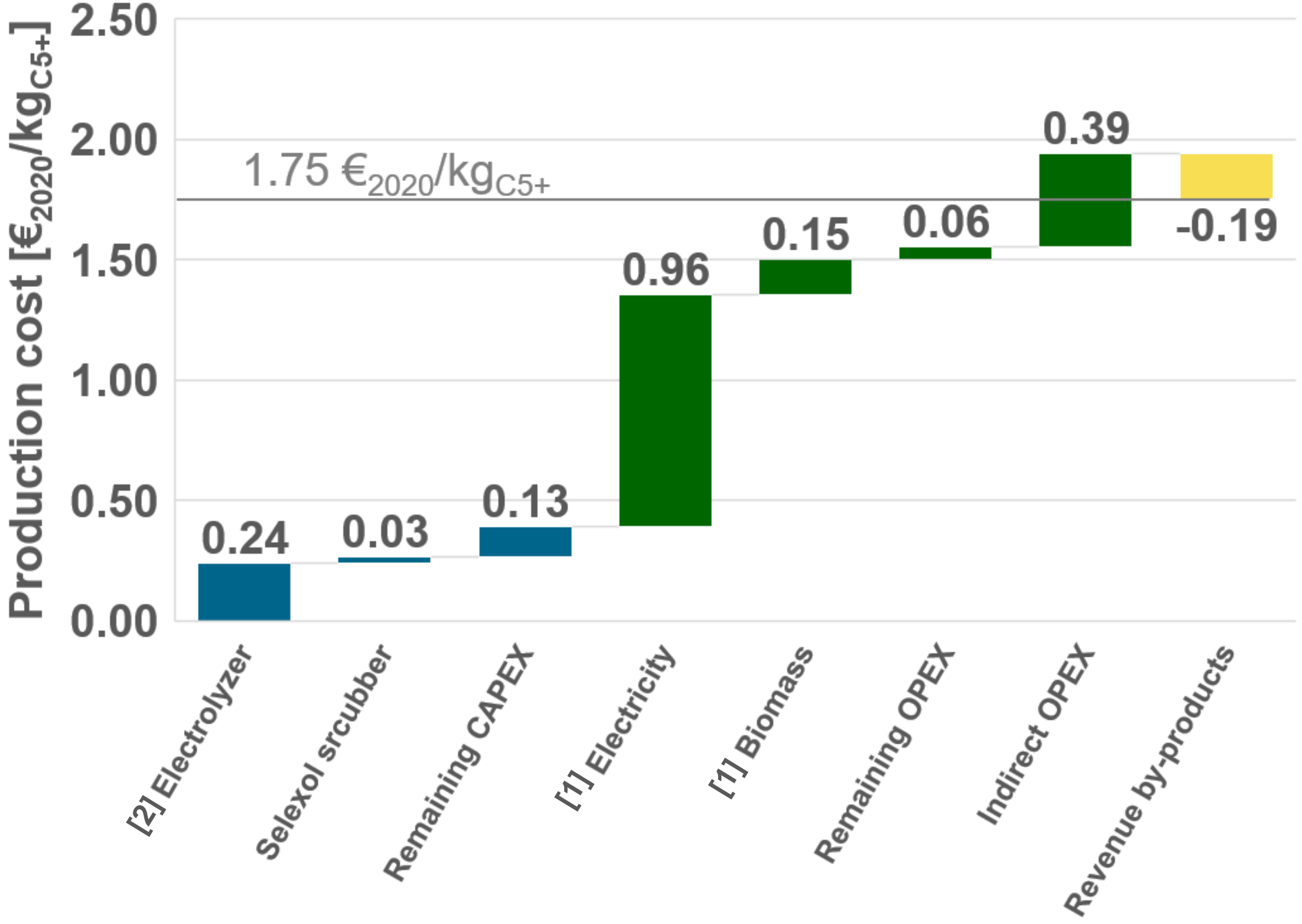

Key economic input data (2020):

- 50.4 €/MWh electricity cost [1]
- 42.2 €/t biomass cost [1]
- Alkaline electrolysis 1 M€/MW [2]
- Labor cost 43.1 €/h [3]

[1] 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.
[2] 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.
[3] Eurostat. (2021). Labour cost levels by NACE Rev. 2 activity (Online) https://ec.europa.eu/eurostat/databrowser/product/page/LC_LCI_LEV$DEFAULTVIEW [Accessed 19.01.2022]

SKIPPED: ENVIRONMENTAL ASSESSMENT

TOWARDS A EUROPEAN SAF ROADMAP

Local production potential analysis

TEPET linked to Aspen Plus, European NUTS statistics

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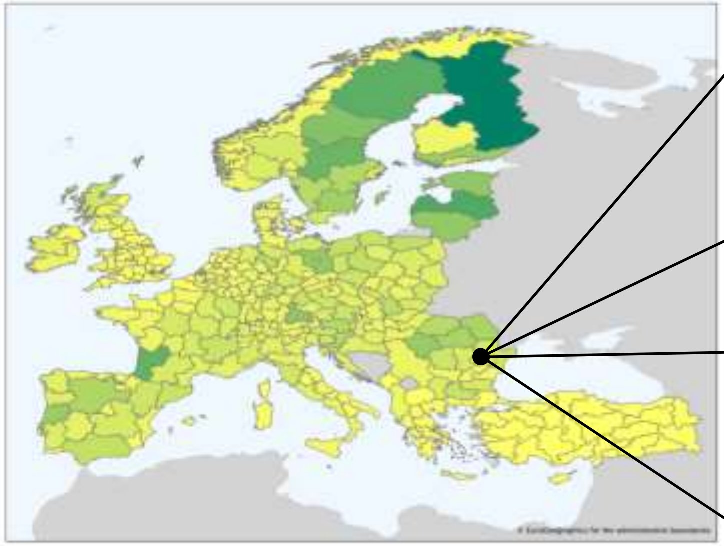
For feedstock potential: TEEA for 300 NUTS2 regions



Biomass density[1]:
(⅓ of forest residue)
+Transport distance

Local labor cost[2]

National grid:
- Price[3]
- GHG footprint[4]

Biomass price[1]

<u>NUTS2 regions specific results:</u>

- Local fuel production cost
- Local fuel production GWP
- Local fuel potential

[1] dataset codes MINBIOFSR1 and MINBIOFSR1a), excluding secondary residues from: Ruiz, P., et al. (2019). ENSPRESO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials *Energy Strategy Reviews*, *26*, 100379.
[2] Eurostat. (2021). Labour cost levels by NACE Rev. 2 activity (Online) https://ec.europa.eu/eurostat/databrowser/product/page/LC_LCI_LEV$DEFAULTVIEW [Accessed 19.01.2022]
[3] Eurostat. (2021). Electricity prices for non-household consumers - bi-annual data (Online) http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do [Accessed 19.01.2022]
[4] European Energy Agency, Greenhouse gas emission intensity of electricity generation by country 2022 [cited 2022 31.1]; Available from: https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tabgooglechartid_googlechartid_googlechartid_chart_1111.

PBtL potential analysis for Europe
Finding the sweet spots

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Key economic Assumptions

Investment costs:			**Average plant size**
AEL-Electrolyzer	**1**	M€/MW [1]	➔ 900 MW_e Electrolyzer
Fischer-Tropsch SBCR:	**5.9**	k€/m^3 [2]	➔ 400 kt/a SAF product
Selexol:	**5.5**	k€/$kmol_{CO2}$/h [3]	
Fluidized bed gasifier:	**0.5**	M€/($kg_{dry\ biomass}$/s) [4]	➔ 400 MW_{th} gasifier
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.

PBtL potential analysis for Europe
Grid connected PBtL: Northern Europe preferred

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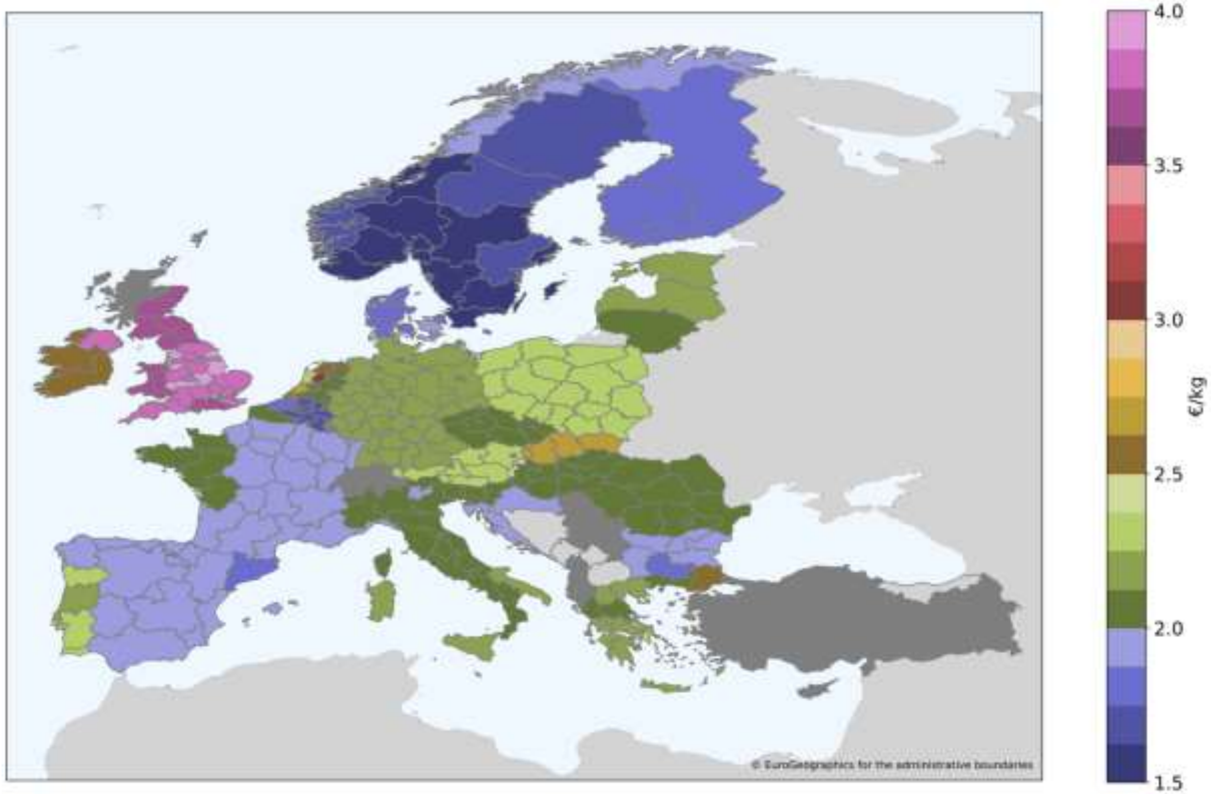
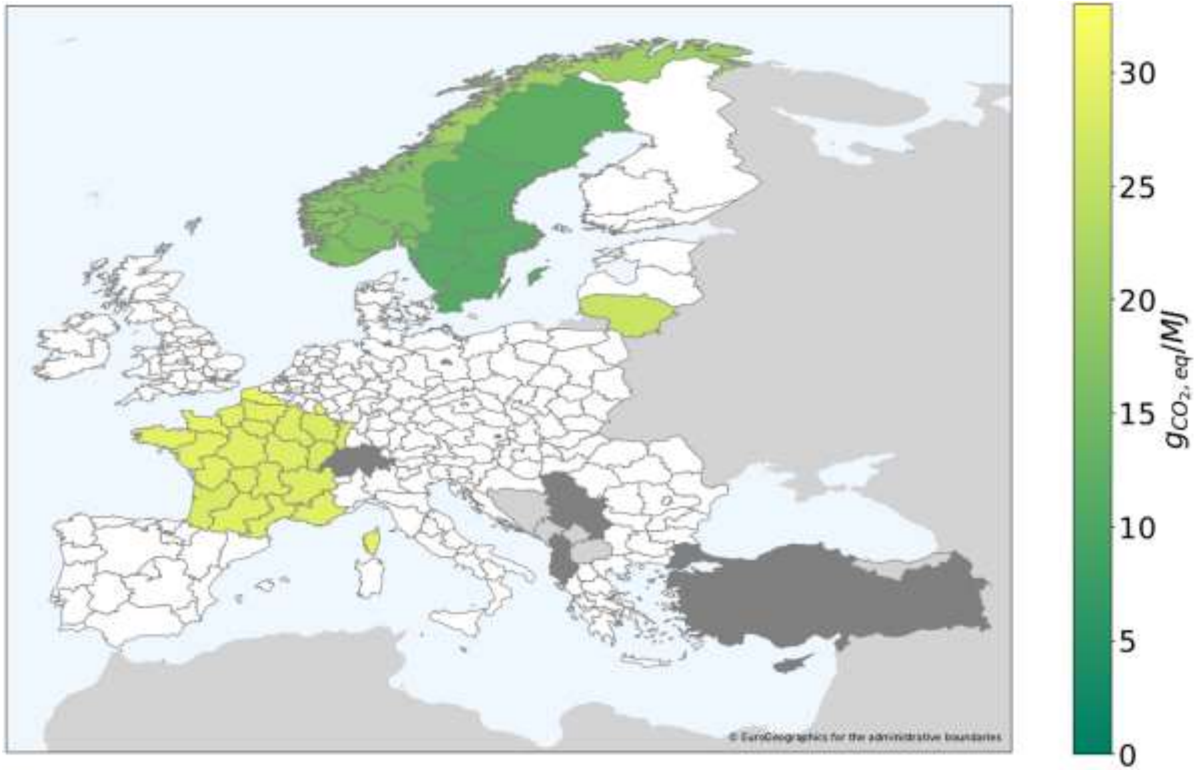
Net production cost [$€_{2020}/kg_{C5+}$]:



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



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

PBtL potential analysis for Europe
On-shore wind connected PBtL: Costal regions preferred

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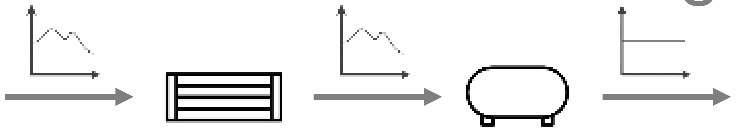
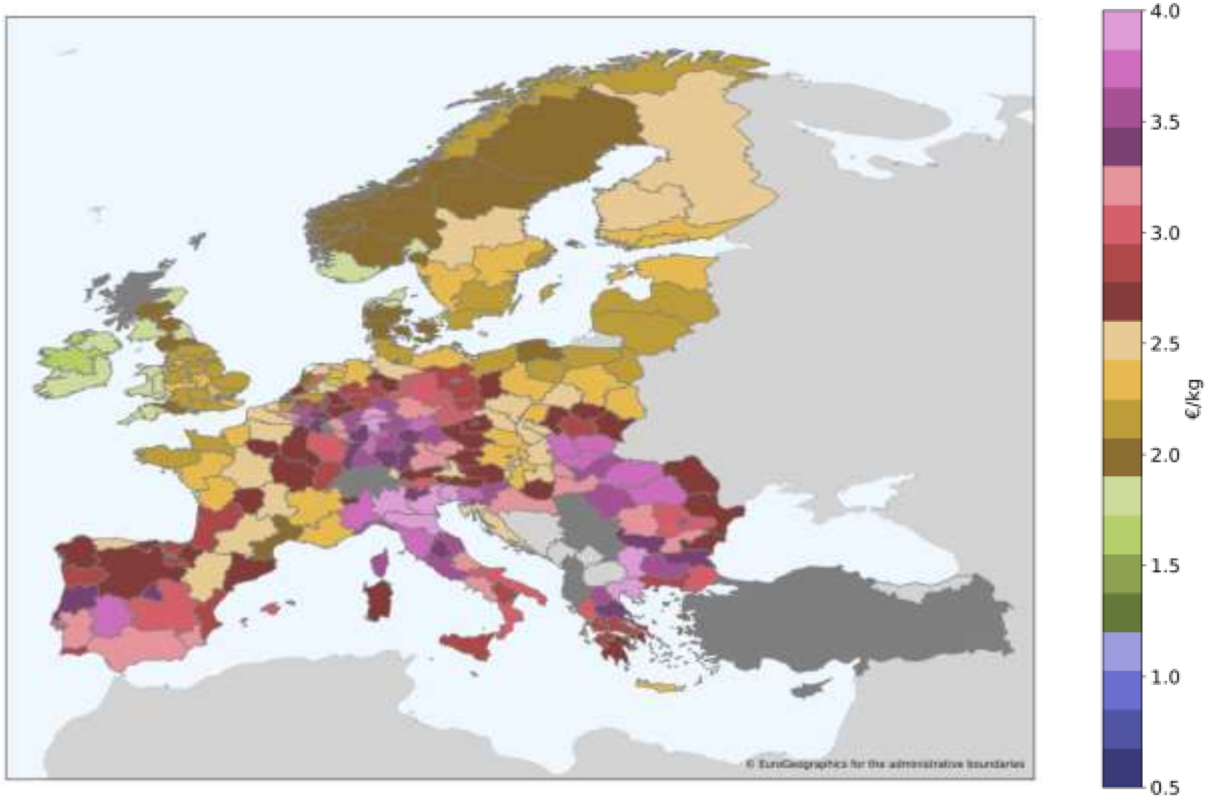
Hydrogen storage included:



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



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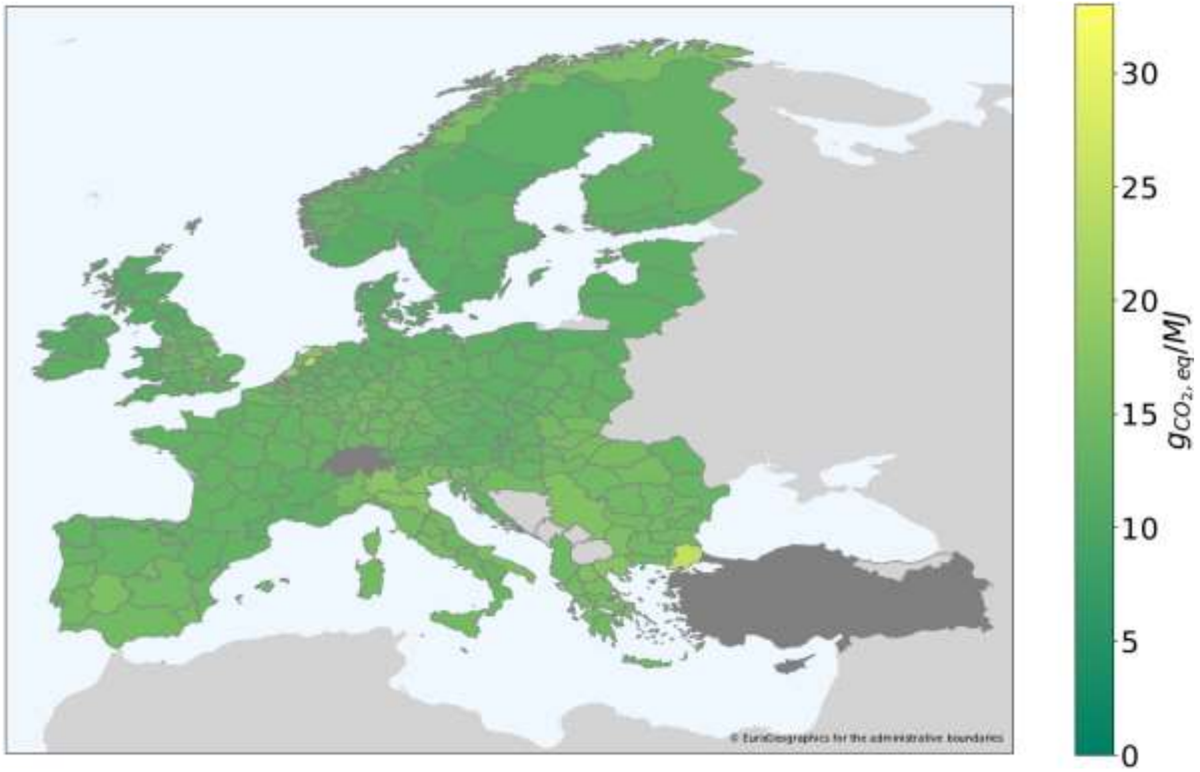

Net Production cost	Greenhouse Gas Abatement
+ High full load hours of wind power required	– No Net Zero SAF anywhere

PBtL potential analysis for Europe
Aggregated SAF production potential

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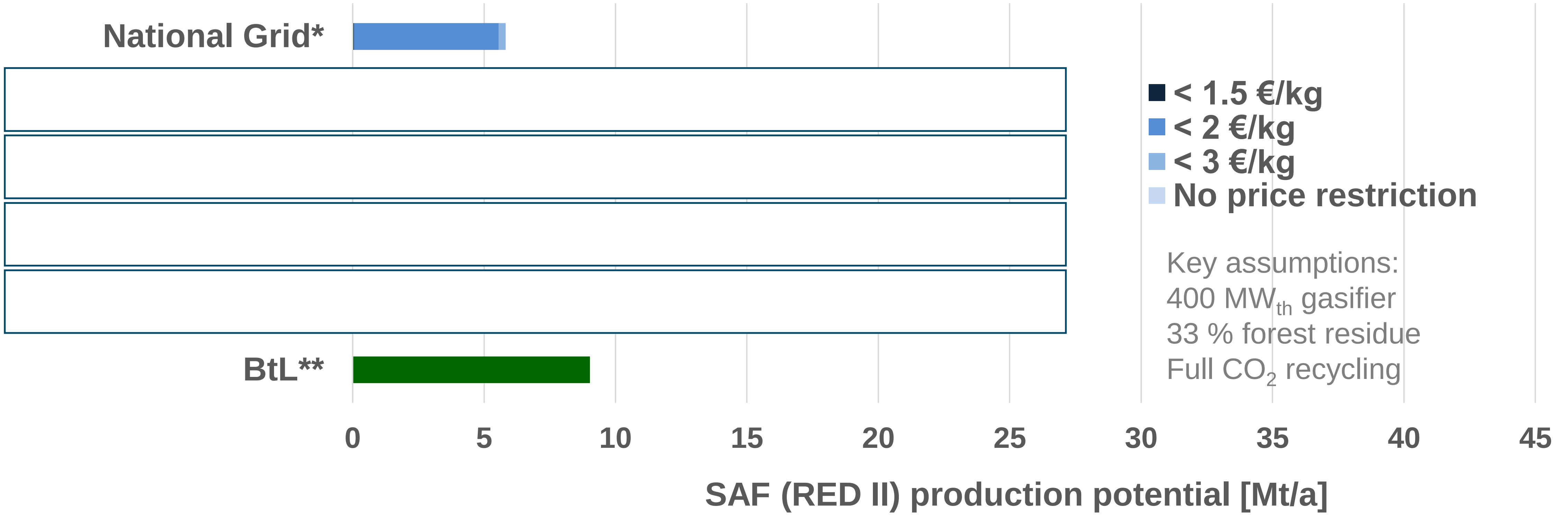
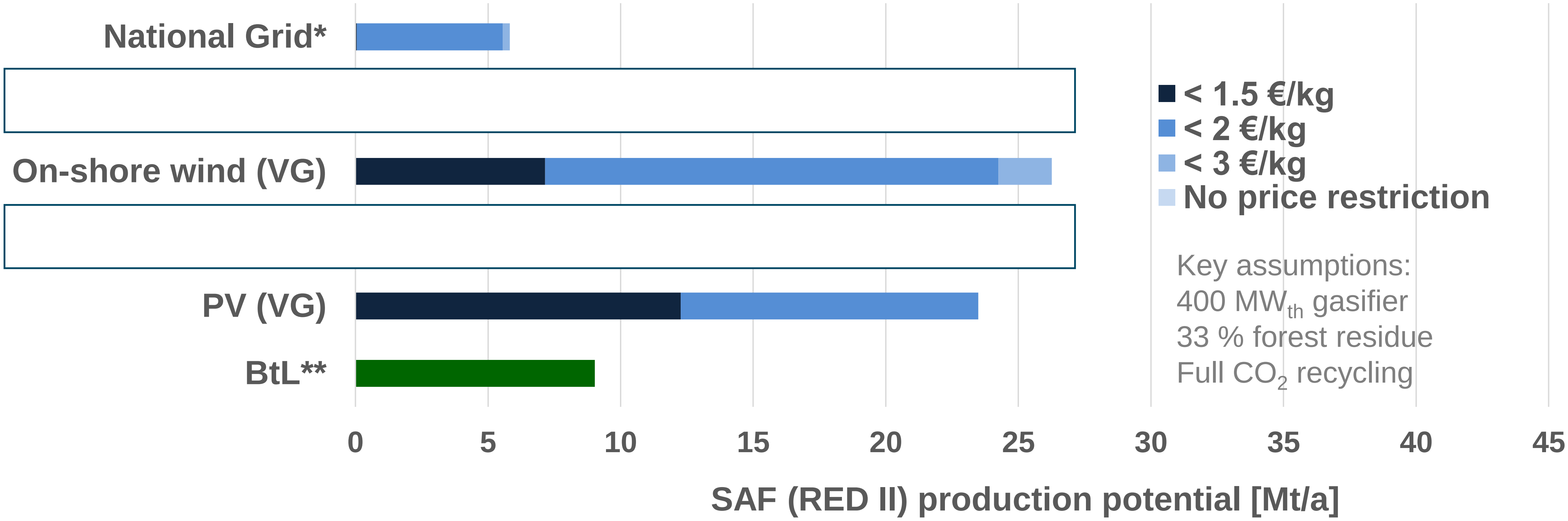


Key assumptions:
400 MW_{th} gasifier
33 % forest residue
Full CO_2 recycling

*grid GWP<120 $g_{CO2\text{-}eq.}/kWh_e$ to confirm with RED II limit | **19.9 % biomass conversion efficiency assumed | forest residue potential according to ENSPRESO

PBtL potential analysis for Europe
Aggregated SAF production potential



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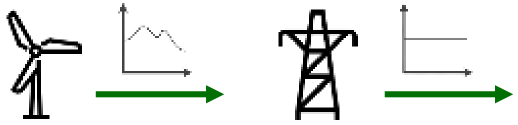
Virtual grid (VG)



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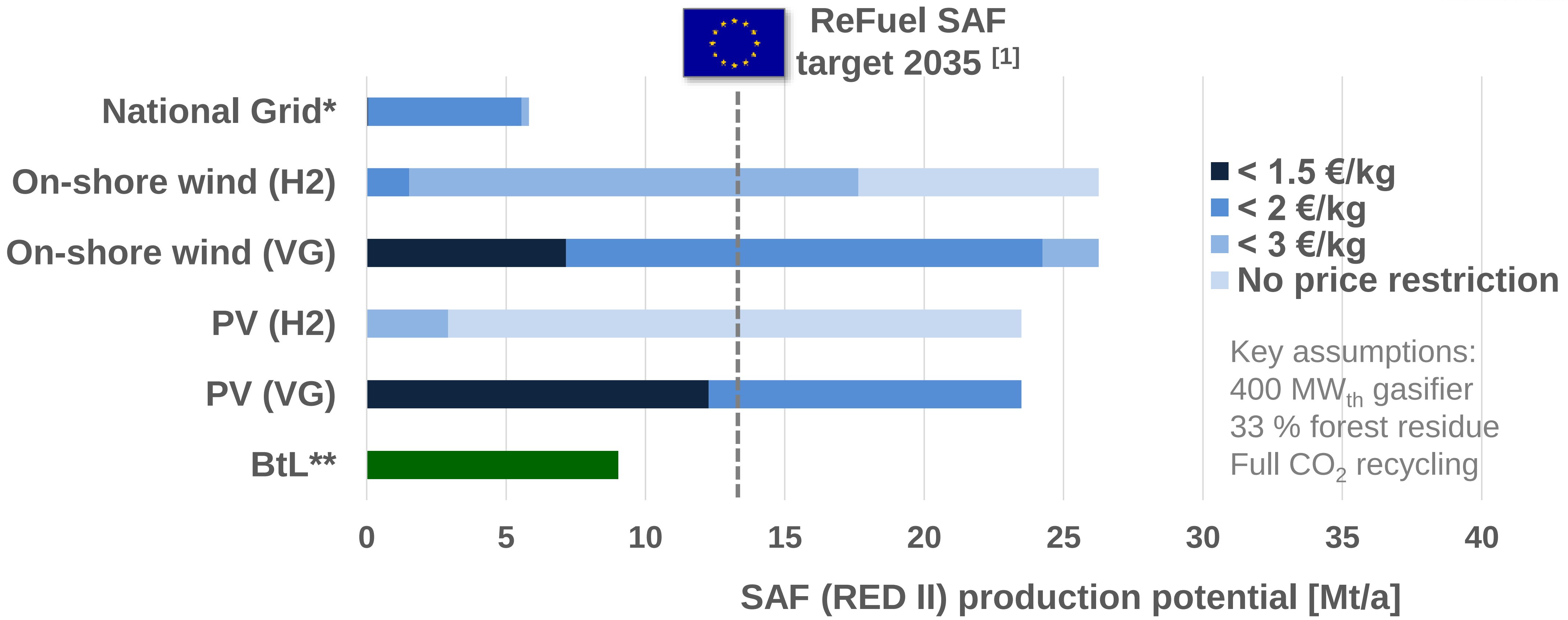

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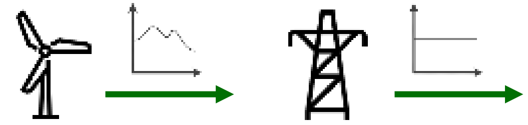
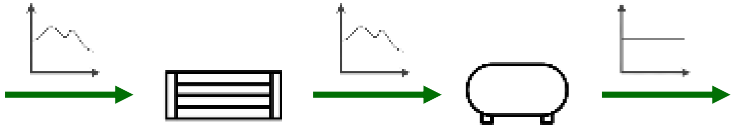


Hydrogen storage (H2)



[1] … ensuring a level playing field for sustainable air transport [Online] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561. SAF should account for at least 5% of aviation fuels by 2030 and 63% by 2050,

*grid GWP<120 $g_{CO2\text{-}eq.}/kWh_e$ to confirm with RED II limit | **19.9 % biomass conversion efficiency assumed | forest residue potential according to ENSPRESO

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)

[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/

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

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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
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Preference palm oil?
Not enough palm oil on earth!

[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/

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

Sustainable Aviation Fuels
time for take-off
7-8 November 2024
Athens, Divani Palace Acropolis

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)

Paris 1.5 degree commitment intentionally violated!

[1] https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector
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SAF deployment plan for Europe
Optimistic way forward (personal view)

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EUROPEAN COMMISSION

	ReFuelEU Aviation SAF targets [1]	**Ambitious, but realistic, just PBtL SAF**
2025	≈ 1 Mt/a	
2030	≈ 3.8 Mt/a	**10 Mt/a**
2035	≈ 13 Mt/a	**30 Mt/a**
2050	≈ 54 Mt/a	**90+ Mt/a = 100 %! (2045?)**

25 PBtL 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

Total Investment? ➔ less than 6 months of Europe's (OECD) crude oil expenses

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

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

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

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

THREE MYTHS AND ONE OFFER FOR SAF

Three myths delaying large-scale SAF deployment

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- Myth 1: Need for fuels research for defossilization of aviation?
  - ➔ ASTM D7566-21: 7 certified SAF, additional game changer unlikely
  - ☞ Renew certification system regarding modern fuel analysis
- Myth 2: Need for process development of SAF production?
  - ➔ all units state-of-the-art, commercially available for decades
  - ☞ Atmosfair e-kerosene plant is running since 2021 – no technical challenges remaining
- Myth 3: SAF production cost uncertain?
  - ➔ (standardized) chemical engineering cost estimation
  - ☞ König, D.H. (2016) *Techno-ökonomische Prozessbewertung der Herstellung synthetischen Flugturbinentreibstoffes aus CO2 und H2*. Ph.D., University of Stuttgart http://dx.doi.org/10.18419/opus-9043
  - ☞ Adelung, S. (2023) *Fischer-Tropsch based Power-to-Liquid process - Technical, economic, uncertainty and sensitivity analysis*. Ph.D., University of Stuttgart http://dx.doi.org/10.18419/opus-13537
  - ☞ … and much more

Toward Sustainable Aviation in Europe

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- Decarbonization of aviation is technically feasible, economically challenging
  - Large scale SAF production using biomass gasification, water electrolysis, FT technology (PBtL), all industrial proven
  - Massive rollout of **European renewable energy production** required
  - New SAF industry to be established – competing with fossil kerosene supply
- SAF production scale-up:
  - Today PBtL only @ sweet spots (Norway / Sweden) – BtL broader application spectrum
  - PBtL necessary to approach towards European SAF goals
  - Net Zero aviation by 2050 not realistic
- DLR assessment for any location, feedstock, technology, regulation, … !

T€P€T
Powered by DLR
Standardizing economic process evaluations

Wednesday, 2024/11/08

Session VI: SAF commercial technologies

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time for take-off

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ΣΑΣ ΕΥΧΑΡΙΣΤΟΎΜΕ ΓΙΑ ΤΗΝ ΕΥΓΕΝΙΚΉ ΣΑΣ ΠΡΟΣΟΧΉ! ΕΡΩΤΉΣΕΙΣ?

Large-scale economic production of sustainable aviation fuels in Europe

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