Thursday, 29. September 2022

Session 8.1: Alternative Kraftstoffe und Ökoeffizienz

DLRK 2022

DEUTSCHER LUFT- UND RAUMFAHRTKONGRESS

DGLR

27. - 29. SEPTEMBER 2022 – DRESDEN

„Luft- und Raumfahrt - gemeinsam forschen und nachhaltig gestalten“

TECHNICAL, ECONOMIC AND ECOLOGICAL ASSESSMENT OF EUROPEAN SUSTAINABLE AVIATION FUELS (SAF) PRODUCTION

Techno-ökonomisch-ökologische Bewertung der Erzeugung nachhaltiger Luftfahrttreibstoffe (SAF)

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

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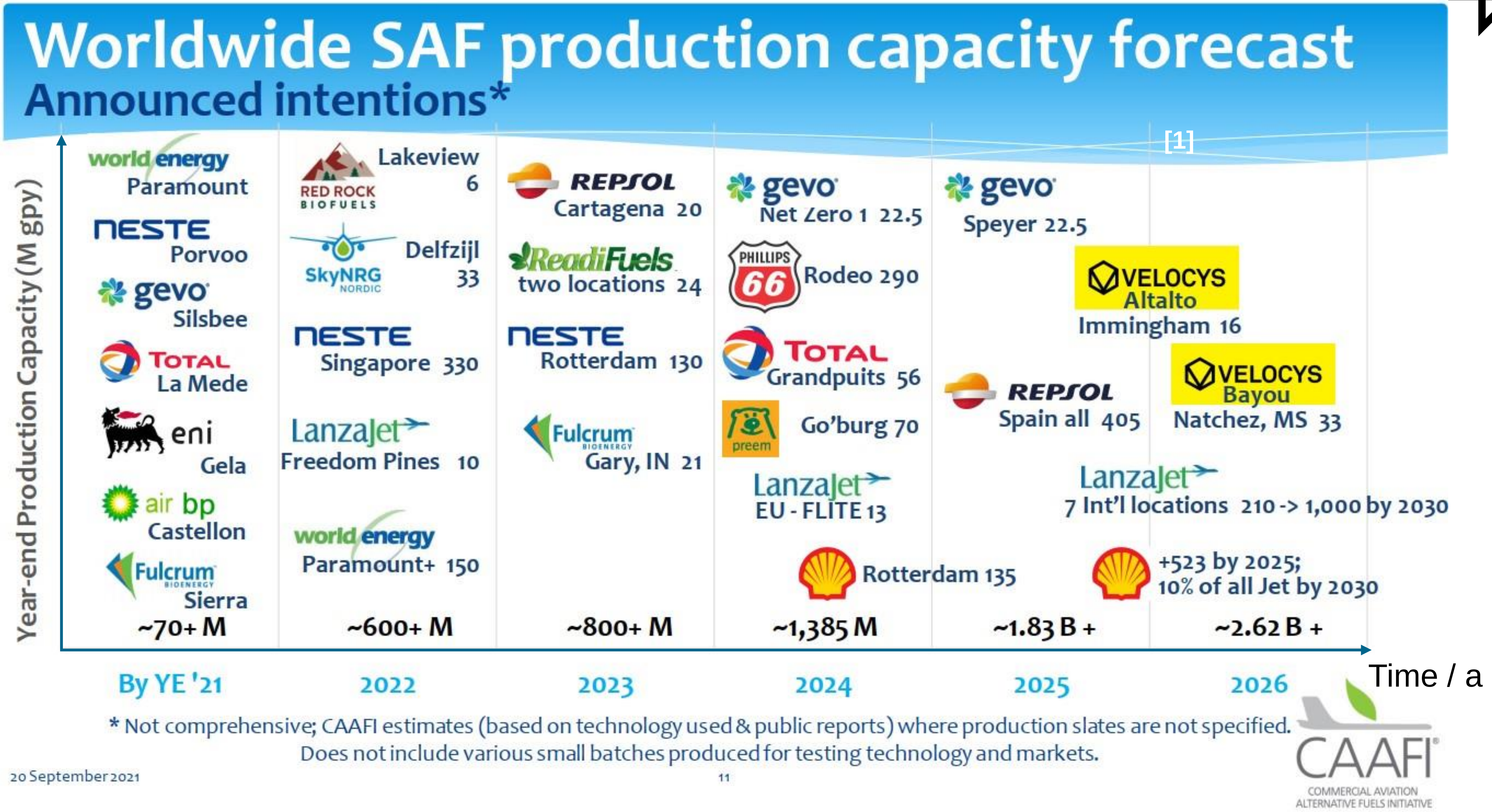
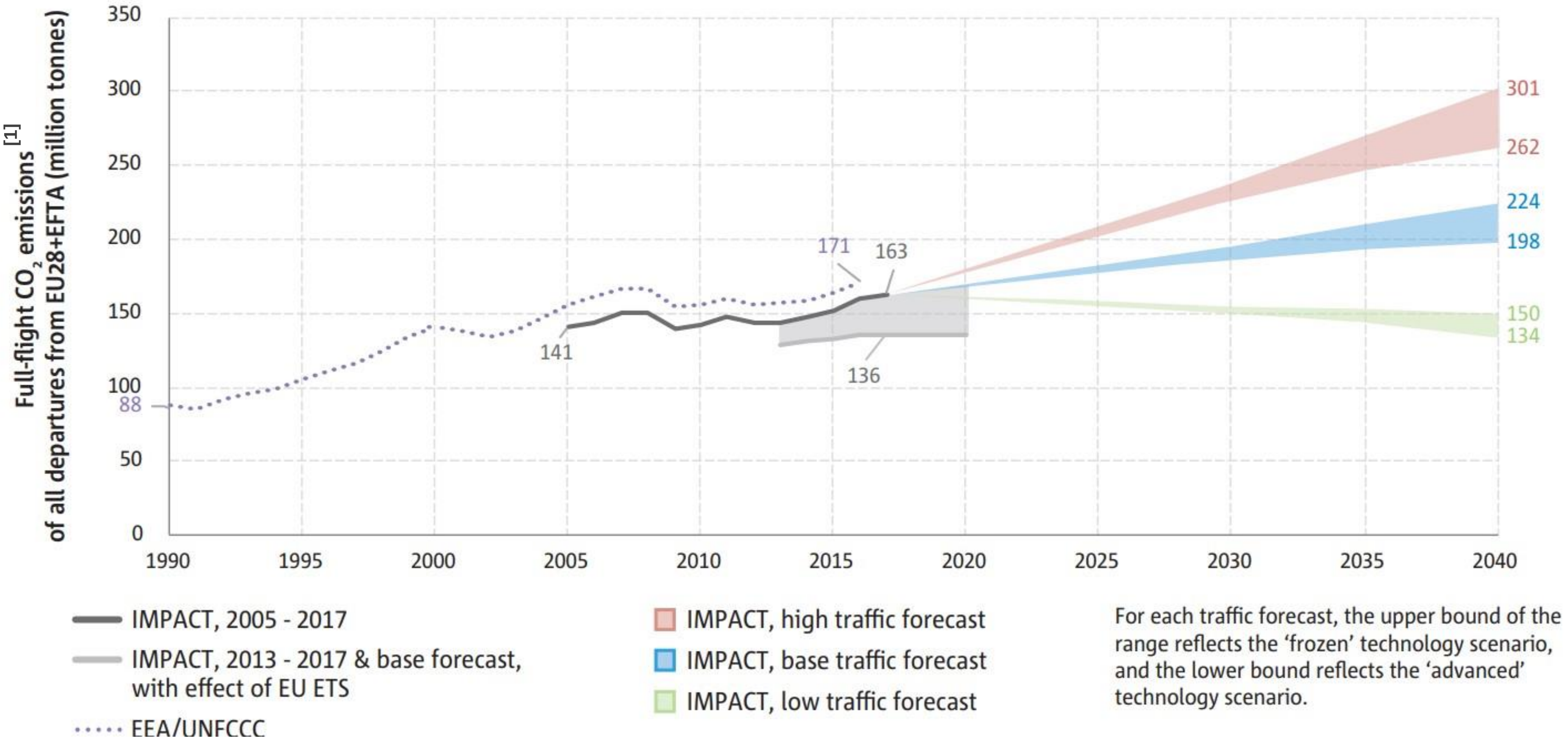
SAF deployment take-off in Europe and U.S.



[1] S. Csonka, Aviation's Market Pull for SAF, https://www.caafi.org/focus_areas/docs/CAAFI_SAF_Market_Pull_from_Aviation.pdf.

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

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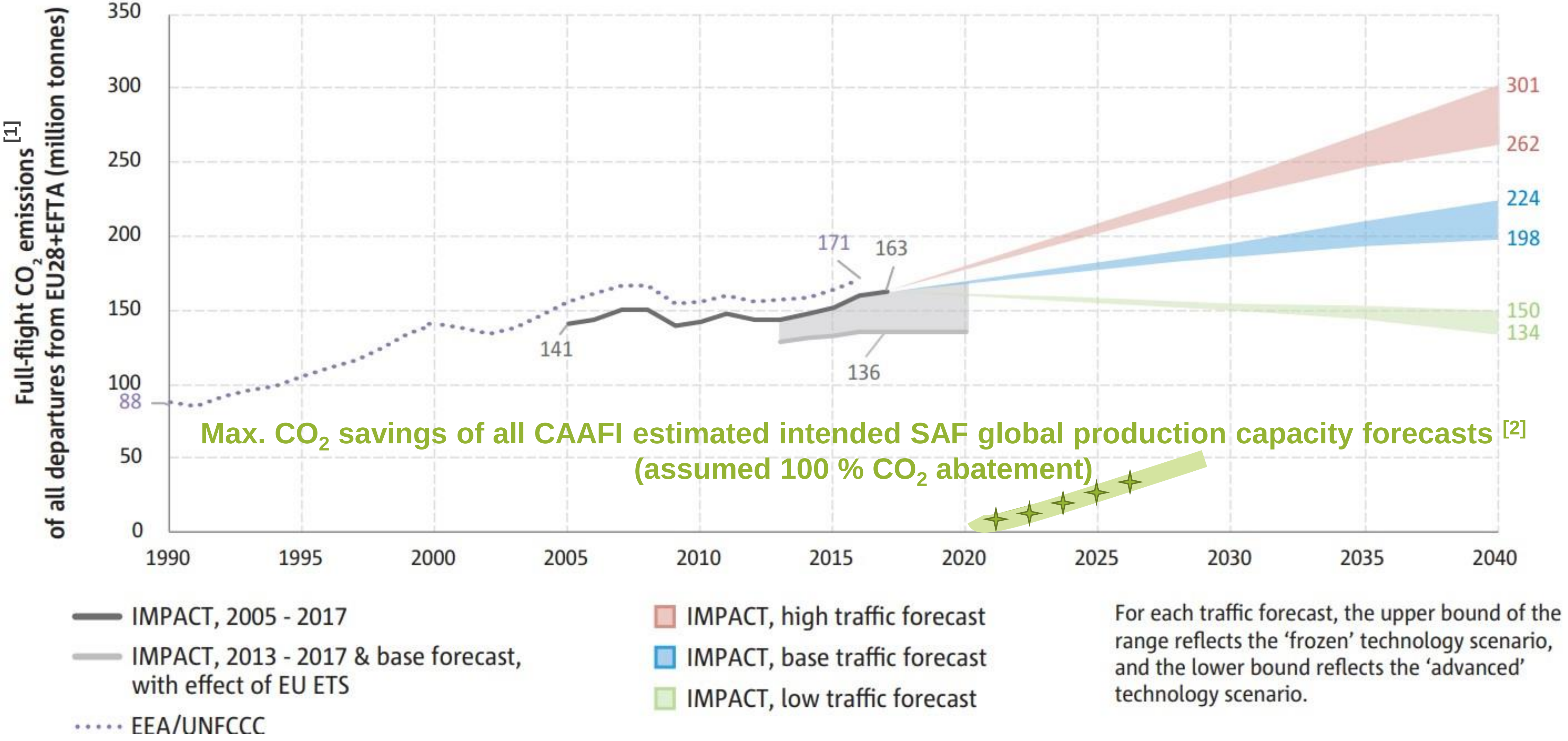

[1] European Aviation Environmental Report 2019, https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_LOW-RES.pdf
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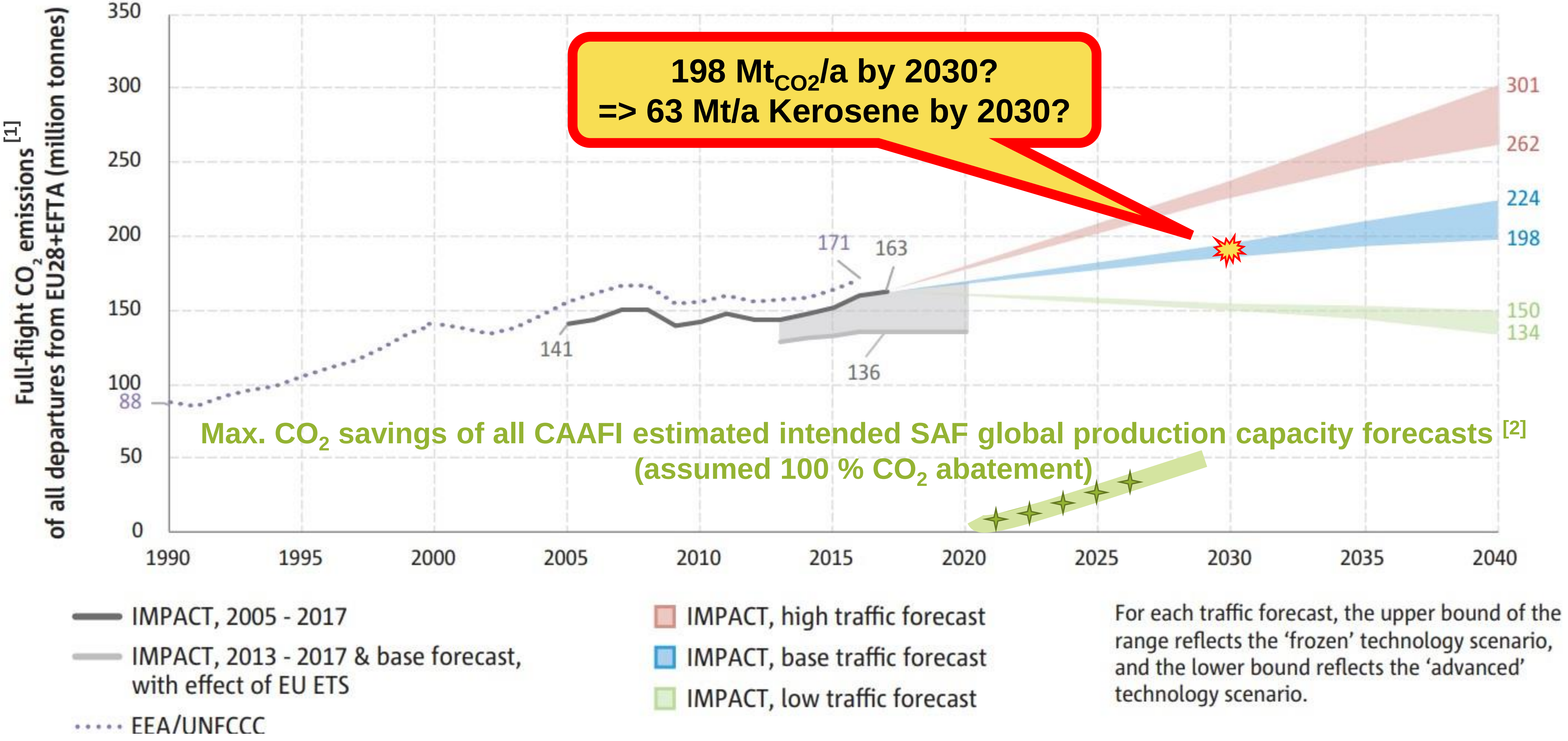

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Certified Alternative Jet Fuels (ASTM D7566 – 21 [1])

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

Feedstock	Synthesis technology	Fuel
Bio-isobutanol (-methanol, -ethanol, -propanol, …)	dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AD-SPK
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Total technical potential of 1st generation European sustainable jet fuel [2-6]:

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

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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
- Low technical development potential

➔ **How / Where / When to deploy 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
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Assessment of SAF concepts / options / configurations / locations / …

Feedstock availability towards 63 Mt/a

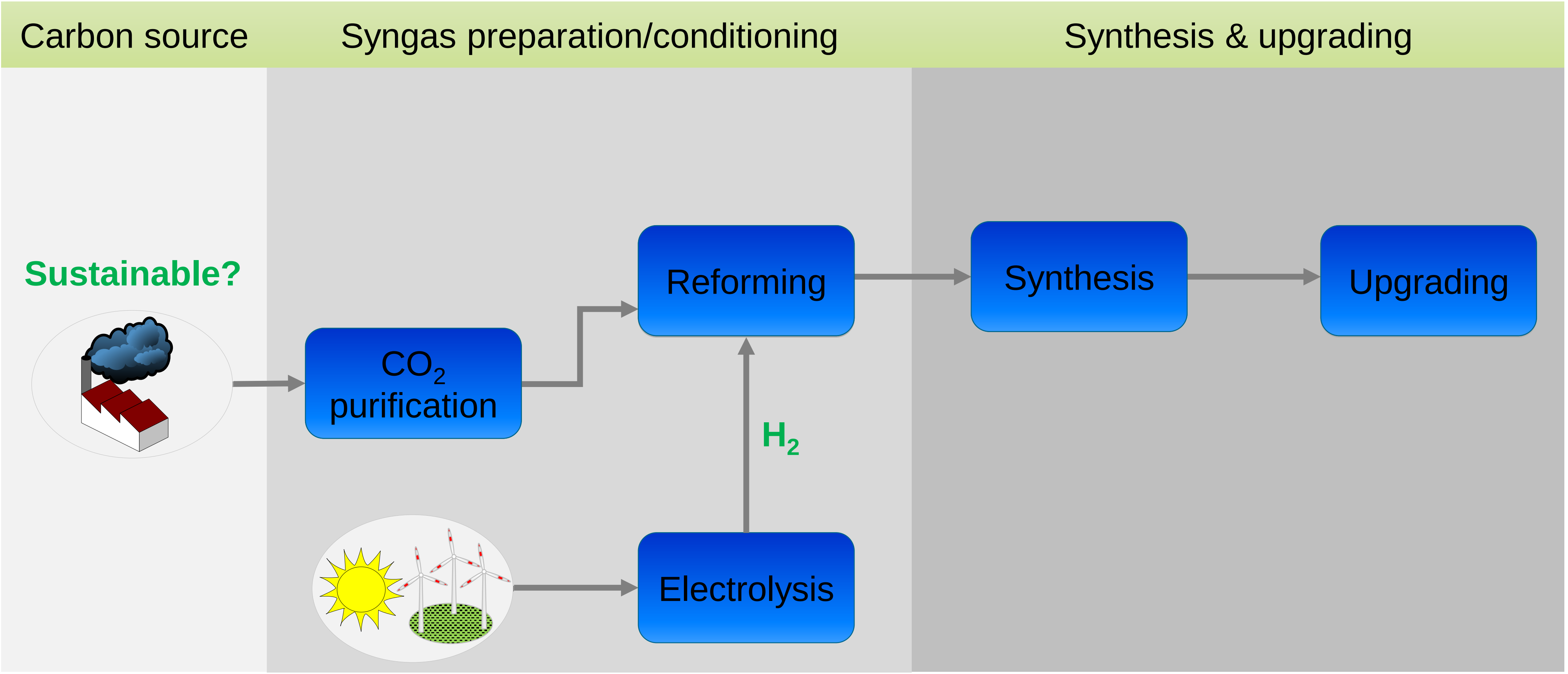
Feedstock	Synthesis technology	Fuel
~~Coal, natural gas~~, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis using Fe or Co catalyst,	Synthetic paraffinic kerosene (FT-SPK)

- 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

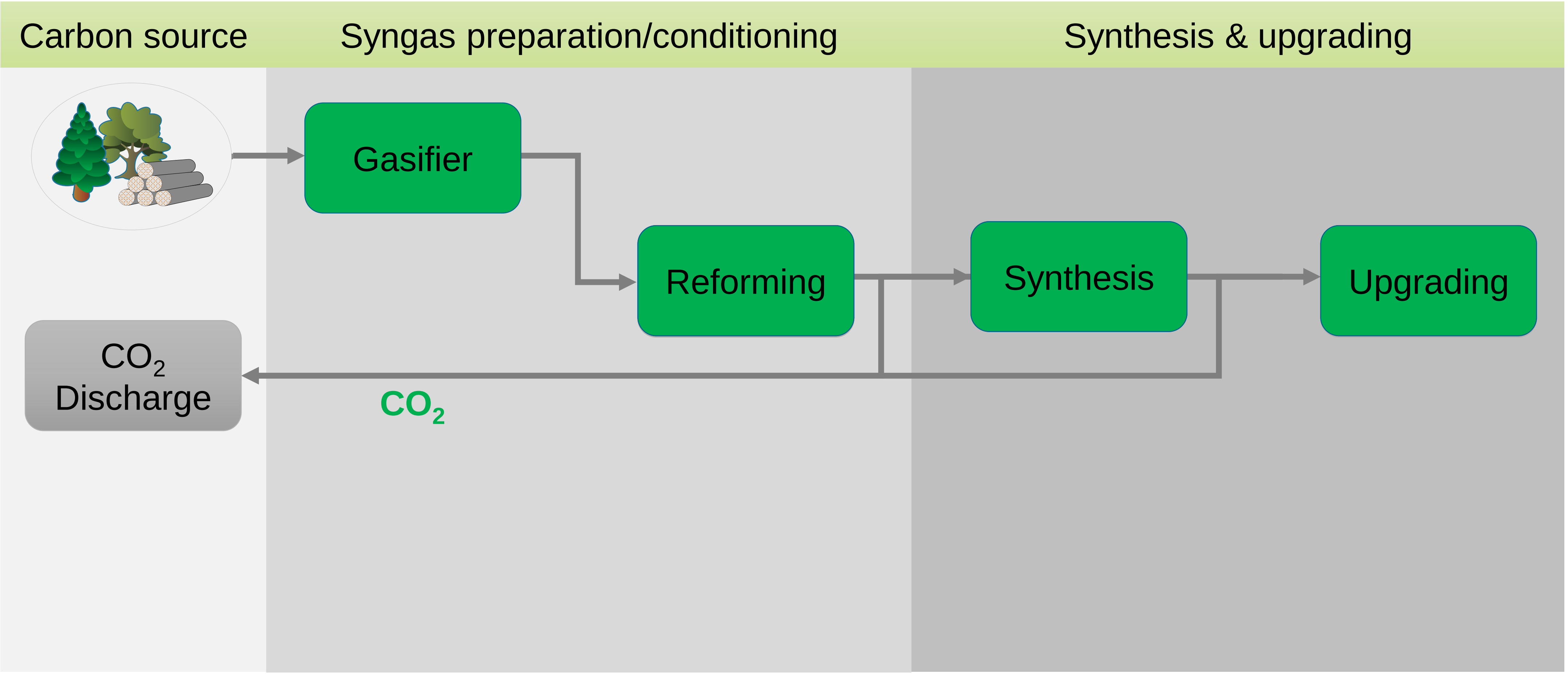
Fischer-Tropsch based SAF concepts:

Power-to-Liquid



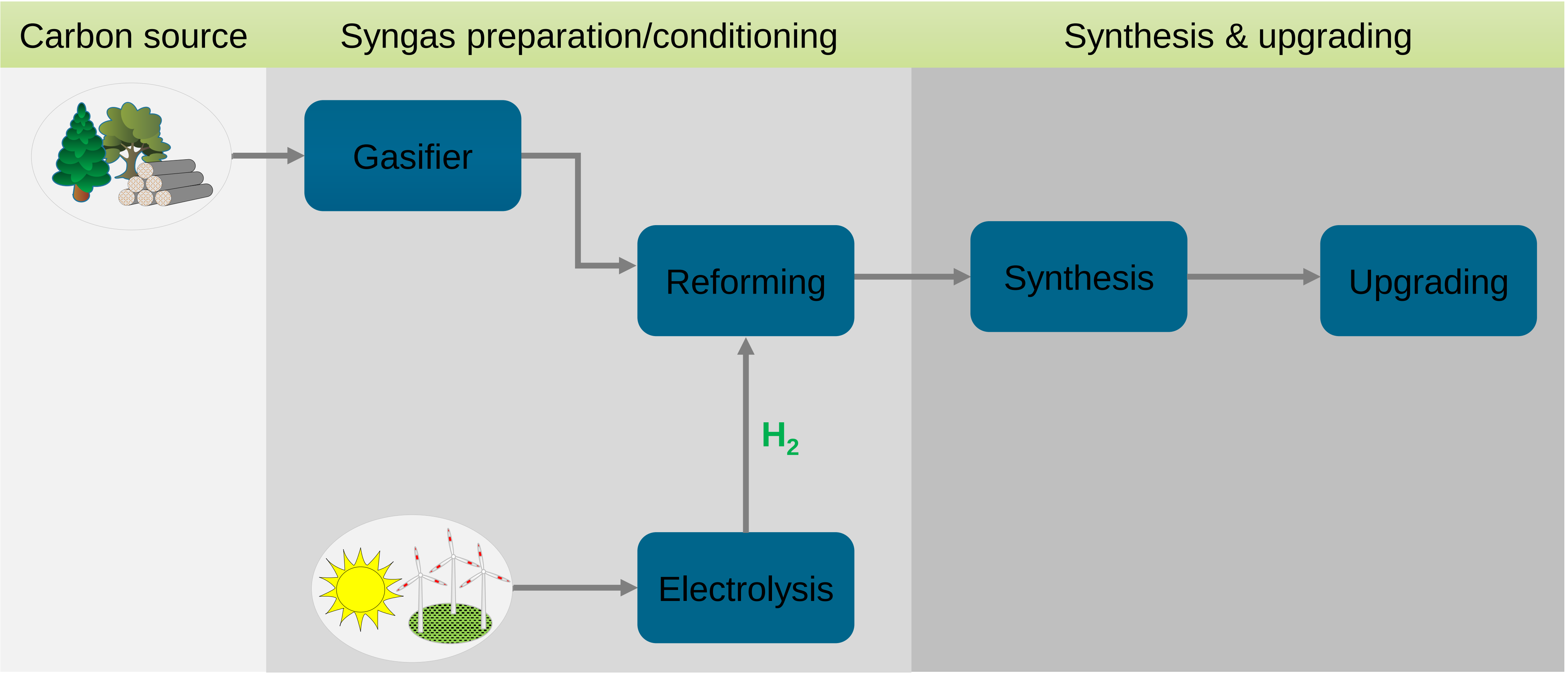
Fischer-Tropsch based SAF concepts:

Biomass-to-Liquid



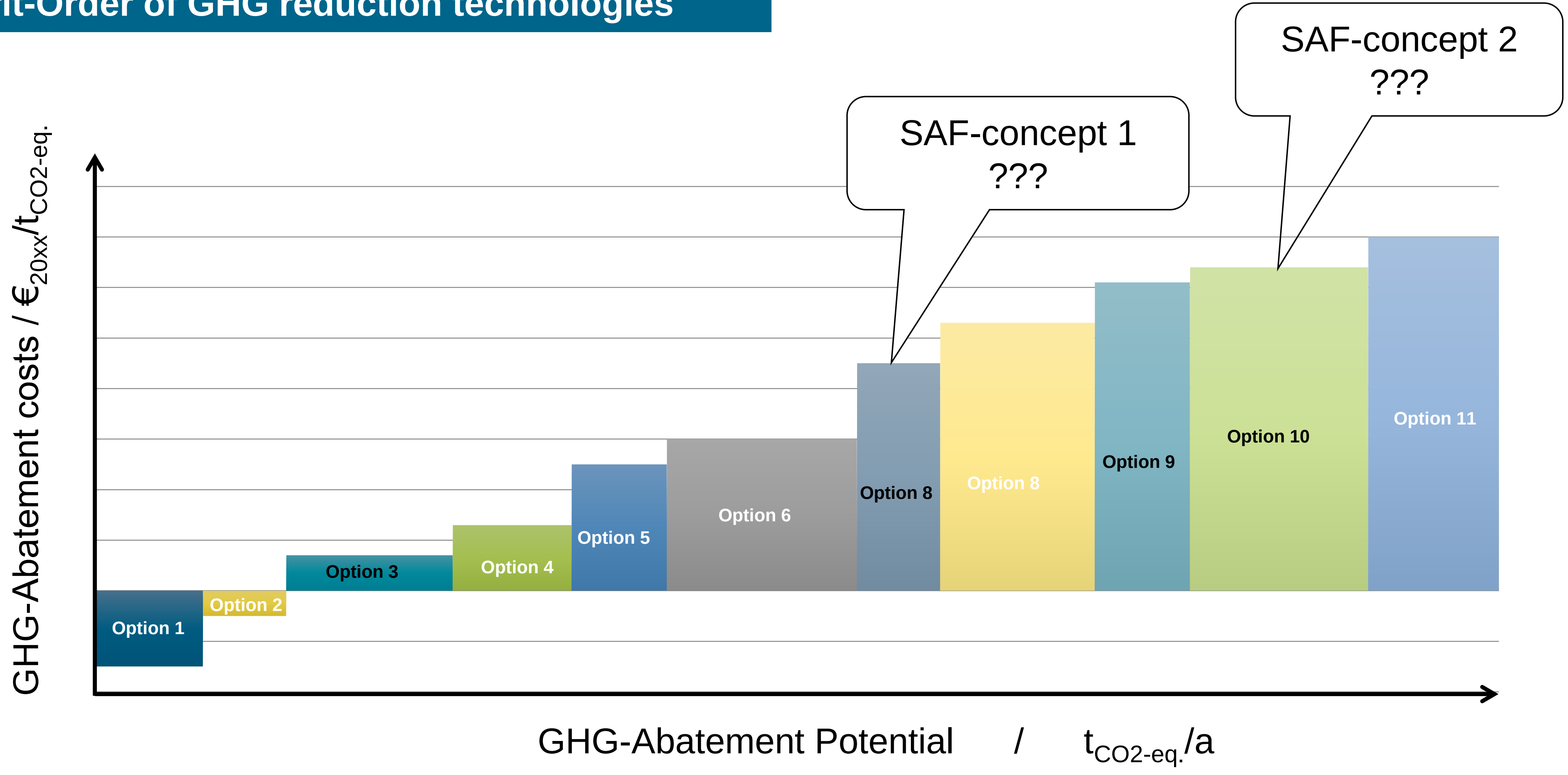
Fischer-Tropsch based SAF concepts:

Power&Biomass-to-Liquid



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

Merit-Order of GHG reduction technologies



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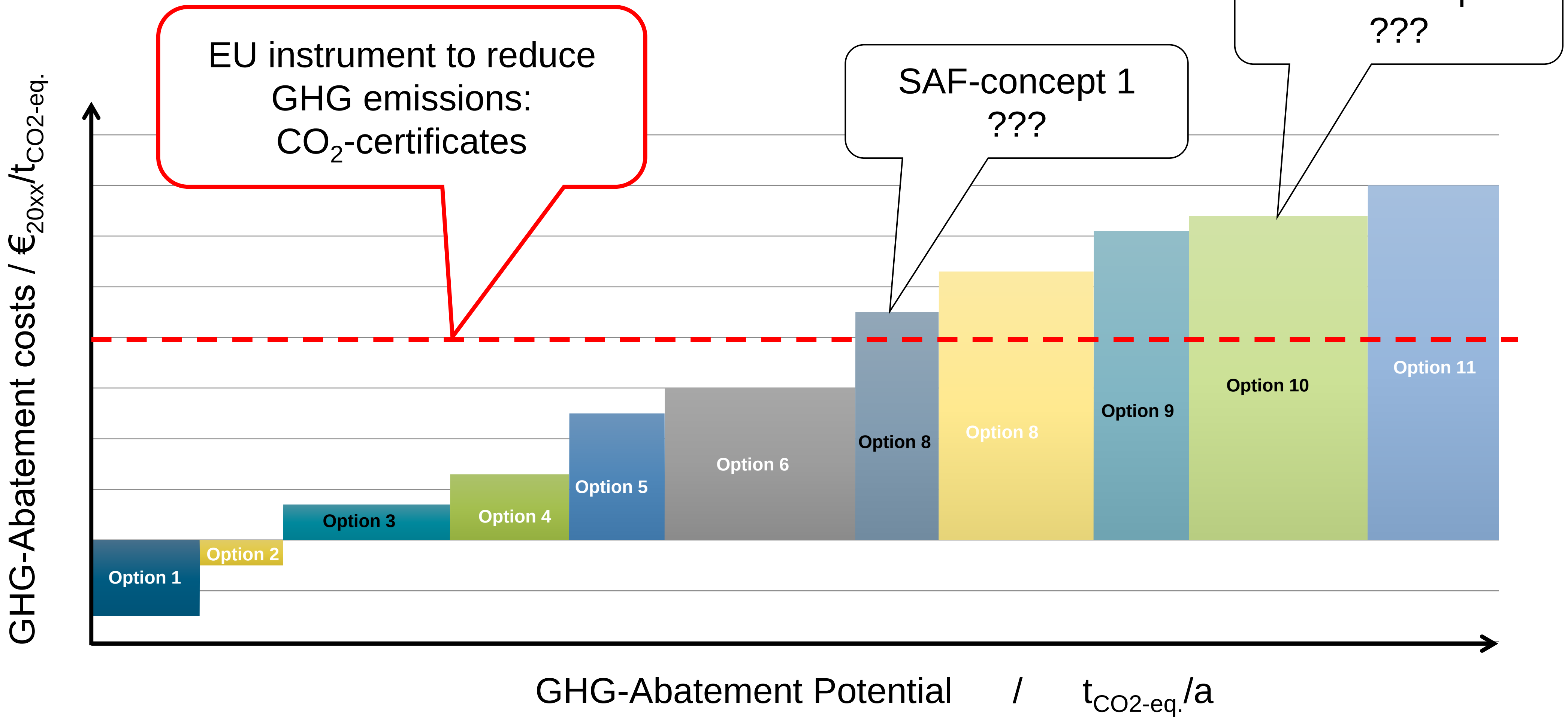

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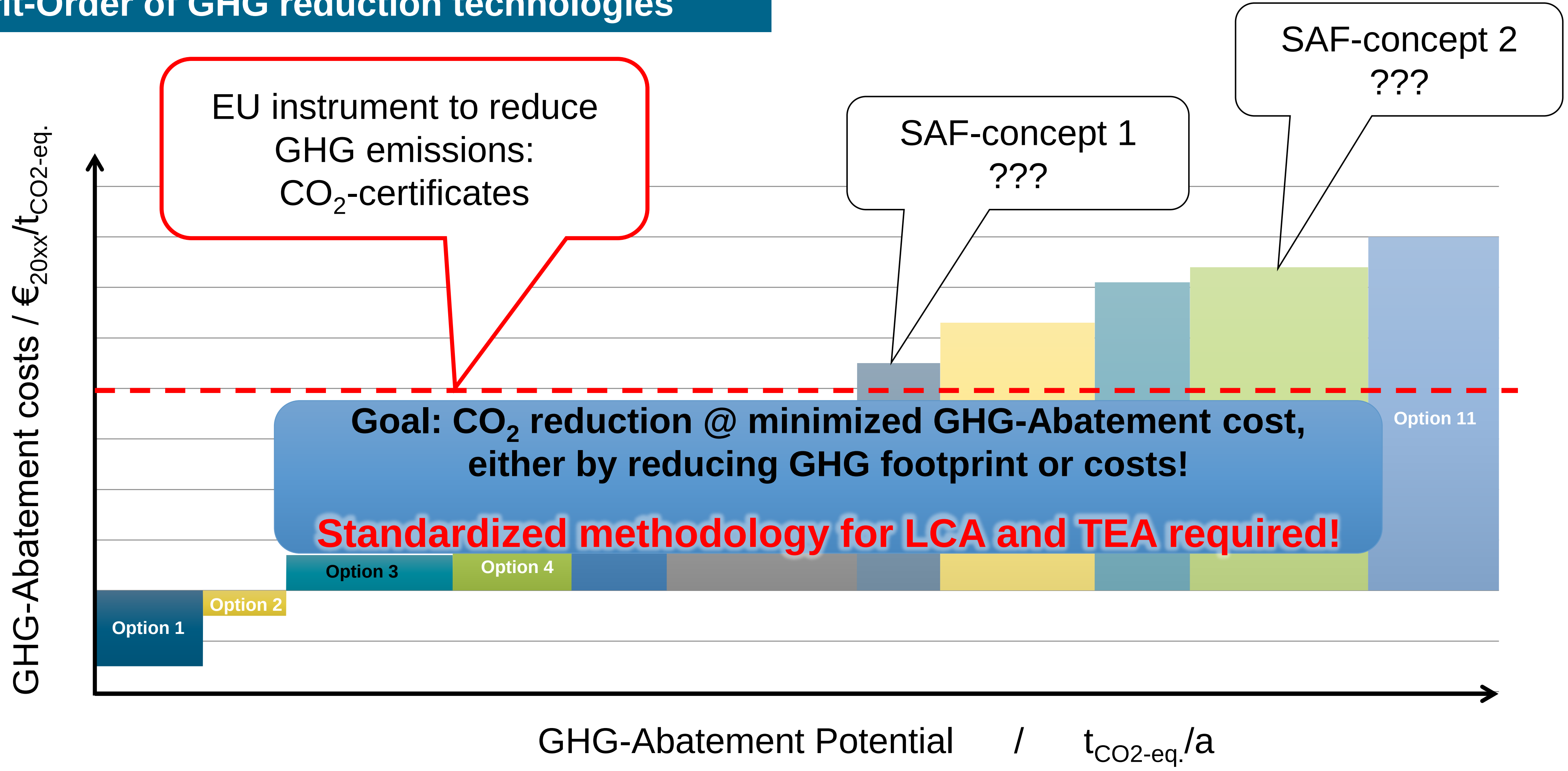
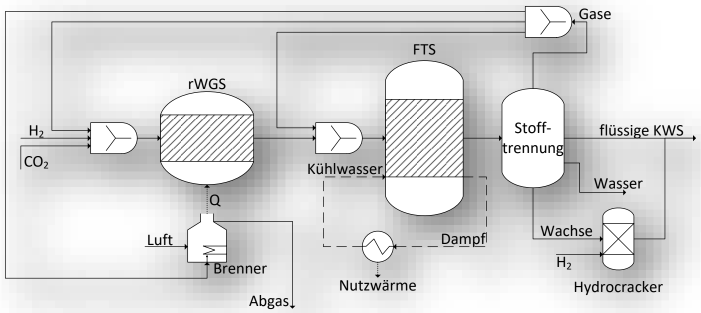
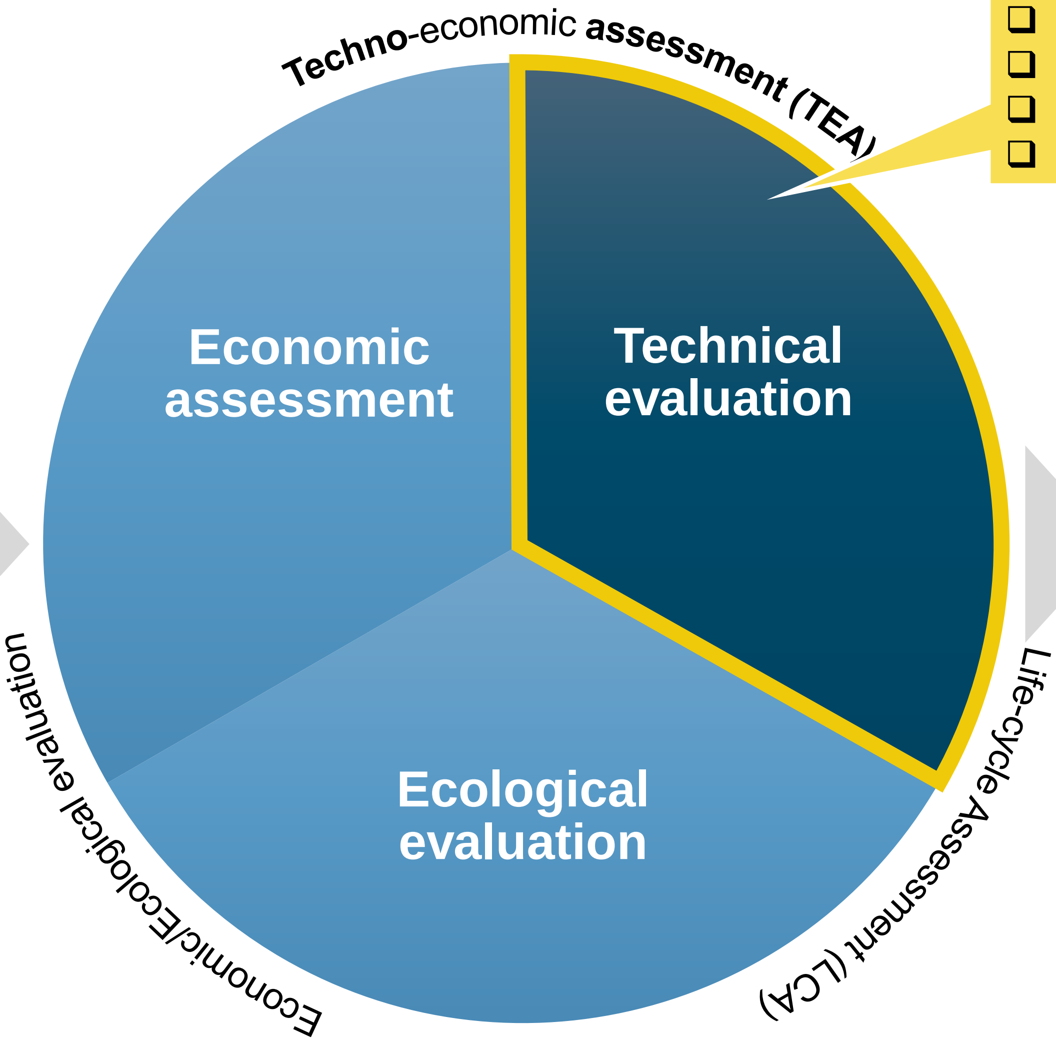
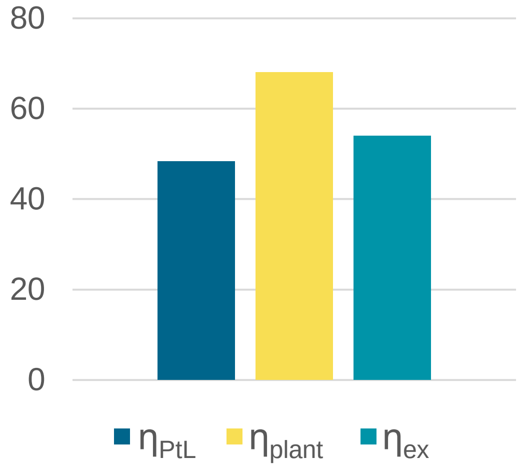


Techno-Economic and ecological assessment (TEEA)





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



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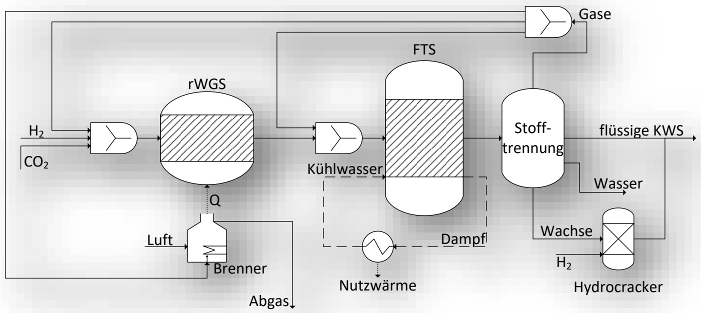

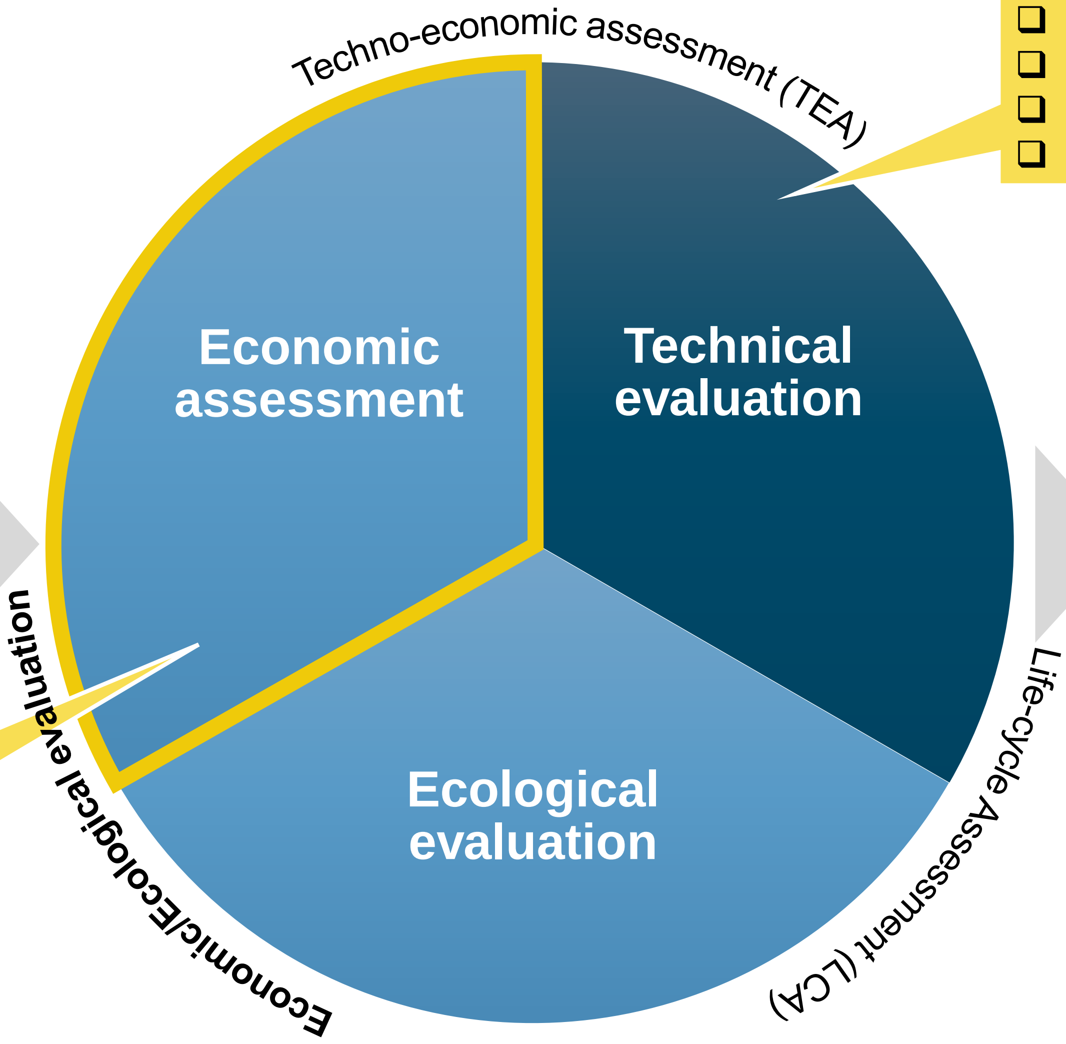

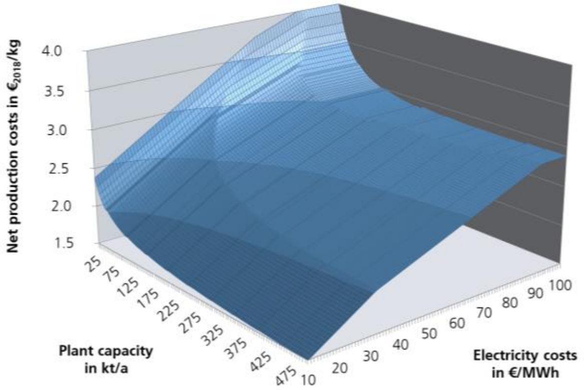

- ❑ CAPEX, OPEX, NPC
- ❑ Sensitivity analysis
- ❑ Identification of most economic feasible process design

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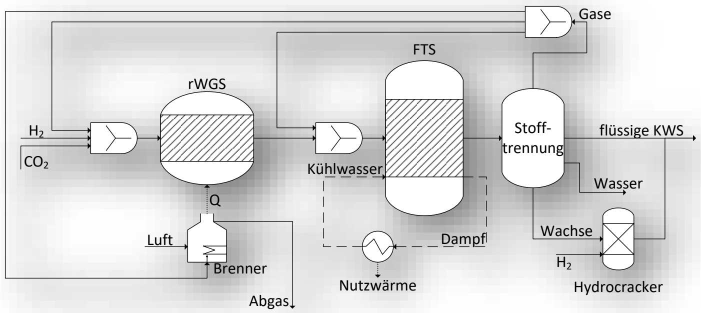

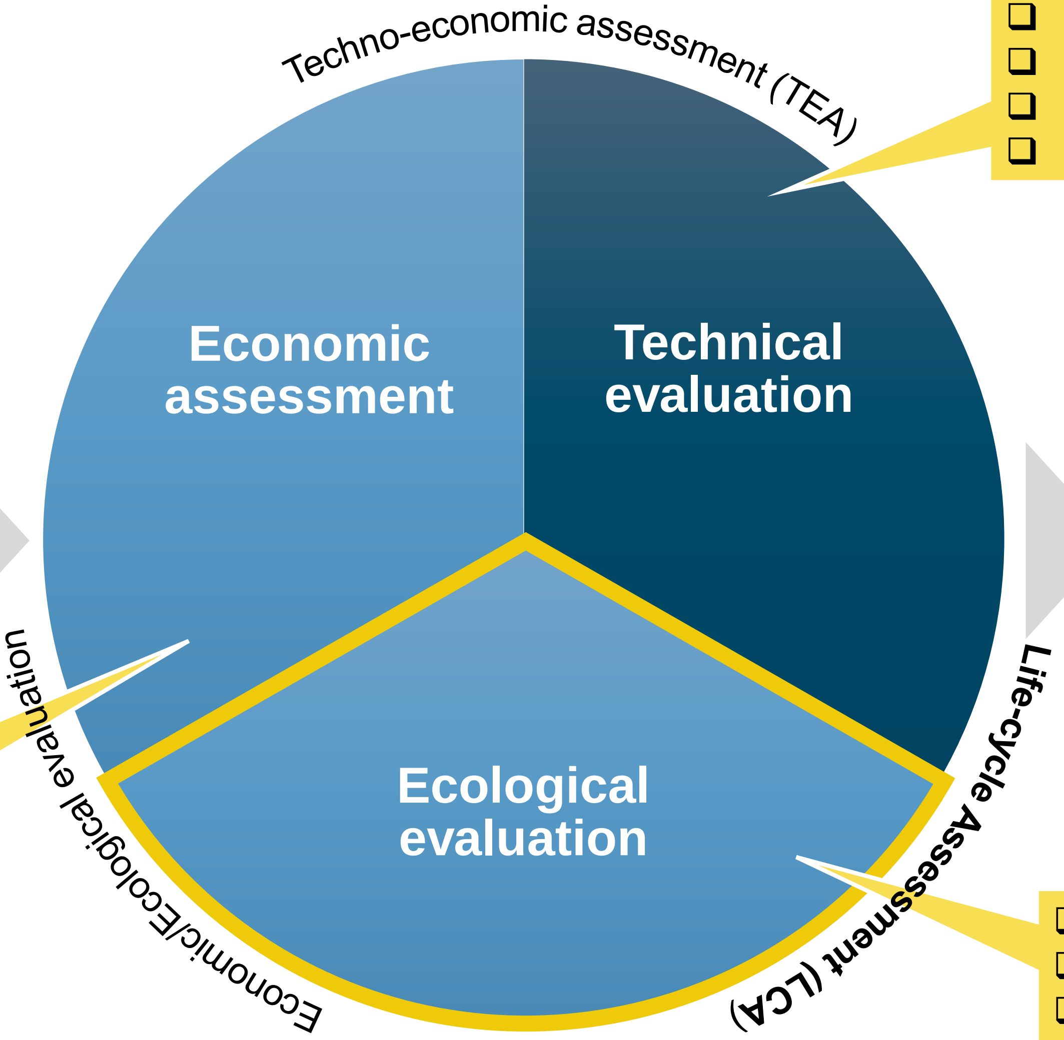

- ❑ CAPEX, OPEX, NPC
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- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

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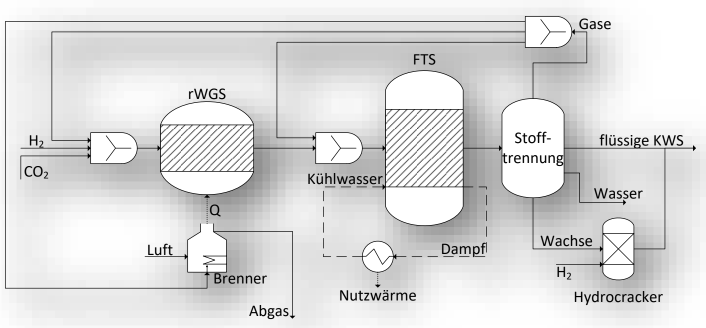

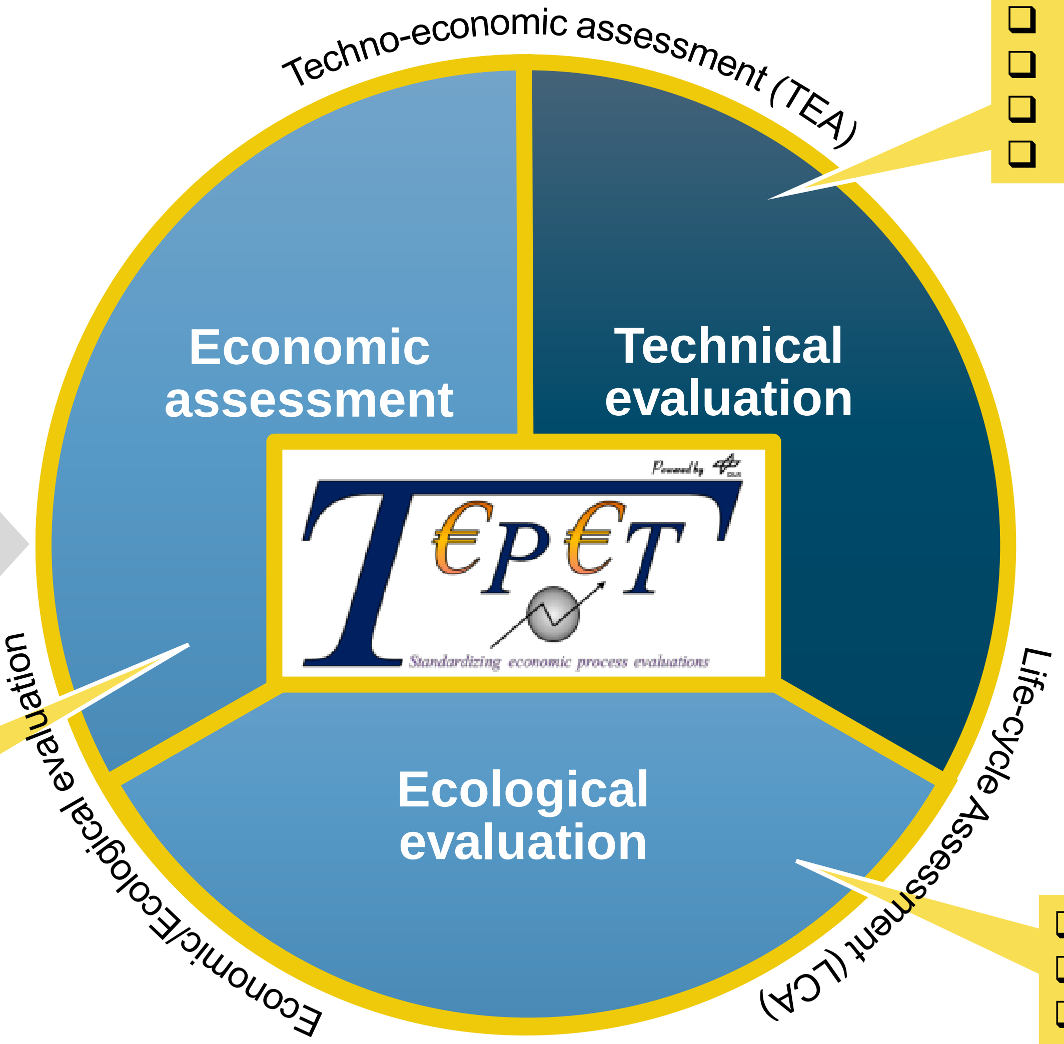

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Techno-Economic and ecological assessment (TEEA) @DLR

DLR

1. Step

Literature survey

Exchange with project partners

Simulation & Process evaluation

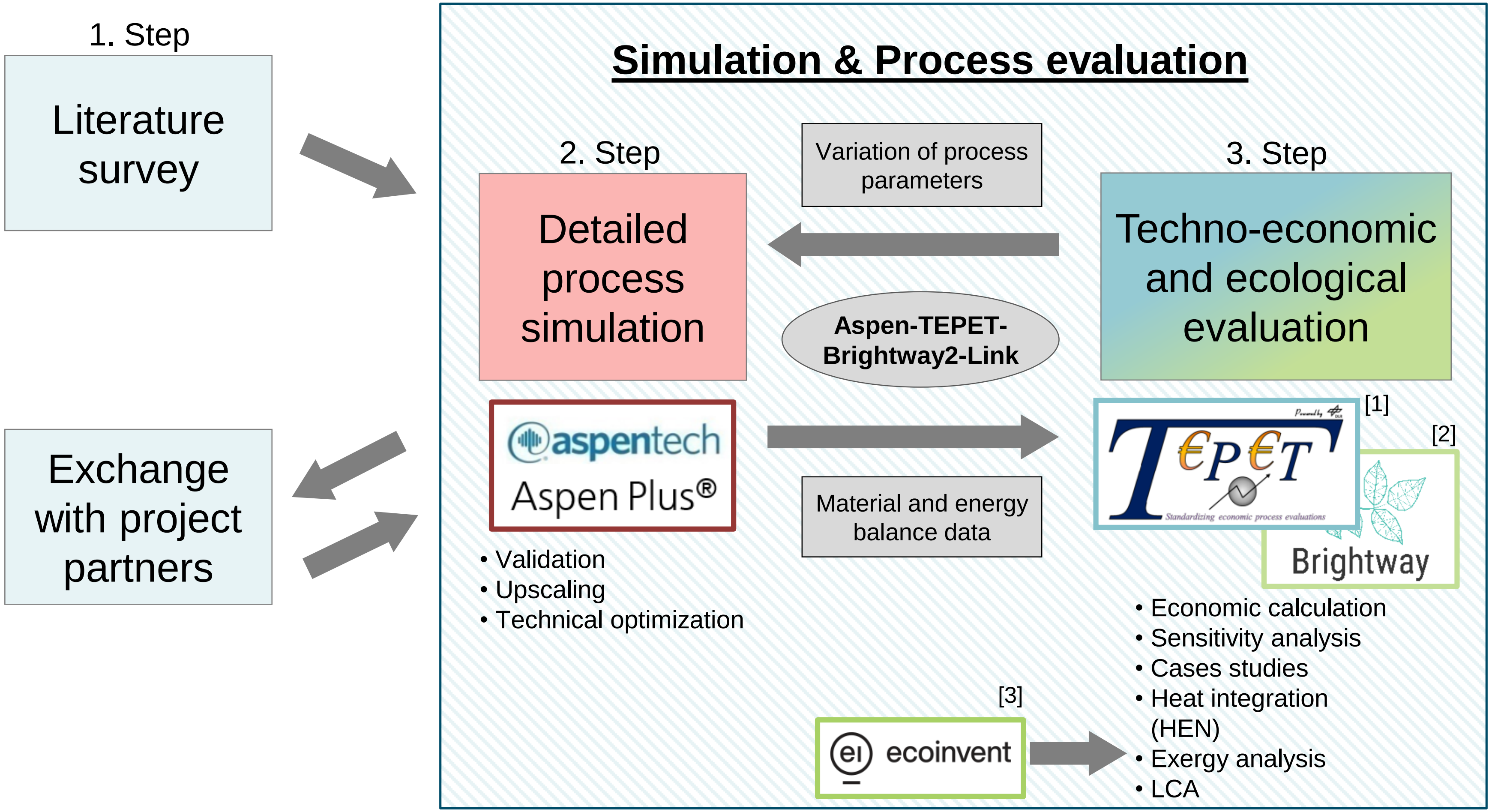
2. Step

Detailed process simulation

aspentech Aspen Plus®

- Validation
- Upscaling
- Technical optimization

Techno-Economic and ecological assessment (TEEA) @DLR



[1] Albrecht et al. (2016) - A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel, 194: 511-526
[2] Mutel (2017) - Brightway: An open source framework for Life Cycle Assessment, Journal of Open Source Software, 2(12): 236
[3] Wernet, G et al. (2016) – The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9): 1218–1230.

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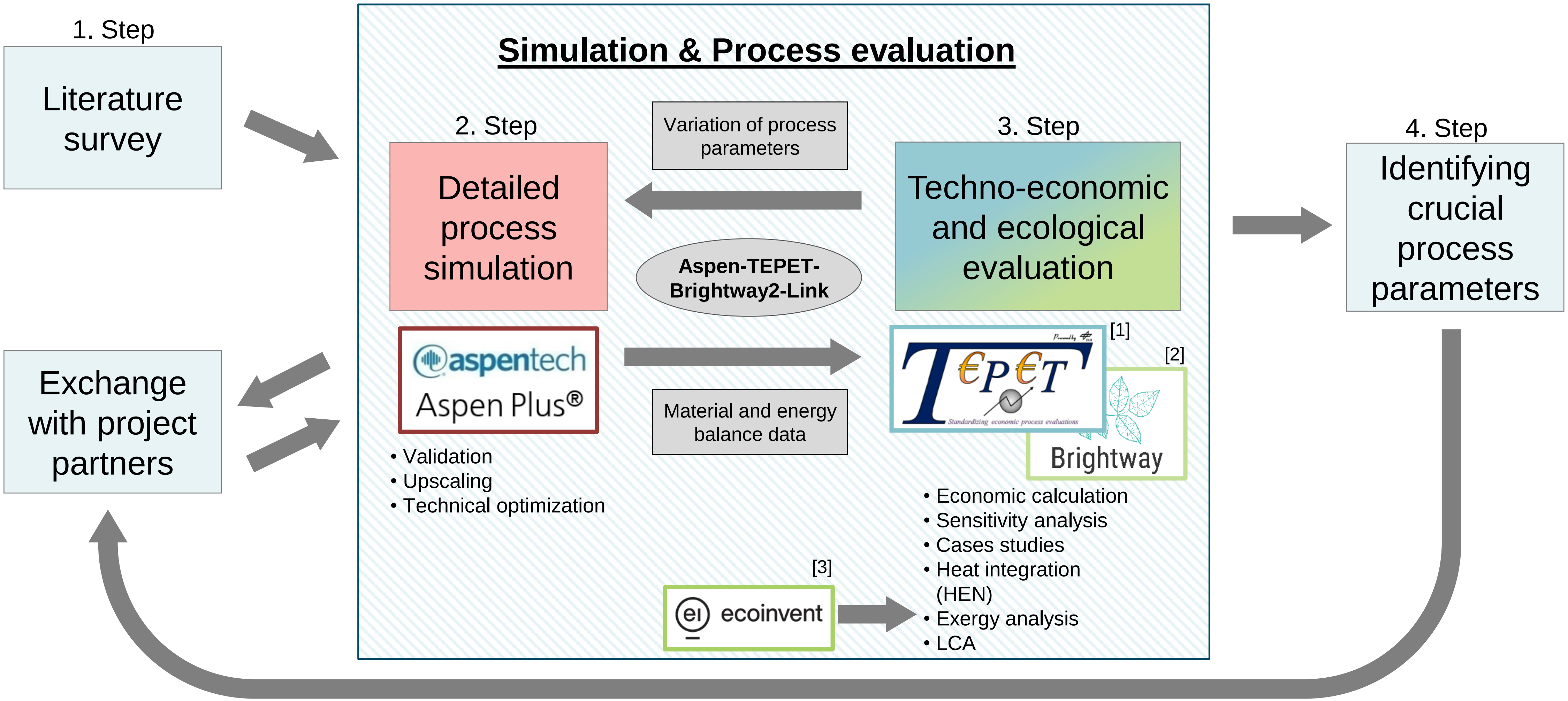

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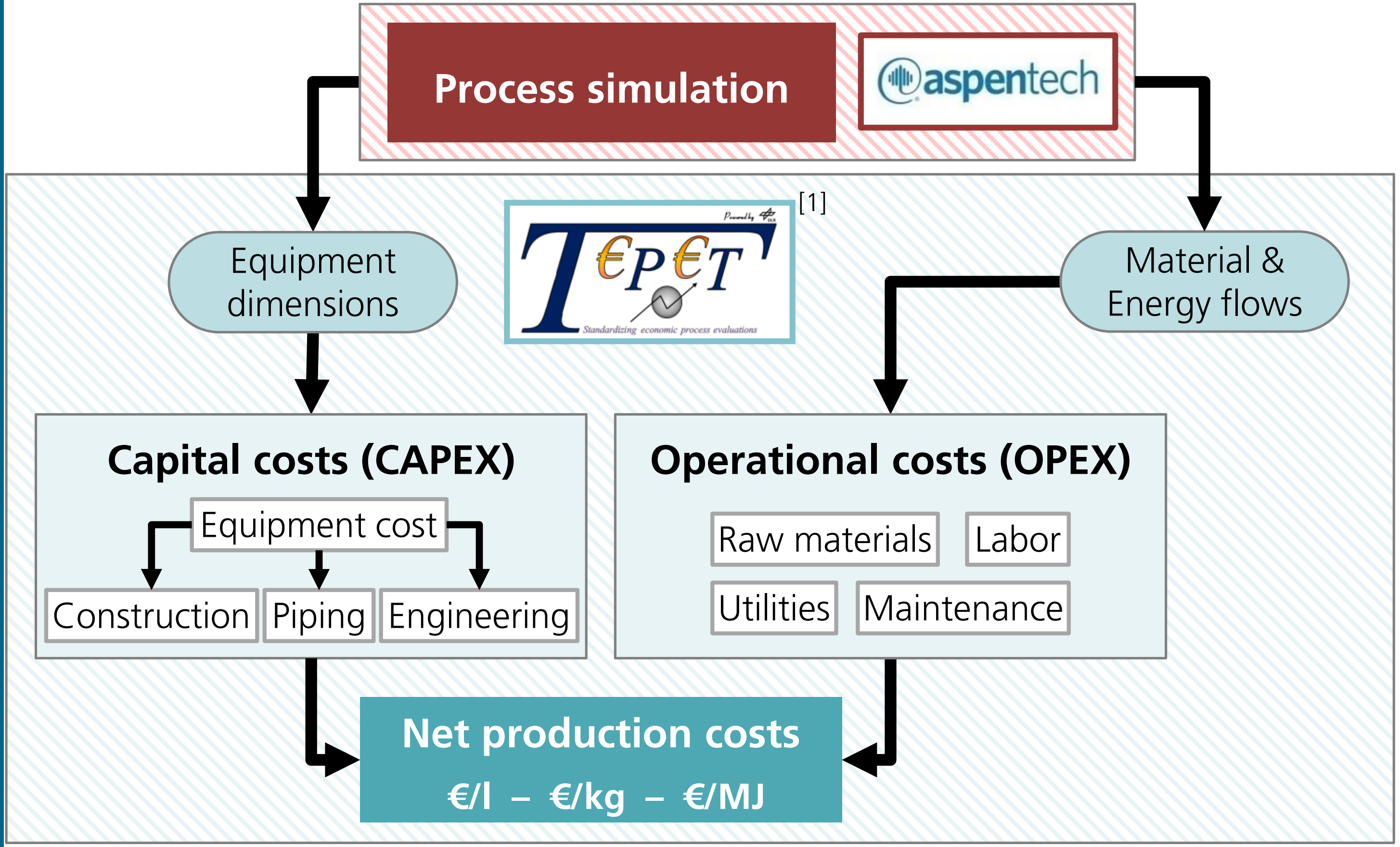
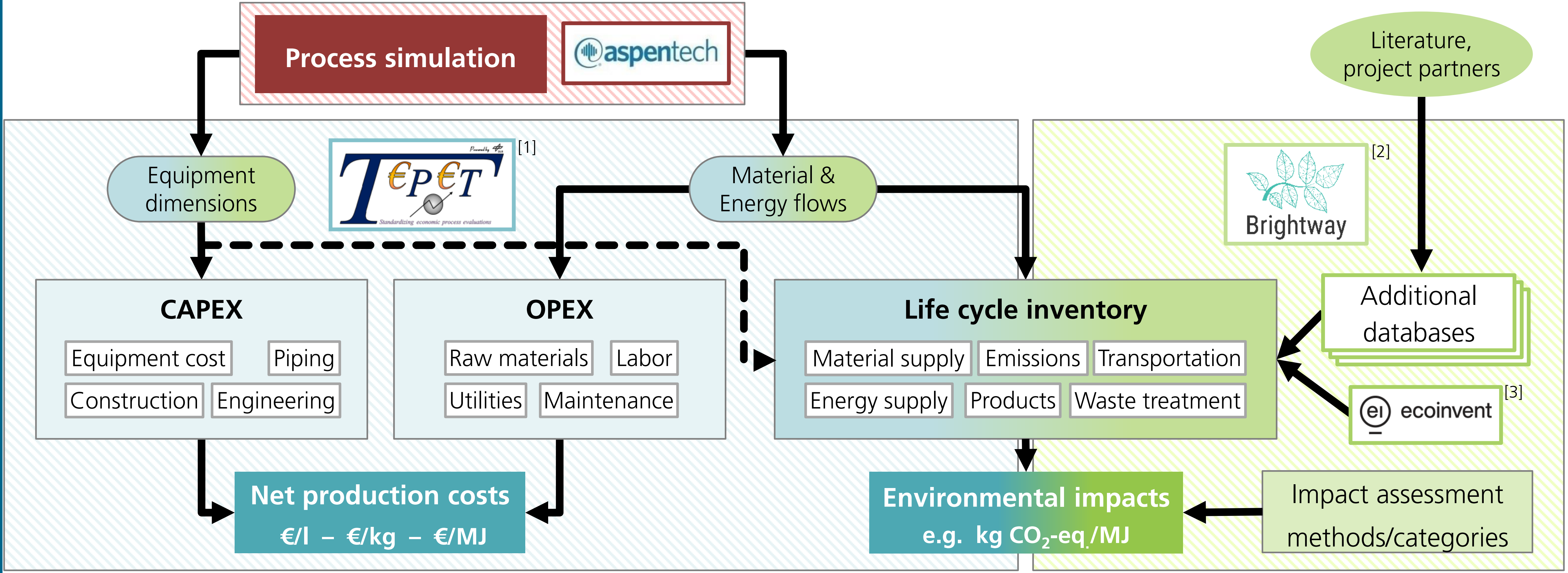
TEEA tool TEPET @ DLR (part 1)



- Adapted from **best-practice chem. eng. methodology**
- Meets AACE class 3-4, Accuracy: **+/- 30 %**
- **Year specific** using annual CEPCI Index
- Automated interface for **seamless integration, heating networks, …**
- Easy sensitivity studies for **each** parameter
- Learning curves, economy of scale, …

[1] Albrecht et al. (2016) - A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel, 194: 511-526

TEEA tool TEPET @ DLR (part 2)



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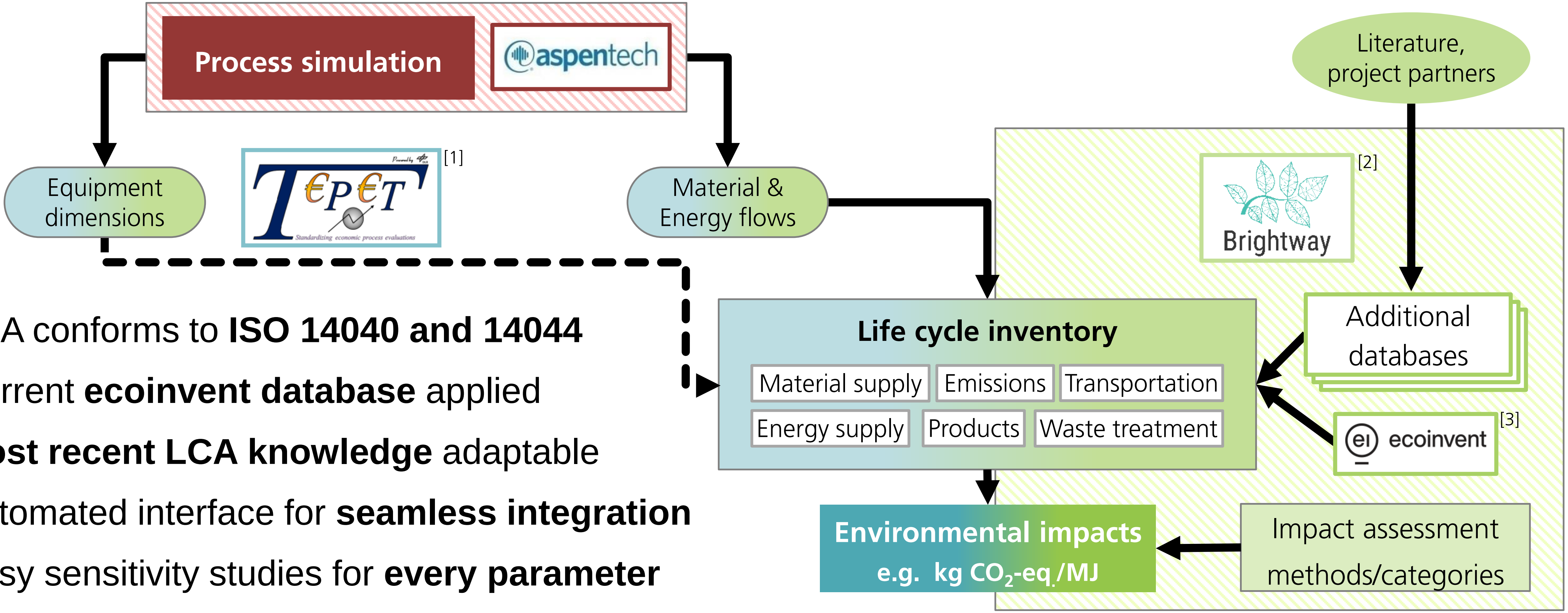

- LCA conforms to **ISO 14040 and 14044**
- Current **ecoinvent database** applied
- **Most recent LCA knowledge** adaptable
- Automated interface for **seamless integration**
- Easy sensitivity studies for **every parameter**

[1] Albrecht et al. (2016) - A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel, 194: 511-526
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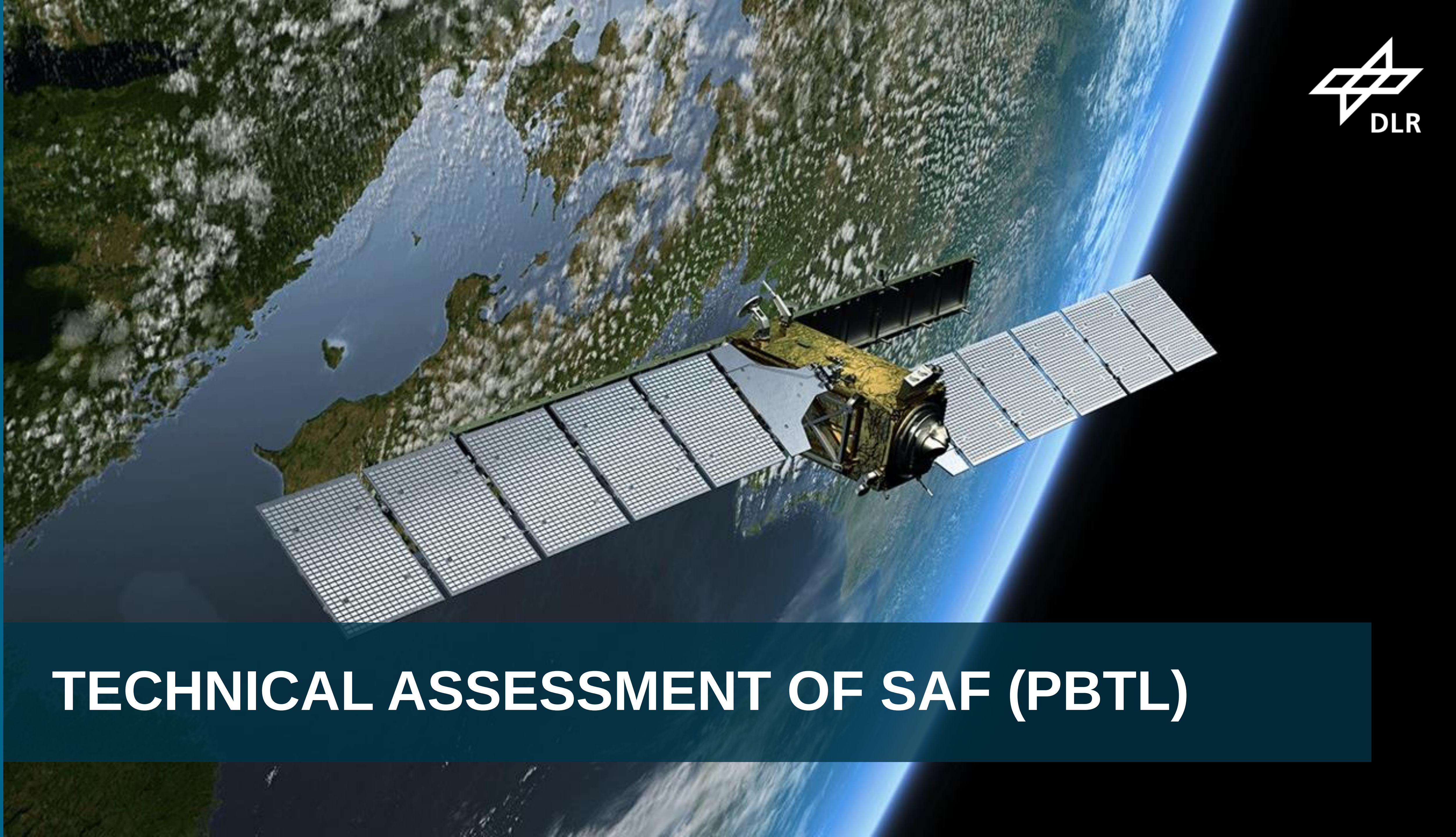


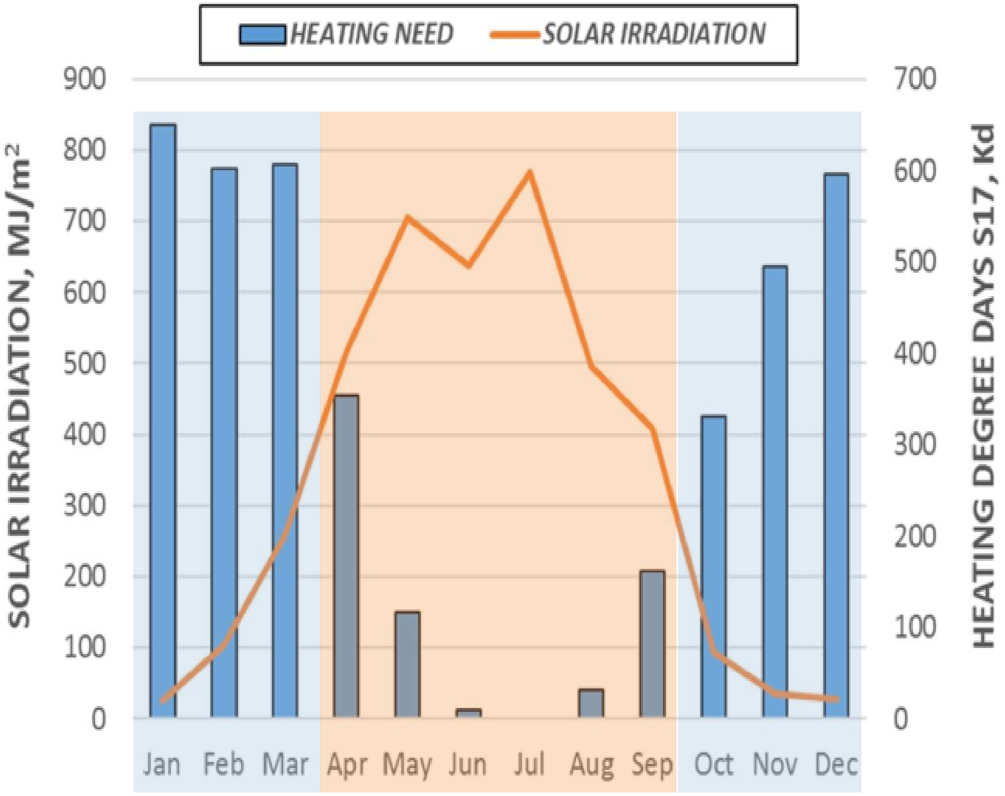
TECHNICAL ASSESSMENT OF SAF (PBTL)

Techno-Economic Assessment of **Power&Biomass-to-Liquid** Application

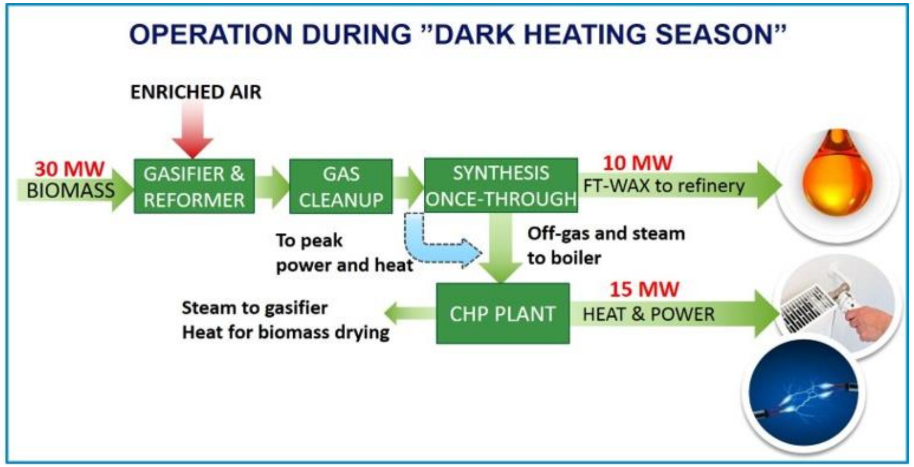
Seasonal market response approach:

FLEXCHX

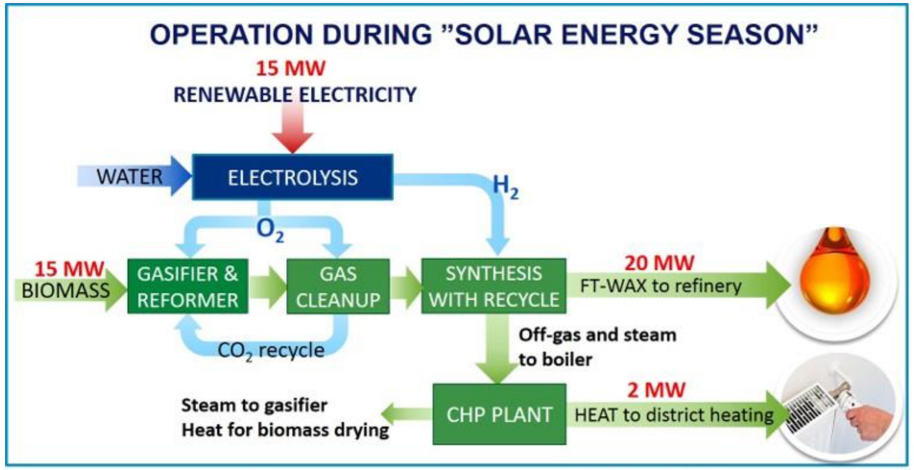
FlexCHX project has received funding from the European Union's Horizon 2020 research and innovation Programme under Grant Agreement No 763919



High heat demand & Low renewable electricity availability



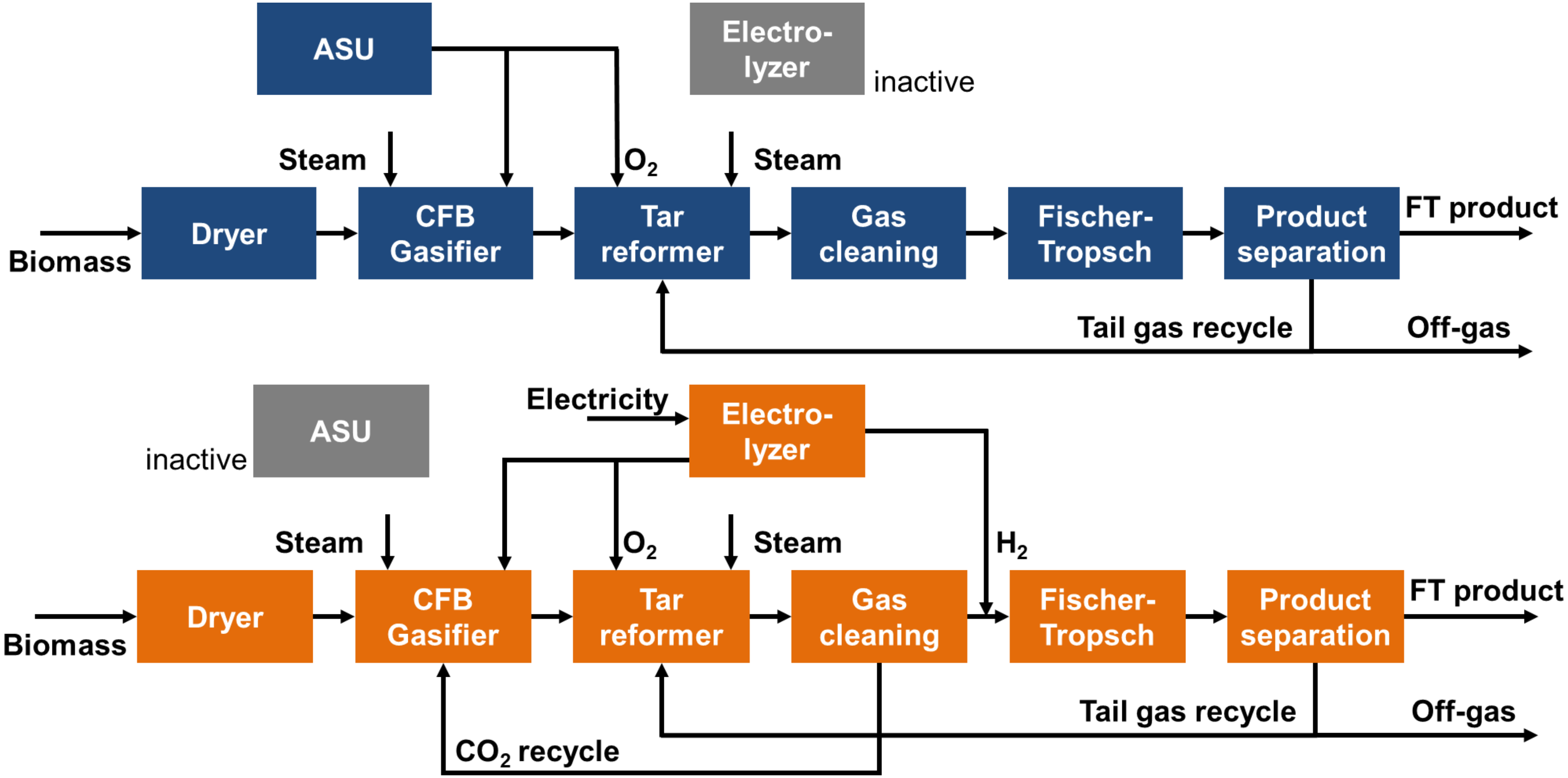
Low heat demand & High renewable electricity availability



Techno-Economic Assessment of 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



Winter mode:

- high heat demand
- low renewable power

Solution: BtL with ASU

Summer mode:

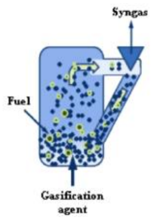
- no heat demand
- PV power available

Solution: electrolyzer assisted PBtL

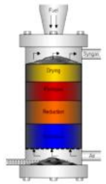
[1]Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774

Technology options for the PBtL process

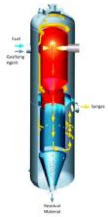
Gasifier [1]



Fluidized bed
+ Fuel flexibility
- Difficult control



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

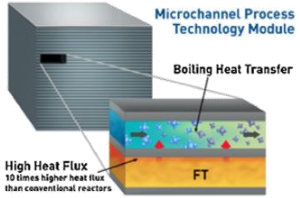


Entrained flow
+ High conversion efficiency
- High fuel specificity

Fischer-Tropsch reactor [2]

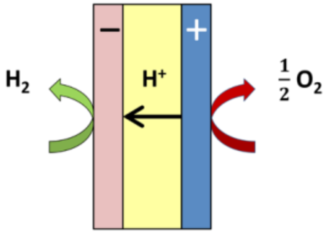
SBCR
+ Simple thermo management
- Difficult product separation

Fixed-bed
+ Easy product separation
- Heat transfer limitations

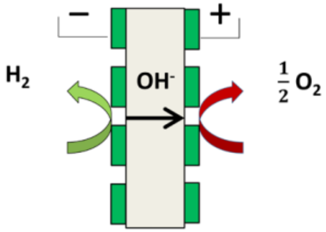


Microreactor
+ High once-through conversion
- High capital cost

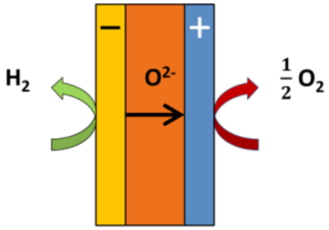
Electrolysis [3]



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)

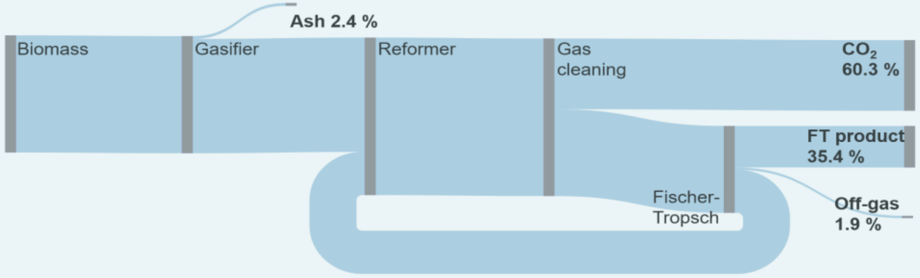
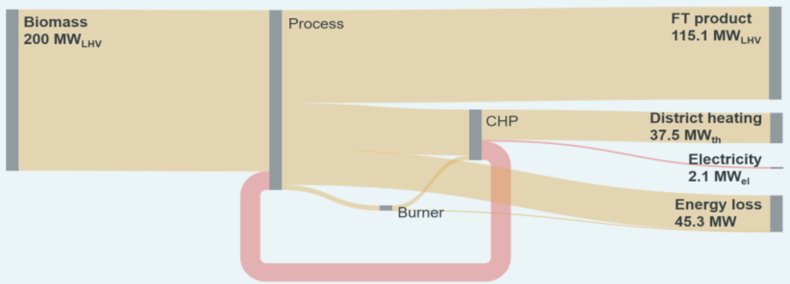
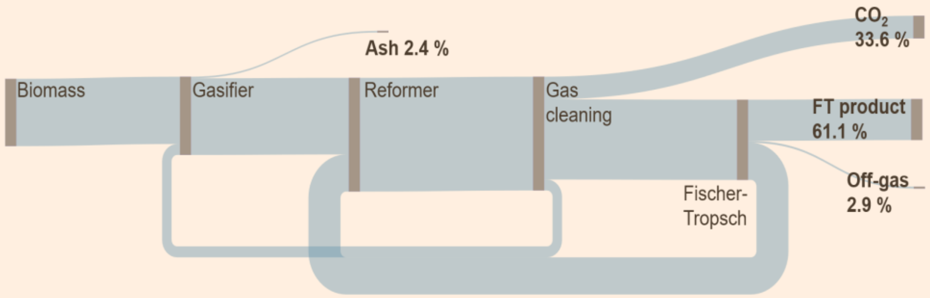
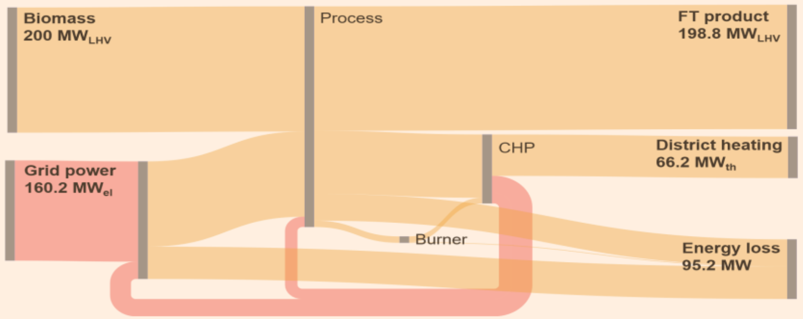
[1] Puig-Arnavat, M., Bruno, J. C., & Coronas, A. (2010). Review and analysis of biomass gasification models. *Renewable and sustainable energy reviews*, *14*(9), 2841-2851.
[2]] LeViness, S., Deshmukh, S. R., Richard, L. A., & Robota, H. J. (2014). Velocys Fischer–Tropsch synthesis technology—new advances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

Technical efficiencies [1]

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

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		

[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

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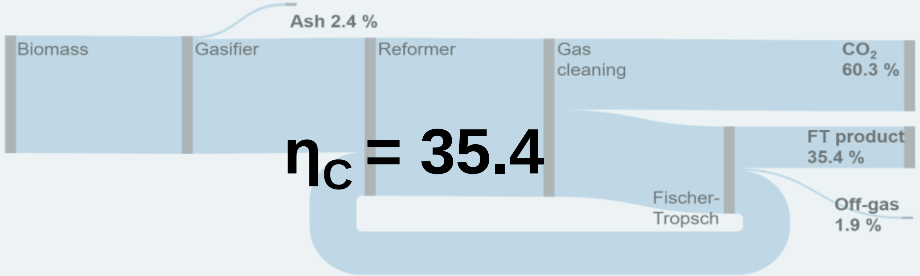
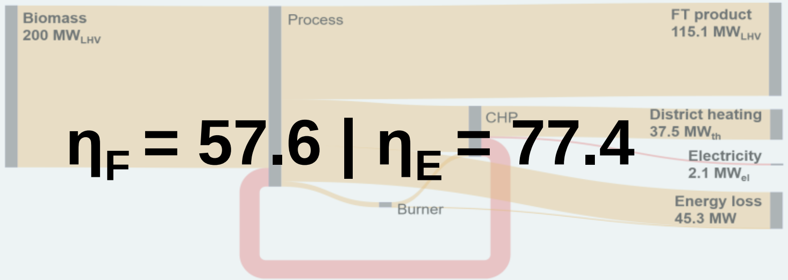
	Carbon efficiency η_C [%]	Fuel η_F | Process efficiency η_E [%]

Winter

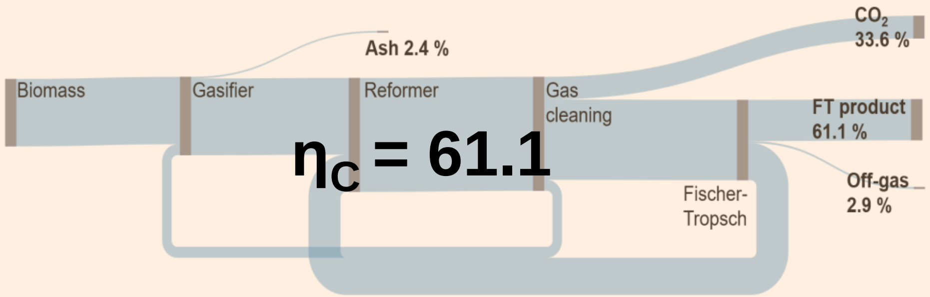


η_C = 35.4

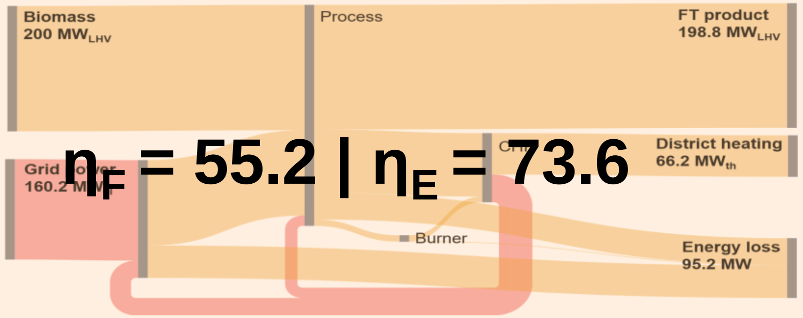


η_F = 57.6 | η_E = 77.4

Summer



η_C = 61.1



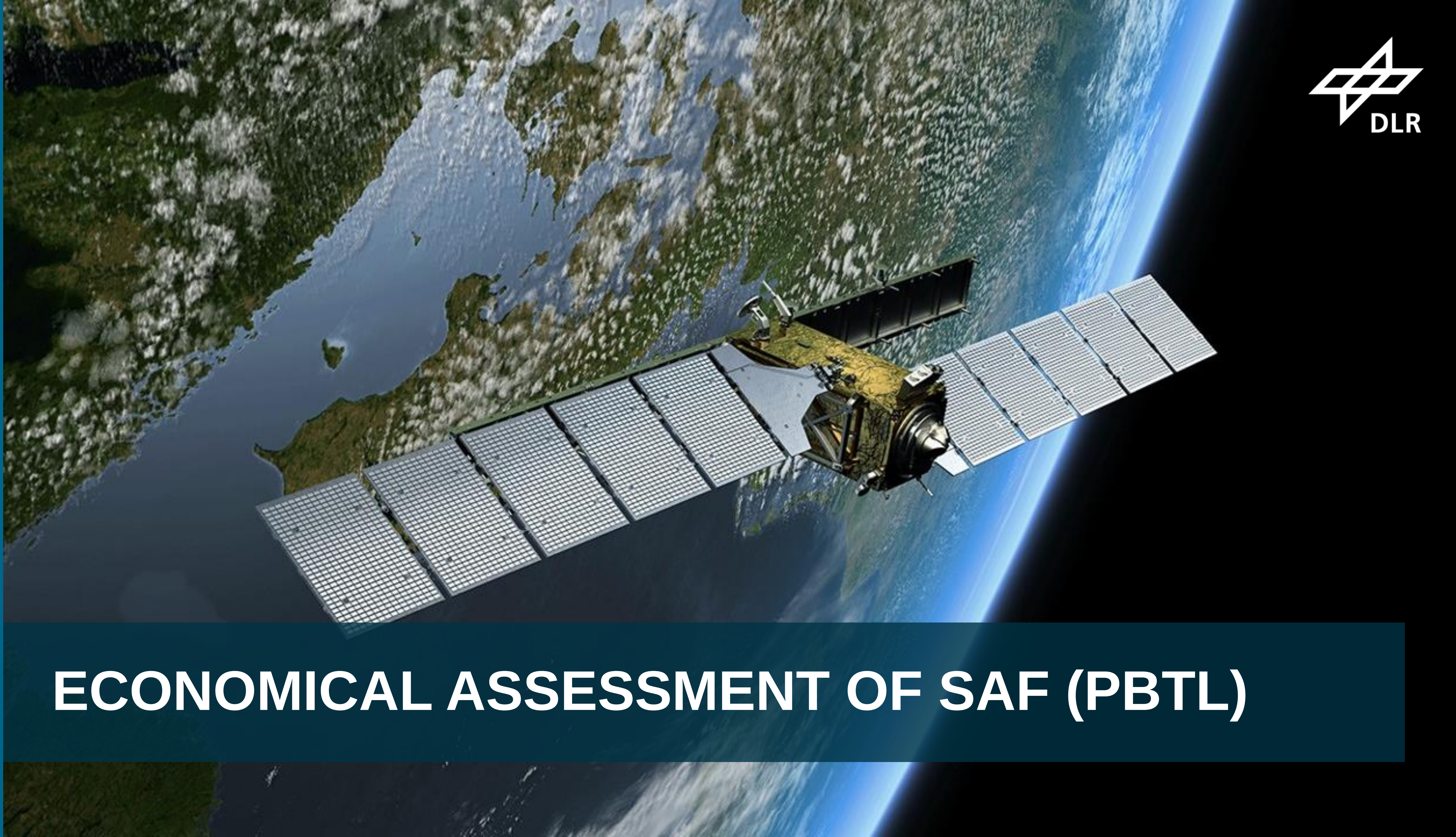
η_F = 55.2 | η_E = 73.6

50-50

$\eta_{C,av.}$ = 48.25

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

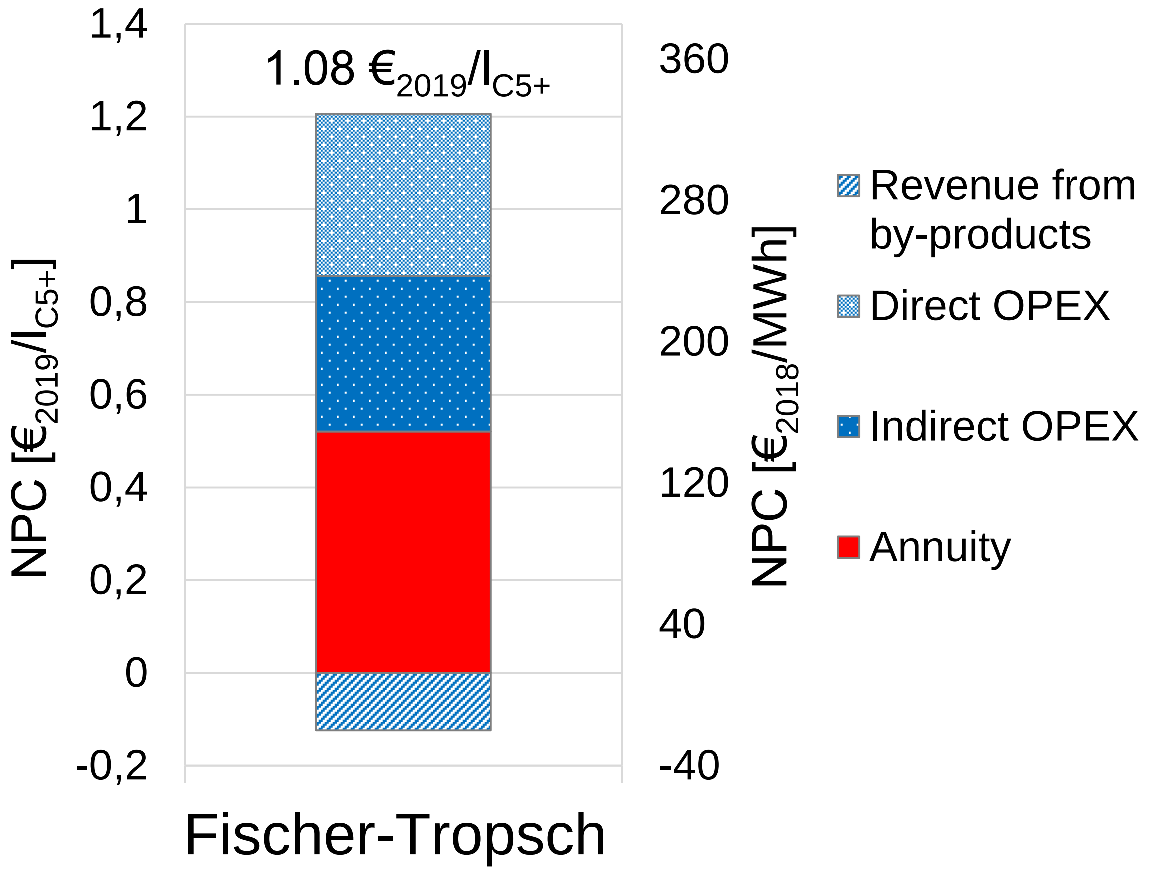
[1]Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774



ECONOMICAL ASSESSMENT OF SAF (PBTL)

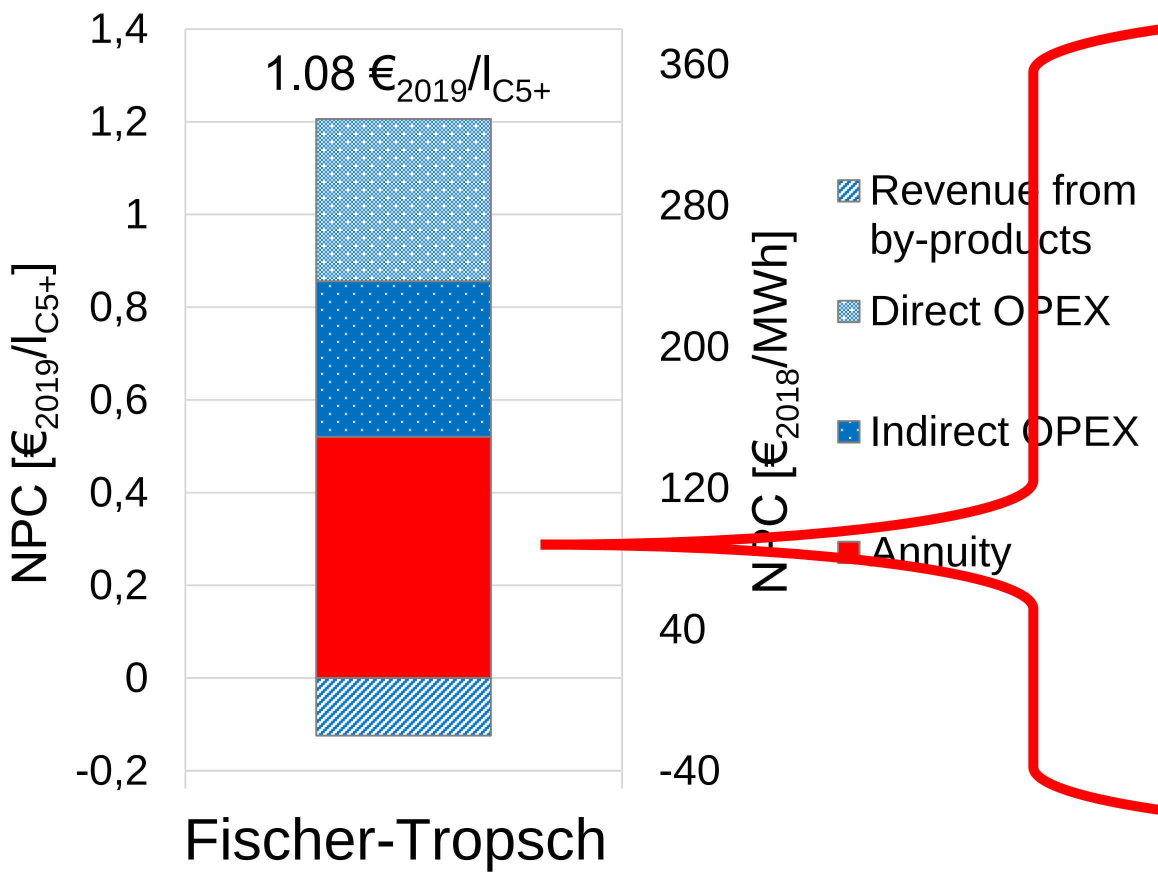
Cost structure FLEXCHX – Winter mode

NPC Breakdown

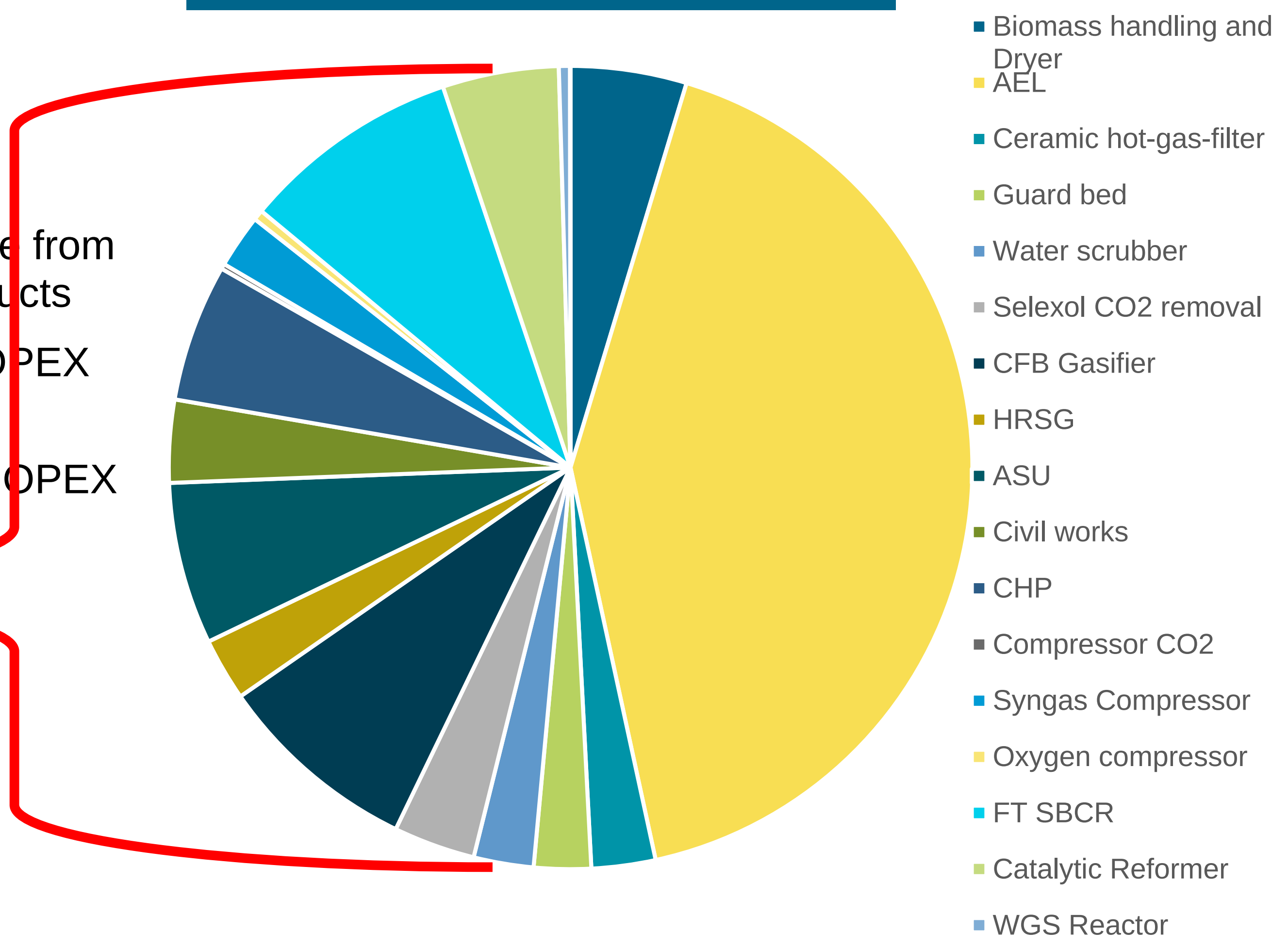


Cost structure FLEXCHX – Winter mode

NPC Breakdown



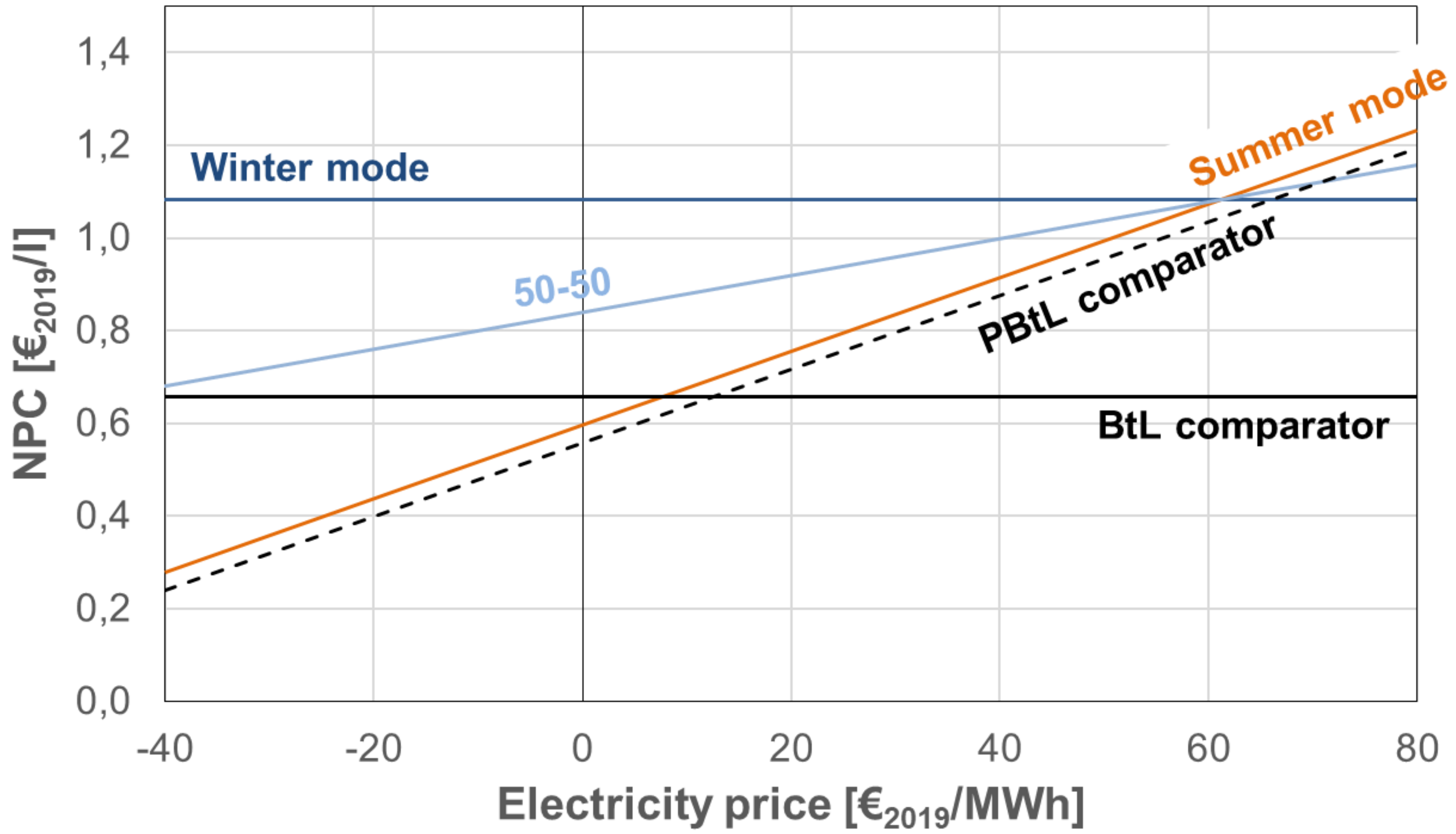
CAPEX



Techno-Economic Assessment of **Power&Biomass-to-Liquid** Application

Net production cost sensitivity [1] :

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



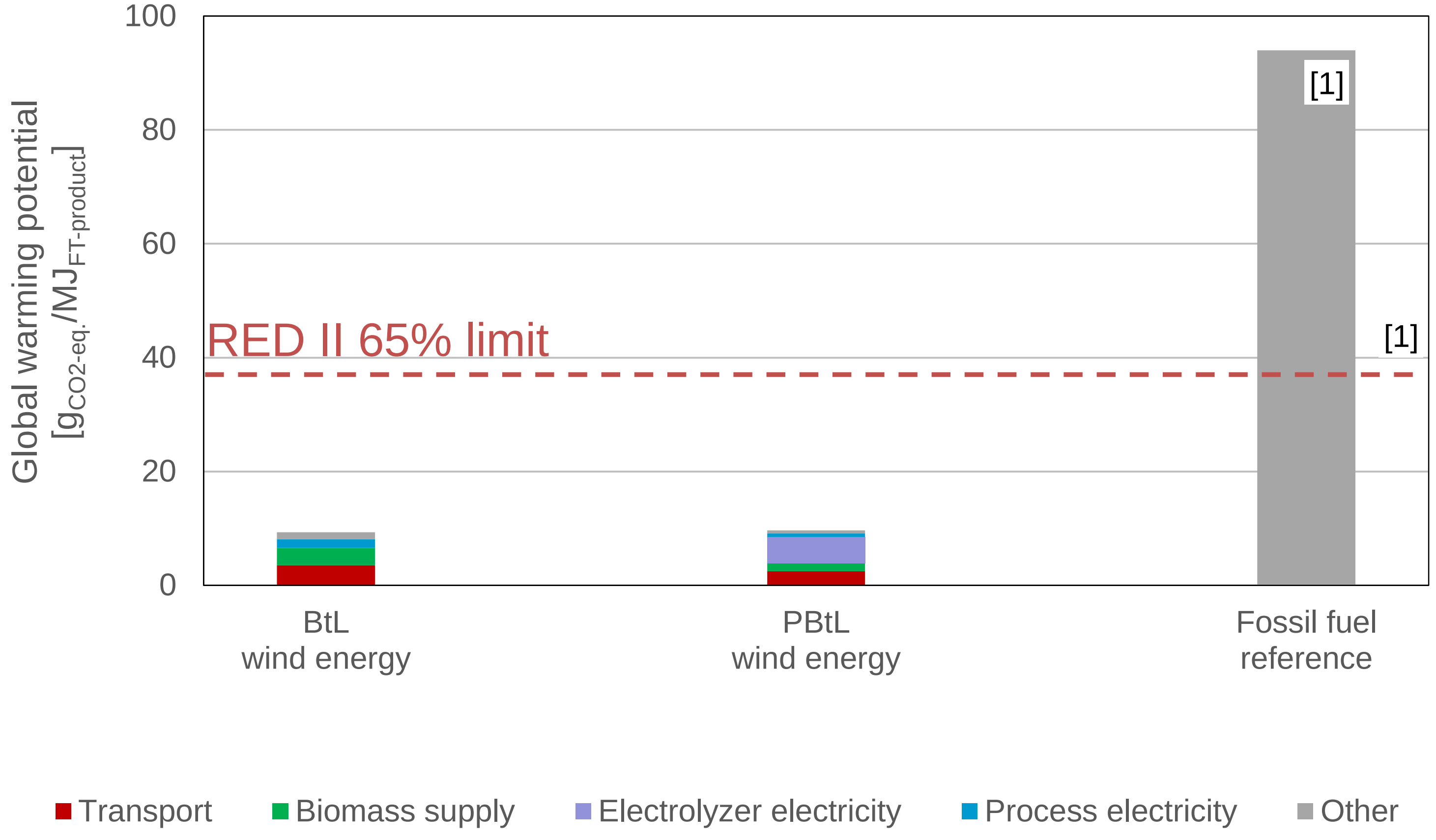
[1]Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774

ENVIRONMENTAL ASSESSMENT OF SAF (PBTL)

Environmental Assessment of Power&Biomass-to-Liquid Application

Global Warming Potential (GWP)

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



- **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 Application

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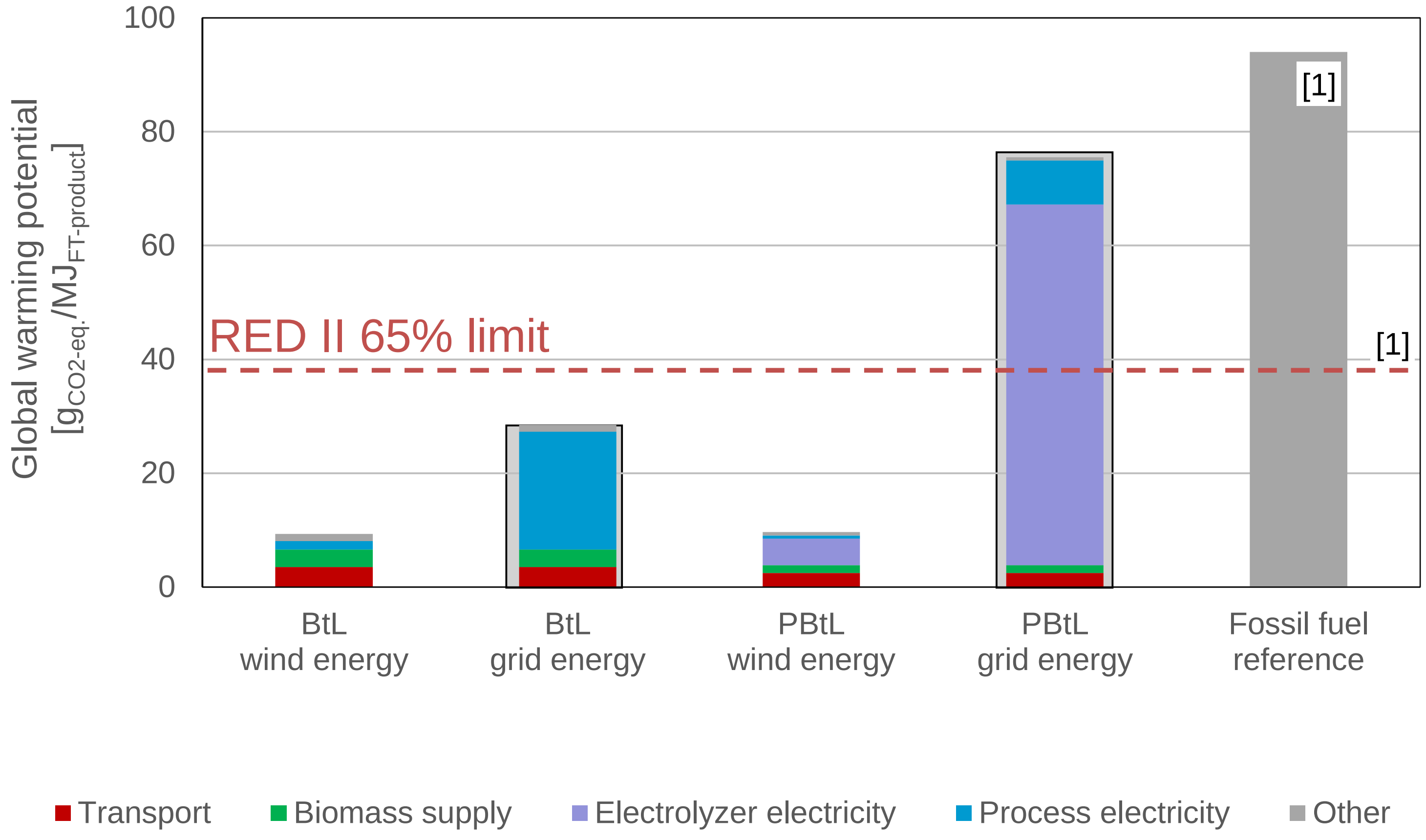

- **Transportation: truck (one-way)**
  - 100 km biomass
  - 200 km FT-products
- **Biomass: Harvesting woody residues (bark, saw dust, wood chips)**
- **Electricity: Finnish wind energy**
  Finnish grid mix

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 Application

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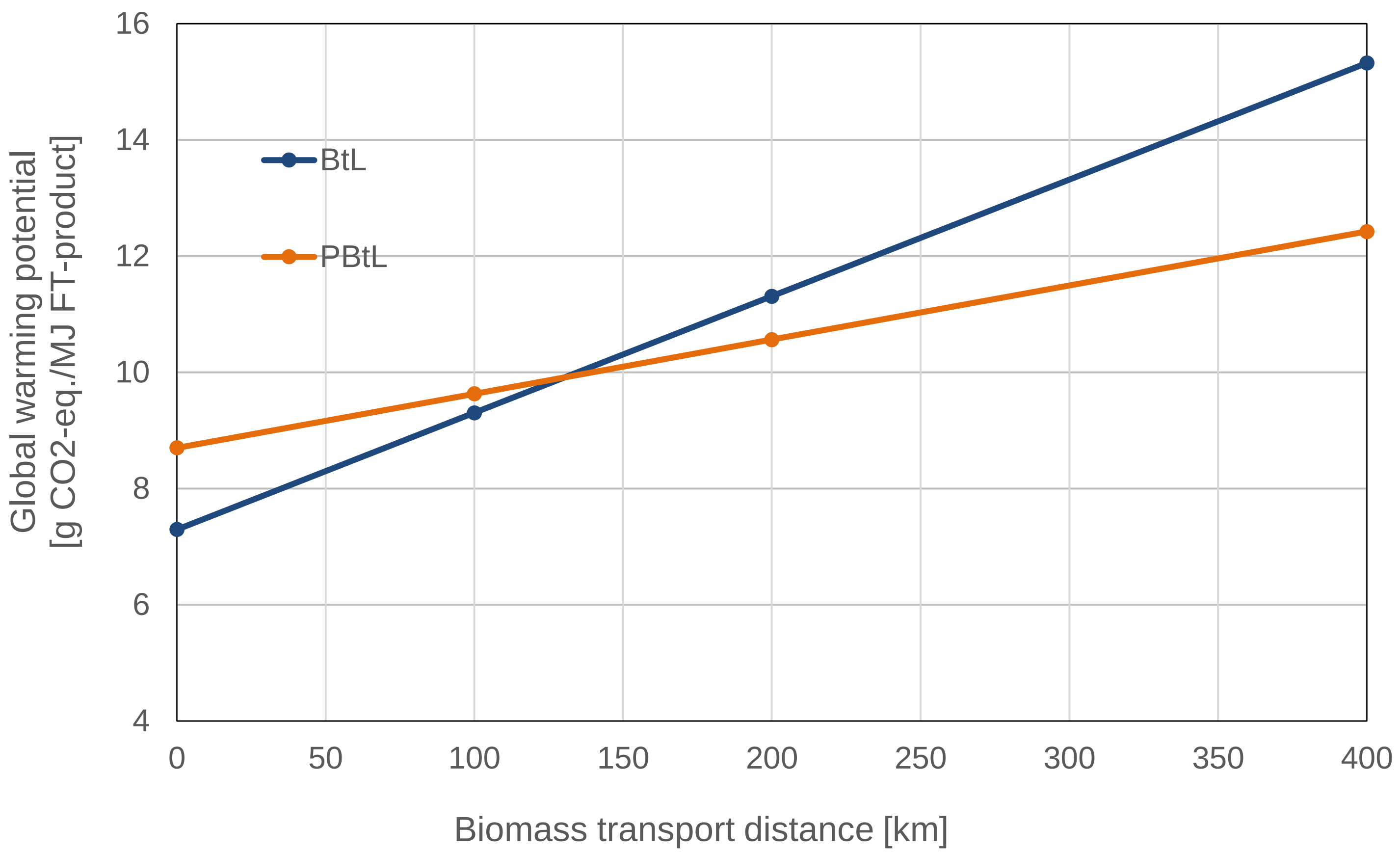
FlexCHX project has received funding from the European Union's Horizon 2020 research and innovation Programme under Grant Agreement No 763919



- **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

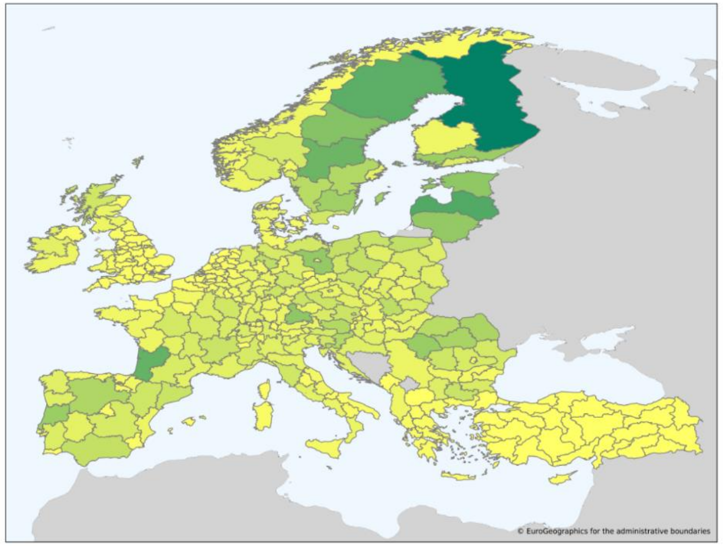
[1] European Union (2018) "Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)", Official Journal of the European Union,

POTENTIAL EUROPEAN SAF ROADMAP

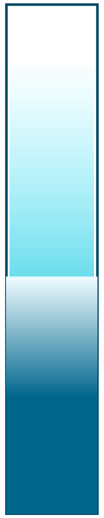
PBtL techno-economic-ecologic analysis for Europe

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?)



European aviation fuel demand

SAF potential ?

SAF potential according to RED II ?

SAF production cost ?

[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

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:

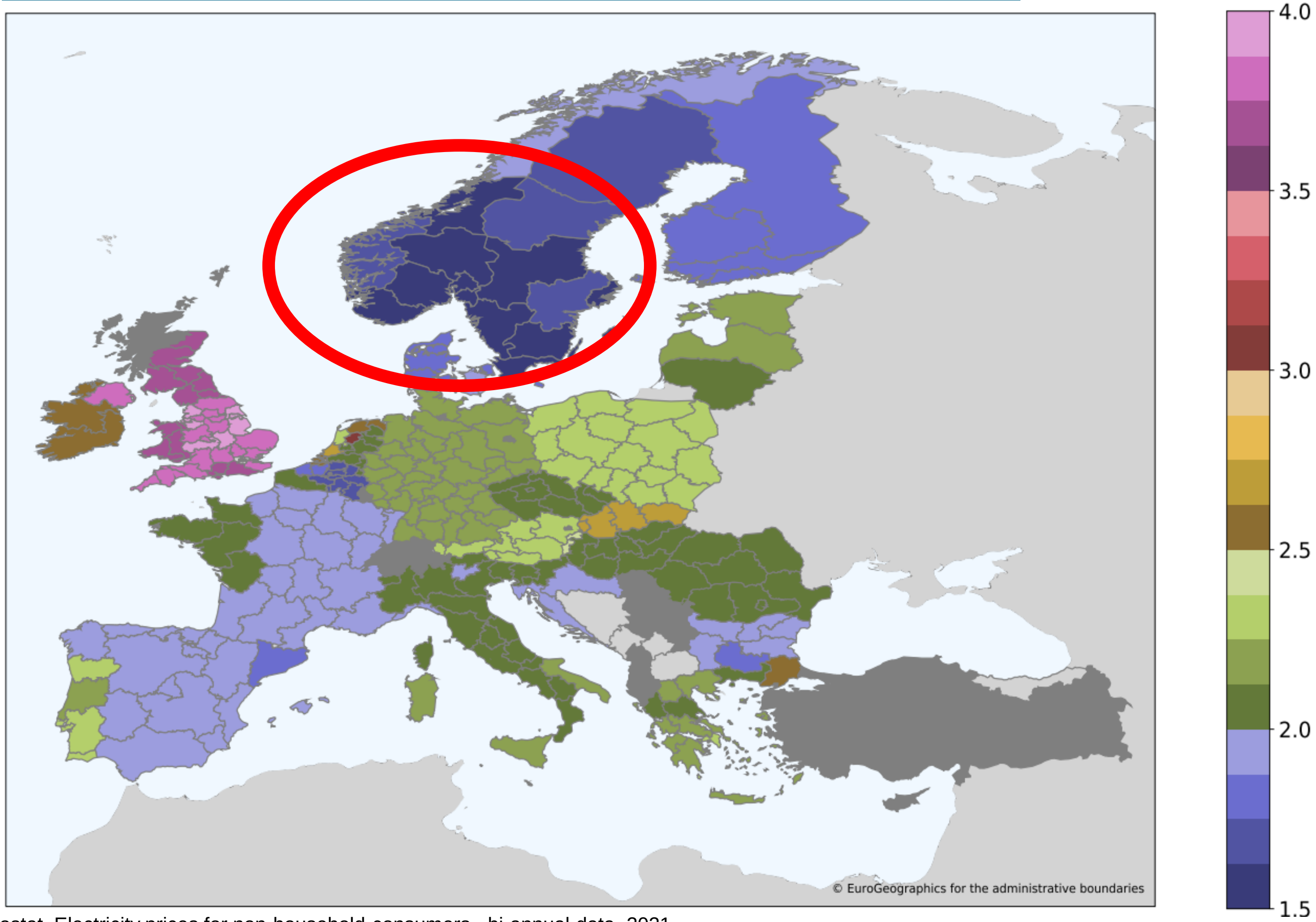
Year:	2020	*Plant lifetime:*	20 years
Full load hours:	8,100 h/a	*Interest rate:*	7 %

[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

DLR

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

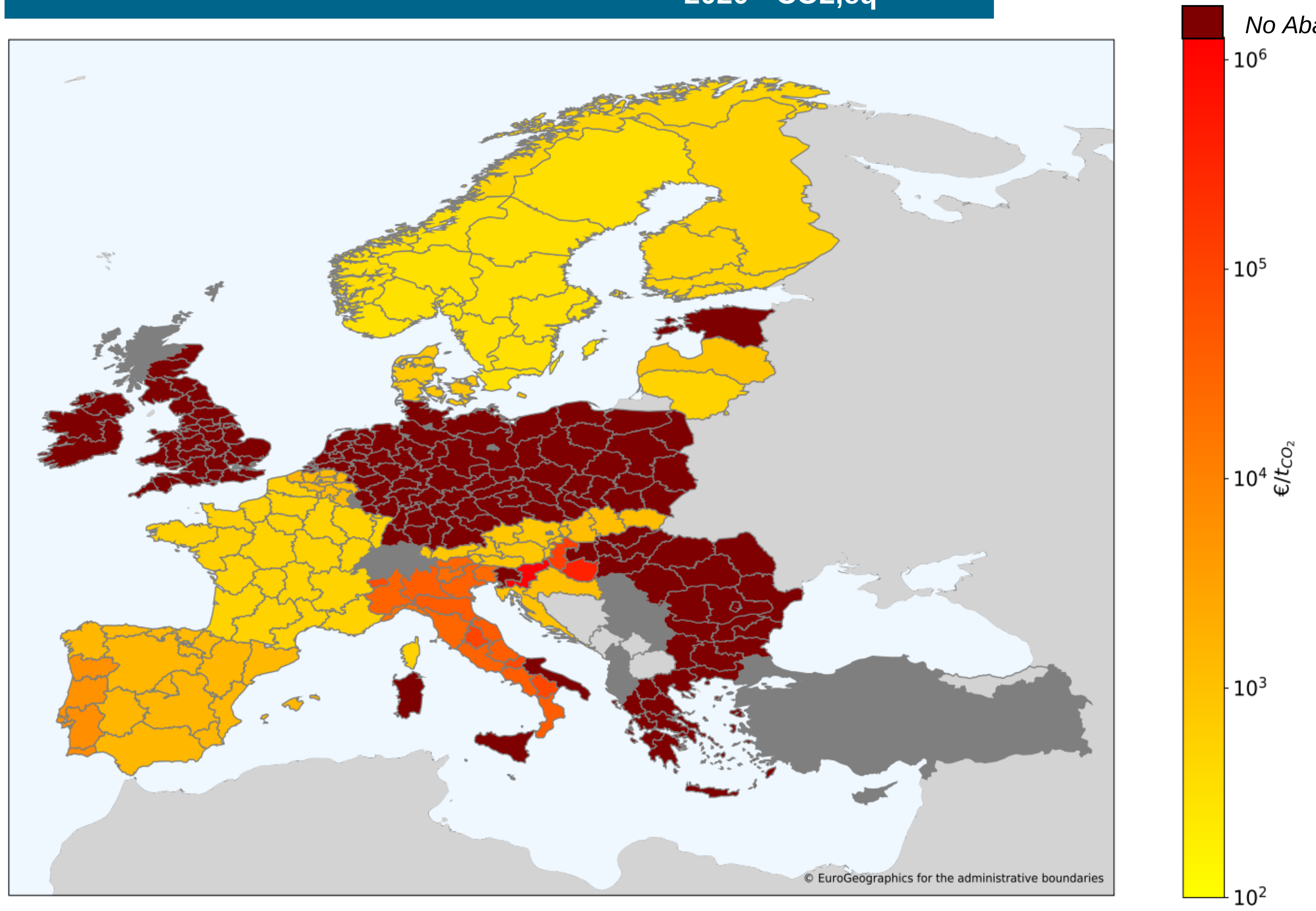
➔ Search for cheap biomass residue and inexpensive renewable power

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 / $€_{2020}/t_{CO2,eq}$



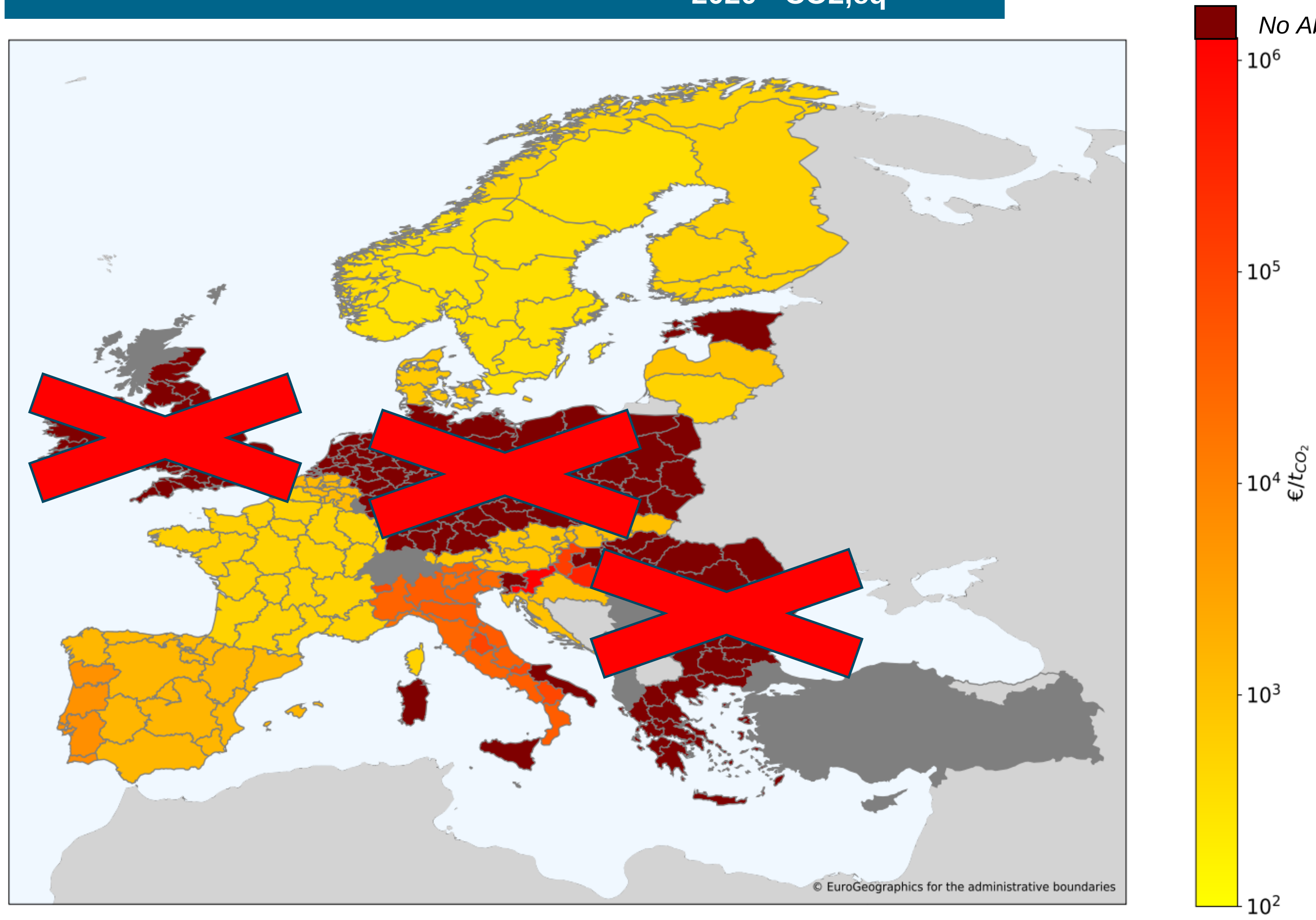
NUTS 2 region specific conditions:

- 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]

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:

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- Region-specific transport emissions
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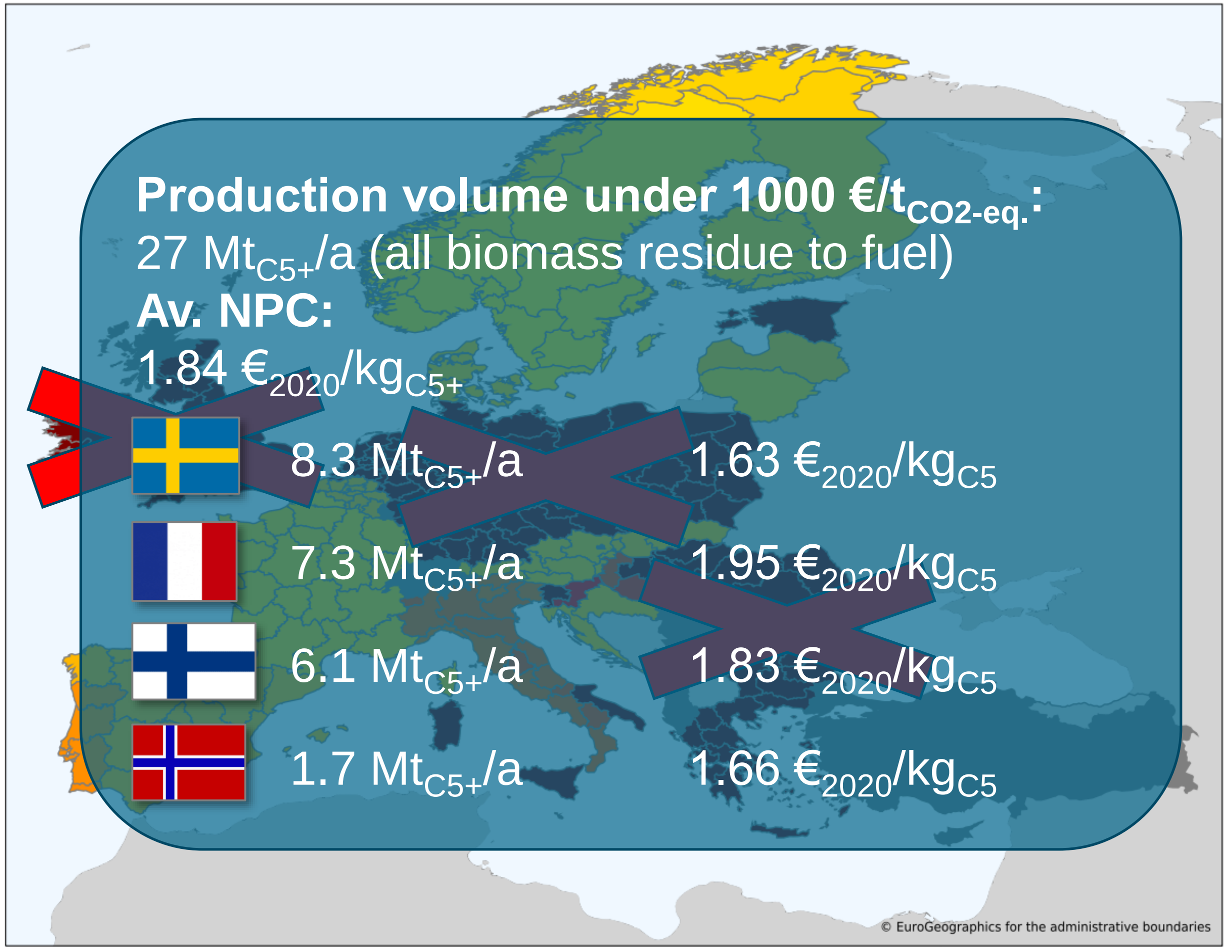
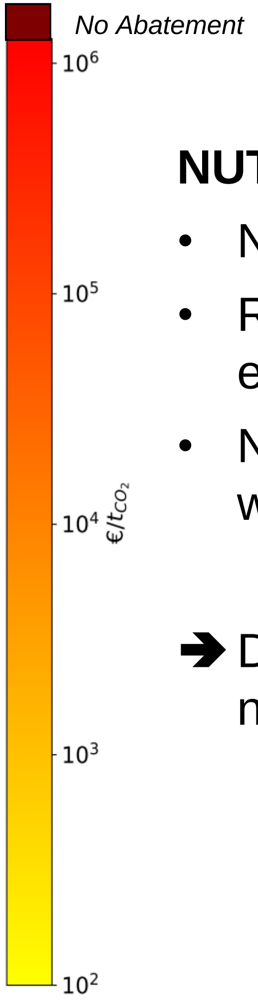
➔ Decarbonized national grids necessary for effective PBtL roll-out

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

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

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





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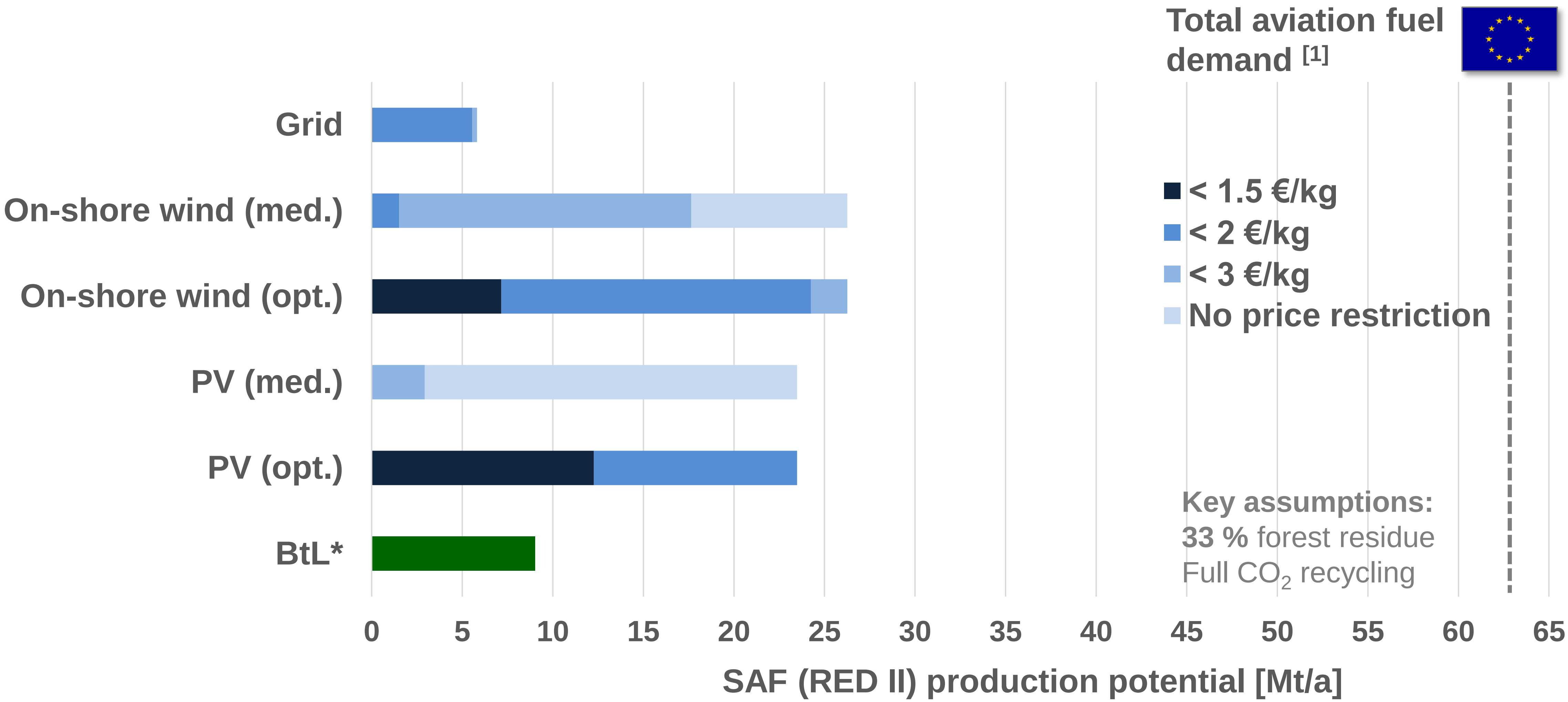
Aggregated European SAF production potential



[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 sustainable aviation fuels (SAF) production

Summary

- Renewable fuels are required to meet the aviation contribution towards European climate change mitigation
- GHG abatement costs shall be the key decision criteria for any climate change mitigation approach ➔ PBtL: < 1.000 €/$t_{CO2\text{-}eq.}$ achievable
- Europe can largely decarbonize its aviation, if it utilizes its biomass residues while investing in renewable power – technology is available and mature
  - Regulation needs to be far more demanding
- Transparent, standardized DLR assessment methodology
  - each technology option, roadmap creation, tracking of progress

Sustainable aviation will be a long journey,

Ramp up needs a shift in dimension!

THANK YOU FOR YOUR ATTENTION !
Questions?

DLRK 2022
DEUTSCHER LUFT- UND RAUMFAHRTKONGRESS
DGLR
27. - 29. SEPTEMBER 2022 – DRESDEN
„Luft- und Raumfahrt - gemeinsam forschen und nachhaltig gestalten“

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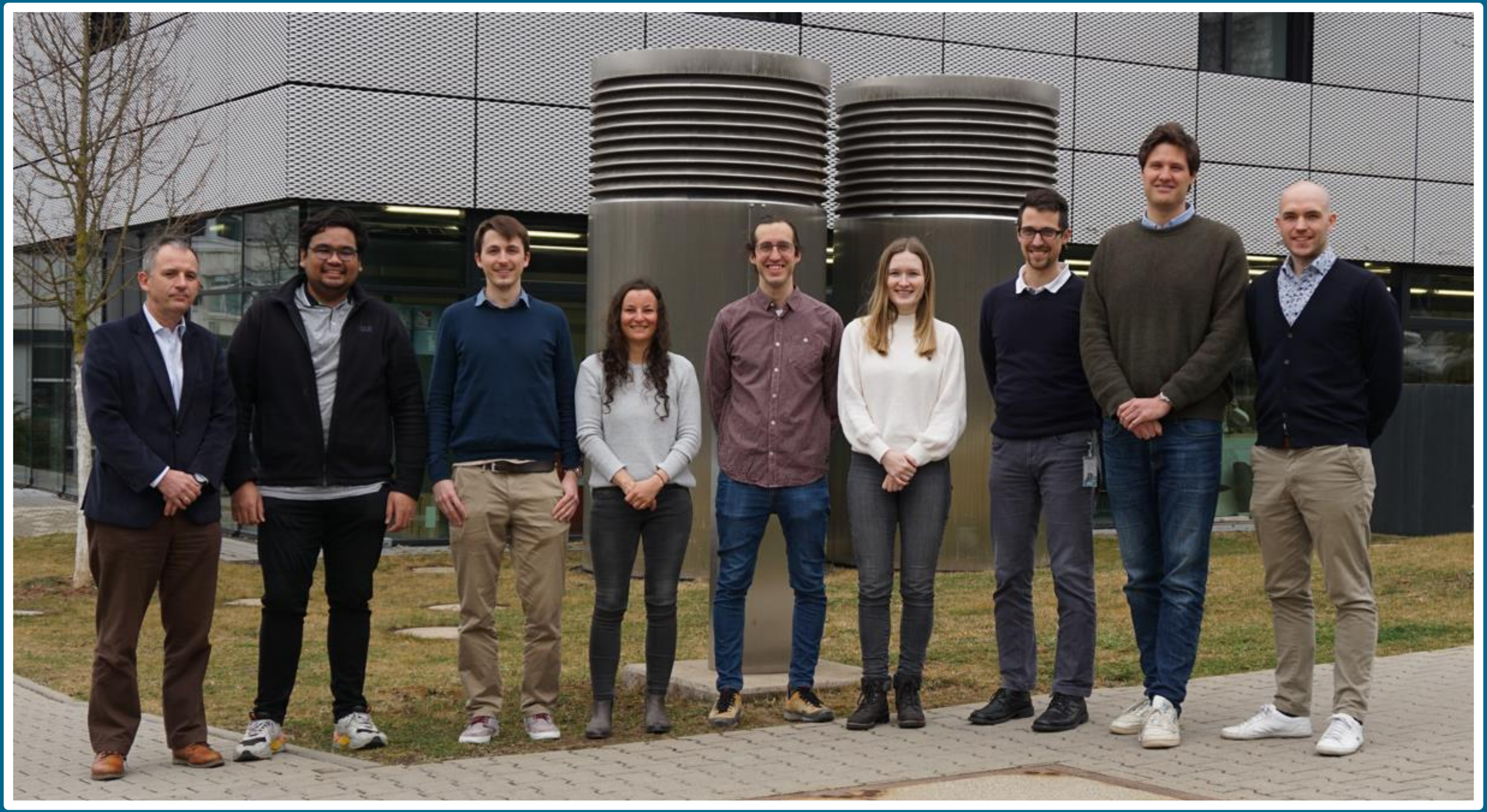

Moritz Raab, Felix Habermeyer, Nathanael Heimann, Julia Weyand, Simon Maier, Sandra Adelung, Francisco Moser, Yoga Rahmat, Ralph-Uwe Dietrich