Wednesday, 2024/09/26

ADV. ESCC 2024 3RD GLOBAL SUMMIT — SEPTEMBER 26-27 2024 BARCELONA, SPAIN

TECHNO-ECONOMIC AND ECOLOGICAL ASSESSMENT

Large-scale economic production of sustainable aviation fuels in Europe

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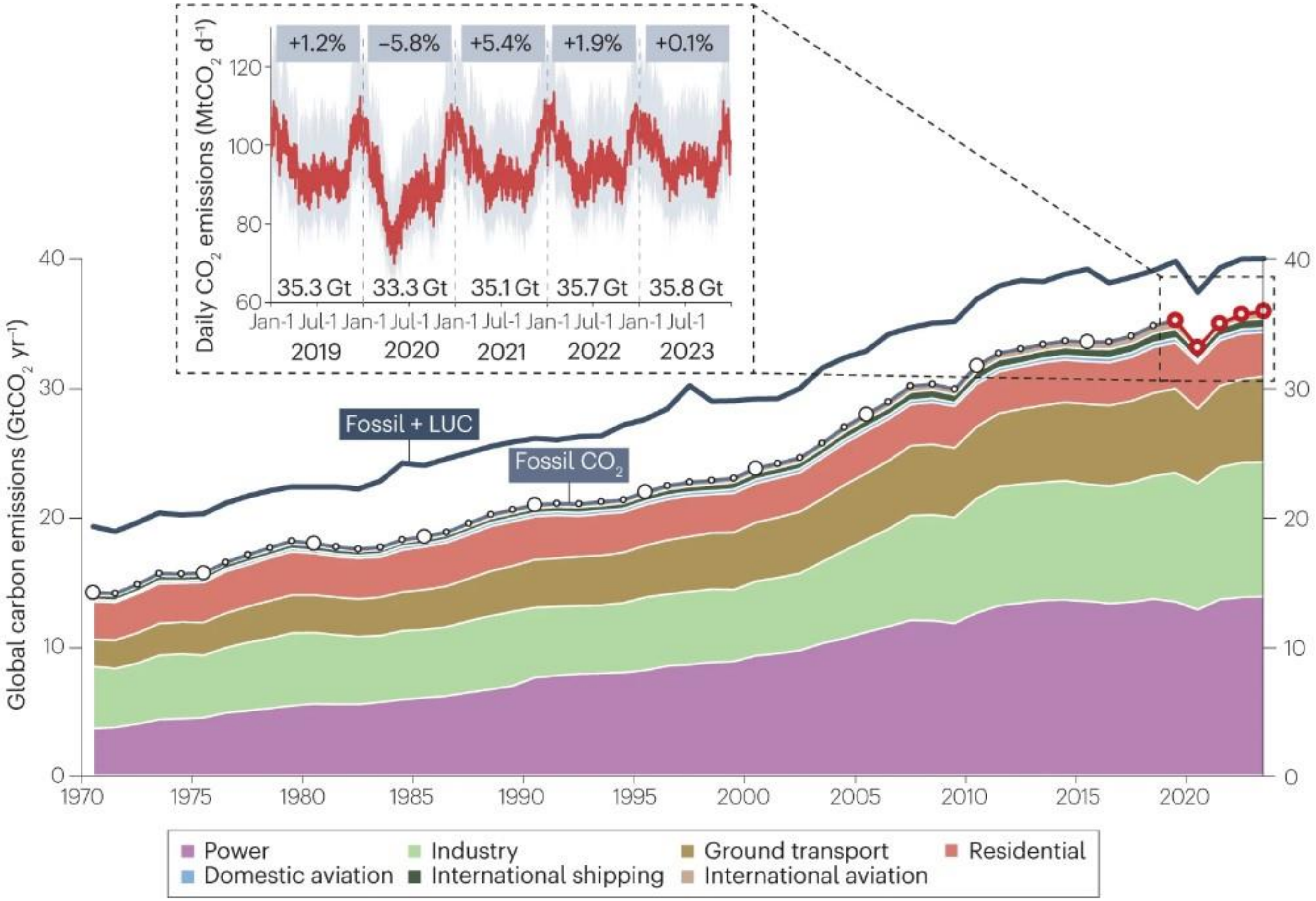
Climate change undeniable

Fig.1: Global CO_2 emissions 1970–2023 [1]



[1] https://www.nature.com/articles/s43017-024-00532-2

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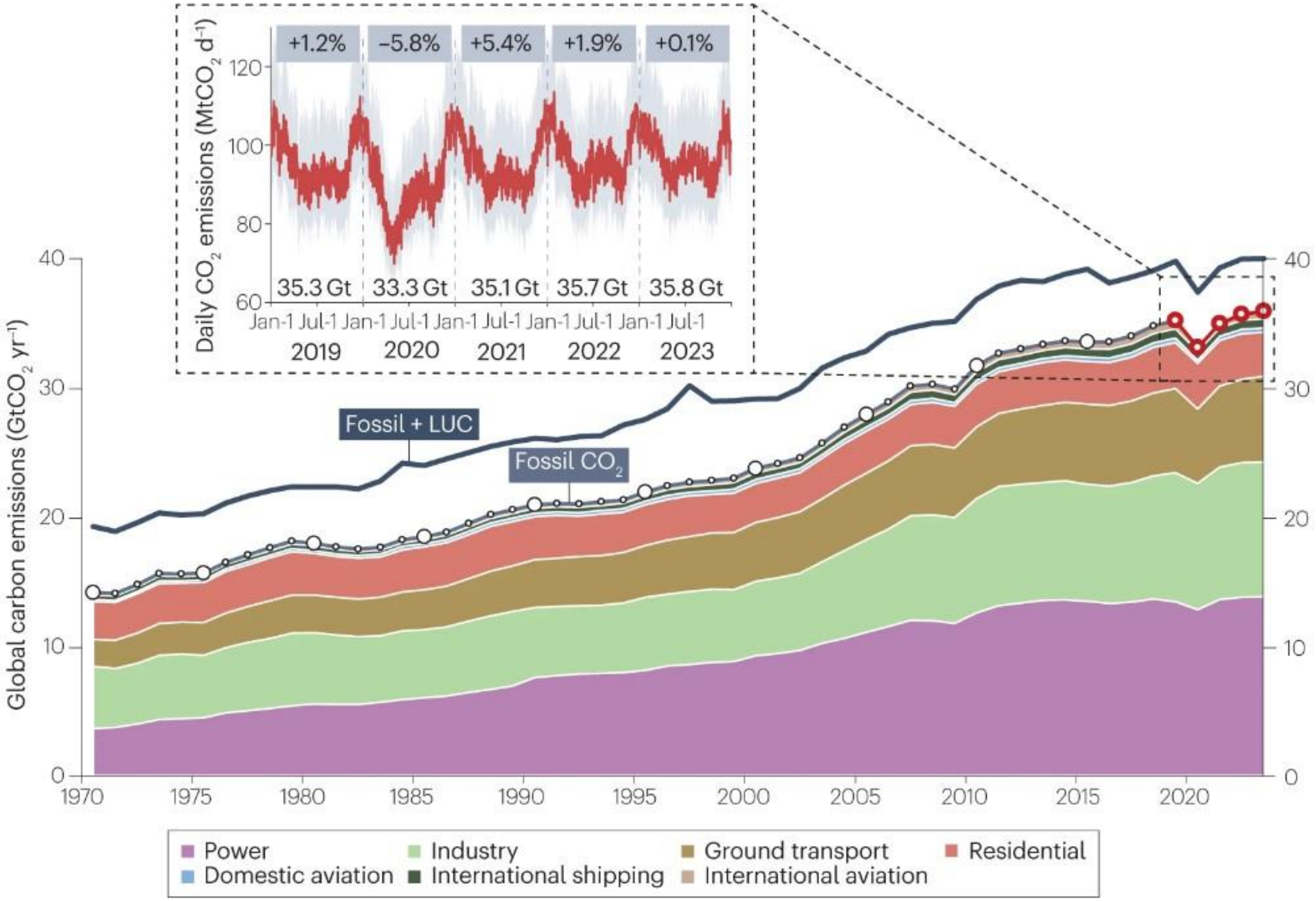

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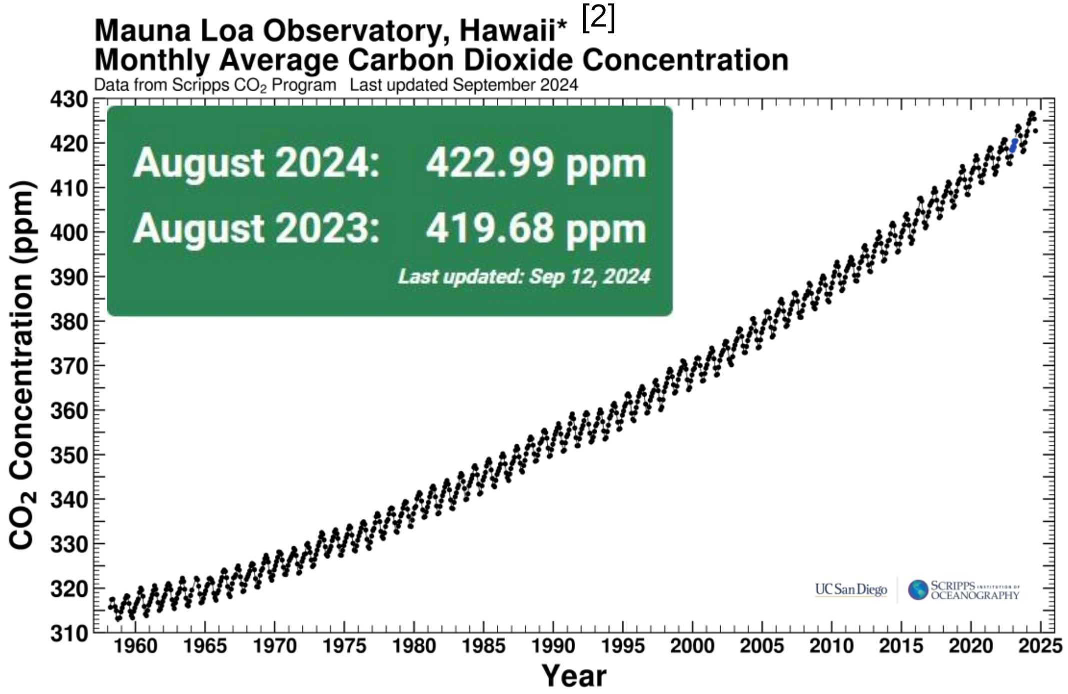

[1] https://www.nature.com/articles/s43017-024-00532-2
[2] https://scrippsco2.ucsd.edu/graphics_gallery/mauna_loa_record/mauna_loa_record.html

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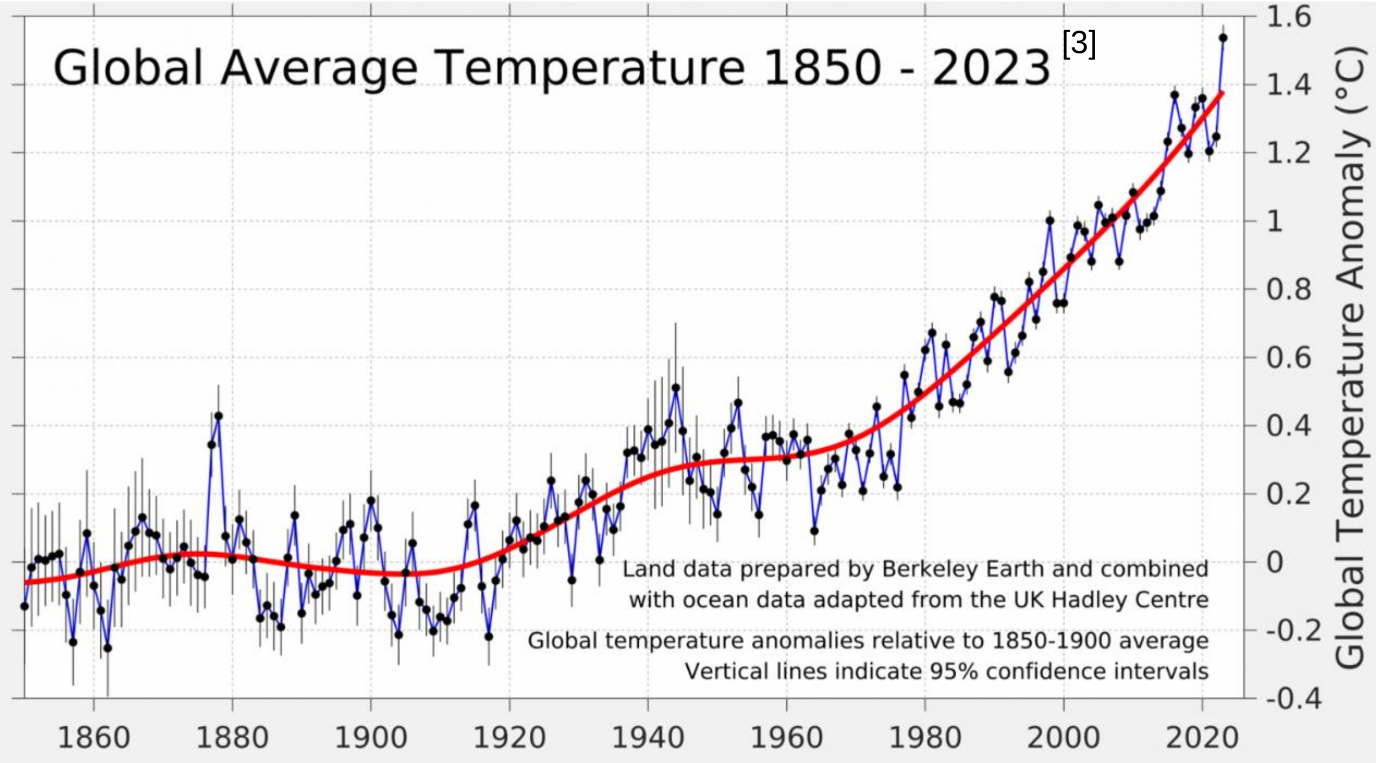

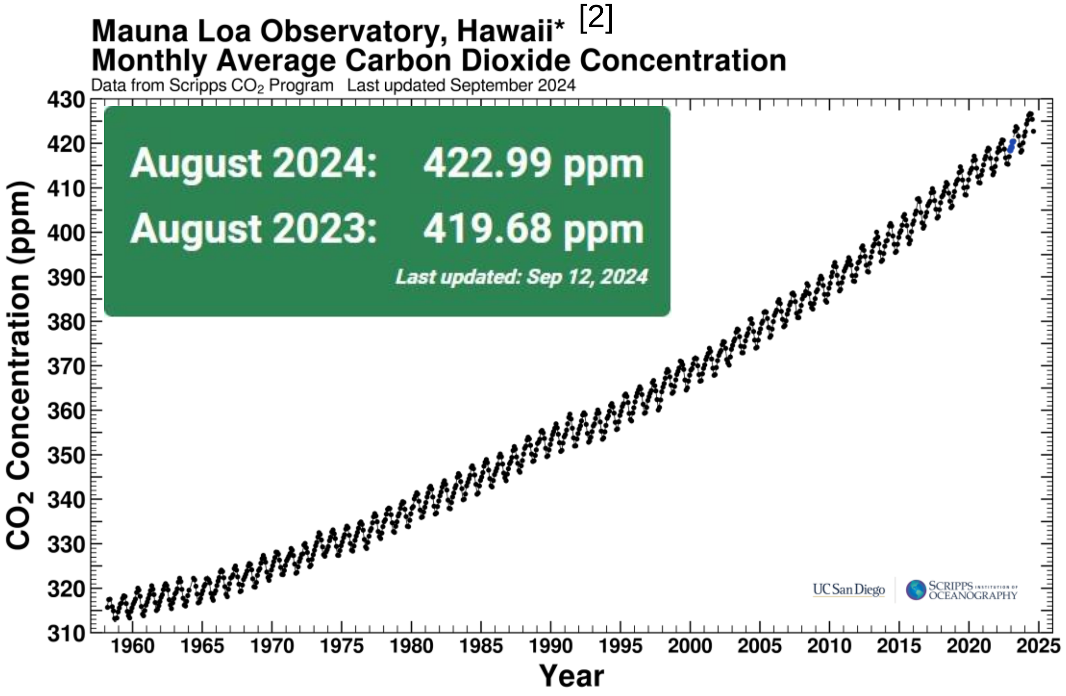

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[3] https://berkeleyearth.org/global-temperature-report-for-2023/

Sector decarbonization for Europe
Mc Kinsey order suggestions [1]

- ***Power:*** wind and solar power generation technologies decarbonize power quickest, reaching net-zero by the mid-2040s. Power demand would double as other sectors switch to electricity and green hydrogen.
- ***Transportation:*** EV supply chains will take some ten years to set up to switch to 100 percent EV sales. Aircraft and ships must opt for switching to biofuels, ammonia, or synfuels.

- ***Buildings:*** Renovating of the EU's building with available technology. Gas usage in buildings need to fall by more than half. The buildings sector would reach net-zero in the late 2040s.
- ***Industry:*** Technology required that is still under development. Even by 2050, industry would continue to generate some residual emissions from activities such as waste management and heavy manufacturing, which would have to be offset.
- ***Agriculture**:* By far the hardest sector to abate. Raising animals for food can't be reduced without significant changes in meat consumption or technological breakthroughs. Requires offsetting agriculture emissions with negative emissions in other sectors and increasing natural carbon sinks.

[1] Mc Kinsey (2020): How the European Union could achieve net-zero emissions at net-zero cost. https://www.mckinsey.com/capabilities/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost#/

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Assessment example: Sustainable Aviation Fuels in Europe

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Assessment of Decarbonization options

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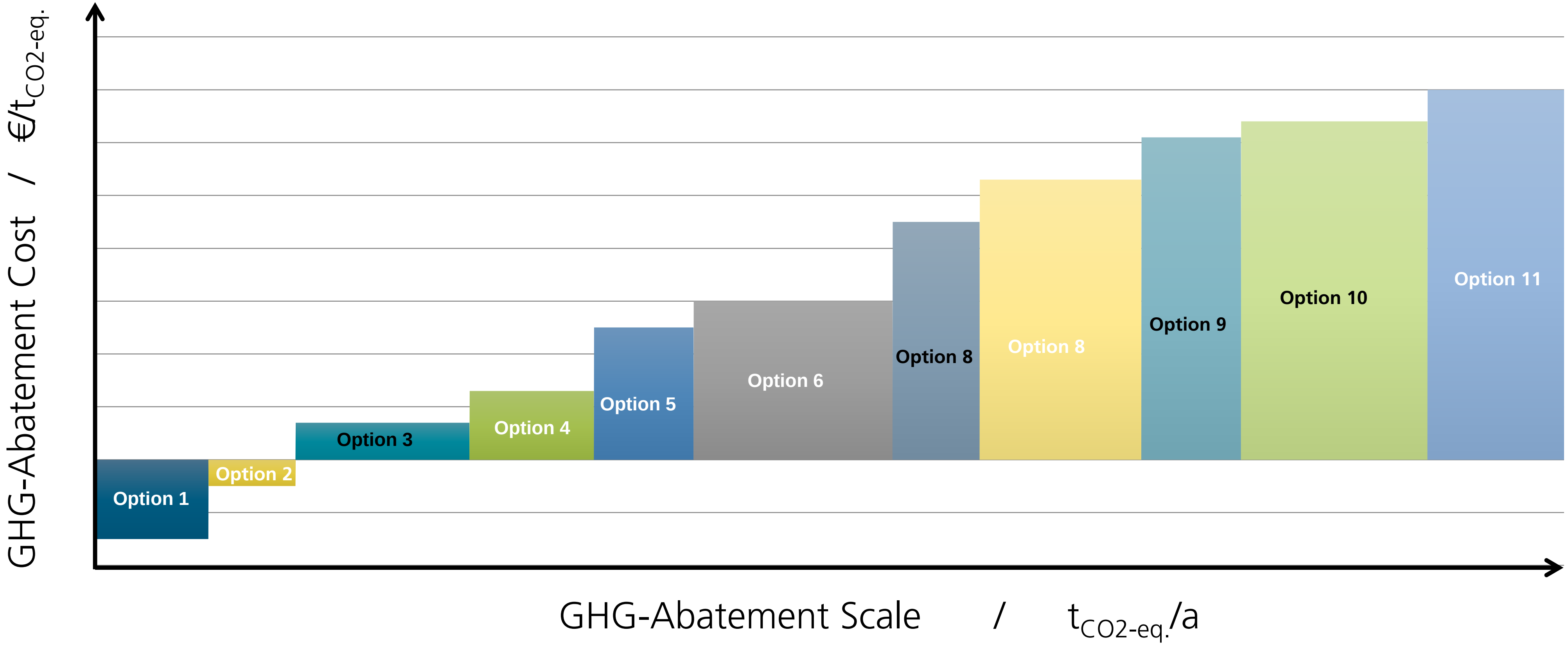
Merit Order of Greenhouse Gas (GHG) emission reduction measures



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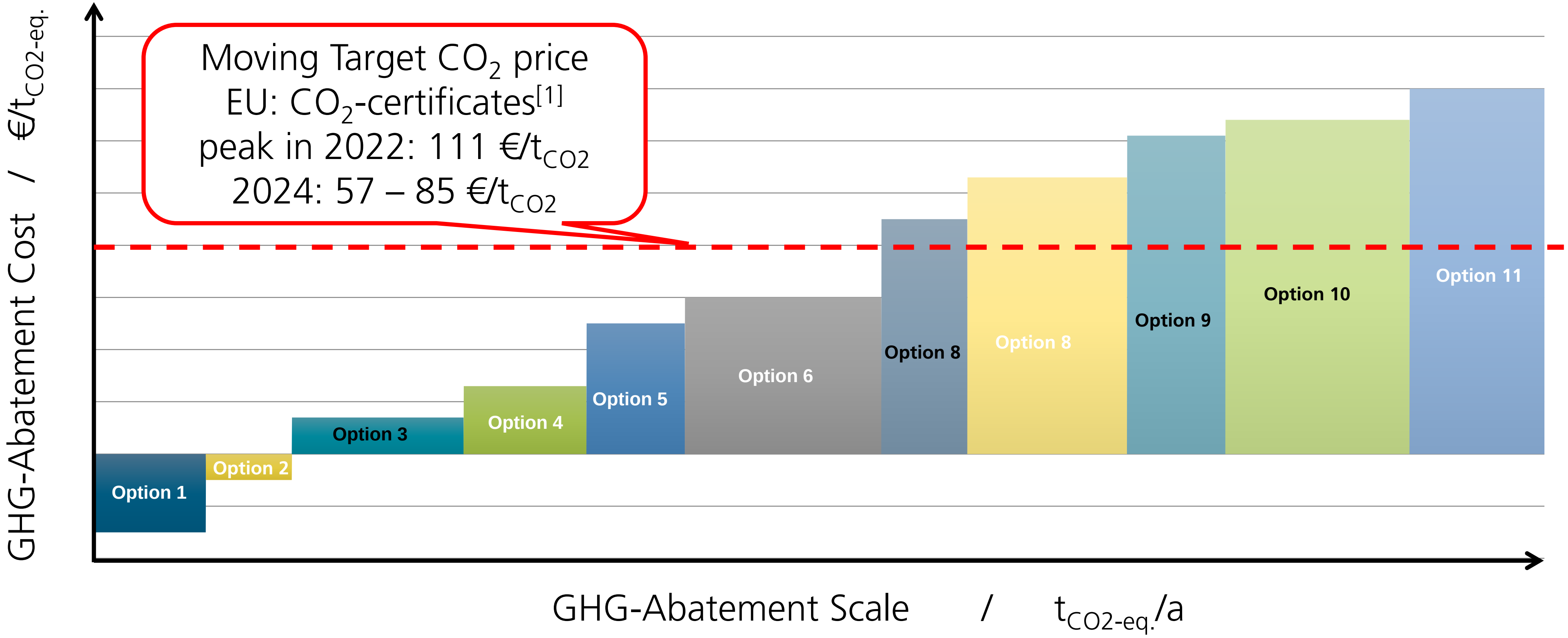

[1] https://www.boerse.de/rohstoffe/Co2-Emissionsrechtepreis/XC000A0C4KJ2

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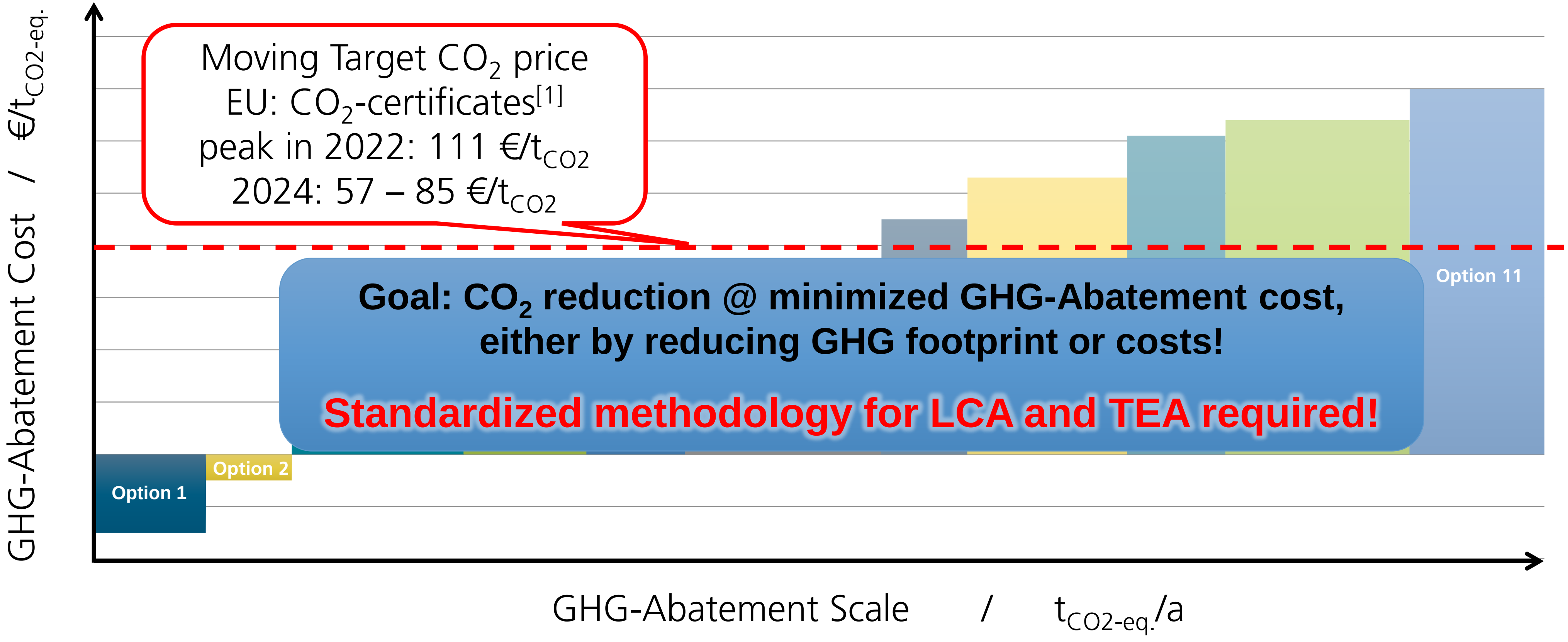

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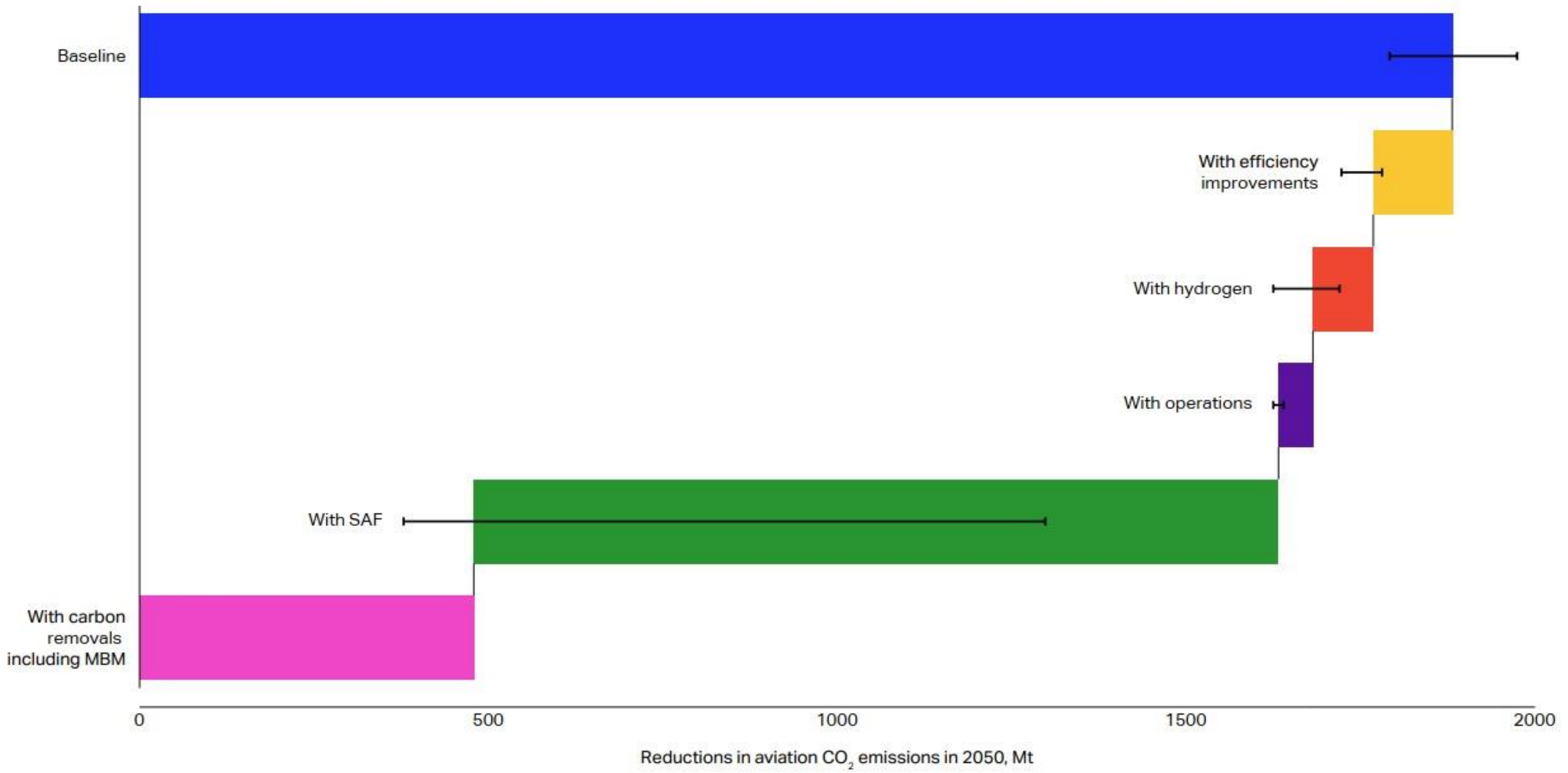
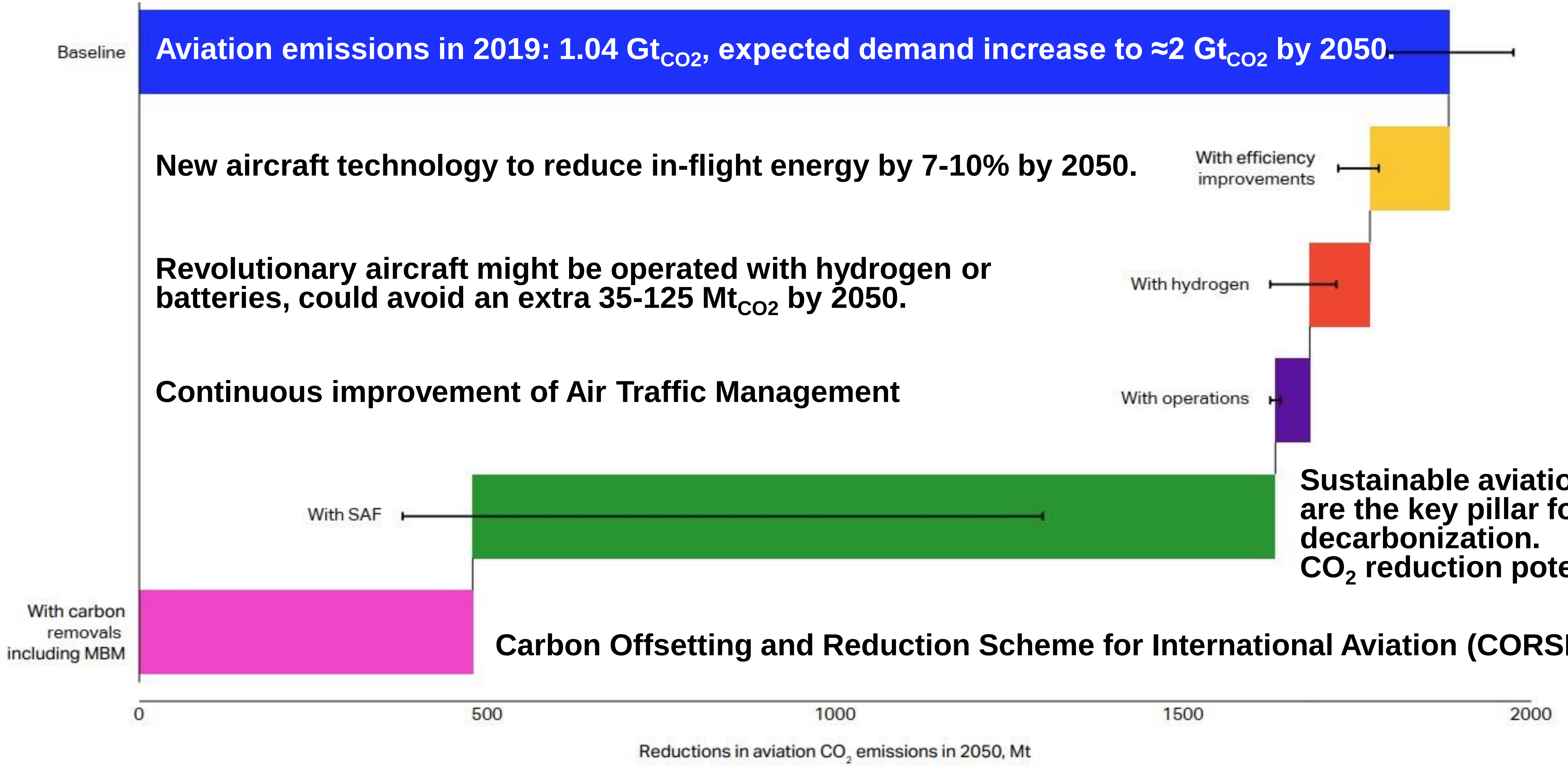
International Aviation Contribution
IATA Net Zero Roadmaps [1]



[1] IATA’s Net Zero roadmaps, https://www.iata.org/en/programs/sustainability/roadmaps/

International Aviation Contribution
IATA measures [1] commented



Aviation emissions in 2019: 1.04 Gt_{CO2}, expected demand increase to ≈2 Gt_{CO2} by 2050.

New aircraft technology to reduce in-flight energy by 7-10% by 2050.

Revolutionary aircraft might be operated with hydrogen or batteries, could avoid an extra 35-125 Mt_{CO2} by 2050.

Continuous improvement of Air Traffic Management

Sustainable aviation fuels (SAF) are the key pillar for aviation decarbonization. CO_2 reduction potential t.b.d.

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

[1] IATA's Net Zero roadmaps, https://www.iata.org/en/programs/sustainability/roadmaps/

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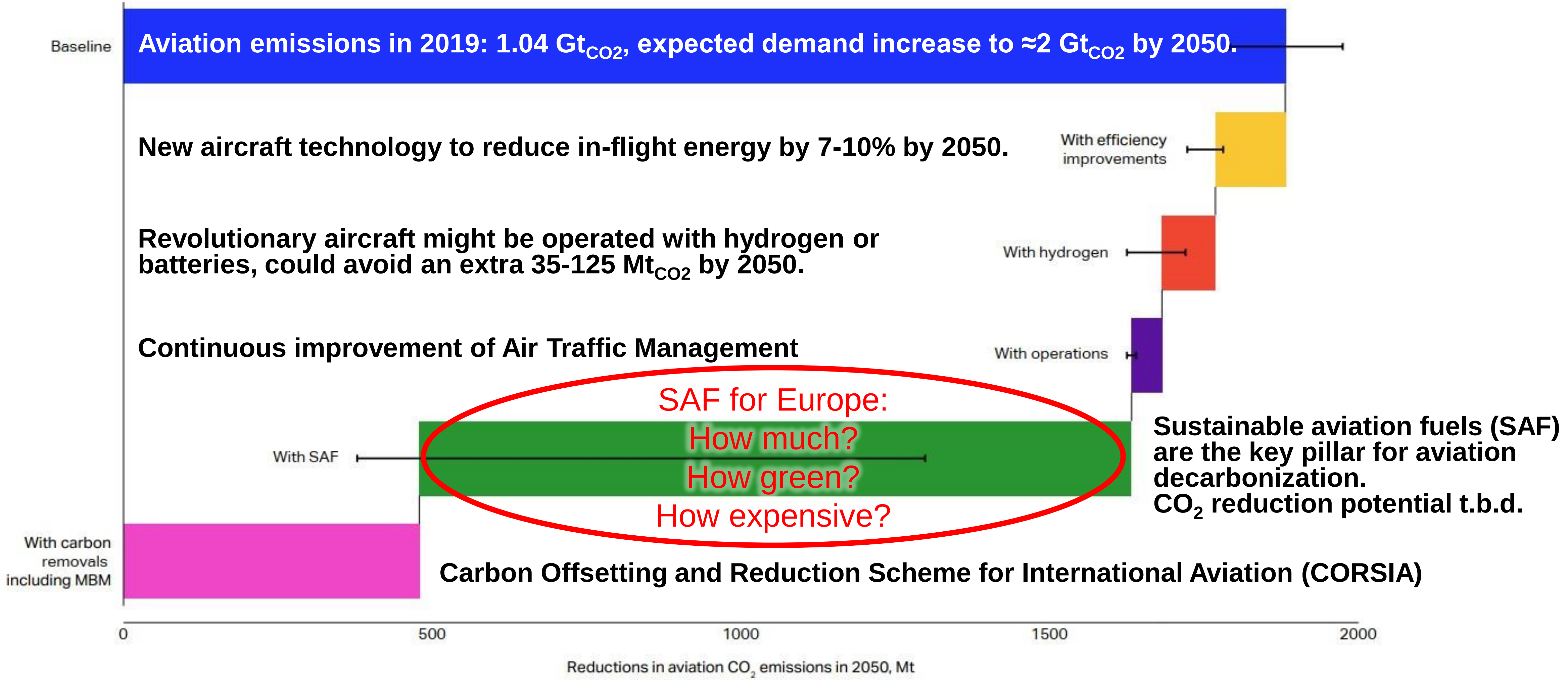
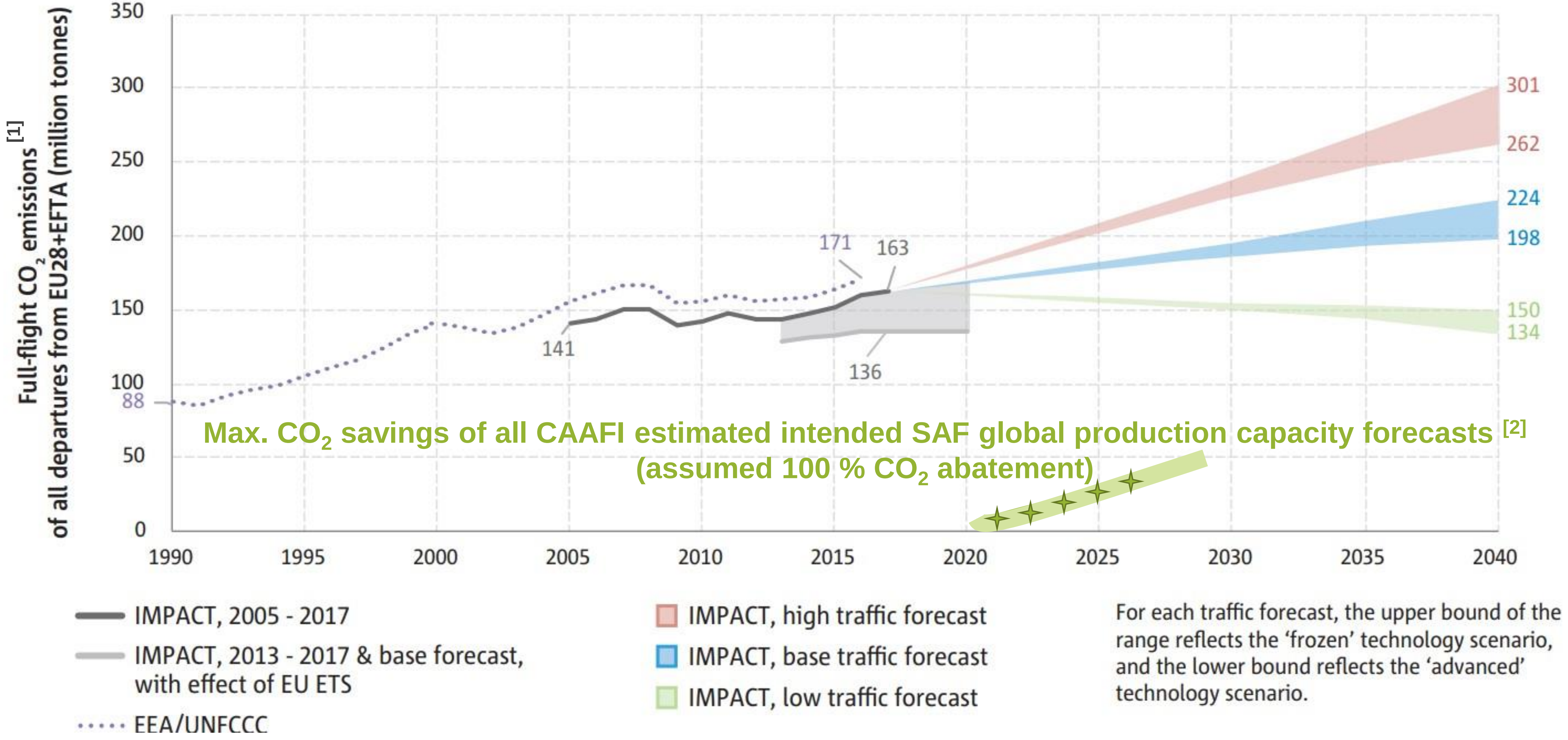
International Aviation Contribution
IATA Roadmap [1] measure that count



[1] IATA's Net Zero roadmaps, https://www.iata.org/en/programs/sustainability/roadmaps/

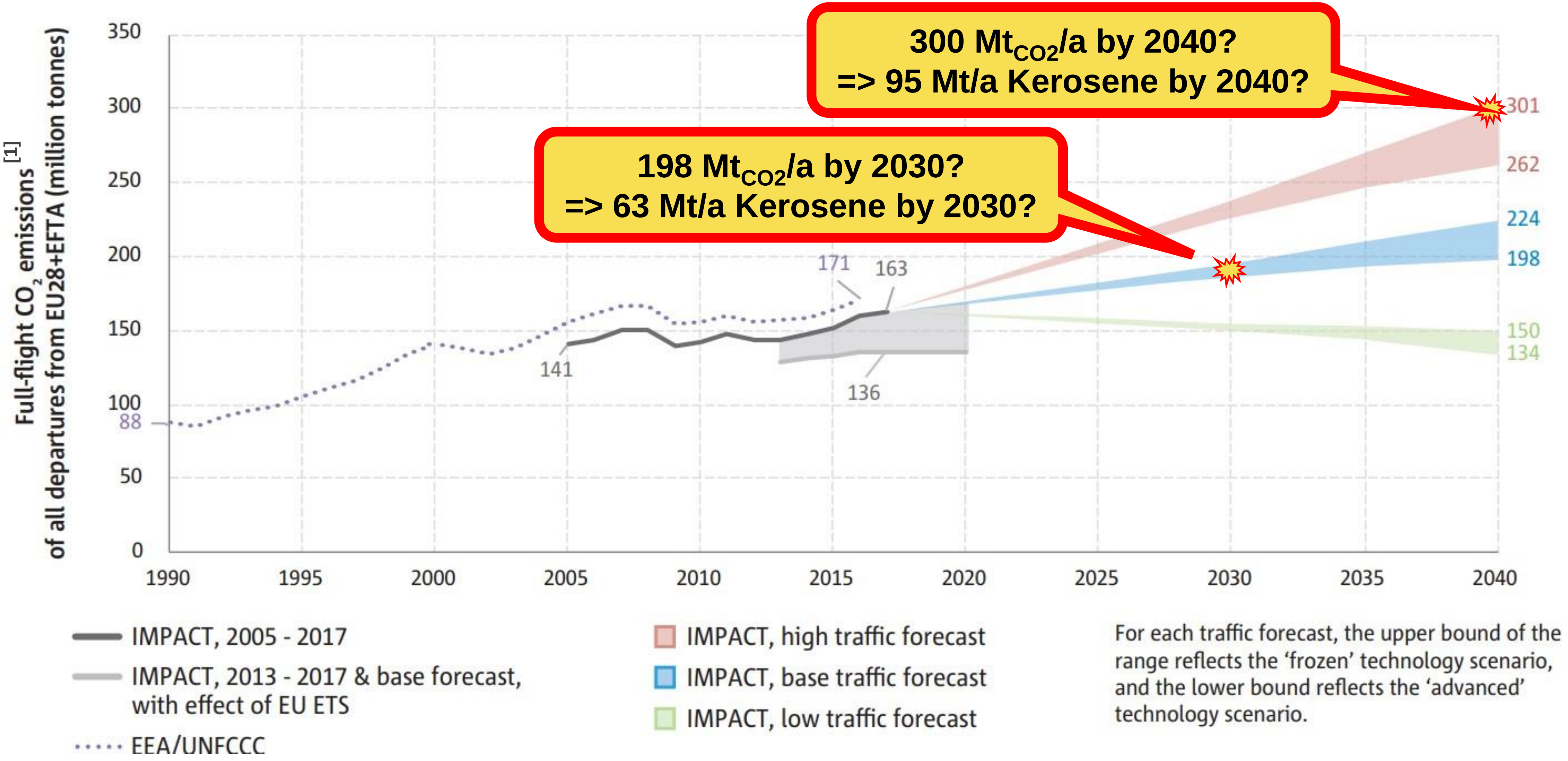
EU aviation CO_2 emissions

Prediction [1] versus current activities [2]



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

EU aviation CO_2 emissions
Prediction [1] in numbers



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

Large-scale economic production of SAF in Europe

Agenda

- Motivation
- SAF production assessment
  - Certification: feedstock, synthesis, fuel
  - Introduction of Power-and-biomass-to-Liquid (PBtL)
  - Local production potential analysis
    - Net production costs (NPC)
    - Global warming potential (GWP)
- Aggregated European SAF production potential
- Conclusions

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

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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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- SAF from crop-based biomass limited
  - Direct competition with food markets
  - Low area-related energy yields and limited cultivation area
  - supplier's reliability
    - e.g. false reclassification of palm oil
  - Low technical development potential

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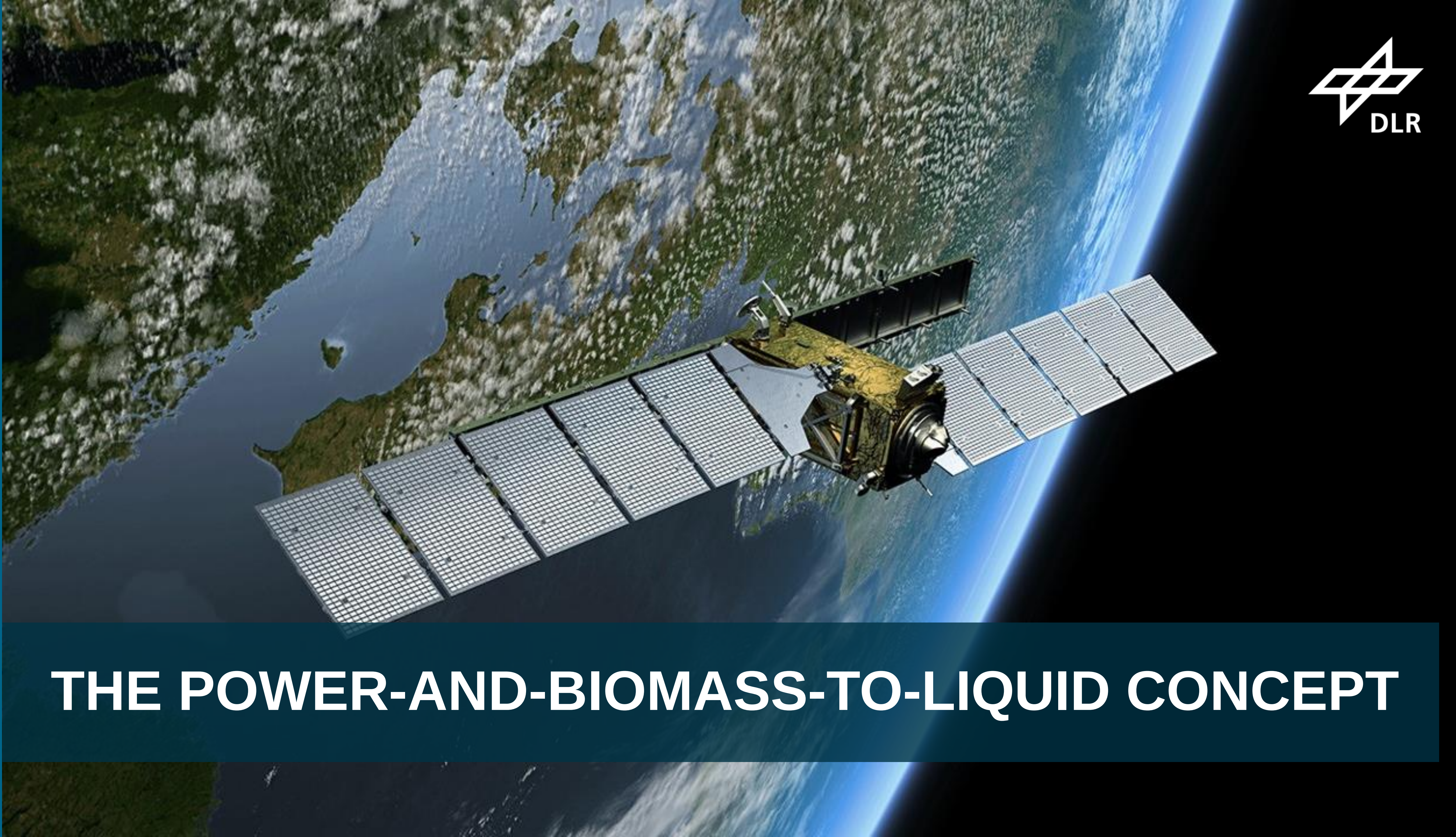
- SAF from Fischer-Tropsch using syngas
  - Feedstock
    - not restricted to certain feedstocks, any sustainable carbon and hydrogen source
    - Sustainable Hydrogen via RE: European wind power potential [2]: 12,200 – 30,400 TWh_e ≈ 10 - 20 times of SAF demand!
    - Sustainable Carbon: carbon sequestration in European forest biomass [3]: 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 [3]

[1] ASTM International, „ASTM D7566-21 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2021
[2] European Environment Agency, “Europe's onshore and offshore wind energy potential,” 2009
[3] FOREST EUROPE, 2020: State of Europe’s Forests 2020
[4] UK Ministry of Defense, „DEF STAN 91-91: Turbine Fuel, Kerosene Type, Jet A-1“, UK Defense Standardization, 2011



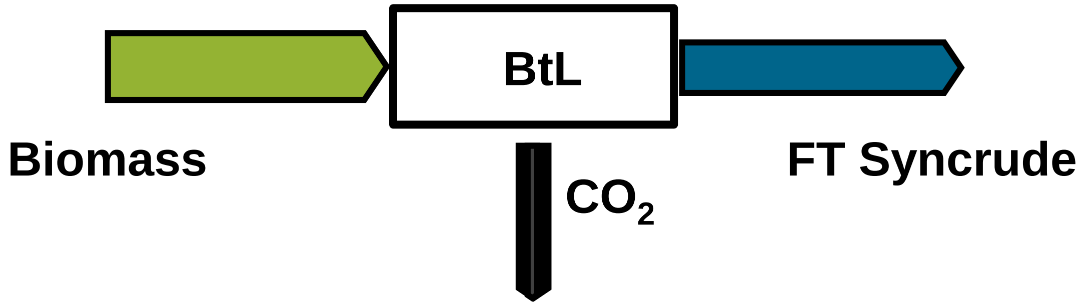
THE POWER-AND-BIOMASS-TO-LIQUID CONCEPT

Fischer-Tropsch based SAF production from biomass

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 via BtL vs. PBtL:



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

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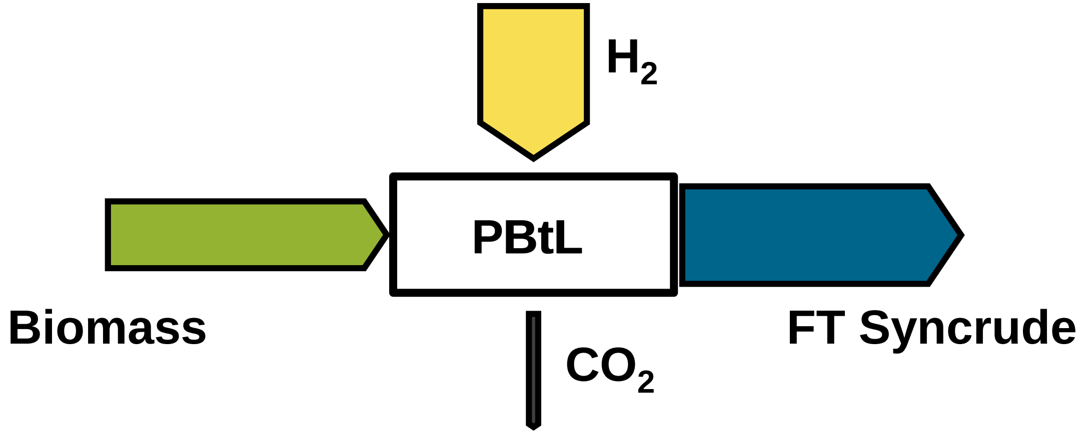
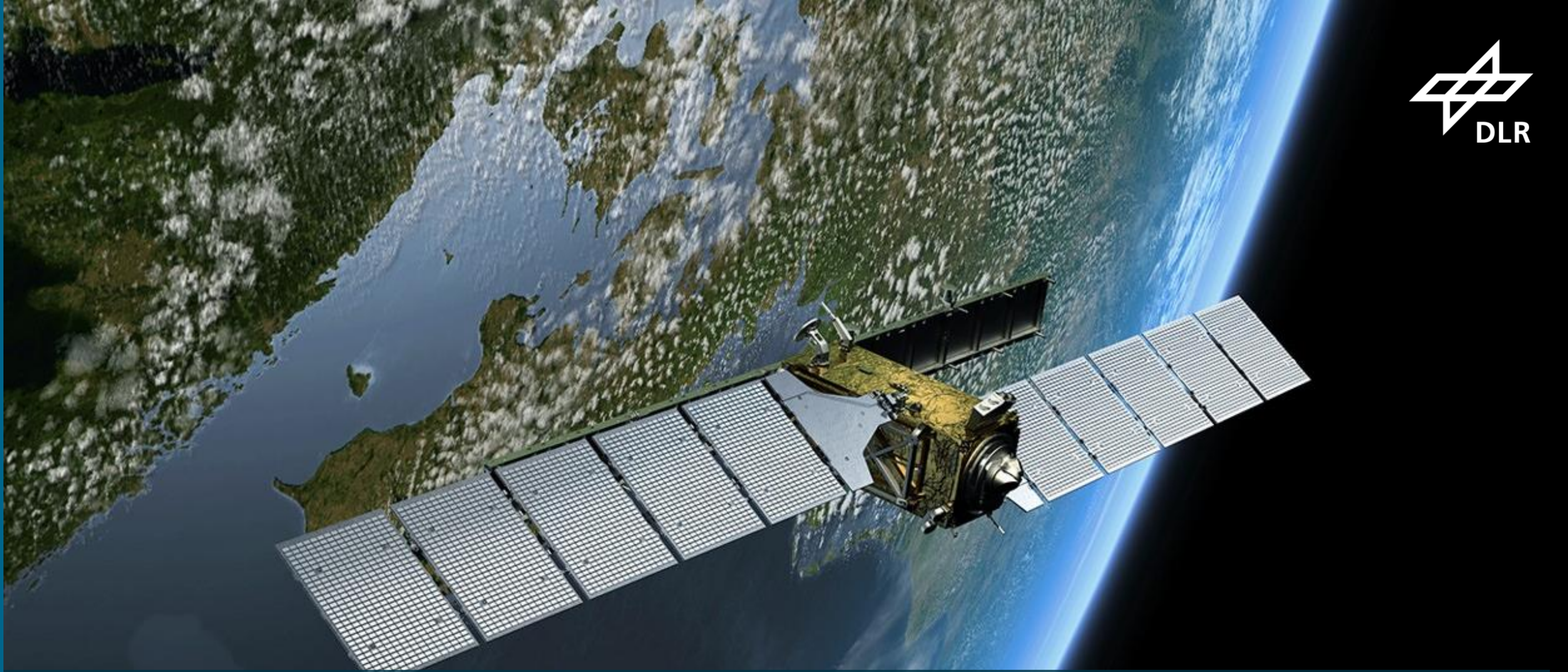


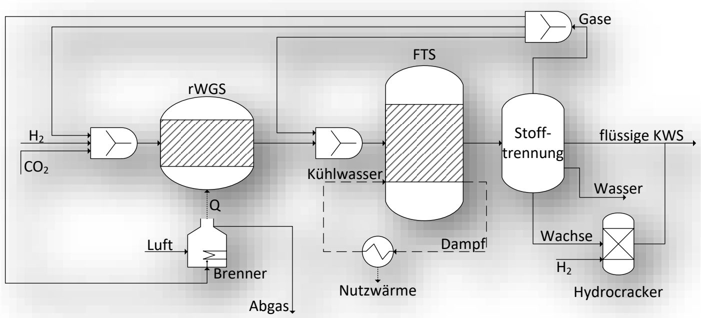
Advantages PBtL	Disadvantages PBtL
+ High conversion of limited biomass feedstock	– Additional cost for electrical power – Additional GHG impact due to electricity production

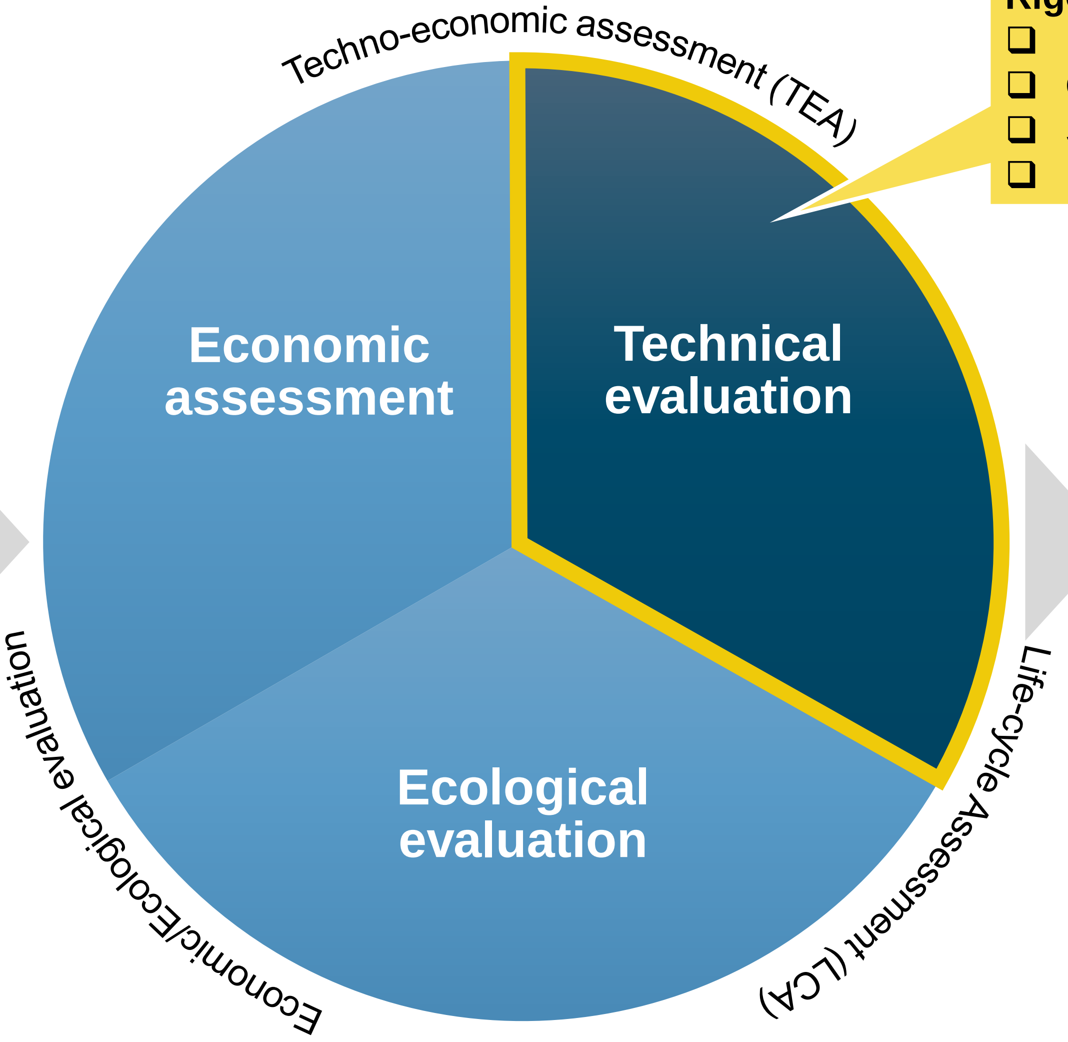
[1] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561 [Accessed: 31.8.2022]



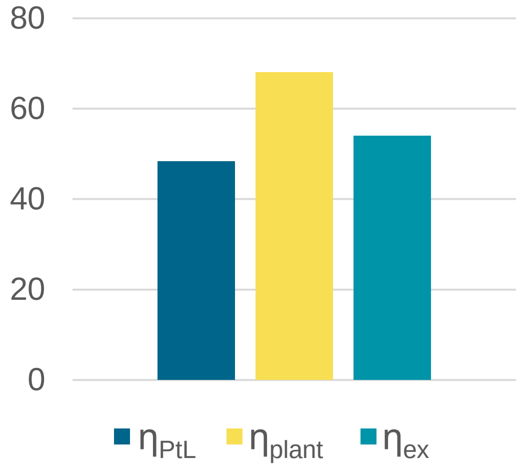
SAF CONCEPT ASSESSMENT METHODOLOGY

Techno-Economic and Life Cycle Assessment @ DLR





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



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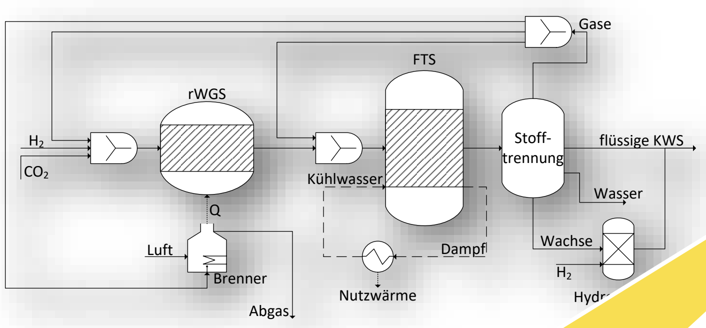

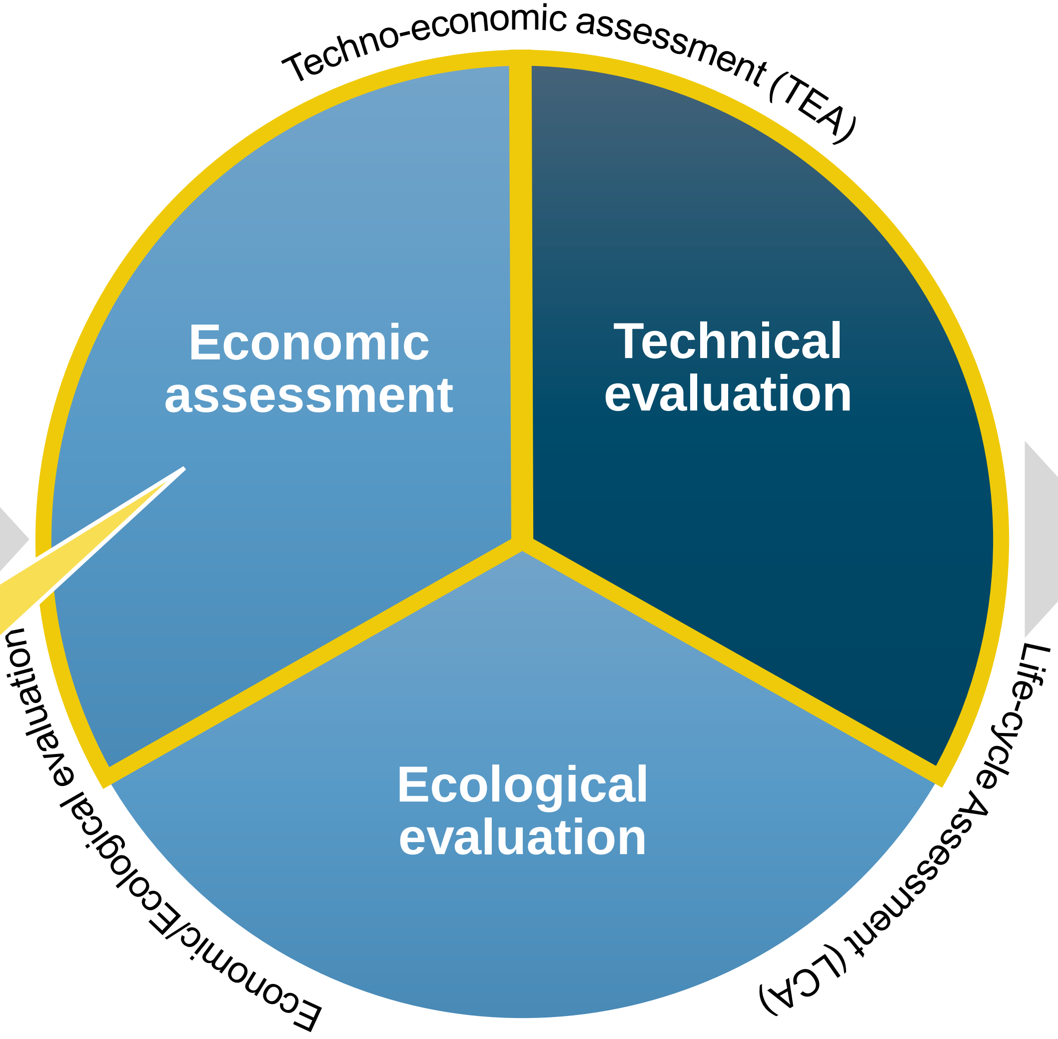

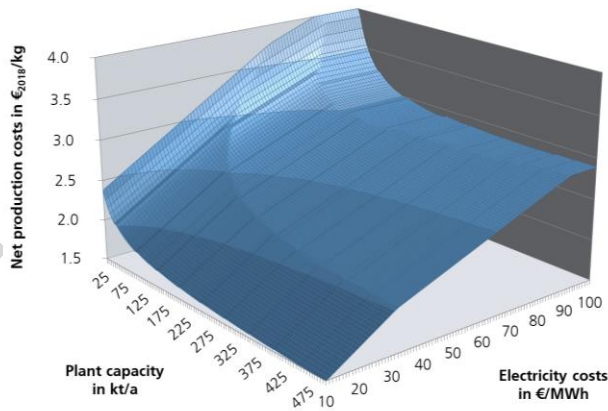

Chemical engineering cost estimation

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- ❑ Identification of most economic feasible process design

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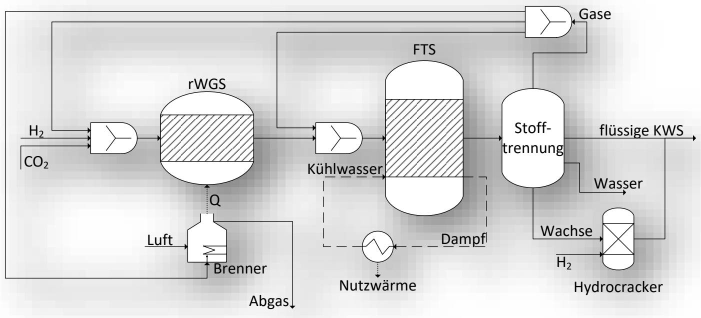

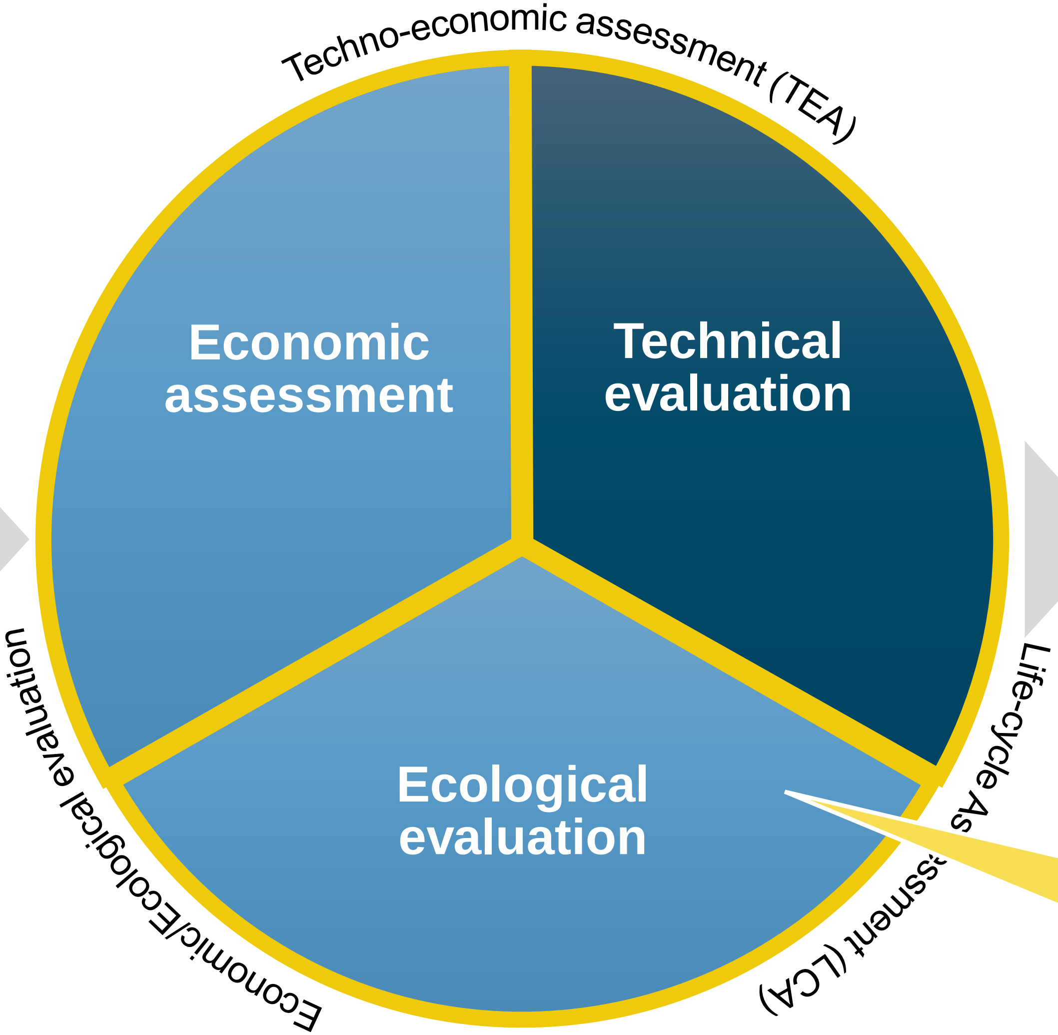

Adapted ISO 14040/14044 LCA

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

Techno-Economic and Life Cycle Assessment

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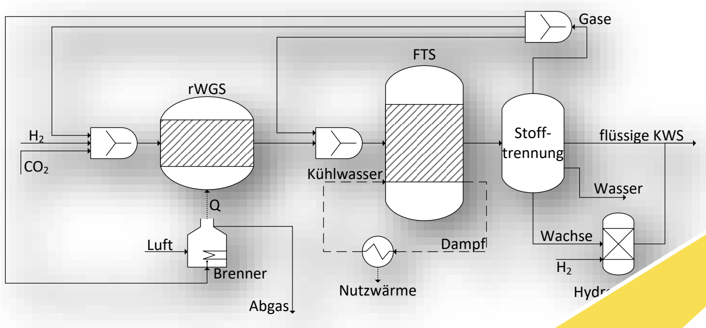

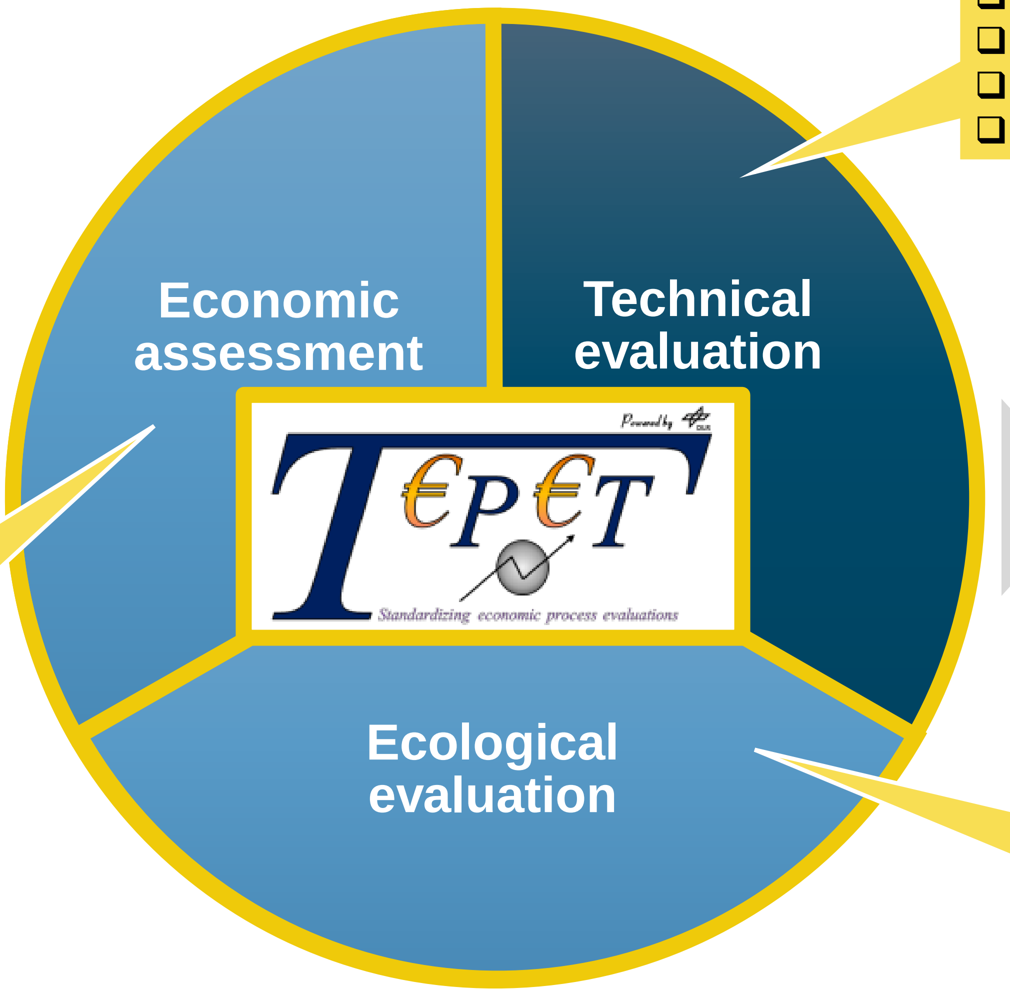

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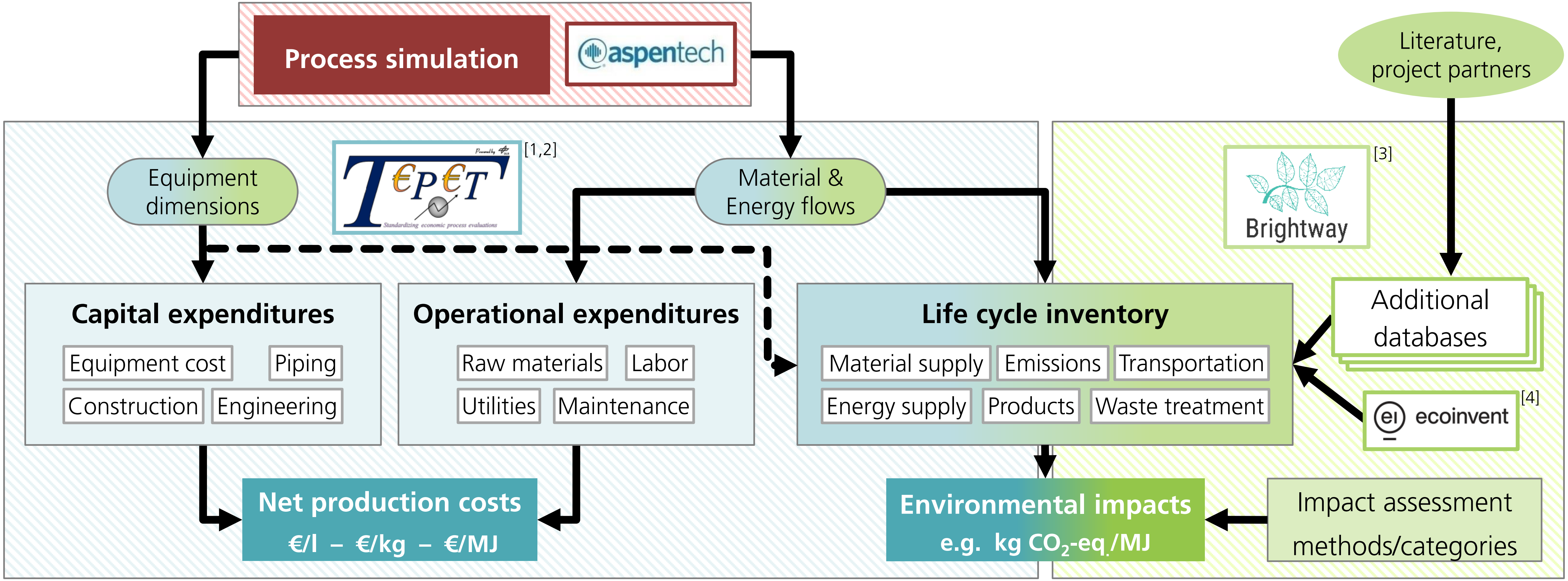
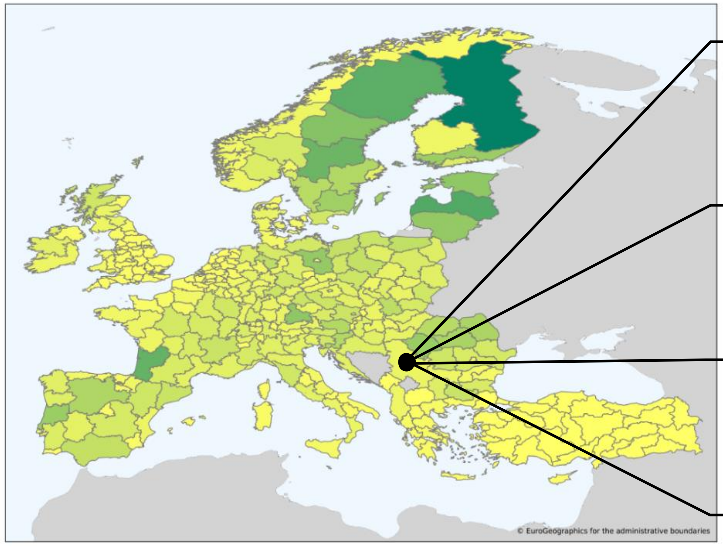
TEPET+ – Methodology



[1] Albrecht et al. (2016): https://doi.org/10.1016/j.fuel.2016.12.003
[2] Maier et al. (2021): https://doi.org/10.1016/j.enconman.2021.114651
[3] Mutel (2017): https://doi.org/10.21105/joss.00236
[4] Wernet et al. (2016): https://doi.org/10.1007/s11367-016-1087-8

Local production potential analysis based on European NUTS statistics

For feedstock potential: TEEA for 300 NUTS2 regions



Biomass density[1]: Transport distance

Local labor cost[2]

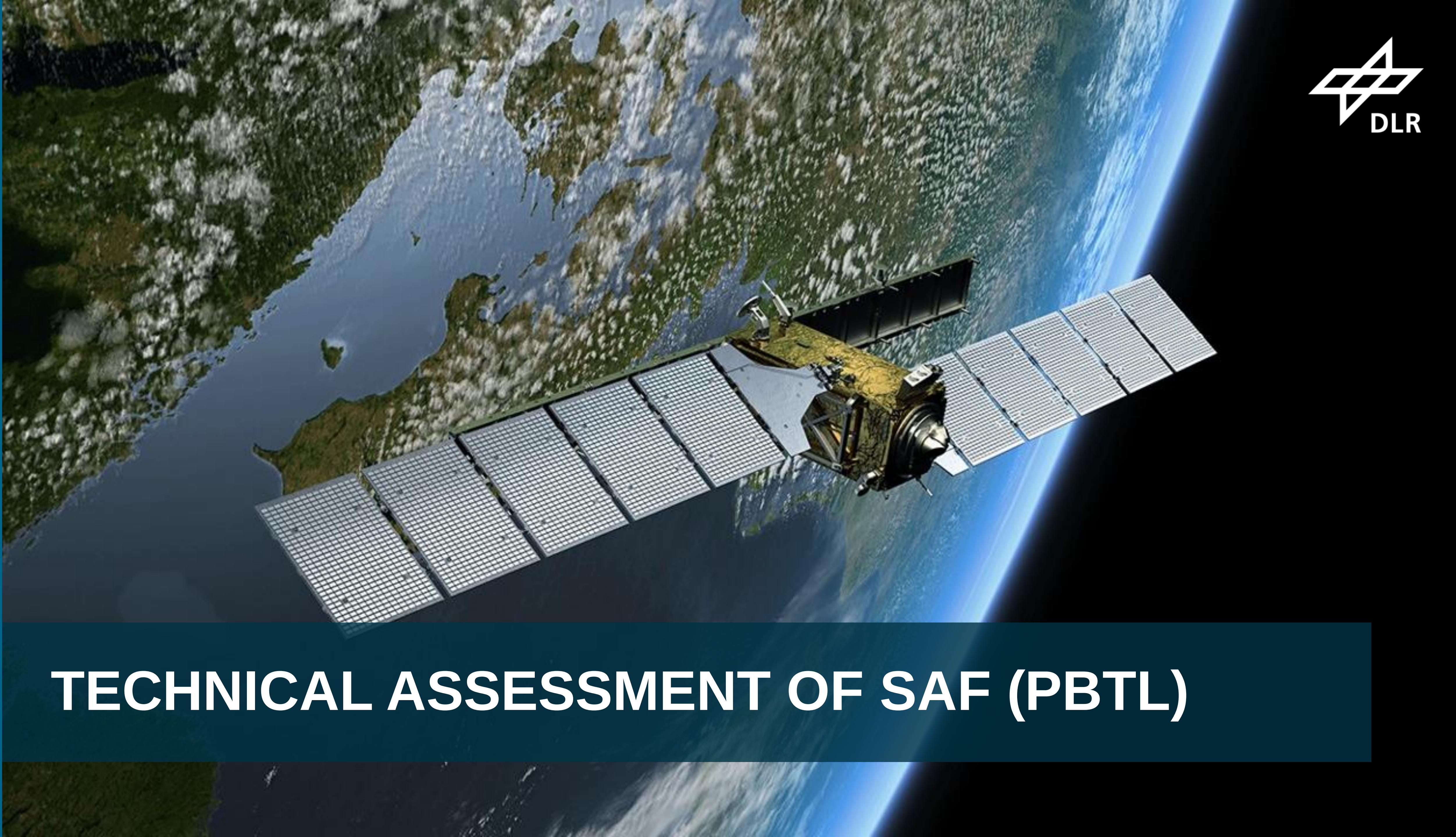
National grid: Price[3]/GHG footprint[4]

Biomass price[1]

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

- Local fuel production cost
- Local fuel production GWP
- Local fuel potential
  - 33 % forest residue for fuel production

[1] 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.



TECHNICAL ASSESSMENT OF SAF (PBTL)

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

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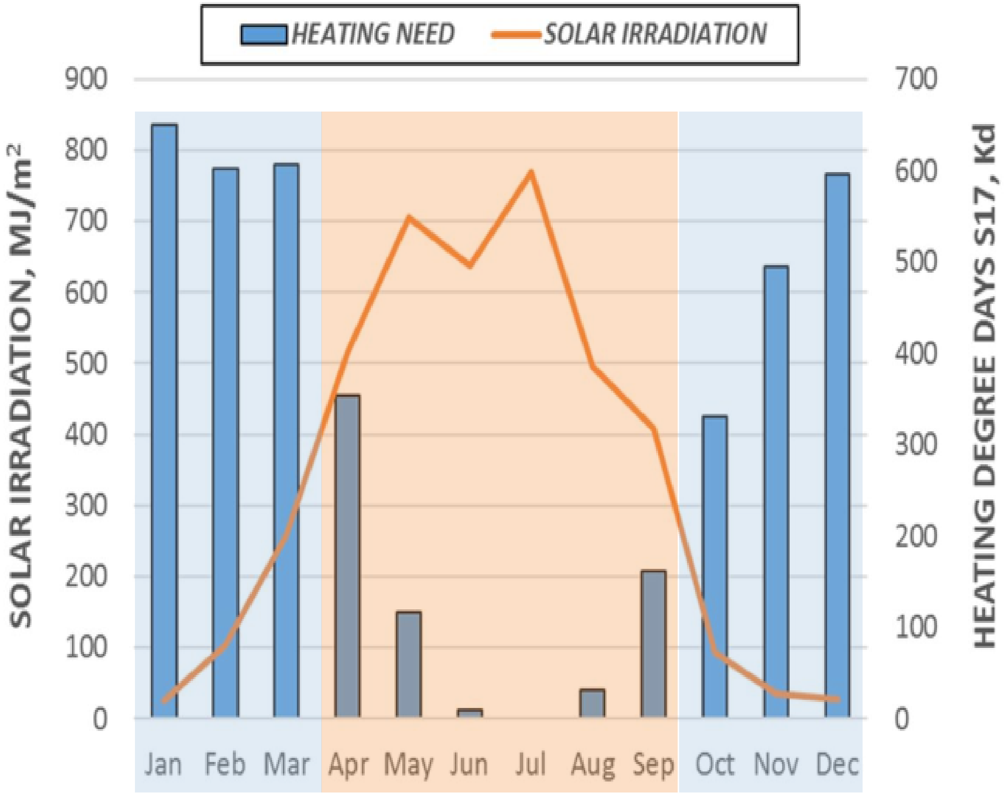
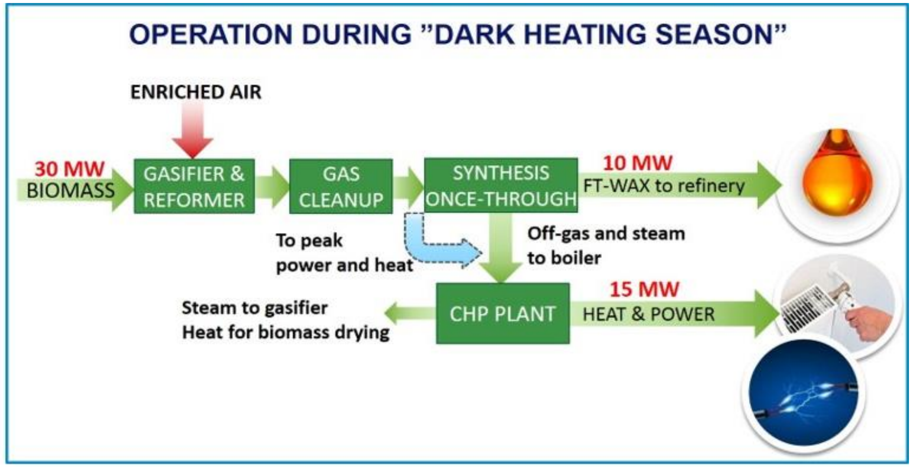
Seasonal market response approach:

FLEXCHX

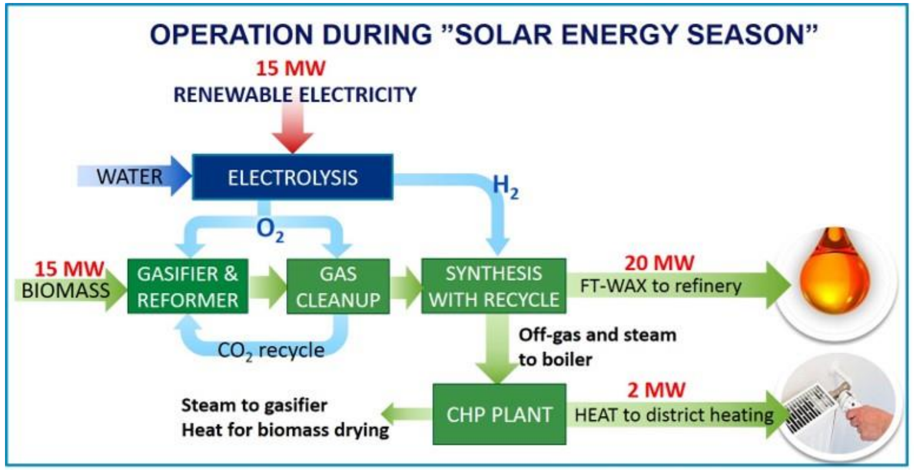
FlexCHX project has received funding from the European Union's Horizon 2020 research and innovation Programme under Grant Agreement No 763919



High heat demand & Low renewable electricity availability



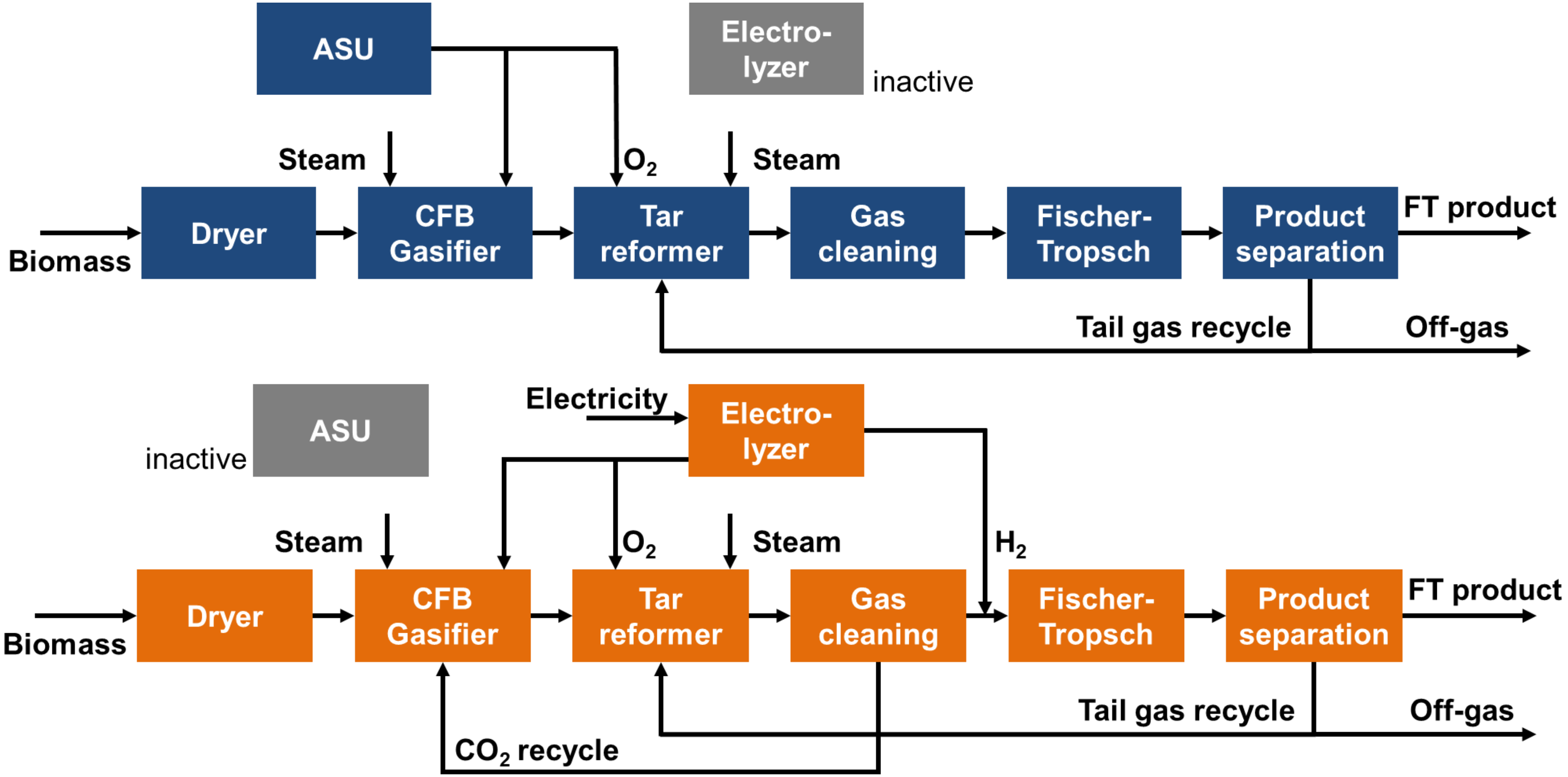
Low heat demand & High renewable electricity availability



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

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

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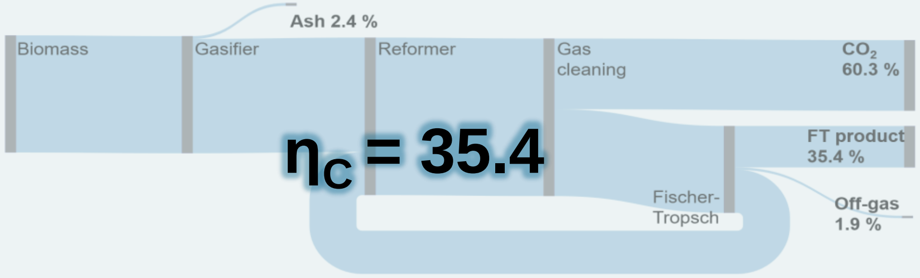
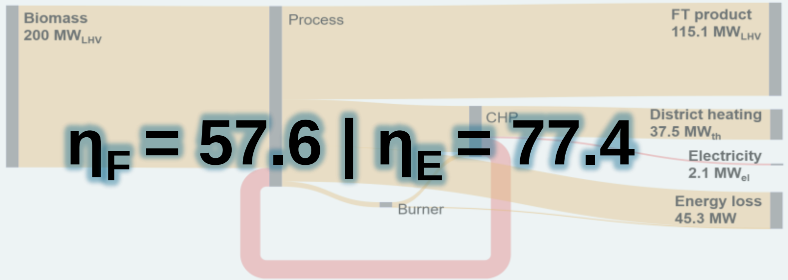
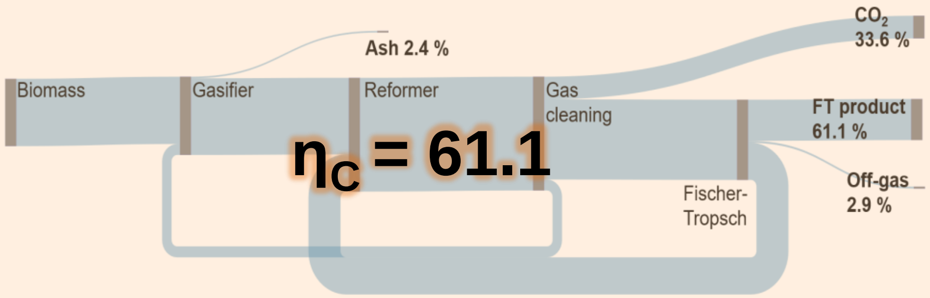
	Carbon efficiency η_C [%]	Fuel η_F | Process efficiency η_E [%]
Winter	η_C = 35.4	η_F = 57.6 | η_E = 77.4
Summer	η_C = 61.1	η_F = 55.2 | η_E = 73.6
50-50	$\eta_{C,av.}$ = 48.25	$\eta_{F,av.}$ = 56.4 | $\eta_{E,av.}$ = 75.5

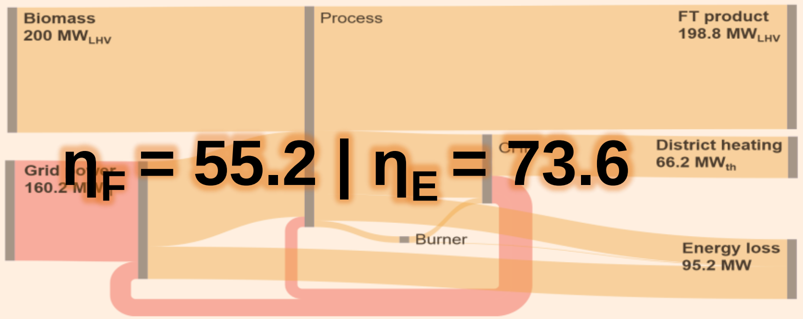
Winter:



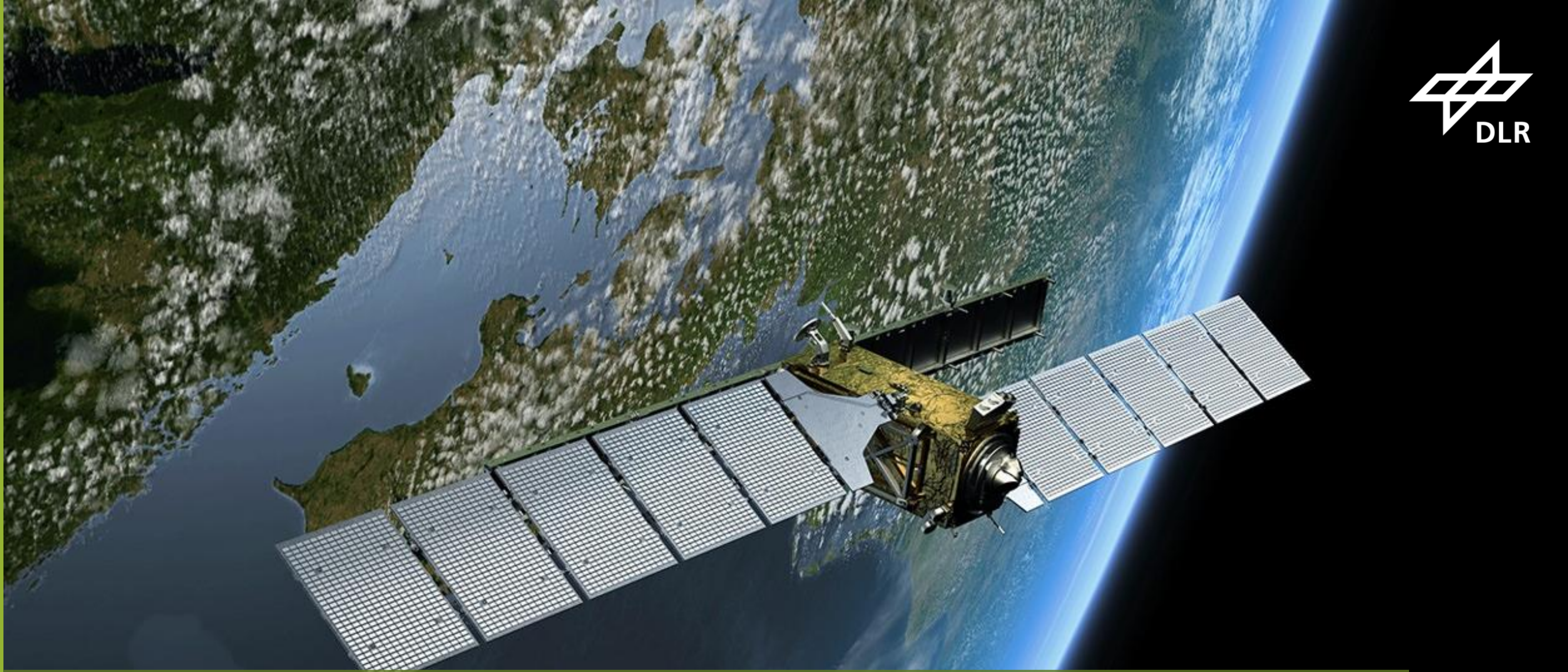


Summer:





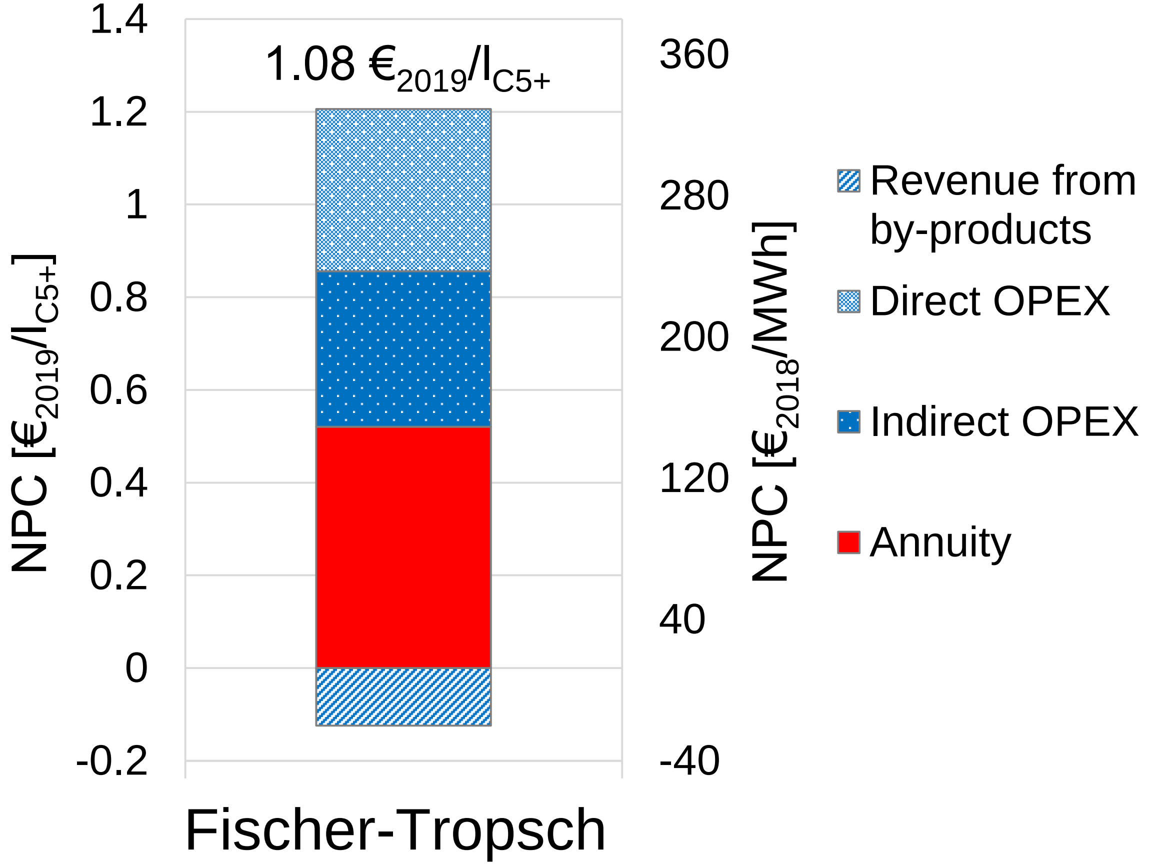
[1]Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774



ECONOMIC ASSESSMENT OF SAF (PBTL)

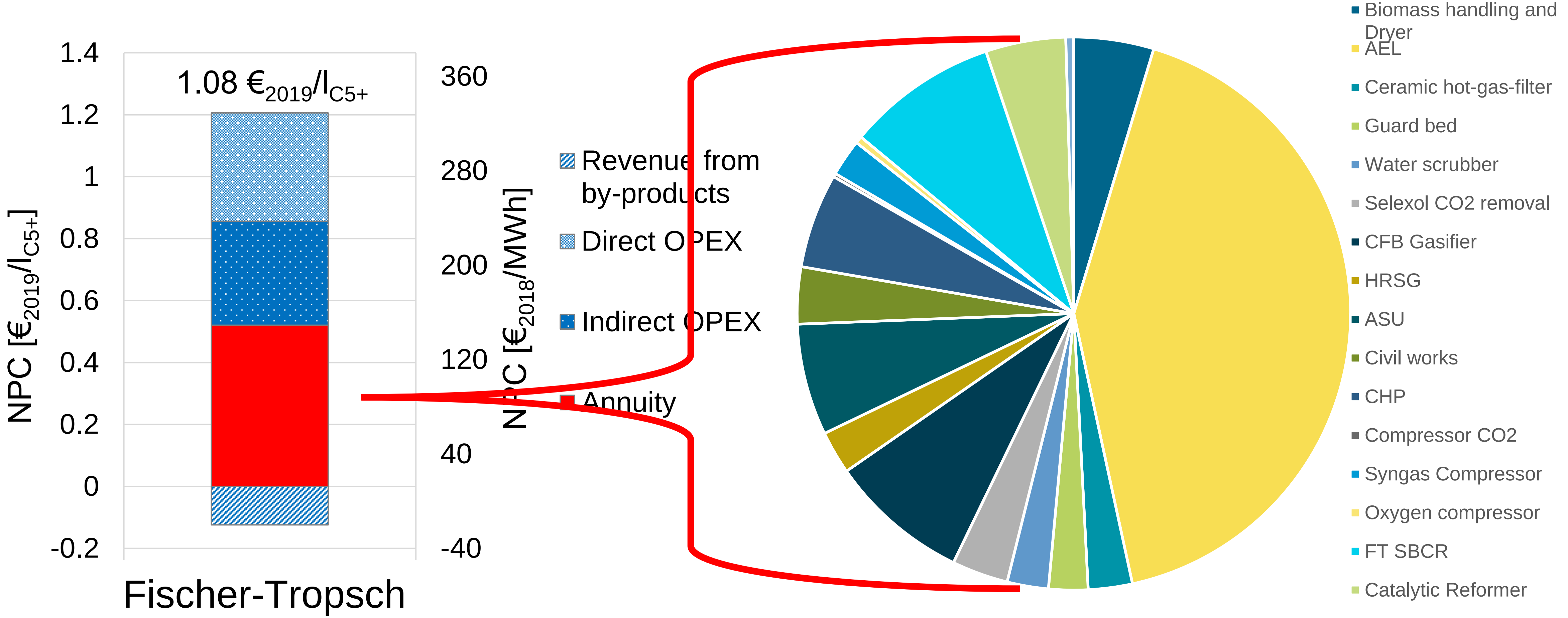
Cost structure FLEXCHX
50/50: Winter mode / Summer mode

NPC Breakdown



Cost structure FLEXCHX
50/50: Winter mode / Summer mode

NPC Breakdown | **CAPEX**



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

Net production cost sensitivity [1] :

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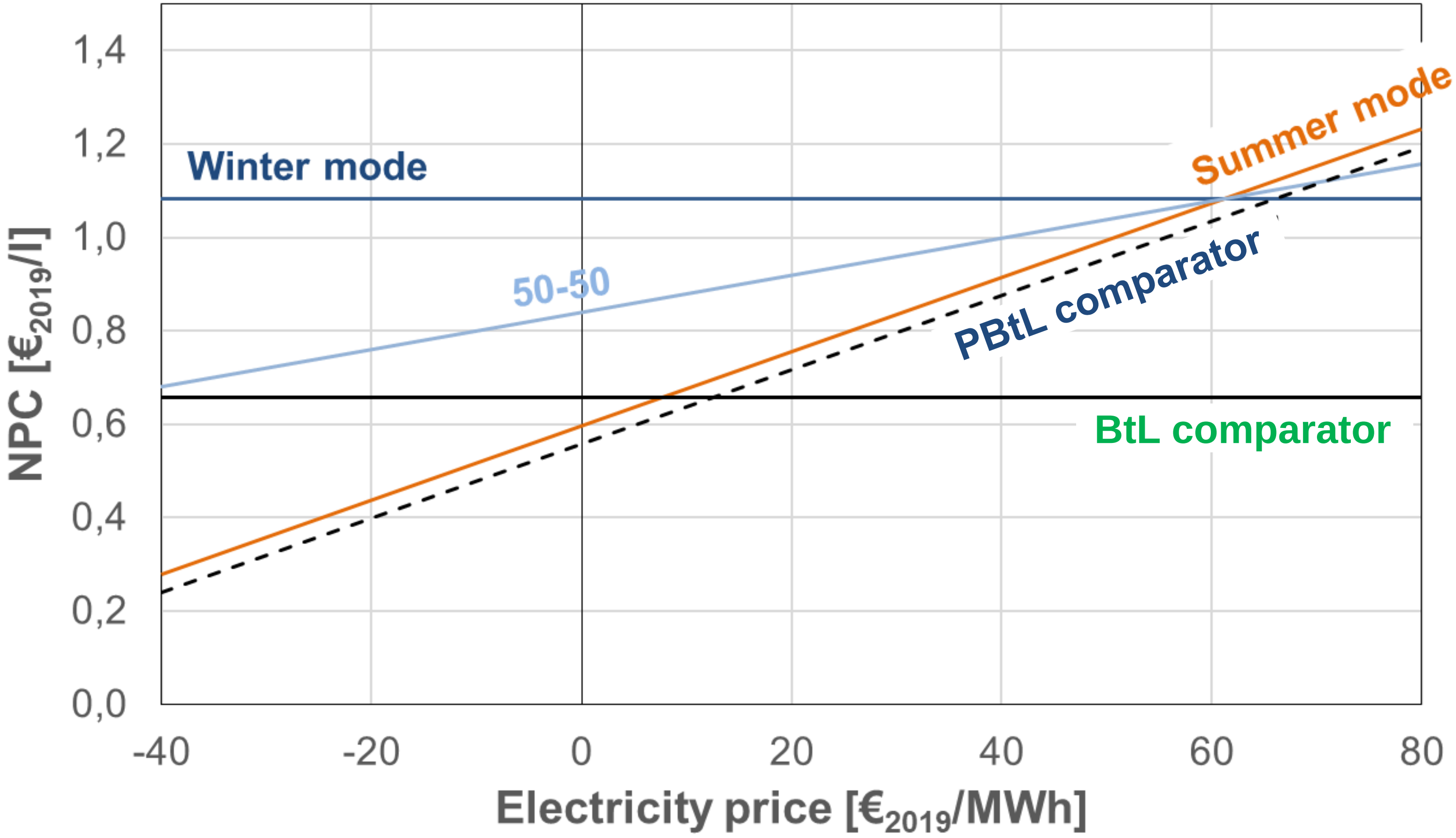
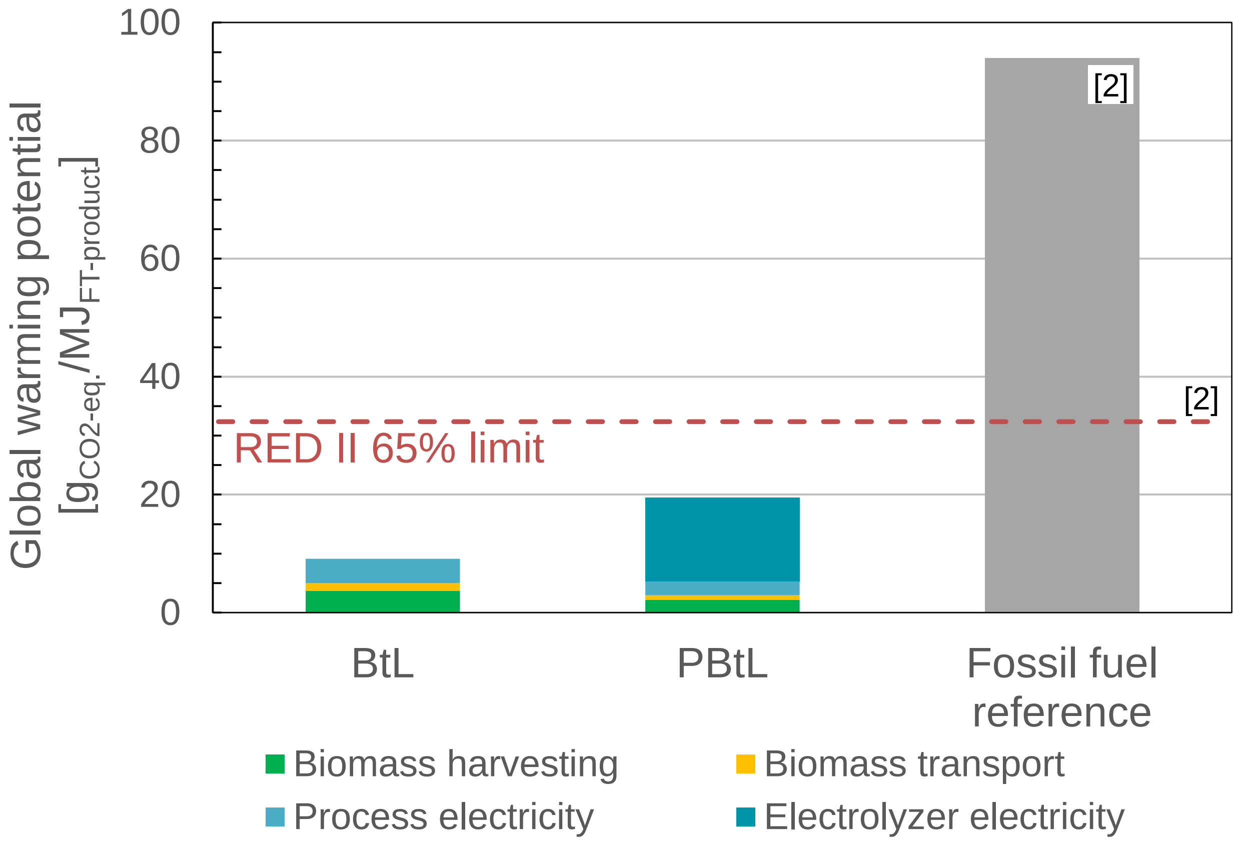


[1] Habermeyer, et. al (2021). Techno-economic analysis of a flexible process concept for the production of transport fuels and heat from biomass and renewable electricity. Front. Energy Res., Nov. 2021 | Volume 9 | Article 723774

ENVIRONMENTAL ASSESSMENT OF SAF (PBTL)

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

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



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

Conclusion

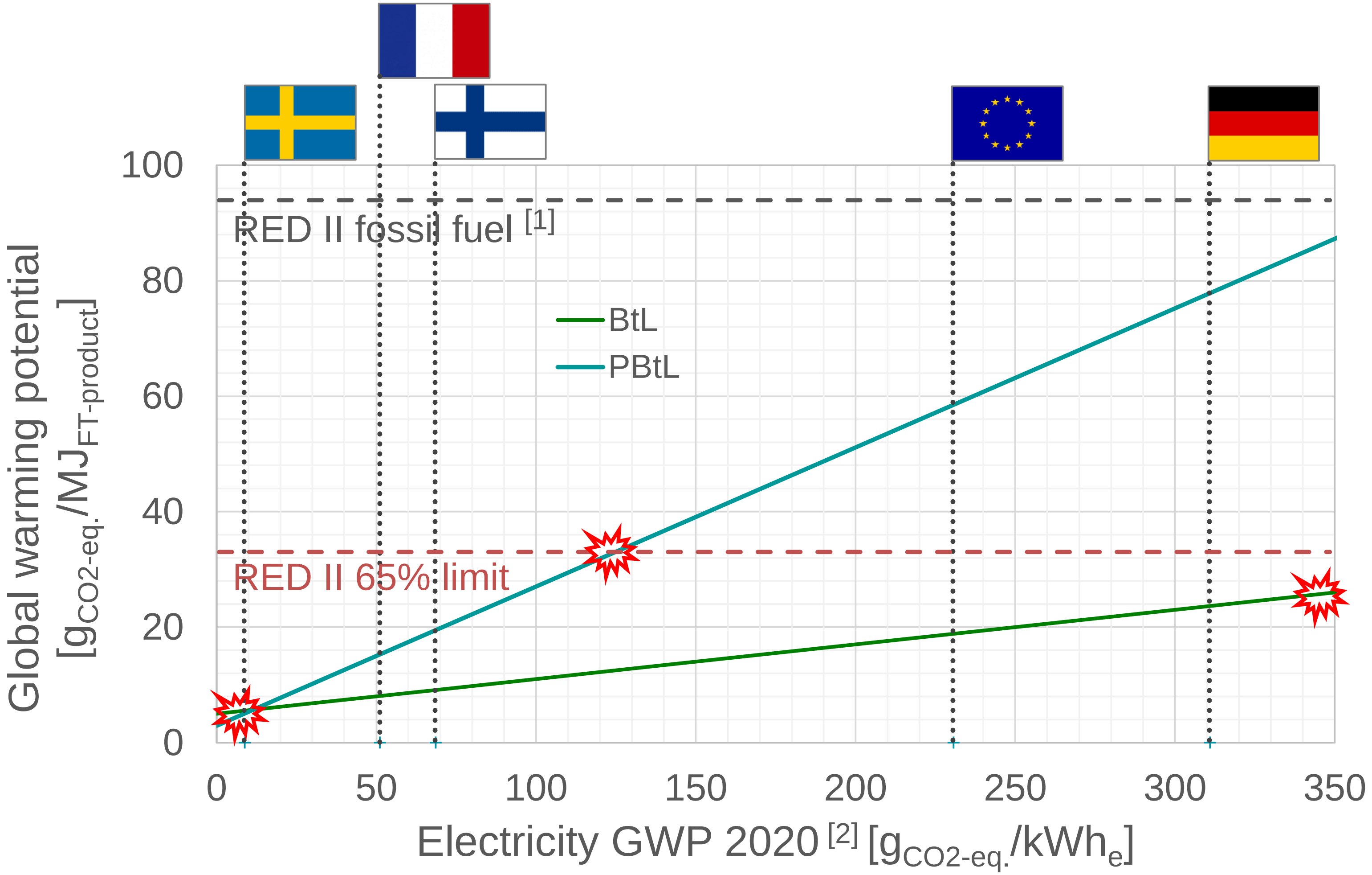
REDII target accomplished @ FLEXCHX base case

[1] Habermeyer et. al (2023) Sustainable aviation fuel from forestry residue and hydrogen. A techno-economic and environmental analysis for an immediate deployment of the PBtL process in Europe. Sustainable Energy and Fuels, 7, p. 4229-4246. doi: 10.1039/d3se00358b.

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

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

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

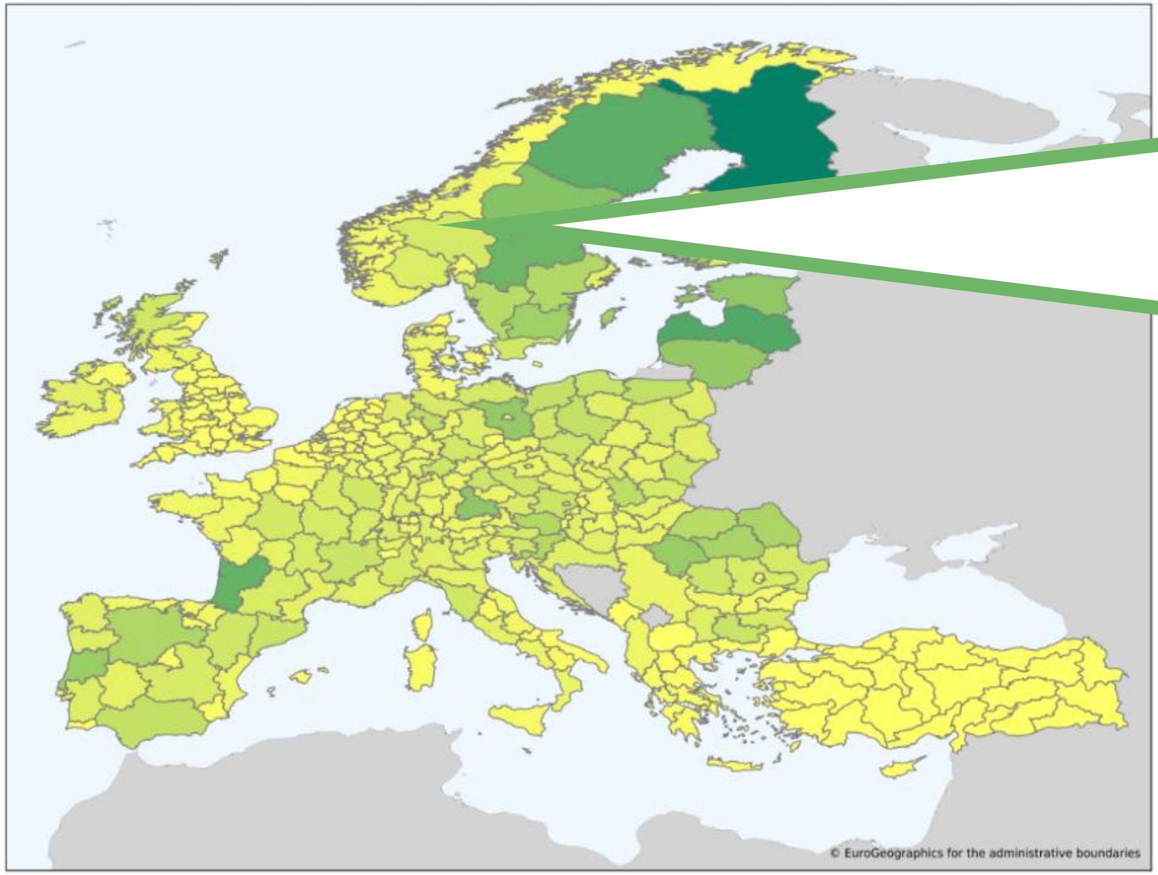


- ➢ REDII 65 % limit can be reached for all depicted electricity grid mixes for BtL
- ➢ PBtL requires electricity with GWP <120 $g_{CO2\text{-}eq.}/kWh_e$ to reach REDII 65 % limit
- ➢ PBtL could have lower GWP than BtL with Swedish grid mix

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

TOWARDS A EUROPEAN SAF ROADMAP

PBtL potential analysis for Europe
Finding the sweet spots



NUTS2 region specific SAF production results:

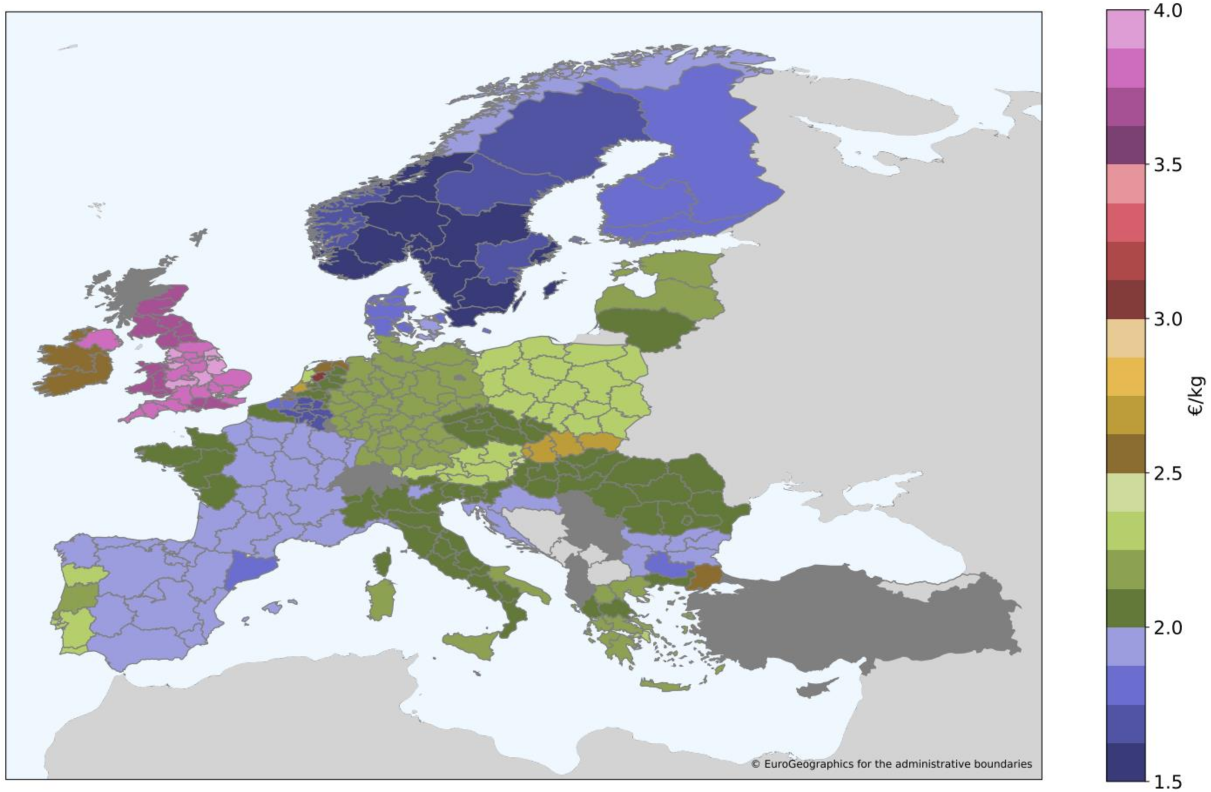
Net production costs (NPC) based on
- 2020 National grid electricity prices [1]
- Woody biomass prices & availability [2]
- Transport distance = f(biomass density)
- Nation-specific transport & labor costs

Global Warming Potential (GWP) from
- 2020 National grid mix GWP [3]
- Region-specific transport emissions

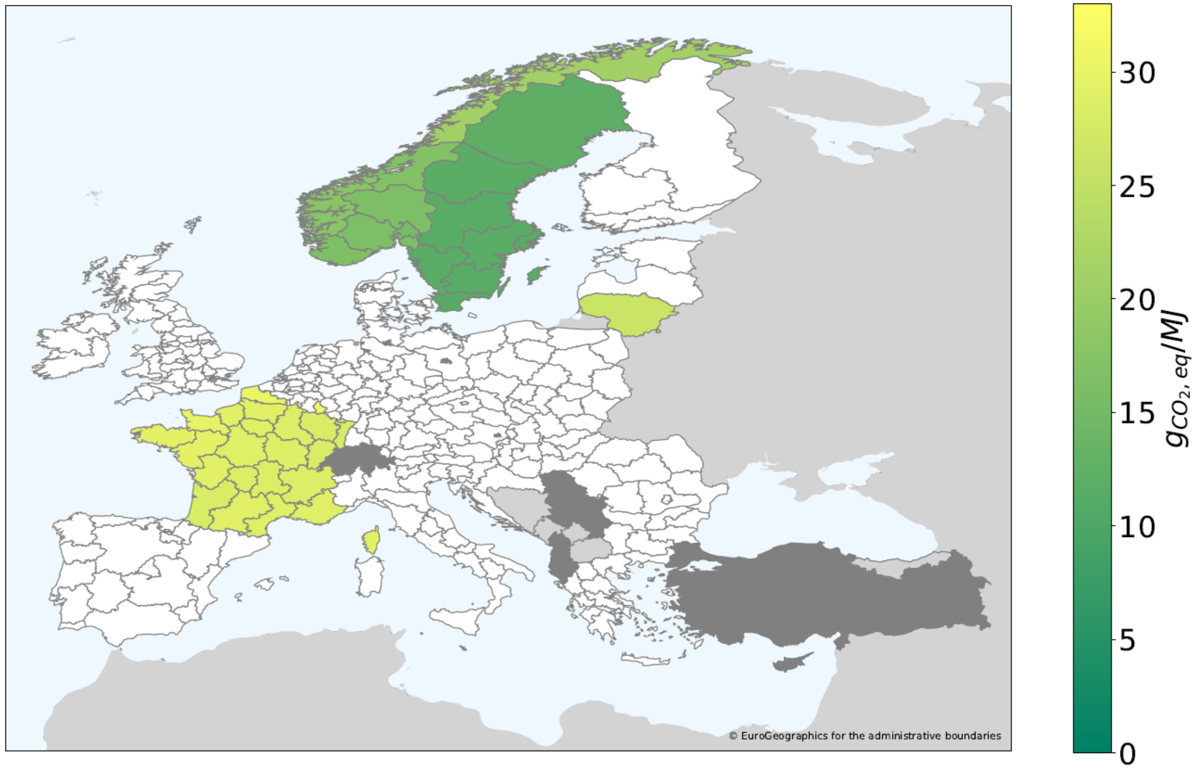
[1] Eurostat, Electricity prices for non-household consumers - bi-annual data. 2021.
[2] Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., ... & Thrän, D. (2019). ENSPRESSO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy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

Grid connected PBtL:
Northern Europe preferred

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



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

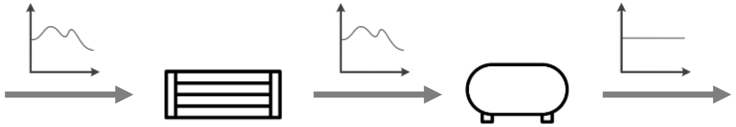


Net Production cost

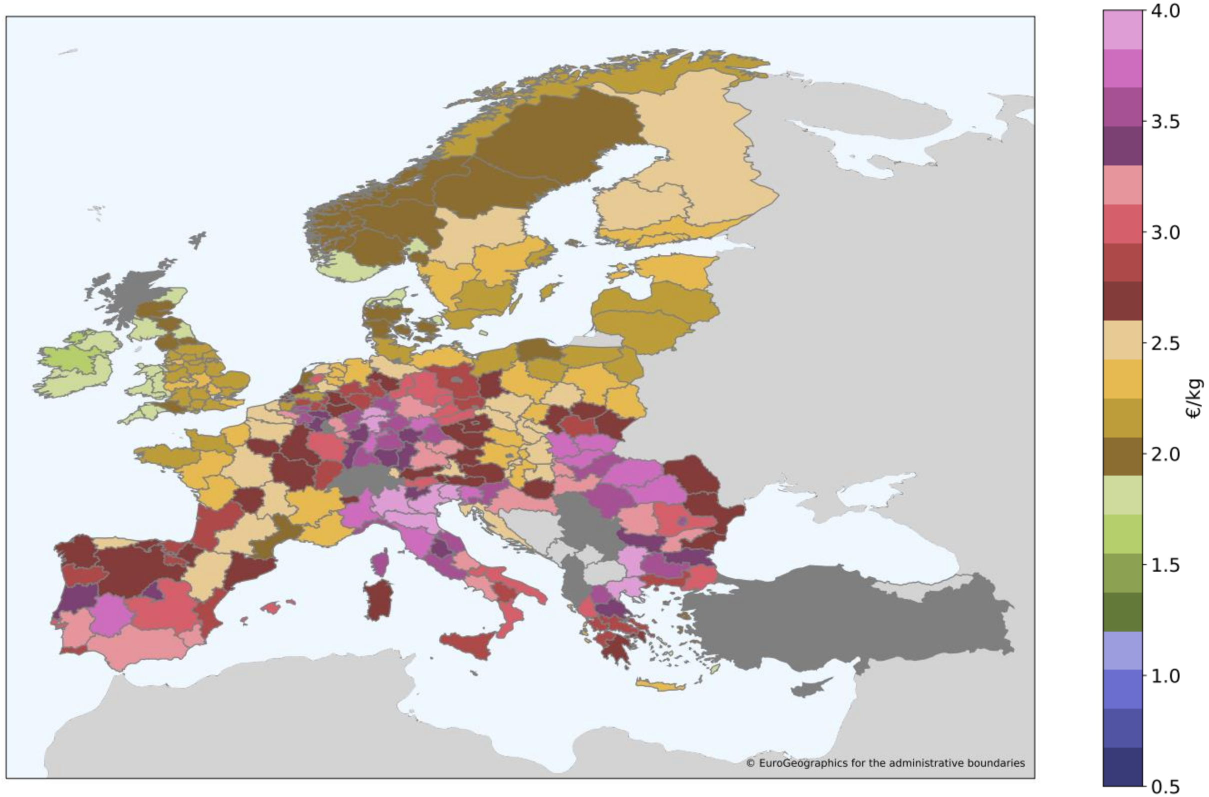
+ Abundant cheap woody biomass and low carbon electricity in Scandinavia

On-shore wind connected PBtL:
Costal regions preferred

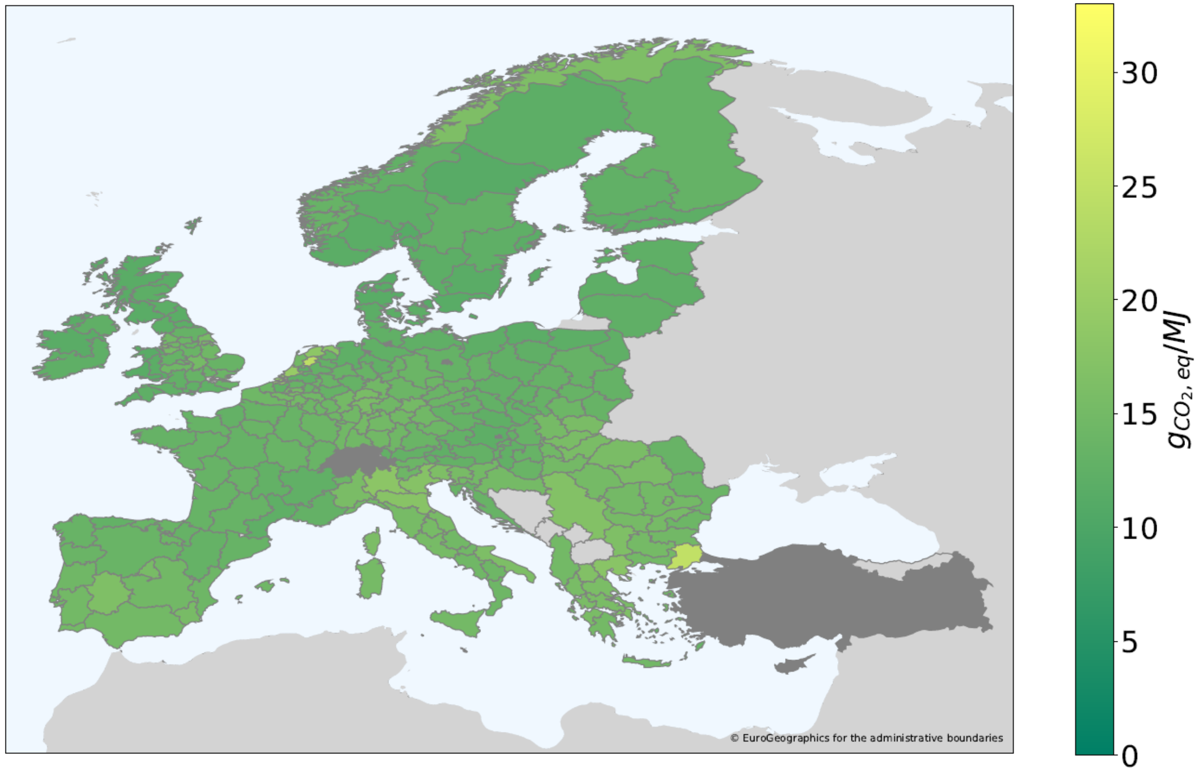
Hydrogen storage included:



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



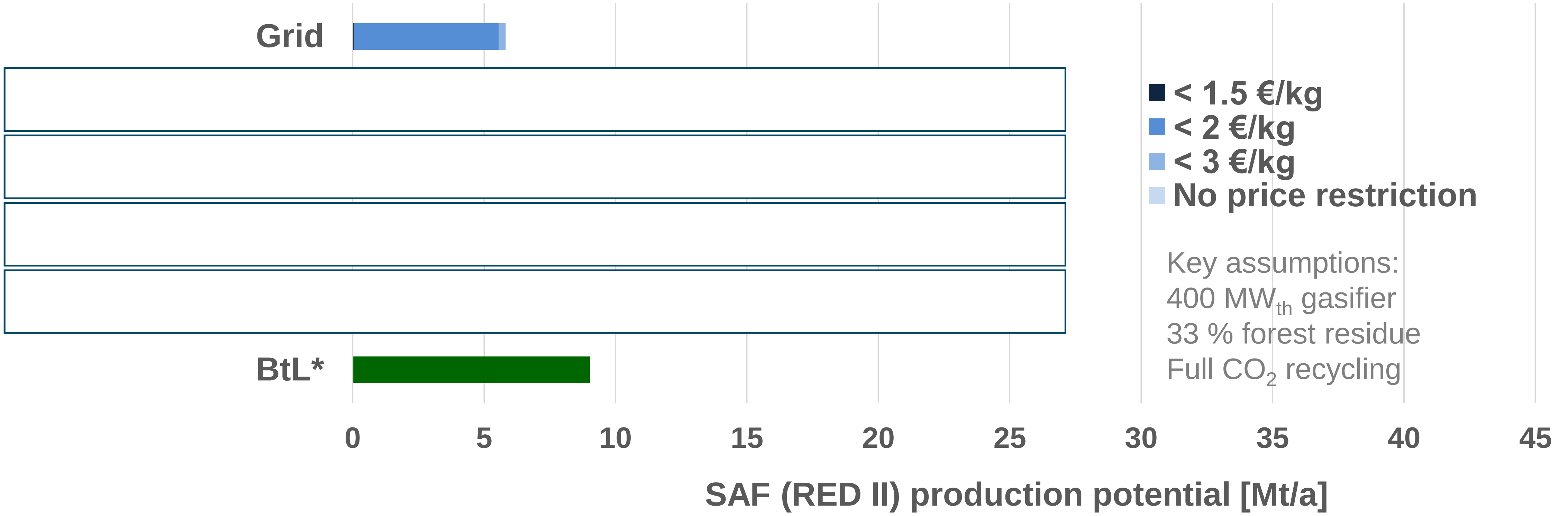
Fuel GWP 2020 [$g_{CO2,eq}/MJ$]:



Net Production cost

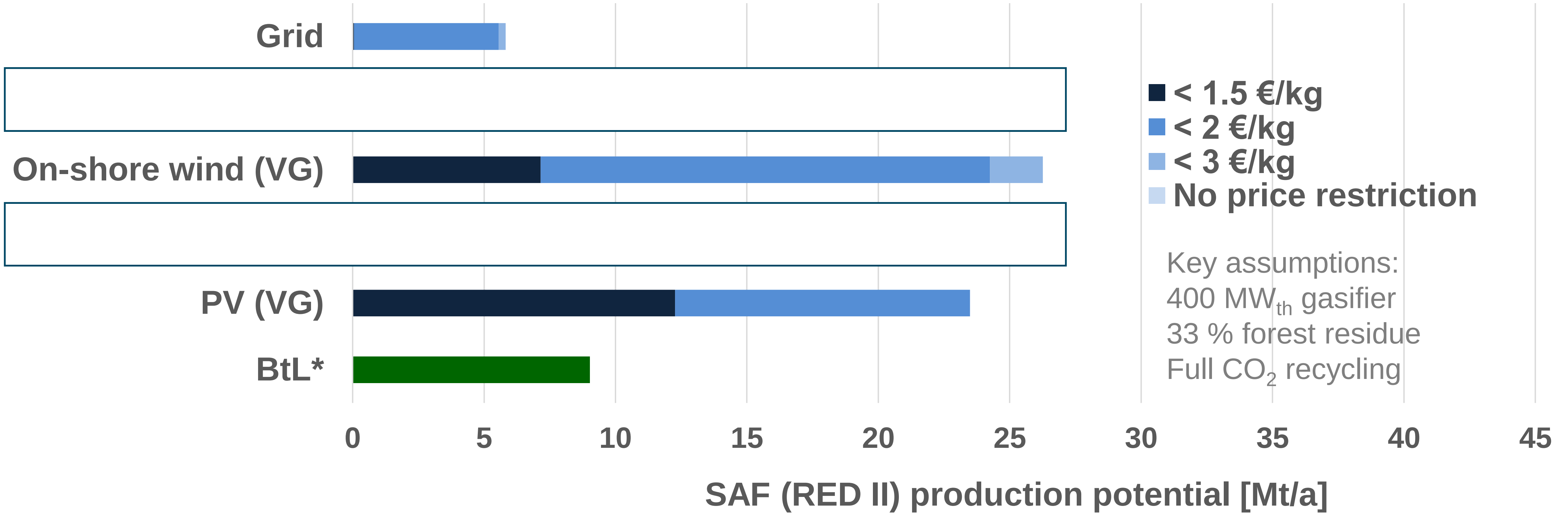
\+ High full load hours of wind power required

Aggregated European SAF production potential



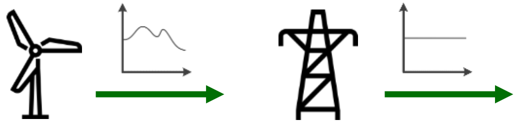
Key assumptions:
400 MW_{th} gasifier
33 % forest residue
Full CO_2 recycling

Aggregated European SAF production potential

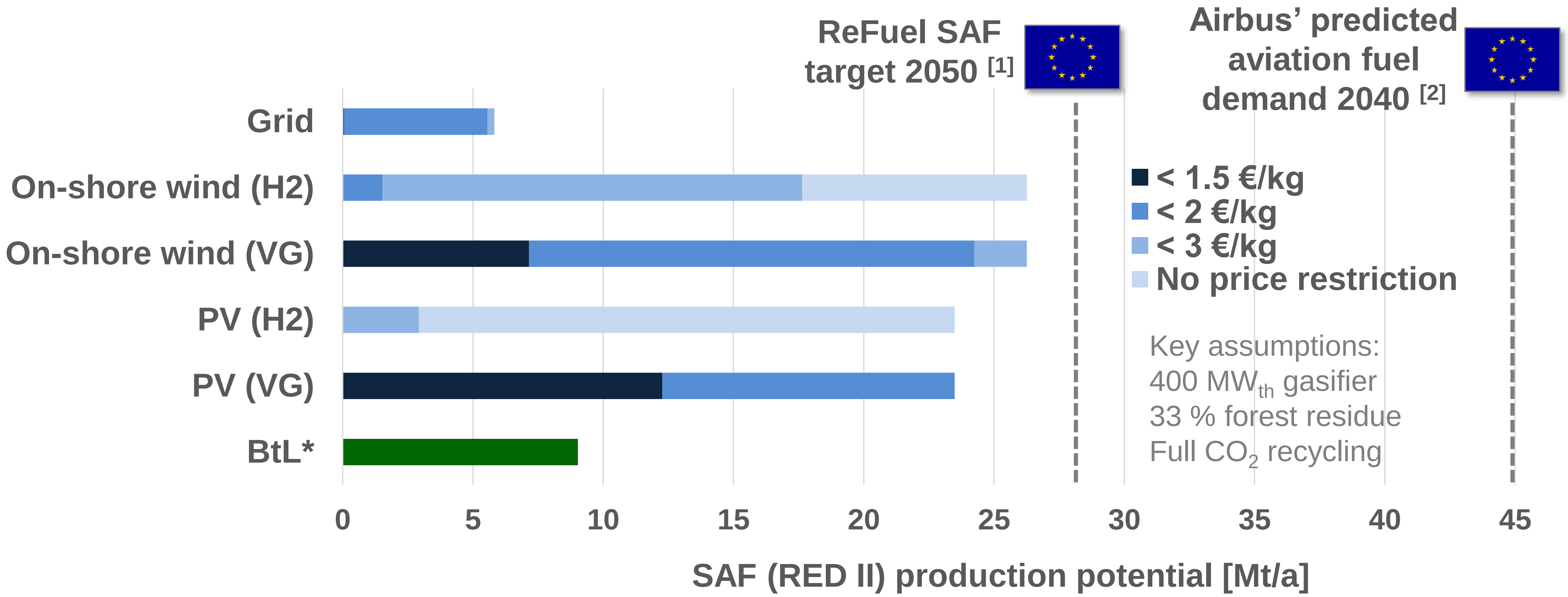


Key assumptions:
400 MW_{th} gasifier
33 % forest residue
Full CO_2 recycling

Virtual grid (VG)



Aggregated European SAF production potential



[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,
[2] Airbus Global Market forecast 2021 – 2040 [Online] https://www.airbus.com/en/newsroom/press-releases/2021-11-airbus-foresees-demand-for-39000-new-passenger-freighter-aircraft (Accessed 02/2022)
*Assumptions: 19.9 % biomass conversion, entire potential under RED II limit

CONCLUSIONS

Conclusions

- Decarbonisation of power, transportation, building, industry, agriculture fails on a global scale – immediate large-scale individual measures required
- Decarbonization of aviation is technically feasible but 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 spot solution (Norway / Sweden) – BtL broader application spectrum
  - PBtL necessary to approach towards European SAF goals
  - Net Zero aviation by 2050 not realistic
- DLR standardized methodology is applicable for any decarbonization measure globally ➔

Wednesday, 2024/09/26

ADV. ESCC 2024 3RD GLOBAL SUMMIT
SEPTEMBER 26-27 2024 BARCELONA, SPAIN

THANK YOU FOR YOUR KIND ATTENTION! QUESTIONS?

Large-scale economic production of sustainable aviation fuels in Europe

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