Wednesday, 2024/09/18, Berlin, Germany

CONFERENCE SESSION ONE
Navigating the Carbon Economy:
Challenges and Opportunities

TECHNO-ECONOMIC AND ECOLOGICAL ASSESSMENT

Decarbonization of Industry and Transport – Two interlinked Carbon Cycles

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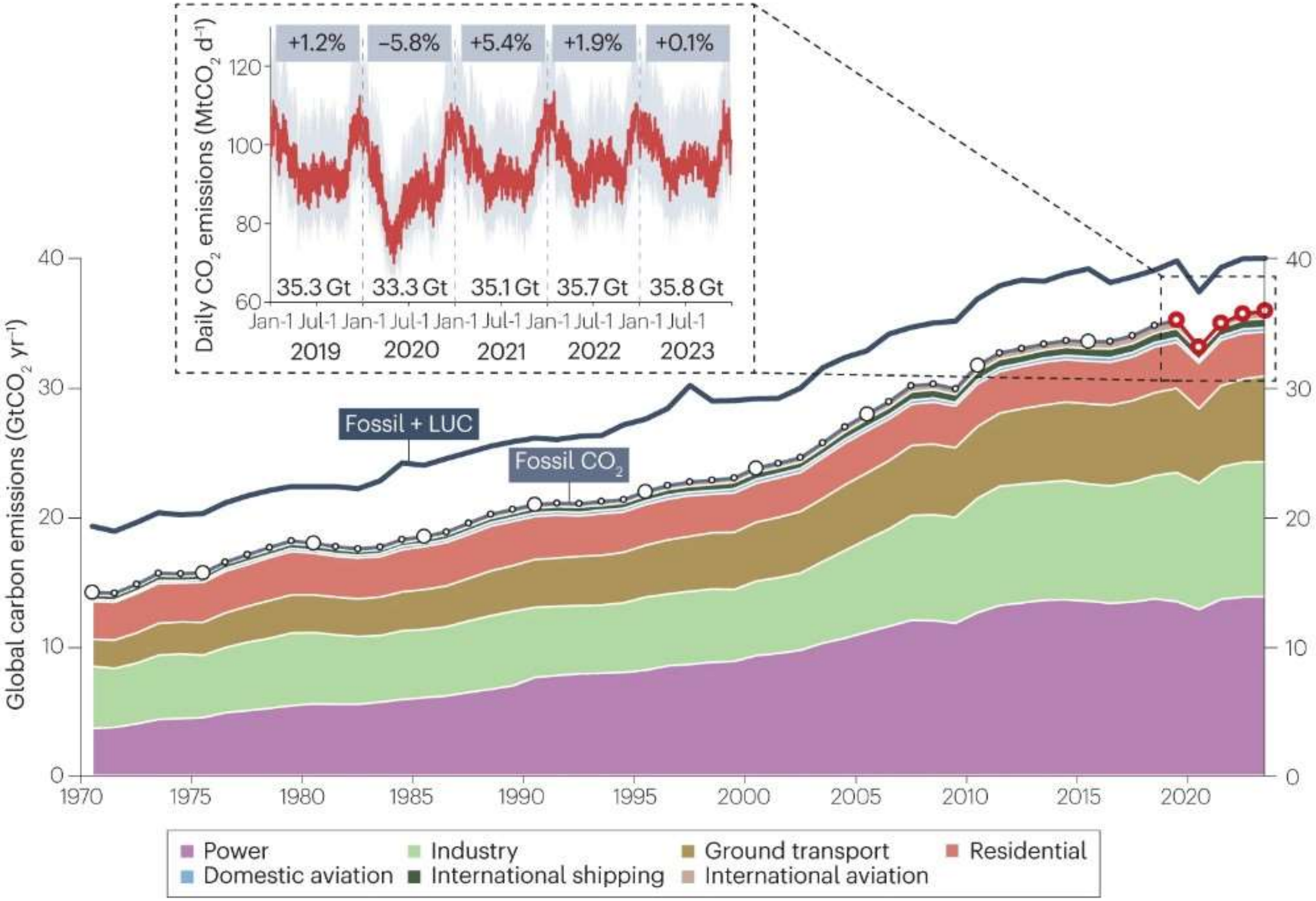
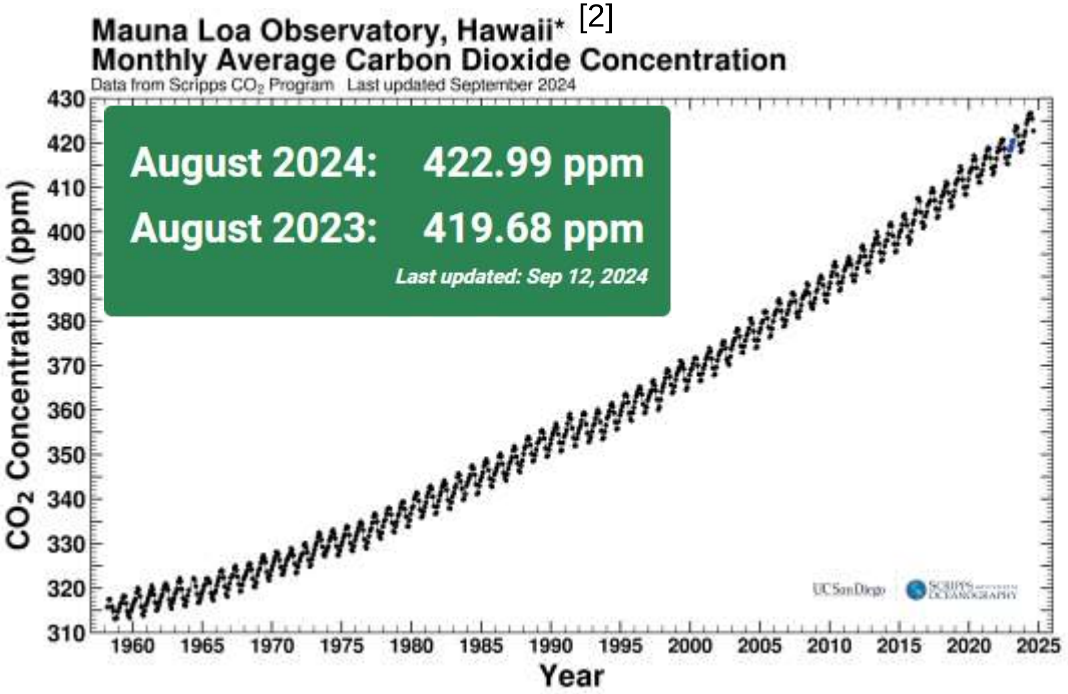
Climate change undeniable

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



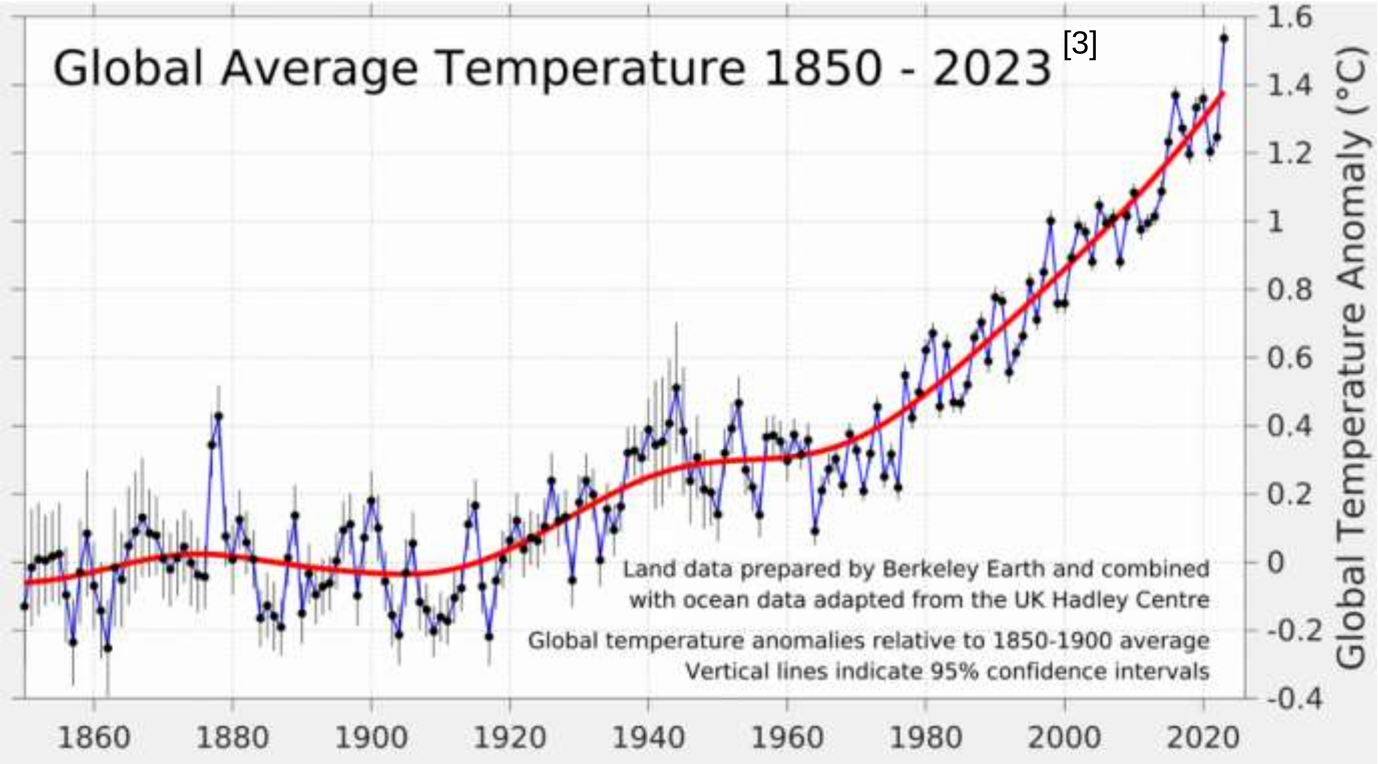
[2]

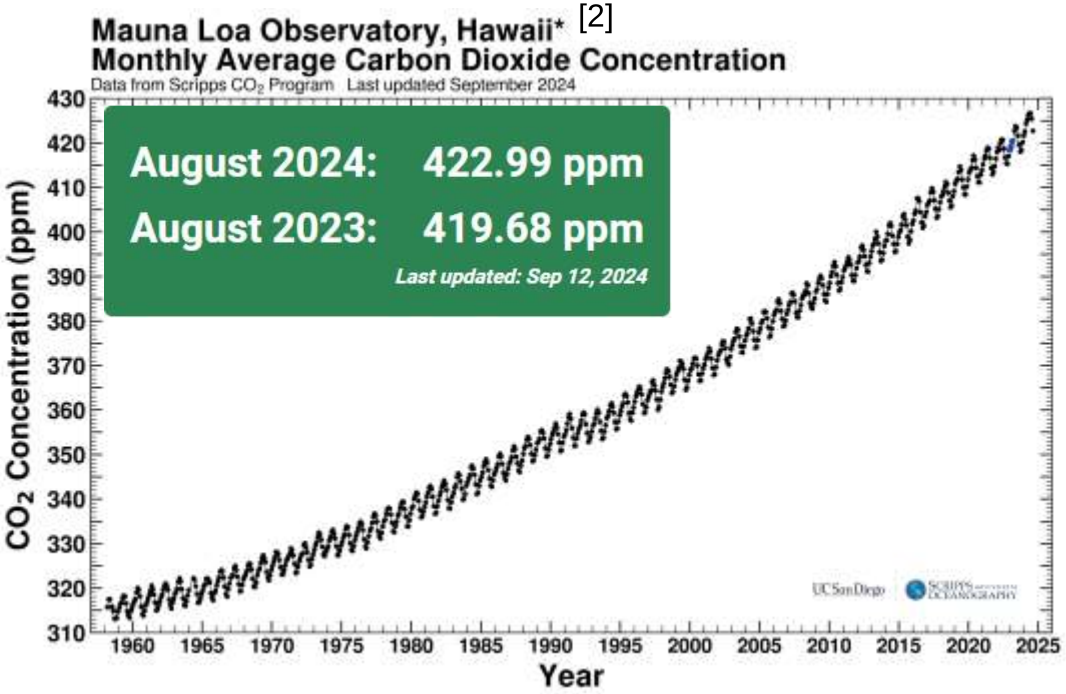


[1] https://www.nature.com/articles/s43017-024-00532-2
[2] https://scrippsco2.ucsd.edu/graphics_gallery/mauna_loa_record/mauna_loa_record.html

Climate change undeniable

[1]





[1] https://www.nature.com/articles/s43017-024-00532-2
[2] https://scrippsco2.ucsd.edu/graphics_gallery/mauna_loa_record/mauna_loa_record.html
[3] https://berkeleyearth.org/global-temperature-report-for-2023/

Decarbonization options

Mc Kinsey order of sector decarbonization for Europe [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.

Assessment example: Retrofit Coal Power Plants

- ***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.

Assessment example: Sustainable Aviation Fuels in Europe

- ***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.

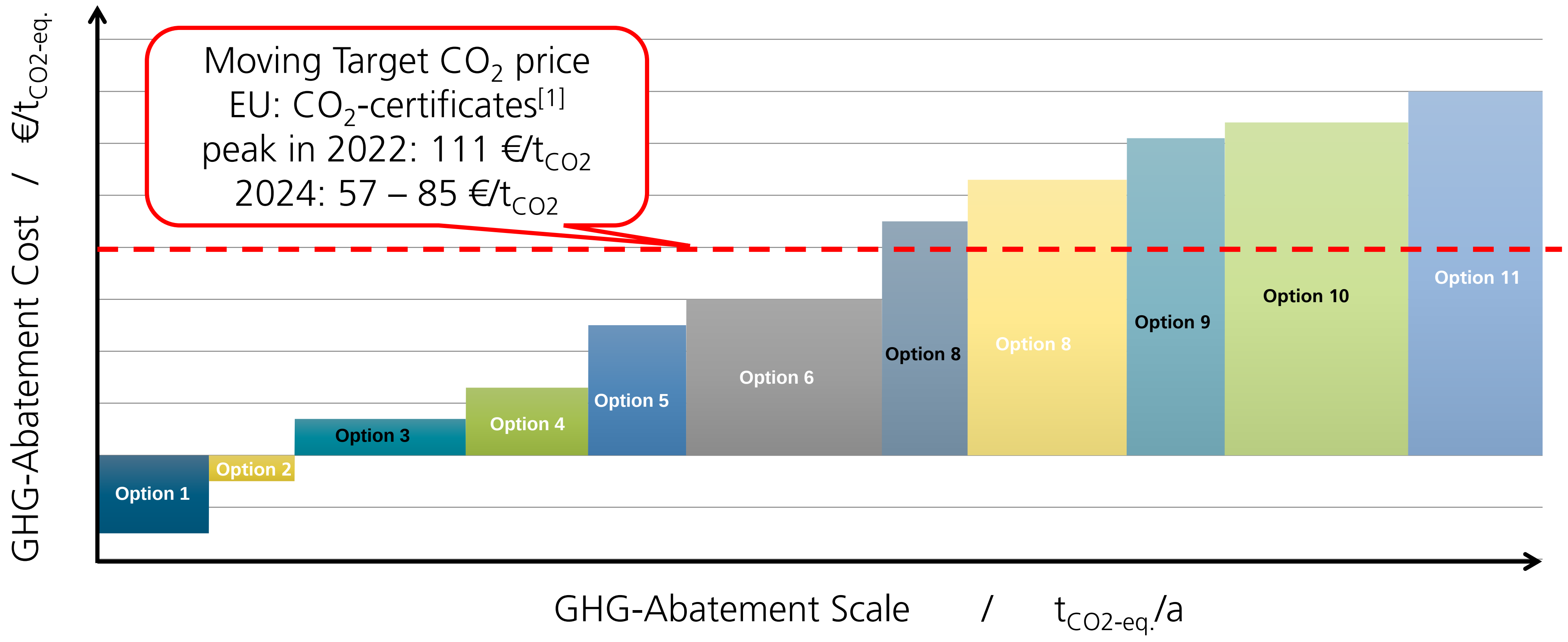
Assessment example: Sustainable Glass Production

- ***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#/

Assessment of Decarbonization options

Merit Order of Greenhouse Gas (GHG) emission reduction measures



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

Assessment of Decarbonization options

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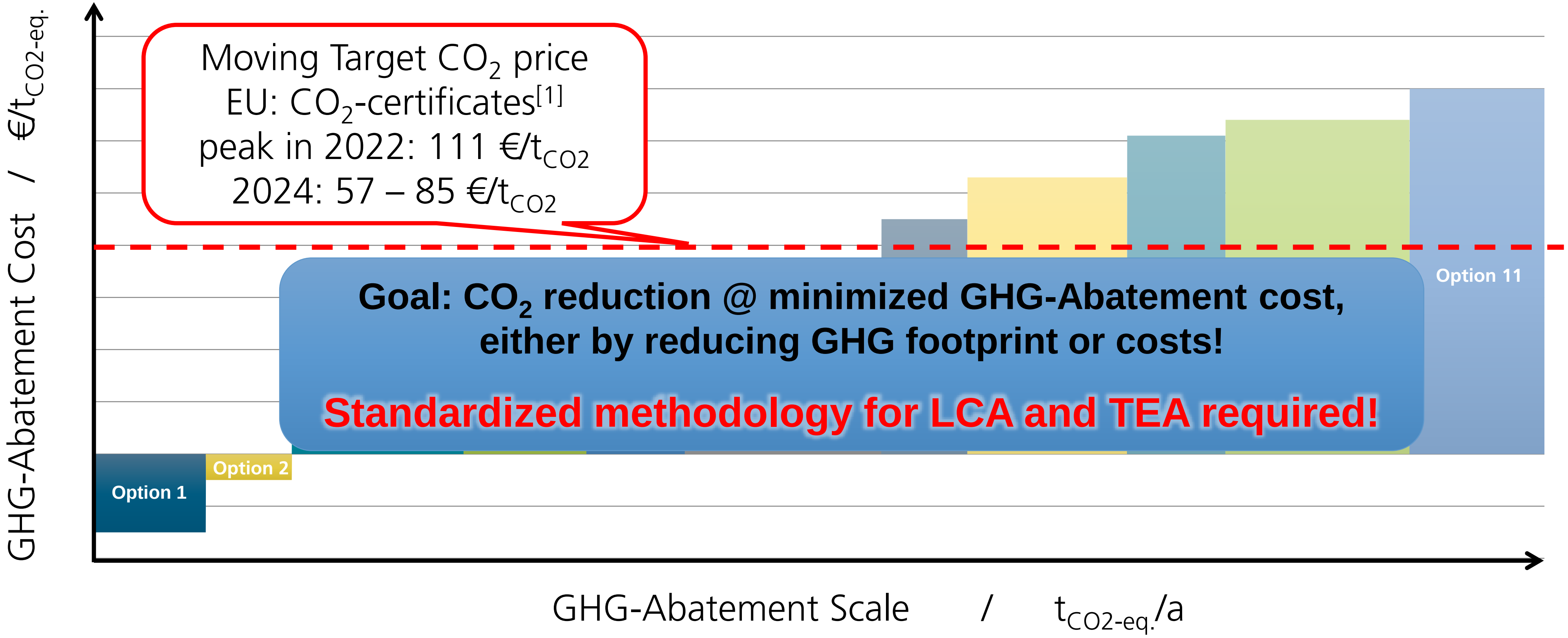
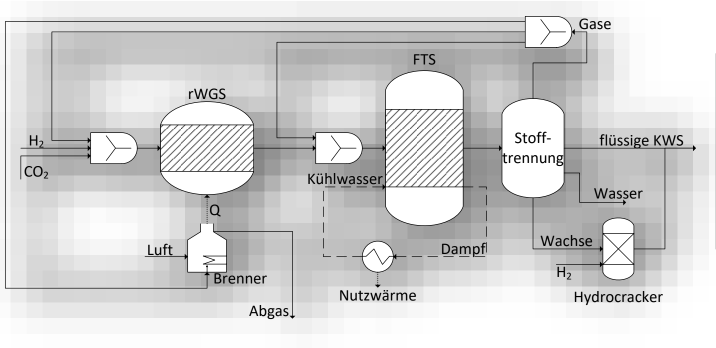
Merit Order of Greenhouse Gas (GHG) emission reduction measures

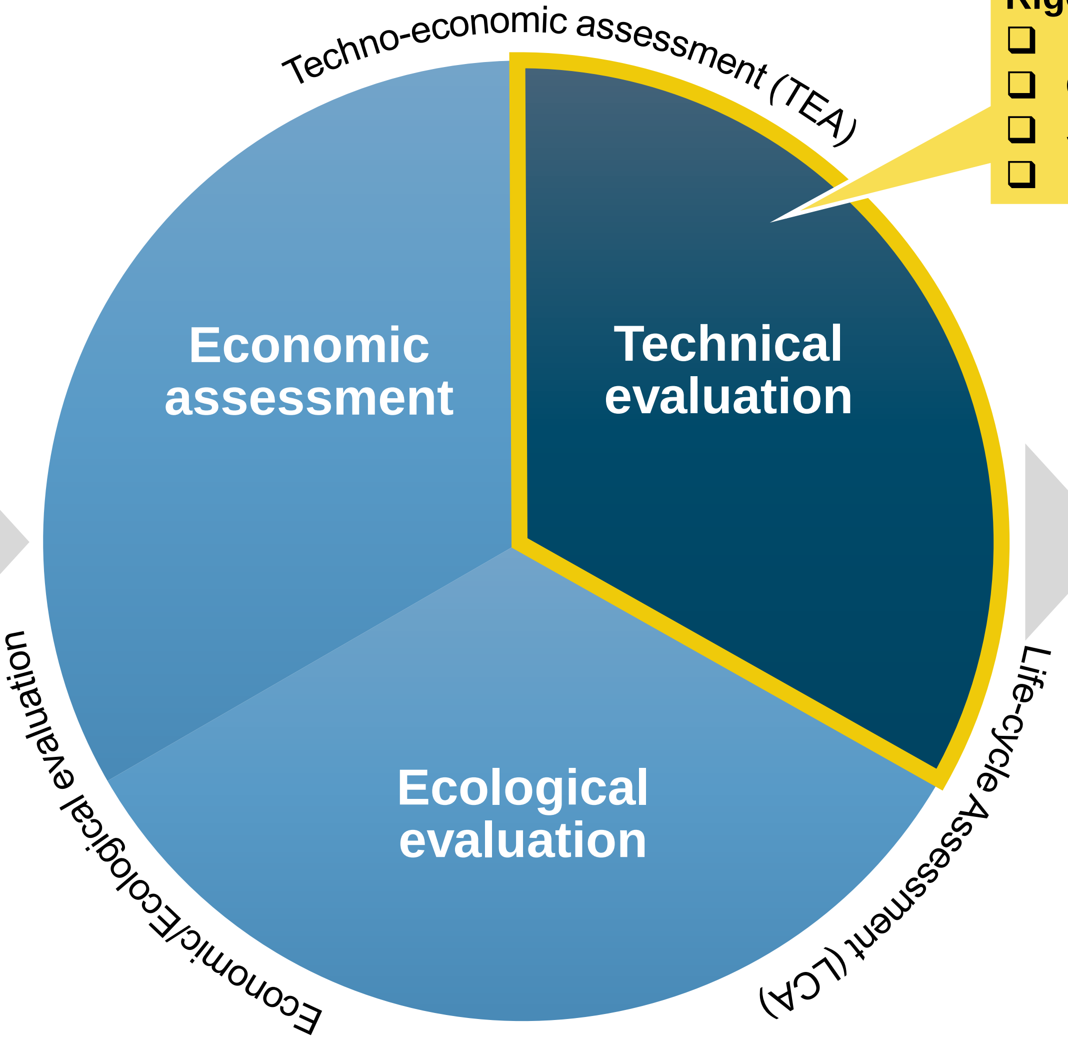


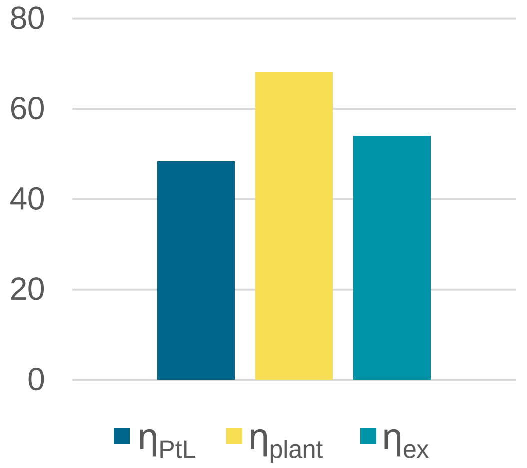
[1] https://www.boerse.de/rohstoffe/Co2-Emissionsrechtepreis/XC000A0C4KJ2

Techno-Economic and Life Cycle Assessment @ DLR

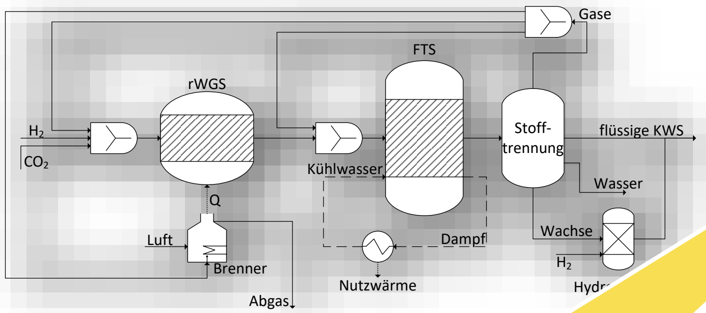
Rigorous process simulation
- ❑ Efficiencies (X-to-Liquid, Overall)
- ❑ Carbon conversion
- ❑ Specific feedstock demand
- ❑ Exergy analysis

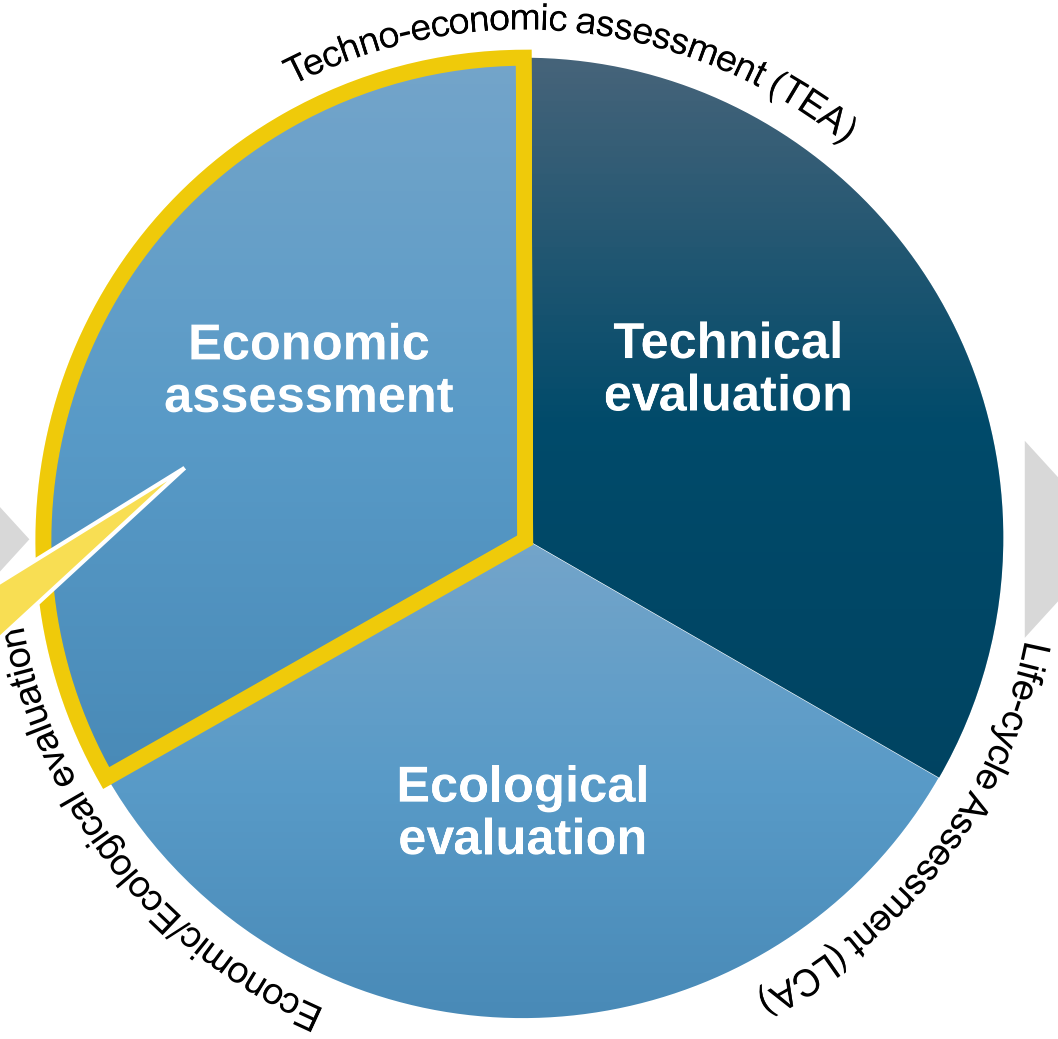


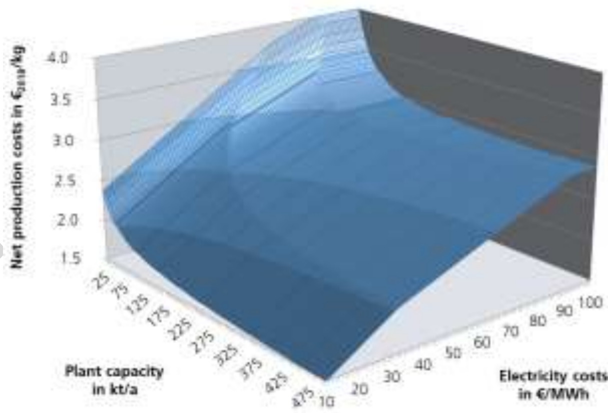




Techno-Economic and Life Cycle Assessment @ DLR



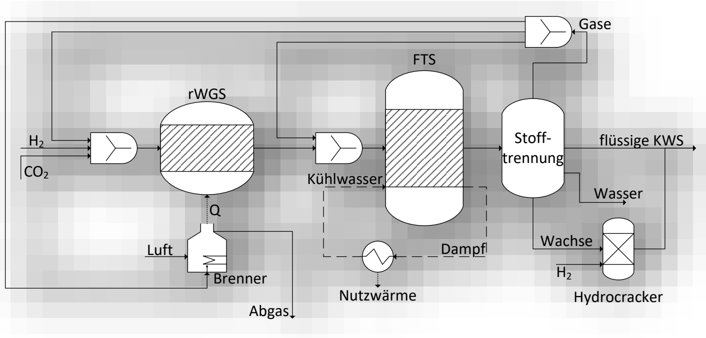


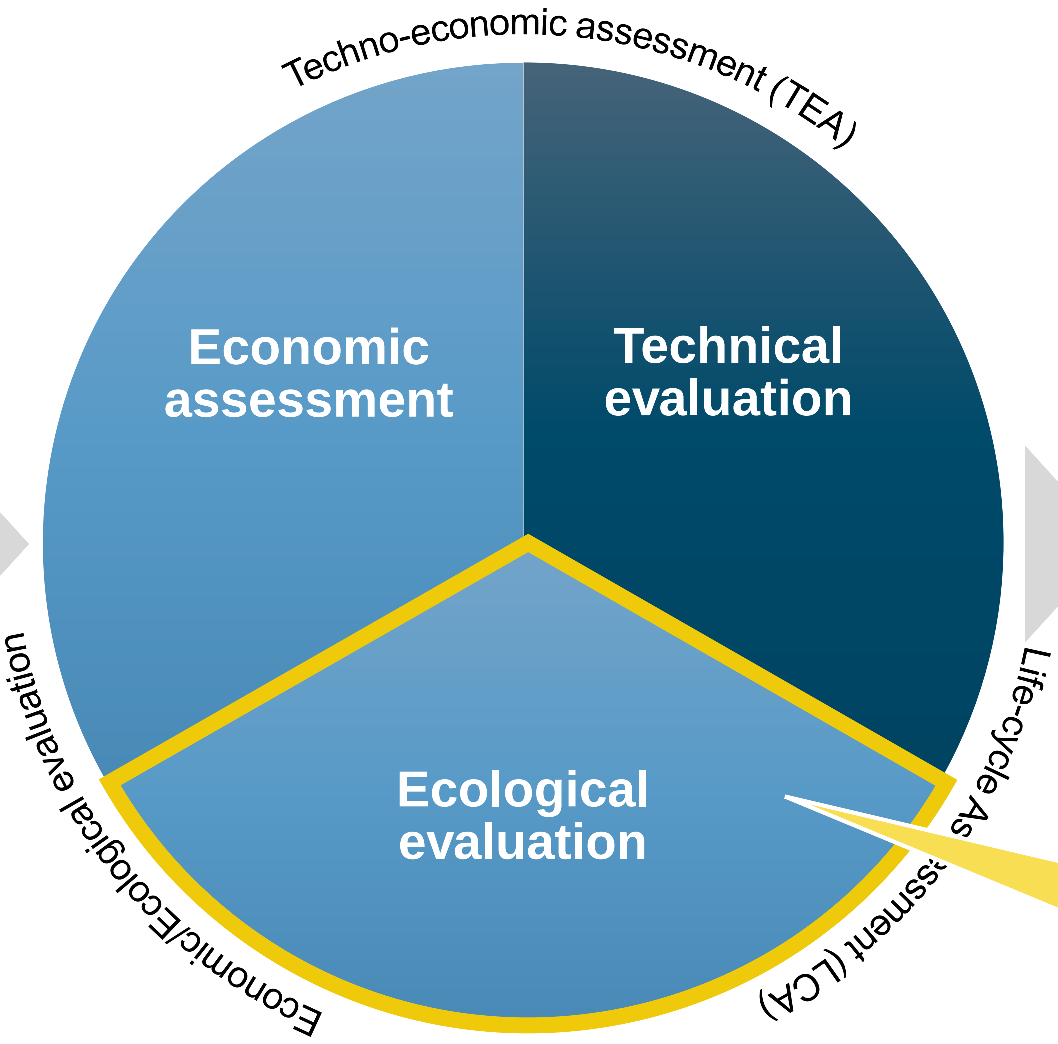


Chemical engineering cost estimation

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

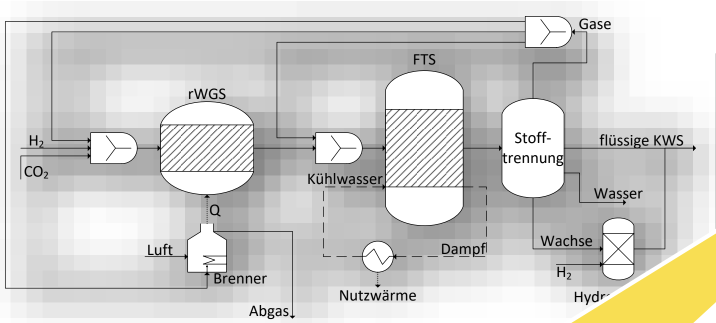
Techno-Economic and Life Cycle Assessment @ DLR

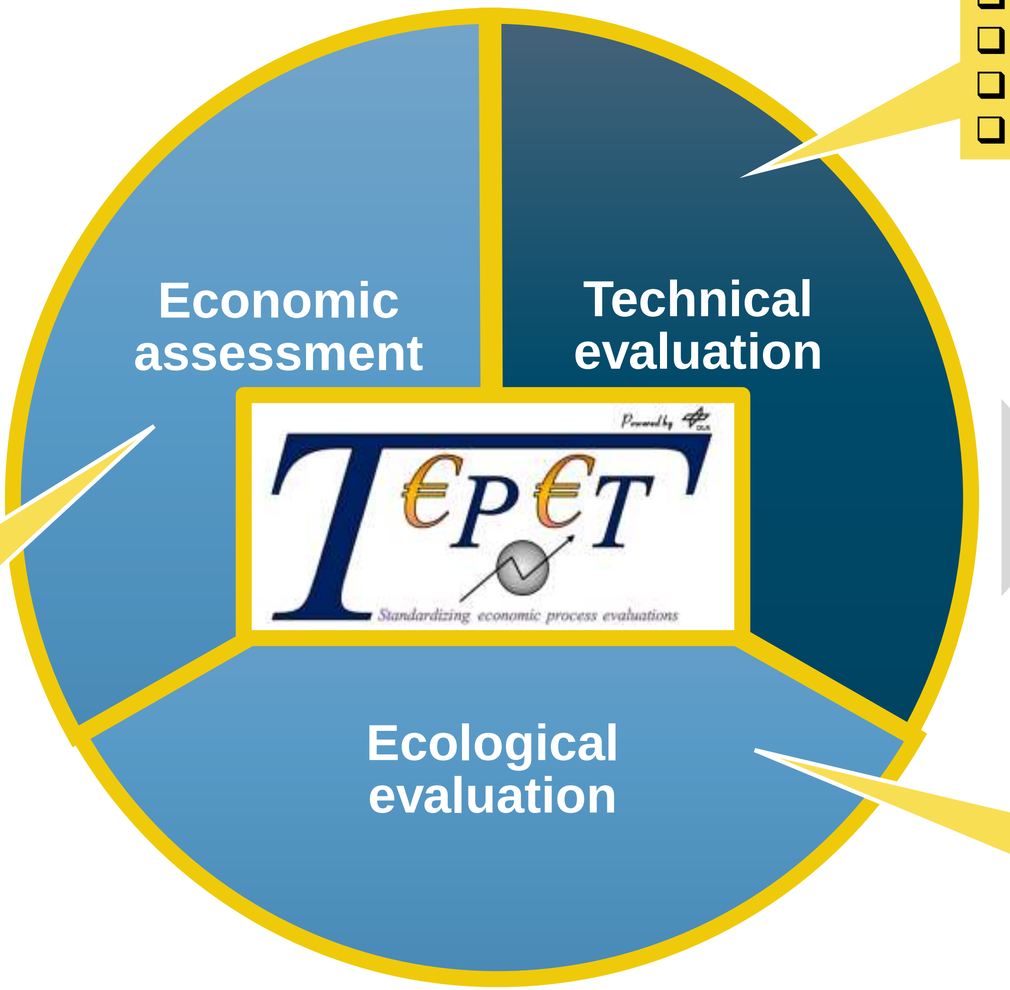




Adapted ISO 14040/14044 LCA
- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

Techno-Economic and Life Cycle Assessment





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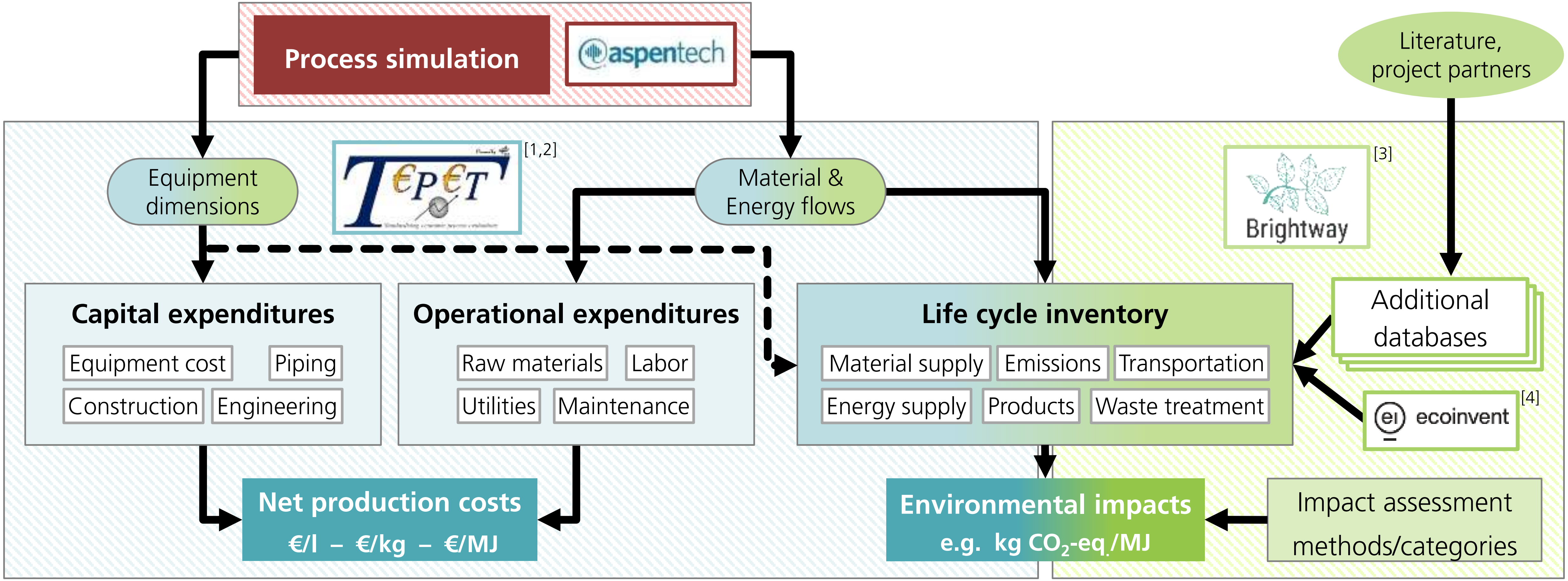
TEPET+ – Methodology

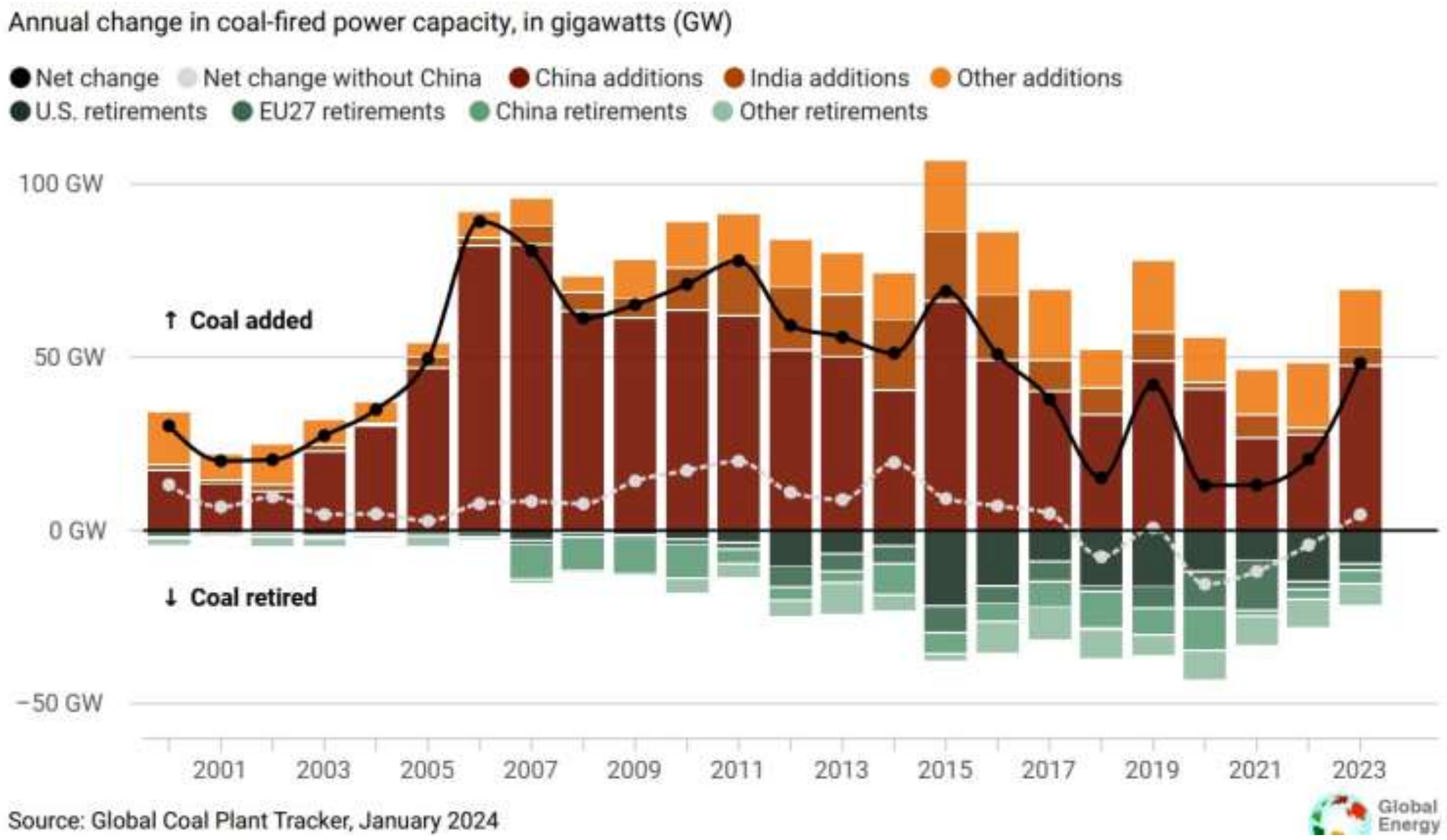


[1] Albrecht et al. (2016): https://doi.org/10.1016/j.fuel.2016.12.003
[2] Maier et al. (2021): https://doi.org/10.1016/j.enconman.2021.114651
[3] Mutel (2017): https://doi.org/10.21105/joss.00236
[4] Wernet et al. (2016): https://doi.org/10.1007/s11367-016-1087-8

DECARBONIZATION OF POWER GENERATION

Coal consumption: Power industry

- Global coal power capacity 2023: 2’130 GW
  - annual growth: +48.4 GW, 2/3 in China
  - Retirements at lowest level in over a decade [1]



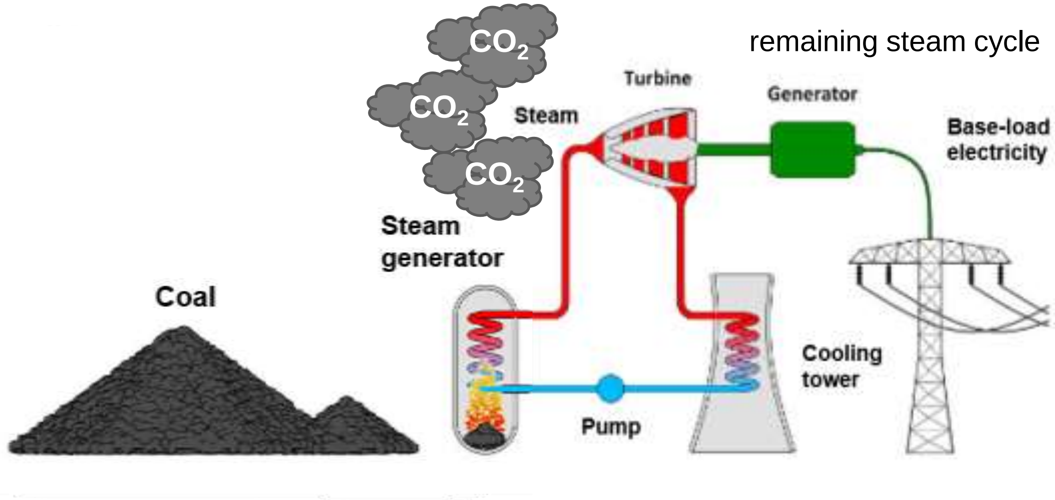
- Emissions: 10.4 Gt_{CO2}/a [2]
- Reduction to ZERO according to COP28?

[1] IEA (2022)
[2] IEA (2022)

Decarbonizing Coal Power plants
Retrofit concept

- If no retirement, individual conversion strategy for each plant required

Locations of the coal power plants worldwide (ca. 7000 in operation)[1]



Conventional coal power plant

[1] https://globalenergymonitor.org/

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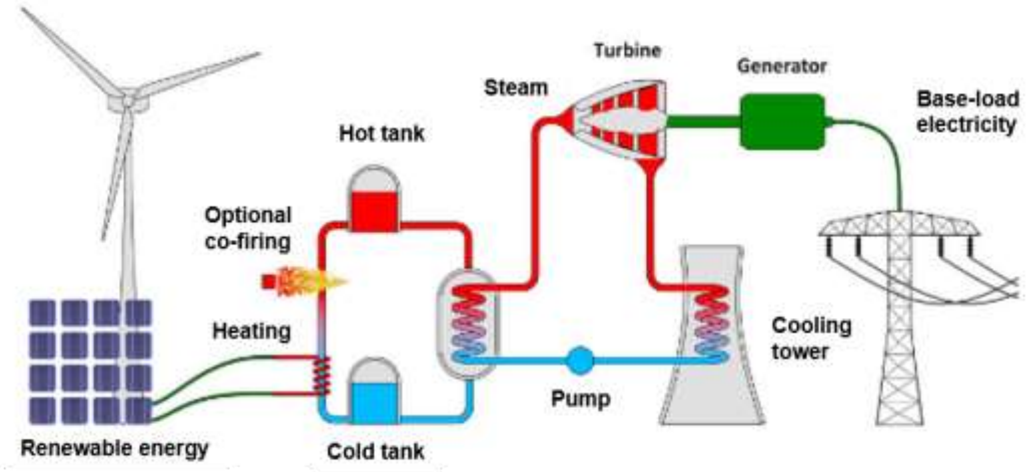

Thermal storage power plant (**TSPP**) concept coupled with Carnot-battery[2]

- Thermal storage electrically heated with fluctuating renewable electricity

[1] https://globalenergymonitor.org/
[2] Iñigo Labairu et al. (2024) Wärmespeicherkraftwerke zur Dekarbonisierung, Jahrestreffen DECHEMA Fachsektion Energie, Chemie und Klima.

Decarbonizing Coal Power plants
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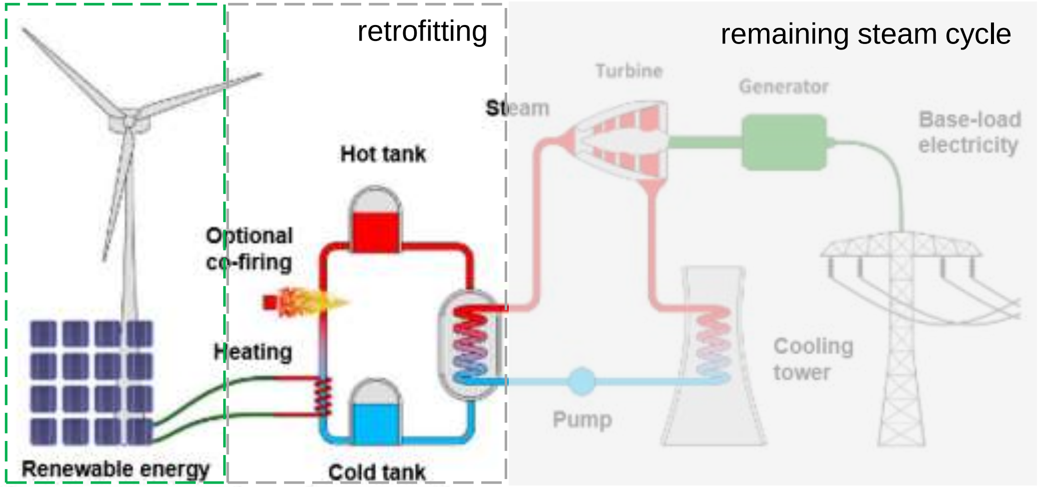


Thermal storage power plant (TSPP) coupled with Carnot-battery[2]

Conventional coal power plant[2]

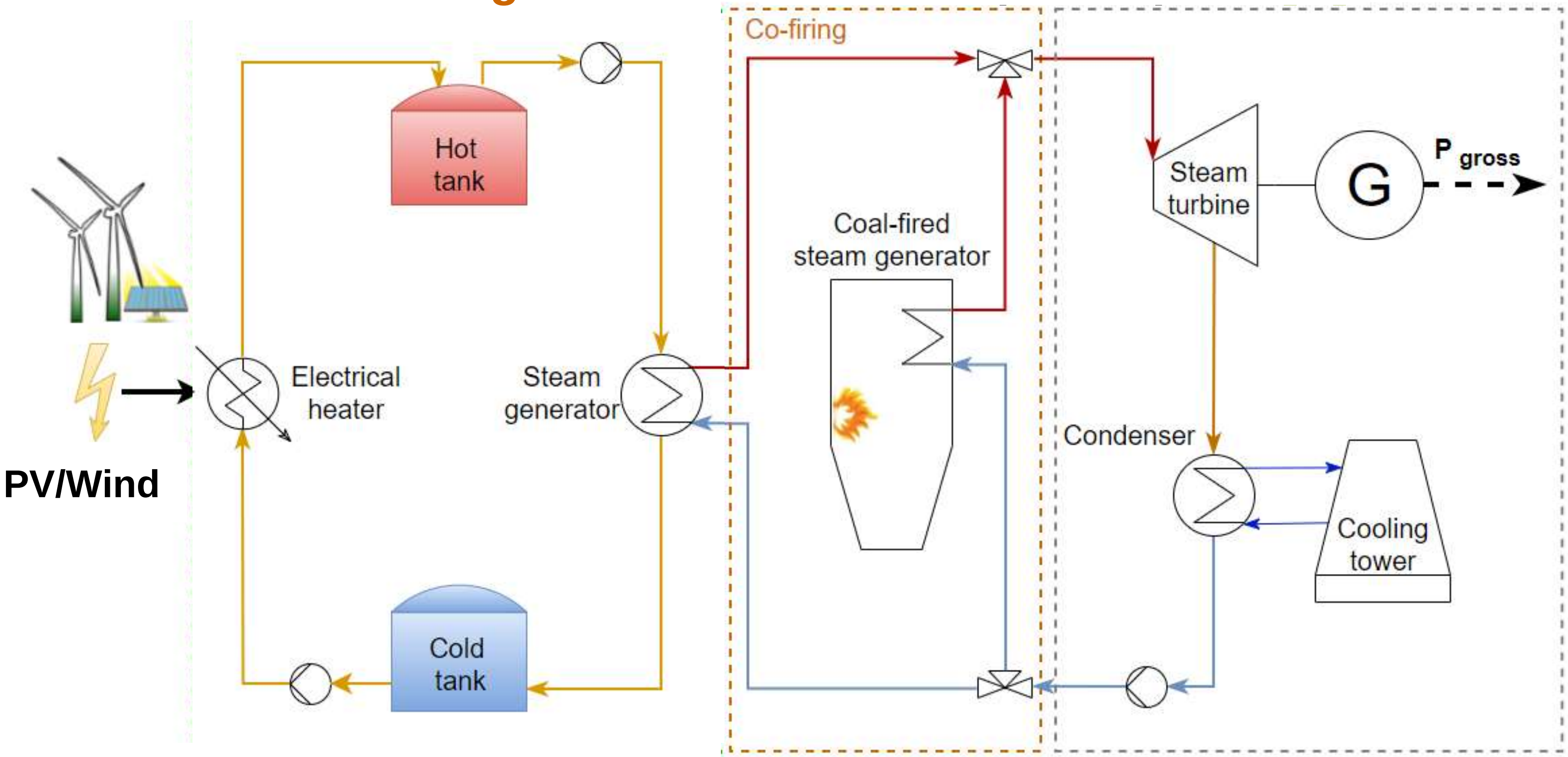
- Thermal storage electrically heated with fluctuating renewable electricity
- Adapted to each capacity, turbine type, steam temperature, pressure, …

[1] https://globalenergymonitor.org/
[2] Iñigo Labairu et al. (2024) Wärmespeicherkraftwerke zur Dekarbonisierung, Jahrestreffen DECHEMA Fachsektion Energie, Chemie und Klima.

Thermal storage power plant (TSPP)
[A E-heater for steam generation

Molten salt storage

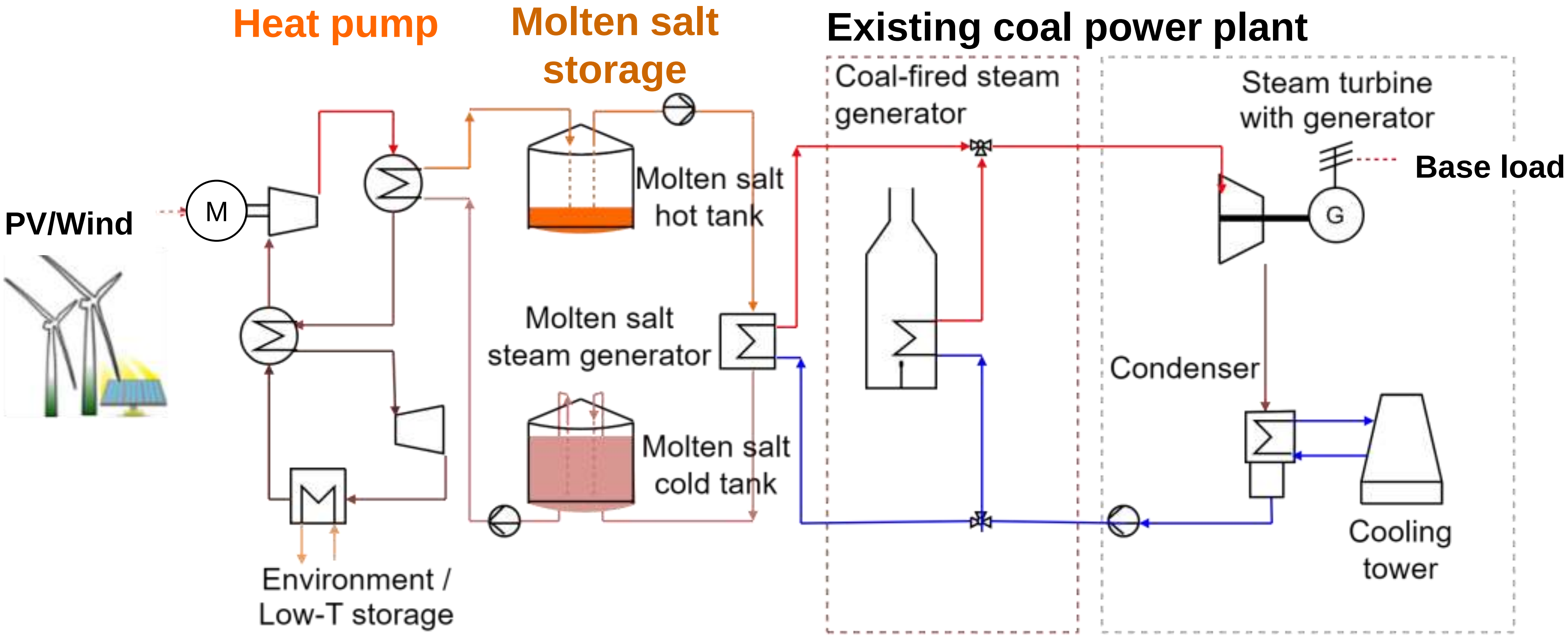
Existing Brown field [A] /



[B] Green field
includes
new steam cycle
(state-of-the-art)

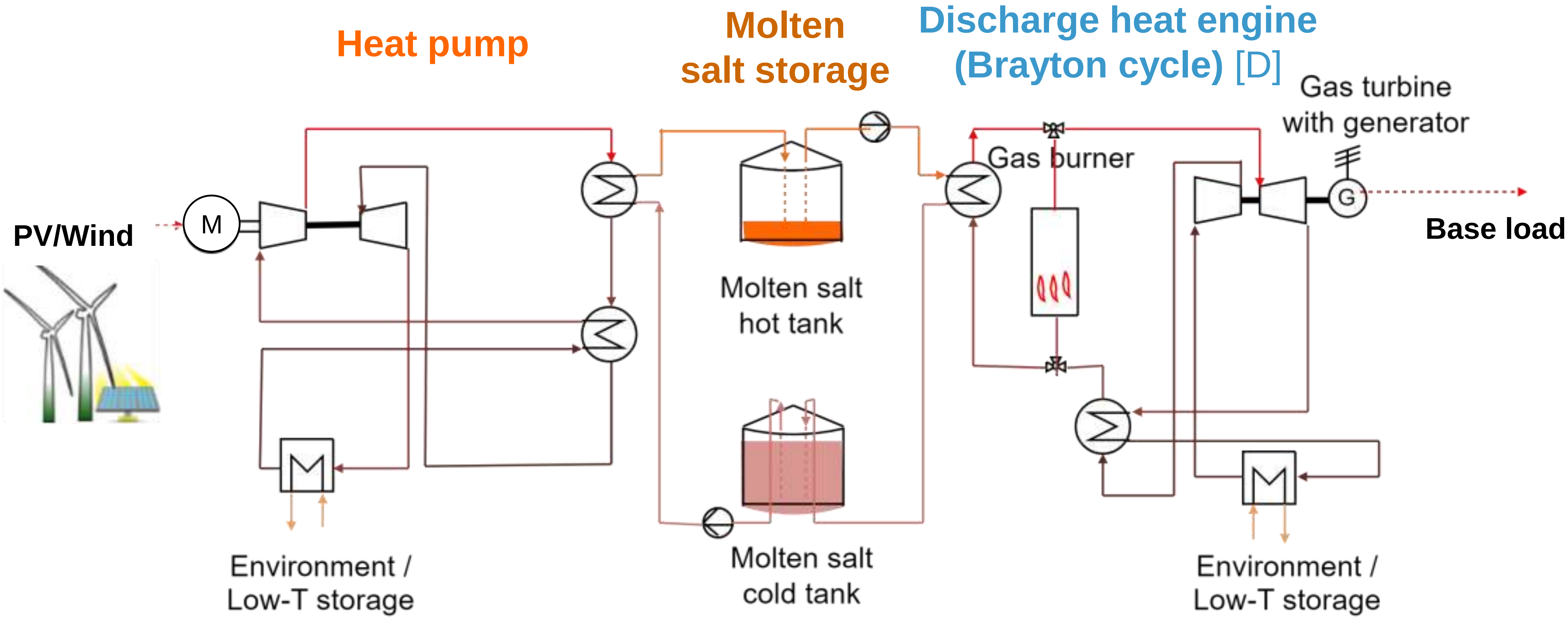
Source: DLR-project Global Coal Atlas

Thermal storage power plant (TSPP)
[C] High temp. heat pump (HT-HP)



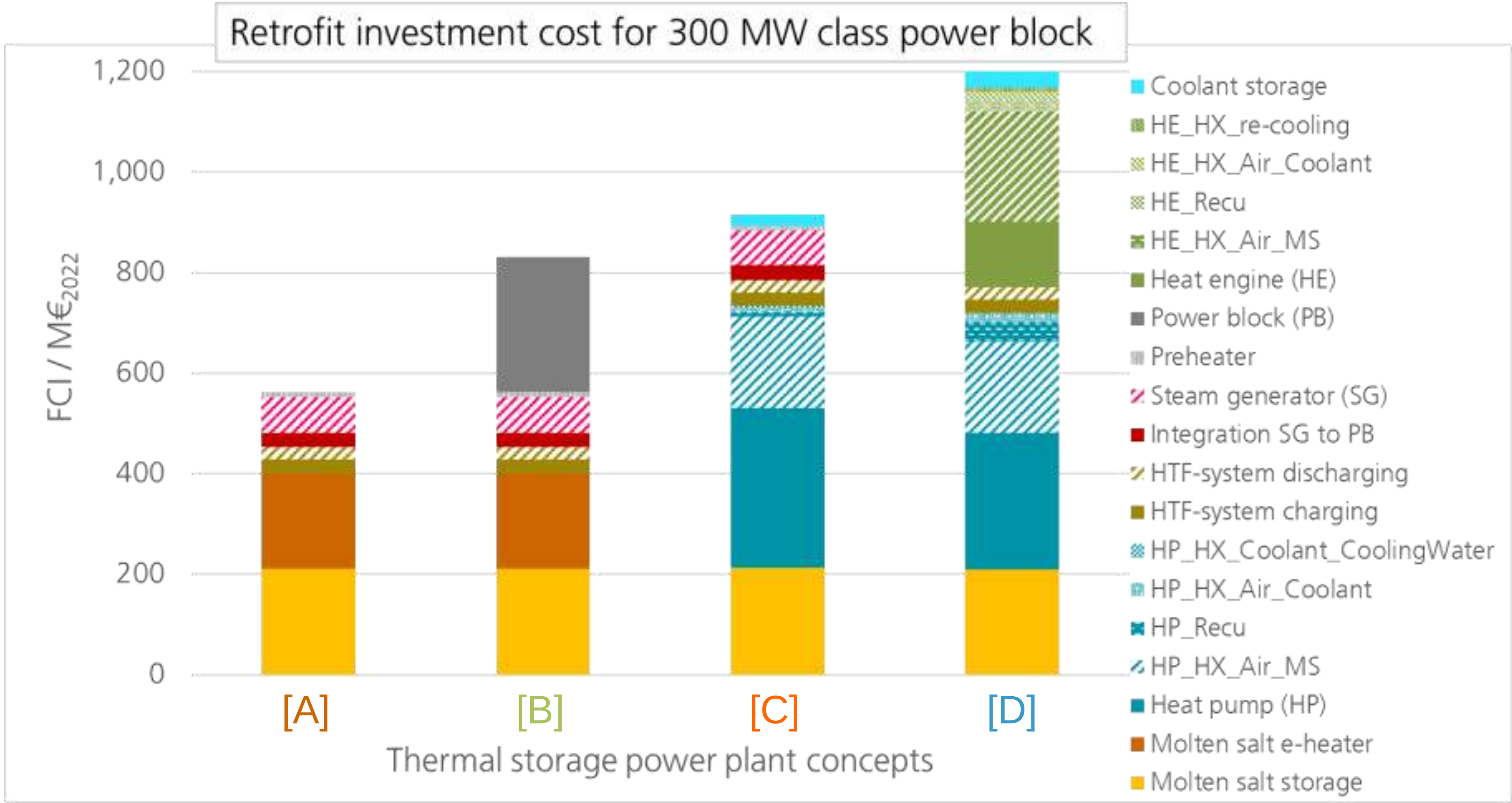
Source: DLR-project Global Coal Atlas

Thermal storage power plant (TSPP)
[D] HT-HP with Brayton cycle



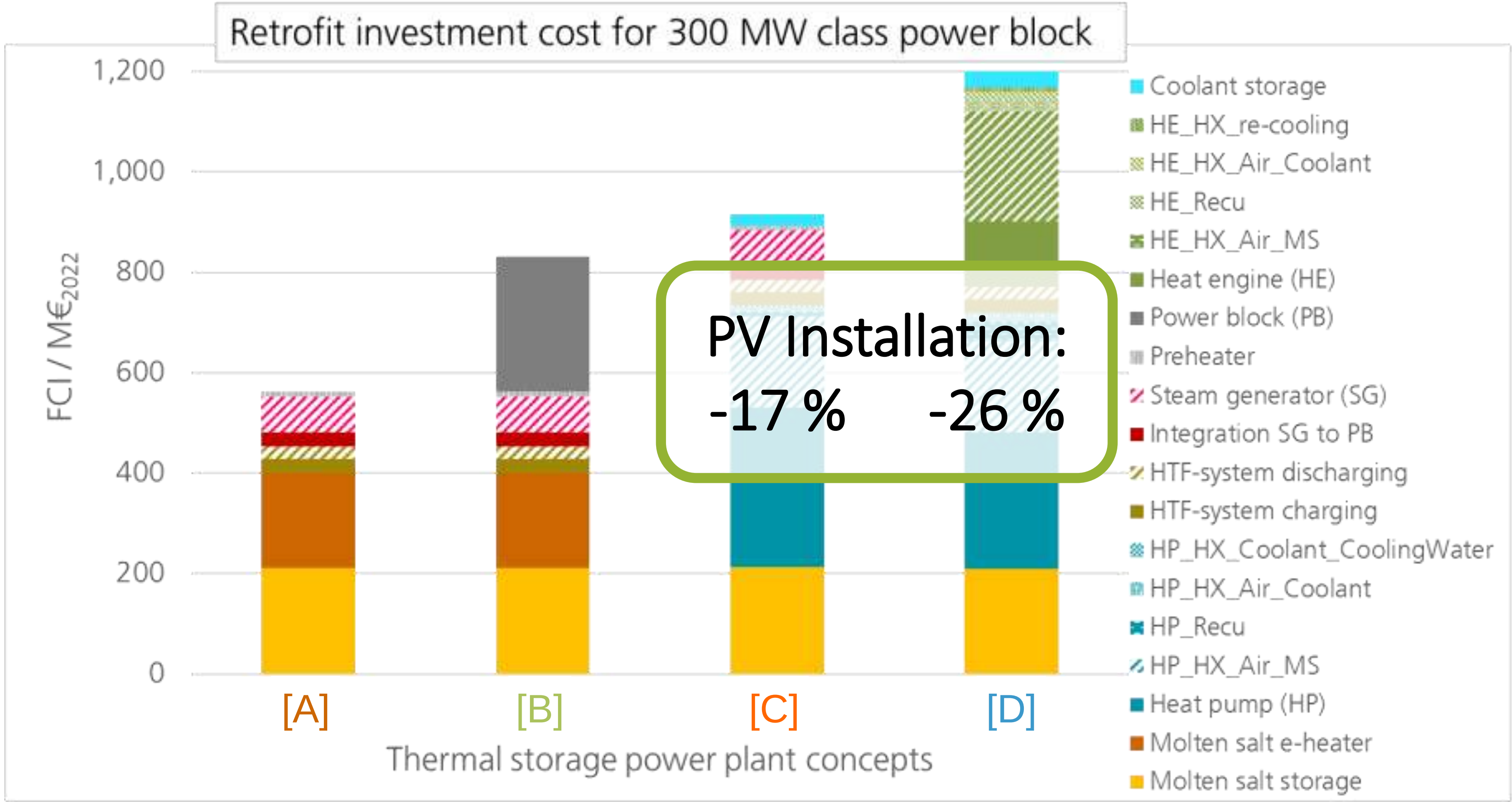
Source: DLR-project Global Coal Atlas

Example Coal Power plant
Thermal storage power plant (TSPP)



- Retrofit / new built cost: 400 – 900 M€ / 800 – 1.200 M€ for 300 MW block
- CO_2 abatement cost: 150 – 200 €/t_{CO2}

Example Coal Power plant
Thermal storage power plant (TSPP)

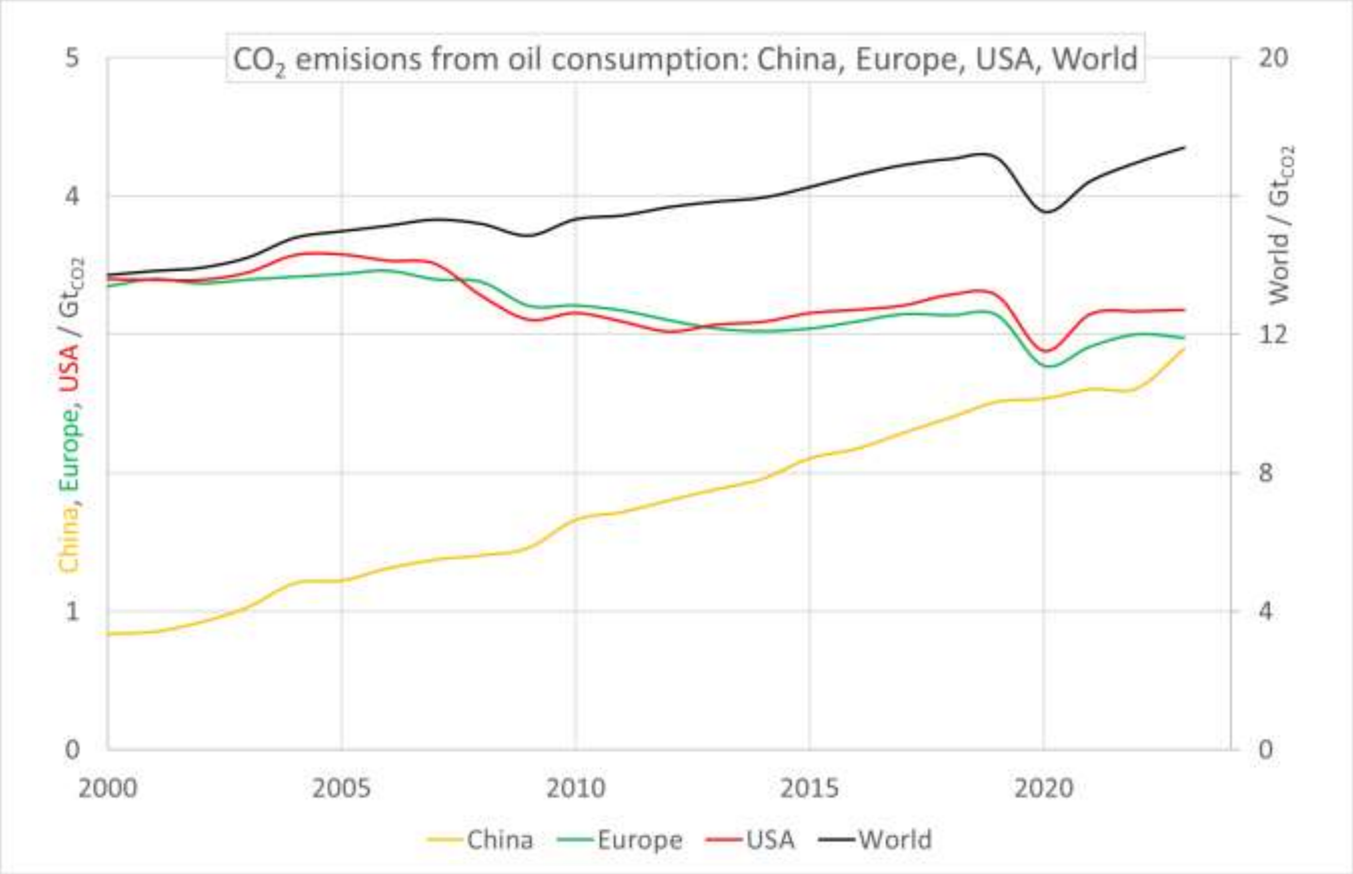


- Retrofit / new built cost: 400 – 900 M€ / 800 – 1.200 M€ for 300 MW block
- CO_2 abatement cost: 150 – 200 €/t_{CO2}

DECARBONIZATION OF TRANSPORT

Oil consumption: Refineries

- Global oil consumption 2023: 54.6 GWh [1]
  - annual growth: +1.34 GWh, 2/3 in China
  - Steady increase of consumption, no sign of mitigation

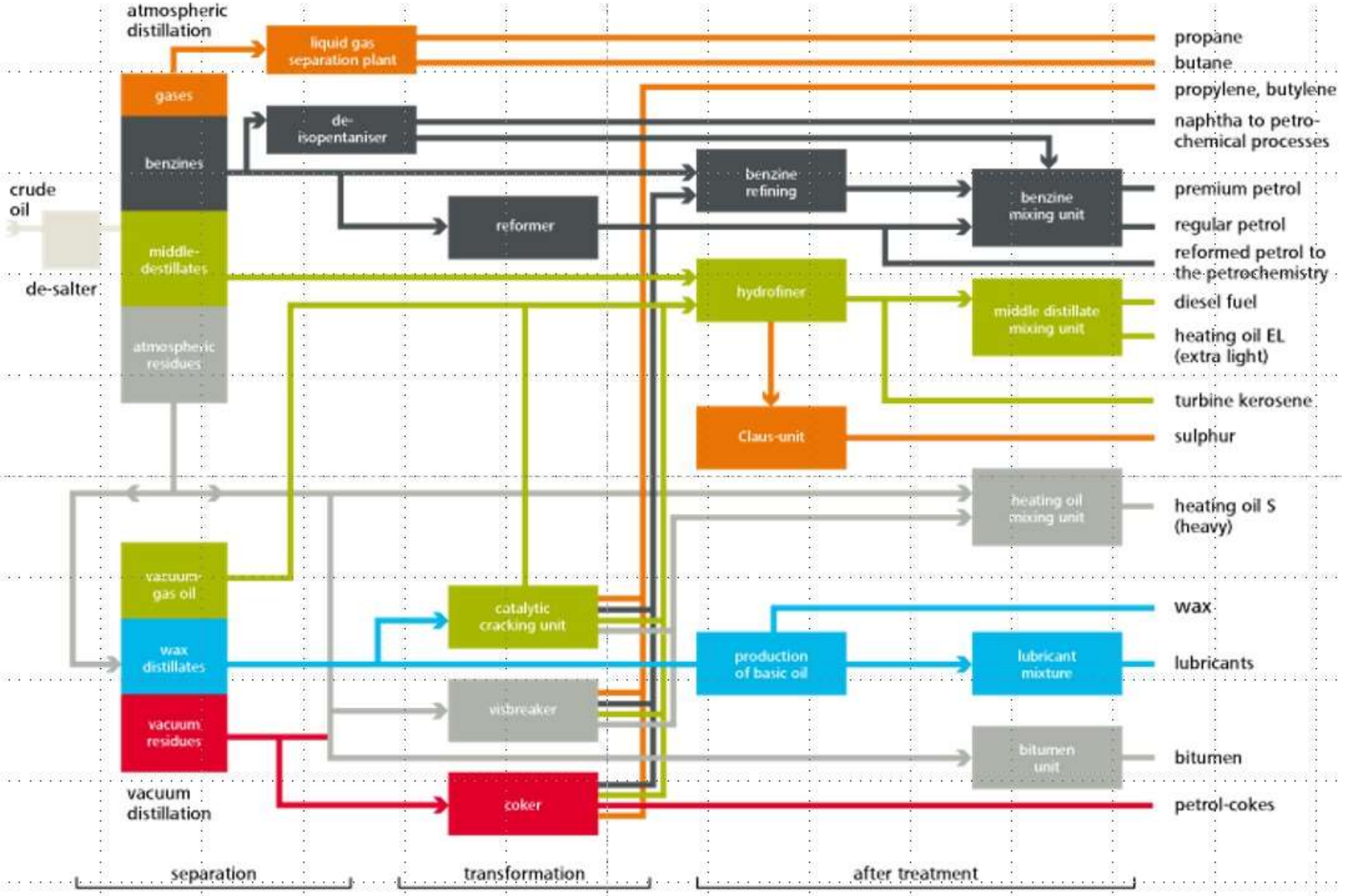


- Emissions: 17.4 Gt_{CO2}/a
- Reduction to ZERO according to COP28?

[1] Oil consumption in TWh from: https://ourworldindata.org/grapher/oil-consumption-by-country, 1 TWh crude oil = 0.319 Mt CO_2

Decarbonization of refineries

Transition towards sustainability



Source: MiRO "Vom Tanker zur Tankstelle" http://miro-ka.de/german/contact/P_PP.pps

Decarbonization of refineries
Transition towards sustainability

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New feedstocks

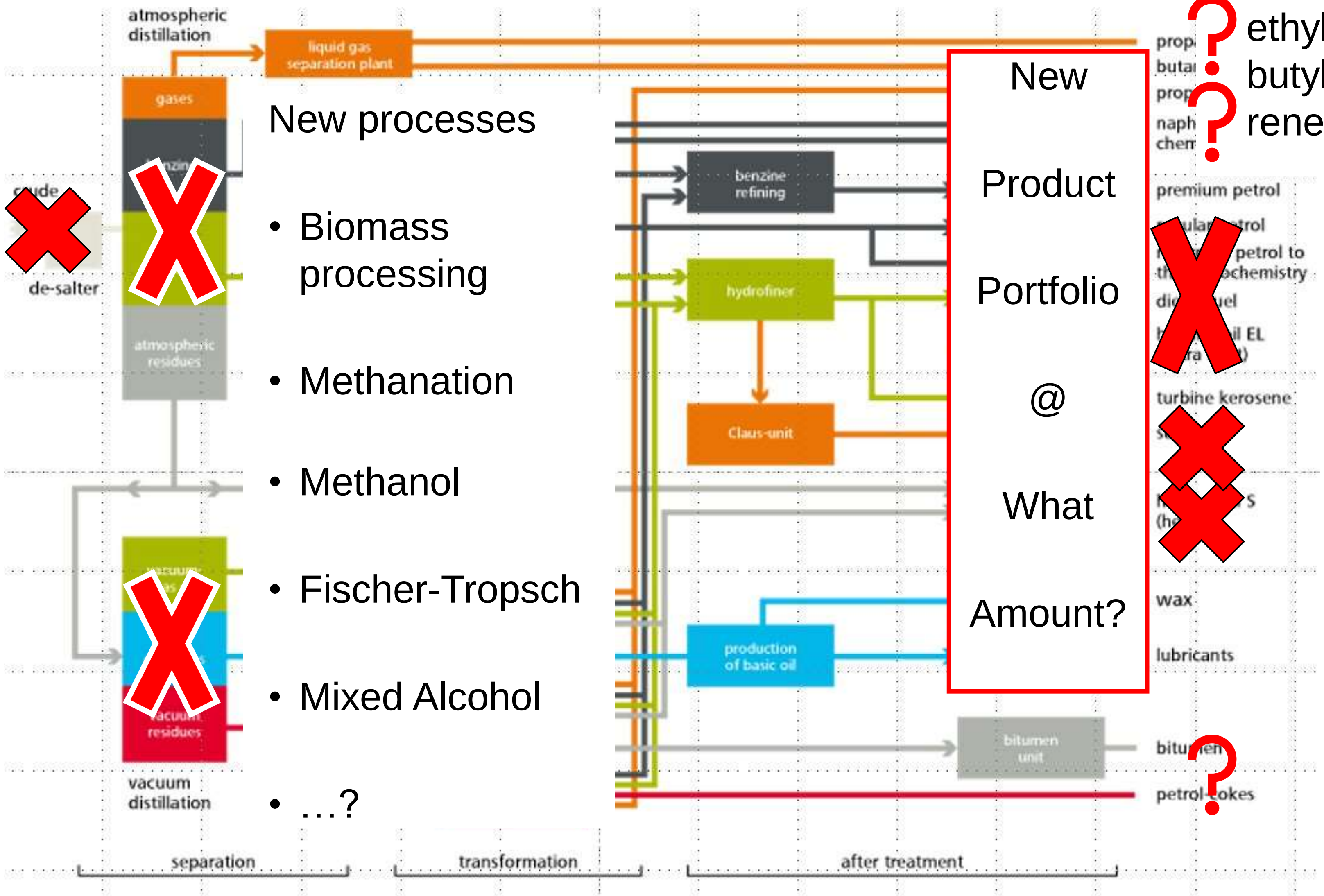
- Sustainable Carbon
  - Biomass
  - Direct Air Capture
  - (Industrial CO_2)
- Sustainable Hydrogen
  - Biomass
  - RE electrolysis

New processes

- Biomass processing
- Methanation
- Methanol
- Fischer-Tropsch
- Mixed Alcohol
- …?

New Product Portfolio @ What Amount?

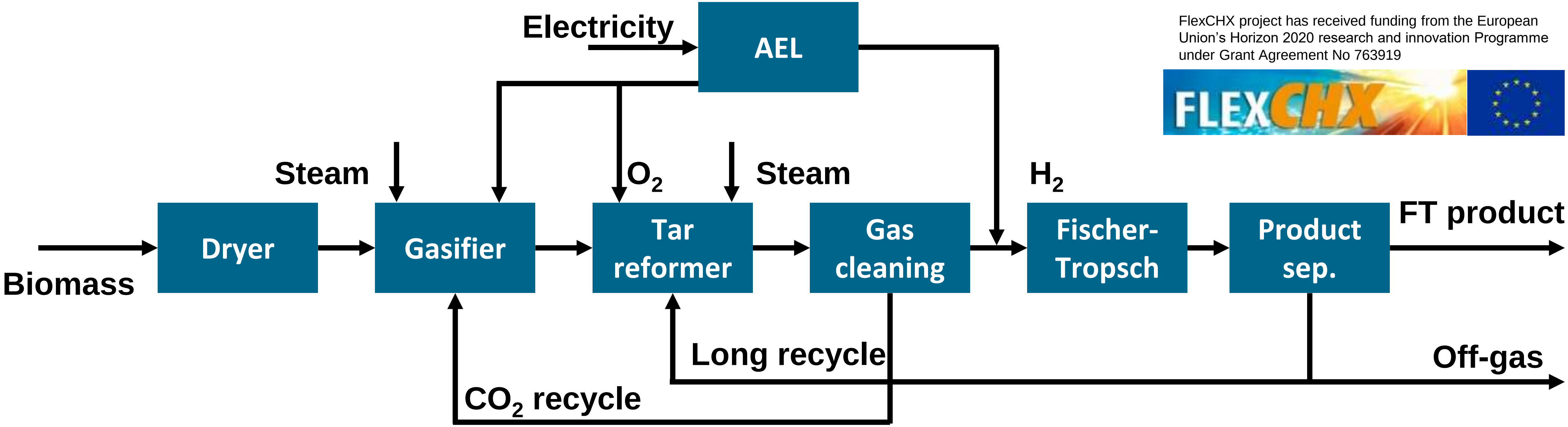
ethylene, propylene, butylene from renewables?



Source: MiRO "Vom Tanker zur Tankstelle" http://miro-ka.de/german/contact/P_PP.pps

Example aviation
Sustainable Aviation Fuels (SAF)

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



Process details:

- Plant size: 50, 200 and 400 MW_{th}
- Experimentally validated gasifier and reformer model (literature/project data)[1,2]
- AEL electrolyzer – most mature electrolysis technology [3]
- Fischer-Tropsch: Slurry bubble column reactor [4]
- Fischer-Tropsch product C_{5+} to be converted in to SAF in central refinery

[1] Hannula, I. (2016). Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. *Energy*, *104*, 199-212.
[2] Kurkela, E., Kurkela, M., & Hiltunen, I. (2021). Pilot-scale development of pressurized fixed-bed gasification for synthesis gas production from biomass residues. *Biomass Conversion and Biorefinery*, 1-22.
[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.
[4] Todic, B., Bhatelia, T., Froment, G. F., Ma, W., Jacobs, G., Davis, B. H., & Bukur, D. B. (2013). Kinetic model of Fischer–Tropsch synthesis in a slurry reactor on Co–Re/Al2O3 catalyst. *Industrial & Engineering Chemistry Research*, *52*(2), 669-679.

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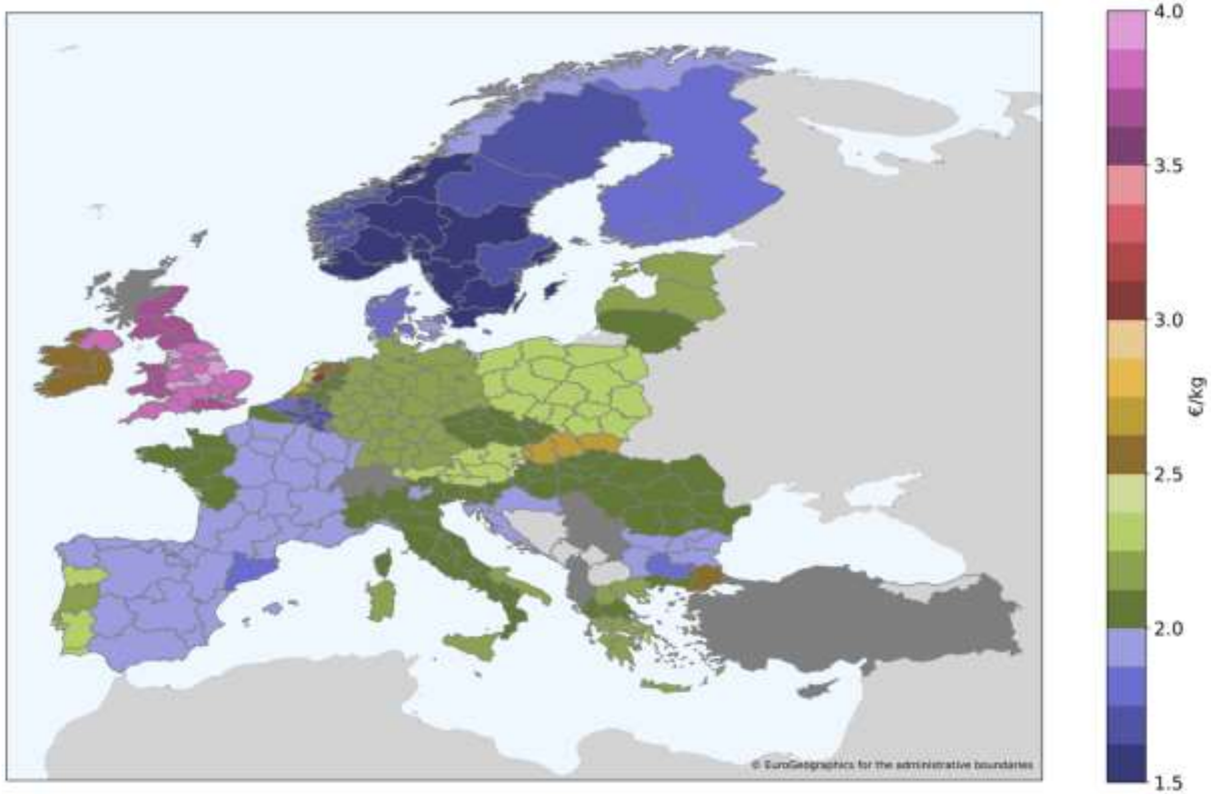
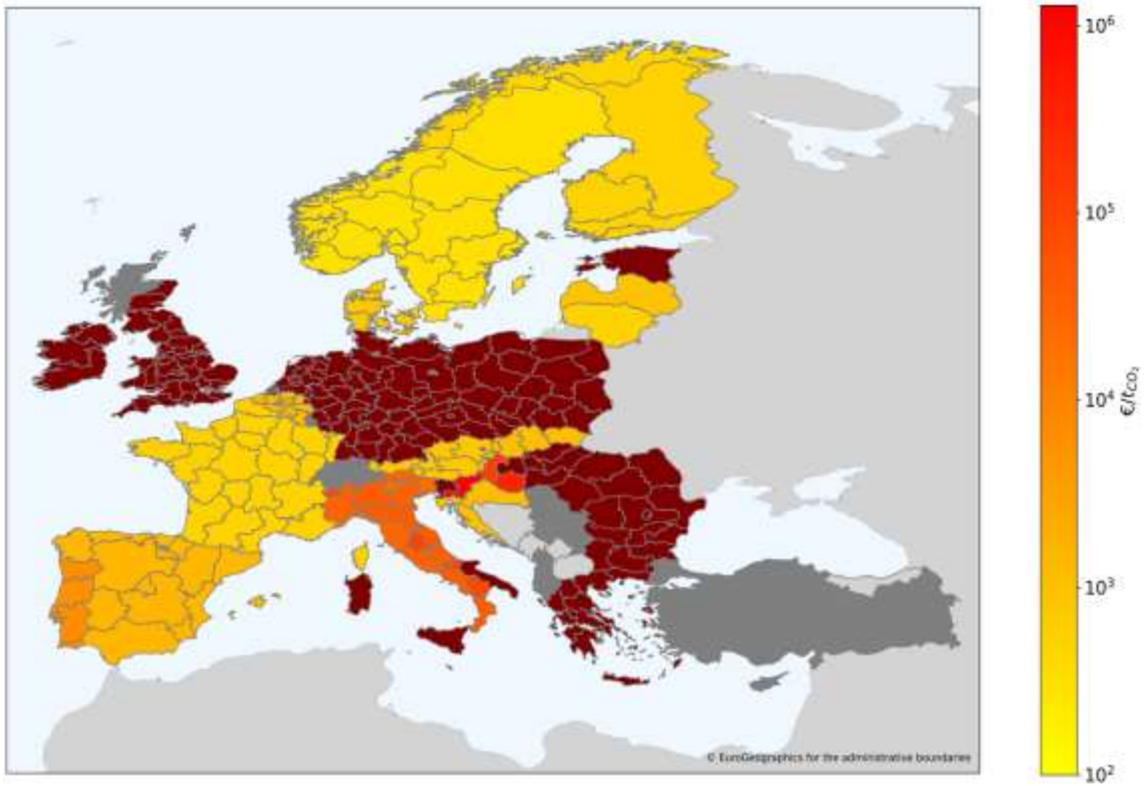
Grid connected PBtL:
Northern Europe preferred

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



GHG Abatement cost of SAF [$€_{2020}/t_{CO2,eq}$]:



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

DECARBONIZATION OF INDUSTRY

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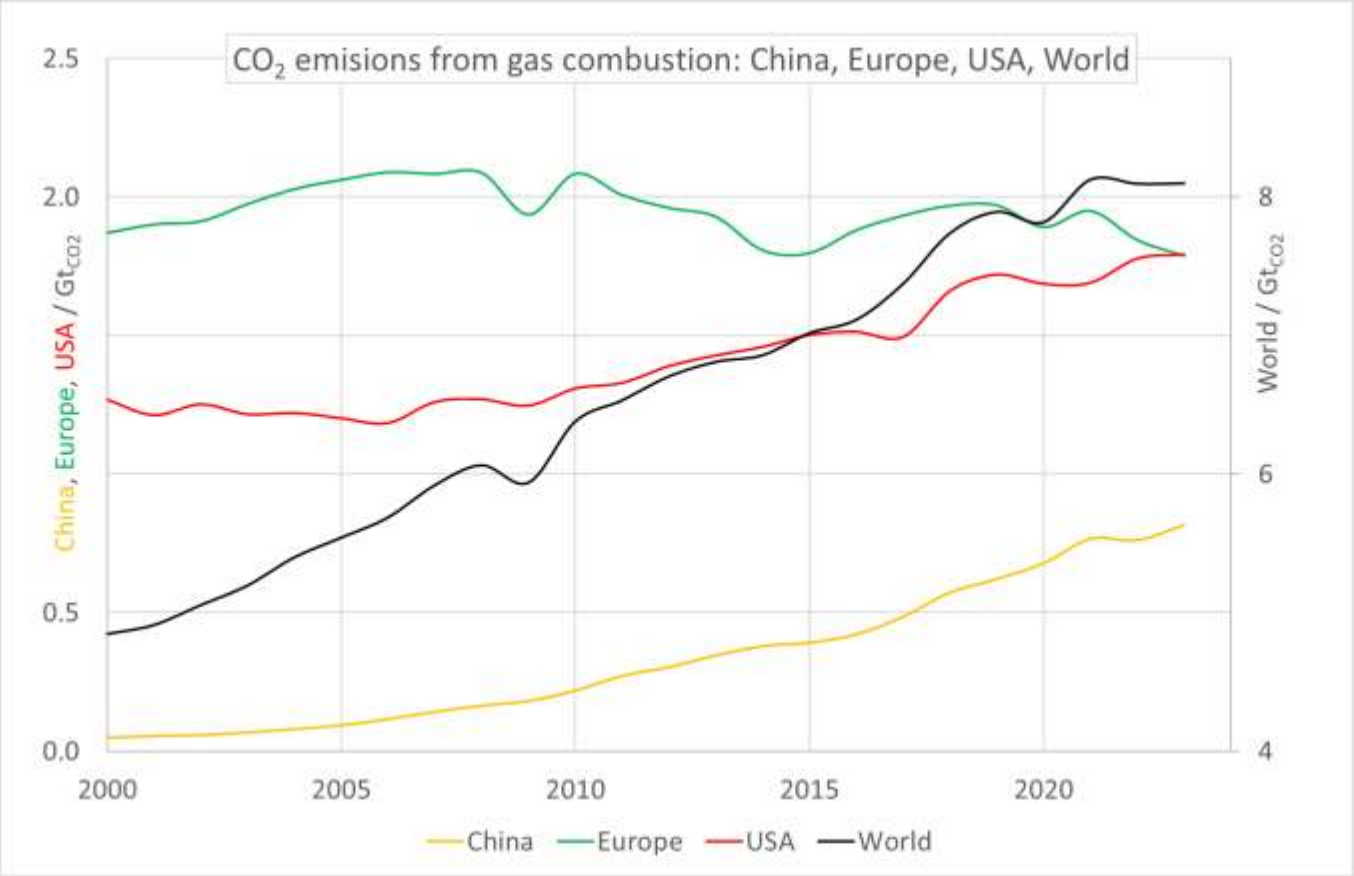
Natural gas consumption

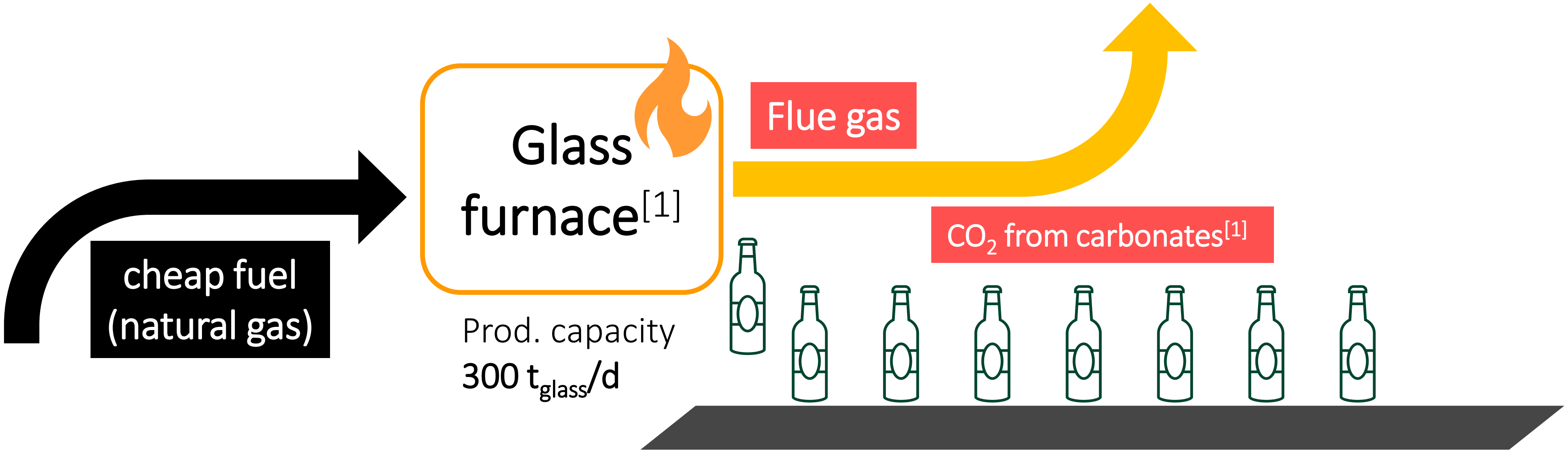
- Global gas consumption 2023: 40.1 GWh [1]
  - annual growth: +0.5 GWh, gradual rebalancing after 2022 gas price shock [2]
  - "expected to see solid growth in 2024" [3], no sign of mitigation



- Emissions: 8.1 Gt_{CO2}/a (+ leakage along supply chain!)
- Reduction to ZERO according to COP28?

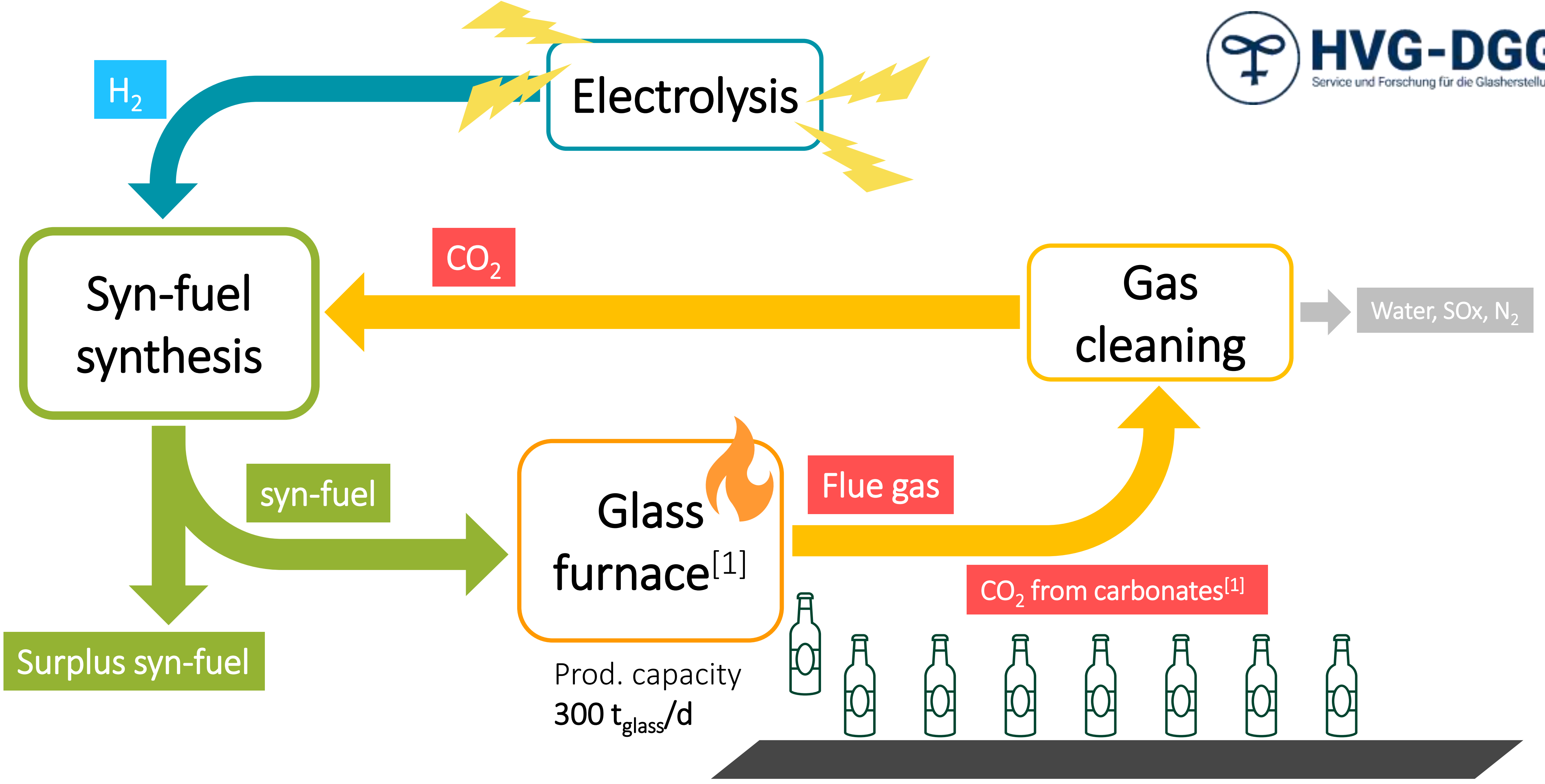
[1] Gas consumption in TWh from https://ourworldindata.org/grapher/gas-consumption-by-country, 1 TWh natural gas = 0.319 Mt CO_2
[2] IEA (2022) https://www.iea.org/reports/gas-market-report-q1-2024
[3] Keisuke Sadamori, IEA Director of Energy Markets and Security, https://www.iea.org/news/global-gas-demand-set-for-stronger-growth-in-2024-despite-heightened-geopolitical-uncertainty,

Example glass furnace
Fossil based container glass production



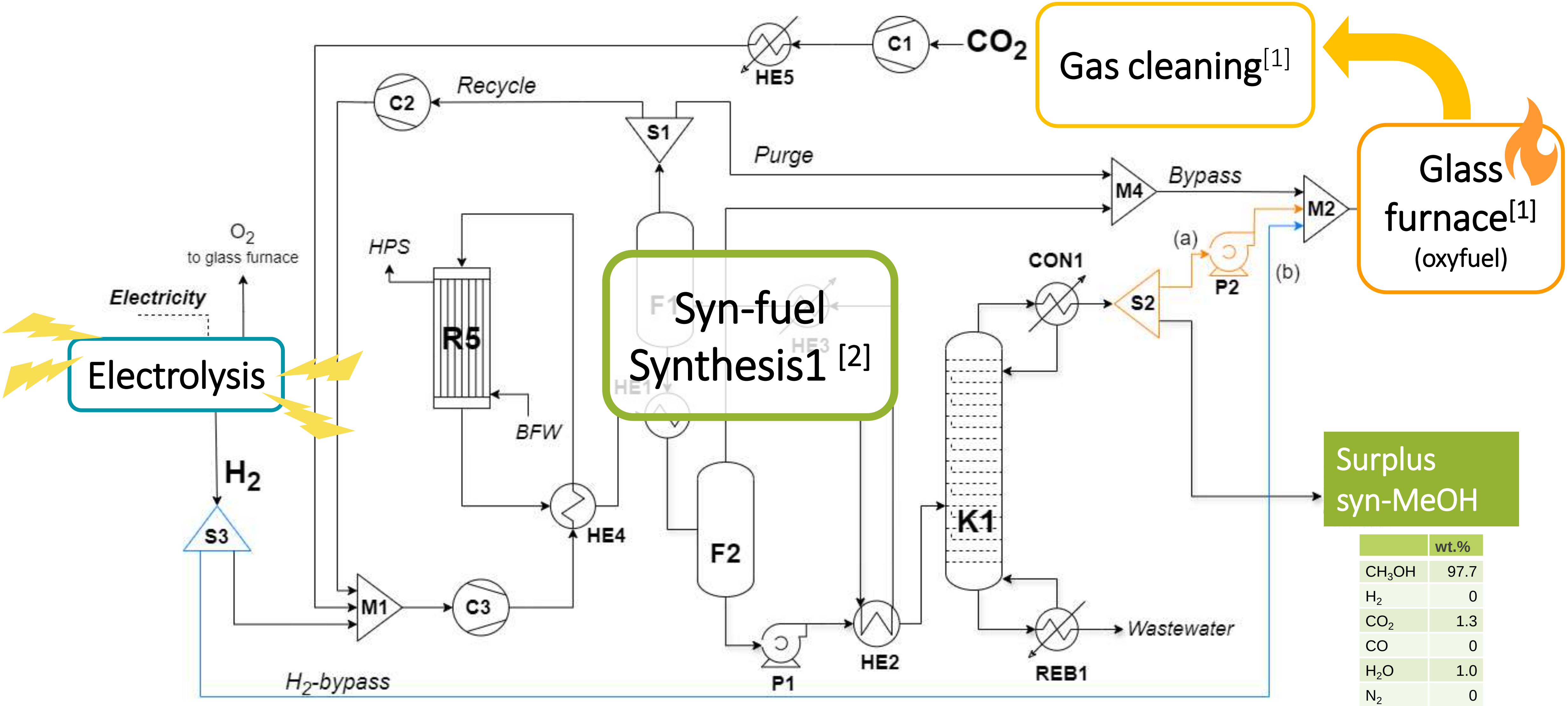
Example glass furnace

CO_2-free glass production [1]



[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production, https://ustv-dgg-2023.sciencesconf.org/44970

Example glass furnace
CCU for e-MeOH production

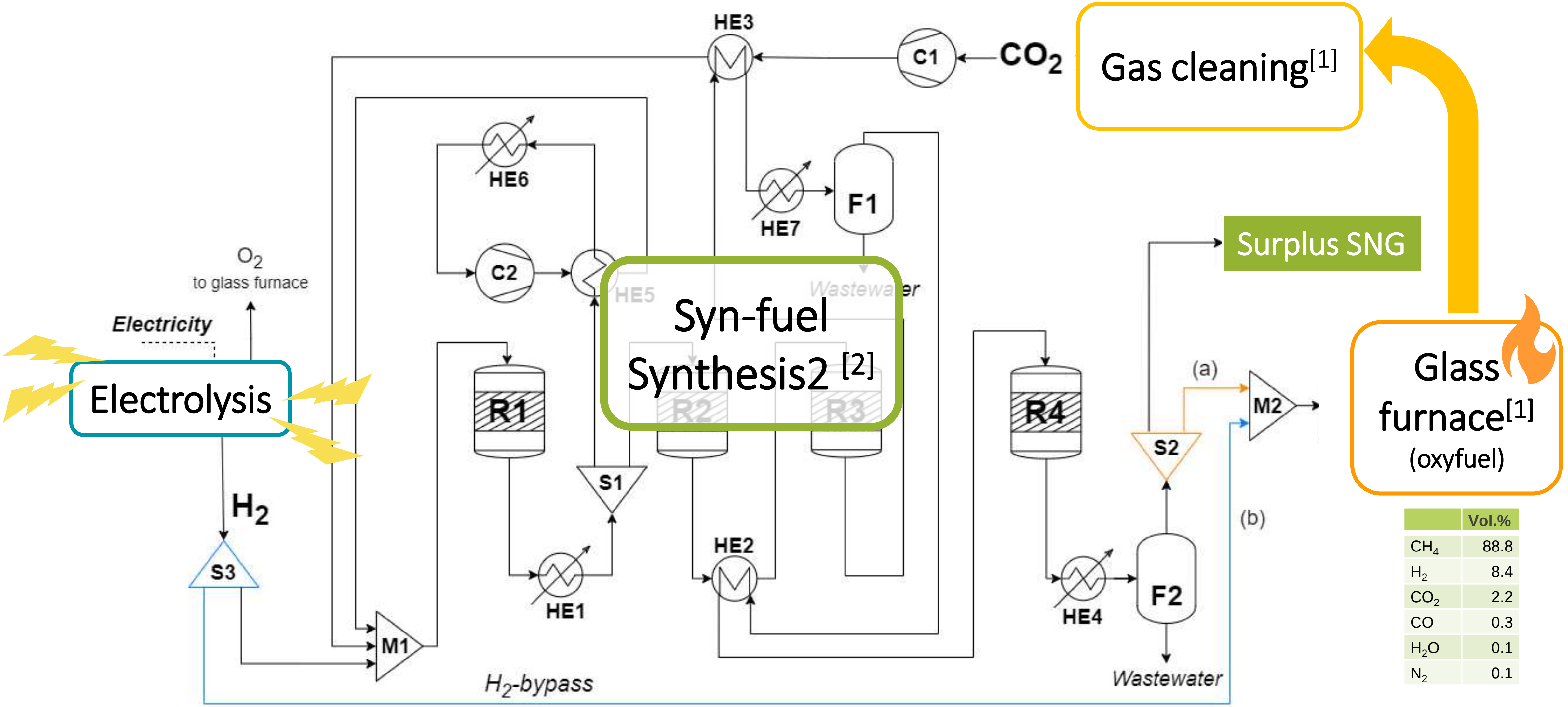


	wt.%
CH_3OH	97.7
H_2	0
CO_2	1.3
CO	0
H_2O	1.0
N_2	0

[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.
[2] Rahmat et al. (2023) Techno-economic and exergy analysis of e-MeOH production https://doi.org/10.1016/j.apenergy.2023.121738

Decarbonization of basic industry

CCU for SNG production



	Vol.%
CH_4	88.8
H_2	8.4
CO_2	2.2
CO	0.3
H_2O	0.1
N_2	0.1

[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.
[2] Rahmat et al.(2024) Sustainable glass production through Power-to-X concepts (syn-methane, syn-methanol, and direct H2 combustion) – a comparative techno-economic assessment. To be submitted

Decarbonization of basic industry
Example: CO_2-free glass production [1]

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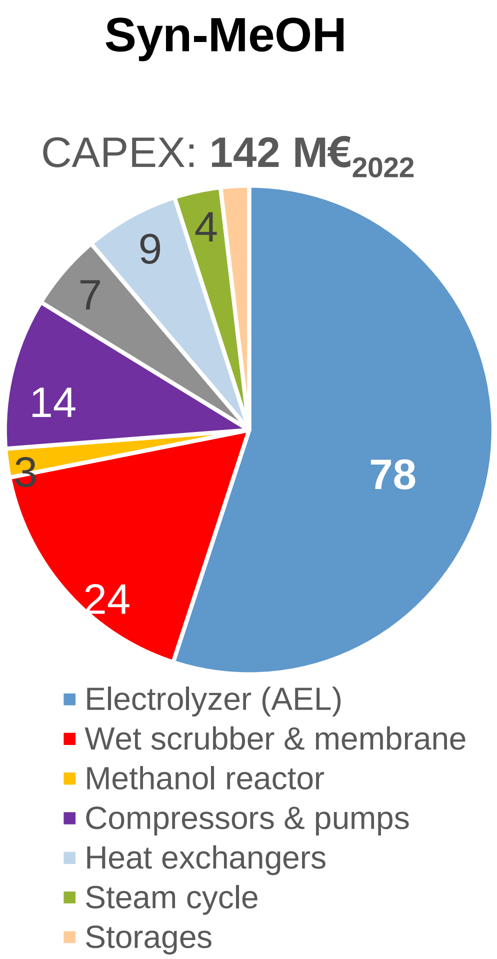
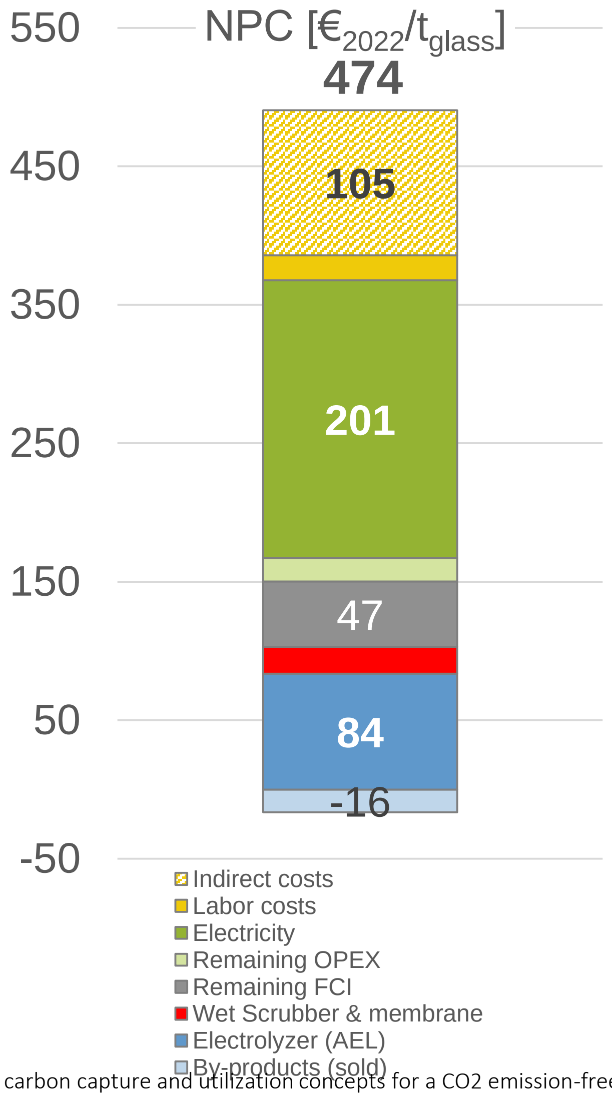
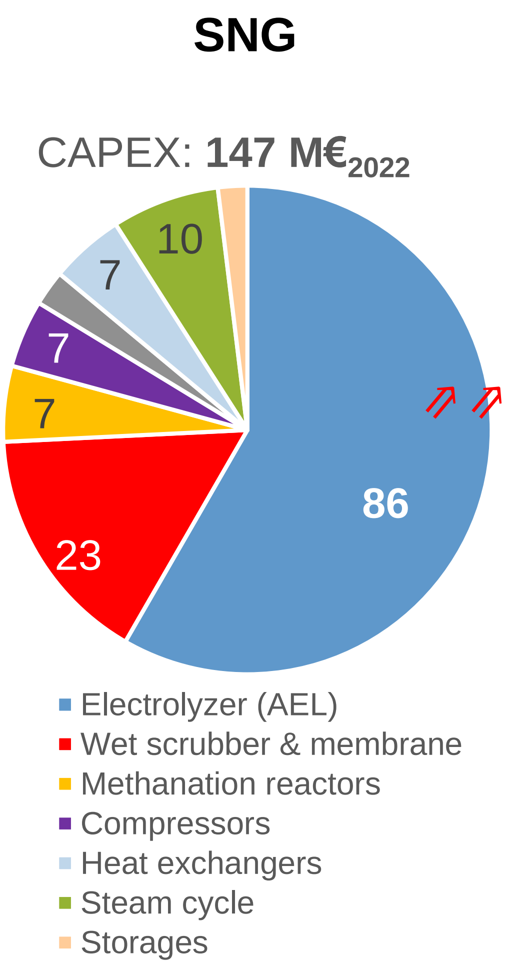
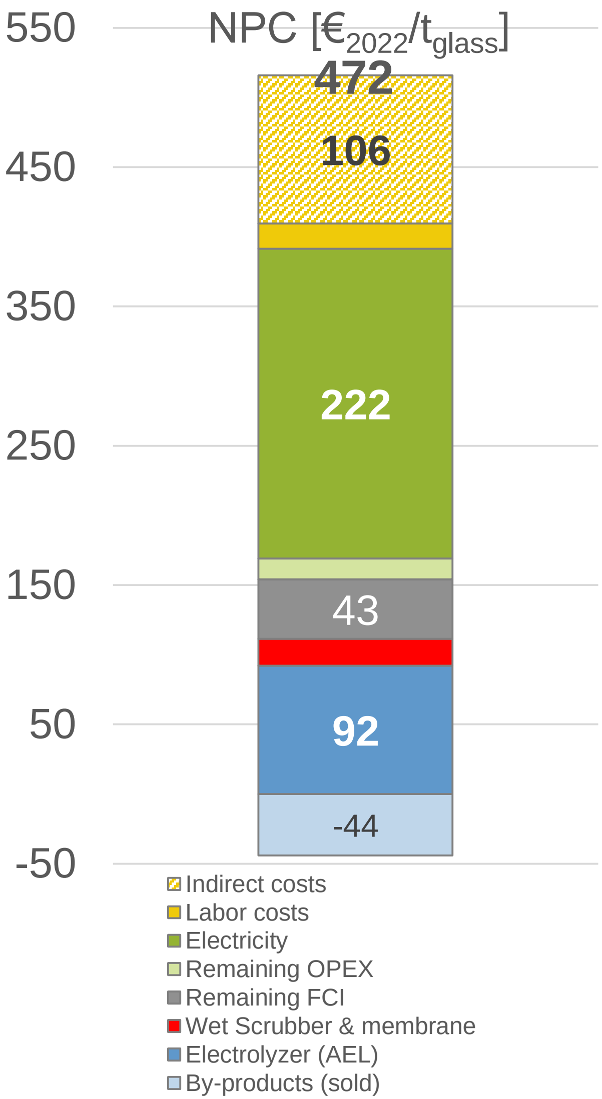
Synthetic fuels from oxyfuel offgas CCU: DE, 2022, 300 t/d container glass









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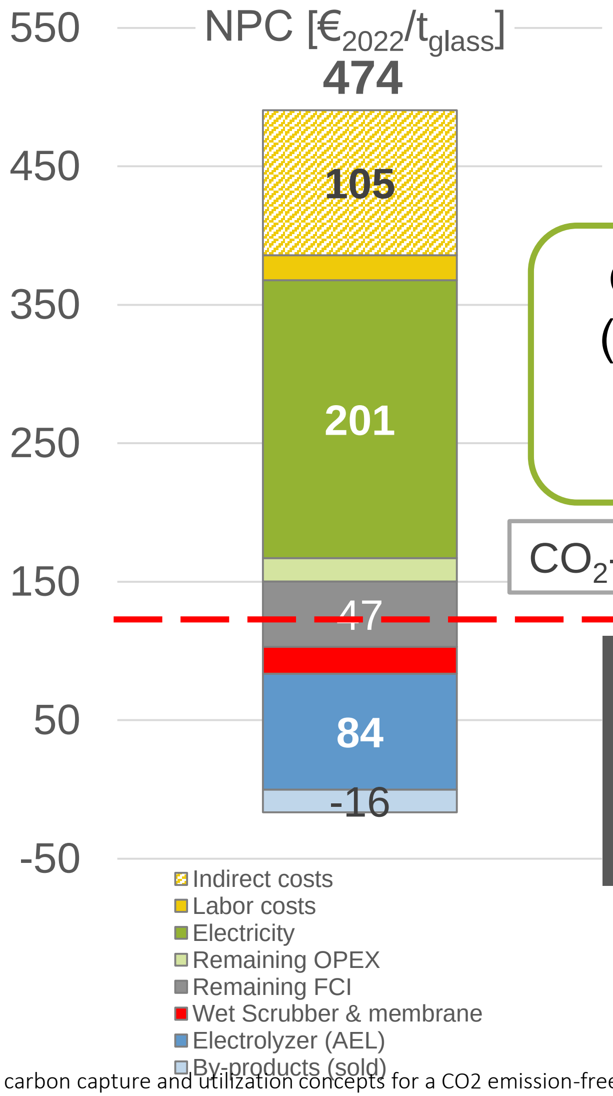
Decarbonization of basic industry

Example: CO_2-free glass production [1]

Synthetic fuels from oxyfuel offgas CCU: DE, 2022, 300 t/d container glass

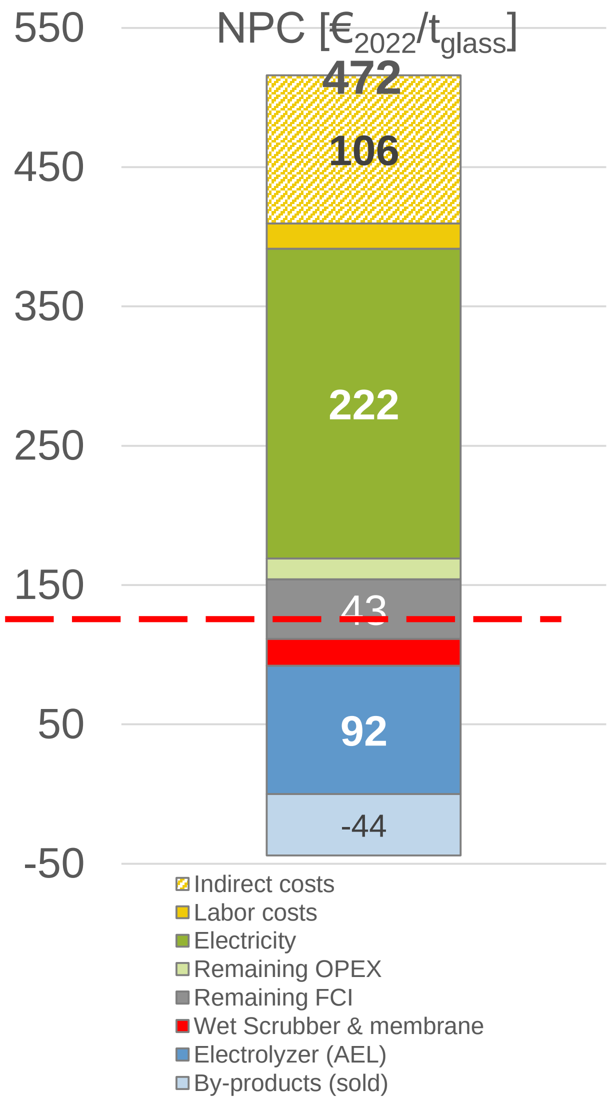


Conventional beer bottle: (330 g) ≈15 ct. $€_{2022}$/bottle

Eco-friendly beer bottle ca. **26 ct.** $€_{2022}$/bottle ⇗ ⇗

CO_2-abatement costs: **643 $€_{2022}/t_{CO2}$**

130 $€_{2022}/t_{glass}$
Natural gas
Avg. market price



[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production, https://ustv-dgg-2023.sciencesconf.org/44970

CONCLUSIONS / OUTLOOK

Outlook

- Climate change mitigation is urgent on a global scale
  - GHG emission reduction required from 35.8 Gt/a to ZERO
- Developed countries need to provide technical solutions, international regulations need to ensure its commercial viability
  - Europe and others can be demonstrators, large emitters have to adapt
- Techno-economical and ecological assessment can provide transparent, technology-agnostic guidance
  - Choosing preferred technologies and locations
  - R&D demand and optimization potential
  - Purposeful regulation
- DLR standardized methodology is applicable for any decarbonization measure globally ➔

Partner search towards Decarbonization

DLR

Looking for research / development / demonstration / deployment partner

- Fuel consumer on the way to sustainable transport
  - Explore new fuels and its impact on your environmental footprint and costs
- Energy / fuel / chemicals supplier with pressure to become sustainable
  - Explore the integration of renewables into your production scheme
  - Find heatpump/electrolyzer applications that optimally fits into your production scheme
- Technology supplier for fuels and chemicals
  - Explore new process routes that include renewable feedstocks
- Technology developer for sustainable products
  - Search for the economic and ecological optimal production
  - Quantify opportunities for improvement, localize bottlenecks
  - Predict new processes market rollout

Wednesday, 2024/09/18, Berlin, Germany

CONFERENCE SESSION ONE
Navigating the Carbon Economy:
Challenges and Opportunities

THANK YOU FOR YOUR ATTENTION!
QUESTIONS?

Decarbonization of Industry and Transport – Two interlinked Carbon Cycles

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