Thursday, 16. October 2025
net4CO$_2$ Winter School in CCUS
Session 5. CCUS ECONOMICS

CCU FOR SUSTAINABLE INDUSTRIES – DOES IT PAY OFF?

Validated Process Models for Techno Economic and Environmental Assessment

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Janmejai Sharma, Julia Weyand
(DLR e.V., www.DLR.de/tt)

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CCU for Sustainable Industries
Agenda

1. Motivation and goals
2. Techno economic and environmental assessment
   1. Technical
   2. Economic
   3. Environmental
   4. Weighing CO_2 reduction versus cost: CO_2 abatement cost
   5. Potential use of AI for TEA and LCA
3. Technological readiness
4. Conclusion and outlook

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Motivation: Reduce CO_2 emission of energy-intensive industries

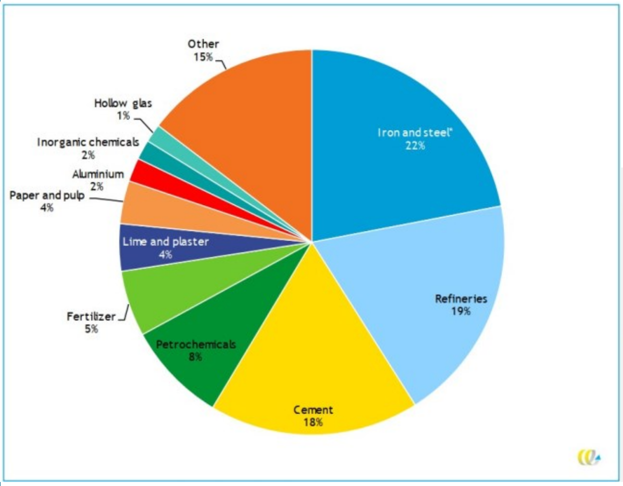

Fig. 1: Share of CO_2 emissions in the total industrial CO_2 emissions in the EU ETS in 2018
https://www.researchgate.net/publication/342707922_Energy-intensive_industries_Challenges_and_opportunities_in_energy_transition

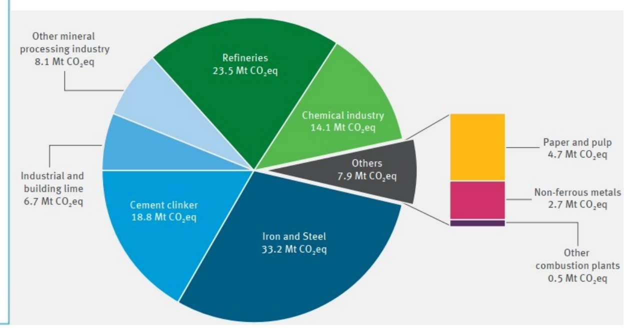

Fig. 2: Distribution of emissions in Germany among individual industrial sectors in 2022 and absolute emissions
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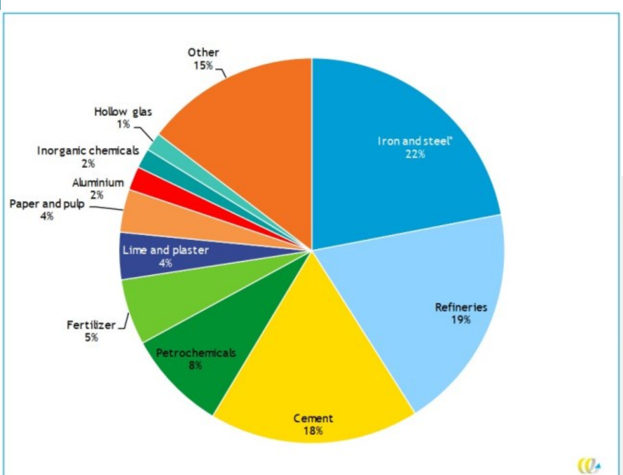

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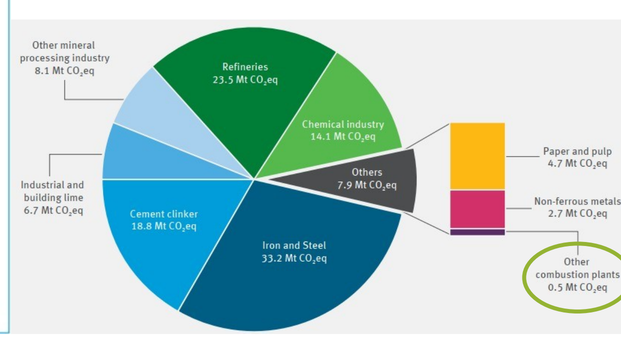
Glass industry as an example for CCU implementation



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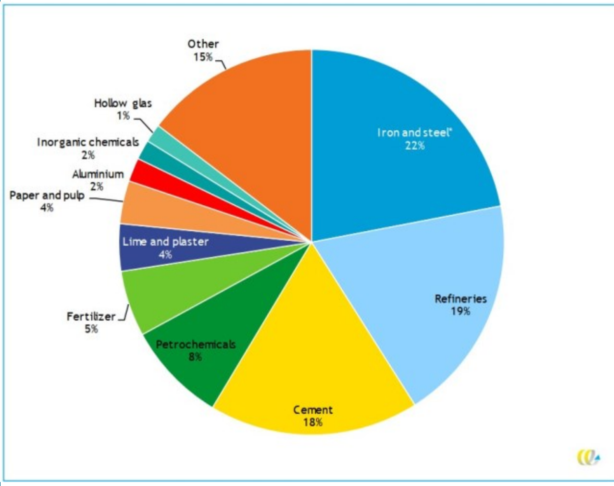

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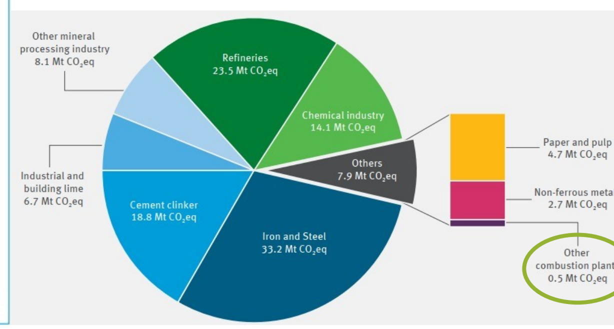
Glass industry as an example for CCU implementation

How much would an eco-friendly beer bottle cost?



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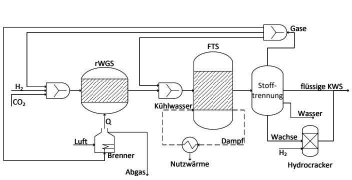
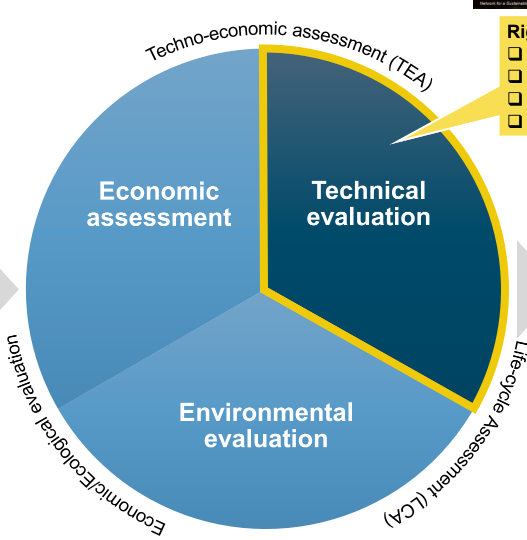
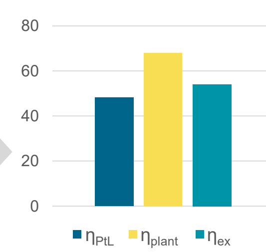
Techno-Economic (TEA) and Life Cycle Assessment LCA) @ DLR





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



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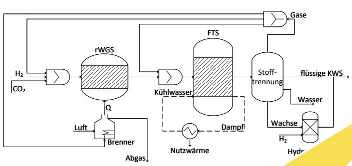
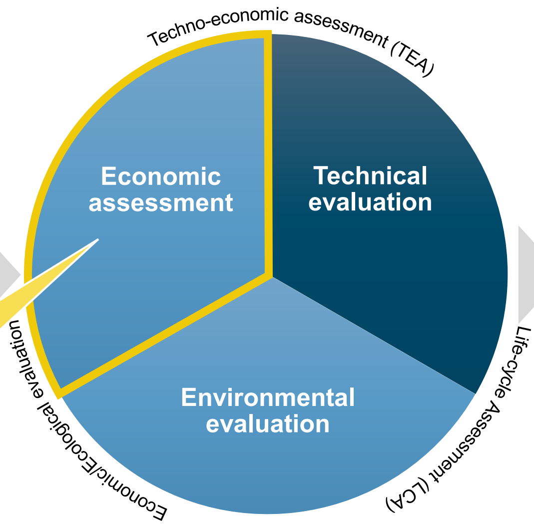
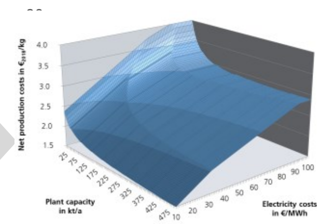
Techno-Economic and Life Cycle Assessment @ DLR







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

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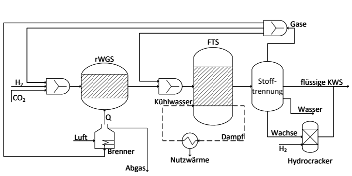

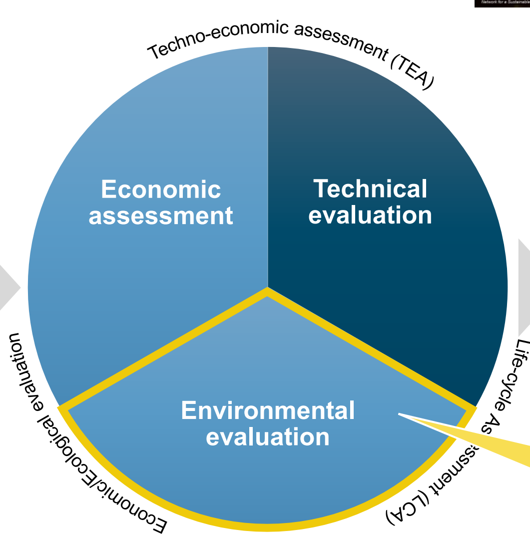

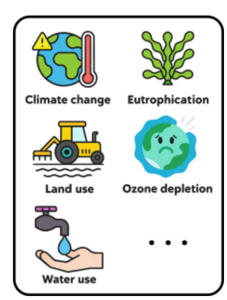

Adapted ISO 14040/14044 LCA
- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

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Techno-Economic and Life Cycle Assessment @ DLR

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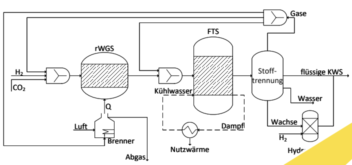

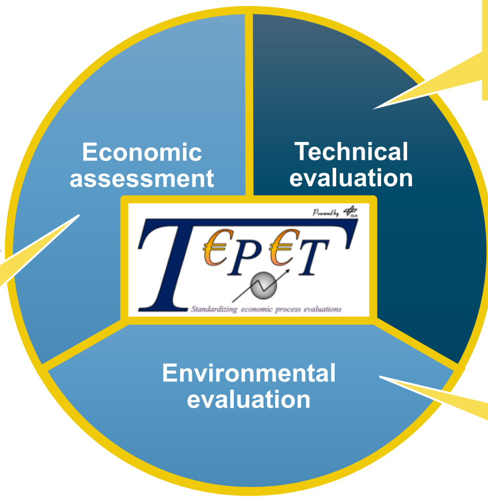

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TECHNICAL ASSESSMENT OF CCU

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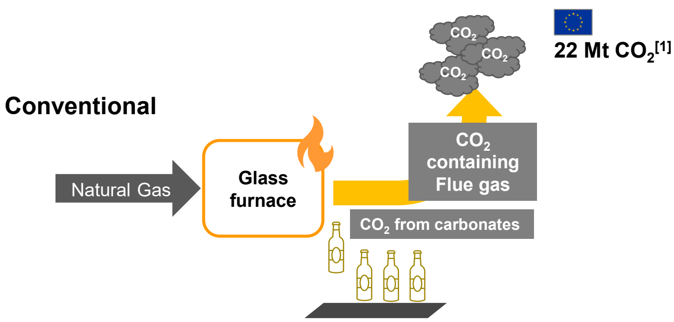
Technical Assessment Example

Challenges of Glass Industry

- Glass furnace journey (campaign): 15 years with 24/7 operation



[1] FEVE (2024) FEVE-Decarbonisation-Report-2024.pdf

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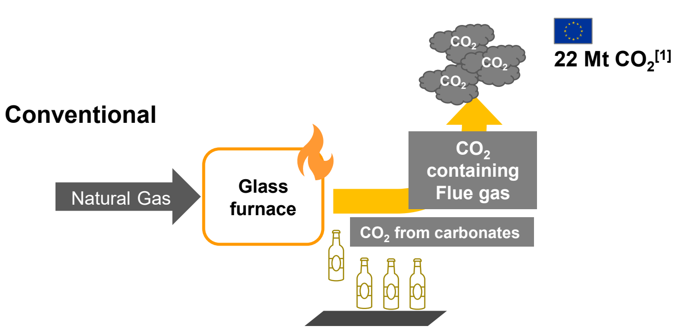
Technical Assessment Example

Challenges of Glass Industry

- Glass furnace journey (campaign): 15 years with 24/7 operation
- Different glass types / processes for various applications

Expected Growth[4] **~1 % p.a.** until 2035

Glass type	EU Production in 2023 [Mt][2,3]	Market Share[2,3]	Key Applications
Container Glass	23.1 ↗	~60 %	Bottles, jars
Flat Glass	10.4 ↗	~27 %	Construction, automotive
Glass Fiber	1.0 ↗	~2-3 %	Reinforcement, insulation
Specialty	0.9 ↗	~2-3 %	Medical, optics, household



[1] FEVE (2024) FEVE-Decarbonisation-Report-2024.pdf
[2] Glass Alliance Europe (2025) statistical-report-glass-alliance-europe.pdf
[3] Glass Fibre Europe (2023) GFE_EU-Economic-Security-Strategy-and-the-Role-of-Glass-Fibre-June-2023.pdf
[4] European Union's Glass Market to Reach 2.5M tons and $430M by 2035 - News and Statistics – IndexBox

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Technical Assessment Example
Challenges of Glass Industry

- Glass furnace journey (campaign): 15 years with 24/7 operation
- Different glass types / processes for various applications
- Dependent on the natural gas supply/import[5]

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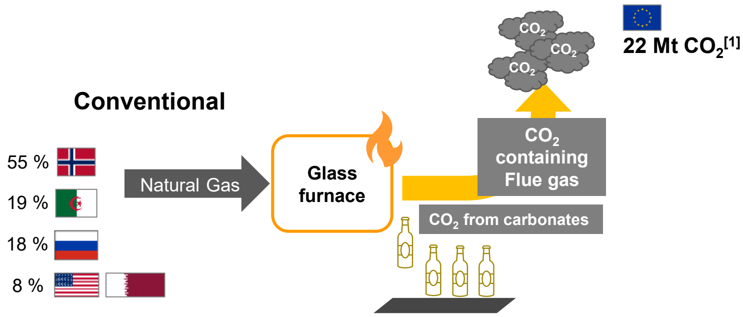

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[4] European Union's Glass Market to Reach 2.5M tons and $430M by 2035 - News and Statistics – IndexBox
[5] Institute for Energy Economics and Financial Analysis (2025) EU Gas Flows Tracker | IEEFA

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Technical Assessment Example
Challenges of Glass Industry

- Glass furnace journey (campaign): 15 years with 24/7 operation
- Different glass types / processes for various applications
- Dependent on the natural gas supply/import[5]
- CO_2-certificate / EU Emissions Trading System (ETS)[6] penalty

Expected Growth[4] **~1 % p.a.** until 2035

Glass type	EU Production in 2023 [Mt][2,3]	Market Share[2,3]	Key Applications
Container Glass	23.1 ↗	~60 %	Bottles, jars
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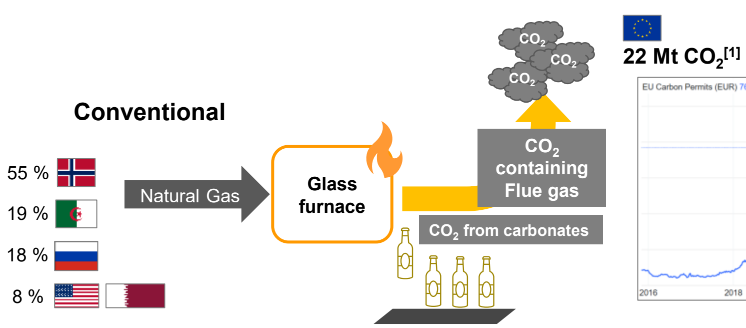

↗ ↗ ↗
149 €/t_{CO_2}
(Europe, 2030)[7]

[1] FEVE (2024) FEVE-Decarbonisation-Report-2024.pdf
[2] Glass Alliance Europe (2025) statistical-report-glass-alliance-europe.pdf
[3] Glass Fibre Europe (2023) GFE_EU-Economic-Security-Strategy-and-the-Role-of-Glass-Fibre-June-2023.pdf
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[5] Institute for Energy Economics and Financial Analysis (2025) EU Gas Flows Tracker | IEEFA
[6] EU Carbon Permits - Price - Chart - Historical Data – News
[7] Europe's New Emissions Trading System Expected to Have World's Highest Carbon Price in 2030 at €149, BloombergNEF Forecast Reveals | BloombergNEF

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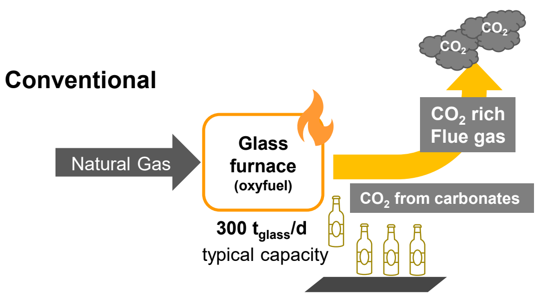
Technical Assessment Example

Glass-CCU concept[1,2]

Solution options:

- Oxyfuel furnace, **~10 %** of all glass furnaces[3]
  - Potentially **reduces 50 % glass CO_2 emissions**[3]



105 t_{CO_2}/d

[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.
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[3] Reducing the environmental footprint of glass manufacturing | glassonweb.com

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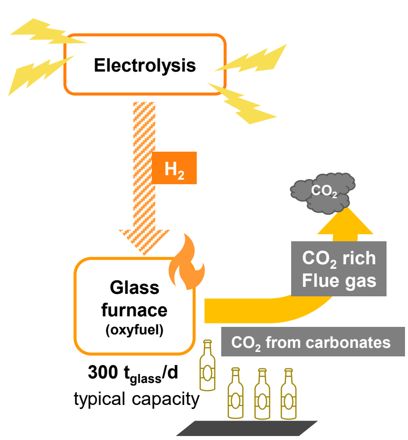
Technical Assessment Example

Glass-CCU concept[1,2]

Solution options:

- Oxyfuel furnace, **~10 %** of all glass furnaces[3]
  - Potentially **reduces 50 % glass CO_2 emissions**[3]
- Retrofitting strategies: **alternative to full electrification**
  - only 60-80 % electrification possible (hybrid)



105 t_{CO_2}/d ⟹ **25 t_{CO_2}/d**

Case	CO_2 capture	Heating fuel	Surplus
H_2 combustion	N/A	H_2	CO_2

[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.
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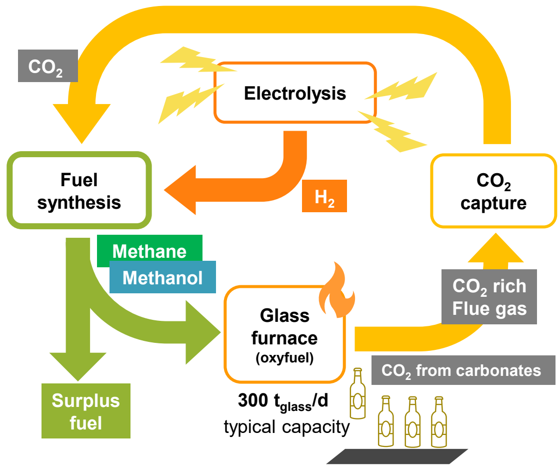
Technical Assessment Example
Glass-CCU concept[1,2]



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- Oxyfuel furnace, **~10 %** of all glass furnaces[3]
  - Potentially **reduces 50 % glass CO_2 emissions**[3]
- Retrofitting strategies: **alternative to full electrification**
  - only 60-80 % electrification possible (hybrid)
- **Valorization of unavoidable CO_2** from carbonates

105 t_{CO_2}/d ⟹ 25 t_{CO_2}/d ⟹ **0 t_{CO_2}/d**

Case	CO_2 capture	Heating fuel	Surplus
H_2 combustion	N/A	H_2	CO_2
Methane	✓	SNG	SNG
Methanol	✓	Syn-MeOH	Syn-MeOH

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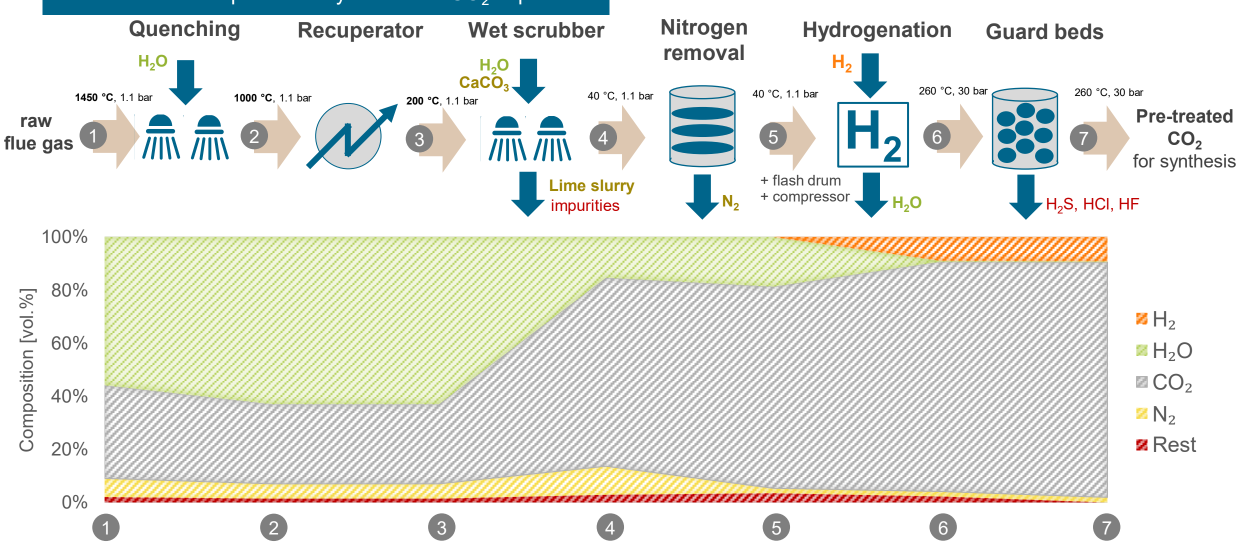
Technical Assessment Example
Glass-CCU CO_2 capture Block Flowsheet

Flowsheet to be experimentally validated: CO_2 capture



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Technical Assessment Example
Glass-CCU Methane PFD[2]

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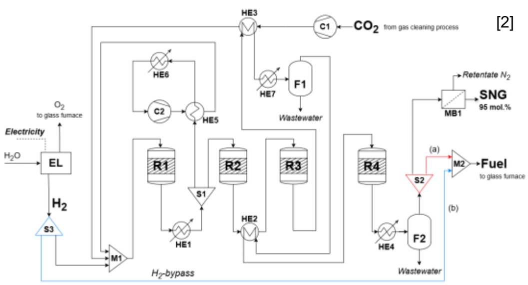
Flowsheet: Adapted TREMP™ process design[1]



AspenPlus® model[2]: RPlug

$T_{max,R1}$[4] = 700 °C

$T_{in,R1}$ = 250 °C

p[3] = 20-30 bar

GHSV[2,7] = 4,000-10,000 h^{-1}

Kinetic model: **Rönsch et al.**[4-6]

- Combination of WGS and CO-Methanation
- Catalyst[3] MCR-2X (Ni-based)

  → CO_2 pre-treatment required

[1] Topsøe, H., From coal to clean energy. 2011
[2] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
[3] Harms, H., B. Höhlein, and A. Skov, 1980, *Methanisierung kohlenmonoxidreicher Gase beim Energie-Transport.*
[4] Rönsch et al., 2016, Review on methanation – From fundamentals to current projects.
[5] Klose, J., 1984, Kinetics of the methanation of carbon monoxide on an alumina-supported nickel catalyst. Journal of Catalysis
[6] Zhang, J., et al., 2013, Kinetic investigation of carbon monoxide hydrogenation under realistic conditions of methanation of biomass derived syngas
[7] Bartholomew and Farrauto, 2006, Fundamentals of Industrial Catalytic Processes, 2nd Edition.

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Technical Assessment Example
Glass-CCU Methane PFD[2]

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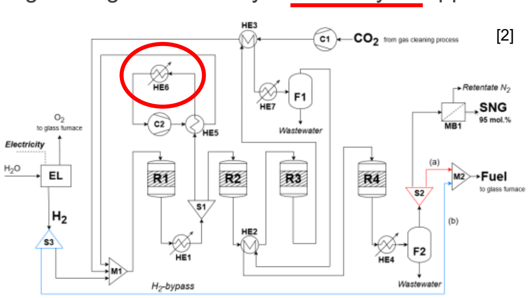
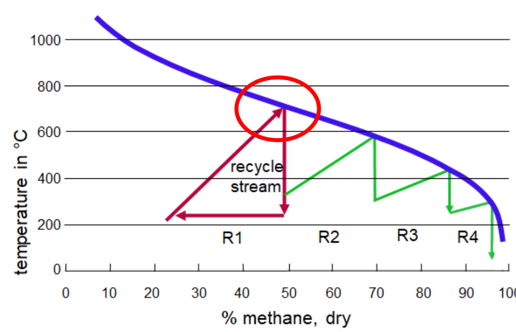
Flowsheet: Adapted TREMP™ process design[1]

high energetic efficiency & steam cycle applicable





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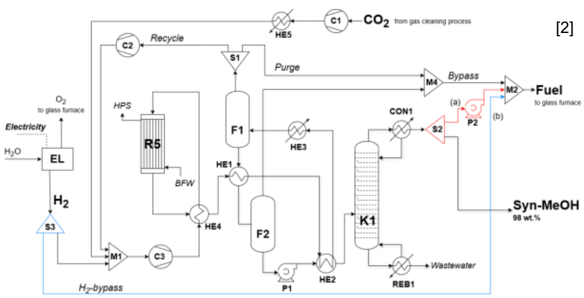
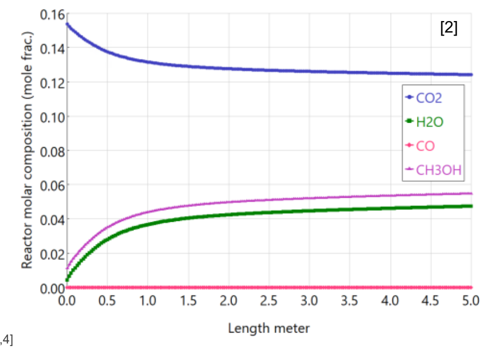
Technical Assessment Example
Glass-CCU Methanol PFD[2]

Flowsheet Lurgi process design[3]:





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$T_{max,R5}$[3,5] = 280-300 °C

$T_{in,R1}$[1,3] = 250 °C

p[1,3] = 80 bar

GHSV[4] = 10,000 h^{-1}

Kinetic model: **Vanden Bussche and Froment**[1,4]

- MeOH synthesis from $CO/CO_2/H_2$ represented as CO_2 hydrogenation & RWGS reactions
- Catalyst: $Cu/ZnO/Al_2O_3$

→ CO_2 pre-treatment required!

[1] Rahmat et al. (2023) *Techno-economic and exergy analysis of e-MeOH production under fixed operating conditions in Germany*. Applied Energy.
[2] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
[3] Metallgesellschaft AG (1996) – EP 0 790 226 B1
[4] Van-Dal and Bouallou (2013) *Design and simulation of a methanol plant plant from CO_2 hydrogenation*. Journal of Cleaner Production.
[5] Bartholomew and Farrauto (2006) *Fundamentals of Industrial Catalytic Processes*, 2. Ed.

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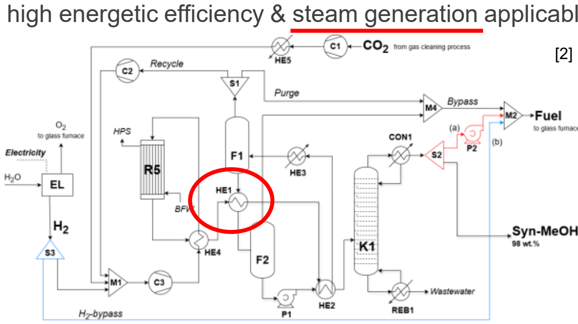
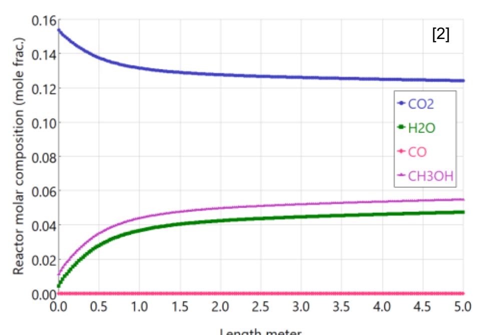
Flowsheet Lurgi process design[3]:

high energetic efficiency & steam generation applicable





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- Catalyst: $Cu/ZnO/Al_2O_3$

→ CO_2 pre-treatment required!

[1] Rahmat et al. (2023) *Techno-economic and exergy analysis of e-MeOH production under fixed operating conditions in Germany*. Applied Energy.
[2] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
[3] Metallgesellschaft AG (1996) – EP 0 790 226 B1
[4] Van-Dal and Bouallou (2013) *Design and simulation of a methanol plant plant from CO_2 hydrogenation*. Journal of Cleaner Production.
[5] Bartholomew and Farrauto (2006) *Fundamentals of Industrial Catalytic Processes*, 2. Ed.

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Technical Assessment Example
Glass-CCU Methane / Methanol

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PORTO, PORTUGAL

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Equipment Design Parameters[1]

Equipment[1-3,5]	AspenPlus® model	Parameters	Remarks
Heat exchangers	HeatX/Heater	Δp = 0.2 bar[4], $\Delta T_{approach}$ = 10 K[4]	U-values[6] method
Compressors	Compr/MCompr	Max. compression ratio = 3[4] $\eta_{isentropic}$ = 80 %[4], $\eta_{mech.}$ = 95 %	range compression ratio 2.5-4[4]
Pumps	Pump	η_{pump} = 95 %, η_{driver} = 95 %	
Flash drums	Flash2	Q = 0 kW, Δp = 0.2 bar[4]	adiabatic
Distillation columns	RadFrac	$p_{cond.}$ = 1.36 bar[1,2], $\Delta p_{col.}$ = 0.34 bar[1,2] n_{stage} = 55, reflux ratio = 1	$d_{col.} = f(\dot{V}_{gas,col.})$[7]
Alkaline Electrolyzer (AEL)	RStoic (Stack) Flash2, Sep, Pump (BoP)	$\eta_{energetic}$ = 53.3 % (LHV)[3]	simplified model
Wet scrubber (limestone)	Flash2, Sep	100 % separation of SO_2, SO_3, HCl, HF[8]	black-box
Membrane PMP	Sep	N_2 separation = 92.75 %[9]	black-box

[1] Rahmat et al. (under review). *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
[2] Rahmat et al. (2023) *Techno-economic and exergy analysis of e-MeOH production under fixed operating conditions in Germany*. Applied Energy.
[3] Sánchez et al. (2020) *Aspen Plus model of an alkaline electrolysis system for hydrogen production*. Journal of Hydrogen Energy.
[4] Woods (2007) Rules of Thumb in Engineering Practices
[5] Heimann, N. et al (under review), *Standardized techno-economic assessment of synthetic natural gas and synthetic hydrogen natural gas production for the transport sector and gas grid.* Energy Conversion and Management.
[6] VDI-Gesellschaft (2006) VDI-Wärmeatlas. 978-3-540-32218-4_13.pdf (springer.com)
[7] Towler (2008) Chemical Engineering Design
[8] Sorrels (2021) Chapter 1 – Wet and Dry Scrubbers for Acid Gas Control. www.epa.gov
[9] Samei and Raisi (2022) Separation of nitrogen from methane by multi-stage membrane

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Technical Assessment Example
Glass-CCU Methane / Methanol heat integration

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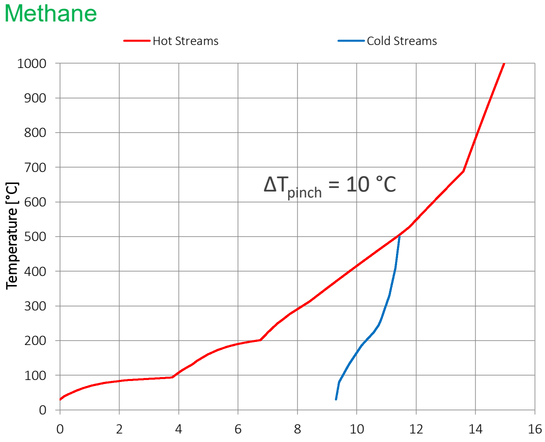
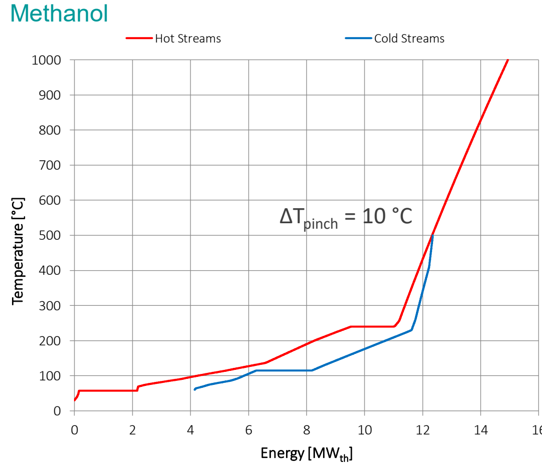
Pinch Analysis using TePeT

Methane



Methanol



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Technical Assessment Example

Glass-CCU Methane / Methanol heat integration

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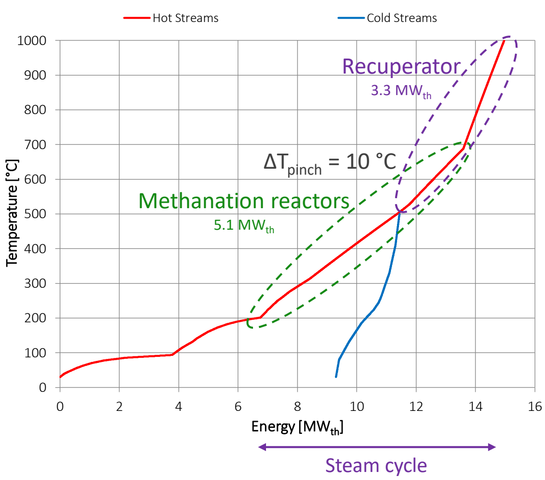
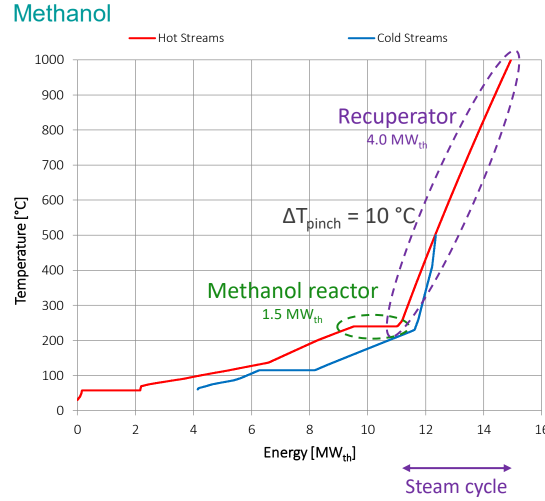
Pinch Analysis using TEPET

Methane



Methanol



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Technical Assessment Example

Glass-CCU Methane / Methanol heat integration

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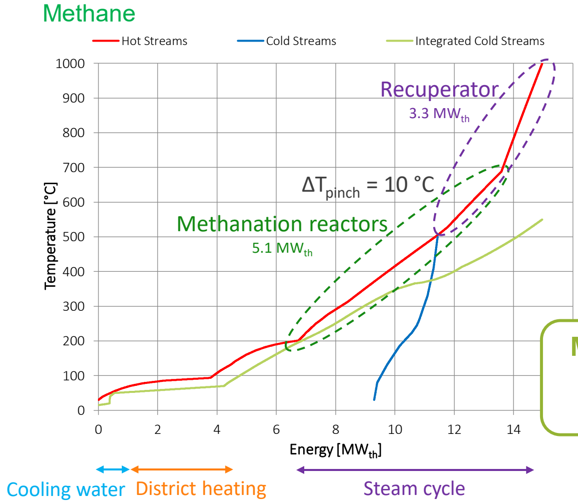
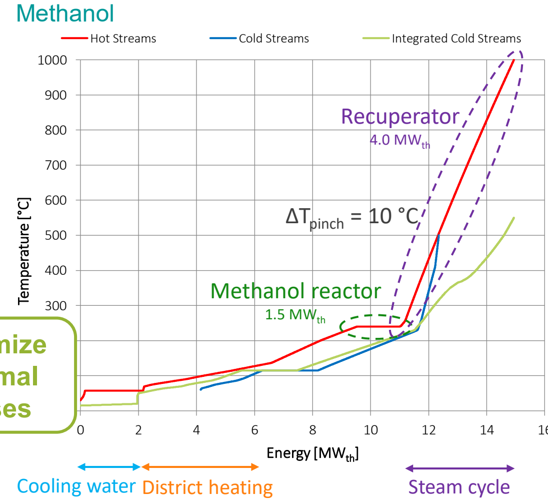
Pinch Analysis using TEPET

Methane



Minimize thermal losses

Methanol



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Technical Assessment
Methodology

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- Definition of KPIs such as:

$$\eta_{C} = \frac{\dot{n}_{C,fuel}}{\dot{n}_{C,feedstock}} \qquad \eta_{HtF} = \frac{\dot{m}_{fuel} \cdot LHV_{fuel}}{\dot{m}_{H_2} \cdot LHV_{H_2}} \qquad \eta_{PtF} = \frac{\dot{m}_{fuel} \cdot LHV_{fuel}}{P_{electrolysis} + P_{pumps} + P_{compressors} - P_{heat\ integration}}$$

- Rigorous steady-state process simulation + validation
  - Experimentally validated process models of most processes from research projects available
  - Adaptable to any new configuration / feedstock / …

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Technical Assessment
Methodology

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OCTOBER 13-16, 2025
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- Rigorous steady-state process simulation + validation
  - Experimentally validated process models of most processes from research projects available
  - Adaptable to any new configuration / feedstock / …
- Aspen Plus extension and automated parameter variation via TEPET
  - Assists to reach convergence of a complex simulation (e.g. multiple recycle streams)
  - Sensitivity of each process parameter on each KPI
  - Automated heat integration – flexibility towards configuration changes

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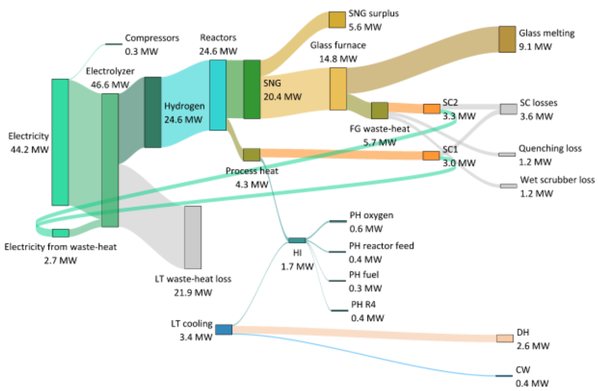
Technical Assessment Example
Glass-CCU Methane / Methanol efficiency

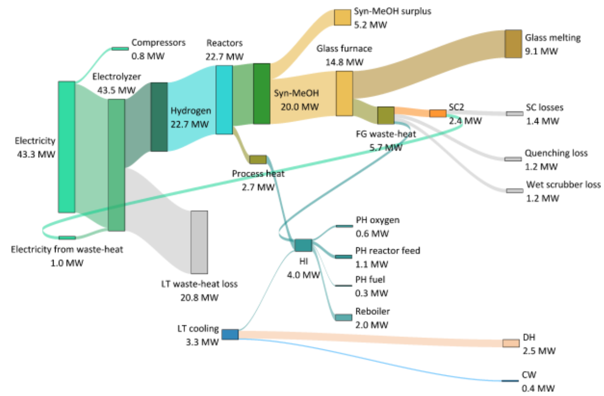
DLR

Energy Flow Sankey Diagrams[1]

Methane (synthetic natural gas, SNG)



Methanol (syn-MeOH)



[1] Rahmat et al. (under review). *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

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Technical Assessment Example
Glass-CCU Methane / Methanol efficiency

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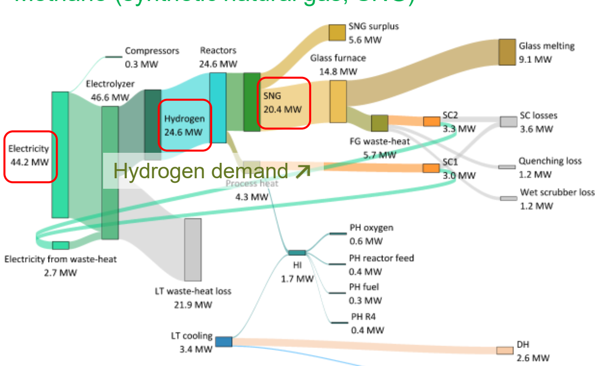
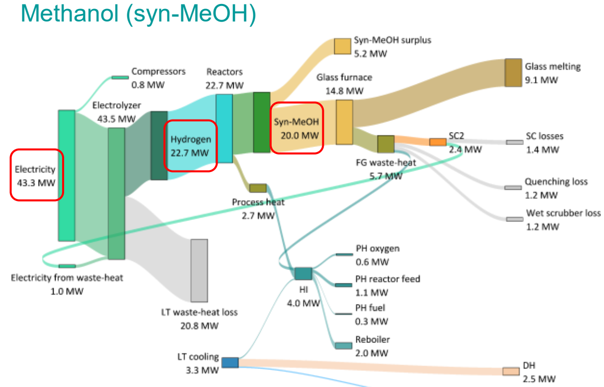


$\eta_{\mathrm{HtF}} = 82.5\ \%$

$\eta_{\mathrm{PtF}} = 45.9\ \%$

Methanol (syn-MeOH)



$\eta_{\mathrm{HtF}} = 88.1\ \%$

$\eta_{\mathrm{PtF}} = 46.2\ \%$

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Technical Assessment Example
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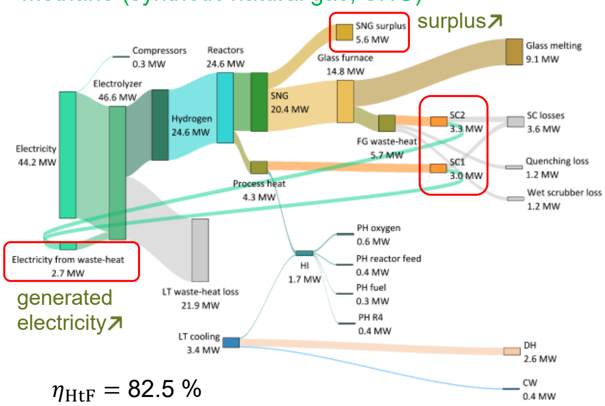

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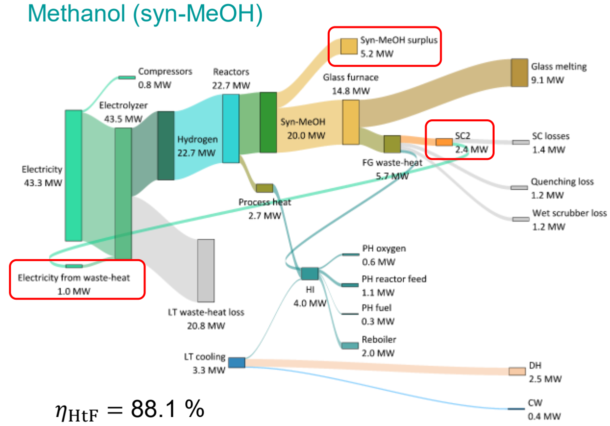

$\eta_{\mathrm{HtF}} = 88.1\ \%$
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Technical Assessment Example
Glass-CCU Methane / Methanol efficiency

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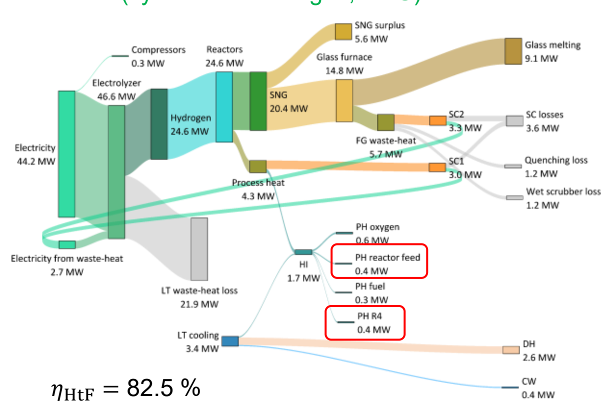

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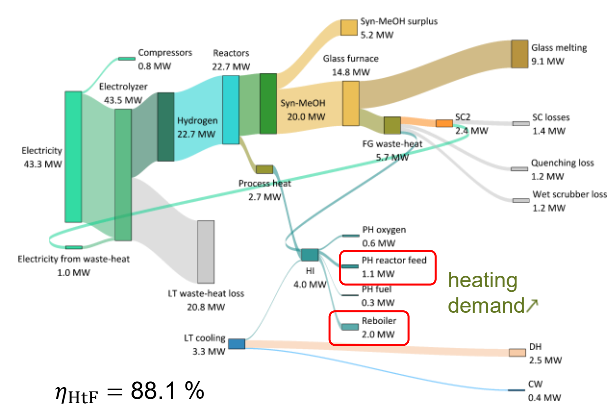

$\eta_{\mathrm{HtF}} = 88.1\ \%$
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Technical Assessment Example
Glass-CCU Methane / Methanol efficiency

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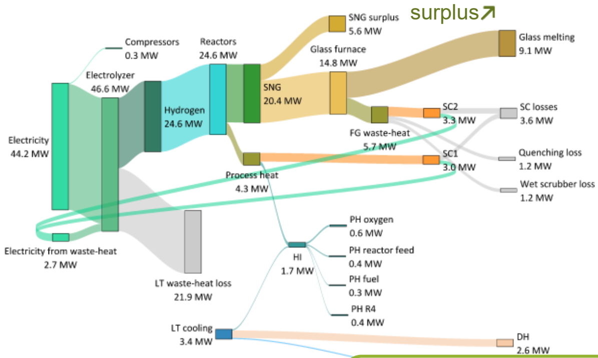
Energy Flow Sankey Diagrams[1]

Methane (synthetic natural gas, SNG)

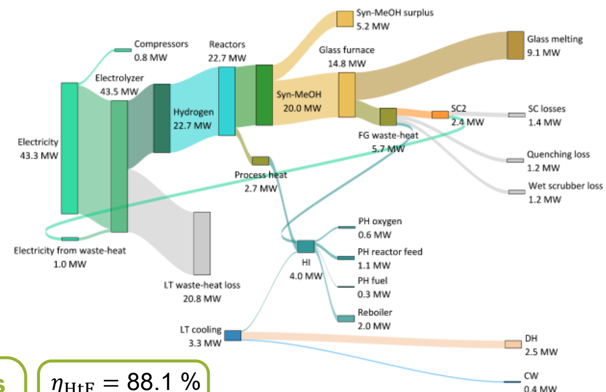


$\eta_{\mathrm{HtF}} = 82.5\ \%$

$\eta_{\mathrm{PtF}} = 45.9\ \%$

Highest efficiencies = Minimal losses

Methanol (syn-MeOH)



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ECONOMIC ASSESSMENT OF CCU

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Economic Assessment
Methodology

- Define each required plant factor (basic conditions ➔ see [1])

Glass-CCU Basic conditions[2]	
Plant location	Germany
Base year	2022
Basis currency	€
FLh	8000 h a^{-1}
Plant lifetime (y)	15 a
Interest rate (IR)	7 %
Labor costs	41 €/h

[1] Heimann et al. (2025) Contribution to the standardization of the economic and ecological analysis of PtX-process [in submission]
[2] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

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Economic Assessment
Methodology

- Define each required plant factor (basic conditions ➔ see [1])
- Standard chemical cost estimation: based on validated basic design
  - Summarizing annualized CAPEX and OPEX in the following Equation:

$$NPC^{[1]}\left[€_{2022}\ \mathrm{t_{glass}}^{-1}\right] = \frac{ACC + \sum OPEX^{[,3]} + labor\ costs}{12.5\ \mathrm{t_{glass}} \cdot FLh\ [\mathrm{h\ a^{-1}}]}$$

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Economic Assessment
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$$\boxed{ACC = FCI\ * Annuity\ factor^{[3]}}$$

  - Annualized Capital Costs (ACC) based on Fixed Capital Investment (FCI) and Annuity factor

Glass-CCU Basic conditions[2]	
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Economic Assessment
Methodology

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$$\boxed{ACC = FCI\ * Annuity\ factor^{[3]}}$$

  - Annualized Capital Costs (ACC) based on Fixed Capital Investment (FCI) and Annuity factor
  - All chemical standard equipment cost available[3]
  - New equipment via analogies, exchange with technology suppliers
  - All equipment cost plus Lang factors: FCI

$$\boxed{FCI_i = EC_i \times \sum Lang\ factors^{[3]}}$$

Glass-CCU Basic conditions[2]	
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Economic Assessment
Methodology

DLR

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See next slide!

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Economic Assessment
Methodology

DLR

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- Fully automated economic cost estimation using DLR in-house tool TEPET

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Economic Assessment
TEPET database

DLR

$$EC_{i,ref} = EC_{ref} \times \left(\frac{sizing_i}{sizing_{ref}}\right)^n \times \left(\frac{CEPCI_i}{CEPCI_{ref}}\right)$$

$$EC_{i,poly} = \left[e \cdot (sizing_i)^2 + f \cdot sizing_i + g\right] \times \left(\frac{CEPCI_i}{CEPCI_{ref}}\right)$$

Reference function ($EC_{i,ref}$)	EC_{ref}	Currency	$sizing_{ref}$	Unit	n	$Year_{ref}$	Source
Compressor	3 035	$	1	kW_{el}	0.68	2002	[1]
Centrifugal pump	16 809	$	1	$m^3 s^{-1}$	0.36	2002	[1]
Distillation column	286 343	$	100	size factor = $HxD^{1.5}$ [$m^{2.5}$]	0.53	2007	[2,3]
AEL stack	800	k€	0.005	kg/s	1	2019	[4]
AEL balance of plant	1	m€	0.025	kg/s	0.8	2019	[4]
Wet scrubber (limestone)	13 061	k$	14	MW_{th}	0.72	2012	[5]
Membrane PMP	9.76	m$	525.6	kmol/h	0.6	2020	[6]**
Methanation fixed-bed reactor	57 794	$	14 000	m³/h	0.52	2007	[2]
Polynomial function ($EC_{i,poly}$)	**e**	**f**	**g**	**Sizing unit**	**Currency**	**$Year_{ref}$**	**Source**
MeOH Lurgi reactor, D_{tube} 2 in.*	0	156.03	11 910	Number of tubes [-]	$	2002	[1]**
Shell & tube heat exchanger*	0	201.29	3853.3	Heat transfer area [m²]	$	2002	[1]
Flash drum	-2.21	369.75	805.42	Length & diameter [m]	$	2002	[1]

*stainless steel as the material construction
**with own reformulation

[1] Peters et al. (2002) *Design and Economics for Chemical Engineers*. Europe: McGraw-Hill Education.
[2] Woods (2007) Rules of Thumb in Engineering Practices
[3] Towler (2008) Chemical Engineering Design
[4] Habermayer et al. (2023) Sustainable aviation fuel from forestry residue and hydrogen. https://doi.org/10.1039/d3se00358b
[5] Sorrels (2021) Chapter 1 – Wet and Dry Scrubbers for Acid Gas Control. www.epa.gov
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Economic Assessment
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$$EC_{i,ref} = EC_{ref} \times \left(\frac{sizing_i}{sizing_{ref}}\right)^n \times \left(\frac{CEPCI_i}{CEPCI_{ref}}\right)$$

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Flash drum	-2.21	369.75	805.42	Length & diameter [m]	$	2002	[1]

Cost functions are available in the TEPET database

Users have a full flexibility to select/update the input data

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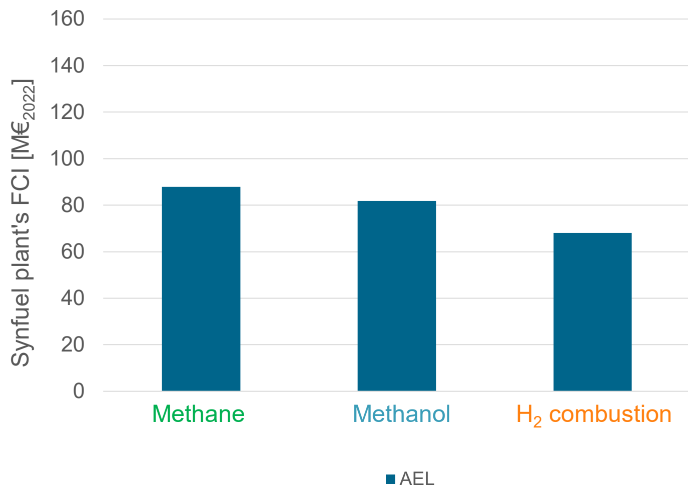
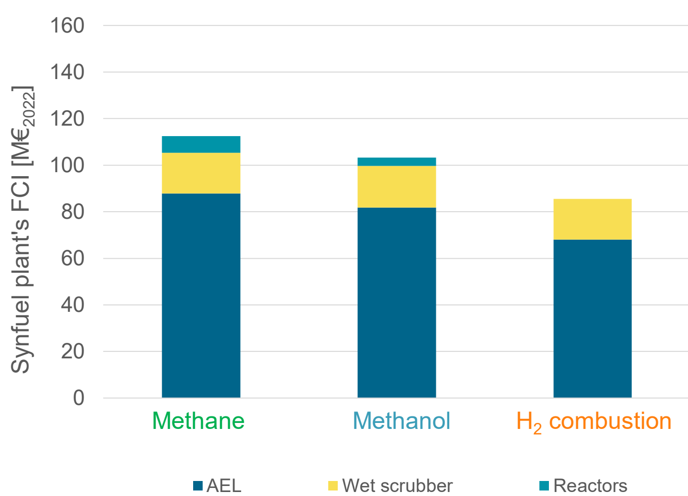
Economic Assessment Example
Glass-CCU Methane / Methanol / H_2 FCI[1]



- **AEL:** Methane requires **more H_2** feedstock than Methanol

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

Economic Assessment Example
Glass-CCU Methane / Methanol / H_2 FCI[1]



- **AEL:** Methane requires **more H_2** feedstock than Methanol
- **Reactors:** Methane fixed-bed **multi-stage**, Methanol multi-tube **single-stage**

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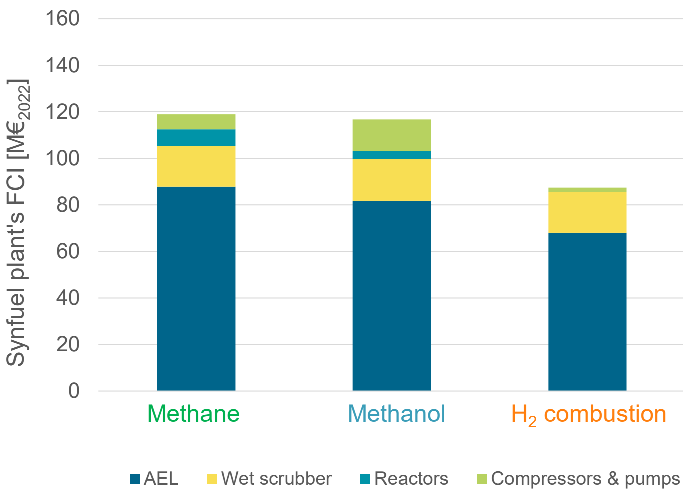
Economic Assessment Example
Glass-CCU Methane / Methanol / H_2 FCI[1]



- **AEL:** Methane requires **more H_2** feedstock than Methanol
- **Reactors:** Methane fixed-bed **multi-stage**, Methanol multi-tube **single-stage**
- **Compressors:**
  $p_{reactor}$ Methane **30 bar**
  $p_{reactor}$ Methanol **80 bar**

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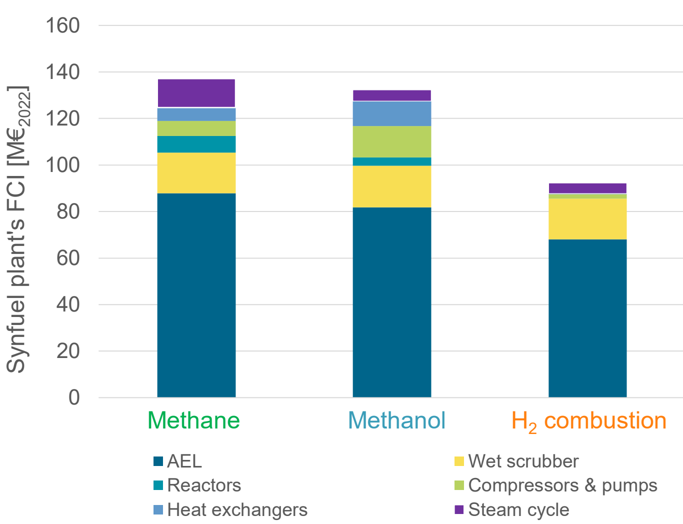
Economic Assessment Example
Glass-CCU Methane / Methanol / H_2 FCI[1]



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- **Steam cycle:**
  Methane in recuperator & reactor
  Methanol in recuperator only

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

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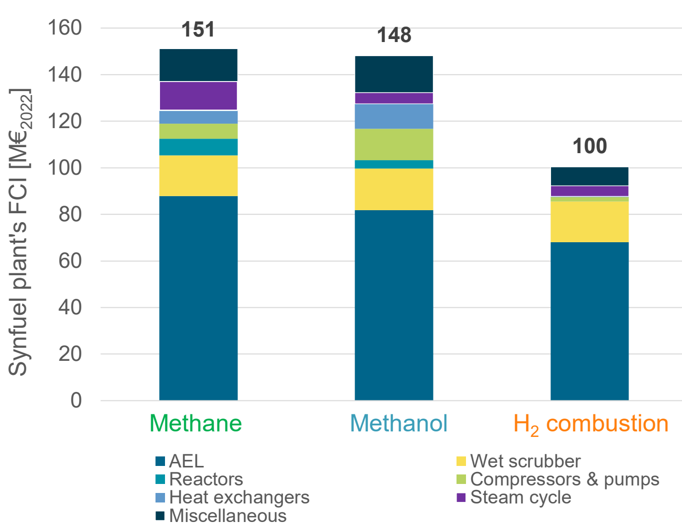
Economic Assessment Example

Glass-CCU Methane / Methanol / H_2 FCI[1]



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- **FCI: Methane ≈ Methanol**

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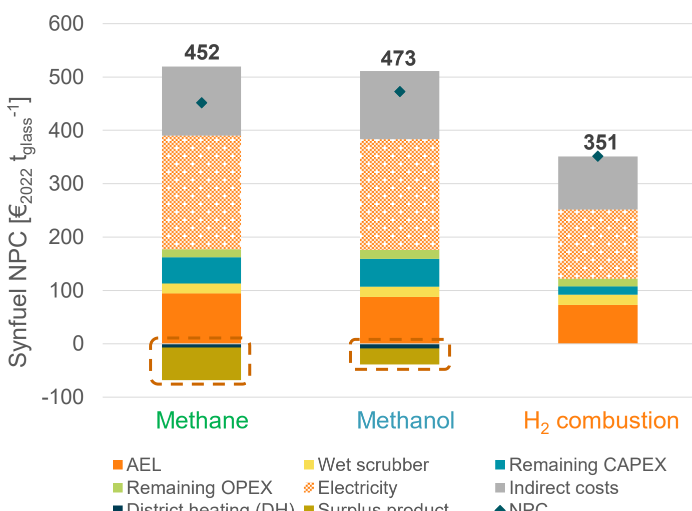
[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

Economic Assessment Example

Glass-CCU Methane / Methanol / H_2 NPC[1]



- Sales of surplus synfuels as fossil fuels

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[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

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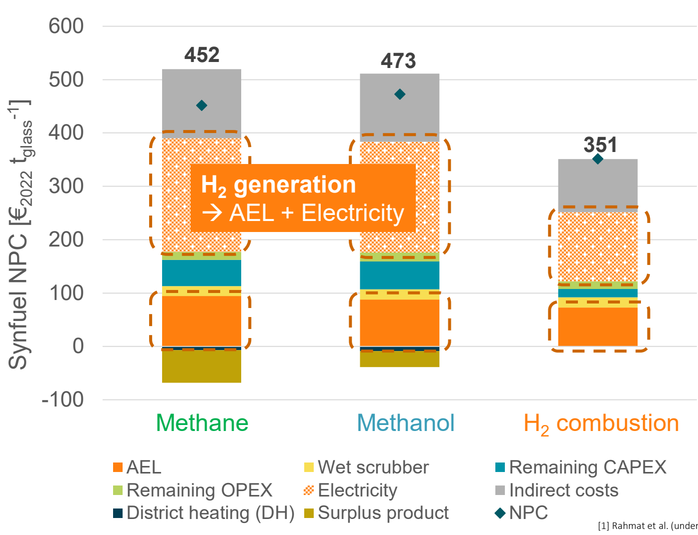
Economic Assessment Example

Glass-CCU Methane / Methanol / H_2 NPC[1]



- Sales of surplus synfuels as fossil fuels
- **Cost driver is H_2 generation**

  → ca. 60-67 % NPC

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

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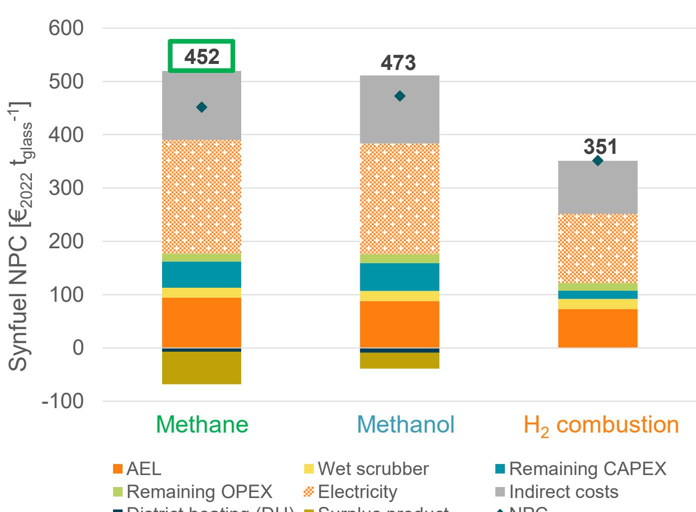
Economic Assessment Example

Glass-CCU Methane / Methanol / H_2 NPC[1]



- Sales of surplus synfuels as fossil fuels
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- Glass-CCU **Methane** is **more preferred**

  → minimum adjustment required

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

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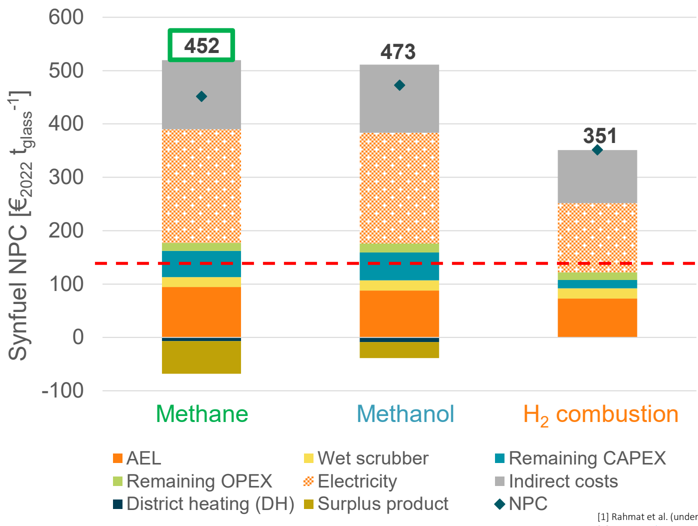
Economic Assessment Example
Glass-CCU Methane / Methanol / H_2 NPC[1]



- Sales of surplus synfuels as fossil fuels
- **Cost driver is H_2 generation**
  → ca. 60-67 % NPC
- Glass-CCU **Methane** is **more preferred**
  → minimum adjustment required

Natural gas costs[2] 128 $€_{2022}\ t_{glass}^{-1}$

Beer bottle (330 g) price[3] up to 15 ct. $€_{2022}$ bottle^{-1}

Eco-friendly beer bottle ca. **26 ct.** $€_{2022}$ bottle^{-1}

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
[2] EU Natural Gas TTF - Price - Chart - Historical Data - News (tradingeconomics.com)
[3] HVG-DGG internal price estimation

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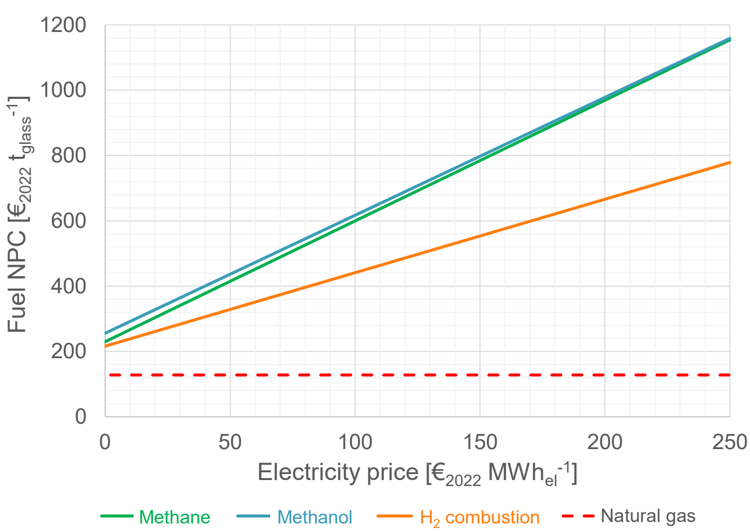
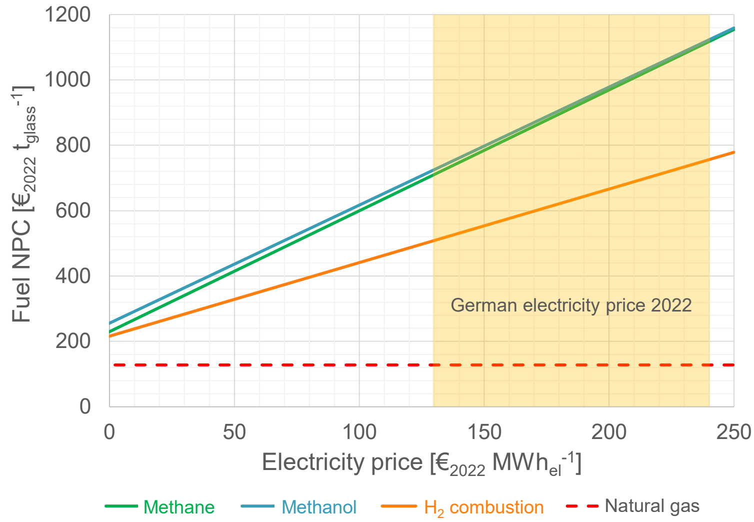
Economic Assessment Example
Glass-CCU Methane / Methanol / H_2 sensitivity



- NPC = f(electricity price)
  - Glass-CCU **Methane** shows **little lower** NPC than **Methanol**
  - Glass from **H_2 combustion** is **attractive** but not state-of-the-art

Economic Assessment Example
Glass-CCU Methane / Methanol / H_2 sensitivity



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  - Glass-CCU **Methane** shows **little lower** NPC than **Methanol**
  - Glass from **H_2 combustion** is **attractive** but not state-of-the-art
- Within the range of German electricity price in 2022, NPC of Glass-CCU **Methane** / **Methanol** are about **5 to 9 times of natural gas avg. price**

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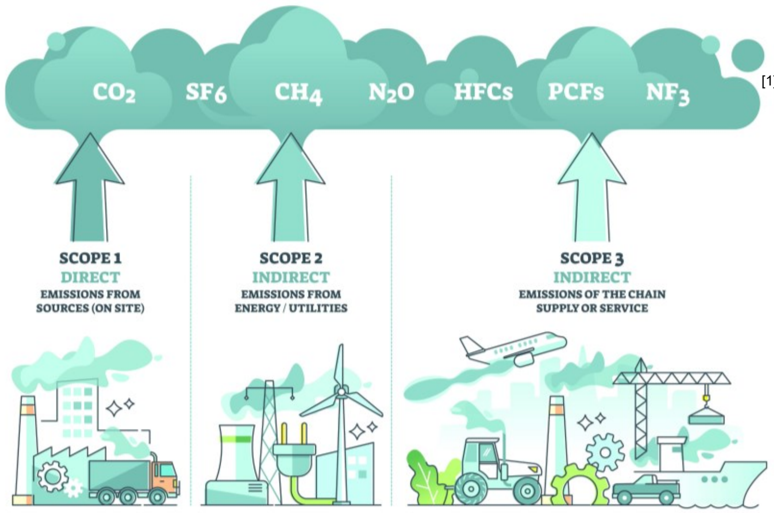
Environmental Assessment
Scope definition



[1]

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[1] 62d0970d68ea166bcd1c010b_AdobeStock_462557114.jpeg (4330×3464)

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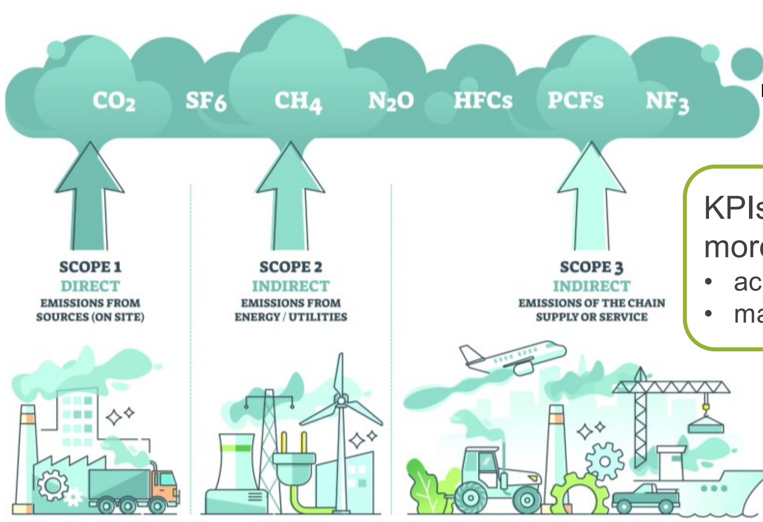
Environmental Assessment
Scope definition



[1]

KPIs of LCA:
more than only climate change!
- acidification, water use, …
- material resources depletion, …

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[1] 62d0970d68ea166bcd1c010b_AdobeStock_462557114.jpeg (4330×3464)

Environmental Assessment
Methodology

- ISO 14040/14044 for standard life cycle assessment (LCA) procedure
- Simplified **Glass-CCU Methane** climate change calculation example:

Electricity consumption × **Emissions factor** = **GHG emissions**

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Environmental Assessment
Methodology

- ISO 14040/14044 for standard life cycle assessment (LCA) procedure
- Simplified **Glass-CCU Methane** climate change calculation example:

Electricity consumption		Emissions factor[1] German grid (2022)		GHG emissions
3,536 $kWh_{el}\ t_{glass}^{-1}$	×	303 $g_{CO_2\text{-eq.}}\ kWh_{el}^{-1}$	=	1.07 $t_{CO_2\text{-eq.}}\ t_{glass}^{-1}$

- Fully automated environmental impact estimation using DLR in-house tool TEPET

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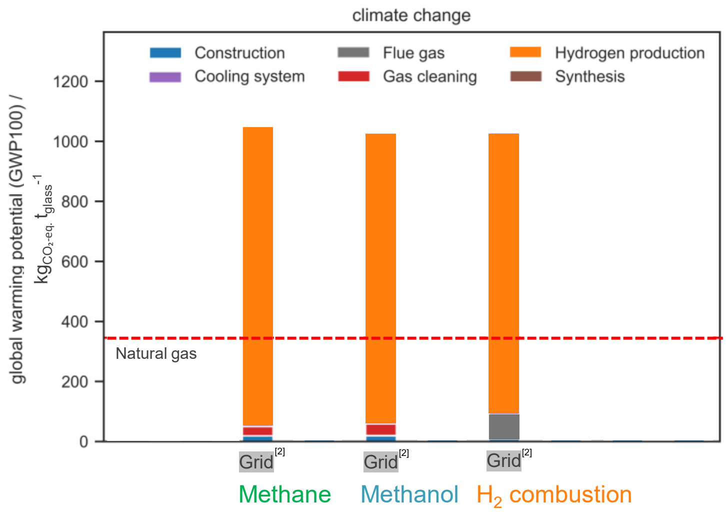
Environmental Assessment Example
Glass-CCU Methane / Methanol GWP[1]



Climate change impact

- Grid electricity (2022)[2]:

303 $g_{CO_2\text{-eq.}}$ kWh_{el}^{-1}

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.

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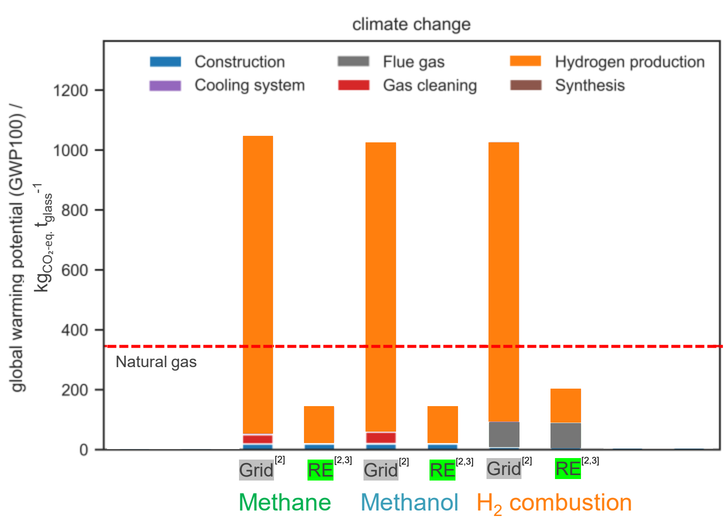
Environmental Assessment Example
Glass-CCU Methane / Methanol GWP[1]



Climate change impact

- Grid electricity (2022)[2]:

303 $g_{CO_2\text{-eq.}}$ kWh_{el}^{-1}

- Renewable energy (RE, 2035)[2,3]:

45 $g_{CO_2\text{-eq.}}$ kWh_{el}^{-1}

  - Wind onshore 37.6 %
  - Wind offshore 23.9 %
  - Solar PV 32.5 %
  - Hydropower 2.4 %
  - Bioenergy 3.5 %

Electricity with **low climate change** impact is **essential** for CCU!
→ In case of Germany, RE is mandatory!

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
[2] Wernet et al. (2016) *The ecoinvent database version 3 (Part I): Overview and methodology.* The International Journal of Life Cycle Assessment.
[3] Althoff et al. (2022) *Climate-neutral power system 2035. How the German power sector can become climate-neutral by 2035.* Agora Energiewende.

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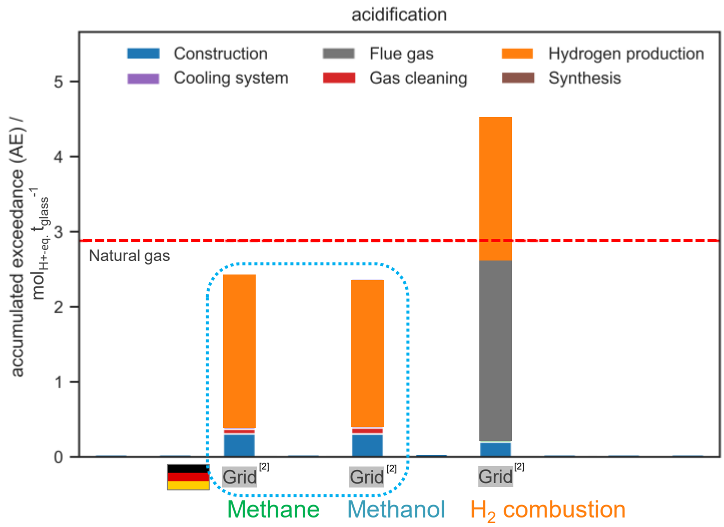
Environmental Assessment Example

Glass-CCU Methane / Methanol acidification[1]



- Glass-CCU **Methane** / **Methanol** gives **less acidification** impact than the use of natural gas

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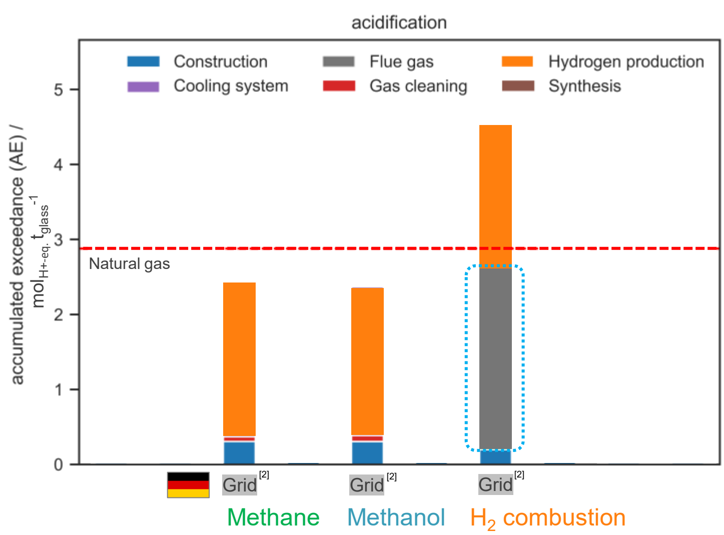
Environmental Assessment Example

Glass-CCU Methane / Methanol acidification[1]



- Glass-CCU **Methane** / **Methanol** gives **less acidification** impact than the use of natural gas
- Glass industry with **H_2 combustion** gives **more acidification** impact than the use of natural gas due to **flue gas emission** without CCU

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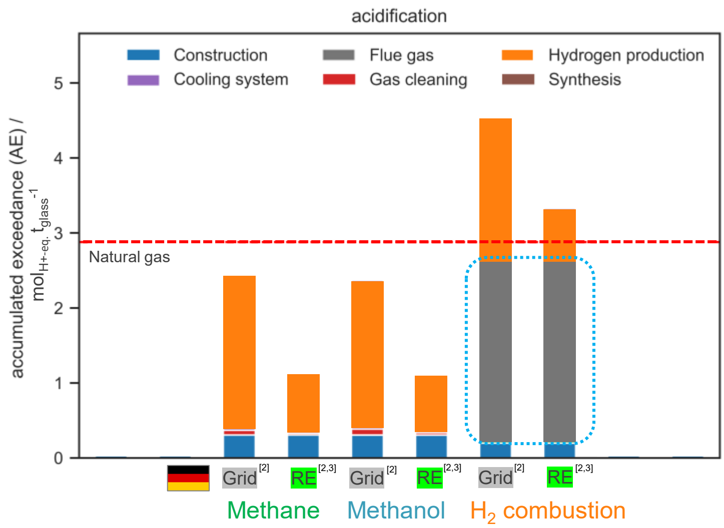
Environmental Assessment Example
Glass-CCU Methane / Methanol acidification[1]



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- Glass industry with **H_2 combustion** gives **more acidification** impact than the use of natural gas due to **flue gas emission** without CCU
- The use of **RE for CCU decreases** the **acidification** impact even further

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[2] Wernet et al. (2016) *The ecoinvent database version 3 (Part I): Overview and methodology.* The International Journal of Life Cycle Assessment.
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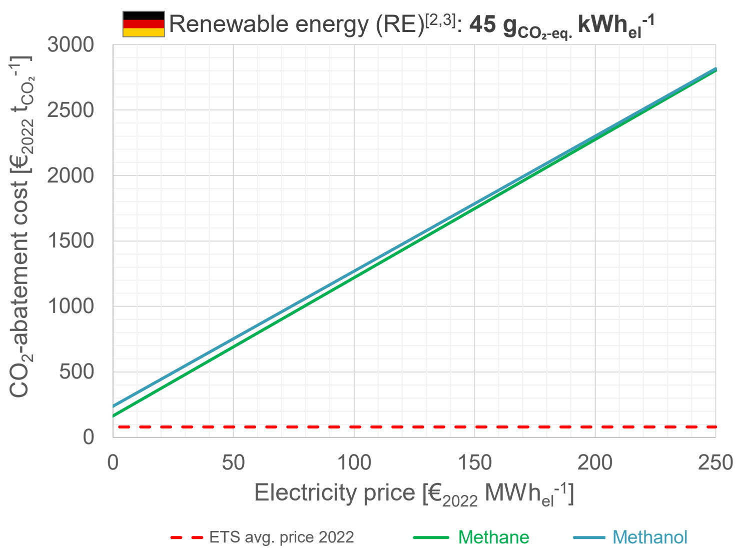
CO_2-abatement cost assessment

Glass-CCU Methane / Methanol / H_2 sensitivity[1]



- Based on **Scope 1 emissions**
- CO_2-abatement costs
  = f(**electricity price**, carbon footprint)
- Glass-CCU **Methane** has **lower** CO_2-abatement costs than **Methanol**

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
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CO_2-abatement cost assessment

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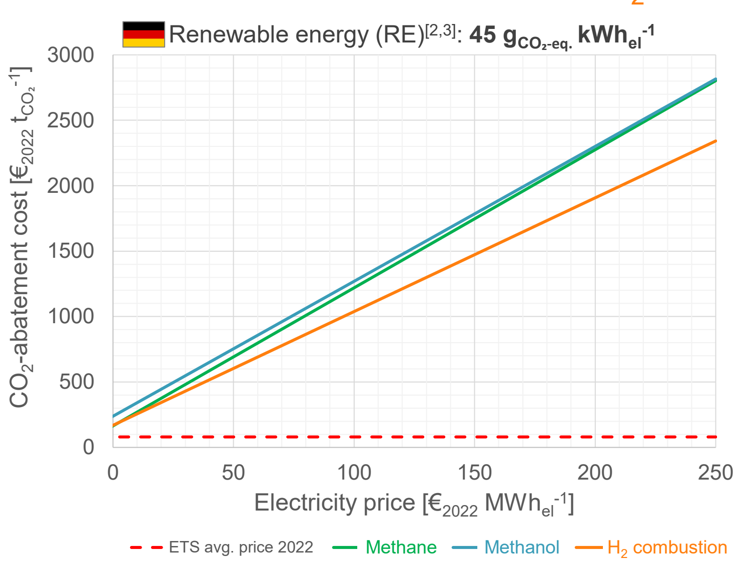

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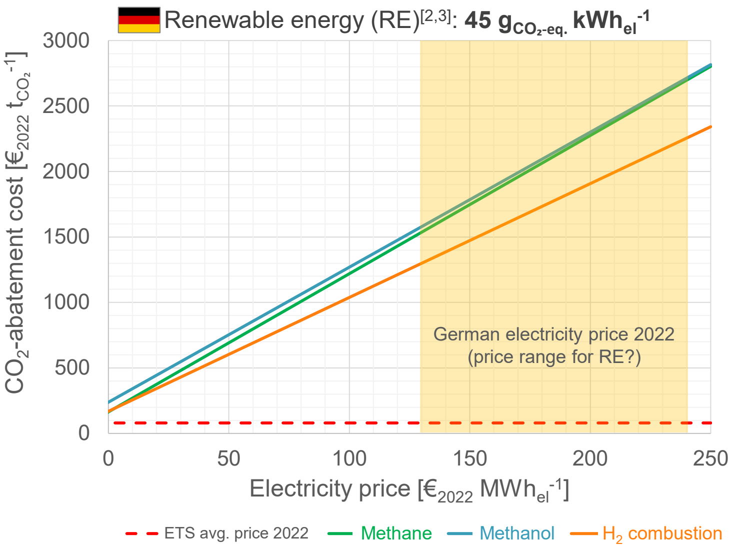
CO_2-abatement cost assessment
Glass-CCU Methane / Methanol / H_2 sensitivity[1]

Renewable energy (RE)[2,3]: **45 $g_{CO_2\text{-eq.}}$ kWh_{el}^{-1}**



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- CO_2-abatement costs = f(**electricity price**, carbon footprint)
- Glass-CCU **Methane** has **lower** CO_2-abatement costs than **Methanol**, **H_2 combustion** looks **attractive**
- Within the range of German electricity price in 2022, CO_2-abatement costs of Glass-CCU **Methane** / **Methanol** are about **19 to 34 times of ETS avg. price**

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CO_2 abatement cost assessment
Glass-CCU Methane / Methanol / H_2 sensitivity

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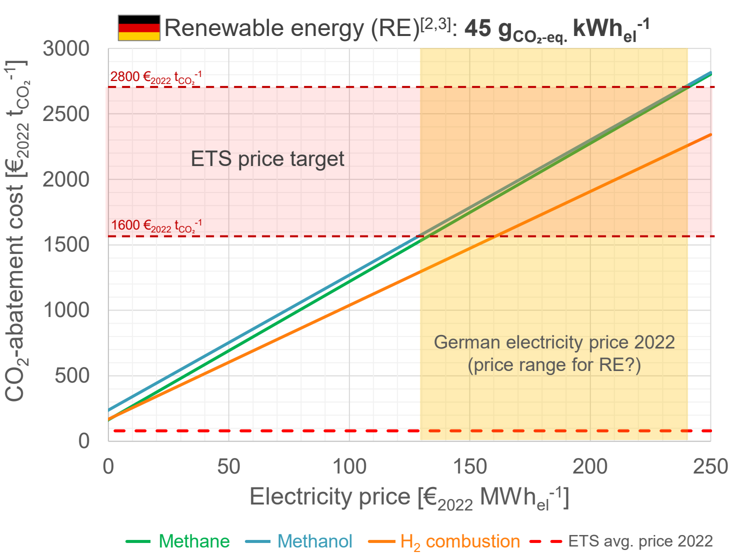

- Within the range of German electricity price in 2022, CO_2-abatement costs of Glass-CCU **Methane** / **Methanol** are about **19 to 34 times of ETS avg. price**
- **ETS price target** need to be: **1600-2800 $€_{2022}$ $t_{CO_2}^{-1}$**

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CO_2 abatement cost assessment
Glass-CCU Methane / Methanol / H_2 sensitivity

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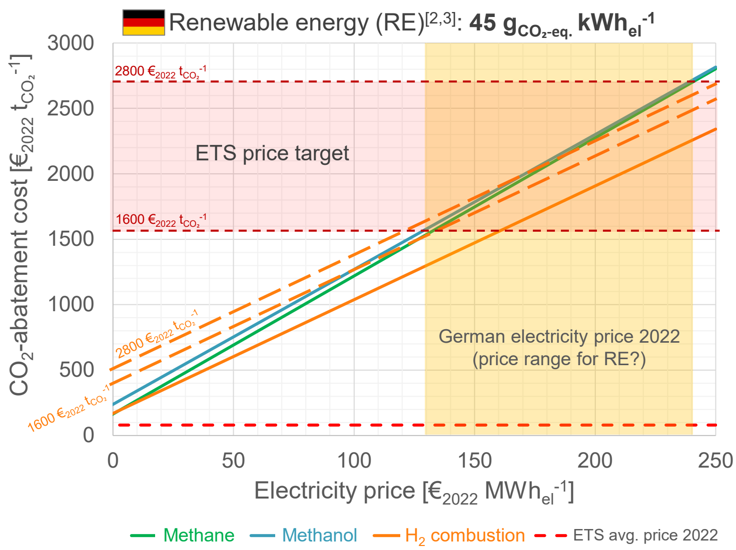

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- **ETS price target** need to be: **1600-2800 $€_{2022}$ $t_{CO_2}^{-1}$**
- CO_2 abatement cost of **H_2 combustion** = f(Electricity, **ETS**) due to the **Scope 1 emissions**

Scope 1 emissions	[kg_{CO_2} t_{glass}^{-1}]
H_2 combustion	91.5 ⇗⇗
Methane	0.03 ⇘⇘
Methanol	0.04 ⇘⇘

[1] Rahmat et al. (under review) *Advancing the defossilization of the glass industry based on the integration of synthetic fuels production*. Fuel.
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Technology Readiness Level (TRL)
Example of Glass-CCU

Needs of further experimental researches

- Each equipment, as a **stand-alone** technology, has **TRL 8-9**
- Typical SoA glass manufacturing plant has a desulphurization and nitrogen removal unit, while CO_2 is emitted to the air

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Technology Readiness Level (TRL)
Example of Glass-CCU

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Needs of further experimental researches

- Each equipment, as a stand-alone technology, has TRL 8-9
- Typical SoA glass manufacturing plant has a desulphurization and nitrogen removal unit, while CO_2 is emitted to the air
- To **get commercial**: search for optimization potential
  - Better **electrolyzer, carbon capture, system (heat) integration, …**

Technology Readiness Level (TRL)
Example of Glass-CCU

Needs of further experimental researches

- Each equipment, as a stand-alone technology, has TRL 8-9
- Typical SoA glass manufacturing plant has a desulphurization and nitrogen removal unit, while CO_2 is emitted to the air
- To get commercial: search for optimization potential
  - Better electrolyzer, carbon capture, system (heat) integration, …
- Glass-CCU technical challenge:
  CO_2 capture unit and **the integration to the glass furnace**
  → the process concept has **TRL 5**
- **Demonstration plant is needed** to proof viability and CO_2 abatement cost

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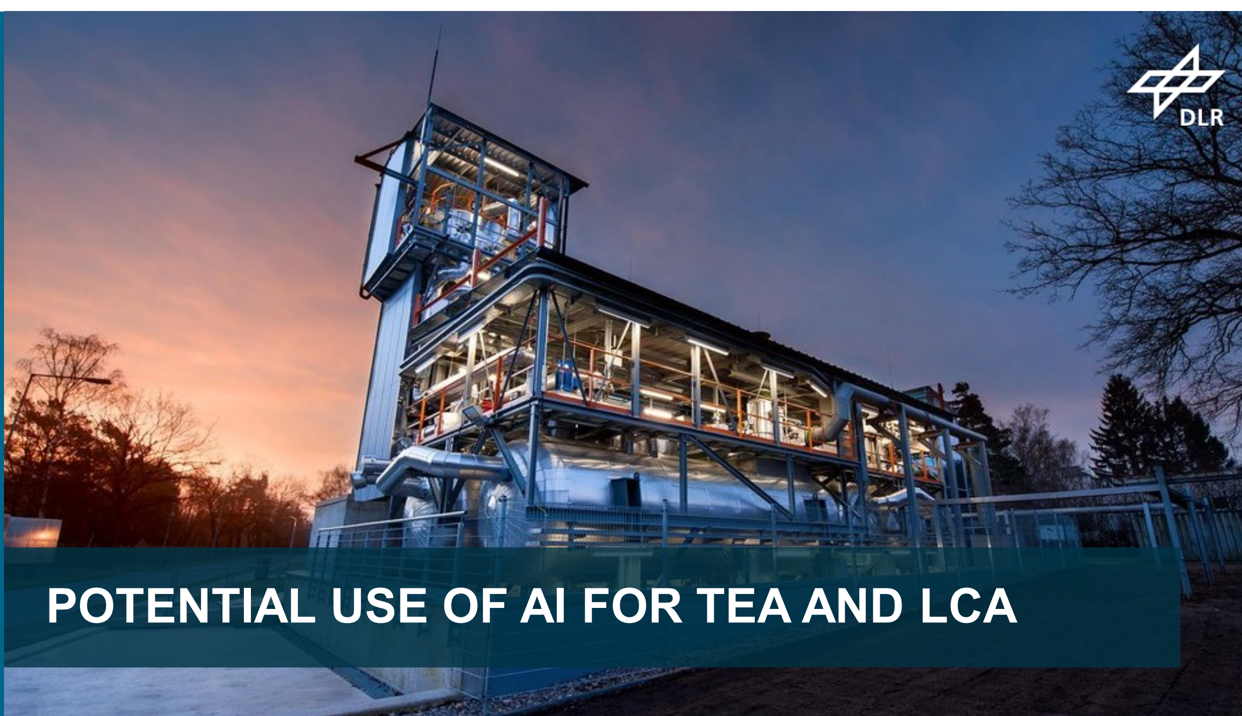

POTENTIAL USE OF AI FOR TEA AND LCA

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Promises of AI in TEA & LCA
It does it for you, does it?

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- Data and Inventory collection
- Methods and Modelling creation
- Uncertainty, Sensitivity analysis
- Dynamics, Scenarios
- Governance, Auditability
- Increase Data Security

- Will AI save you more time for your problem solution compared to your individual time expenditure for AI training and application?

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Think twice when using AI in TEA & LCA

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- Garbage in – Glossy Garbage out
- Hallucination
- Data misclassification
- Unclear validity and sources
- Look for peer-reviewed data

- Uncalibrated points
- Explainability gaps
- Correlation blindness

- Weak audit trails
- Ethical concerns (accountability)

- Data and Inventory collection ?
- Methods and Modelling creation ?
- Uncertainty, Sensitivity analysis ?
- Dynamics, Scenarios ?
- Governance, Auditability ?
- Increase Data Security ?

- Drifting away from compliances and norms
- Overfitting and underfitting of trends
- Far from engineering practice

- Scenario generation without clear decision and relevance

- Data leakage risks
- privacy concerns

- Don‘t undermine the energy consumption of AI

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Can AI help in TEA & LCA, carefully used?

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- Data wrangling & QA-flags
- Draft preparation and model outline
- Document mining and number verification

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Data wrangling & QA-flags
- Spots duplicates, incorrect units, and missing information

Draft preparation and model outline
- Suggests rough estimation for a fuel plant
- Assists in cost assessment
(e.g. more recent data than standard literature)

Document mining and number verification
- Can help in pulling out numbers from documents
- Can help in selecting key parameters

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Can AI help in TEA & LCA, carefully used?

DLR

- Spots duplicates, incorrect units, and missing information

- Can help in pulling out numbers from documents
- Can help in selecting key parameters

Data wrangling & QA-flags

Draft preparation and model outline

Document mining and number verification

- Suggests rough estimation for a fuel plant
- Assists in cost assessment
  (e.g. more recent data than standard literature)

AI is your fast assistant, not your decision-maker. Let it fetch, clean, and test; you set the rules, pick credible data, and sign off.

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CONCLUSION & OUTLOOK

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EU Energy-intensive industries

Opportunities for CCU towards Sustainability*

- Steel and basic metals (irons, aluminum, copper, …) → 160 Mt_{CO_2} p.a.
- Chemicals (ammonia, fertilizers, plastics, …) → 130 Mt_{CO_2} p.a.
- Cement and non-metallic minerals (glass, ceramics) → 100 Mt_{CO_2} p.a.
- Petrochemicals (oil refining, …) → 80 Mt_{CO_2} p.a.
- Pulp and paper (forest-based products) → 50 Mt_{CO_2} p.a.

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* see: Fig. 1: Share of CO_2 emissions in the total industrial CO_2 emissions in the EU

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Glass-CCU is **adaptable** to other energy-intense industries with other scale, GHG concentration, temp., pressure, …

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EU Energy-intensive industries

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Glass-CCU is **adaptable** to other energy-intense industries with other scale, GHG concentration, temp., pressure, … each application unique ➔ **chemical engineering homework**

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Conclusion

- CCU in energy-intensive industry requires:
  - Deep understanding on the technical processes and process simulation skills
  - Standardized economic assessment
  - Environmental impact assessment beyond CO_2
- Findings of Glass-CCU:
  - Methane is the low-hanging fruit for the decarbonization of glass industry
  - Greenflation of beer bottle is expected with about 70 % higher price (15 ct€ → 26 ct€)
- CCU technology transfer from glass industry to other energy-intense industries is feasible but not straightforward
- AI is a fast assistant, but not your guide!
- DLR provides standardized assessment for any CCU technology, feed gas, scale, location, regulation, … !

Outlook

- Standardized techno-economic and environmental assessment is based on basic engineering design
  - **AACE class III/IV (FCI accuracy of ±30 % assumed)**
  - Detailed design will proof if you were right
- Demonstration plant will experimentally validate the findings

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- CCU regulation should reflect the real benefits
  - EU ETS price target should be fulfilled to make CCU economically attractive
  - Binding environmental policies are essential for the deployment of CCU
- The greener the electricity source, the more attractive becomes CCU technology!
  - CCU applications will evolve or the plants will shut down*

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* See EU Net-Zero Industry Act: https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en

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Dedicate your career to a sustainable industry?

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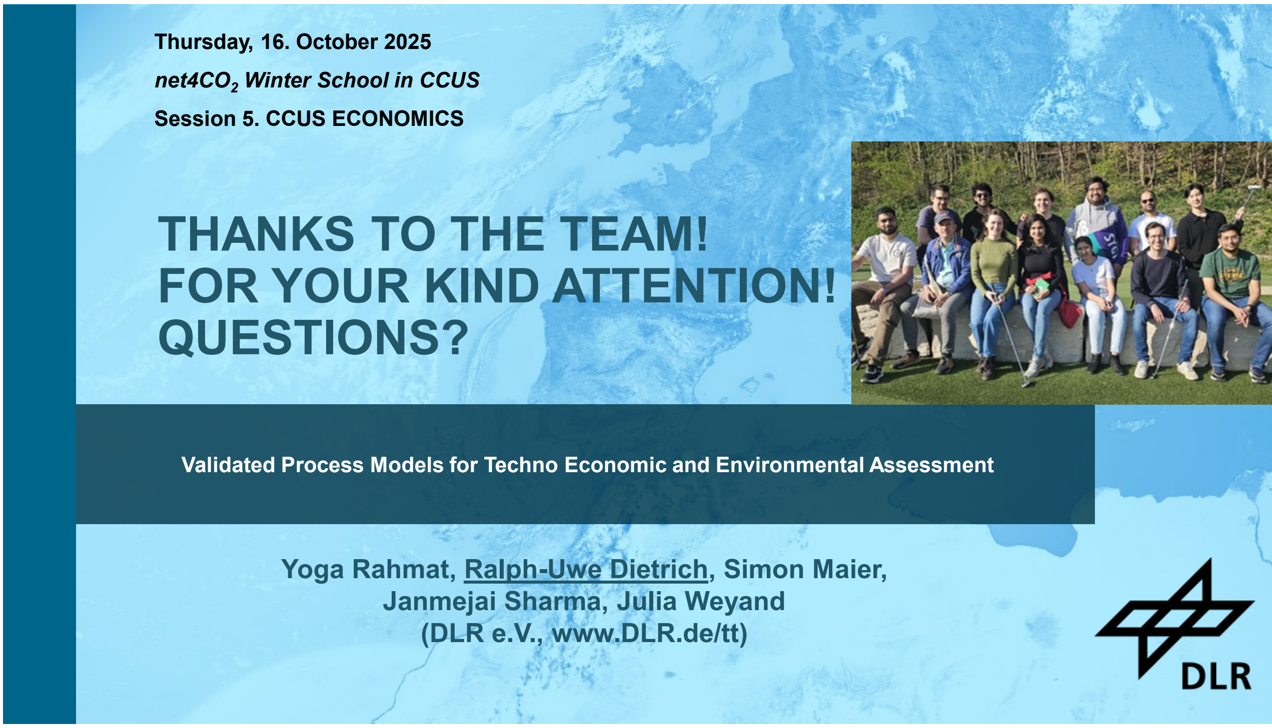
* See EU Net-Zero Industry Act: https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en


Thursday, 16. October 2025
net4CO2 Winter School in CCUS
Session 5. CCUS ECONOMICS
THANKS TO THE TEAM!
FOR YOUR KIND ATTENTION!
QUESTIONS?
Validated Process Models for Techno Economic and Environmental Assessment
Yoga Rahmat, Ralph-Uwe Dietrich, Simon Maier,
Janmejai Sharma, Julia Weyand
(DLR e.V., www.DLR.de/tt)
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