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Making our world more productive

POWER-TO-X FOR SUSTAINABLE GLASS PRODUCTION A TECHNO-ECONOMIC AND LIFE CYCLE ASSESSMENT

Project Glas-CO2: Carbon Capture and Utilization Cycles for a CO_2 Neutral Glass Production
KlimPro BMBF 01LJ2005 (A+B)

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[a] Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Stuttgart
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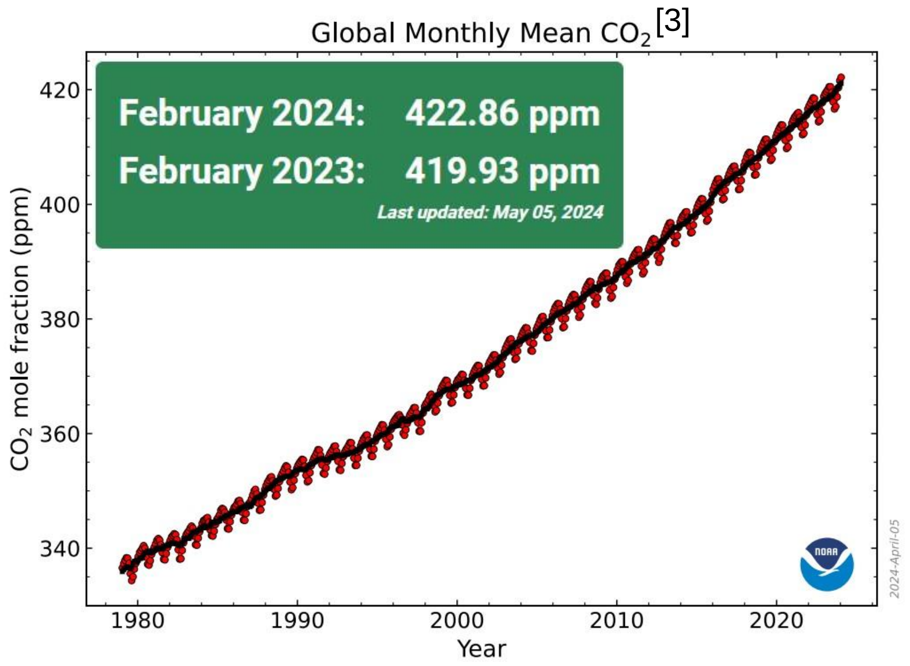
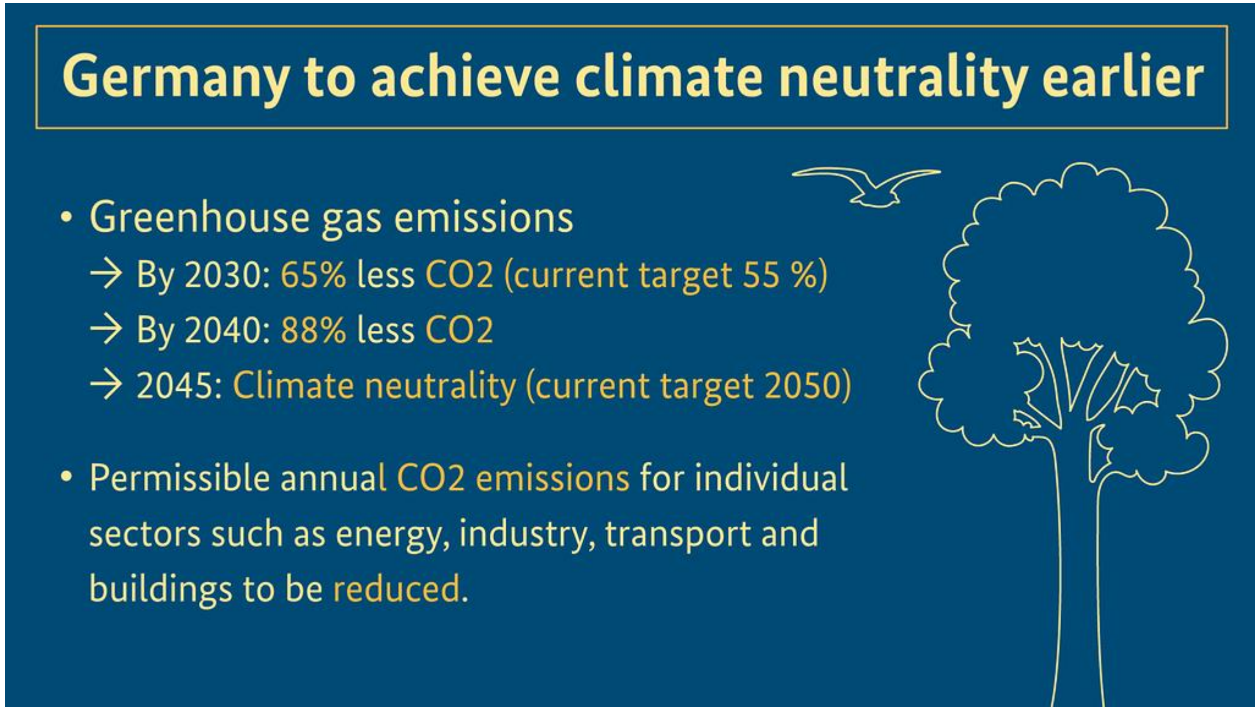
Bundesministerium für Bildung und Forschung

Background

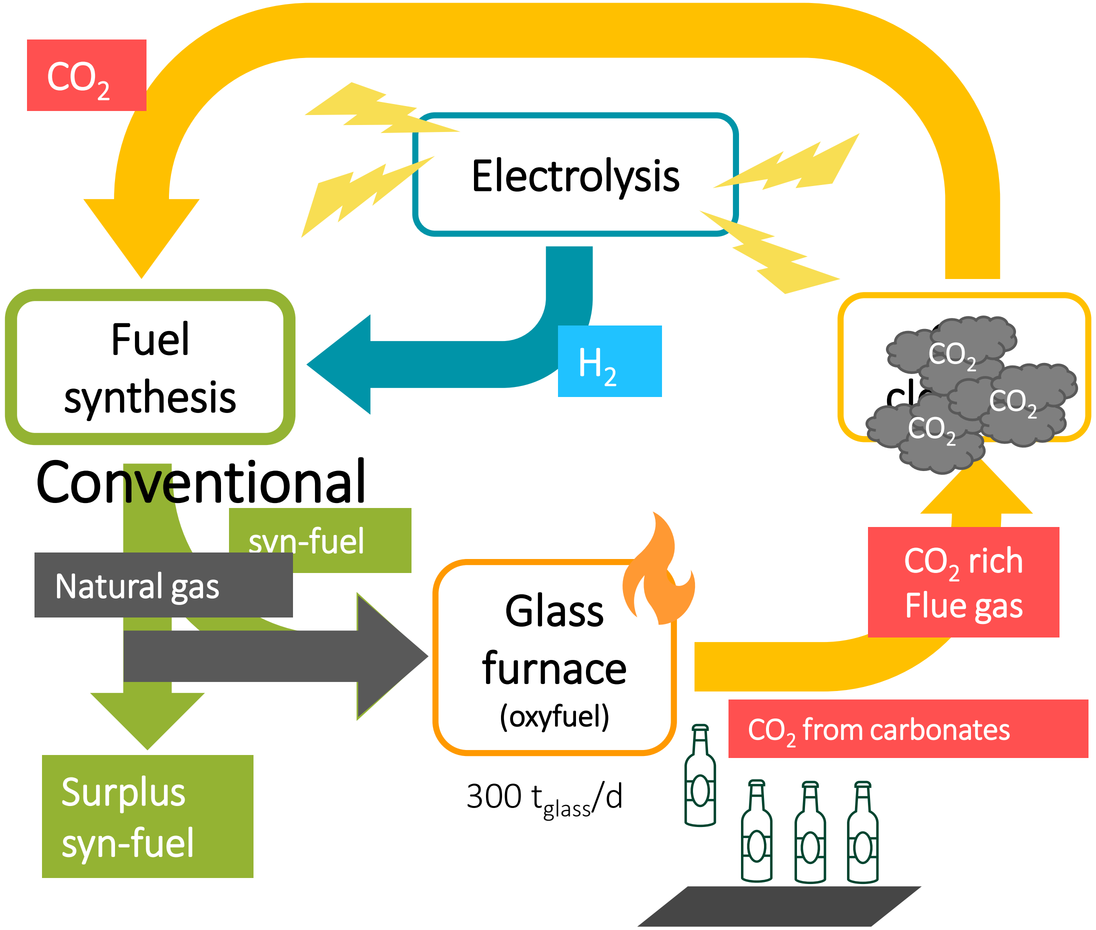
- EU Climate Neutral Goal by 2050 (Germany already by 2045)[1][2]





[1] European Climate Law (europa.eu)
[2] Jedamzik et al. (2020) Energiewende in Deutschland: Definition, Kosten & Ziele | co2online
[3] https://gml.noaa.gov/webdata/ccgg/trends/co2_trend_all_gl.pdf

Background



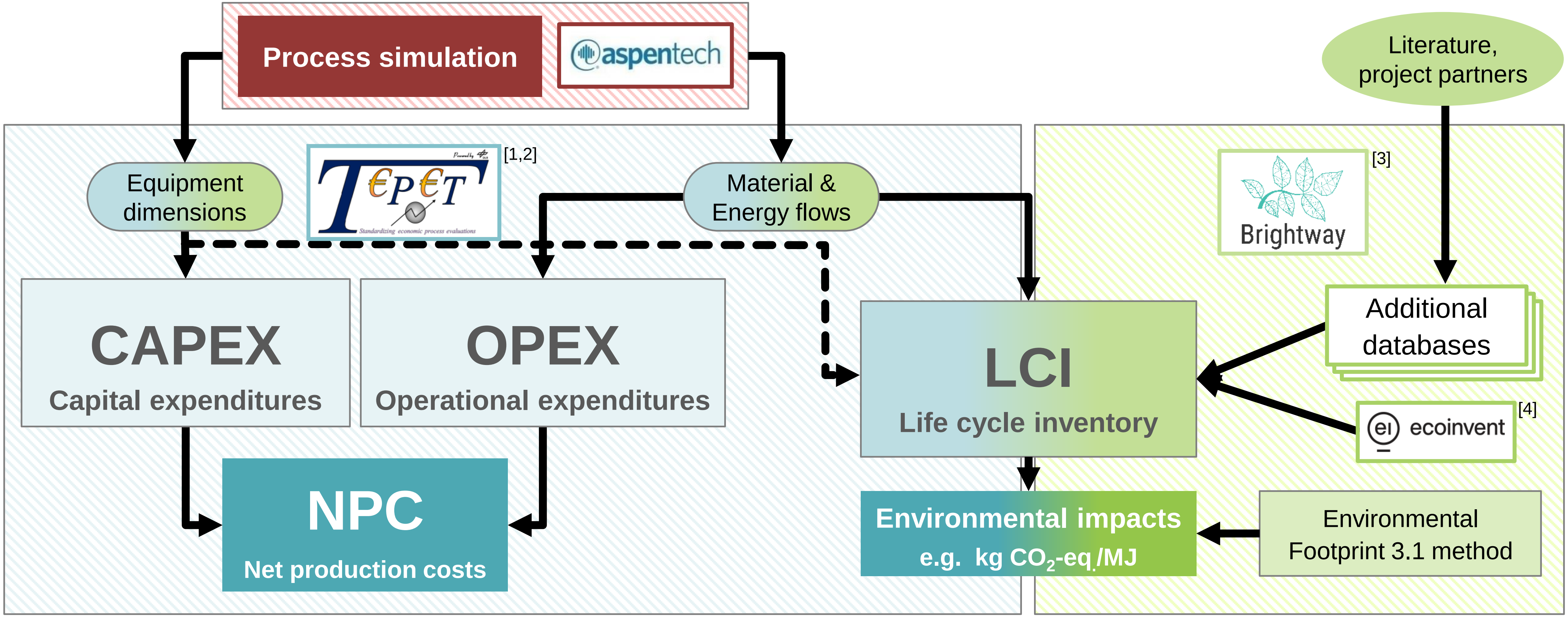
- Power-to-X: alternative to full electrification
  - only 60-80 % electrification possible (hybrid)
- Valorization difficult-to-avoid CO_2 from carbonates
  - ca. 1 Mt CO_2 from carbonates in Germany 2021

4.2 Mt CO_2 ⟹ 1 Mt CO_2

Case	Gas cleaning	Surplus	Heating fuel
(ref) Ref/H_2	N/A	CO_2	H_2

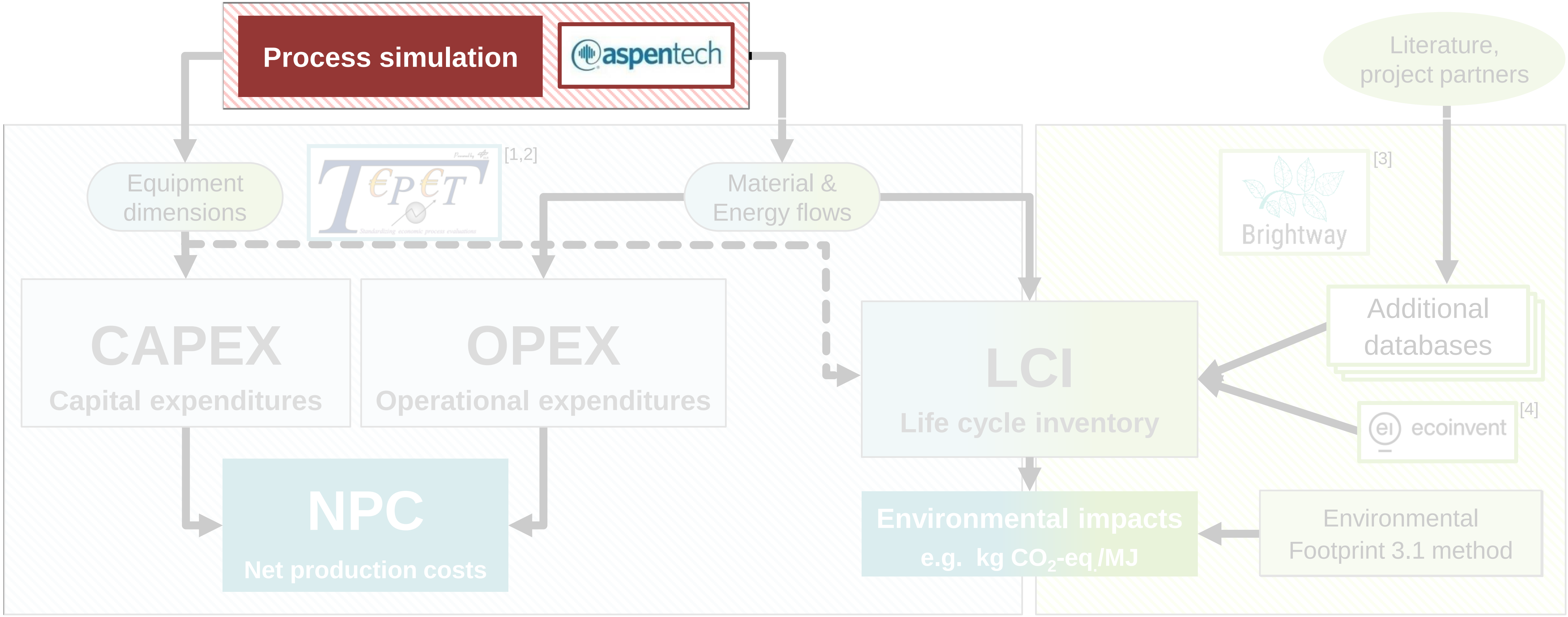
[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.

Methodology
Techno-economic (TEA) and life cycle assessment (LCA)



[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

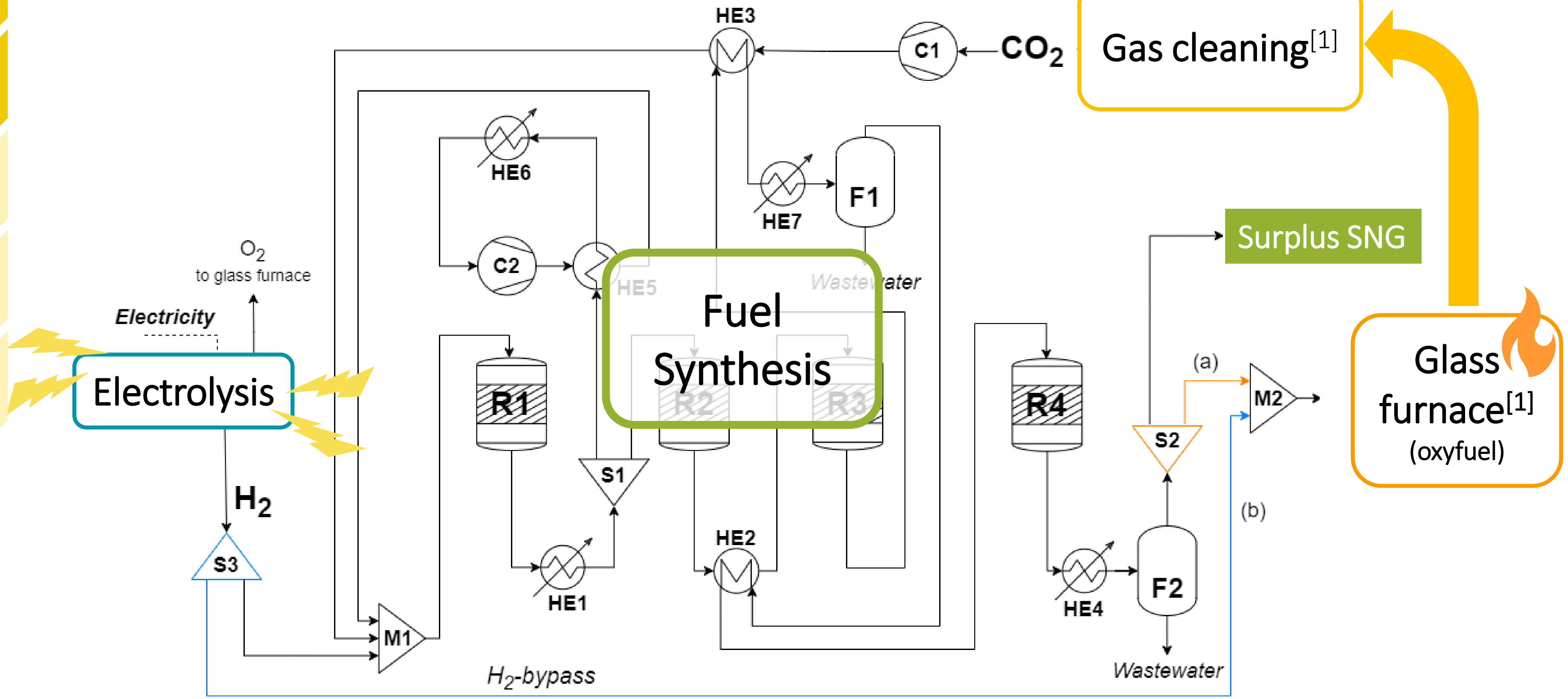
Process description



[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

Process description

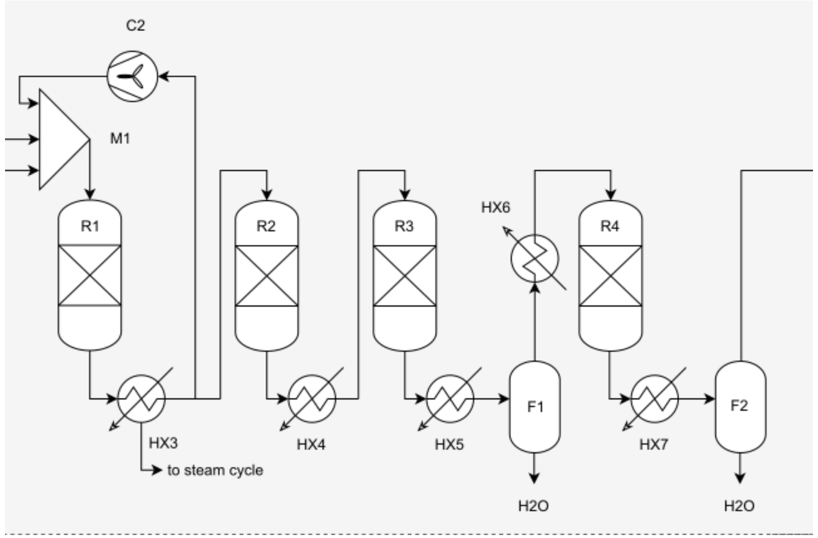
Process flow diagram: SNG



[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.

Process description
Reactor design and parameters: SNG

TREMP™ reactor design[1]: high energetic efficiency & steam cycle applicable



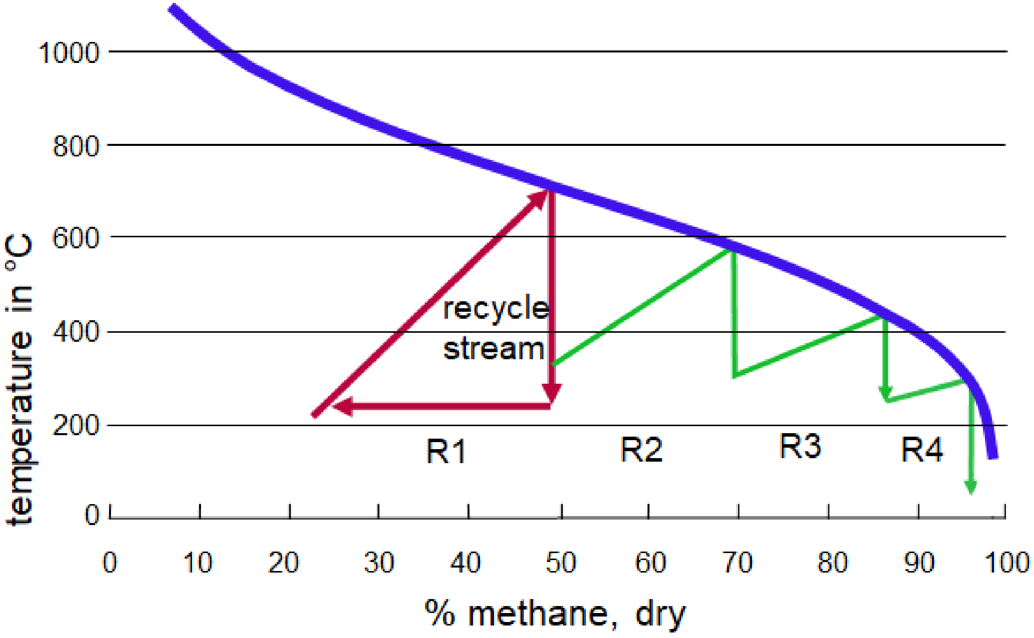
AspenPlus® model: RPlug

$T_{max,R1}$[3] = 700 °C

$T_{in,R1}$ = 250 °C

p[2] = 20-30 bar

GHSV[2] = 4200-8900



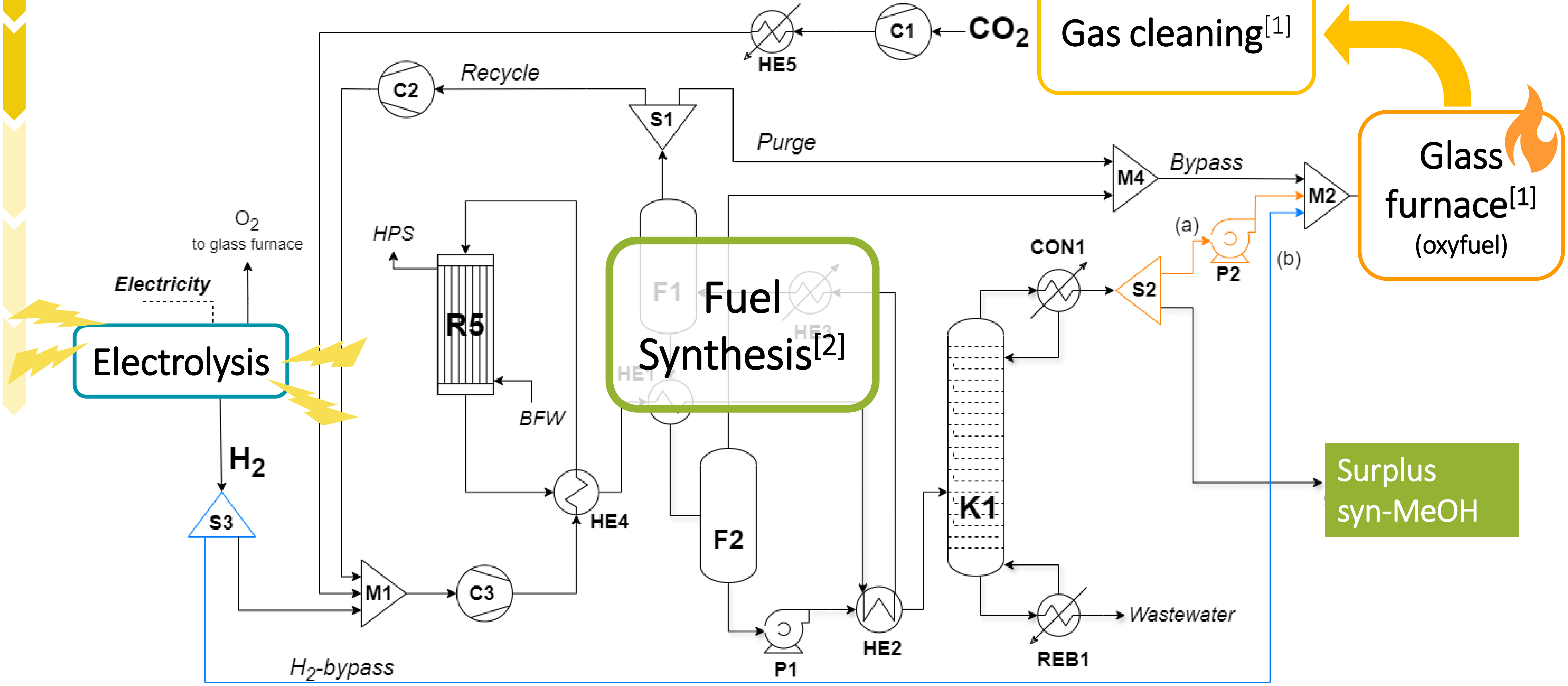
Kinetic model: **Rönsch et al.**[3-5]
Combination of WGS and CO-Methanation

Catalyst[2] MCR-2X (Ni-based)
→ Gas cleaning required

[1] Topsøe, H., From coal to clean energy. 2011
[2] in range of: Harms, H., B. Höhlein, and A. Skov, 1980, Methanisierung kohlenmonoxidreicher Gase beim Energie-Transport.
[3] Rönsch et al., 2016, Review on methanation – From fundamentals to current projects.
[4] Klose, J., 1984, Kinetics of the methanation of carbon monoxide on an alumina-supported nickel catalyst. Journal of Catalysis
[5] Zhang, J., et al., 2013, Kinetic investigation of carbon monoxide hydrogenation under realistic conditions of methanation of biomass derived syngas
[6] Meylan et al., 2016, Material constraints related to storage of future European renewable electricity surpluses with CO2 methanation

Process description

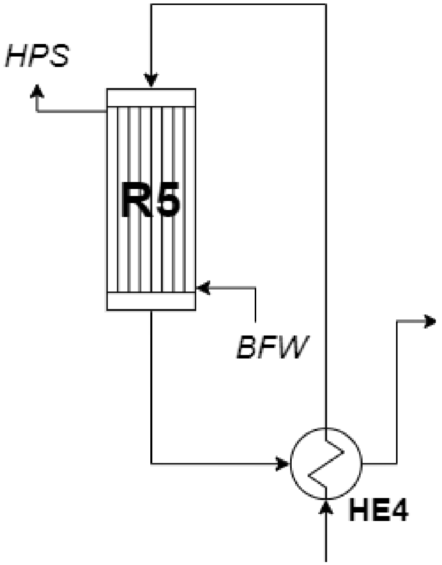
Process flow diagram: Syn-MeOH



[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

Process description
Reactor design and parameters: Syn-MeOH

Lurgi reactor design[2]: high energetic efficiency & steam generation applicable



AspenPlus® model[1]: RPlug

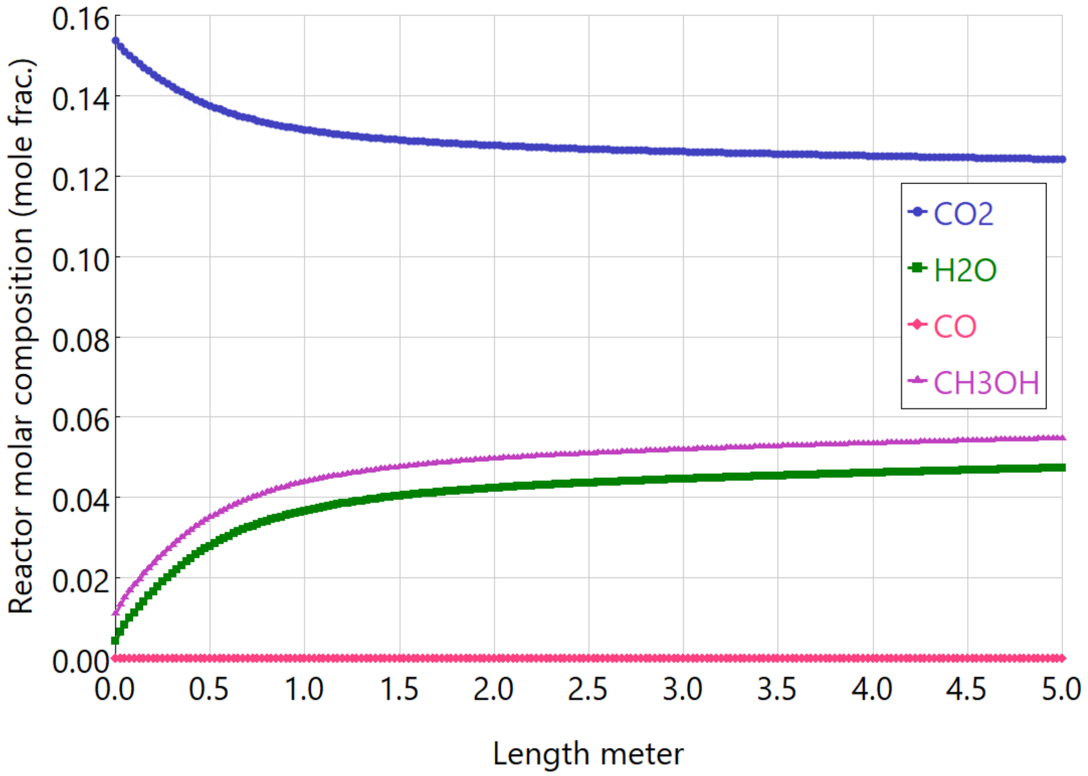
$T_{max,R1}$[2,5]= 280-300 °C

$T_{in,R1}$[1] = 230 °C

p[1,2] = 80 bar

Catalyst[3] $Cu/ZnO/Al_2O_3$

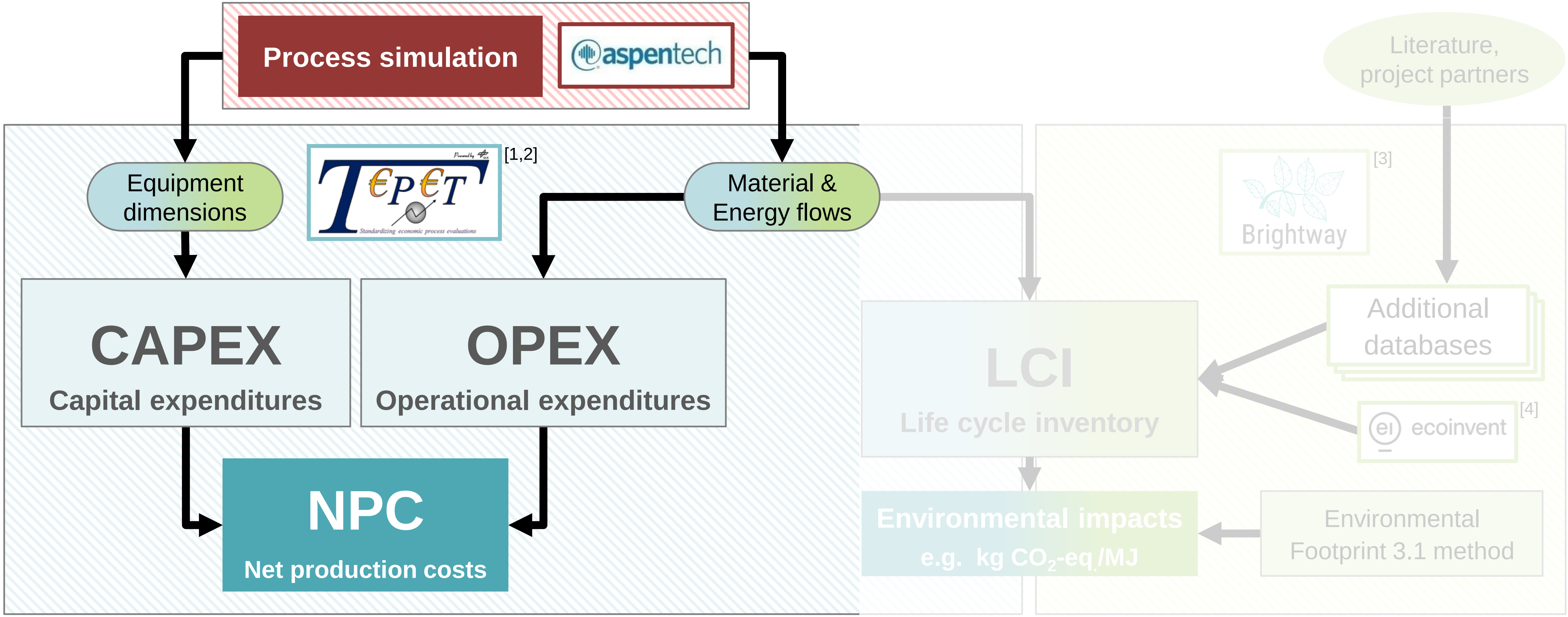
→ Gas cleaning required



Kinetic model: **Vanden Bussche and Froment**[1,3]
MeOH synthesis from $CO/CO_2/H_2$ represented as CO_2 hydrogenation & RWGS reactions

[1] Rahmat et al. (2023) Techno-economic and exergy analysis of e-MeOH production https://doi.org/10.1016/j.apenergy.2023.121738
[2] Metallgesellschaft AG (1996) – EP 0 790 226 B1
[3] Van-Dal and Bouallou (2013) Design and simulation of a methanol plant plant from CO_2 hydrogenation
[4] Bartholomew and Farrauto (2006) Fundamentals of Industrial Catalytic Processes, 2. Ed.

Techno-economic assessment (TEA)



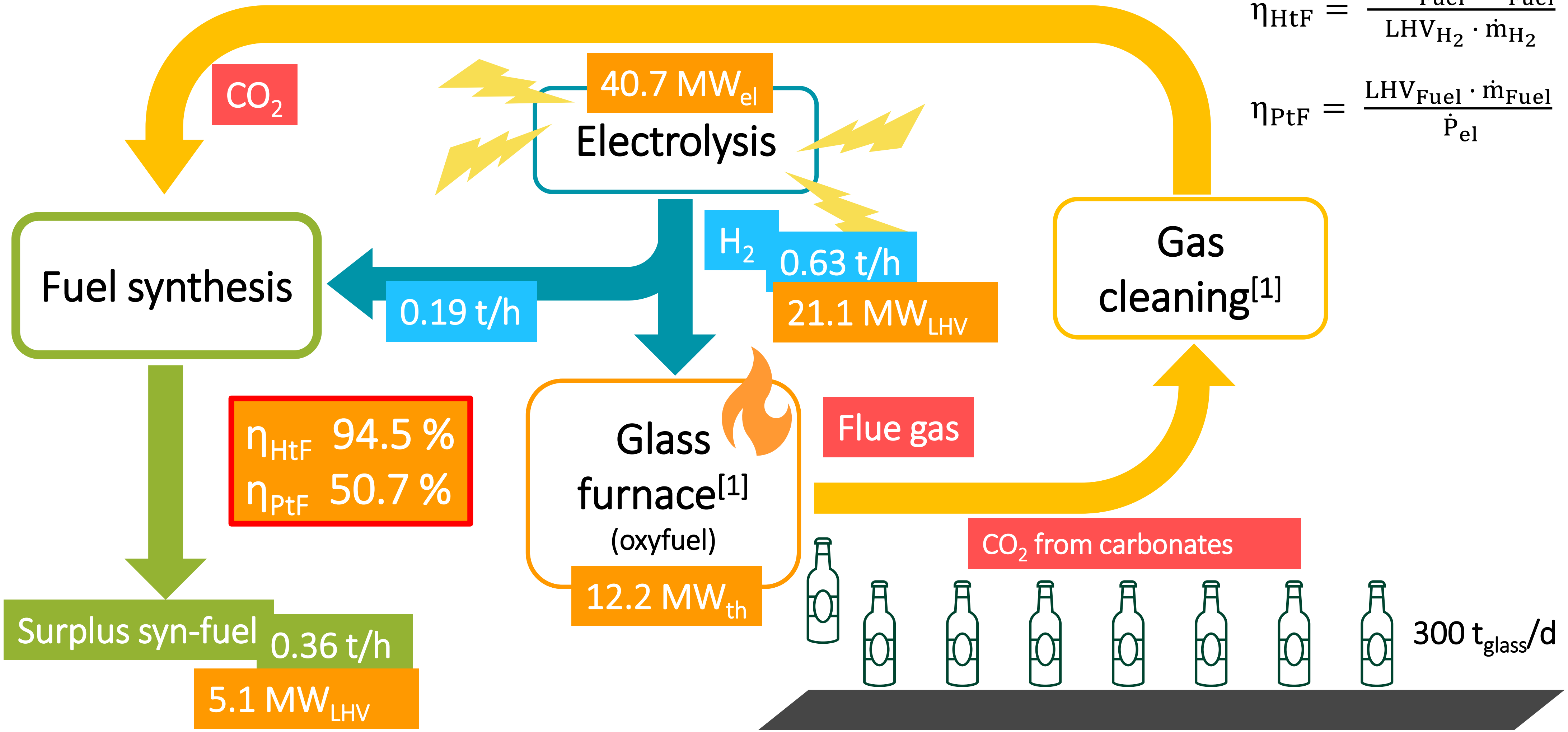
[1] Albrecht et al. (2016): https://doi.org/10.1016/j.fuel.2016.12.003
[2] Maier et al. (2021): https://doi.org/10.1016/j.enconman.2021.114651
[3] Mutel (2017): https://doi.org/10.21105/joss.00236
[4] Wernet et al. (2016): https://doi.org/10.1007/s11367-016-1087-8

Techno-economic assessment (TEA)

Efficiencies: SNG/H_2

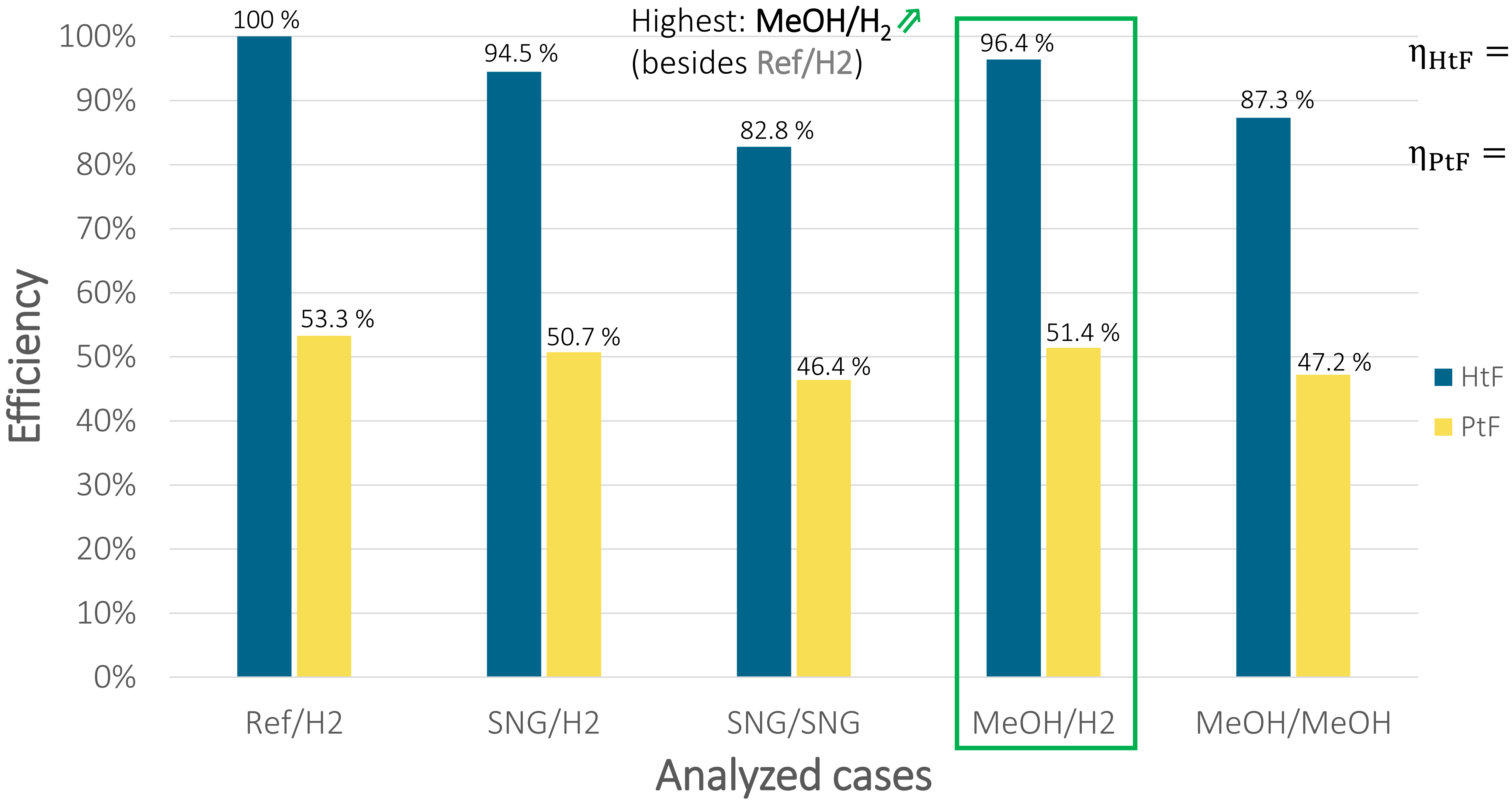
$$\eta_{HtF} = \frac{LHV_{Fuel} \cdot \dot{m}_{Fuel}}{LHV_{H_2} \cdot \dot{m}_{H_2}}$$

$$\eta_{PtF} = \frac{LHV_{Fuel} \cdot \dot{m}_{Fuel}}{\dot{P}_{el}}$$



[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.

Techno-economic assessment (TEA)
Efficiencies



$$\eta_{HtF} = \frac{LHV_{Fuel} \cdot \dot{m}_{Fuel}}{LHV_{H_2} \cdot \dot{m}_{H_2}}$$

$$\eta_{PtF} = \frac{LHV_{Fuel} \cdot \dot{m}_{Fuel}}{\dot{P}_{el}}$$

Techno-economic assessment (TEA)
Input – basis conditions & OPEX

Basis conditions	
Plant location	Germany
Base year	2022
Basis currency	€
Full-load hours	8000 h/a
Plant lifetime (y)	15 a
Interest rate (IR)	7 %
Labor costs	41 €/h

Raw materials	
CO_2	Flue gas & carbonates
H_2	AEL electrolysis
Electricity[1]	60-250 €/MWh_{el}
Utilities	taken from [2]

$$NPC\ \left[{}^{€}/_{MWh_{LHV}}\right] = \frac{ACC + \sum OPEX + labor\ costs}{\dot{m}_{synfuel} * LHV_{synfuel}}$$

[2,3]

$$ACC = FCI * Annuity\ factor$$

$$FCI_i = EC_i \times \sum CAPEX\ cost\ factors$$

See next slide!

[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.
[2] Heimann et al. (2023) Contribution to the standardization of the economic and ecological analysis of PtX-process [in submission]
[3] Peters et al. (2002) *Design and Economics for Chemical Engineers*. Europe: McGraw-Hill Education.

Techno-economic assessment (TEA)
Input – CAPEX cost functions

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

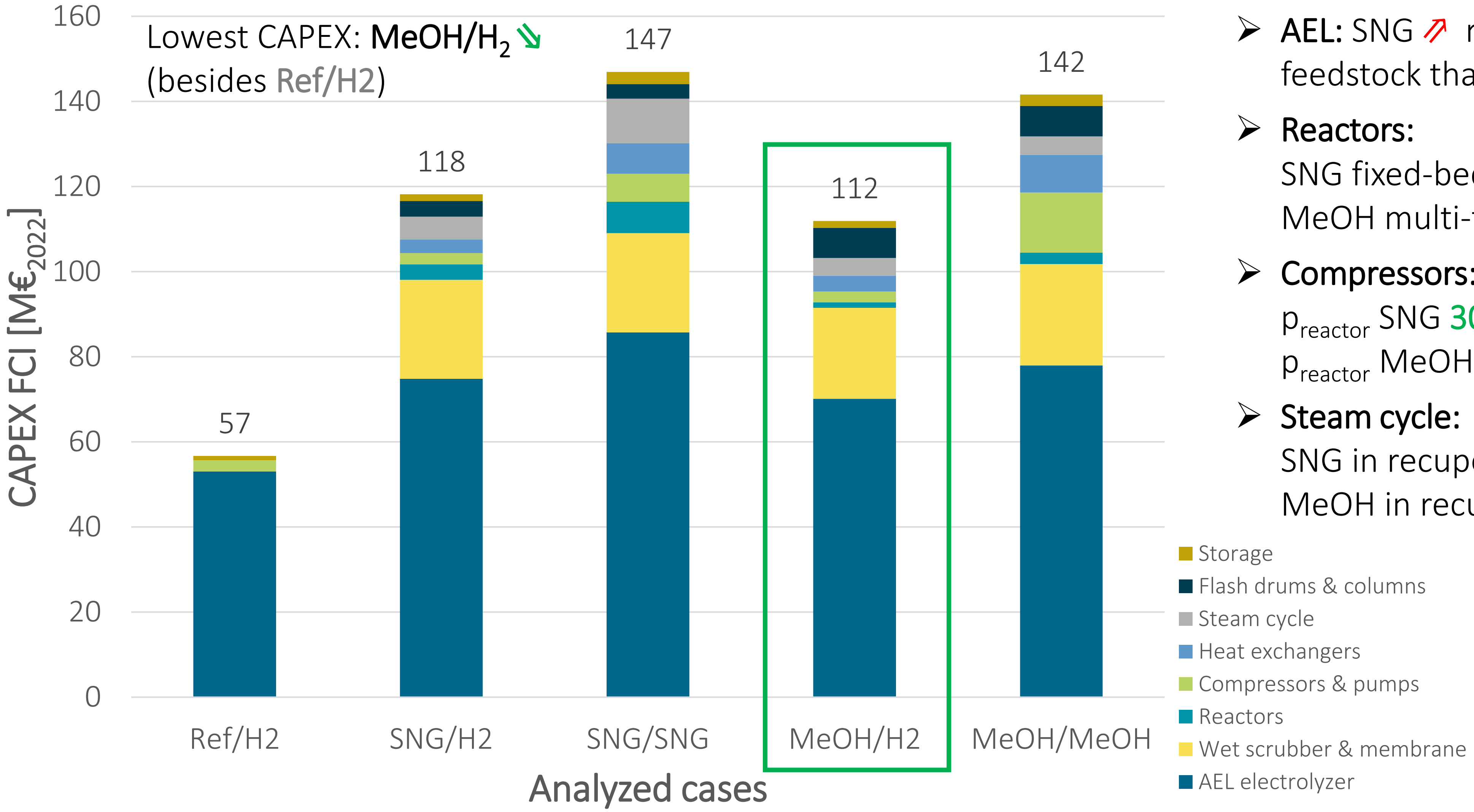
$$EC_{i,poly} = \left[e \cdot (sizing_i)^2 + f \cdot sizing_i + g\right] \times \left(\frac{CEPCI_i}{CEPCI_{ref}}\right)$$

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	m^3/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 [m^2]	$	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
[6] Samei and Raisi (2022) Separation of nitrogen from methane by multi-stage membrane

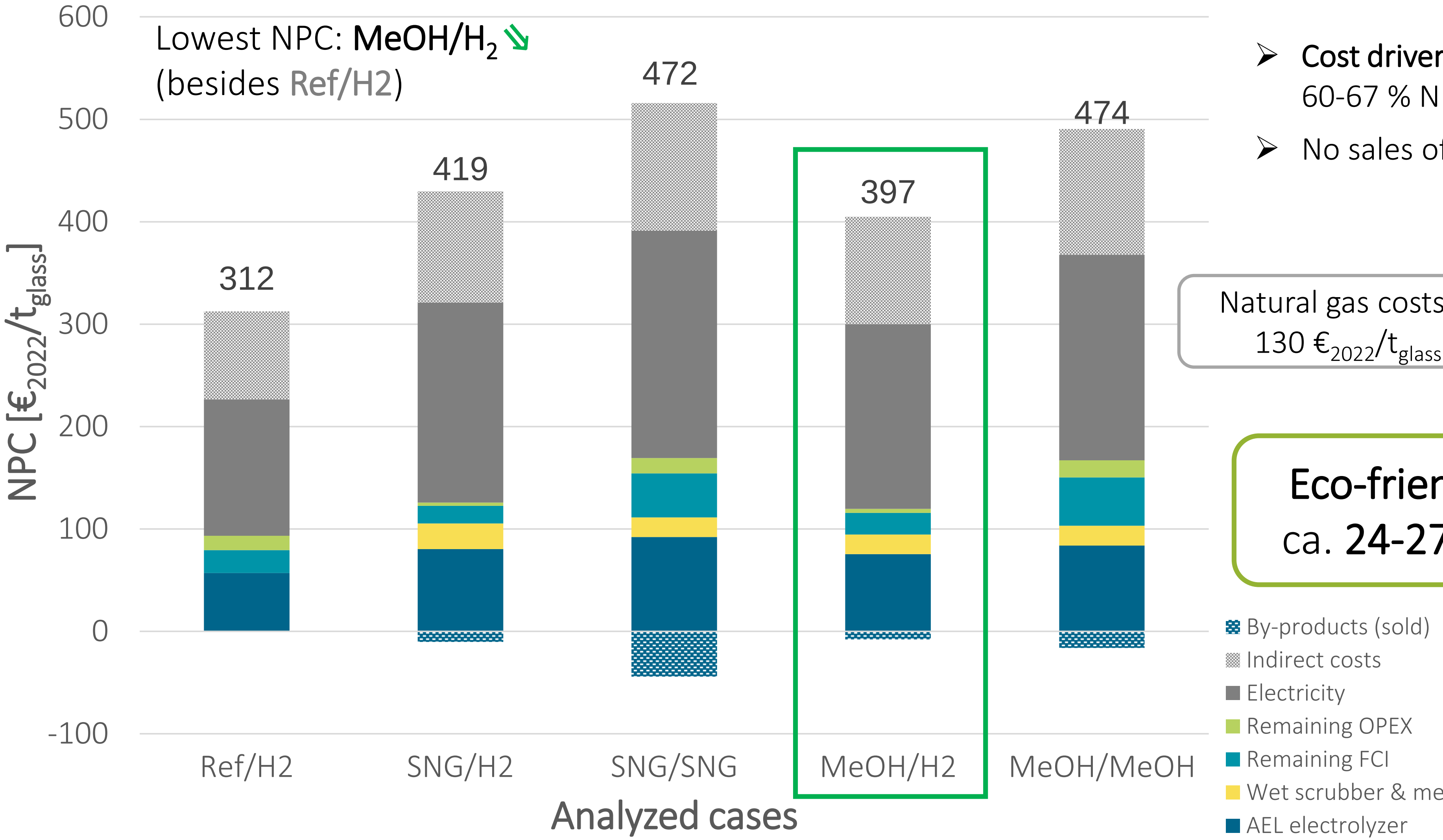
TEA for 12.2 MW_{th} Glass Furnace
Results – CAPEX Fixed Capital Investment (FCI)



- **AEL:** SNG ⇗ requires more H_2 feedstock than MeOH ⇘
- **Reactors:**
  SNG fixed-bed **multi-stage** ⇗
  MeOH multi-tube **single-stage** ⇘
- **Compressors:**
  $p_{reactor}$ SNG **30 bar** ⇘
  $p_{reactor}$ MeOH **80 bar** ⇗
- **Steam cycle:**
  SNG in recuperator & reactor
  MeOH in recuperator only

TEA for 12.2 MW_{th} Glass Furnace

Results – NPC with electricity price 60 $€_{2022}/MWh_{el}$



- **Cost driver is H_2 generation**
  60-67 % NPC
- No sales of surplus synfuel products

Natural gas costs[1]
130 $€_{2022}/t_{glass}$

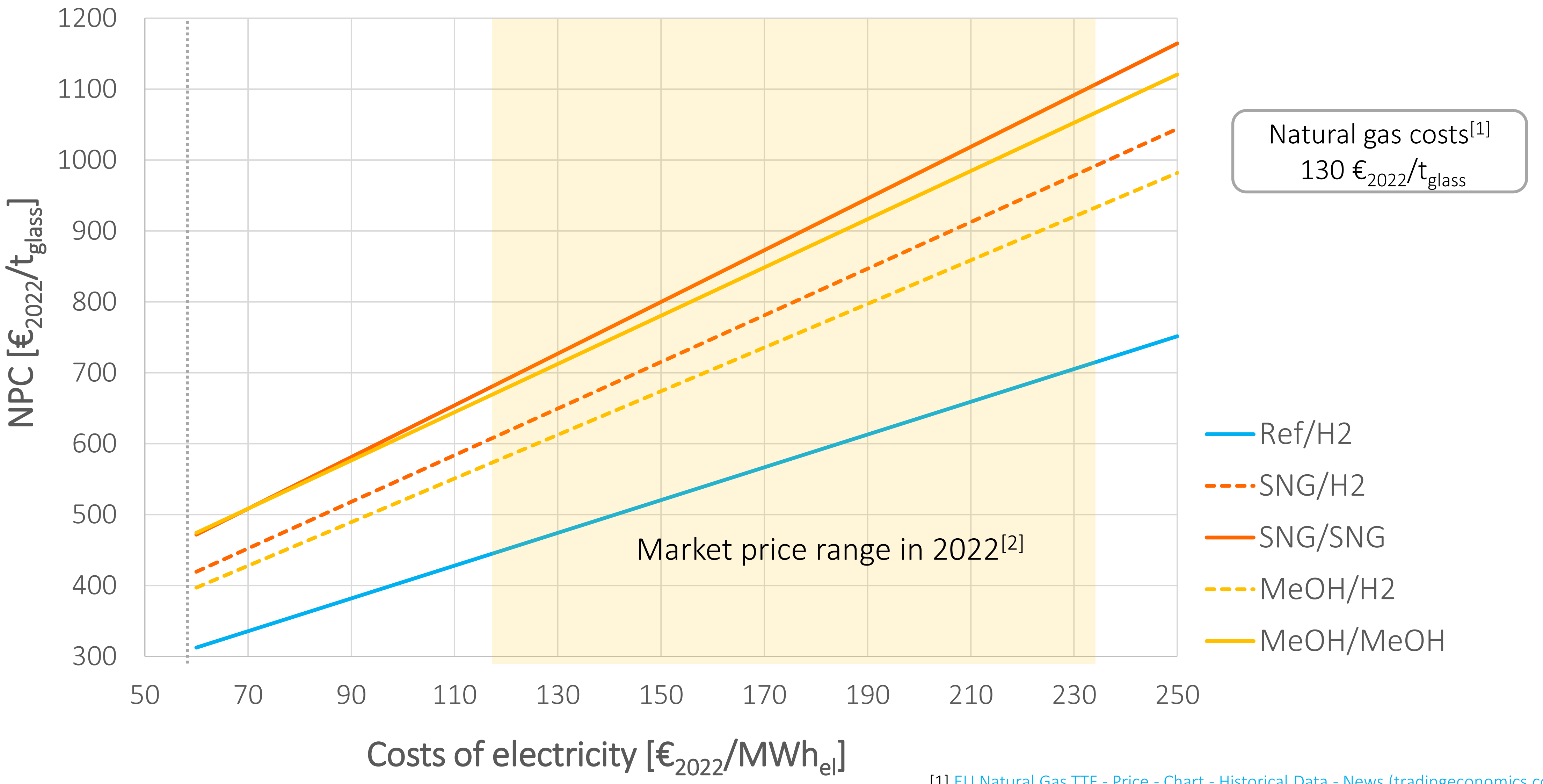
Beer bottle (330 g) price
up to 15 ct. $€_{2022}$/bottle[2]

Eco-friendly beer bottle
ca. **24-27 ct.** $€_{2022}$/bottle

[1] EU Natural Gas TTF - Price - Chart - Historical Data - News (tradingeconomics.com)
[2] HVG-DGG internal price estimation

Techno-economic assessment (TEA)

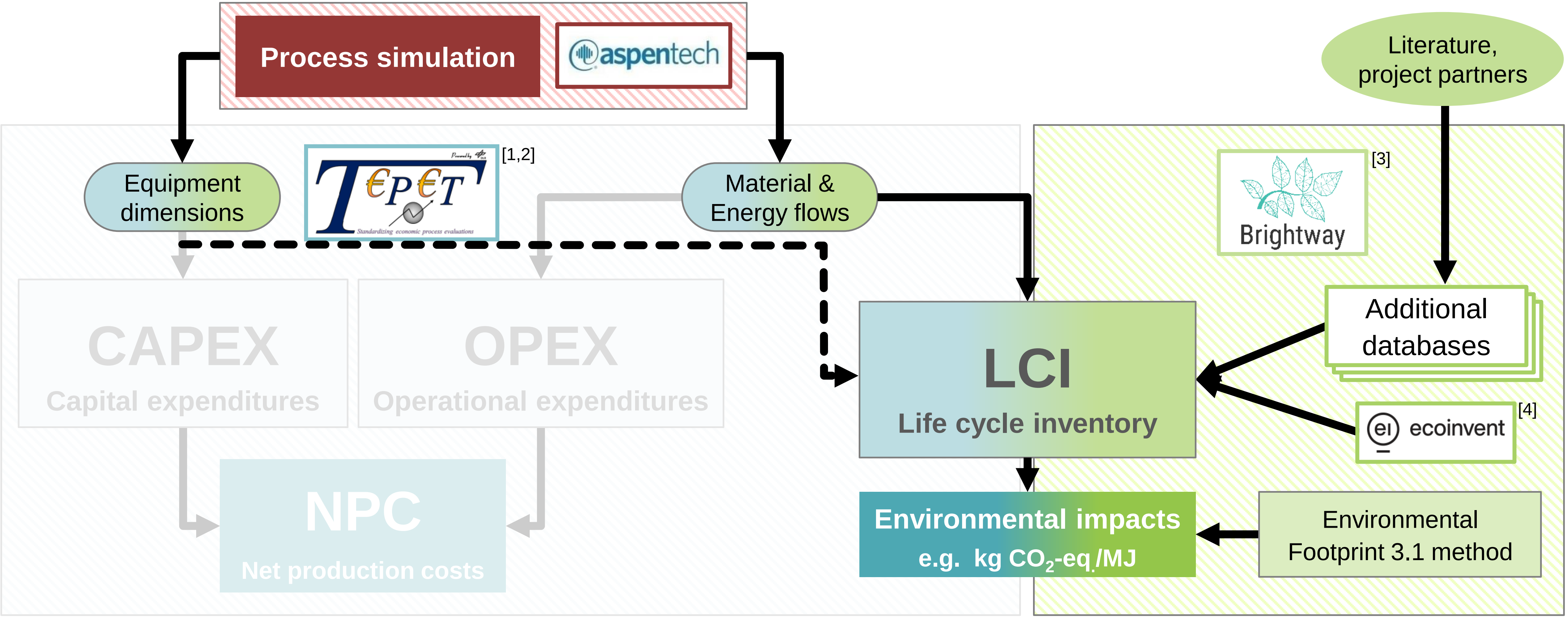
Results – NPC sensitivity analysis



[1] EU Natural Gas TTF - Price - Chart - Historical Data - News (tradingeconomics.com)
[2] SMARD.de

Life cycle assessment (LCA)

Functional unit: 1 tonne glass produced



[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

LCI dataset (preliminary)
SNG/SNG case

Functional unit: 1 tonne glass produced

German grid electricity as the el. source

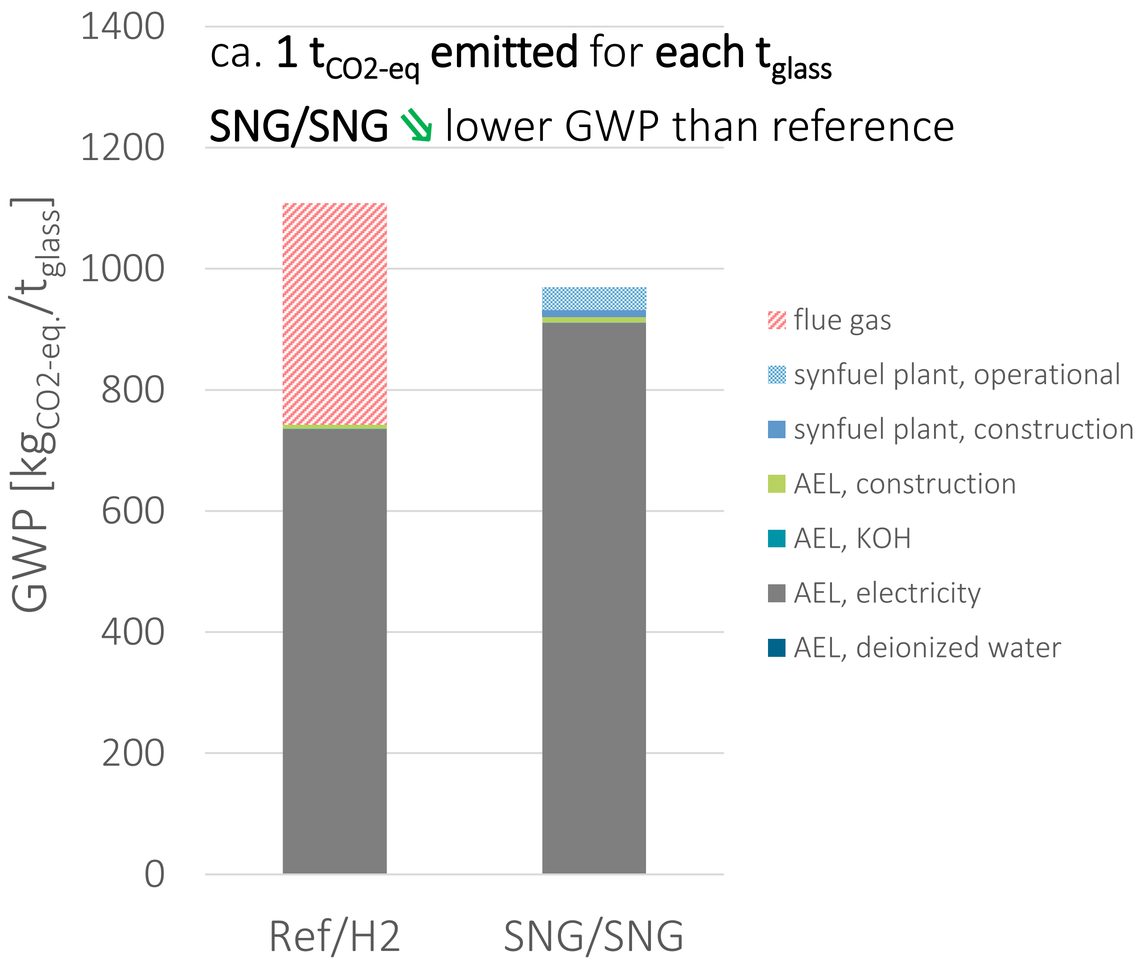
Case:	SNG/SNG							
Subsystem:	**Synthesis**							
Description	**Stream**	**Material**	**Value**	**Unit**	**Comments**	**Acitivity**	**Location**	**Ecoinvent Key**
Catalyst		Ni/Al_2O_3	897	kg/year		Ni/Al2O3 catalyst	GLO	('GlasCO2_ MeOH', '44376fc1035a4ff198ace35afec4e1ec_copy1')
Purge	PURGE	CO_2, etc.						
Excess MeOH	MEOHSALE	MeOH, etc.	0.20435	kg/s				
Wastewater 3	WW3	H_2O			wasterwater,average			('GlasCO2_ MeOH', '44d4f7c95e2241e08c6979e87fb404e6_copy3')
Wastewater 4	WW3	H_2O			wasterwater,average			('GlasCO2_ MeOH', '44d4f7c95e2241e08c6979e87fb404e6_copy4')
Subsystem:	**Furnace**							
Description	**Stream**	**Material**	**Value**	**Unit**	**Comments**	**Acitivity**	**Location**	**Ecoinvent Key**
N_2-IN	N_2-IN	Nitrogen	0.2	kg/sec				
O_2-IN	O2-IN	Oxygen	0.87311	kg/sec				
Contaminants and CO_2	60-16-IN	CO_2, etc.	0.37507	kg/sec				
Subsystem:	**Gas Cleaning**							
Description	**Stream**	**Material**	**Value**	**Unit**	**Comments**	**Acitivity**	**Location**	**Ecoinvent Key**
Quench water IN	CWQUENCH	H_2O				freshwater quench stream conversion		('GlasCO2_stream conversion', 'fa7b75f6c48840fd86c7ce41e2ee491c')
Quench water OUT	WWQUENCH	H_2O, SO_3, etc...			wastewater average + pollution	wastewater quench stream conversion		('GlasCO2_stream conversion', 'baf33e7e827e46bcbbcd9966b0472a06')
Retentant from membran	RETENTAT	N_2, CO_2				membrane retentant stream conversion		('GlasCO2_stream conversion', '7b8a65c32d02487da4793ad5ae6afd14')
PMP-Membrane	MEMB-OUT	PMP Membran				membrane stream conversion		('GlasCO2_stream conversion', 'ee296759315341eaa3b1f295c2525d08')
H_2 (hydrogenation)					in H_2-Produktion enthalten			
Fe/Al_2O_3 -catalyst (hydrogen	60-32-33	Fe/Al_2O_3				hydrogenation stream conversion	RER	('GlasCO2_stream conversion', '125287071cdb4b50a21b09339524f8de_copy1')
Alaklized Aluminum-guard b	60-32-33	Alkalized Aluminum			Sodium aluminate	Al2O3 guard bed stream conversion	GLO	('GlasCO2_stream conversion', '6983676d7fc8455d997bf99c6d3ca7a2_copy1')
ZnO IN	H2S-FLOW	ZnO	0.00028	kg/sec	berechnung ZnO anhand H2S stream	H2S stream conversion	RER	('GlasCO2_stream conversion', '383e324de9cf42e38817b7f9281ee4e9')

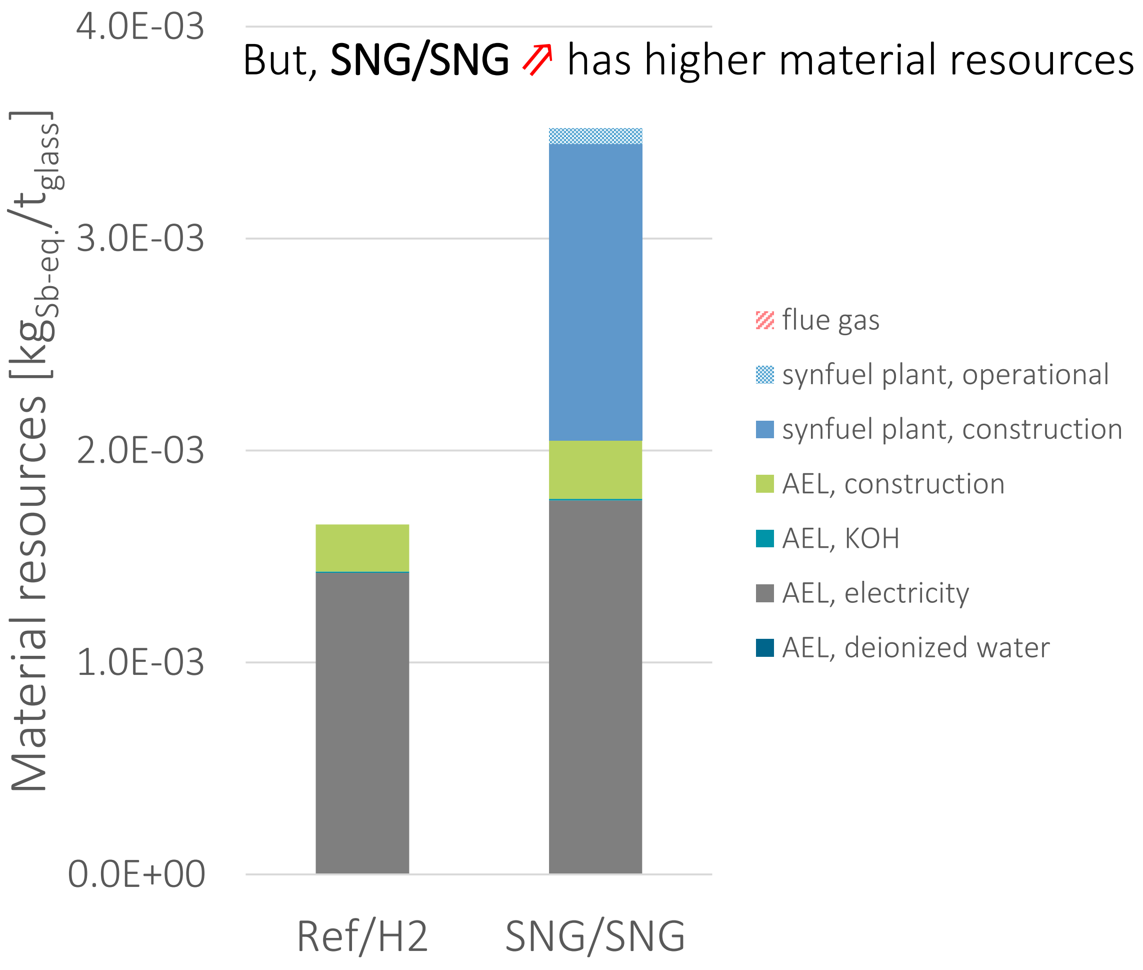
LCA results (preliminary)

Ref/H_2 vs. SNG/SNG

Functional unit: 1 tonne glass produced

German grid electricity as the el. source





Conclusion

- Implementation of Power-to-X concepts for a sustainable industrial glass production
  → Valorization of the difficult-to-avoid CO_2 emissions from carbonates
- Glass industry can be **sustainable**, depending on the electricity source
- CCU is **theoretically applicable**
  → Practical tests must be conducted
- **Eco-friendly container glass** (beer bottle) would cost **almost twice** of the current price
  → depending on the electricity costs
- **Preliminary LCA** shows good potential of the PtX concept compared to the reference case, however a trade-off is expected, e.g. material resources impact

Realization = f(**user-acceptance**)
Industry? Market?

Outlook

- Complete **LCA** for all PtX cases, along with sensitivity analyses regarding electricity source and allocation approach, i.e. economic and energetic allocation
- Concept **adaptation to other industries**, e.g. cement, steel, chemical
- Pilot plant in the follow-up project
  → Currently looking for project partners

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