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ArdaghGlass

SCHOTT
glass made of ideas

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Making our world
more productive

DECHEMA FORUM
Wissenschaft und Industrie im Dialog

POWER-TO-X FOR SUSTAINABLE GLASS PRODUCTION (SYN-METHANE, SYN-MEOH, AND DIRECT H_2 COMBUSTION) 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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GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Background

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

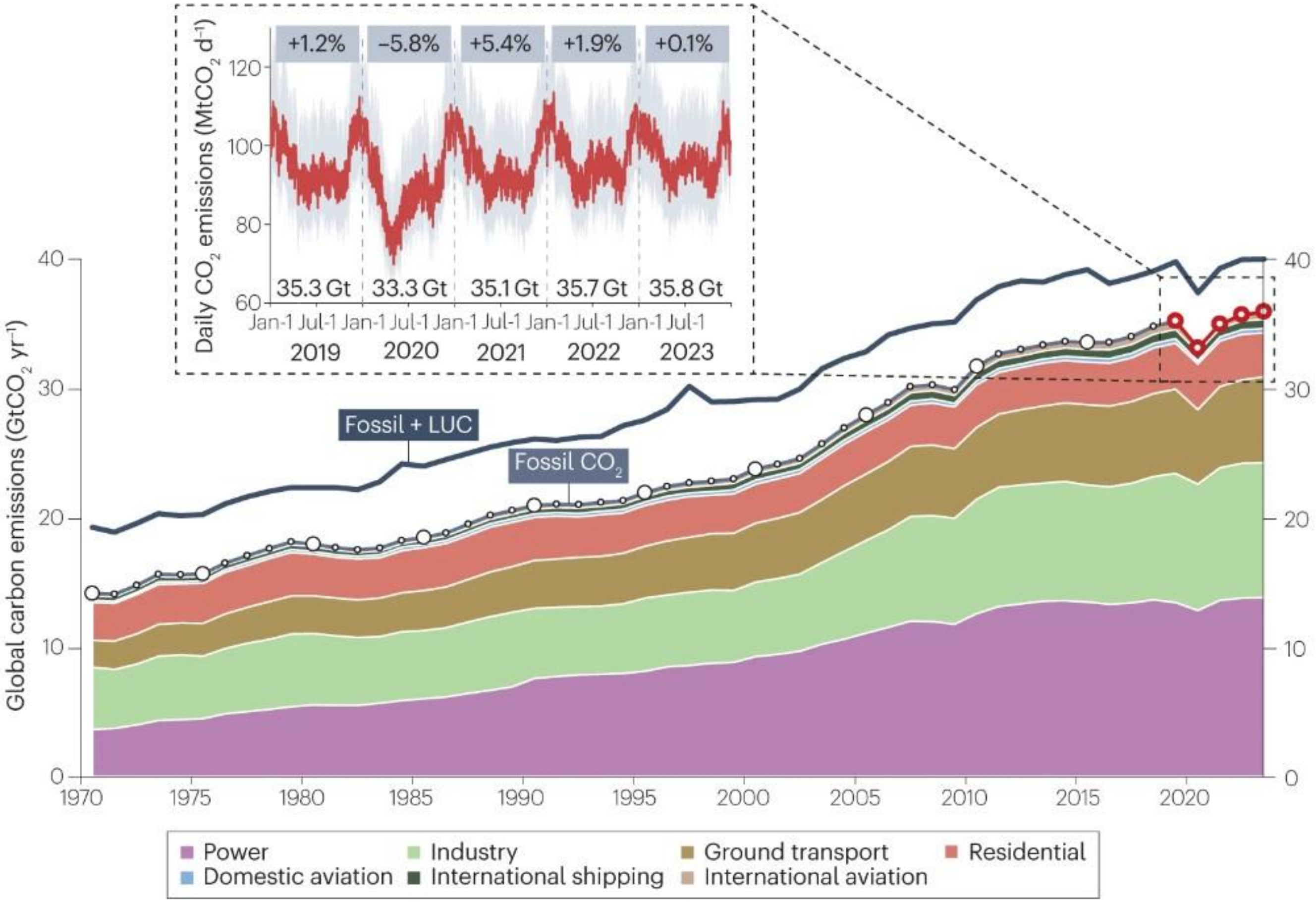
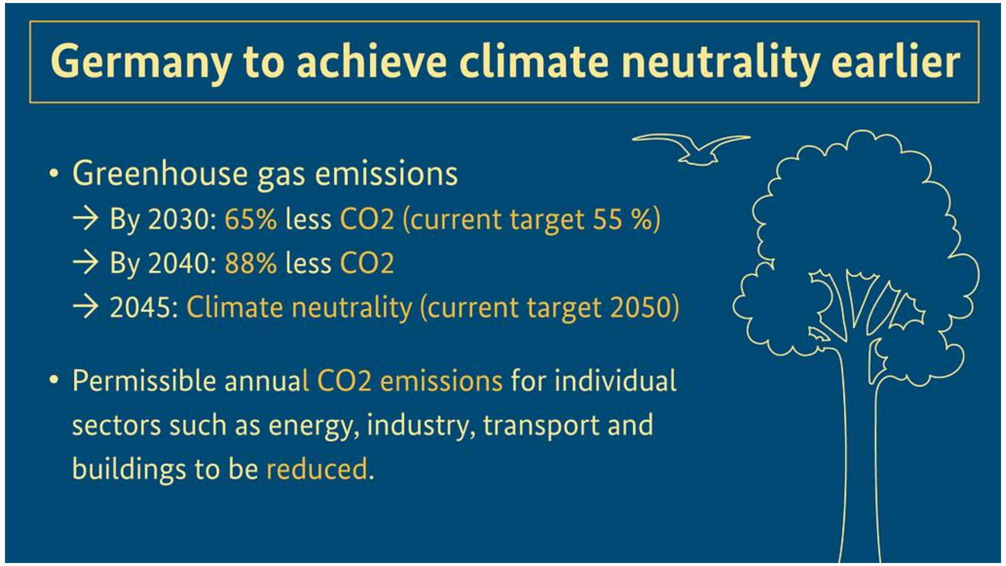


Fig.2: German climate neutrality goal [2]



Germany to achieve climate neutrality earlier

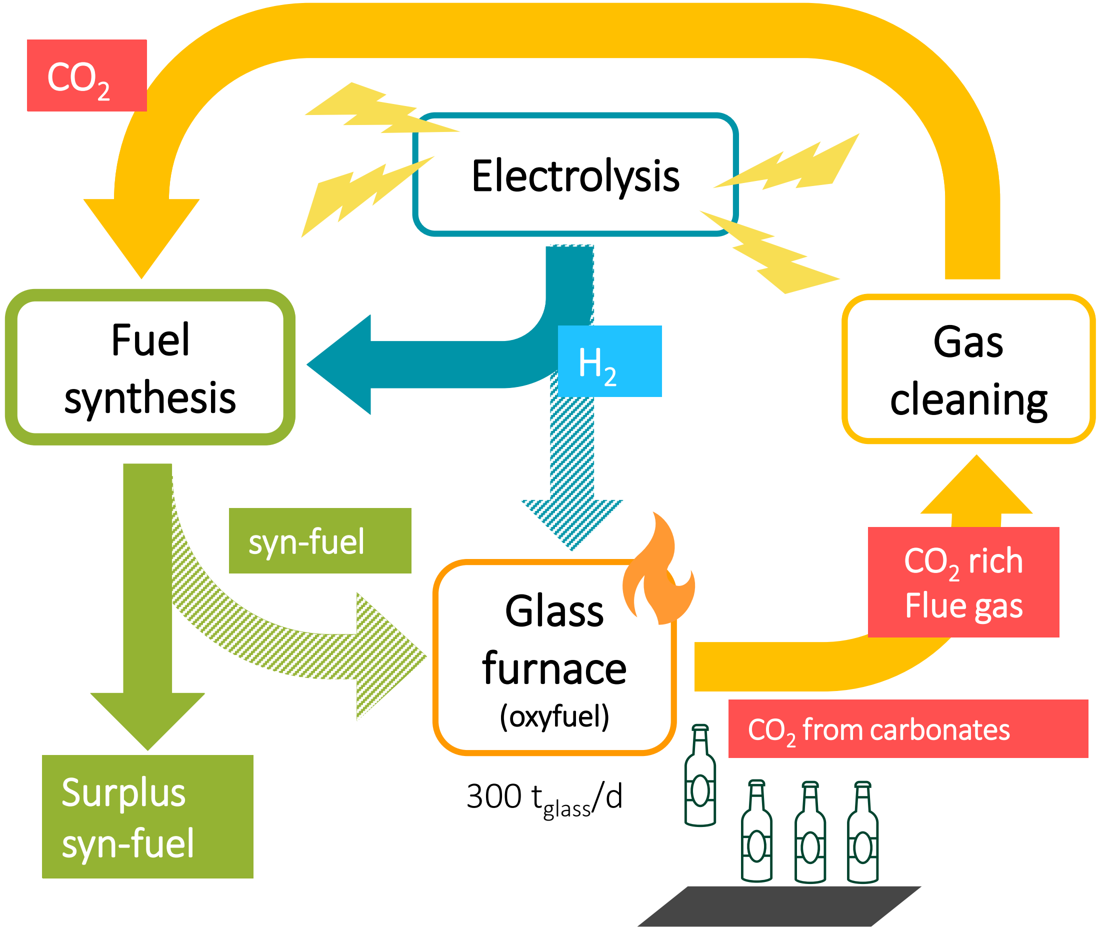
- Greenhouse gas emissions
  - → By 2030: 65% less CO2 (current target 55 %)
  - → By 2040: 88% less CO2
  - → 2045: Climate neutrality (current target 2050)
- Permissible annual CO2 emissions for individual sectors such as energy, industry, transport and buildings to be reduced.

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

[2] Climate Change Act - climate neutrality by 2045 (bundesregierung.de)

Background

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



- Power-to-X: alternative to full electrification
  - only 60-80 % electrification possible (hybrid)
- Valorization difficult-to-avoid CO_2 from carbonates

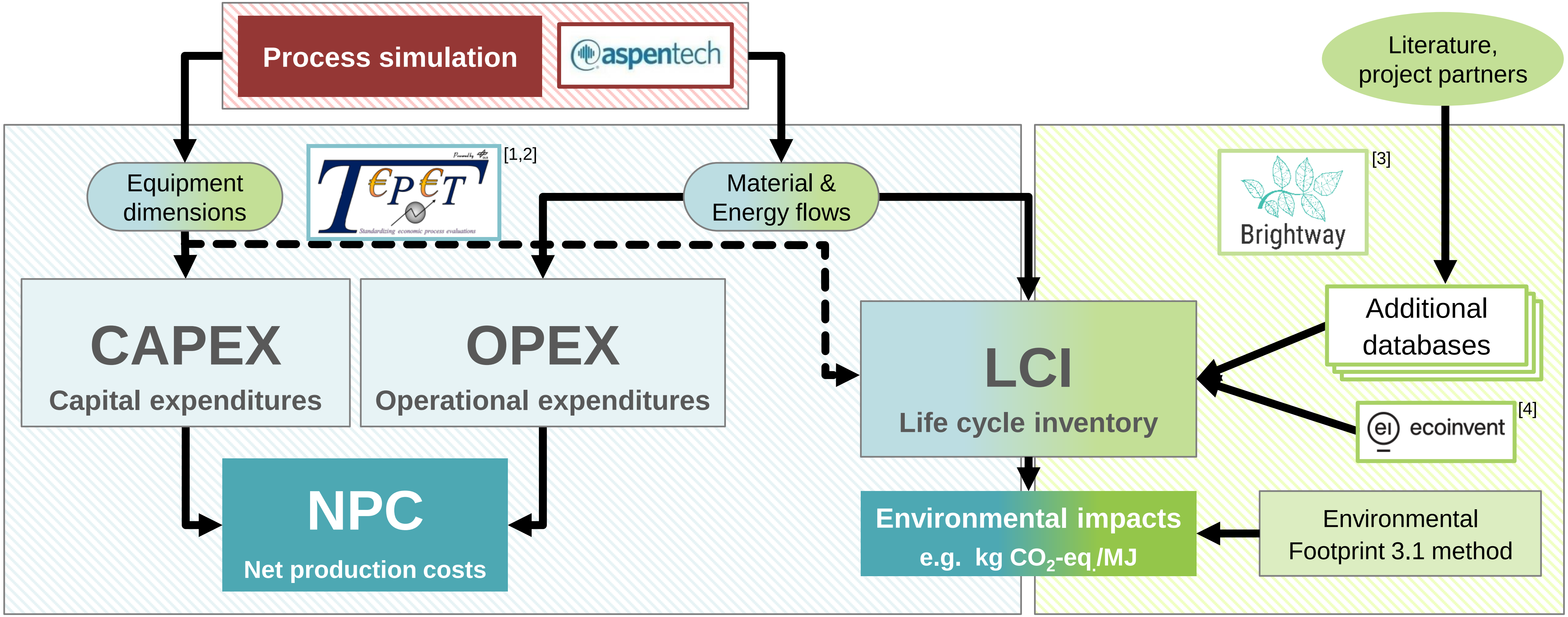
4.2 Mt CO_2 ⟹ 1 Mt CO_2

Case	Gas cleaning	Heating fuel	Surplus
SNG/SNG	✓	SNG	SNG
MeOH/MeOH	✓	Syn-MeOH	Syn-MeOH
H_2/SNG	✓	H_2	SNG
H_2/MeOH	✓	H_2	Syn-MeOH
H_2/CO_2	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.

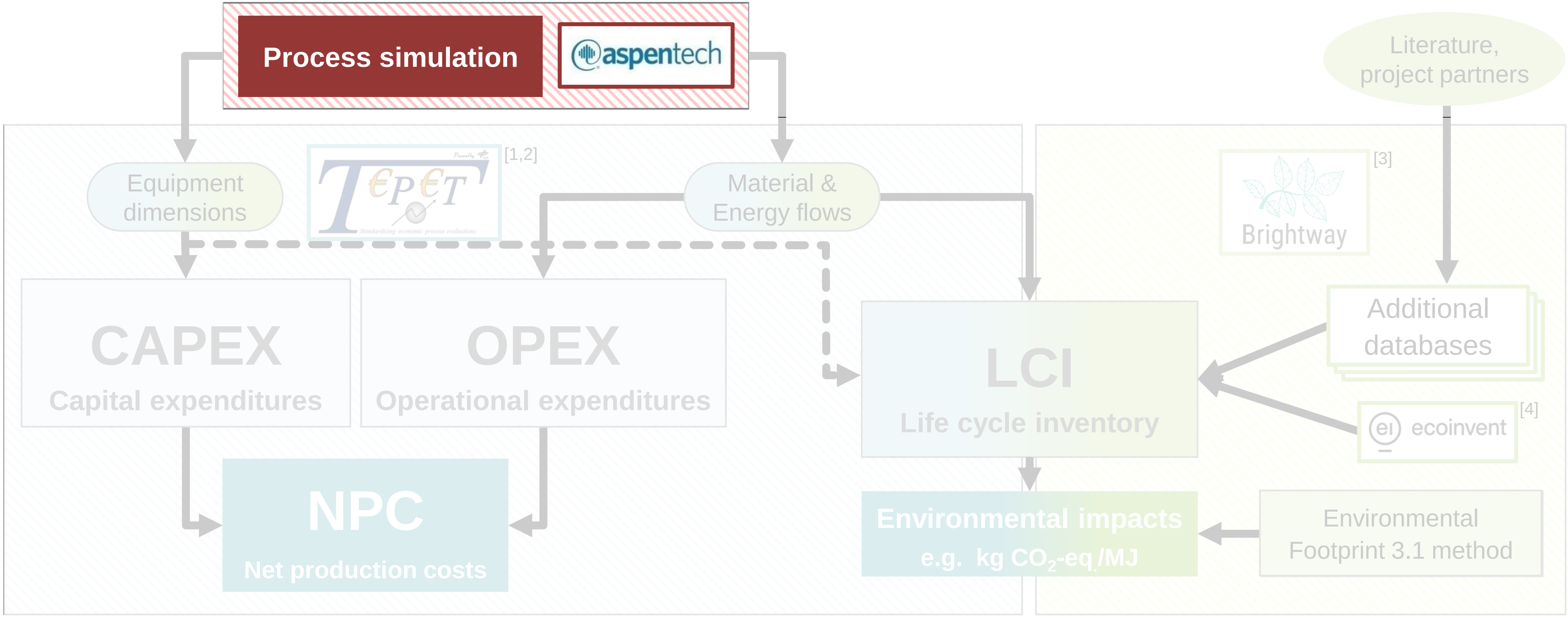
Methodology

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



Process simulation

aspentech

Equipment dimensions

[1,2]

Material & Energy flows

Literature, project partners

[3]

Brightway

CAPEX

Capital expenditures

OPEX

Operational expenditures

LCI

Life cycle inventory

Additional databases

[4]

ecoinvent

NPC

Net production costs

Environmental impacts

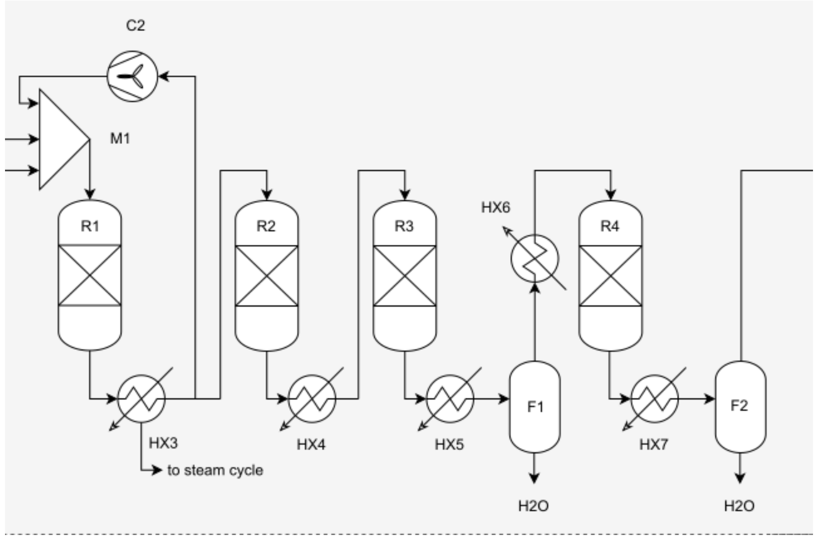
e.g. kg CO_2-eq./MJ

Environmental Footprint 3.1 method

[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
Reactor design and parameters: SNG

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



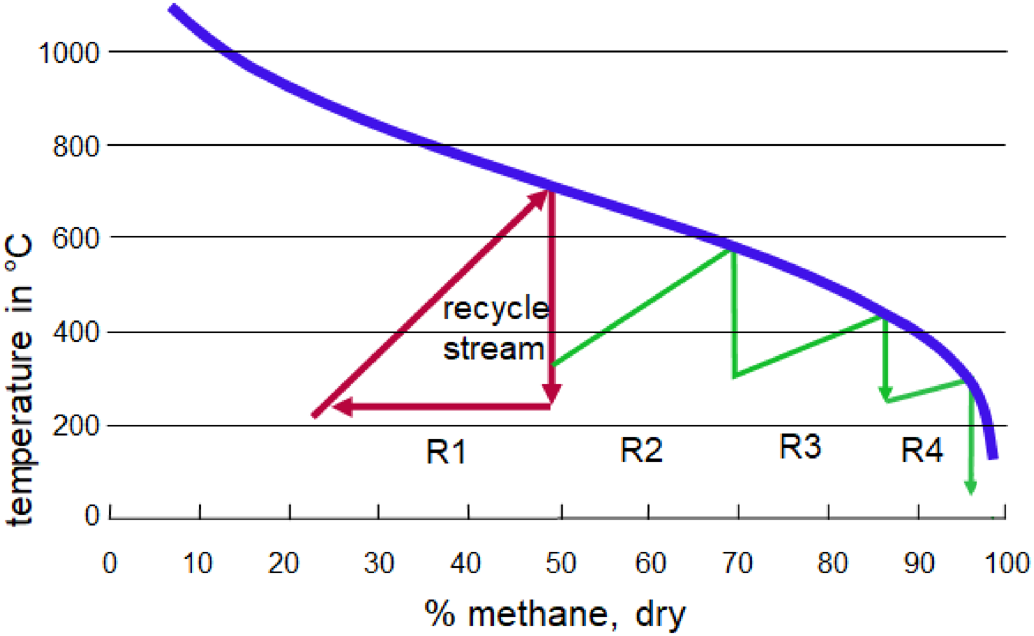
AspenPlus® model: RPlug

$T_{max,R1}$[3] = 700 °C

$T_{in,R1}$ = 250 °C

p[2] = 20-30 bar

GHSV[2] = 4200-8900



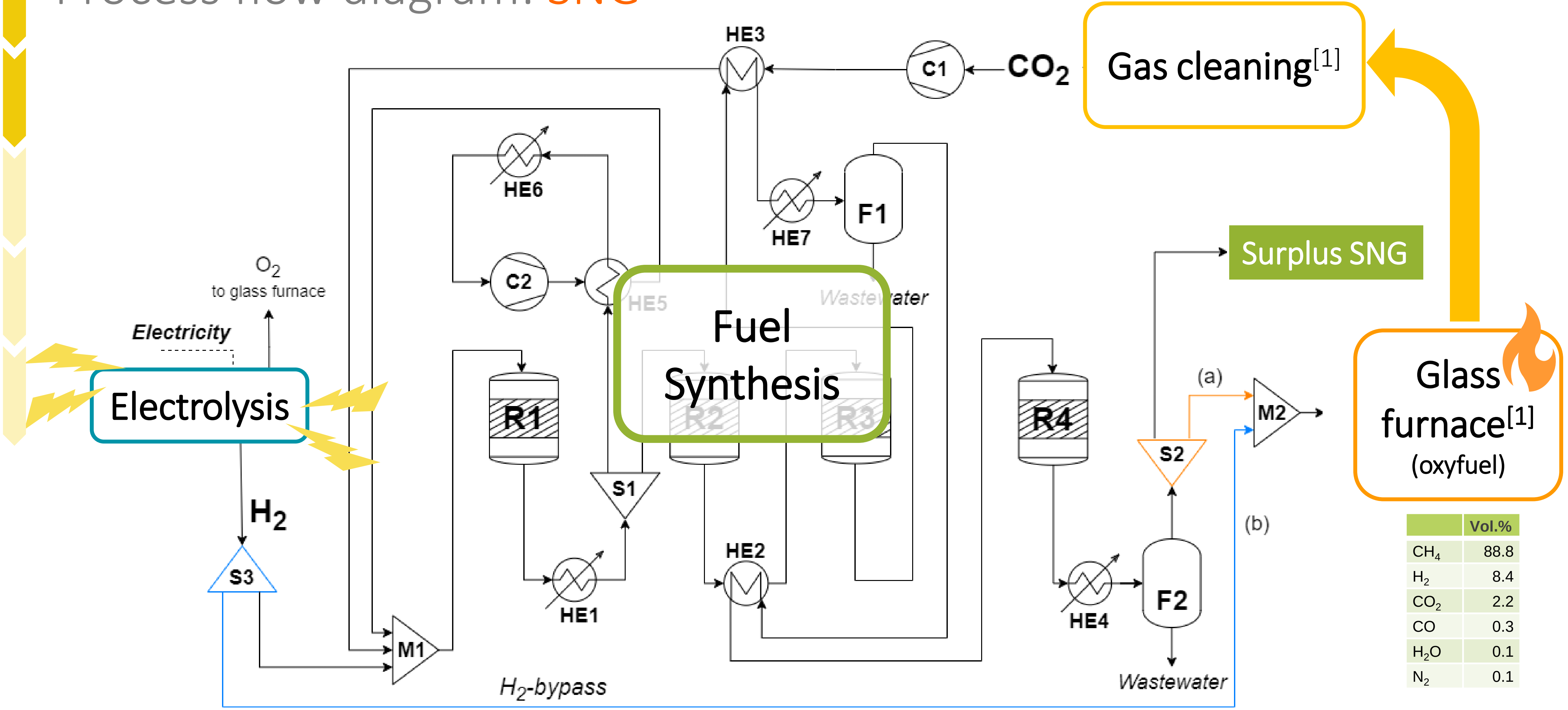
Kinetic model: **Rönsch et al.**[3-5]
Combination of WGS and CO-Methanation

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: SNG



Gas cleaning[1]

Electrolysis

Fuel Synthesis

Surplus SNG

Glass furnace[1]
(oxyfuel)

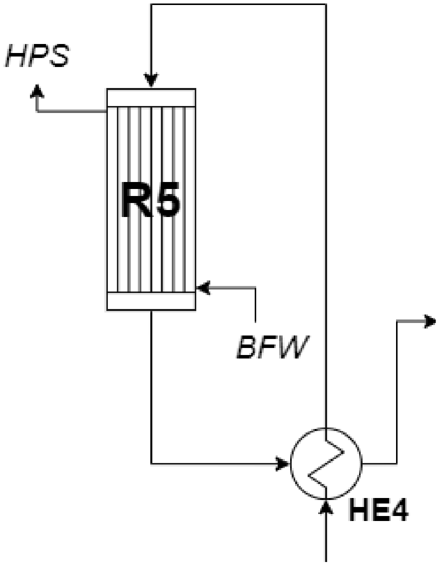
	Vol.%
CH_4	88.8
H_2	8.4
CO_2	2.2
CO	0.3
H_2O	0.1
N_2	0.1

---

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

Process description
Reactor design and parameters: Syn-MeOH

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



AspenPlus® model[1]: RPlug

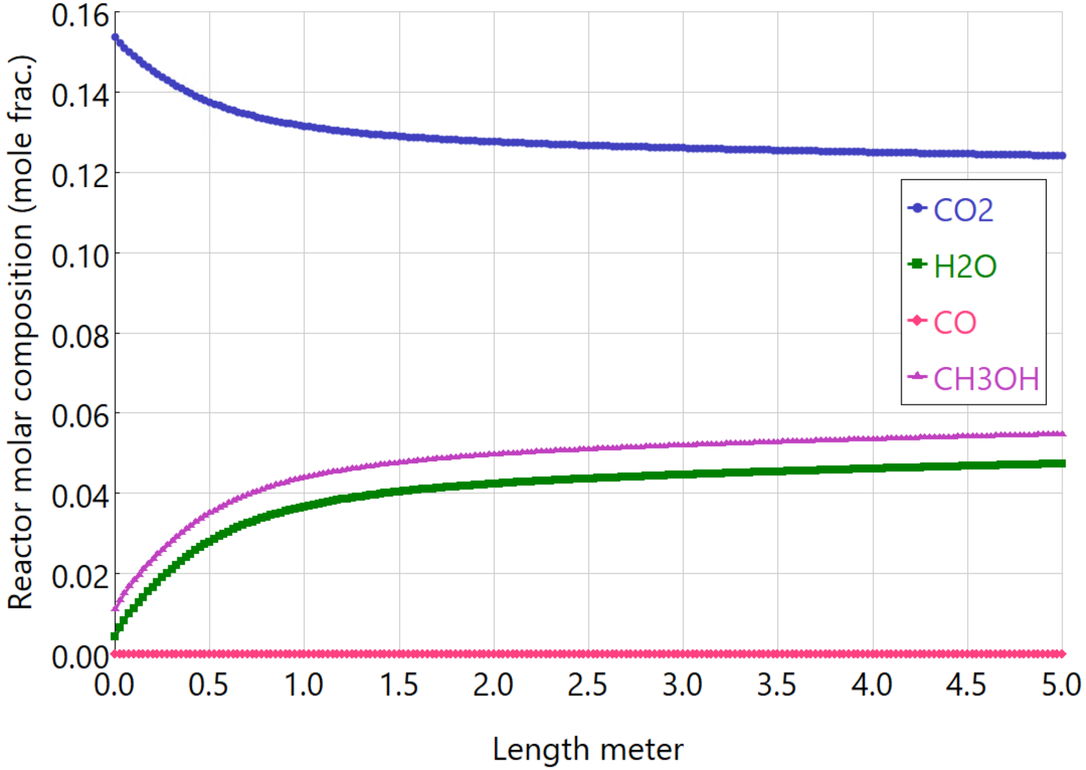
$T_{max,R1}$[2,5]= 280-300 °C

$T_{in,R1}$[1] = 230 °C

p[1,2] = 80 bar

Catalyst[3] Cu/ZnO/Al_2O_3

→ Gas cleaning required

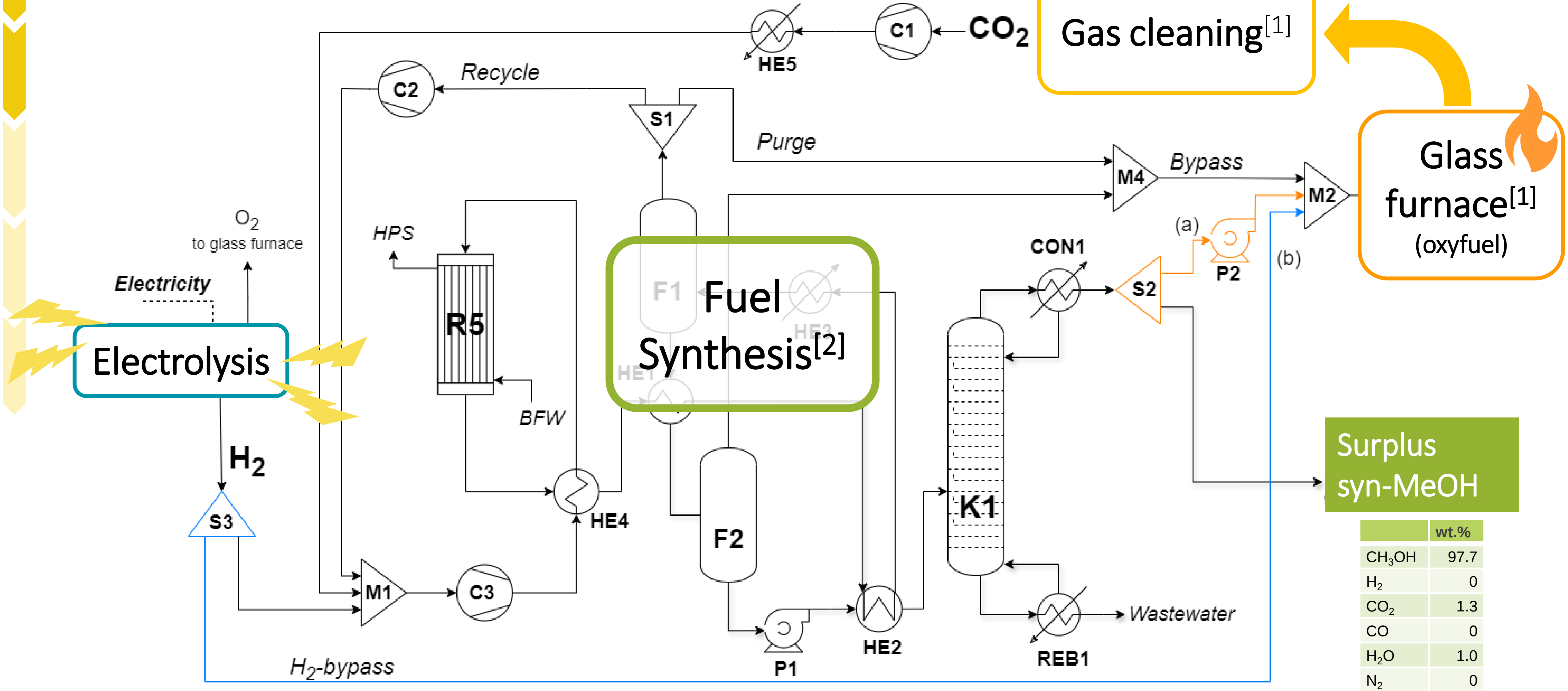


Kinetic model: **Vanden Bussche and Froment**[1,3]
MeOH synthesis from CO/CO_2/H_2 represented as CO_2 hydrogenation & RWGS reactions

[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.

Process description

Process flow diagram: Syn-MeOH



Gas cleaning[1]

Glass furnace[1] (oxyfuel)

Electrolysis

Fuel Synthesis[2]

Surplus syn-MeOH

	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

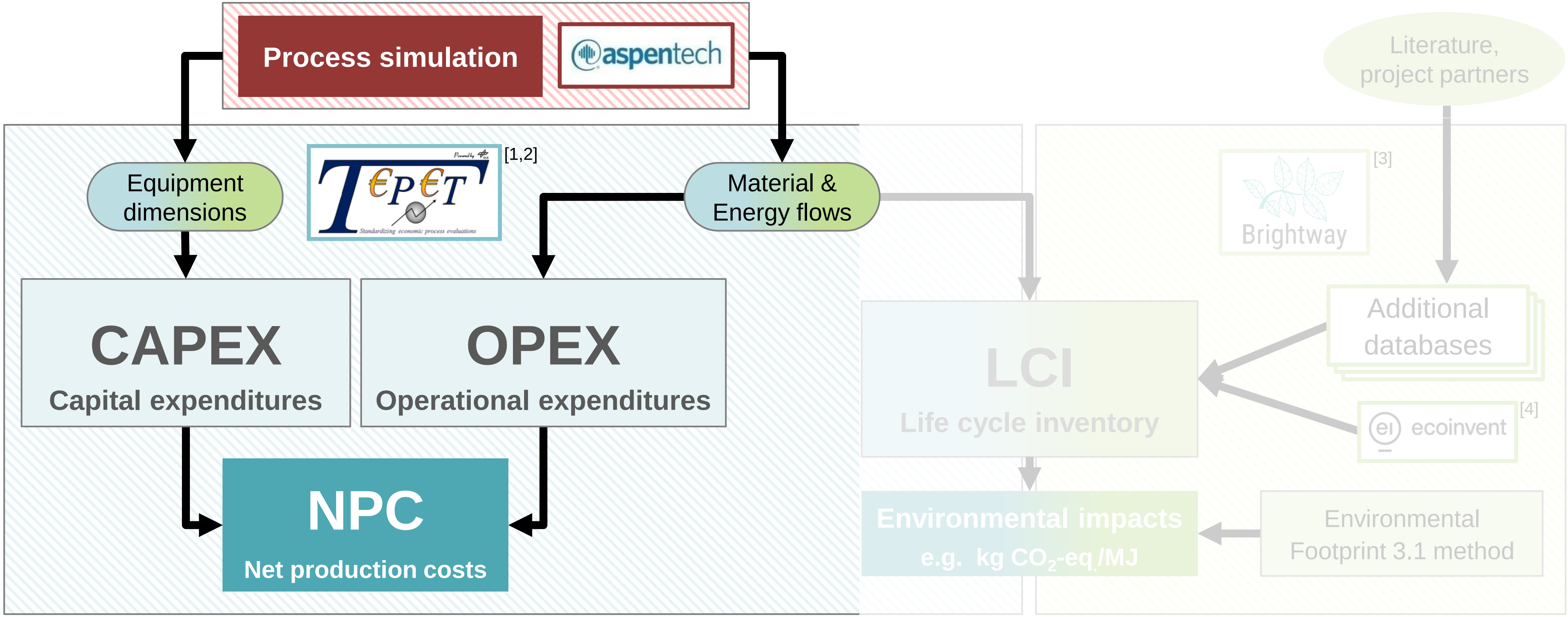
Process description

Equipment design and parameters

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

[1] Rahmat et al. (2023) Techno-economic and exergy analysis of e-MeOH production https://doi.org/10.1016/j.apenergy.2023.121738
[2] Sánchez et al. (2020) Aspen Plus model of an alkaline electrolysis system for hydrogen production. https://doi.org/10.1016/j.ijhydene.2019.12.027
[3] Heimann, N. et al (2023), Standardized tea of sCNG and HCNG, to be submitted
[4] Woods (2007) Rules of Thumb in Engineering Practices
[5] VDI-Gesellschaft (2006) VDI-Wärmeatlas. 978-3-540-32218-4_13.pdf (springer.com)
[6] Towler (2008) Chemical Engineering Design
[7] Sorrels (2021) Chapter 1 – Wet and Dry Scrubbers for Acid Gas Control. www.epa.gov
[8] Samei and Raisi (2022) Separation of nitrogen from methane by multi-stage membrane

Techno-economic assessment (TEA)



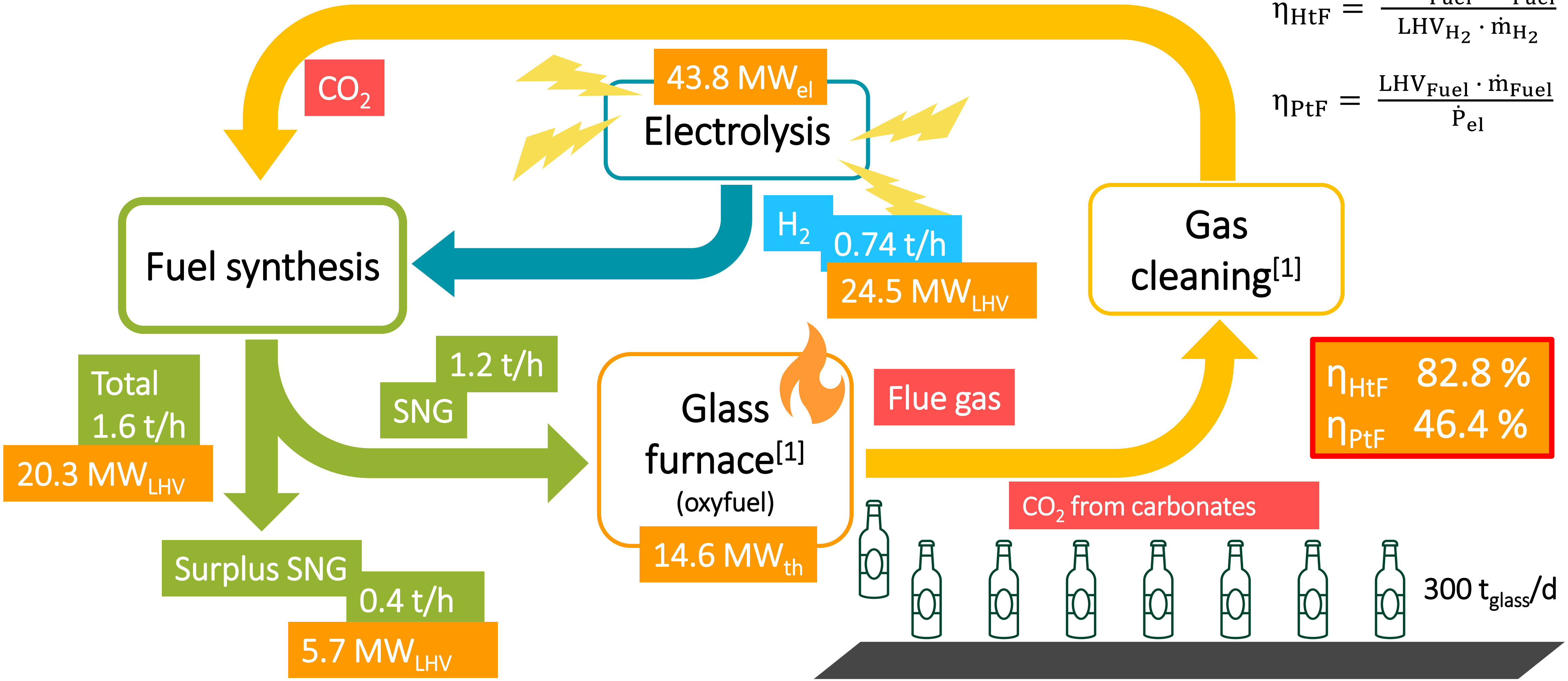
[1] Albrecht et al. (2016): https://doi.org/10.1016/j.fuel.2016.12.003
[2] Maier et al. (2021): https://doi.org/10.1016/j.enconman.2021.114651
[3] Mutel (2017): https://doi.org/10.21105/joss.00236
[4] Wernet et al. (2016): https://doi.org/10.1007/s11367-016-1087-8

Techno-economic assessment (TEA)

Efficiencies: SNG/SNG

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

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



CO_2

43.8 MW_{el}

Electrolysis

Fuel synthesis

H_2 0.74 t/h

24.5 MW_{LHV}

Gas cleaning[1]

Total 1.6 t/h

20.3 MW_{LHV}

SNG 1.2 t/h

Glass furnace[1] (oxyfuel)

14.6 MW_{th}

Flue gas

CO_2 from carbonates

Surplus SNG 0.4 t/h

5.7 MW_{LHV}

300 t_{glass}/d

η_{HtF} 82.8 %

η_{PtF} 46.4 %

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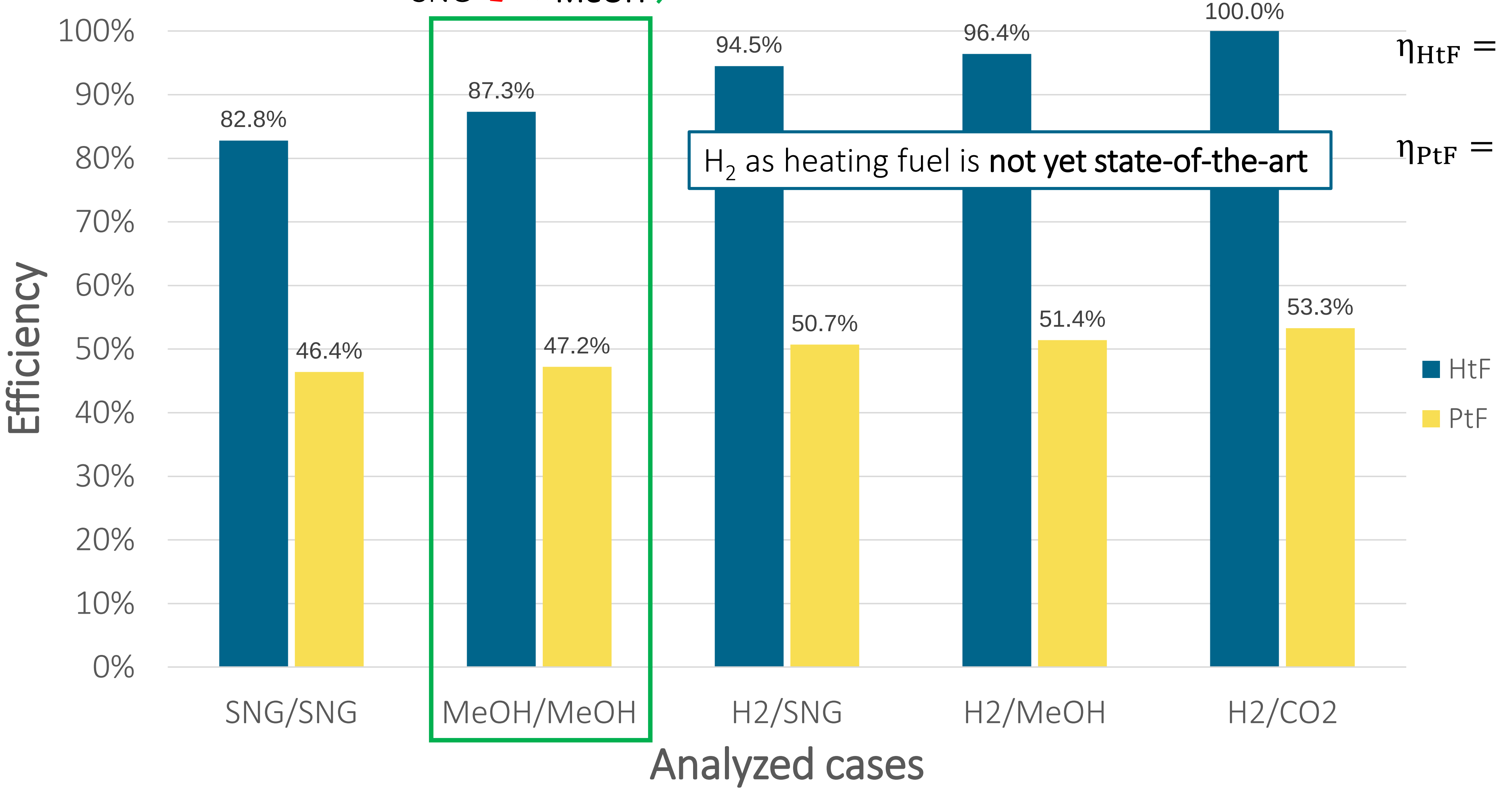
[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.

Techno-economic assessment (TEA)

Efficiencies

SNG ⇘ < **MeOH** ⇗



H_2 as heating fuel is **not yet state-of-the-art**

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

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

Rahmat et al., PtX sustainable glass production, DECHEMA Forum, Friedrichshafen, 12.09.2024

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]

$$NPC\left[{}^{€}/_{MWh_{LHV}}\right] = \frac{ACC + \sum OPEX \overset{[2,3]}{+} labor\ costs}{\dot{m}_{synfuel} * LHV_{synfuel}}$$

$$\boxed{ACC = FCI * Annuity\ factor}$$

$$\boxed{FCI_i = EC_i \times \sum CAPEX\ cost\ factors}$$

See next slide!

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[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

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

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

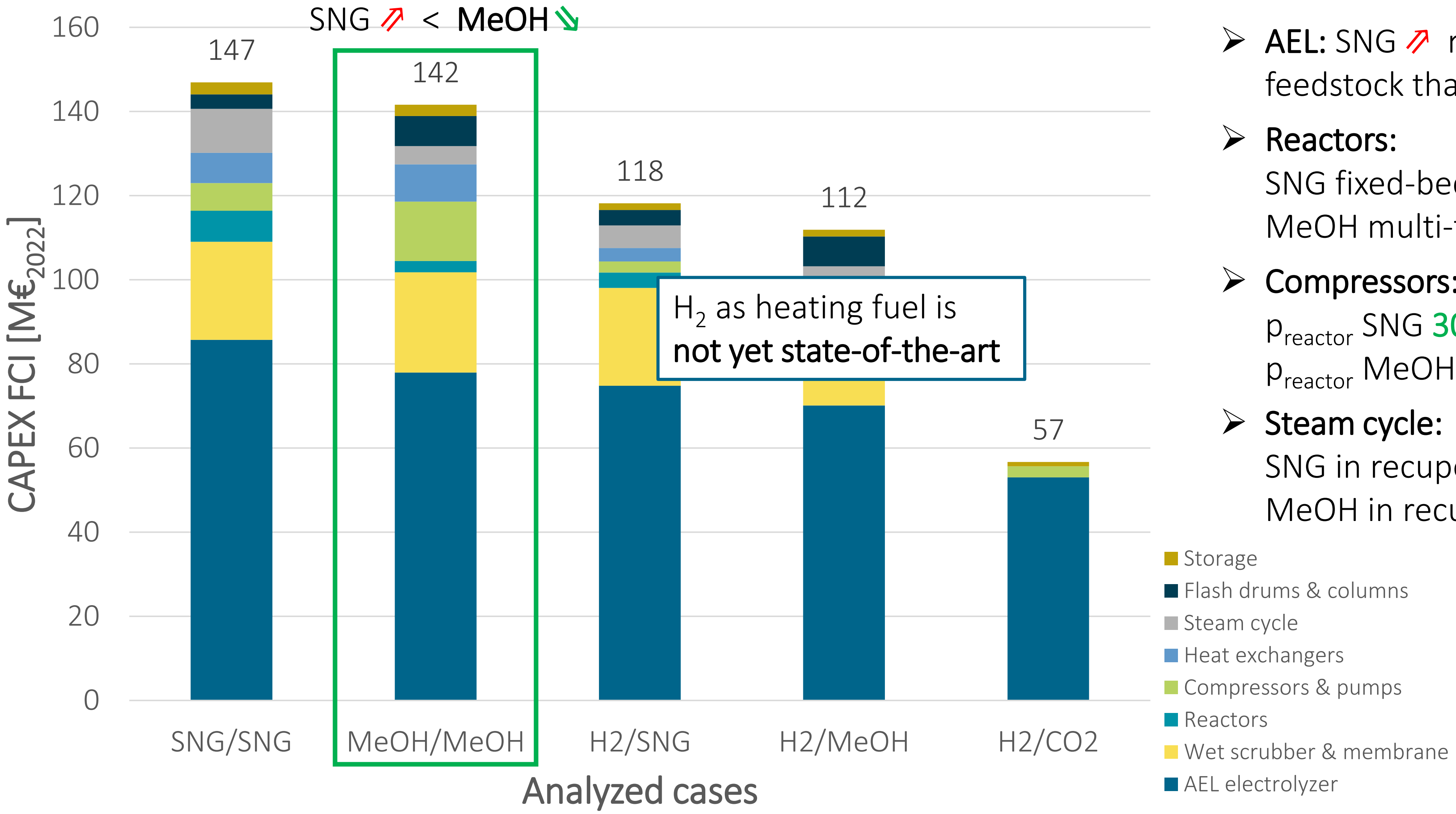
Reference function ($EC_{i,ref}$)	EC_{ref}	Currency	$sizing_{ref}$	Unit	n	$Year_{ref}$	Source
Compressor	3 035	$	1	kW_{el}	0.68	2002	[1]
Centrifugal pump	16 809	$	1	$m^3 s^{-1}$	0.36	2002	[1]
Distillation column	286 343	$	100	size factor = $HxD^{1.5}$ [$m^{2.5}$]	0.53	2007	[2,3]
AEL stack	800	k€	0.005	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)



SNG ⇗ < **MeOH** ⇘

H_2 as heating fuel is
not yet state-of-the-art

- **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

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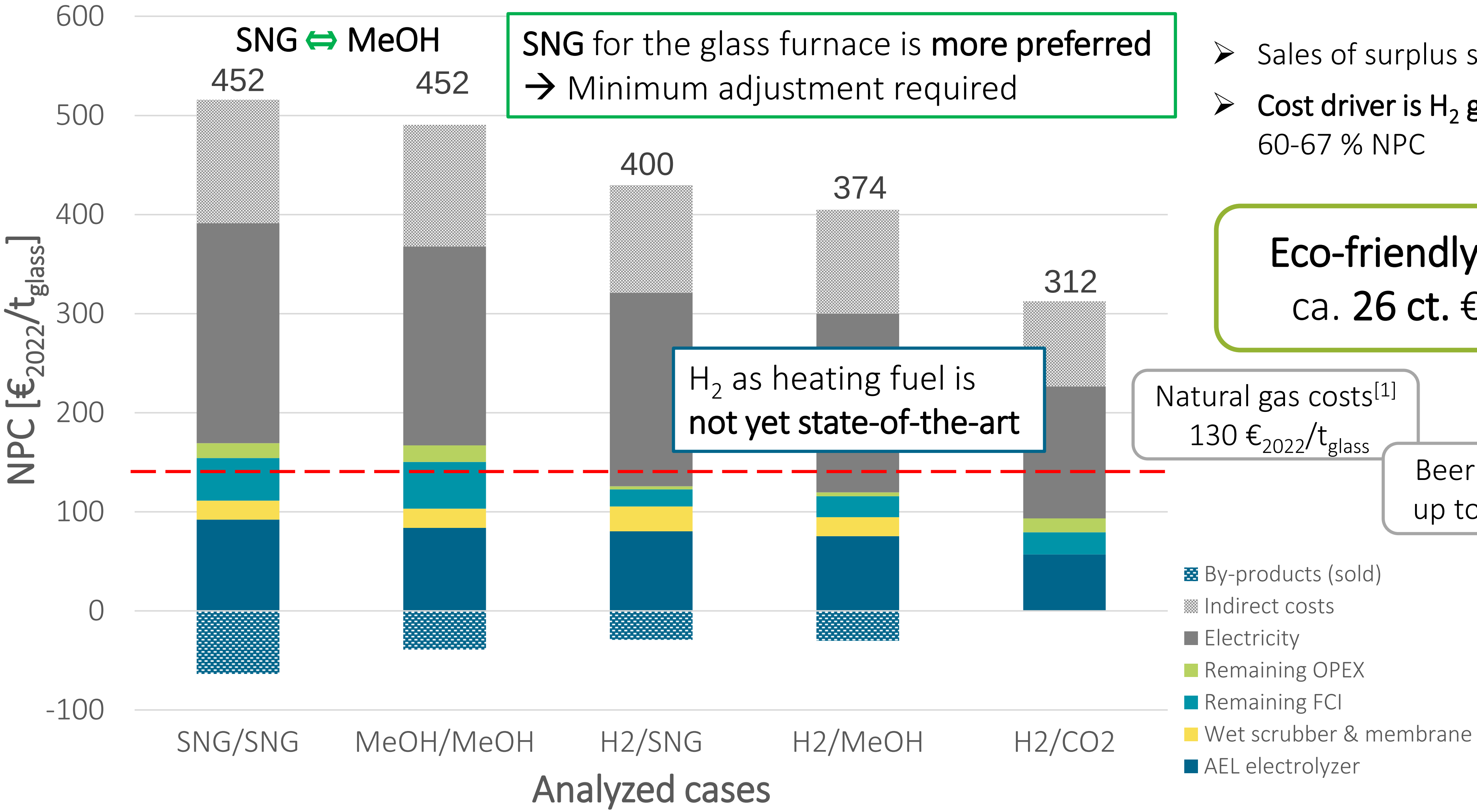
TEA for 12.2 MW_{th} Glass Furnace

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



SNG ⇔ MeOH

SNG for the glass furnace is **more preferred**
→ Minimum adjustment required

H_2 as heating fuel is
not yet state-of-the-art

- Sales of surplus synfuels as fossil fuels
- **Cost driver is H_2 generation**
  60-67 % NPC

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

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

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

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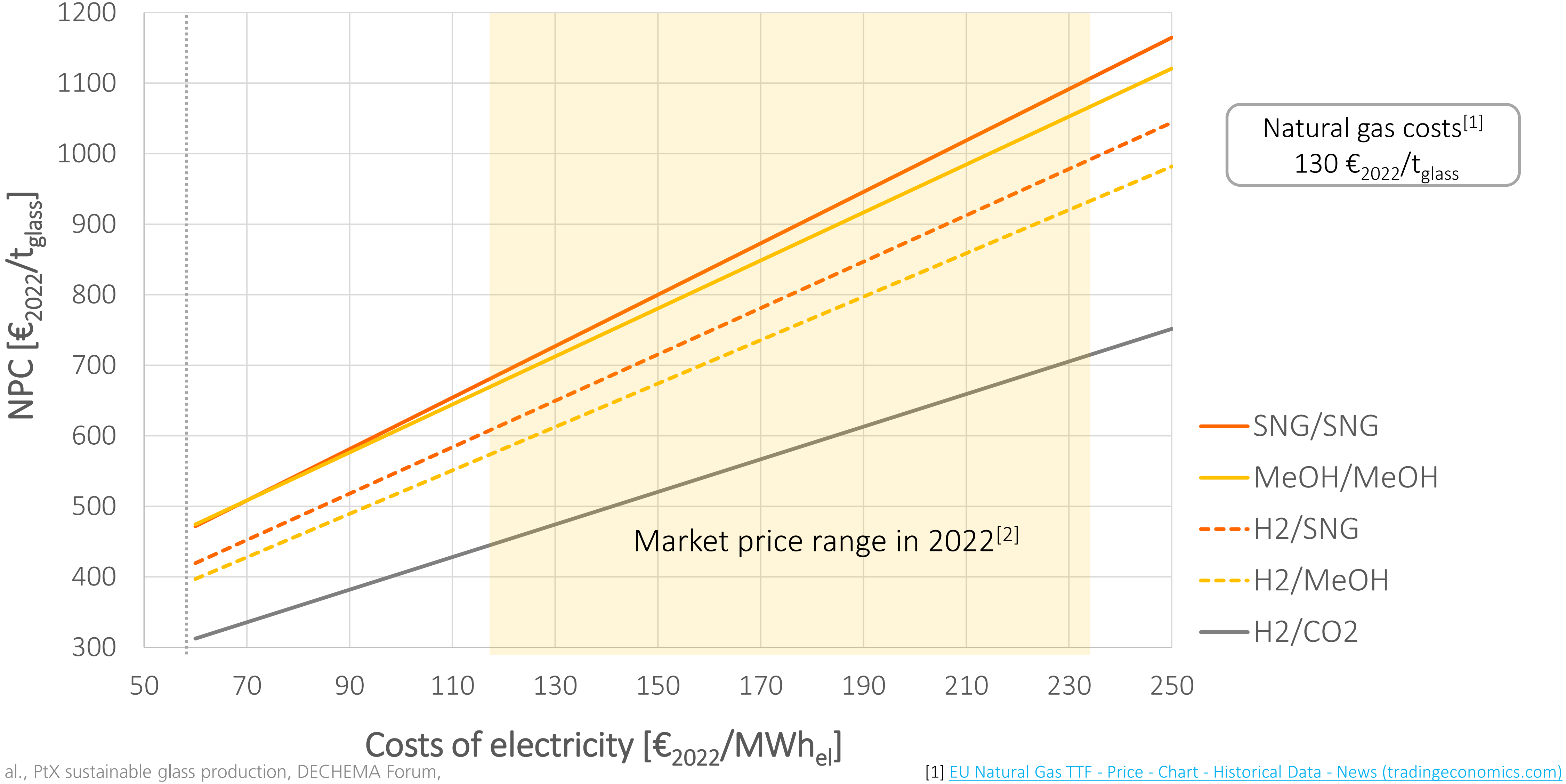
[1] EU Natural Gas TTF - Price - Chart - Historical Data - News (tradingeconomics.com)

[2] HVG-DGG internal price estimation

Techno-economic assessment (TEA)

Results – NPC sensitivity analysis

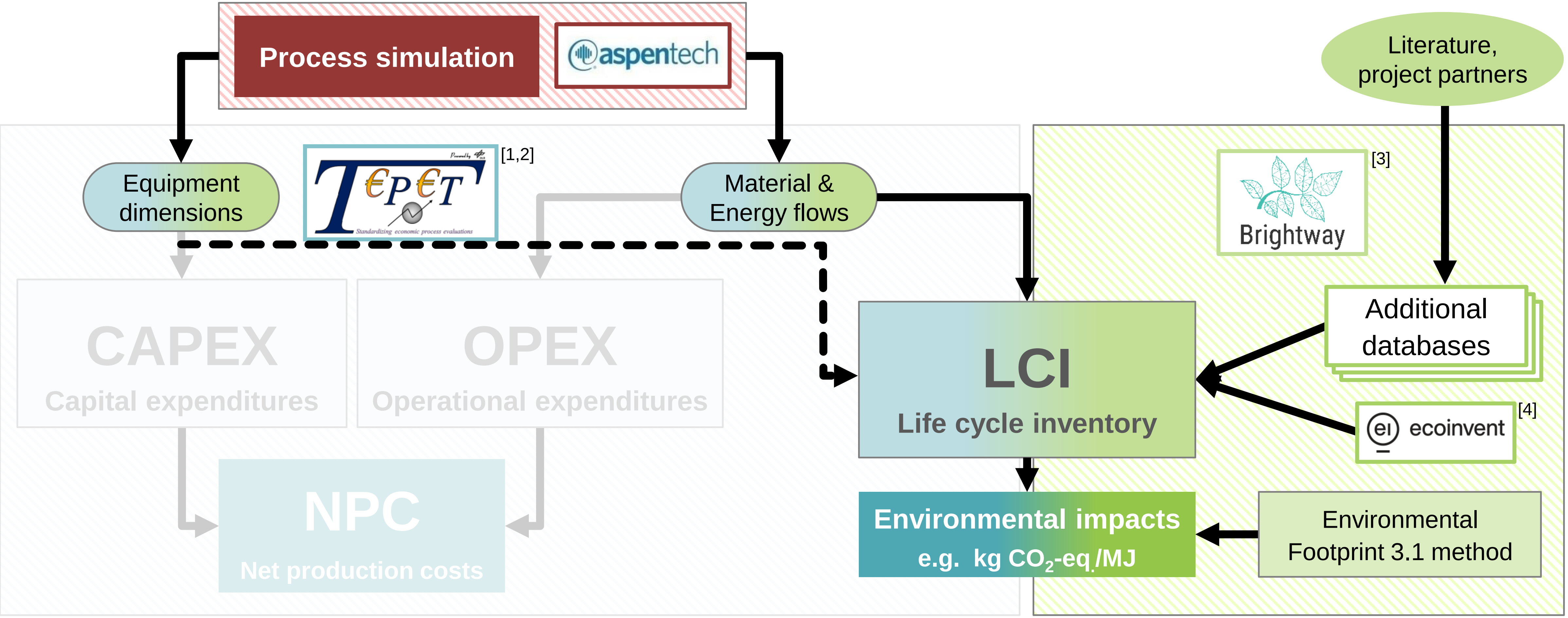


Natural gas costs[1]
130 €$_{2022}$/t$_{glass}$

[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



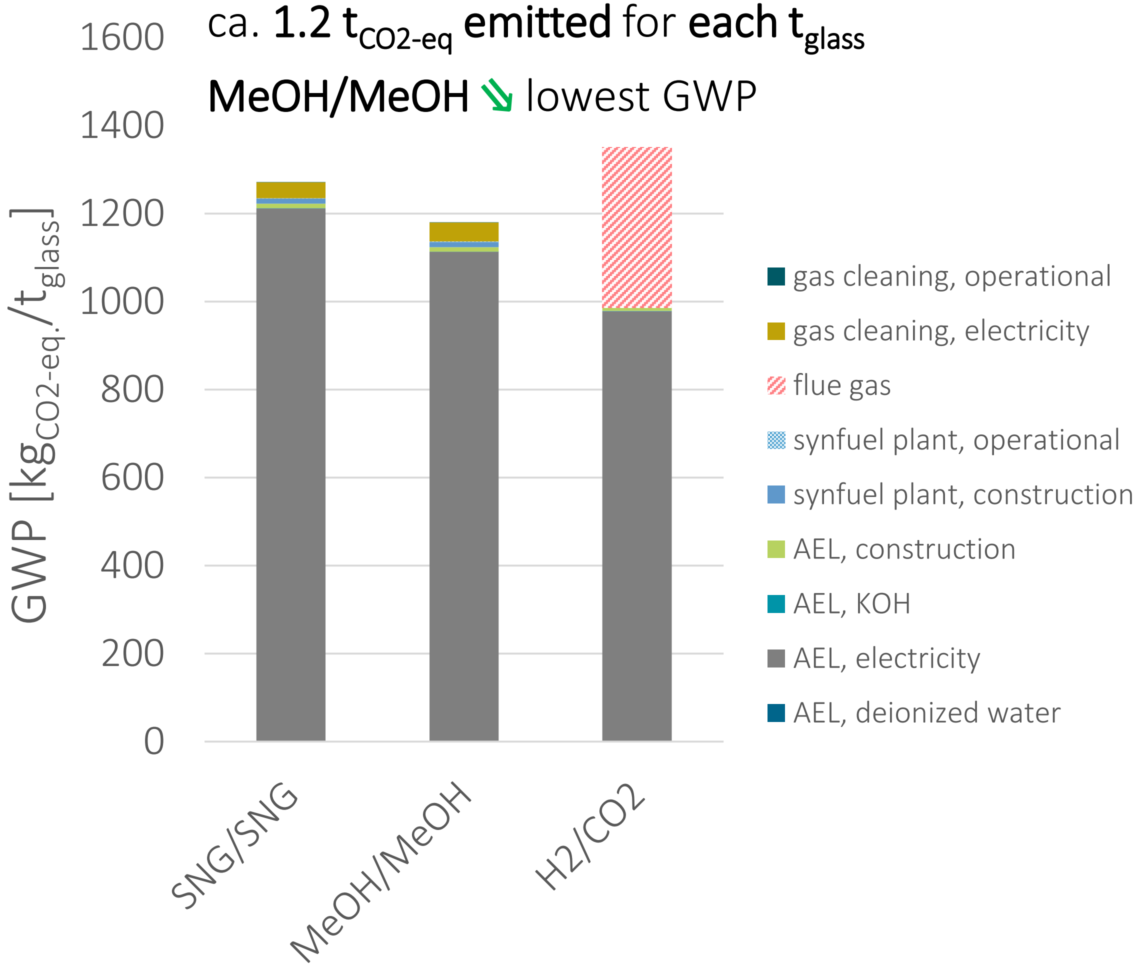
[1] Albrecht et al. (2016): https://doi.org/10.1016/j.fuel.2016.12.003
[2] Maier et al. (2021): https://doi.org/10.1016/j.enconman.2021.114651
[3] Mutel (2017): https://doi.org/10.21105/joss.00236
[4] Wernet et al. (2016): https://doi.org/10.1007/s11367-016-1087-8

LCA results (preliminary)

SNG/SNG vs MeOH/MeOH vs H_2/CO_2

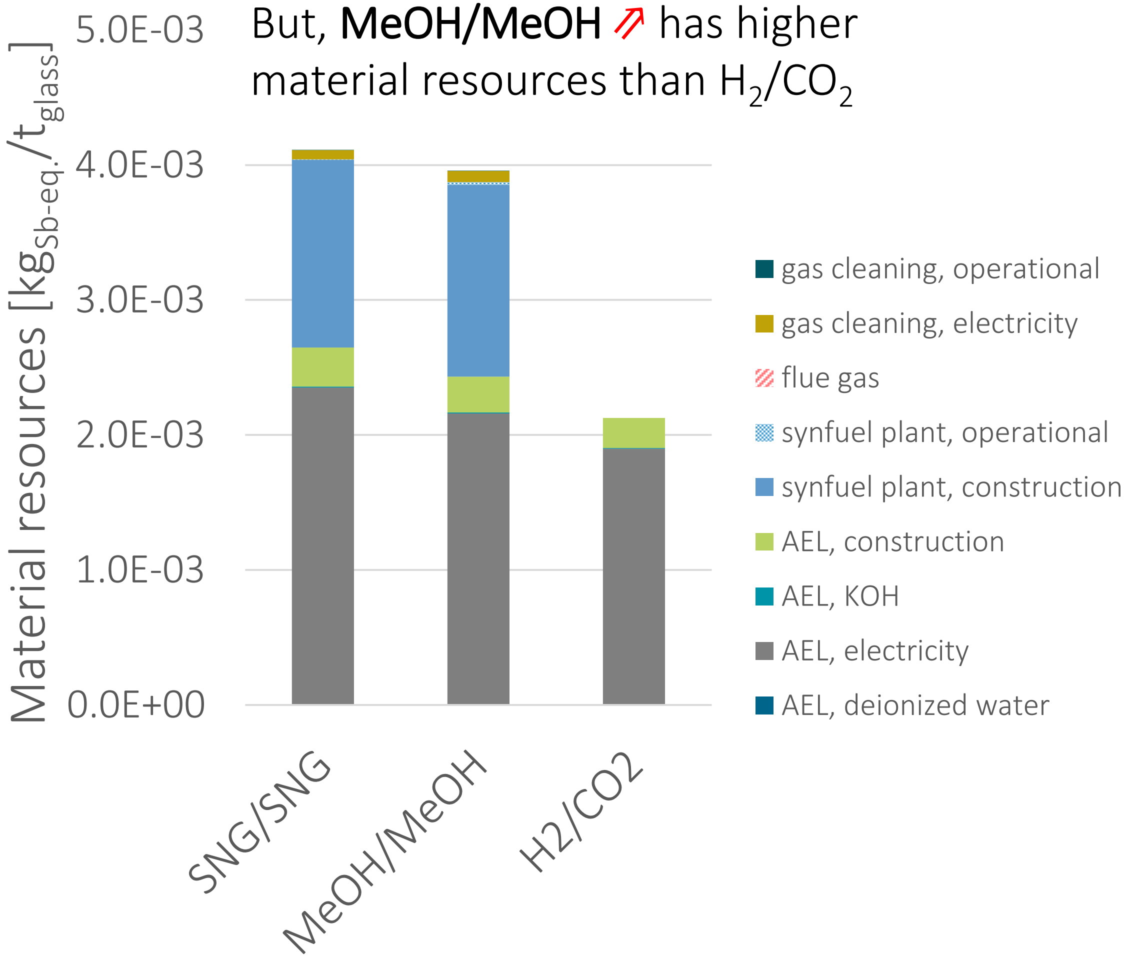
Functional unit: 1 tonne glass produced

German grid electricity as the el. source



ca. **1.2 t_{CO2-eq} emitted** for **each t_{glass}**

MeOH/MeOH ⇘ lowest GWP



But, **MeOH/MeOH** ⇗ has higher material resources than H_2/CO_2

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Conclusion

- Implementation of Power-to-X concepts for a sustainable industrial glass production
  → Example for industry decarbonization
- Glass industry can be **sustainable**, depending on the electricity source
  → **Case SNG/SNG** is the most suitable as direct substitution for natural gas
- Glass furnace requires adjustments for direct H_2 combustion
- 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 concepts, however a trade-off is expected, e.g. material resources impact

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

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German Aerospace Center

HVG-DGG
Service und Forschung für die Glasherstellung

ArdaghGlass

SCHOTT
glass made of ideas

Linde
Making our world more productive

DECHEMA FORUM
Wissenschaft und Industrie im Dialog

THANK YOU FOR YOUR ATTENTION!

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