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HVG-DGG
Service und Forschung für die Glasherstellung

ArdaghGlass | SCHOTT glass made of ideas | Linde Making our world more productive

SUSTAINABLE INDUSTRIAL GLASS PRODUCTION THROUGH POWER-TO-FUEL CONCEPTS (SYN-METHANE AND SYN-MEOH) A COMPARATIVE TECHNO-ECONOMIC ASSESSMENT

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

DECHEMA Jahrestreffen der Fachsektion Energie, Chemie und Klima
Frankfurt am Main, 12.03.2024

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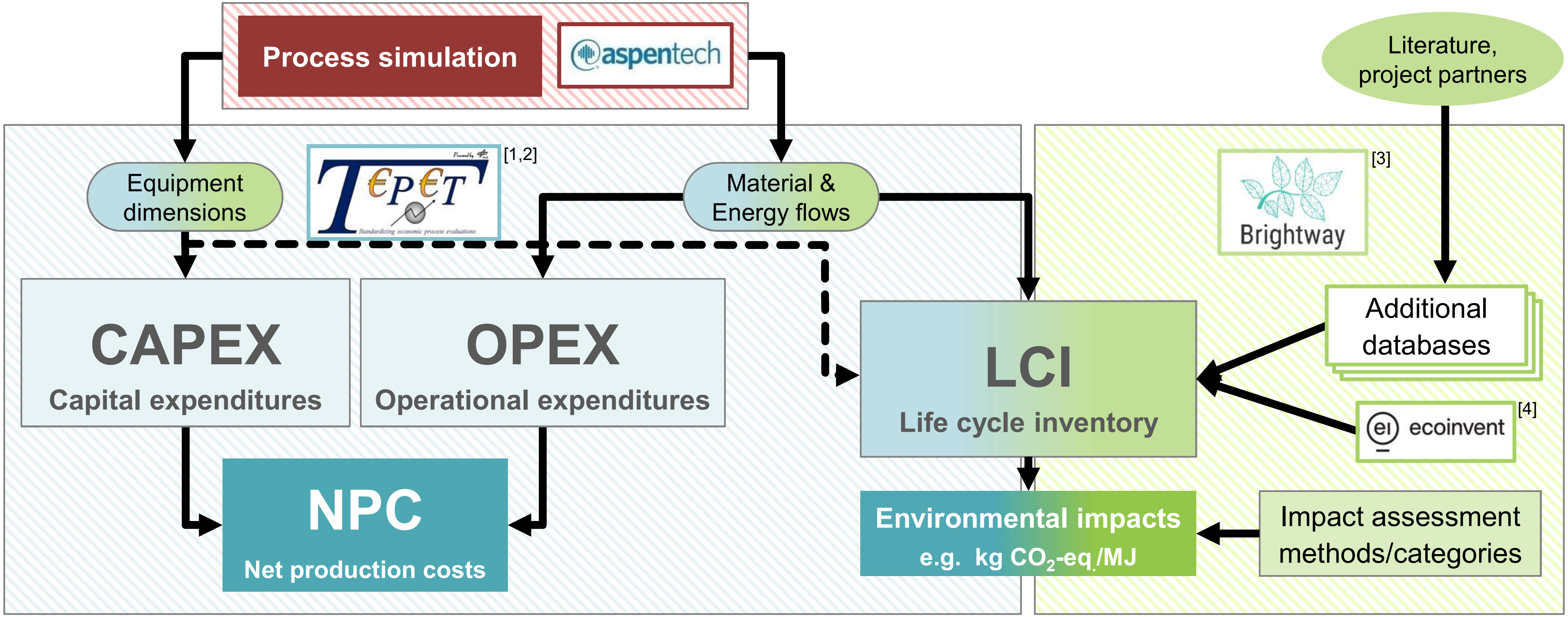
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Motivation

- EU Climate Neutral Goal by 2050 (Germany already by 2045)[1][2]
- Closing the carbon cycle in the glass production
  - ca. 3.2 Mt CO_2 from fuel combustion, 1 Mt CO_2 from carbonates in Germany 2021
- Valorization of the difficult-to-avoid CO_2 emissions from carbonates
- Power-to-Fuel technology is an alternative to full electrification
  - Currently, only 60-80 % electrification of glass production possible (hybrid)
- Syn-methane / SNG:
  - Direct substitute of natural gas, relatively clean combustion due to lower impurities content
  - Storage and handling could be challenging
- Syn-MeOH:
  - Fuel as well as basic chemicals, simple storage and handling
  - Adjustment of the glass furnace might be required

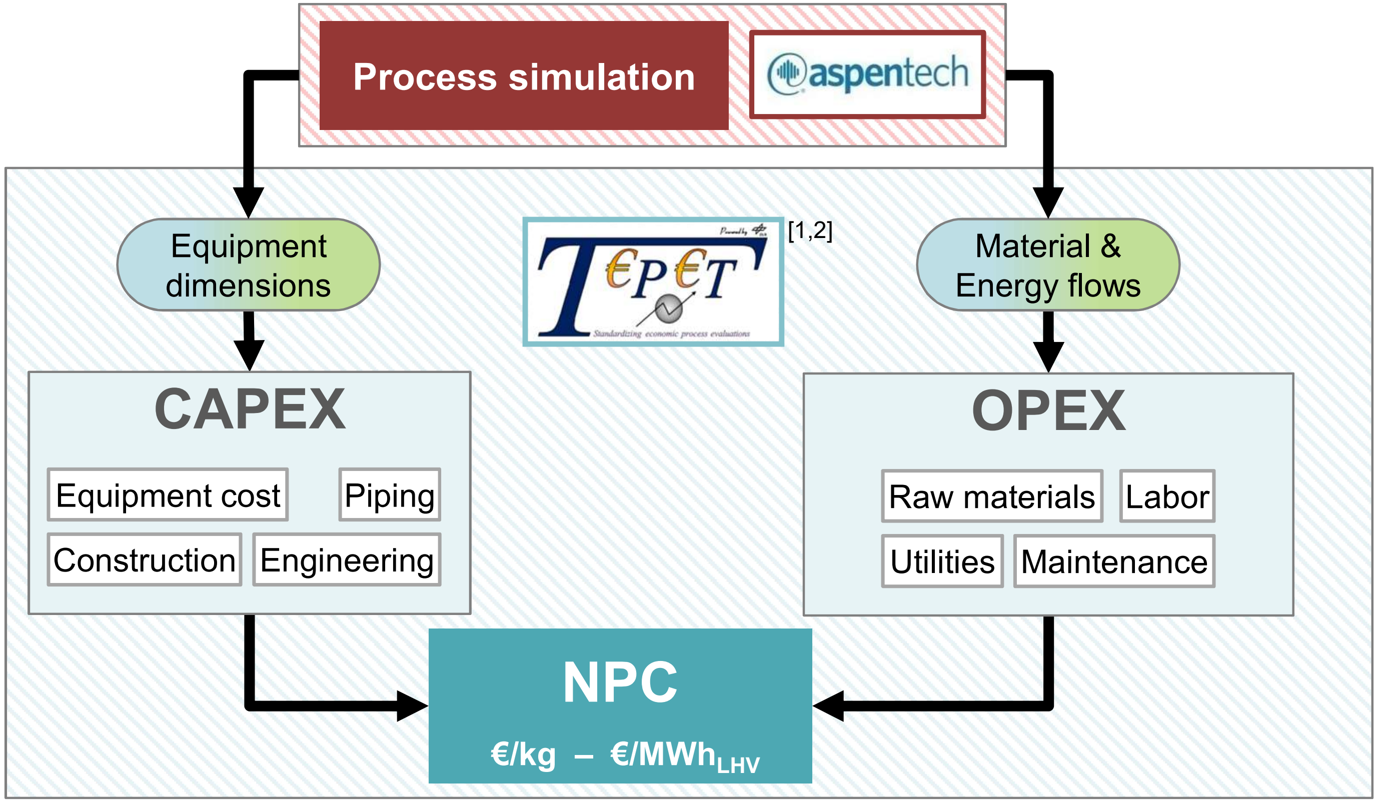
[1] European Climate Law (europa.eu)
[2] Jedamzik et al. (2020) Energiewende in Deutschland: Definition, Kosten & Ziele | co2online

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

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

Methodology
Key performance indicator (KPI)

KPI / efficiencies[1]

$$\eta_{H_2tF} = \frac{LHV_{Fuel} \cdot \dot{n}_{Fuel}}{LHV_{H_2} \cdot \dot{n}_{H_2}}$$

$$\eta_{thermodynamic} = \frac{\eta_{H_2tF}}{\eta_{H_2tF,\,ideal}}$$

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

4 moles H_2 → 1 mole Methane
$\eta_{H_2tF,\,ideal}$ = 83.3 % ⇘

3 moles H_2 → 1 mole MeOH
$\eta_{H_2tF,\,ideal}$ = 87.9 % ⇗

Theoretically, MeOH⇗ can achieve higher $\boldsymbol{\eta_{H_2tF}}$ than Methane⇘

Methane synthesis reactions[2]

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O \quad \Delta H_o = -206\,\frac{kJ}{mol} \quad (1)$$

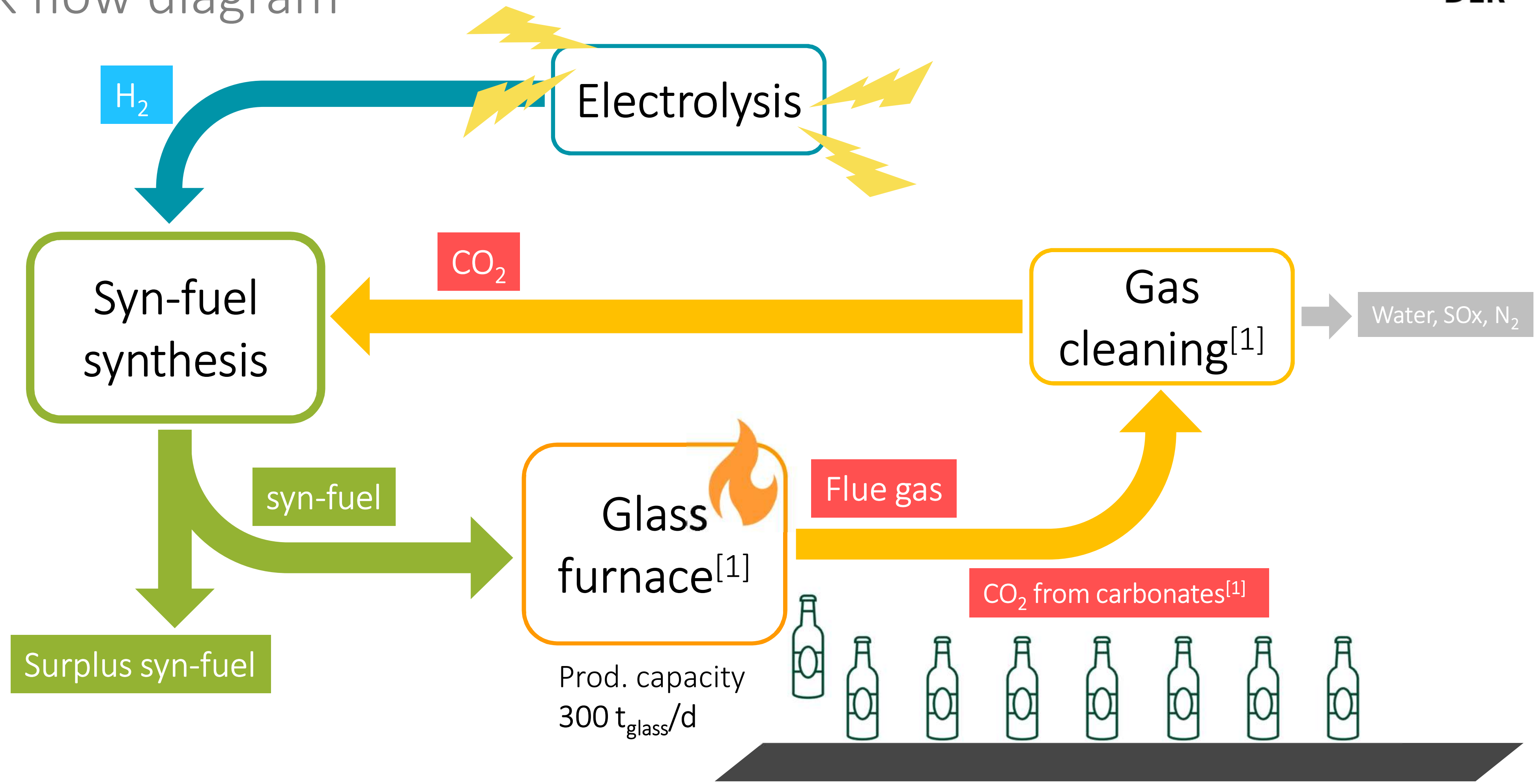
MeOH synthesis reactions[3]

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \quad \Delta H_o = -49.8\,\frac{kJ}{mol} \quad (1)$$

LHV
H_2 : 120 MJ/kg
Methane : 50 MJ/kg
MeOH : 19.9 MJ/kg

[1] Rahmat et al. (2023) Techno-economic and exergy analysis of e-MeOH production https://doi.org/10.1016/j.apenergy.2023.121738
[2] Rönsch, S., et al., *Review on methanation – From fundamentals to current projects.* Fuel, 2015. 166: p. 276-296.
[3] Van-Dal and Bouallou (2013) Design and simulation of a methanol plant plant from CO_2 hydrogenation

Process description
Block flow diagram



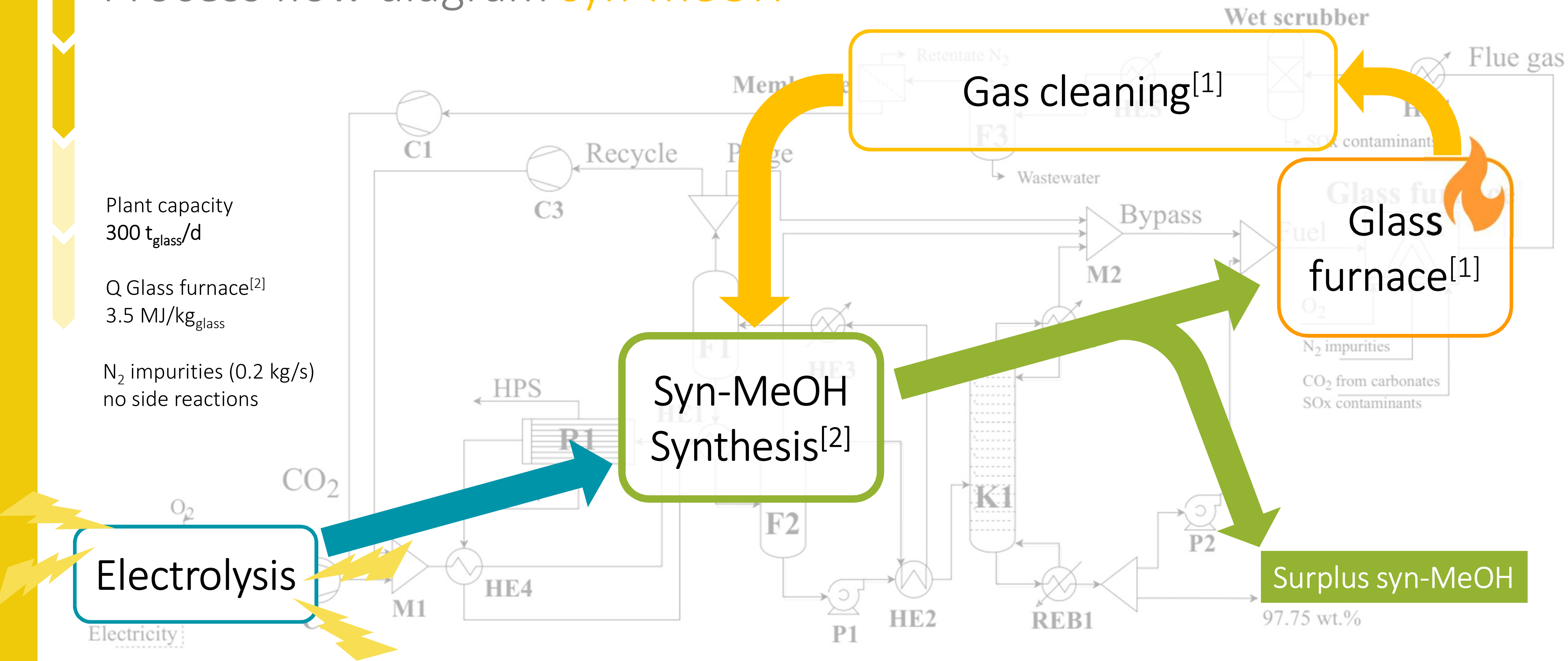
[1] Drünert et al. (2023) Techno-economic assessment of carbon capture and utilization concepts for a CO2 emission-free glass production.

Process description
Process flow diagram syn-MeOH

Plant capacity
300 t_{glass}/d

Q Glass furnace[2]
3.5 MJ/kg_{glass}

N_2 impurities (0.2 kg/s)
no side reactions



[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

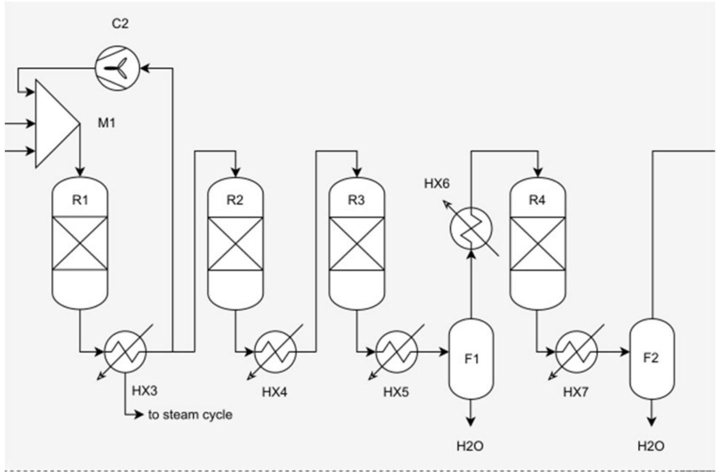
Equipment[1-3]	AspenPlus® model	Parameters	Remarks
Heat exchangers	HeatX/Heater	Δp = 0.2 bar[4], $\Delta T_{approach}$ = 10 K[4]	U-values[5] method
Compressors	Compr/MCompr	Max. CR = 3[4] $\eta_{isentropic}$ = 80 %[4], $\eta_{mech.}$ = 95 %	range CR = 2.5-4[4]
Pumps	Pump	η_{pump} = 95 %, η_{driver} = 95 %	
Flash drums	Flash2	Q = 0 kW, Δp = 0.2 bar[4]	adiabatic
Distillation columns	RadFrac	$p_{cond.}$ = 1.36 bar[1], $\Delta p_{col.}$ = 0.34 bar[1] n_{stage} = 55, reflux ratio = 1	$d_{col.} = f(\dot{V}_{gas,col.})$[6]
Electrolyzer PEM / AEL	RStoic (Stack) Flash2, Sep, Pump (BoP)	PEM : $\eta_{energetic}$ = 51 % (LHV)[2] AEL : $\eta_{energetic}$ = 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

Color coding process parameters:
Blue → taken from literature
Green → own assumption/calculation

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

Process description
Reactor design and parameters: Syn-methane / SNG

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



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

AspenPlus® model: RPlug

$T_{max,R1}$[3] = 700 °C

$T_{in,R1}$ = 250 °C

p[2] = 20-30 bar

GHSV[2] = 4200-8900

Catalyst[2] MCR-2X (Ni-based)

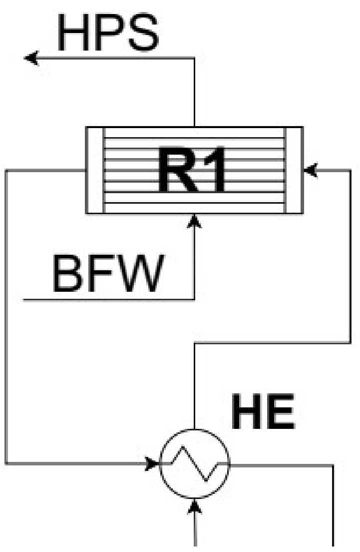
→ Gas cleaning required

N. Heimann, 12 March 2023 at 9:45 am
Standardized techno-economic analysis SNG and H-SNG?

[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
Reactor design and parameters: Syn-MeOH

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



AspenPlus® model[1]: RPlug

$T_{max,R1}$[2,5] = 280-300 °C

$T_{in,R1}$[1] = 230 °C

p[1,2] = 80 bar

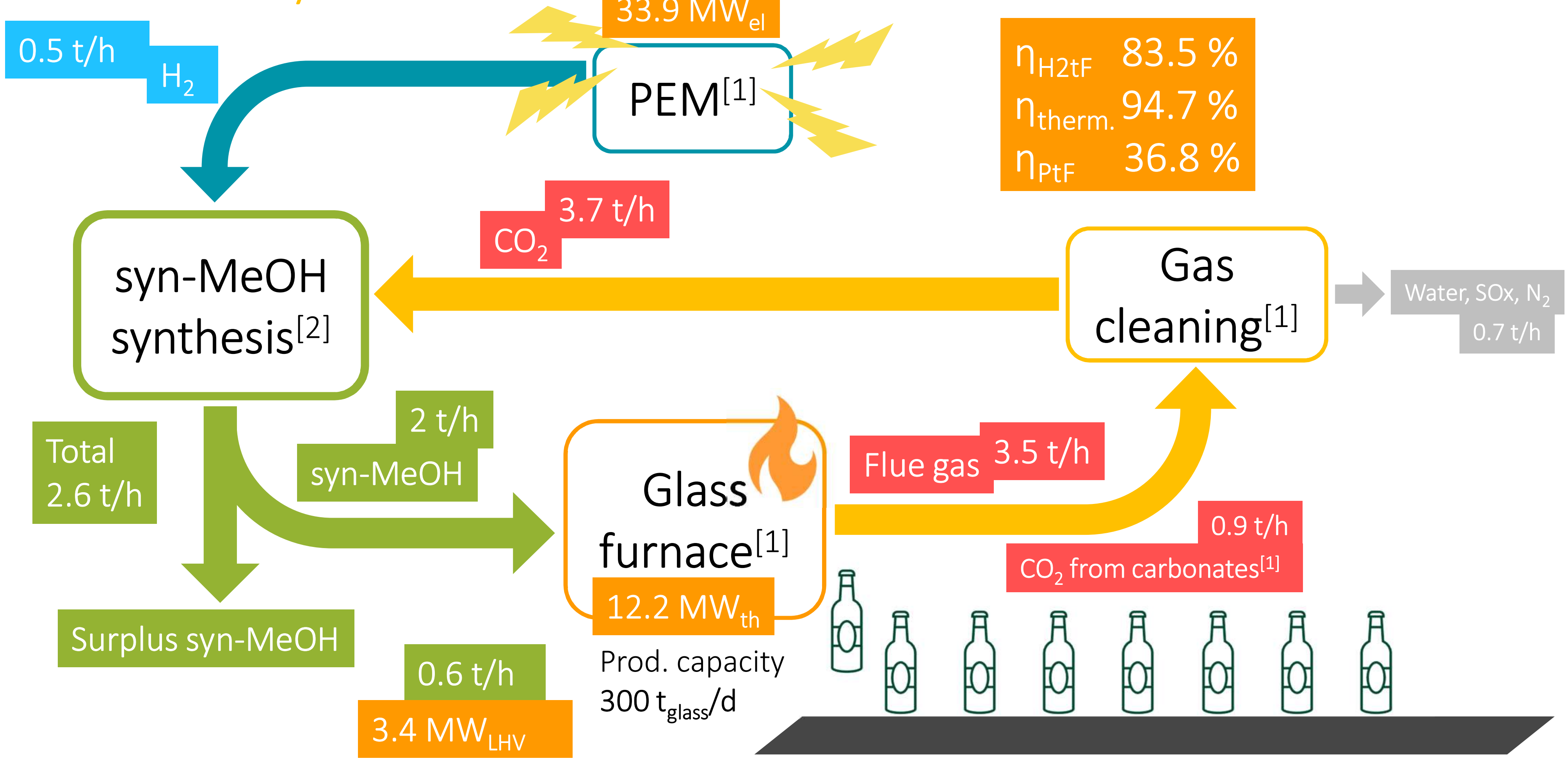
Catalyst[3] $Cu/ZnO/Al_2O_3$

→ 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

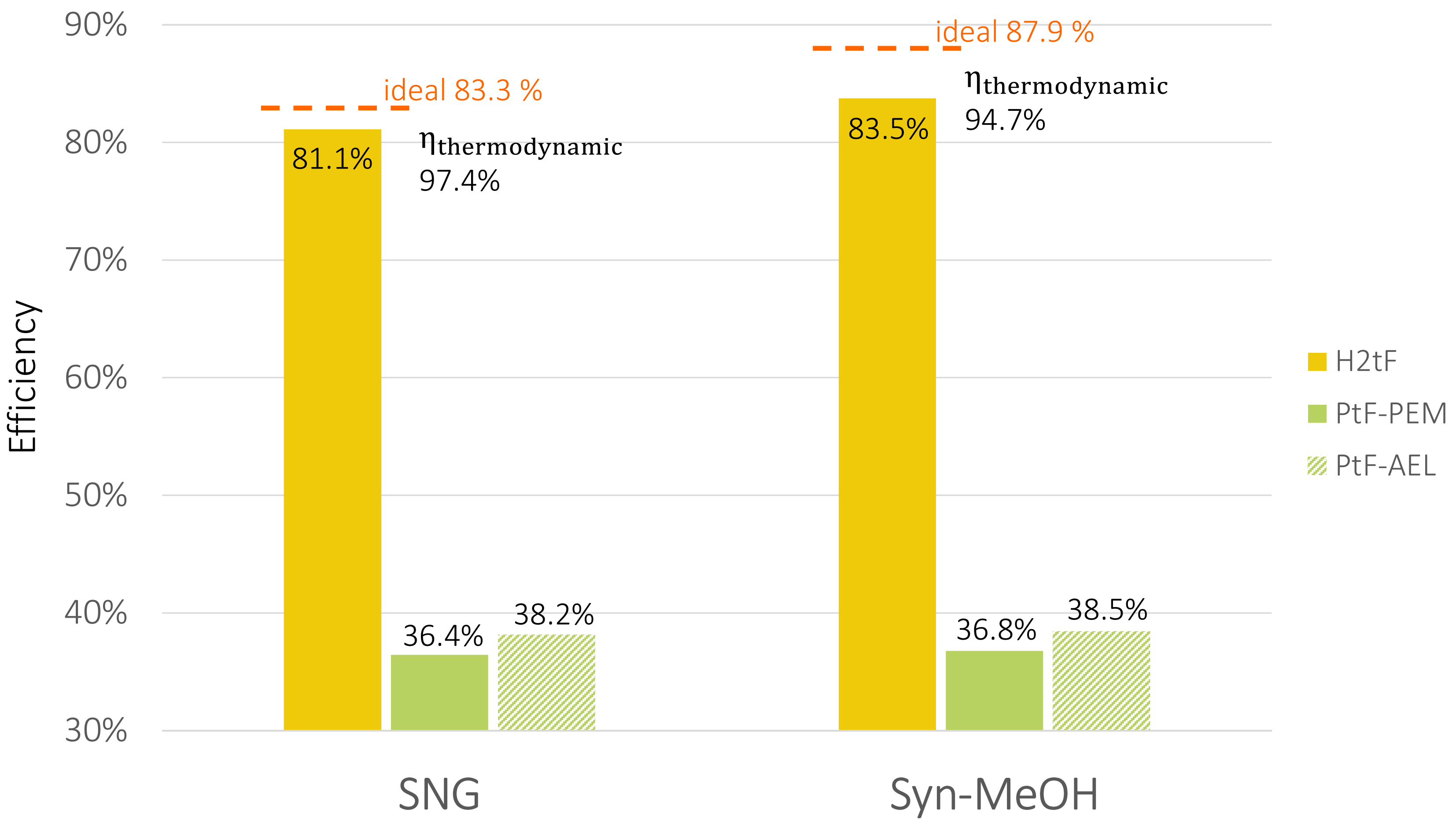
[1] Rahmat et al. (2023) Techno-economic and exergy analysis of e-MeOH production https://doi.org/10.1016/j.apenergy.2023.121738
[2] Metallgesellschaft AG (1996) – EP 0 790 226 B1
[3] Van-Dal and Bouallou (2013) Design and simulation of a methanol plant plant from CO_2 hydrogenation
[4] Bartholomew and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

Techno-economic assessment (TEA)
Results – KPI: 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

Techno-economic assessment (TEA)
Results – KPI



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	Electrolysis PEM / AEL
Electricity[1]	60*-250 €/MWh_{el}
Utilities	taken from [2]

*discussed "Industriestrompreis"

$$NPC\left[{}^{€}/_{MWh_{LHV}}\right] = \frac{ACC + \sum OPEX + labor\ costs}{\dot{m}_{synfuel} * LHV_{synfuel}}$$ [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]
PEM electrolysis	957	€	1	kW_{el}	1	2016	[4]
AEL stack	800	k€	0.005	kg/s	1	2019	[5]
AEL balance of plant	1	m€	0.025	kg/s	0.8	2019	[5]
Wet scrubber (limestone)	13 061	k$	14	MW_{th}	0.72	2012	[6]
Membrane PMP	9.76	m$	525.6	kmol/h	0.6	2020	[7]**
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] DLR, Ludwig Bölkow Systemtechnik, Fhg ISE, KBB (2014) Abschlussbericht der Studie Plan-DelyKad, Stuttgart.
[5] Habermayer et al. (2023) Sustainable aviation fuel from forestry residue and hydrogen. https://doi.org/10.1039/d3se00358b
[6] Sorrels (2021) Chapter 1 – Wet and Dry Scrubbers for Acid Gas Control. www.epa.gov
[7] 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) with PEM

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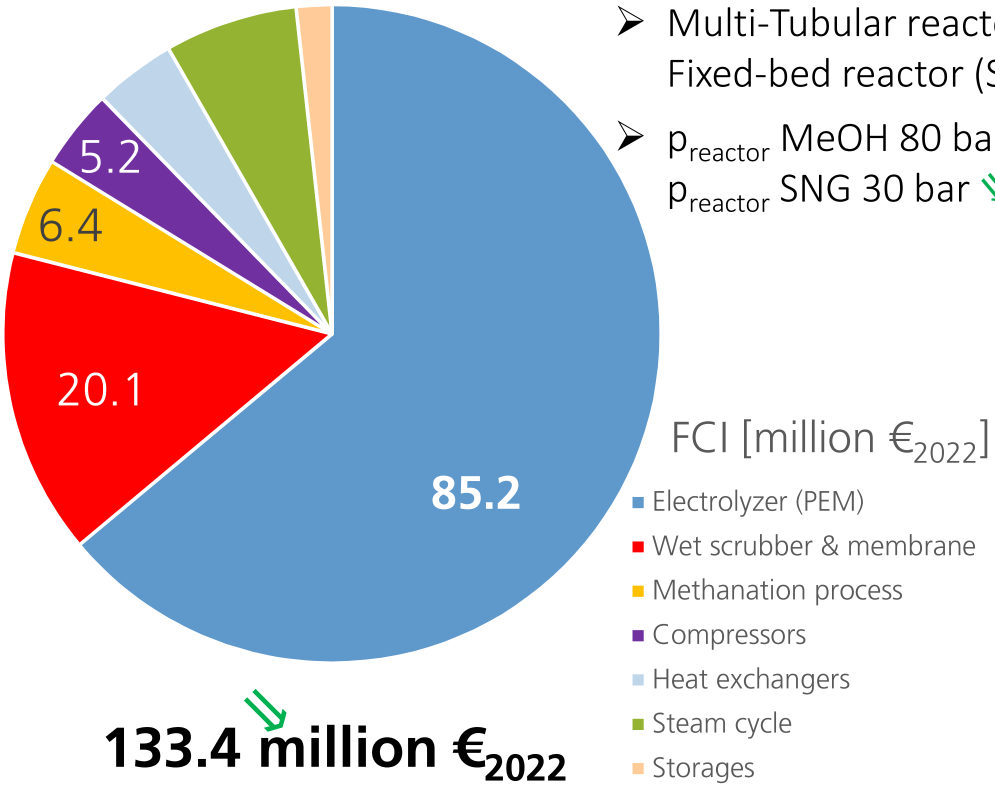
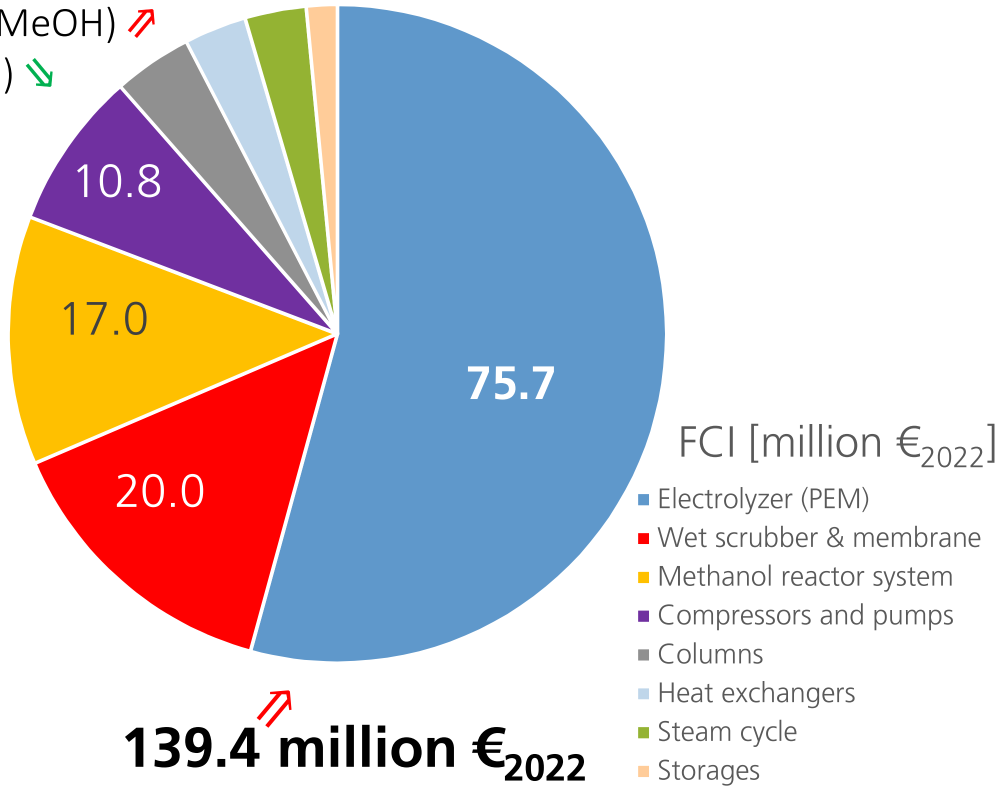
SNG



⇘ **133.4 million $€_{2022}$**

- SNG requires more H_2 feedstock
- Multi-Tubular reactor (MeOH) ⇗
  Fixed-bed reactor (SNG) ⇘
- $p_{reactor}$ MeOH 80 bar ⇗
  $p_{reactor}$ SNG 30 bar ⇘

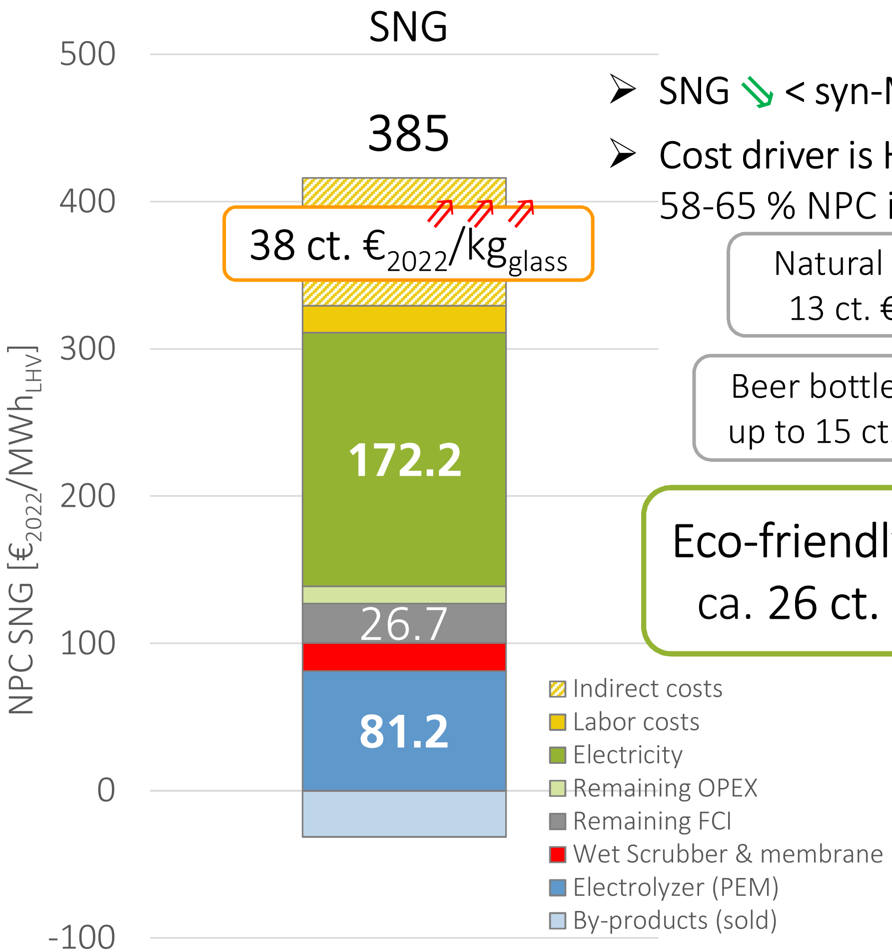
Syn-MeOH



⇗ **139.4 million $€_{2022}$**

TEA for 12.2 MW_{th} Glass Furnace
Results – NPC with PEM and electricity price 60 $€_{2022}/MWh_{el}$

HVG-DGG Service und Forschung für die Glasherstellung
DLR

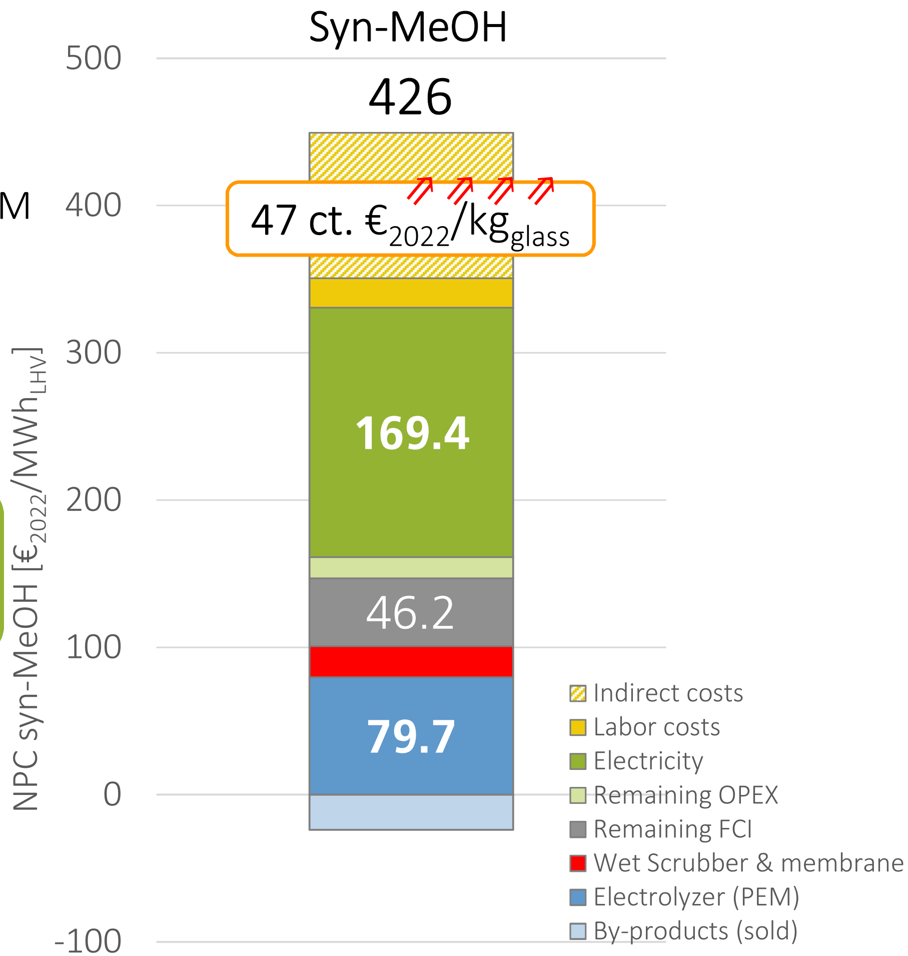


- SNG ↘ < syn-MeOH ↗
- Cost driver is H_2 generation
  58-65 % NPC is electricity & PEM

Natural gas costs[1]
13 ct. $€_{2022}/kg_{glass}$

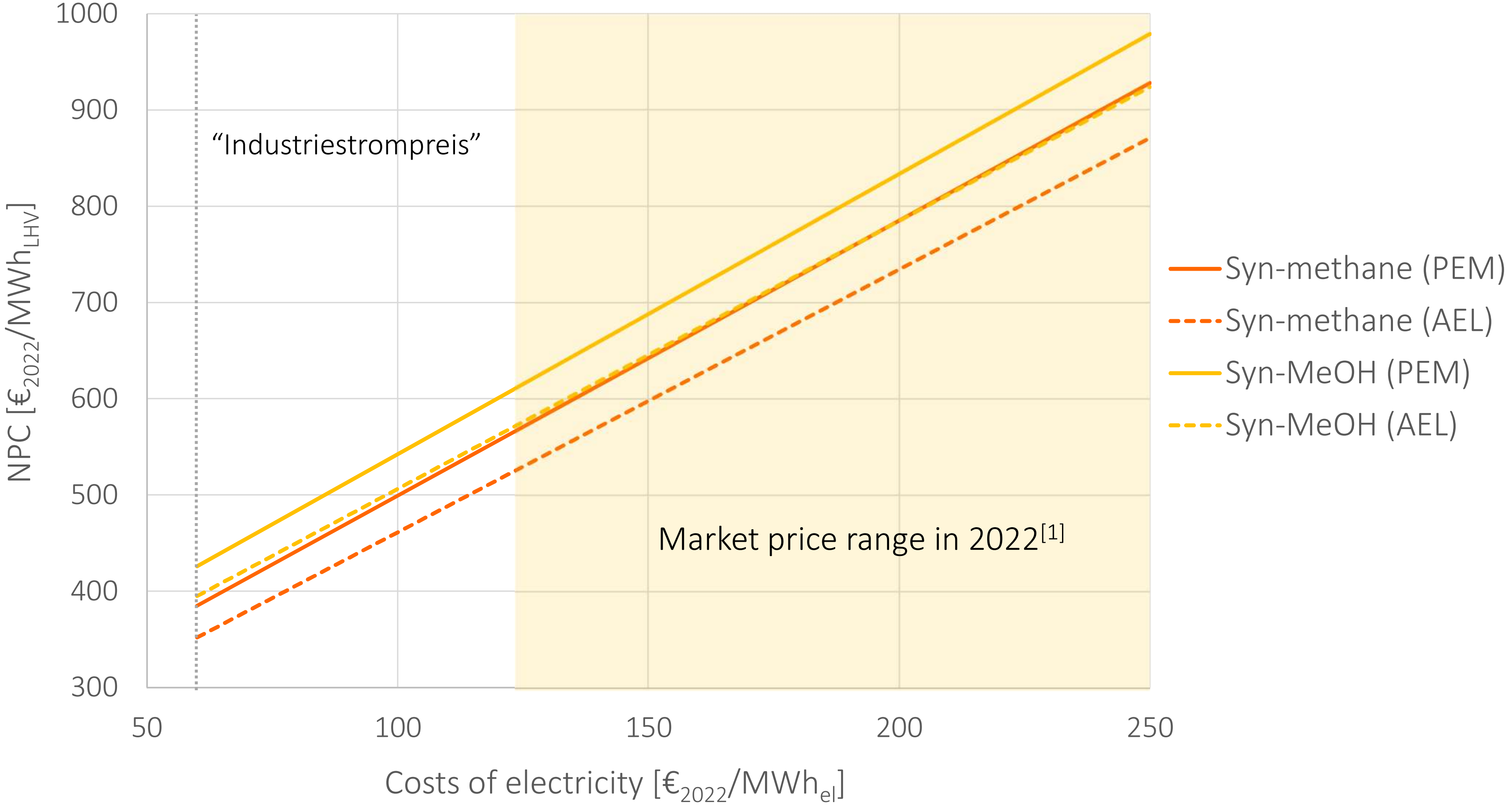
Beer bottle (330 g) price
up to 15 ct. $€_{2022}$/bottle[2]

Eco-friendly beer bottle
ca. 26 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] SMARD.de

Conclusion

- Implementation of Power-to-Fuel concepts for a sustainable industrial glass production
  → Valorization of the difficult-to-avoid CO_2 emissions from carbonates
- Glass industry can be **CO_2-neutral** and 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 electricity costs

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

Outlook

- Alternative concept with **direct H_2 combustion** for the glass furnace
  → CO_2 from carbonates will still be transformed into syn-fuels
- Conducting **life cycle assessment** of the sustainable glass production
- 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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glass made of ideas

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