Chair of Energy Systems
TUM School of Engineering and Design
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Process Simulation of Plasma-Assisted Entrained Flow Gasification for Hydrogen-rich Syngas Production

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TwinPeaks

Objectives for today: Present rationale for overall plasma entrained gasification process and simulation approach with first results

Objectives of this presentation

1) Share **context and motivation** for innovative thermochemical recycling/conversion process

2) Introduce **rationale for steam plasma entrained flow gasification** process

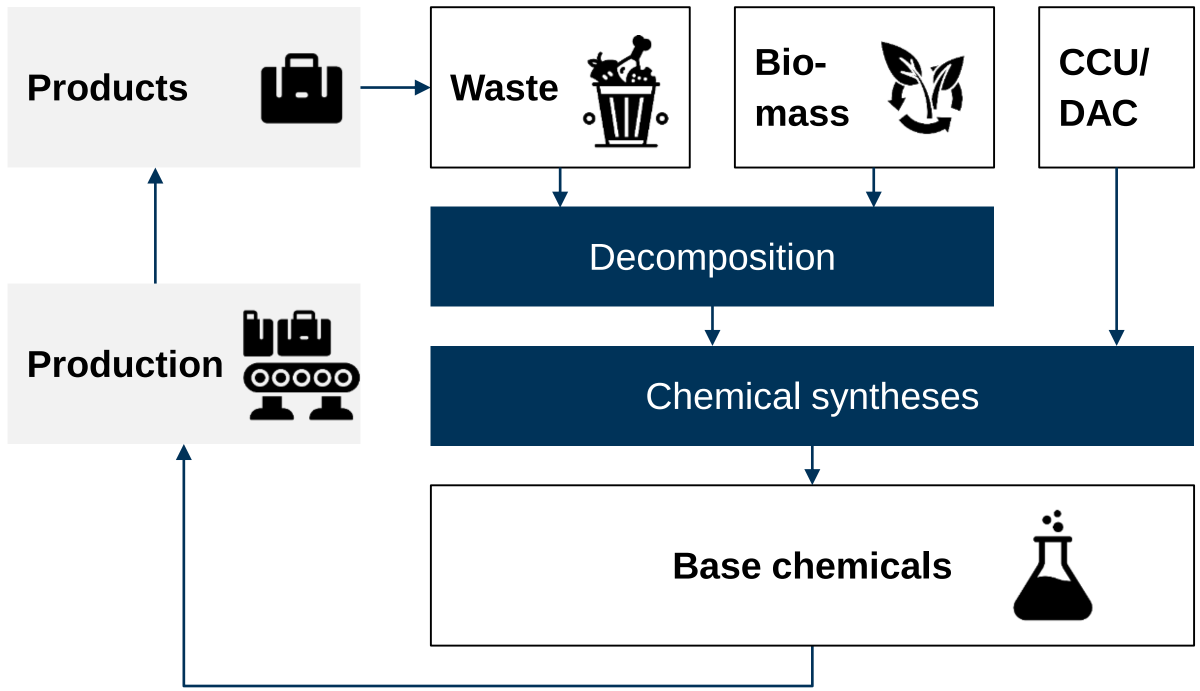
3) Present **simulation models** for **pyrolysis** pre-treatment and **plasma gasification**

4) Share **first preliminary results of simulation**

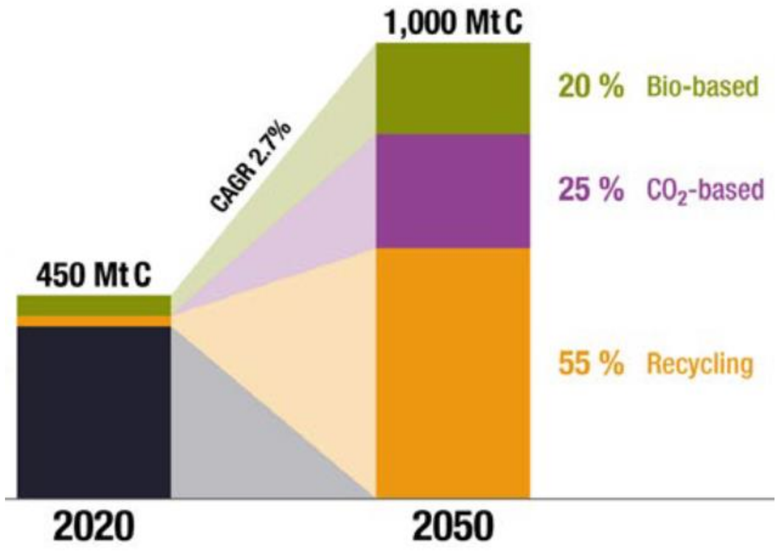
5) Discuss **next steps**

Waste and biomass are key carbon sources in a future closed loop economy – with sustainable carbon becoming a rare raw material

Sustainable carbon in closed loop system



Scenario for future carbon mix



Recycling and biomass utilization need to **grow massively**. **Sustainable carbon** will be **valuable** and potentially rare raw material **requiring conversion processes at high carbon efficiencies**.

Source: German VCI (2018), nova-Institute (2021)

Combination of rotary kiln pyrolysis and EF[1] gasification can utilize even complex inhomogeneous feedstocks for syngas production

Problem statement

Mechanical recycling advantageous for homogenous waste, but **not suitable for complex feedstocks**

Potential for **thermochemical recycling/conversion**:

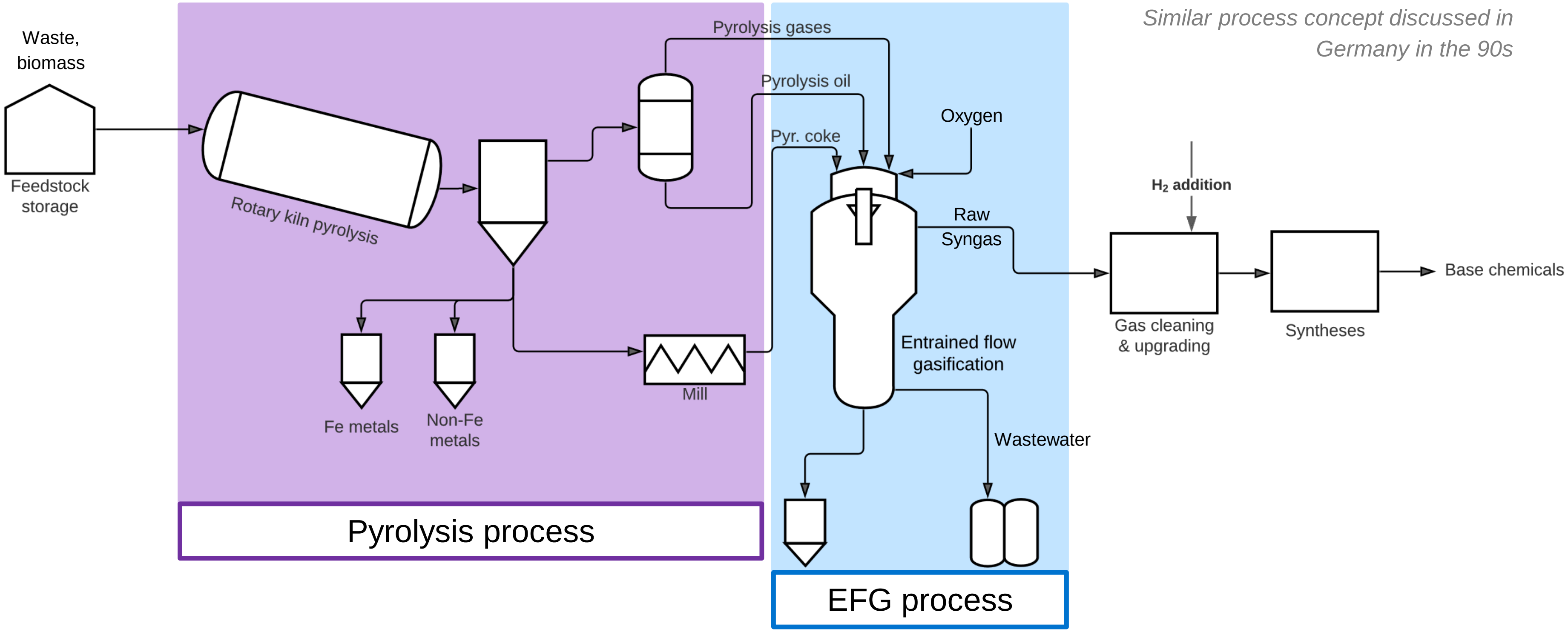
Entrained flow gasification (EFG) creates **high quality mostly tar-free syngas**, but requires extensive pre-treatment of feedstock

Rotary kiln pyrolysis has proven **track record for inhomogeneous wastes** during continuous operation (e.g., Burgau-Pyrolysis, 1985-2016)

Pyrolysis coke often not used due to low reactivity and energy content

Potential base case process

Similar process concept discussed in Germany in the 90s

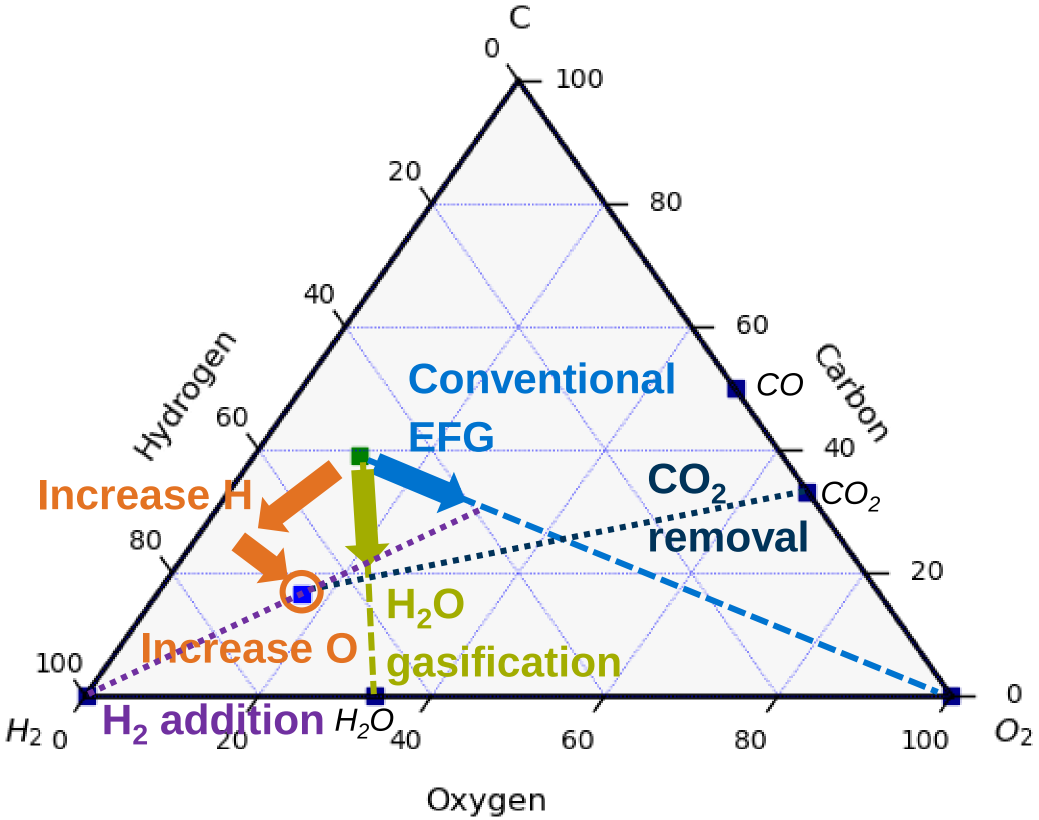


Combined process of **rotary kiln pyrolysis pre-treatment** and **entrained flow gasification** could be an attractive **thermochemical recycling/conversion** technology for utilizing **complex wastes** and a **wide range of biomasses**

1 | entrained flow

Source: Carl, Fritz (1994)

Hydrocarbon base chemicals require higher H_2 content than biomass/MSW – making allothermal steam gasification attractive

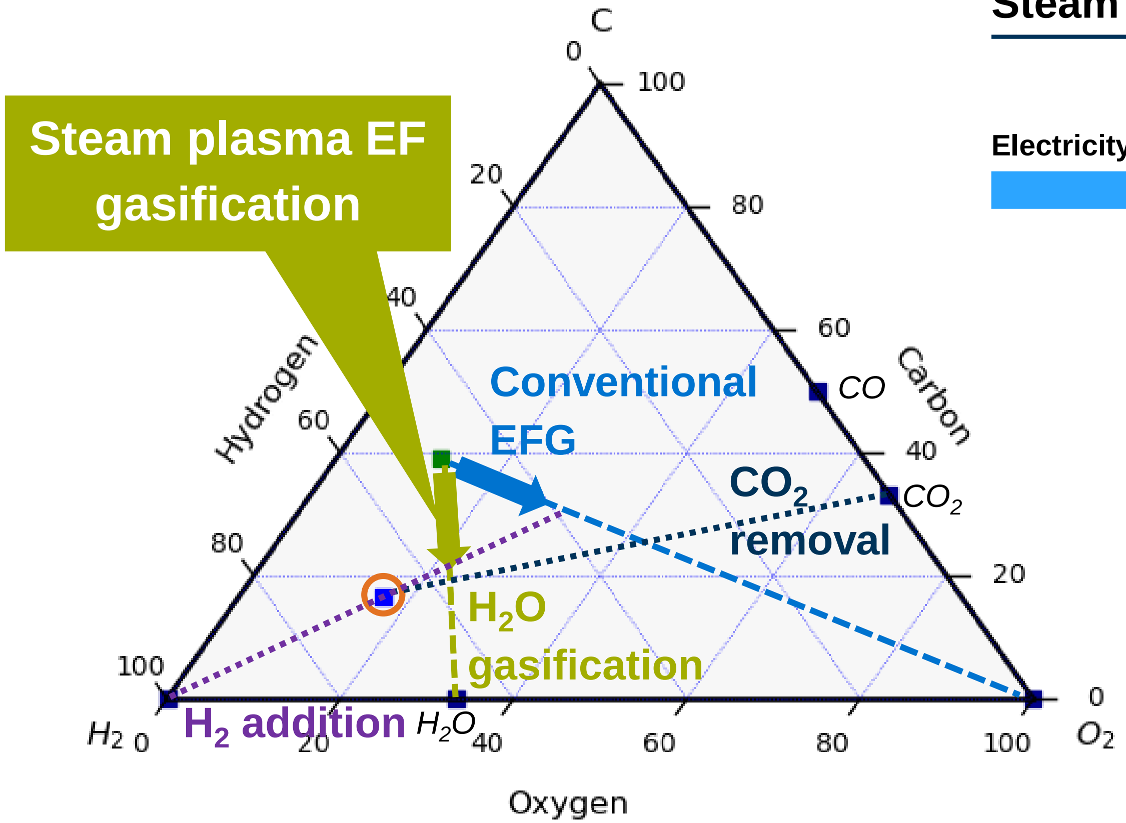


Substance	w%, daf H	C	O
Biomass/MSW (e.g., torr. wood)	**48.9**	**39.0**	**12.1**
Gasoline (Octane)	69.2	30.8	0
SNG (Synth. Natural Gas, CH_4)	80.0	20.0	0
DME (Dimethyl-Ether)	66.7	22.2	11.1
Methanol	66.6	16.7	16.7
OME (Oxymethylene-Ether)	56.0	24.0	20.0

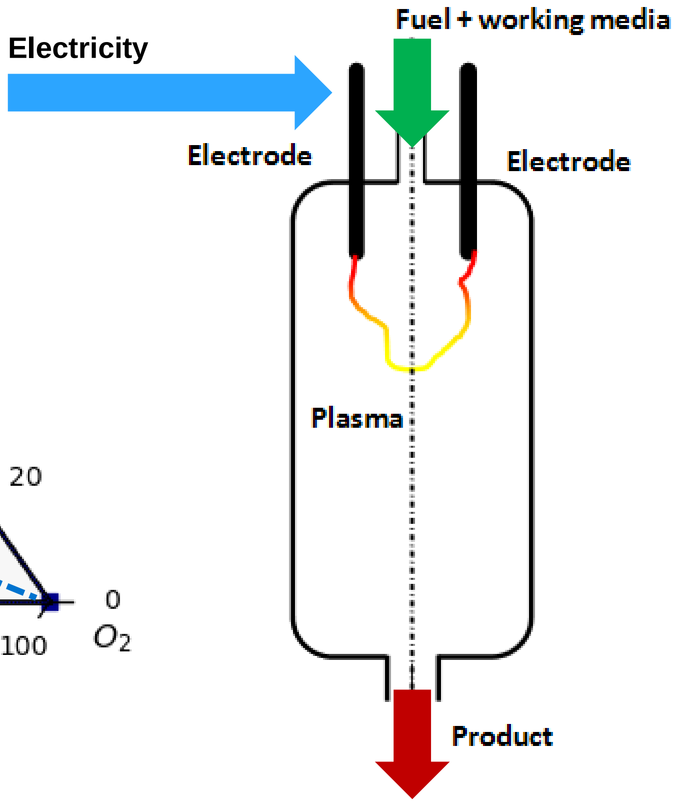
Hypothesis: **Allothermal steam gasification** beneficial for **high C-conversion** into base chemicals/fuels

Source: Phyllis database

Steam plasma EFG is a highly flexible process which achieves high carbon-to-syngas efficiencies at high H_2/CO ratios



Steam plasma entrained flow gasification as potential solution



Advantages

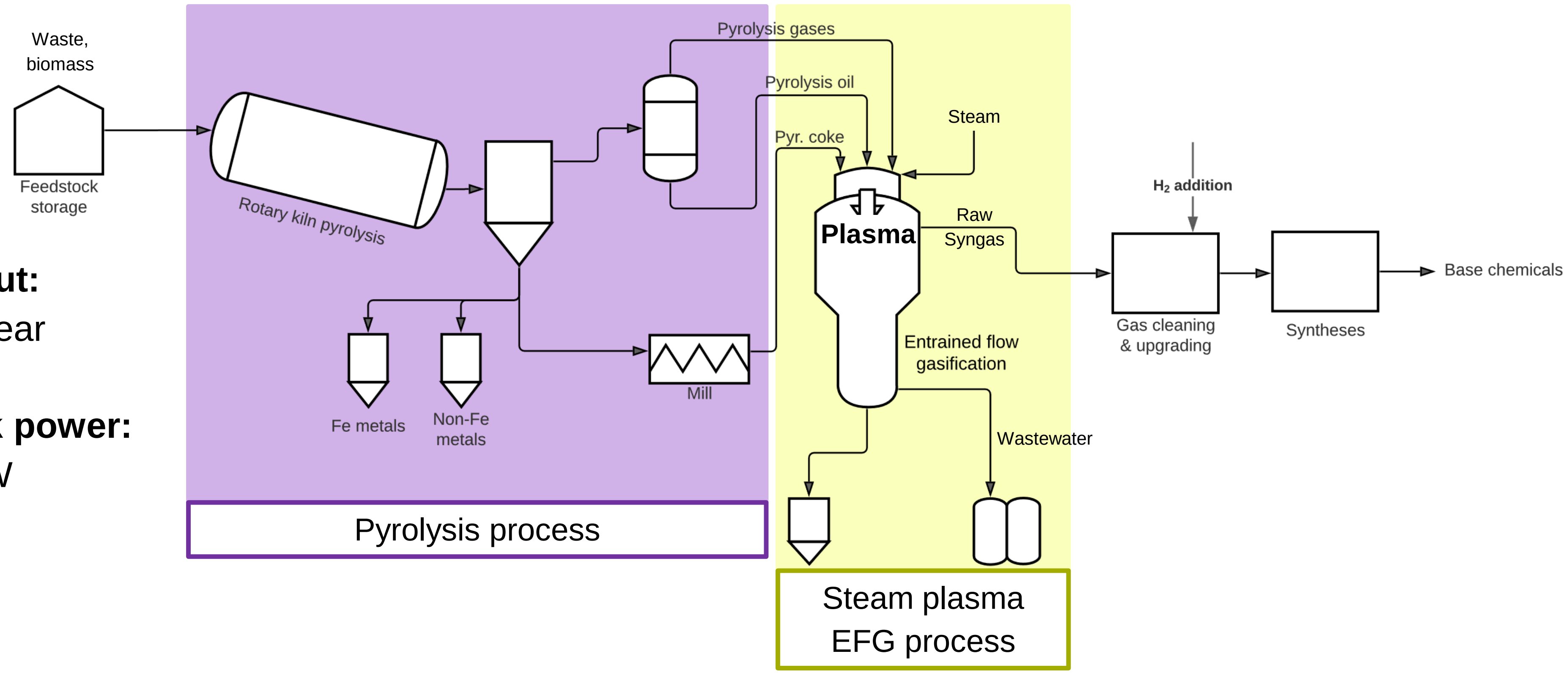
- **High carbon conversion** despite allothermal gasification
- **High H_2 content** of produced syngas due to steam addition
- **Minimization of tar content** in syngas
- **Low carbon losses** via CO_2 formation
- **High feedstock flexibility**, also low caloric, comparatively inert feeds possible

Source: Pang (2020)

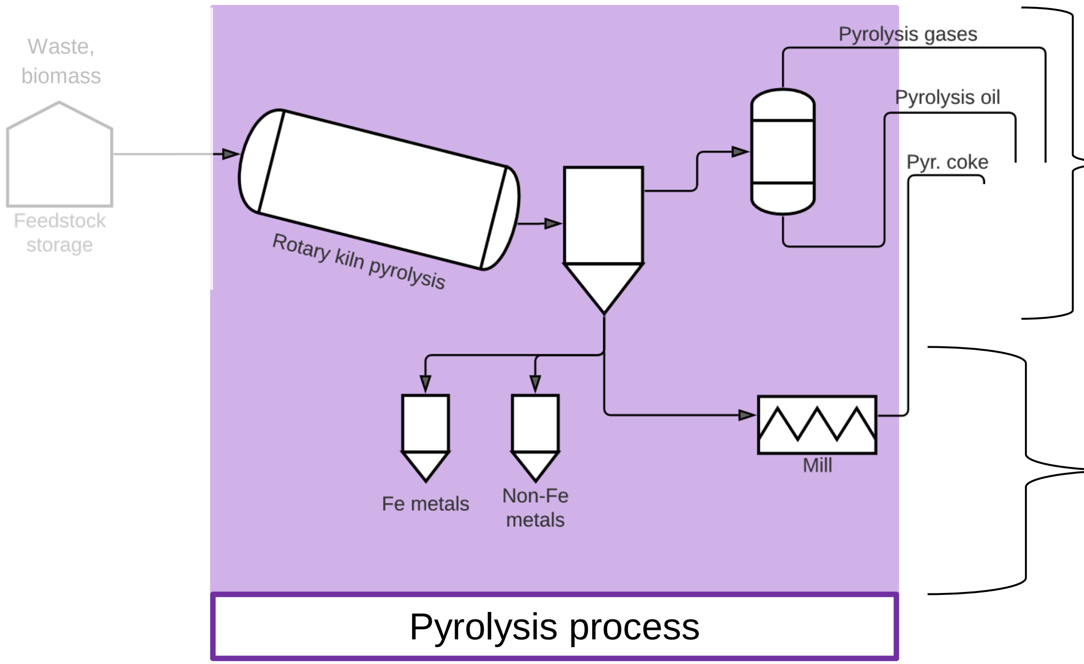
Simulation of steam plasma EFG with pyrolysis pre-treatment in Aspen Plus to benchmark against alternative P-B/W-tX processes

Waste input:
45 kt per year

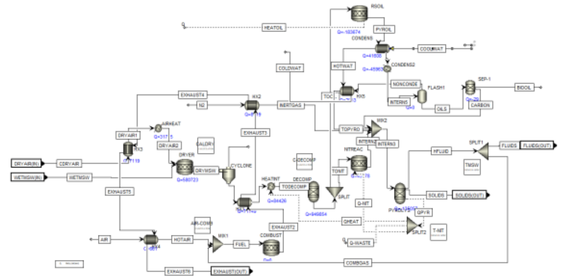
Feedstock power:
~10-15 MW



Pyrolysis process model: Rotary kiln pyrolysis simulation consists of pyrolysis and chart treatment sub-models

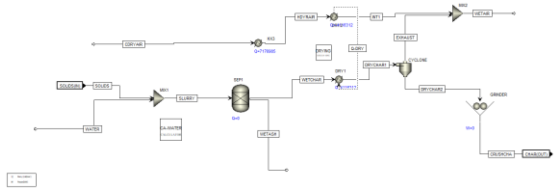


Pyrolysis sub-model



is sub-model

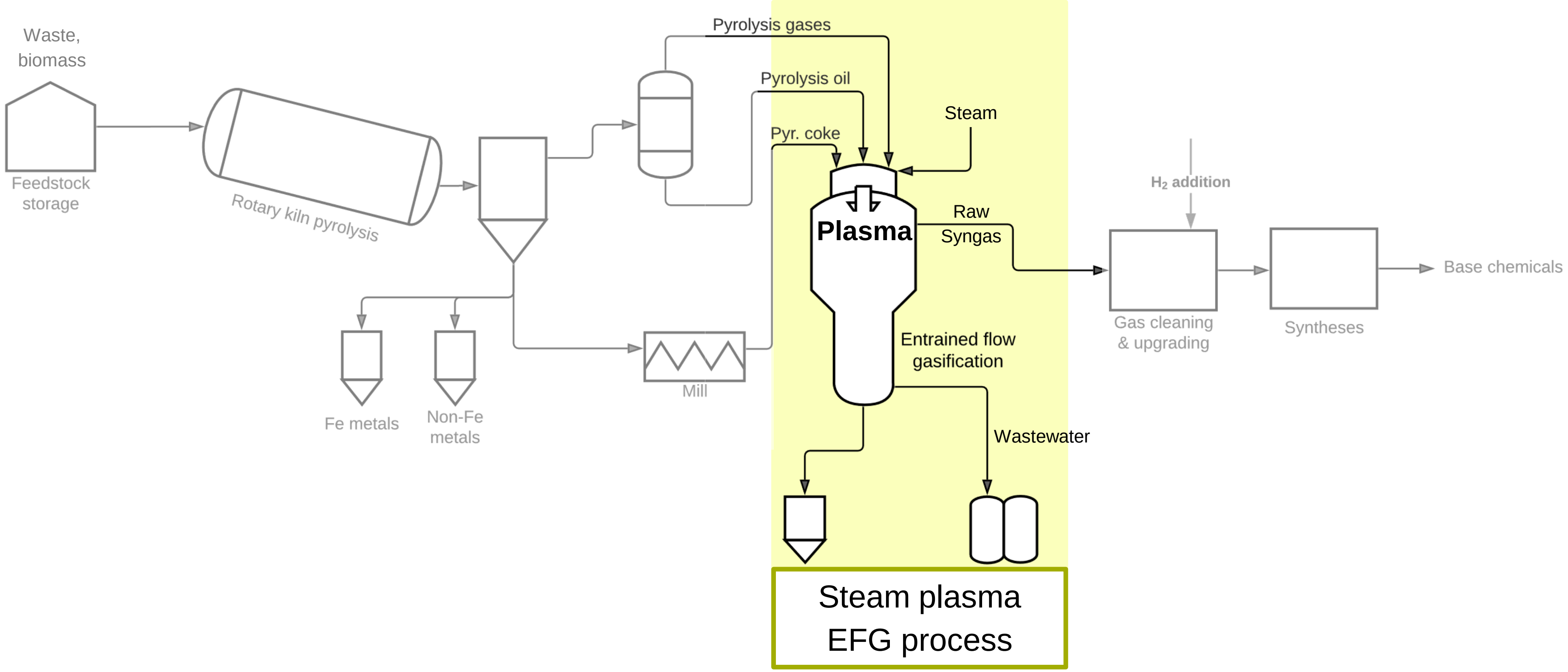
Char treatment sub-model



Screenshot of Aspen Plus flowsheet for char treatment

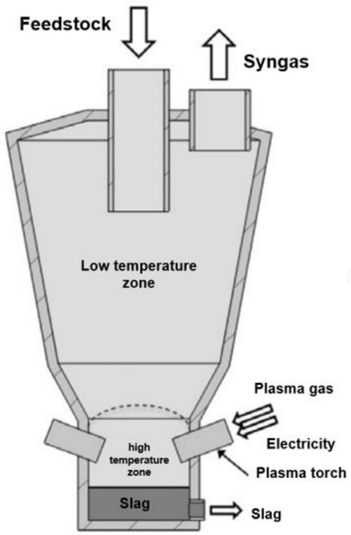
- Char treatment sub-model consisting of:
  - Wet char-inorganics separation
  - Char drying
  - Char milling/grinding

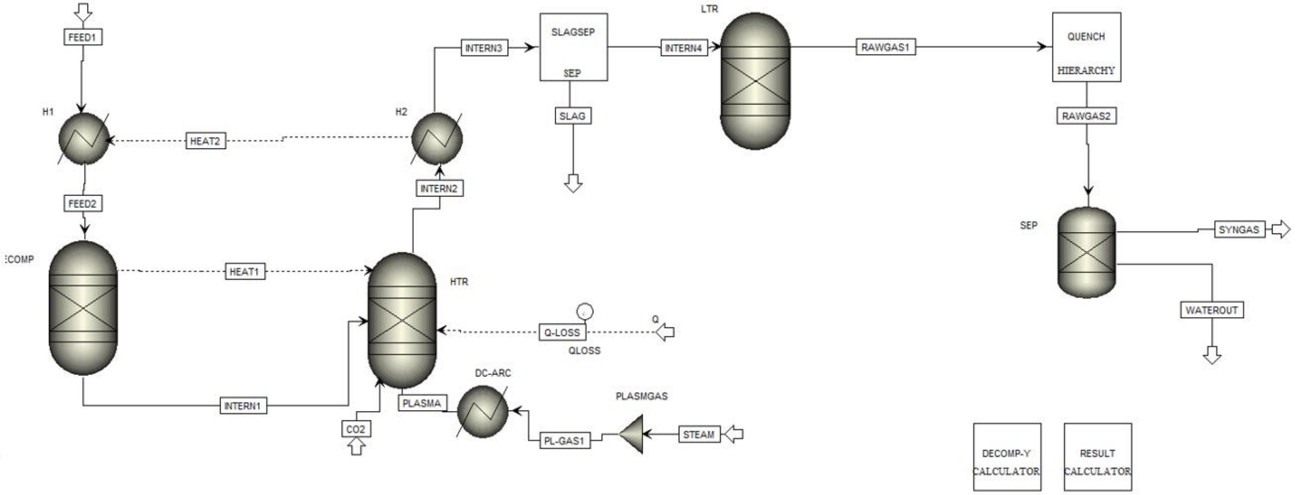
Plasma gasification model: Steam plasma EFG has been modelled using an equilibrium-based approach for the gasifier



Plasma gasification model: Equilibrium-based approach shows good alignment with experimental results

Model for validating simulation approach based on experiments by Agon et al.





Comparison to experimental data

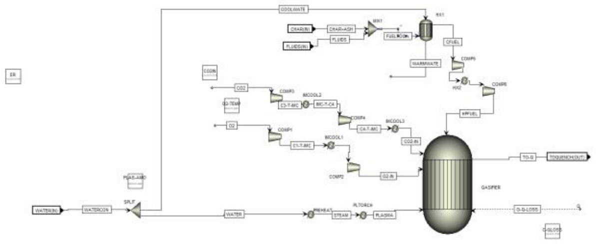
Mole fraction in % (dry syngas)	Agon et al.	simulation
y_{CO}	32.93	32.16
y_{H_2}	58.56	61.09
y_{CO_2}	3.98	6.44
y_{CH_4}	4.53	0.32
Performance metrics		
LHV in MJ/Nm^3	10.9	10.2
η_E in %	56.0	52.9
Y_{H_2}	0.66	0.83
Y_{CO}	0.66	0.69

Equilibrium-based modelling approach via **RGibbs reactor** seems to be **acceptable representation of plasma gasification** reactor for process simulation purposes

Source: Agon et al (2016), Mazzoni et al (2020)

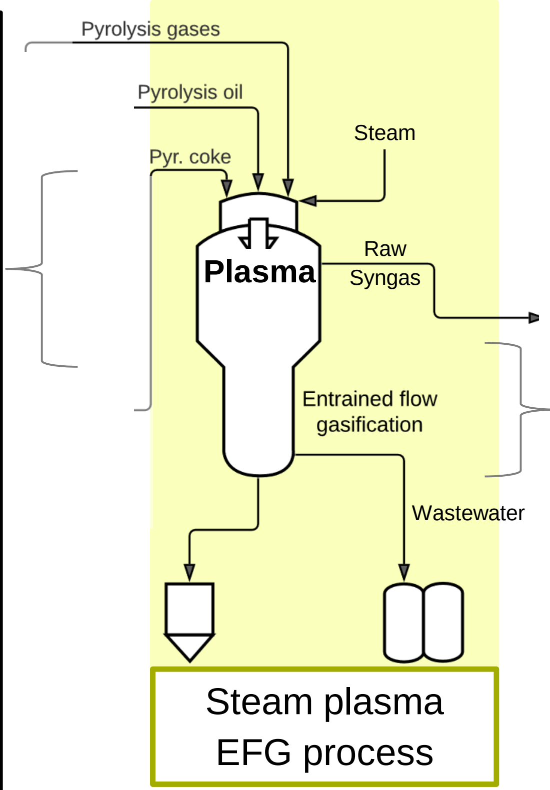
Simulation of steam plasma EFG with pyrolysis pre-treatment for in-depth assessment and benchmark against P-B/W-tX processes

Entrained flow gasif. sub-model

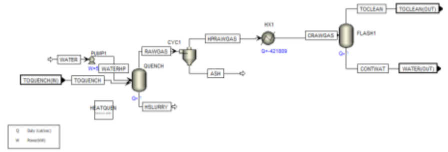


Screenshot of Aspen Plus flowsheet for plasma gasifier

- Gasifier outlet temperature (pre-quench) of T=1400°C and p = 30 bar
- Steam plasma via DC arc plasma torch (= "electric heater") with respective thermal efficiency
- Additional O_2 input if plasma power not sufficient to reach T=1400°C at gasifier outlet
- Equilibrium-based approach



Quench sub-model



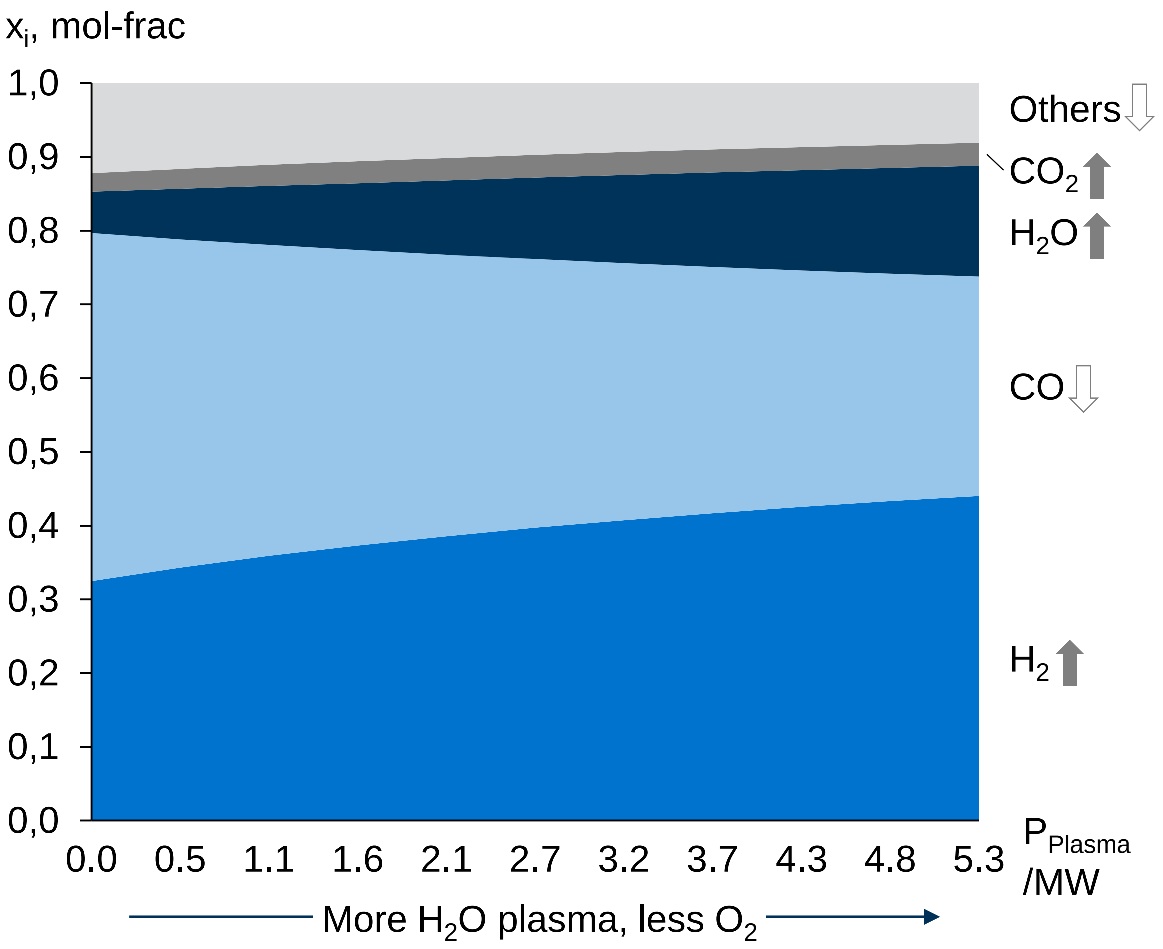
Screenshot of Aspen Plus flowsheet for quench model

- Water quench to T=300°C
- Ash and particulates removal from raw syngas via cyclone
- Condenser to T=50°C and subsequent gas-liquid separation

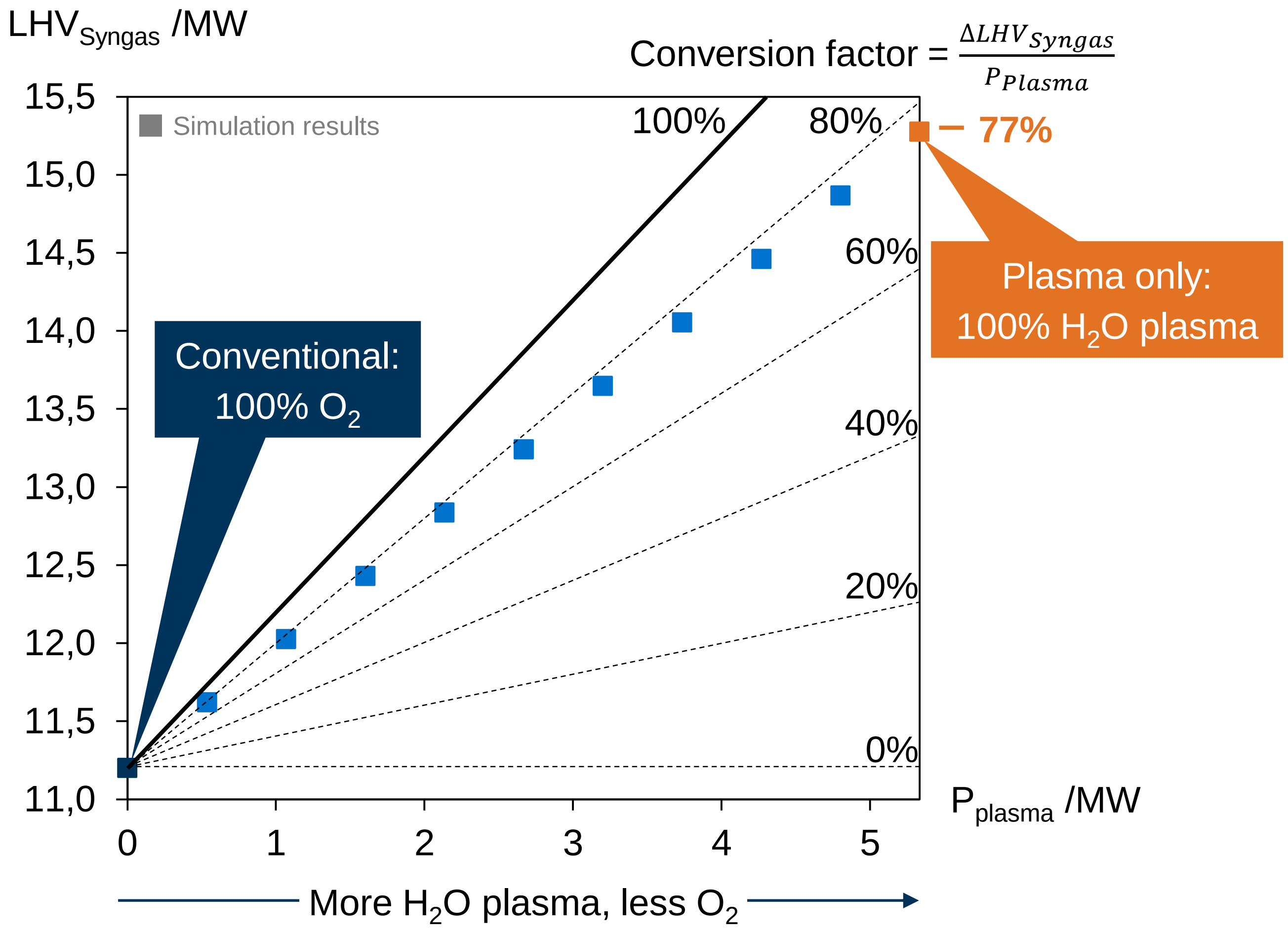
Initial analysis focuses on comparison of two edge cases: conventional oxygen-blown EF with steam plasma EF gasification

		Conventional gasification (= base case)	Pure steam plasma gasification
Process input:		6 tph MSW (wet) = 11.2 MW (LHV)	
Pyrolysis:	**Temperature**	T_{Pyr} = 500°C	
	Heating mode	External (electric)	
Gasification:	**Gasifier feed**	Pyrolysis gases, oil and char	
	Pre-Quench temperature	$T_{Pre\text{-}Quench}$ = 1400°C	
	Gasifying agent	100% O_2	100% H_2O (steam) plasma
	Pneumatic carrier gas	CO_2	
	Plasma power	-	5.3 MW

H_2/CO ratio increases by factor of >2 from conventional to pure steam plasma gasification case while CCE remains high

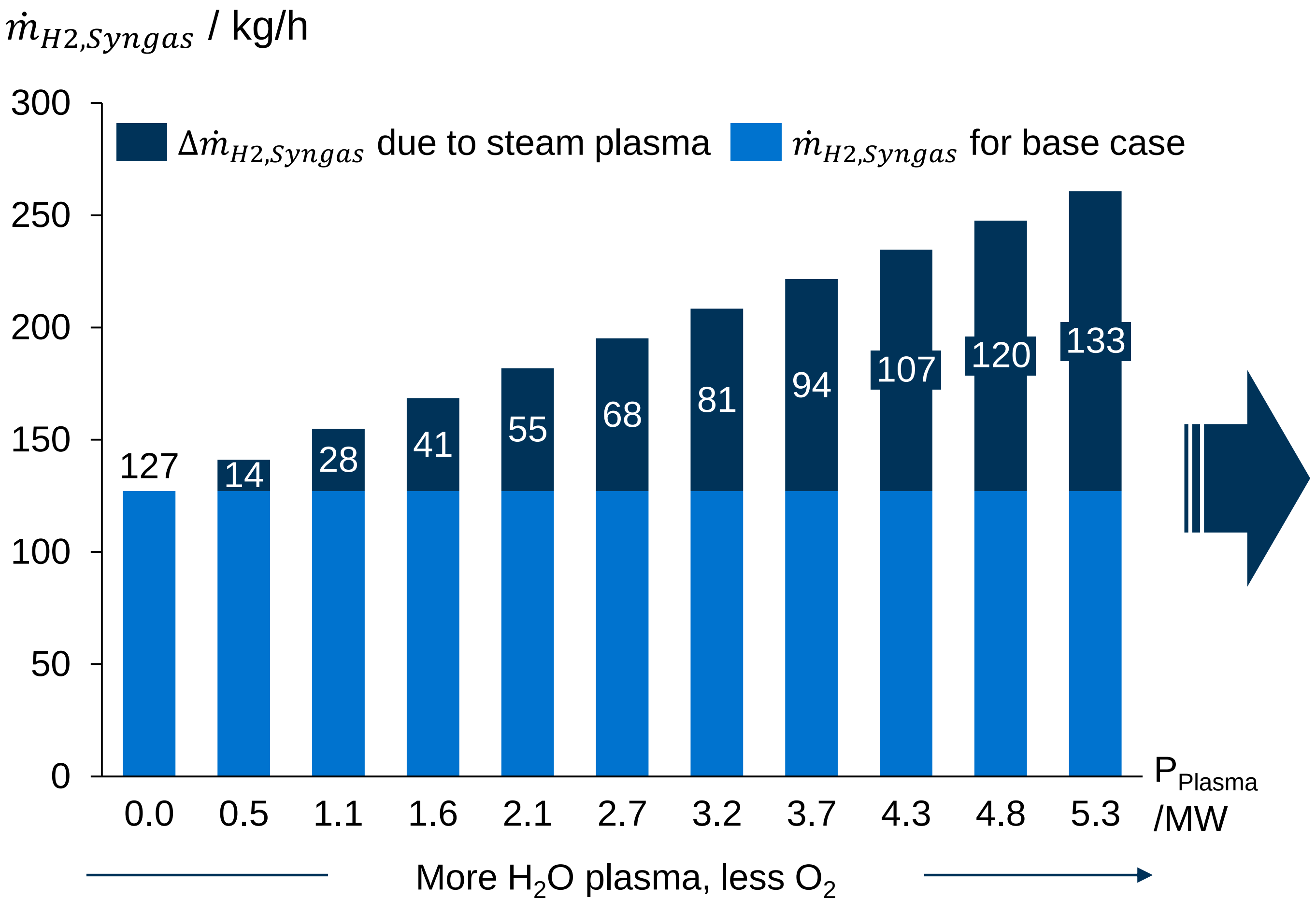


Steam plasma gasification achieves high conversion (77%+) of electricity input into chemical energy of the produced syngas



- Electrification of gasification process via steam plasma shows **high conversion efficiencies**
- Plasma input shows **diminishing returns** with >90% conversion factor at low plasma powers and 77% for full steam plasma operation
- Flexible switching between conventional and plasma operation **might be attractive for grid balancing**

Additional hydrogen produced from steam plasma seems to be energetically competitive with alternative production via electrolysis



1 | At 80% efficiency

Steam plasma EFG will be further evaluated based on this model and benchmarked against other P-B/W-tX processes

Conclusion

- Increased importance of **efficient biomass and waste utilization** in the future
- Combination of **pyrolysis and entrained flow gasification** can turn **broad range of feedstock** into syngas and base chemicals
- Integration of **steam plasma gasification** technology attractive for achieving **high carbon conversion and high H_2/CO ratio** in syngas
- Model of **pyrolysis** process makes use of both **empirical fitting** and **equilibrium-based approaches**
- **First modelling results** indicate **high attractiveness** of **steam plasma gasification**

Next steps

- **Further investigation** of proposed plasma entrained flow gasification process

  → **Identify sweet spot of operating conditions**
- **Further validation** of process concept with **smaller scale experimental set-up**
- **Benchmark against alternative** waste/biomass utilization and recycling **processes**
- **Publish results**

Please feel free to get in touch!

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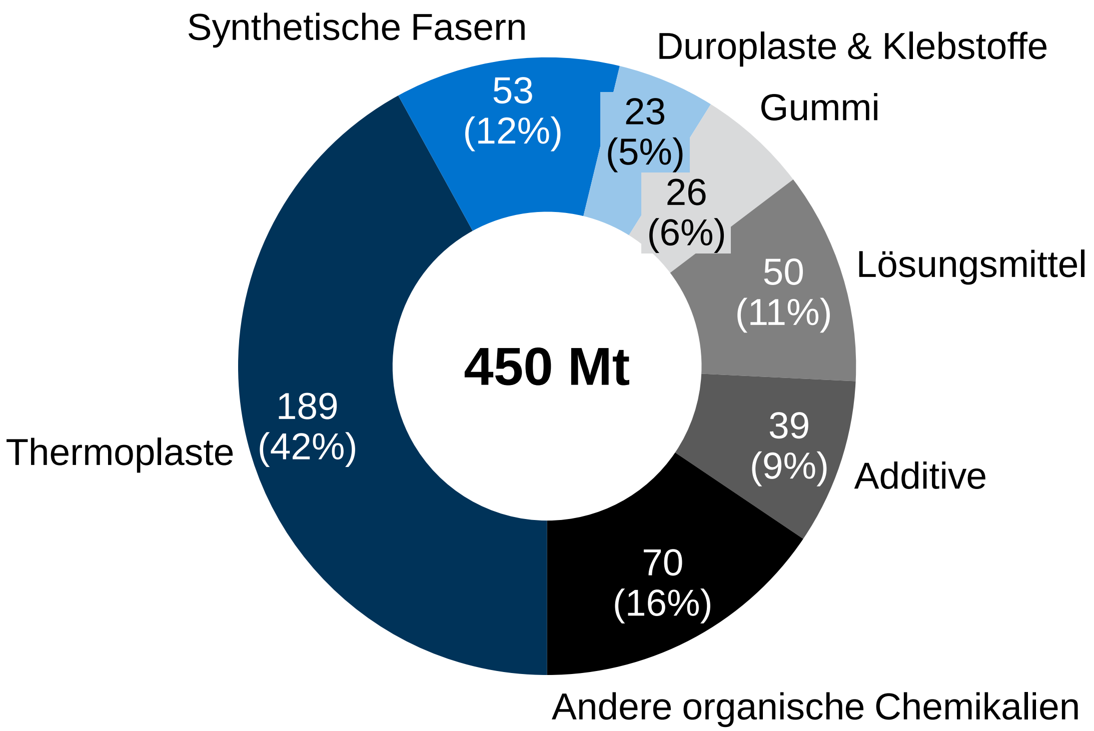
BACKUP

Chemieindustrie mit Kohlenstoffbedarf von ~450 Mt für Polymere und organische Chemikalien – heute zu 84% fossil gedeckt

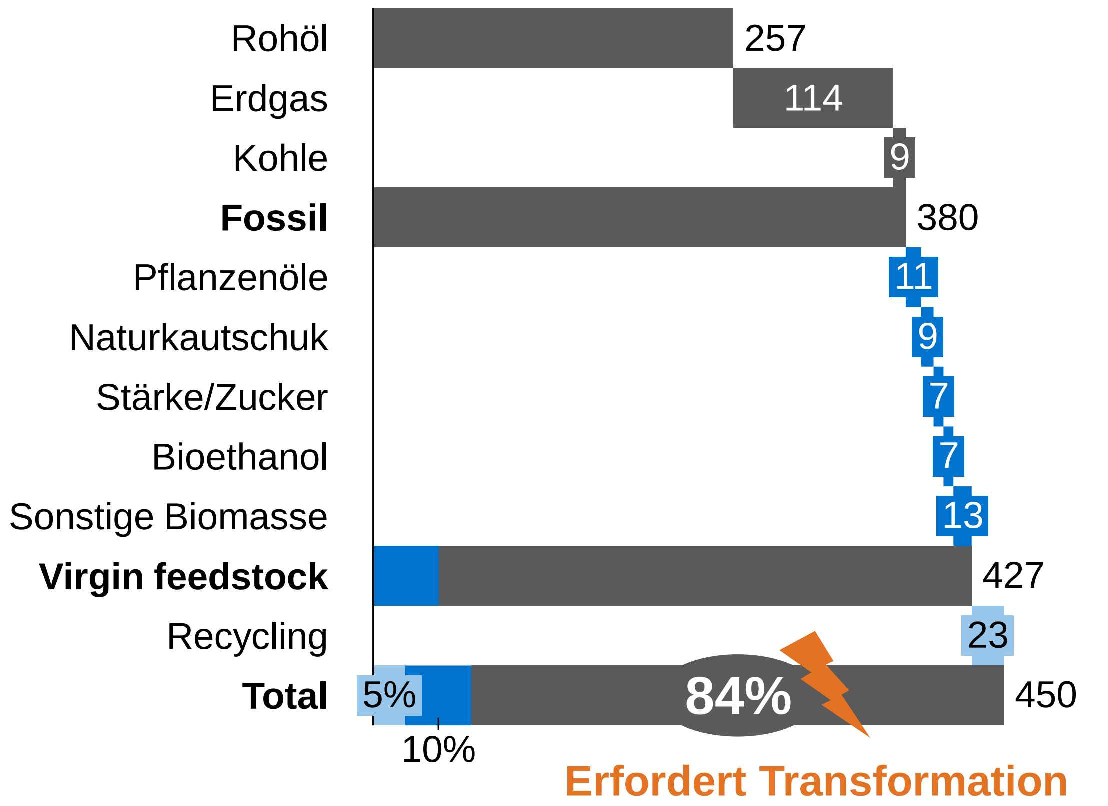
Weltweite C-Nachfrage der Chemieindustrie

C-Gehalt in Mt (% der Gesamtsumme), Ø2015-2020



Deckung C-Bedarf der Chemieindustrie nach Quelle

C-Gehalt in Mt, Ø2015-2020



Source: nova-Institute (2021)