Design and Control Concept of a 1 MW_{th} Chemical Looping Gasifier Allowing for Efficient Autothermal Syngas Production

Paul Dieringer, Falko Marx, Jochen Ströhle, Bernd Epple

Energy Systems & Technology
Prof. Dr.-Ing. B. Epple
www.est.tu-darmstadt.de

Outline

1

Introduction – BtL Process Chain

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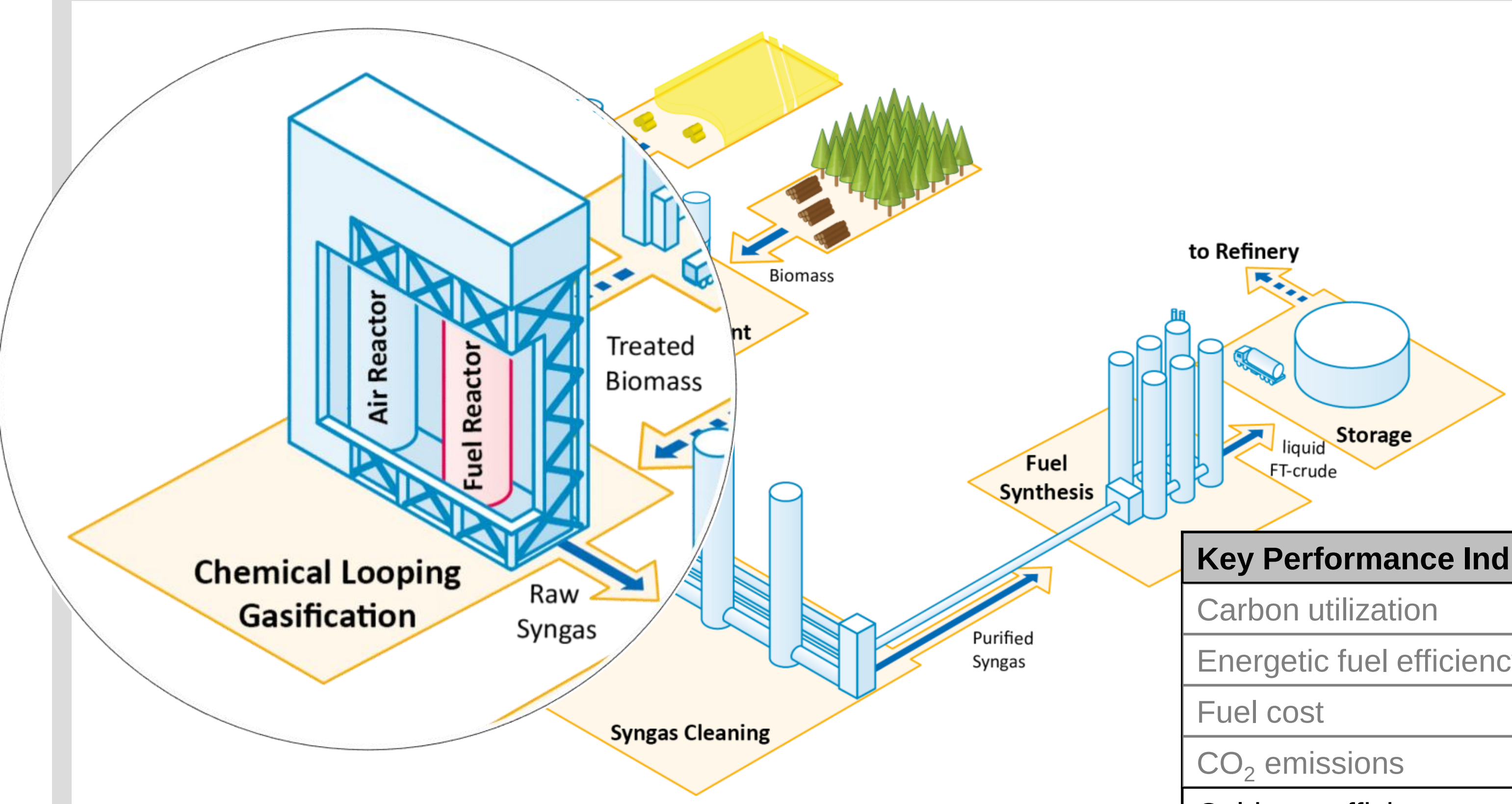
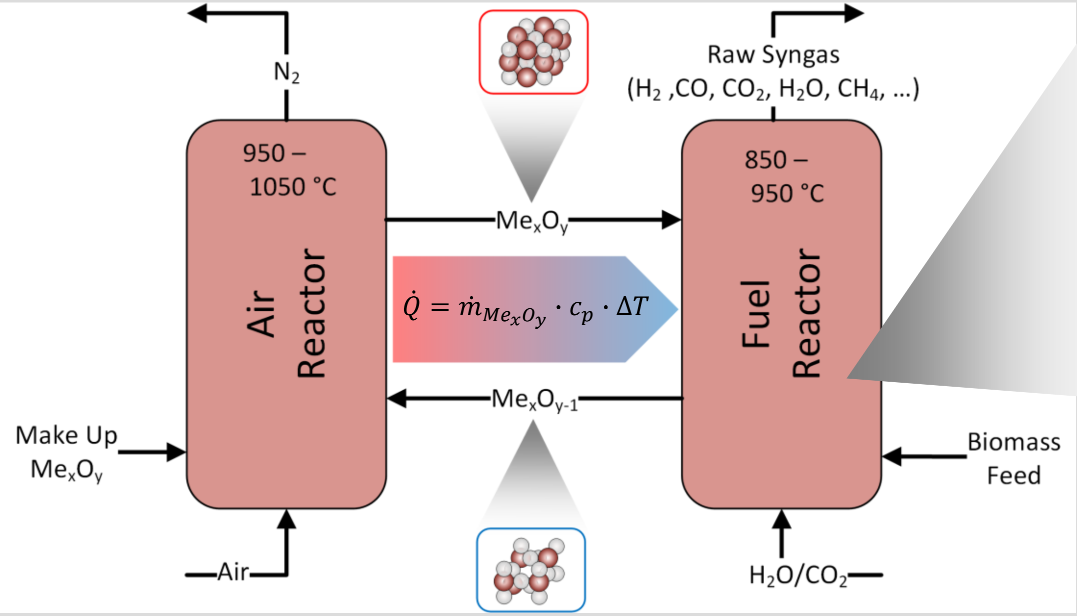
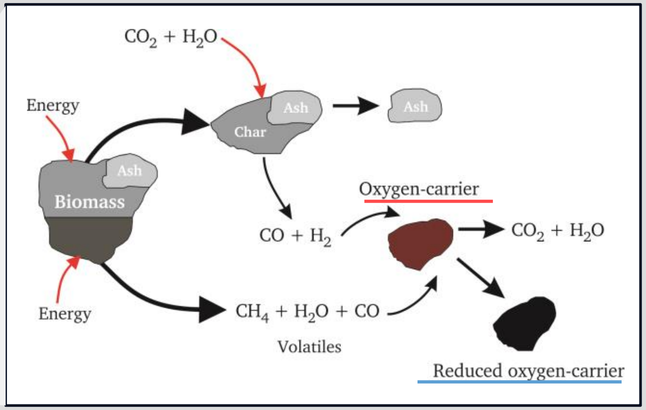
Novel biomass-to-biofuel process chain for the production of 2nd generation biofuels



Key Performance Indicators	Target
Carbon utilization	> 33 %
Energetic fuel efficiency	> 55 %
Fuel cost	< 0.7 €/l
CO_2 emissions	< 0
Cold gas efficiency	> 82 %
Carbon conversion	> 98 %

1 Introduction - CLG





[1] Alobaid et al., Energy (2015)

- FR: Conversion of feedstock into raw syngas via steam & Me_xO_y
- AR: Oxidation of Me_xO_{y-1} & combustion of remaining char
- Metal oxide: Oxygen & <u>Heat transport</u> (← decisive for CLG operation)
- Key performance indicators:
  - High cold gas efficiency (CGE)
  - Low tar content in FR producer gas
  - High char conversion in FR (X_C) = low CO_2 content in AR flue gas

1 Introduction - Highlights

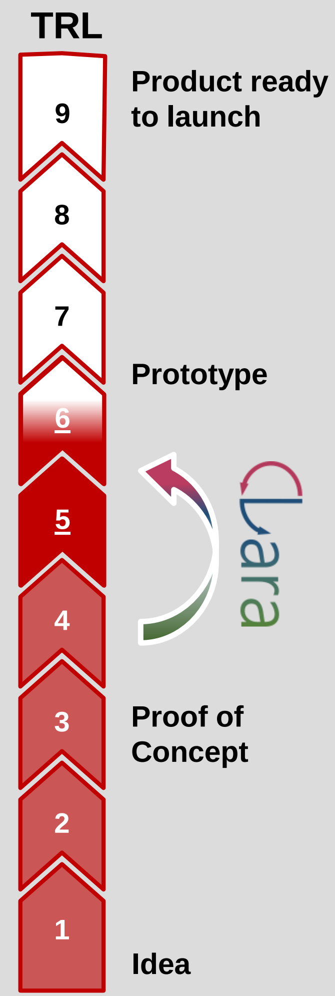
- CLG operation in 1 MW_{th} scale with three different feedstocks:

Industrial Wood Pellets

Pine Forest Residue Pellets

Wheat Straw Pellets

- Firing of more than 75 tons of biomass pellets in CL-mode
- Steady state CLG operation with novel control concept for 240 hours
- First ever demonstration of autothermal CLG
  - Approx. 130 hours of autothermal CLG operation
  - Cold gas efficiencies exceeding 50 % achieved
- Investigation of effect of different variables on process efficiency, e.g.
  - Reactor temperatures
  - Thermal loads
  - Particle size distribution of OC
  - …
- Elevation of technology readiness level (TRL) from TRL4 to TRL5/6



2 Pilot Plant Overview

1 MW_{th} pilot plant

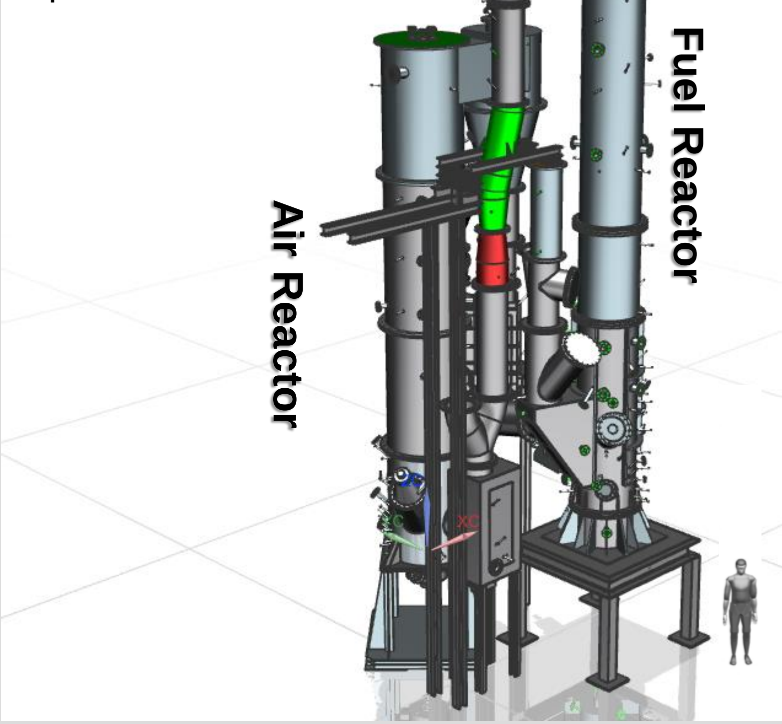
- Two coupled refractory-lined CFBs
- Previously used for CLC, CaL, HTW™ gasification, combustion

CLG Process Demands

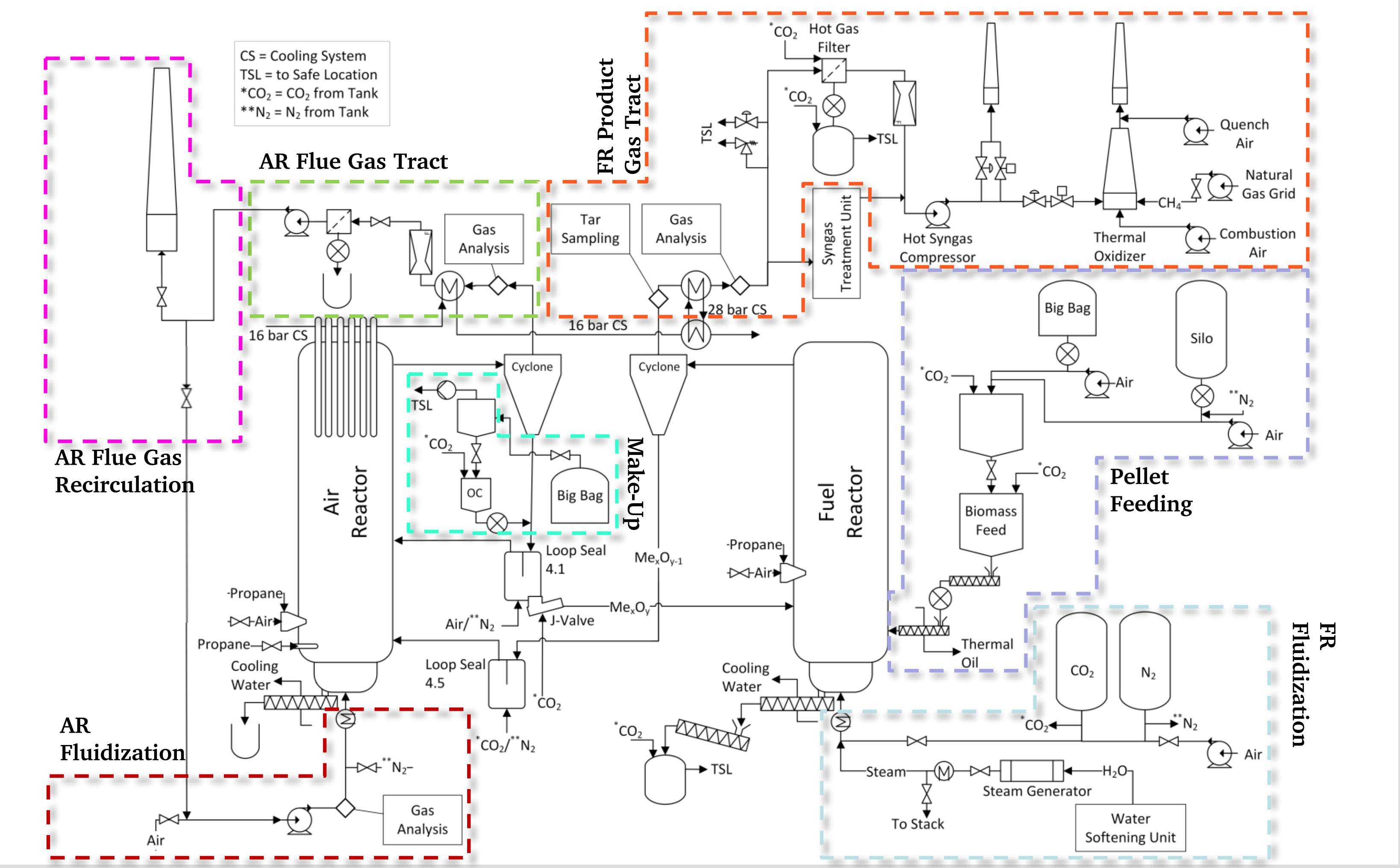
✓ Provide gasification conditions in FR
✓ Allow for safe handling of FR product gas
✓ Achieve autothermal operation

→ Adaption of existing 1 MW_{th} pilot, allowing for CLG operation

	AR *CFB600*	FR *CFB400*
d_i	0.6 m	0.4 m
d_o	1.3 m	1.0 m
h_i	8.7 m	11.4 m



2 Pilot Plant Layout



2 Process Control Concept

- Large heat fluxes to FR = large solid circulation rates from AR to FR
- Restriction of oxidation reactions in FR = limitation of O-transport to FR
  → Uncoupling of solid and oxygen transport via AR flue gas recirculation

Control Loop 1: FYC1

Material entrainment from CFB controlled by $u_{0,AR}$

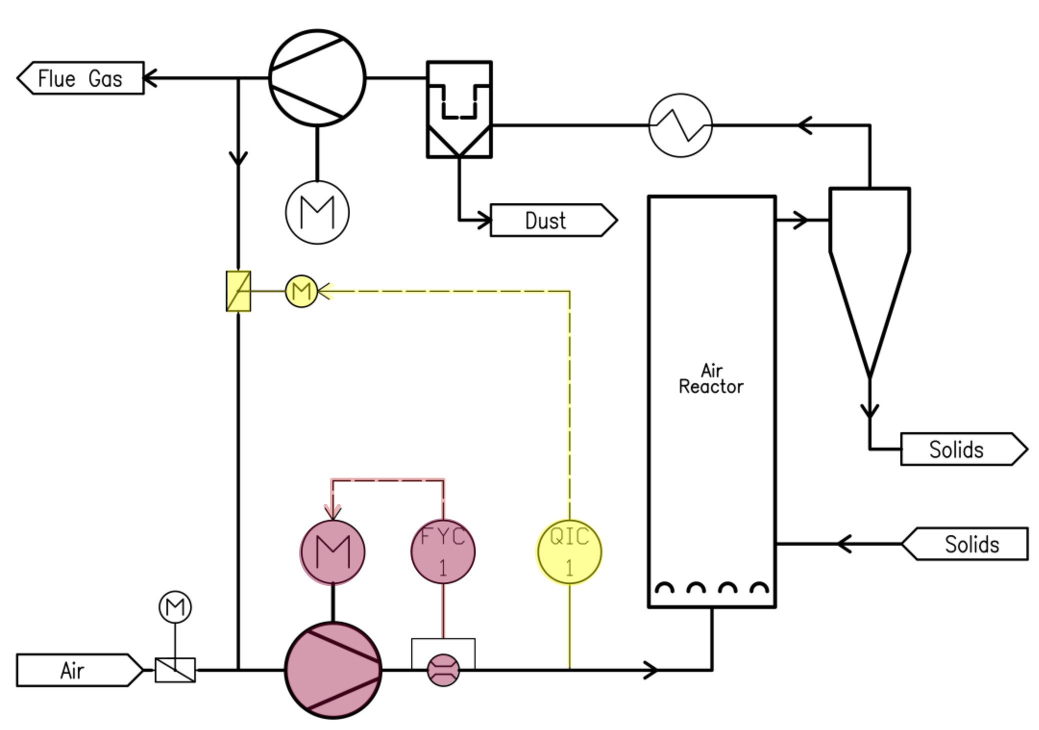
$u_{0,AR}$ controlled via primary air fan (SIC1)

Control Loop 2: QIC1

O_2 input to AR ($x_{O2,in,AR}$) determines oxidation extent in AR

Regulating flap in AR flue gas line used to control $x_{O2,in,AR}$

Independent control of $u_{0,AR}$ & λ



Evaluation Parameters

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AR Flue Gas Recycling Ratio

$$RR_{AR} = \frac{\dot{V}_{Rec.,AR}}{\dot{V}_{Rec.,AR} + \dot{V}_{Air,AR}}$$

$RR_{AR} = 0$
→ Only air into AR

$RR_{AR} = 1$
→ Only flue gas into AR

H_2 to CO Ratio

$$H_2 : CO = \frac{x_{H2,FR,out}}{x_{CO,FR,out}}$$

$H_2 : CO = 2:1$
→ Ideal for FT synthesis

Air-to-Fuel-Equivalence Ratio

$$\lambda = \frac{\dot{m}_{O,AR} - \dot{m}_{C3H8,AR} \cdot R_{C3H8}}{\dot{m}_{Feedstock} \cdot R_{Feedstock}}$$

$\lambda = 0.25 - 0.35$
→ Autothermal CLG operation

Cold Gas Efficiency

$$\eta_{CG} = \frac{\dot{n}_{gas,FR} \cdot (x_{CH4} \cdot LHV_{CH4} + x_{CO} \cdot LHV_{CO} + x_{H2} \cdot LHV_{H2})}{\dot{m}_{Feedstock} \cdot LHV_{Feedstock}}$$

$\eta_{CG} = 1$
→ Entire energy in syngas

$\eta_{CG} = 0$
→ Full feedstock conversion

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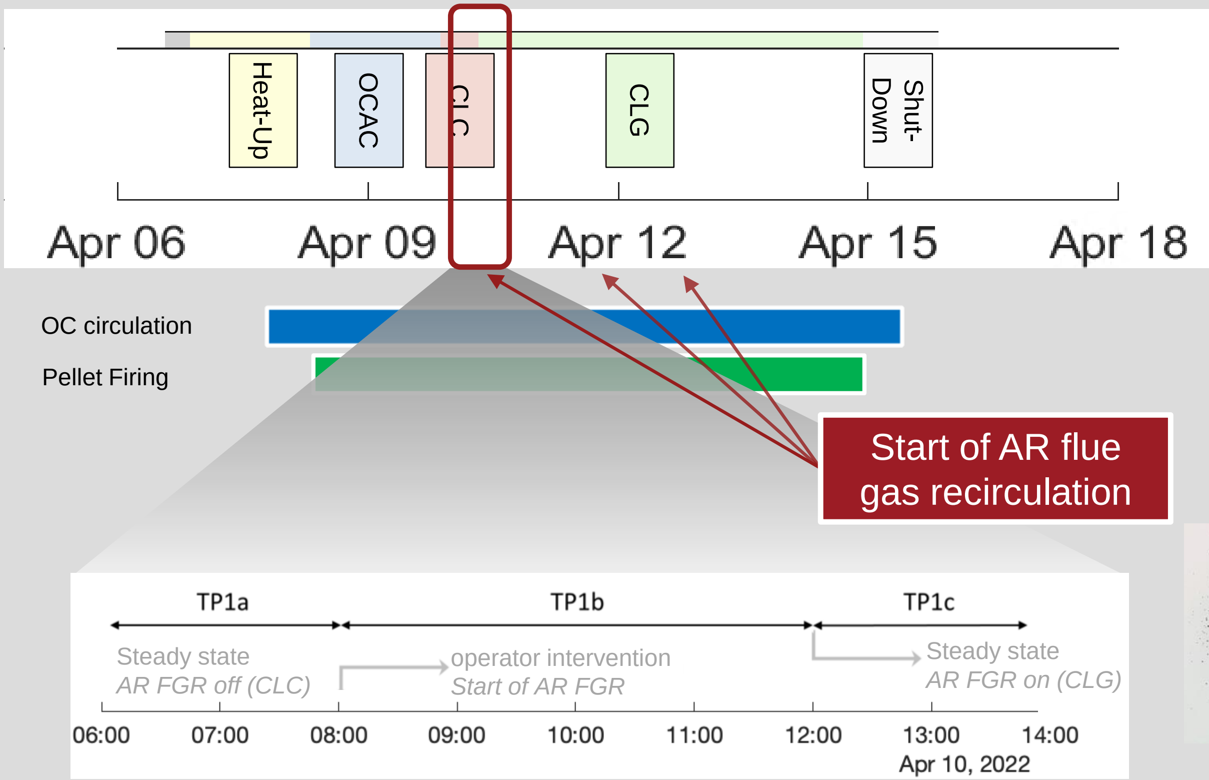
2 Boundary Conditions



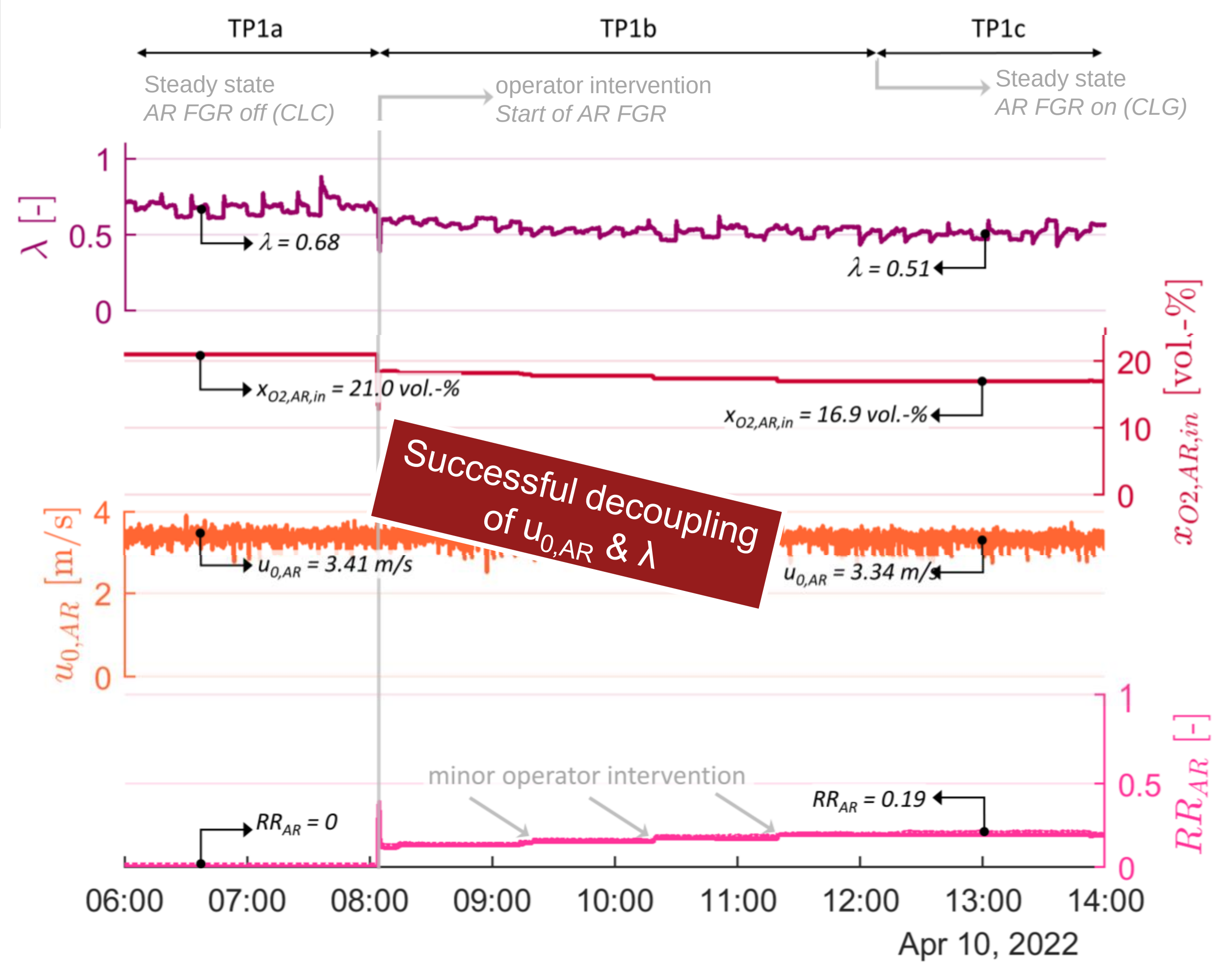
Variable	TP-1	Unit
$\dot{m}_{Feedstock}$	227.6	kg/h
T_{AR}	973.1	°C
T_{FR}	889.9	°C
Δp_{AR}	48.6	mbar
Δp_{FR}	68.0	mbar
$\dot{m}_{H2O,FR}$	239.5	kg/h
$\dot{m}_{Fluid.M.,AR}$	968.4	kg/h
$\dot{m}_{C3H8,AR}$	10.1	kg/h

Ilmenite

Industrial Wood Pellets

- During long-term operation three distinct transient chemical looping phases observed
  - → Induced by start of AR flue gas recirculation (FGR)
  - → Each phase shows characteristic progression of selected process parameters
- → Exemplary analysis of first transient period (TP-1)

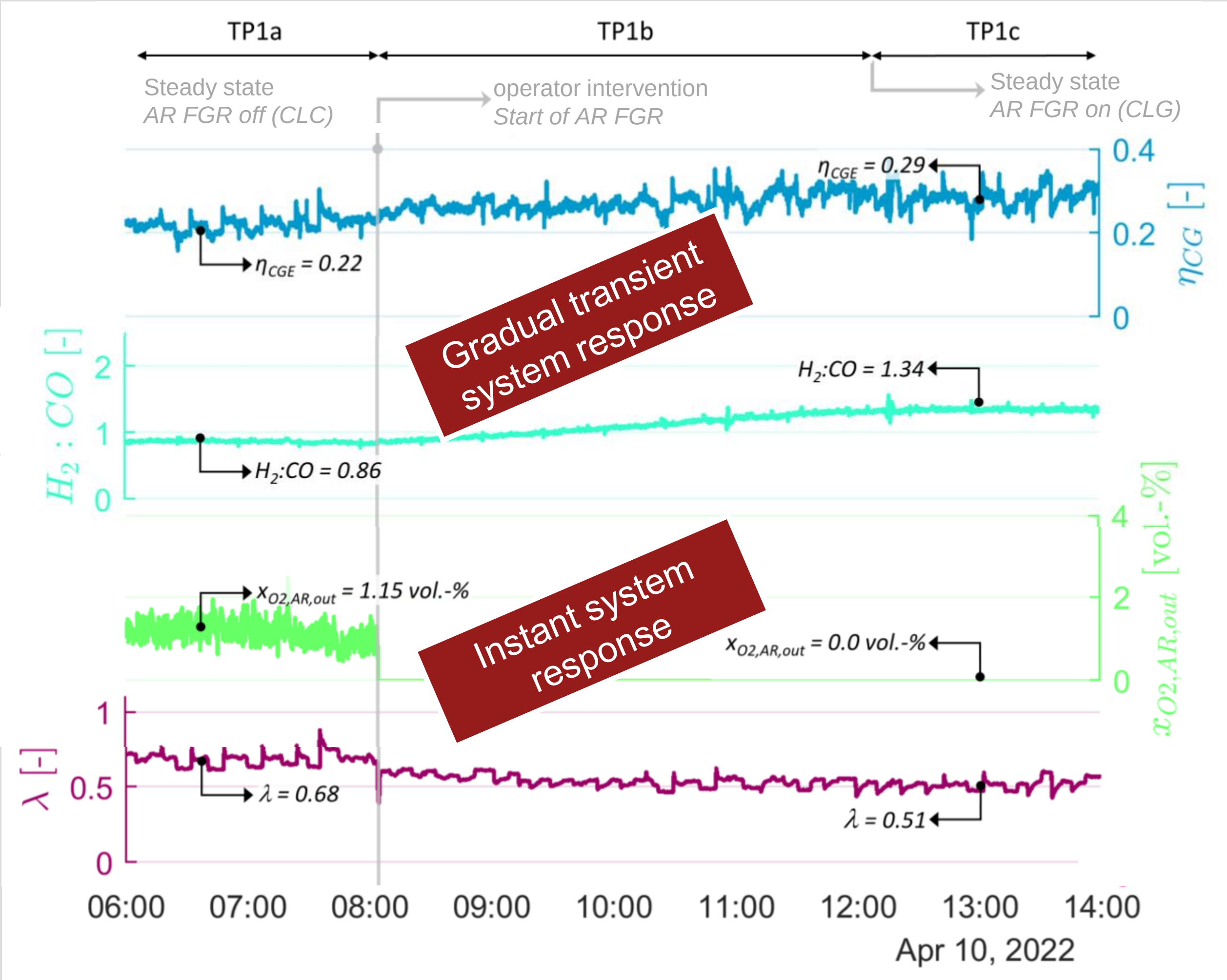
3 Results (I)



Key Findings

- Sudden adaption of RR_{AR} by operator
  → Goal: increase syngas yield in FR
- No change in $u_{0,AR}$
  → Stable hydrodynamics
- Step response in $x_{O2,in}$
  → Lower O_2 input into AR
- Rapid drop in λ
  → Less oxygen available in FR for feedstock conversion

3 Results (II)

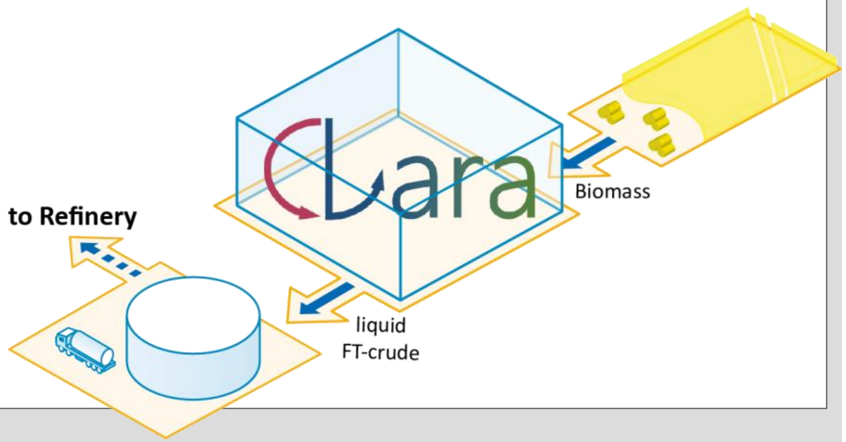


Key Findings

- Rapid drop in λ
  → Less oxygen available in FR for feedstock conversion
- Step response in $x_{O2,out}$
  → Complete O_2 consumption in AR
- Gradual increase in H_2:CO-ratio
  → Less oxygen available in FR
  → OC reduced more strongly with time
- Slowly increasing η_{CGE}
  → Less oxidation in FR
  → More energy remains in syngas

4 Summary

- Successful development, implementation & demonstration of novel CLG control concept in 1 MW_{th} scale based on flue gas recycling (FGR) for AR
- AR FGR allows for de-coupling of oxygen and heat transport in CLG
  - → Process λ & T_{FR} can be controlled independently
  - → Efficient CLG operation
- Changes in λ instantly take effect in the AR but propagate slowly into FR
  - → Transient behavior has to be considered for CLG units of substantial size



4 Outlook

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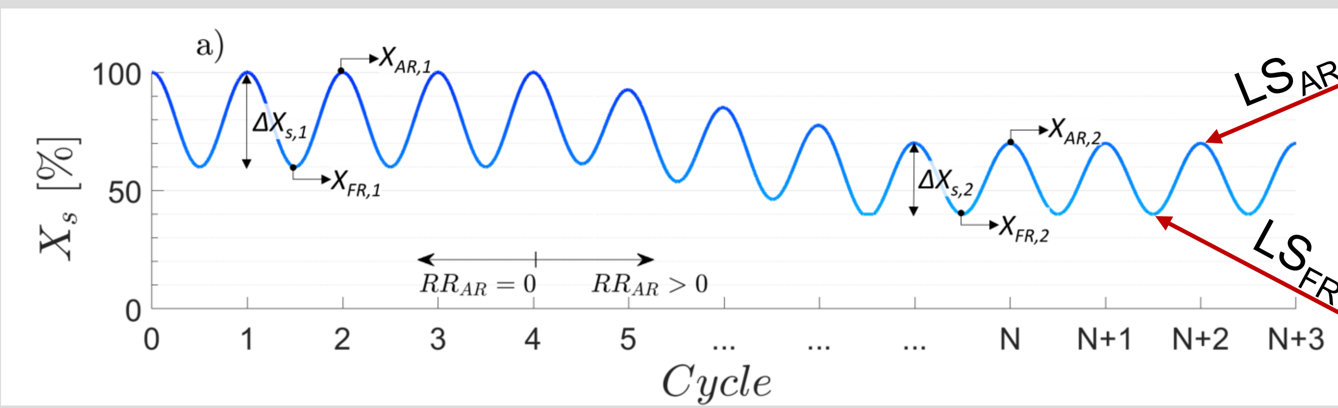
- Analysis of solid OC samples from loop seals to determine oxidation degree (X_s)
- Qualitative and quantitative comparisons between different transient switch-over phases
- Application of control concept to reach lower λ (0.35-0.45) at thermal loads up to 1.5 MW_{th} to further increase the process cold gas efficiency

$$X_{s,i} = \frac{m_{OC,i} - m_{OC,red}}{R_{OC} \cdot m_{OC,ox}}$$



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Thank You for Your Attention!

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EST Homepage

Paul Dieringer
Energy Systems and Technology

Mail: paul.dieringer@est.tu-darmstadt.de
Phone: +49 6151 16 22692
Otto-Berndt-Straße 2, 64287 Darmstadt / Germany
www.est.tu-darmstadt.de