PCCC-8 conference, Marseille, France - Session 4C – 17th September 2025

Investigation of a MEA-based CO_2 capture process applied to fluctuating flue gases through dynamic simulations

Dr L. Dubois, Dr A. Verhaeghe, Prof. G. De Weireld and Prof. D. Thomas

NKL Project

Wallonie Relance

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UMONS CCUS Projects

MOF4AIR — CO_2 capture by aDsorption with MOFs

BUTTERFLY — CO_2 Purification Unit (CPU) modeling

Presentation by Ir A. Henrotin (VPSA-CPU)

DEMIX4C2 — CO_2 capture using demixing solvents

Presentation by Ir D. Verdonck

DRIVER — CO_2 capture, purification, liquefaction & conversion Units

SATURN — CO_2 capture application to different CO_2 emitters

Presentation by Dr L. Dubois

$MOFC^4M_2$ — CO_2 capture with MOFs & Microwave Swing Adsorption

Presentation by Ir A. Houzé

FARADAY — Triphasic electrolyzer modeling

NKL — CO_2 capture & integration with conversion into e-kerosene

Presentation by Dr A. Verhaeghe

ATLANTIS — CO_2 capture using catalytic abs-regen process

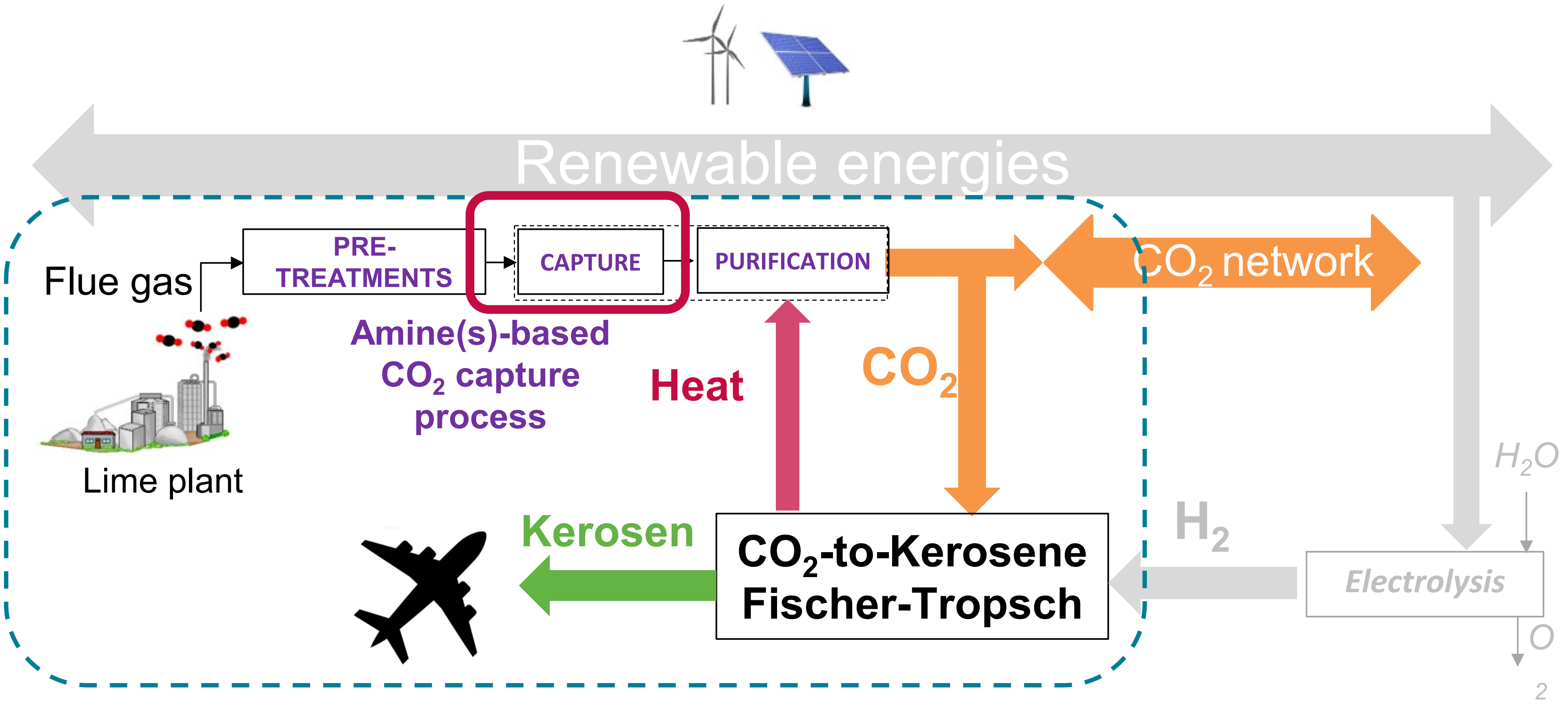
Presentation by Ir C. Pasté

BEST — Micro-Gas Turbines & CO_2 capture unit integration

Waste2Emission0 (0Carbon4Wal) — CO_2 capture in the Waste-to-Energy sector

SORBINNOV — CO_2 capture using innovative aD/aB-sorbents

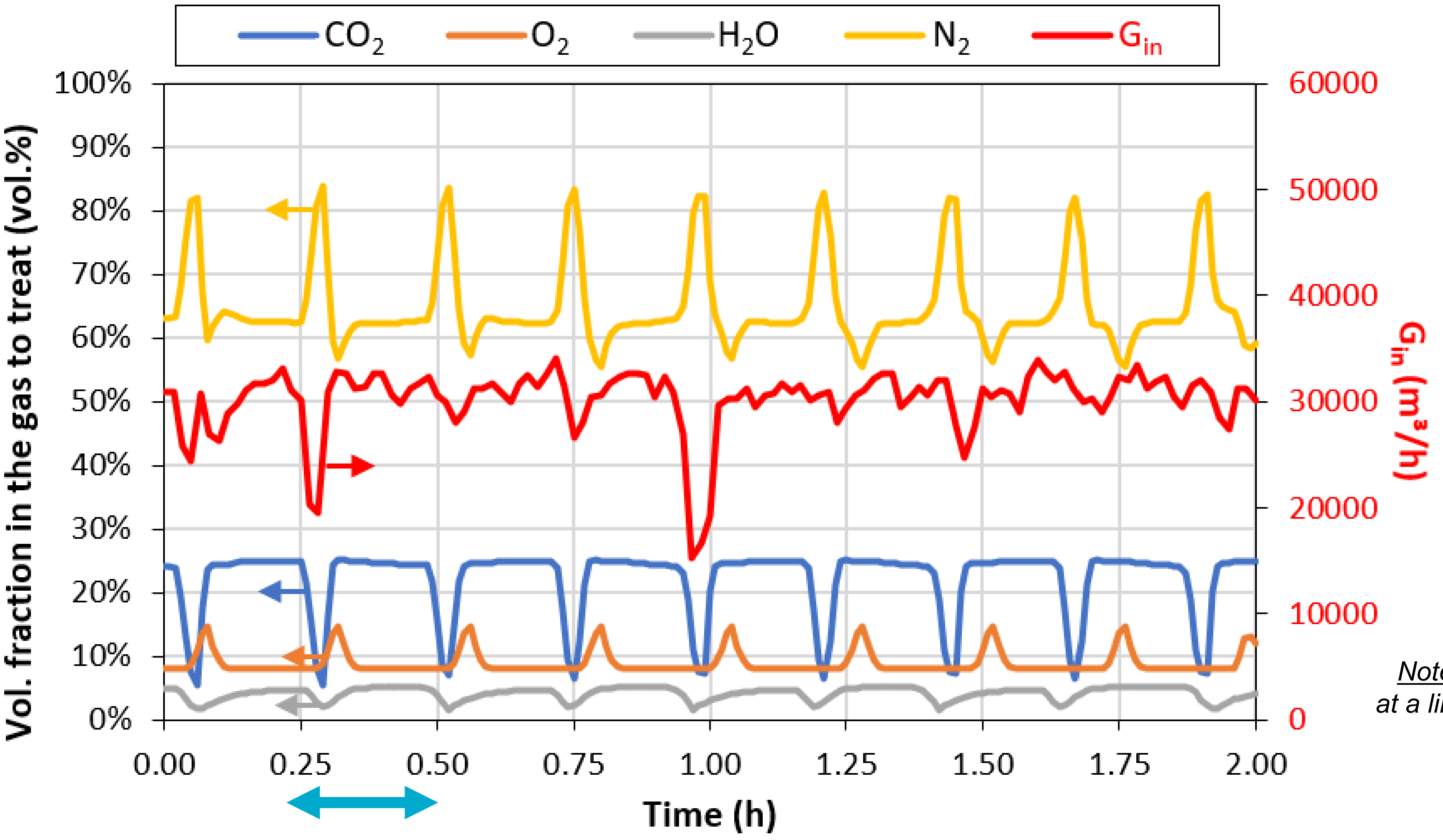
NKL project scope



NKL SCOPE

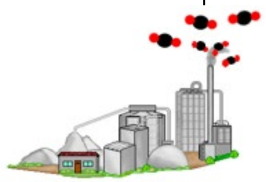
Wallonie Relance

Lime plant flue gas



15 min cycle = 11 min nominal + 4 min low G_{in} x low y_{CO2} = low $G_{CO2,in}$

Flue gas

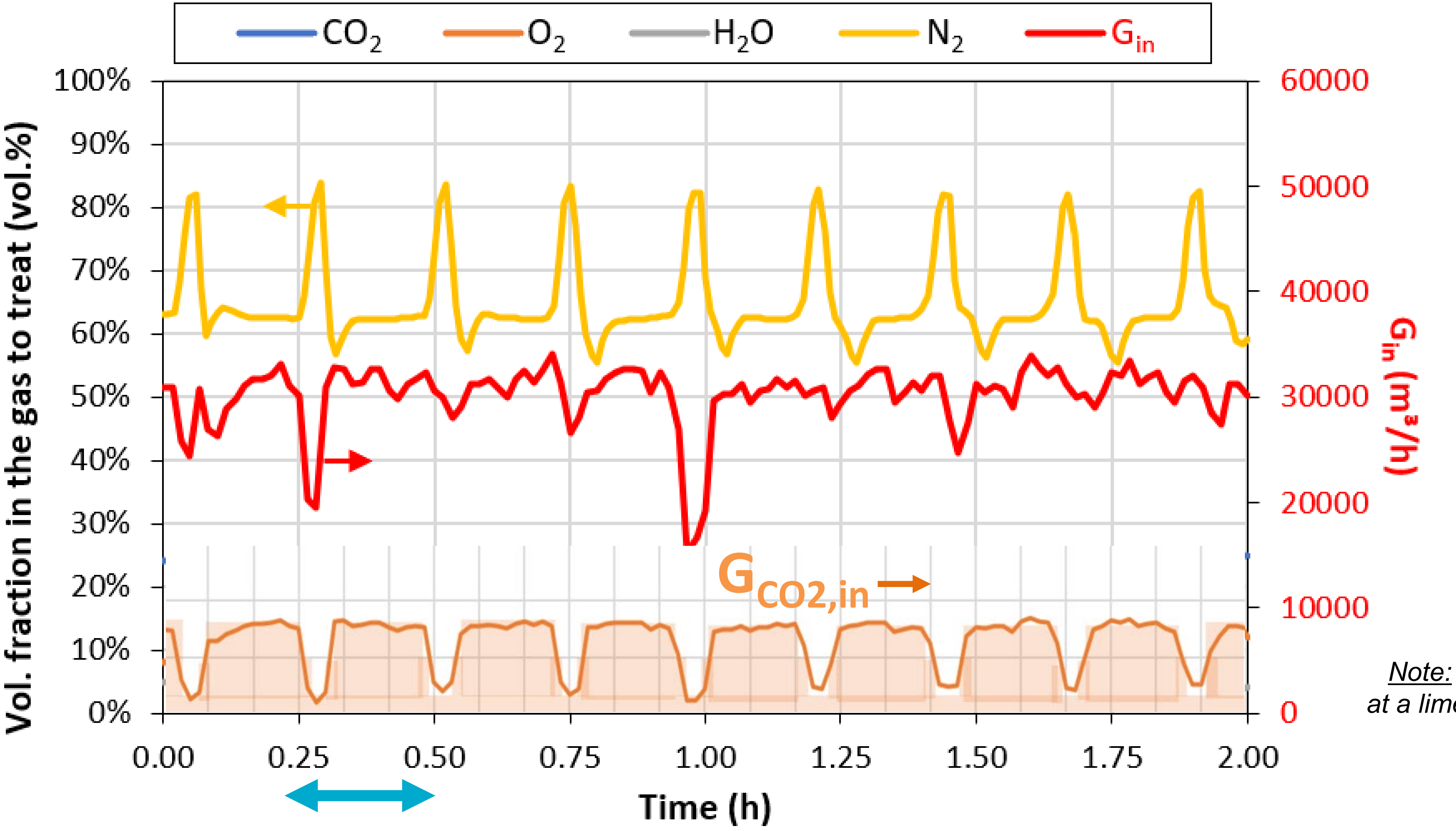


Lime production (230 tpd)

Parallel Flow Regenerative Kiln (PFRK)

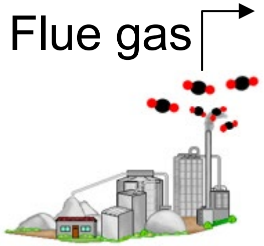
Note: Measurement campaign at a lime plant in the framework of the NKL project.

Lime plant flue gas



Note: Measurement campaign at a lime plant in the framework of the NKL project.

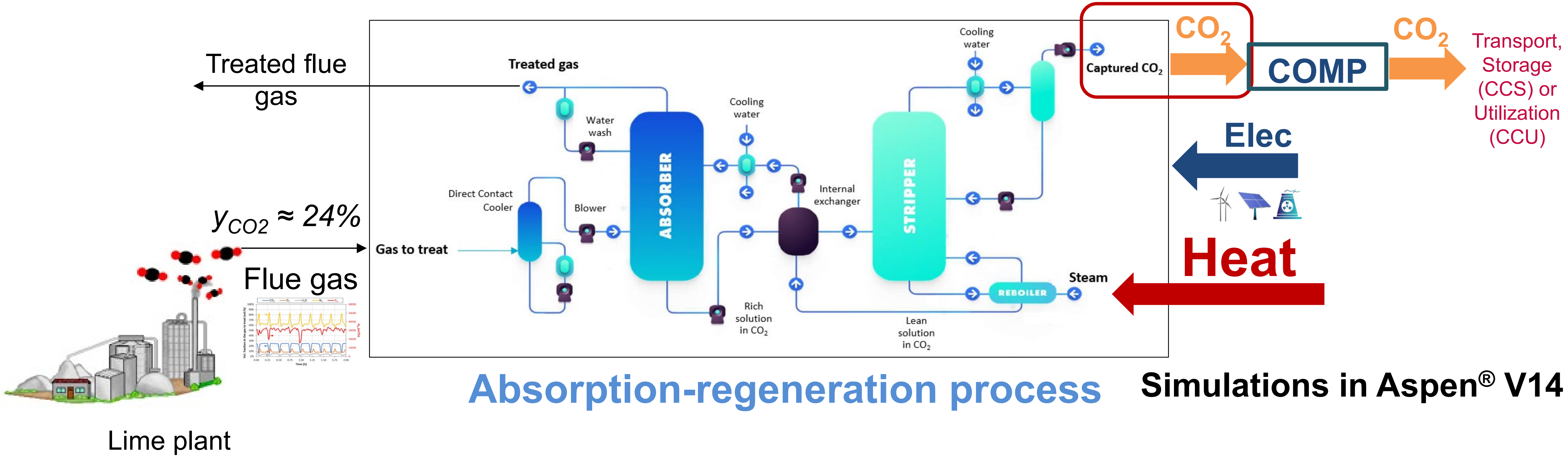
Flue gas



Lime production (230 tpd)

In terms of total CO_2 content in the gas ($G_{CO2,in}$) ≈ 15% decrease during a 15 min cycle

Scope of the study



Absorption-regeneration process

Simulations in Aspen® V14

- **Study of the dynamic answer of the CO_2 capture process to the flue gas fluctuations.**
- **Parametric study on the flue gas fluctuation parameters.**
- **Investigation of technical solutions to keep a stable recovered CO_2 flow + TEA.**

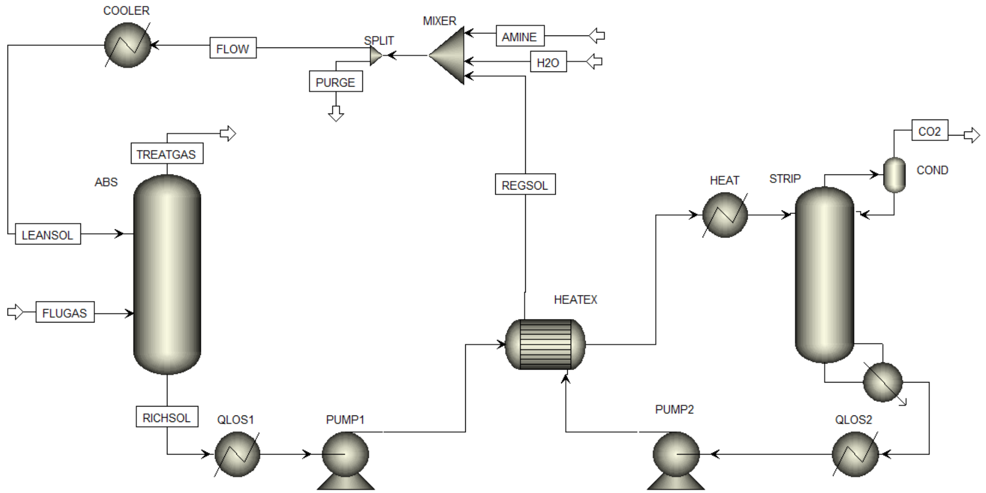
Micro-pilot scale model validation

RadFrac columns in Aspen Dynamics®:
need to switch from « Rate based » mode to « Equilibrium » mode

UMONS Micro-pilot unit:

Note: other unit working under pressure and with a decanter available.

Aspen Plus® steady state model:



$H_{packing,ABS}$ = 1 m	$H_{packing,STRIP}$ = 0.5 m	$D_{columns}$ = 0.05 m	Glass Raschig rings (6 x 6 mm) packing
$y_{CO2,in}$ = 20 vol.%	G = 2.7 m^3/h	L = 0.014 m^3/h	P = 101.3 kPa
$Q_{reboiler}$ = 2 kW	Q_{HEAT} = 1 kW	$T_{ABS,in}$ = 40°C	$T_{STRIP,in}$ = 95°C

Micro-pilot scale model validation

RadFrac columns in Aspen Dynamics®: need to switch from « Rate based » mode to « Equilibrium » mode

UMONS Micro-pilot unit:

Note: other unit working under pressure and with a decanter available.

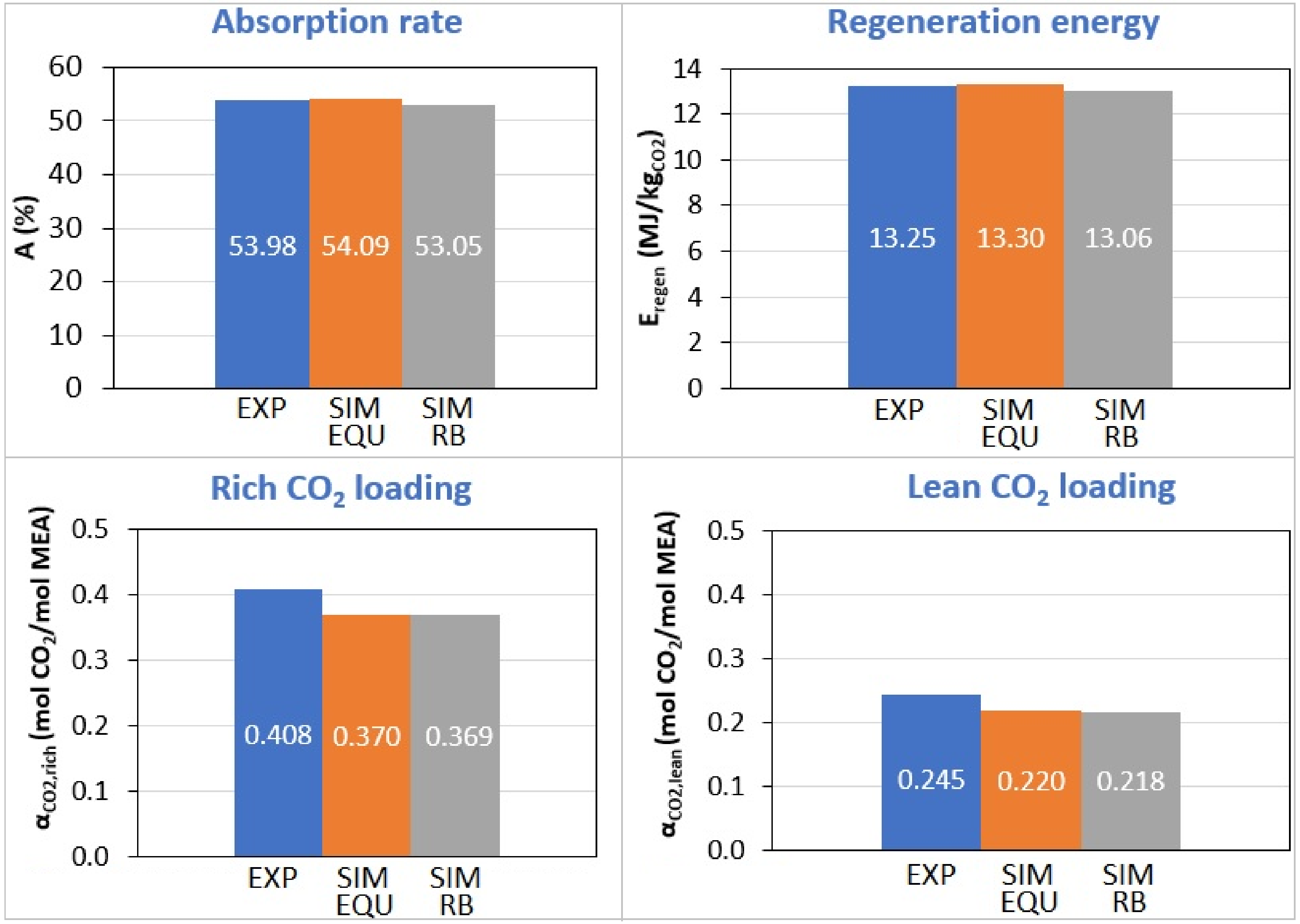
Aspen Plus® steady state model:

Solvent: aqueous monoethanolamine (MEA) 30 wt.%

Type	Stoichiometry	
Equilibrium	2 H2O <--> H3O+ + OH-	(Edwards et al., 1978)
Equilibrium	CO2 + 2 H2O <--> HCO3- + H3O+	Gibbs free energy minimization
Equilibrium	HCO3- + H2O <--> CO3-2 + H3O+	(Edwards et al., 1978)
Equilibrium	MEA+ + H2O <--> MEA + H3O+	(Hamborg & Versteeg,2009)
Equilibrium	MEACOO- + H2O <--> MEA + HCO3-	Gibbs free energy minimization

Thermodynamic models:
Vapor phase: Redlich Kwong (RK)
Liquid phase: Electrolyte Non-Random Two-Liquid (ELEC-NRTL)

Micro-pilot scale model validation



Aspen Plus® steady state model

<2% relative difference

max ≈10% relative difference

“EXP”: UMONS micro-pilot unit results - “SIM EQU”: Aspen Plus® simulation results with RadFrac columns in equilibrium mode & “SIM RB” in rate-based mode

Dynamic simulations conditions

Lime kiln flue gas flow rate (temporal variations)	
Flue gas composition (temporal variations)	
Targeted recovered CO_2 flow rate	
Recovered CO_2 purity	
Solvent	
Columns height	
Columns (and sumps) diameter	
Columns sump height	
Columns packing	
Inlet liquid temperature	
Columns bottom pressure Liquid flow rate (absorber inlet) Nominal reboiler heating power ("$P_{boiler-fix}$")	
Dynamic calculation step	

Dynamic simulations conditions

Lime kiln flue gas flow rate (temporal variations)	15000 m^3/h to 34000 m^3/h (at 110°C and 1 atm)
Flue gas composition (temporal variations)	N_2: 55 vol.% to 84 vol.% / CO_2: 5 vol.% to 25 vol.% O_2: 8 vol.% to 15 vol.% / H_2O: 2 vol.% to 5 vol.%
Targeted recovered CO_2 flow rate	~12600 kg_{CO2}/h (~ 90% of inlet CO_2 on average)
Recovered CO_2 purity	99.0 wt.%
Solvent	Monoethanolamine (MEA) 30 wt.% in aqueous solution
Columns height	
Columns (and sumps) diameter	
Columns sump height	
Columns packing	
Inlet liquid temperature	
Columns bottom pressure **Liquid flow rate (absorber inlet)** **Nominal reboiler heating power (“$P_{boiler\text{-}fix}$”)**	
Dynamic calculation step	

Dynamic simulations conditions

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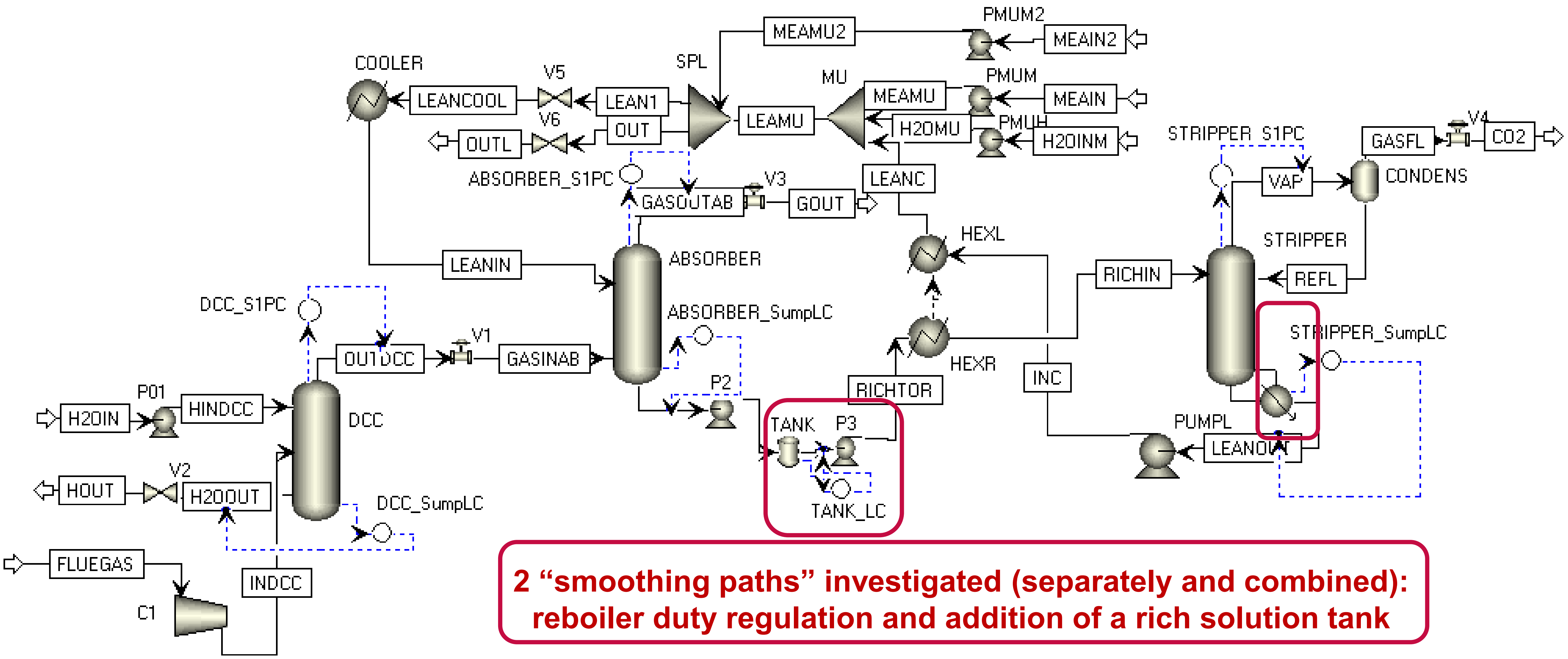
Recovered CO_2 purity	99.0 wt.%
Solvent	Monoethanolamine (MEA) 30 wt.% in aqueous solution
Columns height	DCC: 8 m (8 stages x 1m) / Absorber: 17 m (17 stages x 1 m) Stripper: 10 m (10 stages x 1 m)
Columns (and sumps) diameter	DCC: 3 m / Absorber: 3.4 m / Stripper: 4.2 m
Columns sump height	≈25% of columns height (DCC: 2 m / Absorber: 4 m / Stripper: 2.5 m)
Columns packing	Random metal packing IMTP 50
Inlet liquid temperature	DCC: 30°C / Absorber: 40°C / Stripper: 110°C
Columns bottom pressure	DCC: 1.2 bar / Absorber: 1.2 bar / Stripper: 2 bar
Liquid flow rate (absorber inlet)	192 m^3/h (value minimizing E_{regen} in steady state mode)
Nominal reboiler heating power (“$P_{boiler-fix}$”)	42.54 GJ/h → E_{regen} = 3.38 GJ/t_{CO2}
Dynamic calculation step	0.01 h

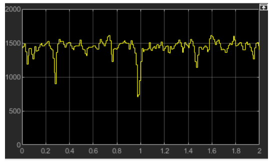
Aspen Dynamics® flow sheet

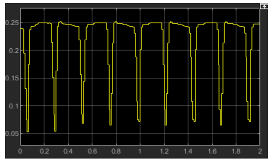


2 "smoothing paths" investigated (separately and combined): reboiler duty regulation and addition of a rich solution tank

Note: gas holder not considered as option (expensive and needs a lot of space available)

Integration with Matlab/Simulink®



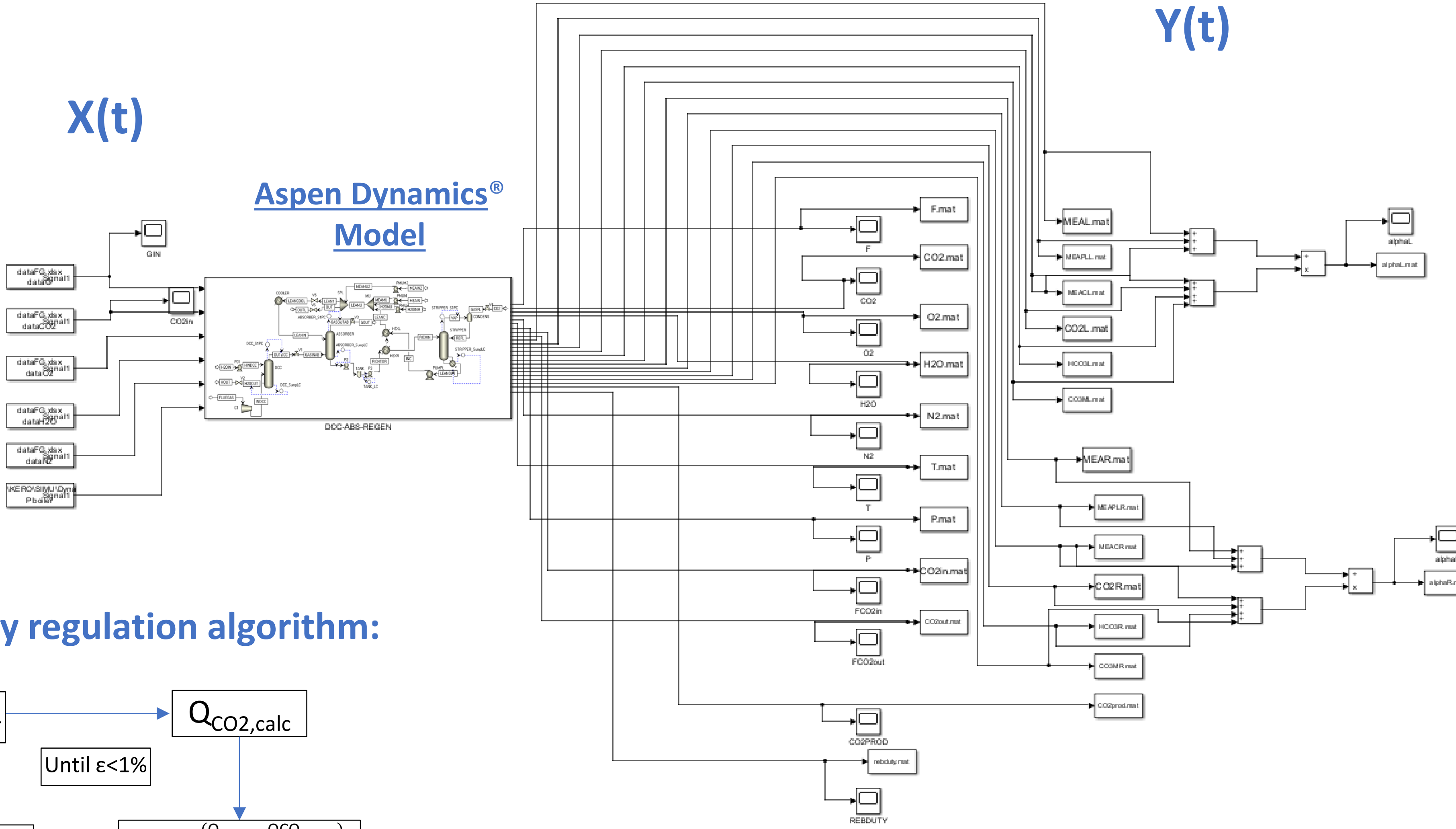


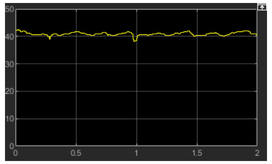
Excel spread sheets

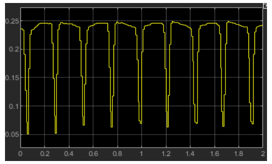
X(t)

Aspen Dynamics® Model

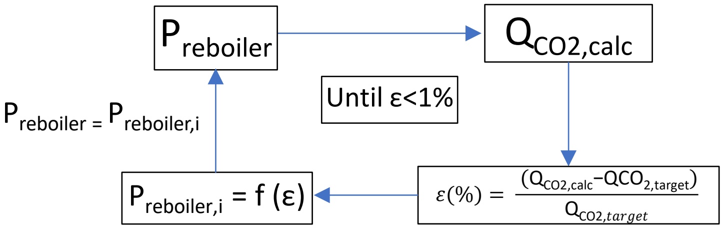
Y(t)







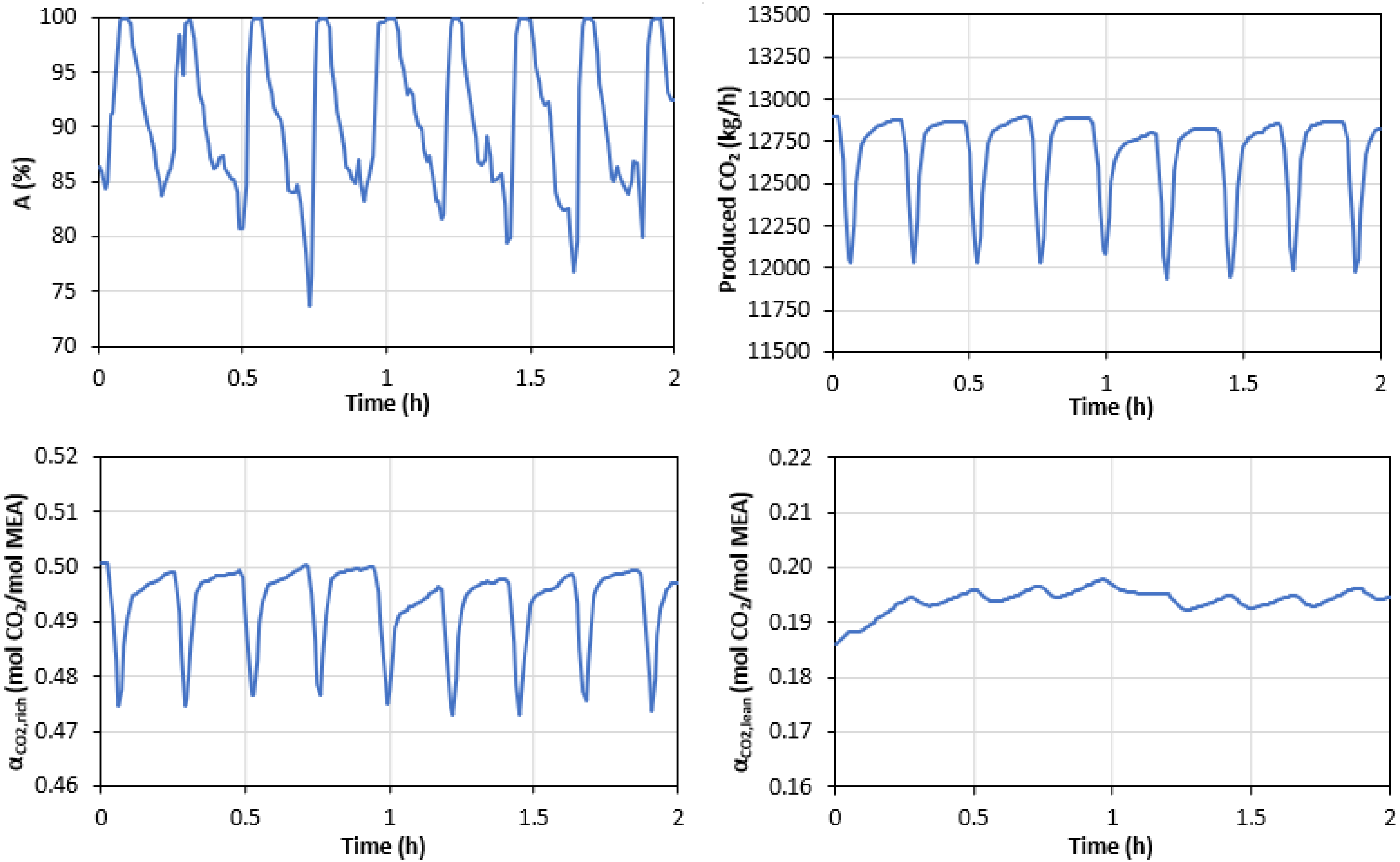
Reboiler duty regulation algorithm:



Base case results

As G & y_{CO2}↓
A↑↓

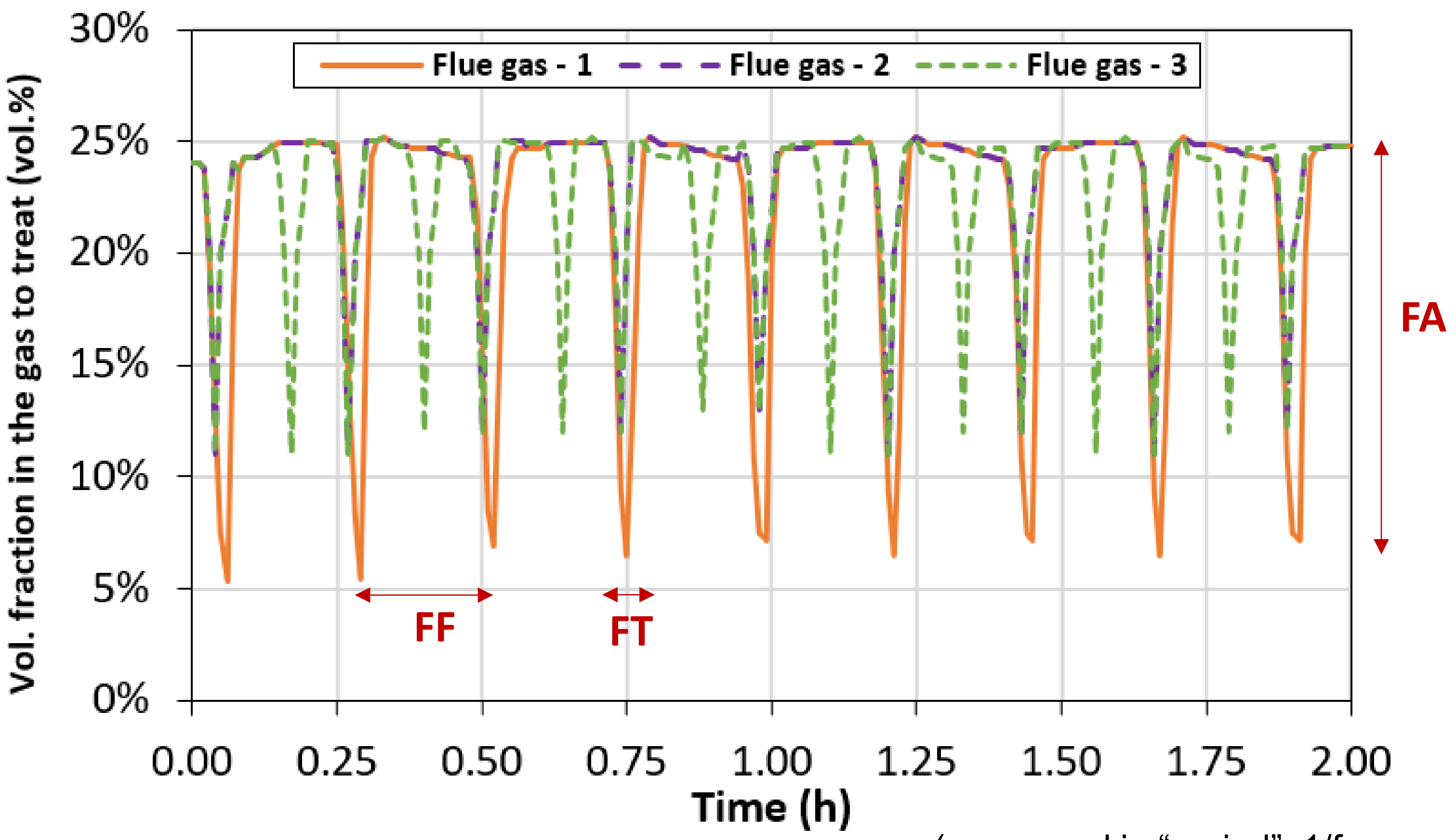
CO_2 production ↓
during 4 min



$\alpha_{CO2,rich}$↓
during 4 min

$\alpha_{CO2,lean}$
less impacted

Fluctuation parameters

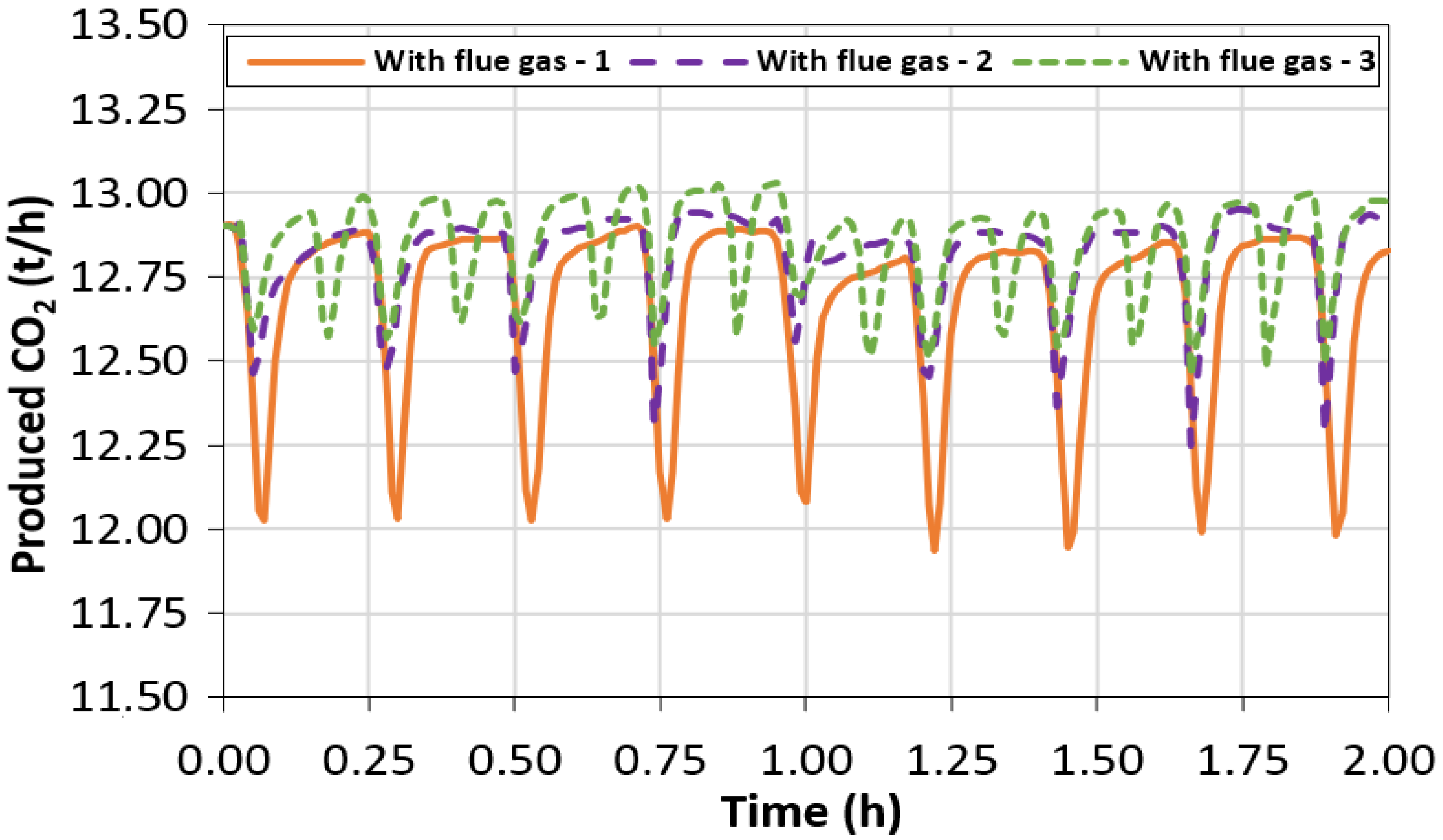


Flue gas n°	FF	FT	FA
1	~15 min	~4 min	~25%
2	~15 min	~2 min	~50%
3	~9 min	~2 min	~50%

(expressed in "period", 1/frequency)

FF: Fluctuation Frequency – time between two minima ("cycle time")
FT: Fluctuation Time – time below nominal value for one cycle
FA: Fluctuation Amplitude – minimum/nominal CO_2 content (%)

Dynamic simulations results



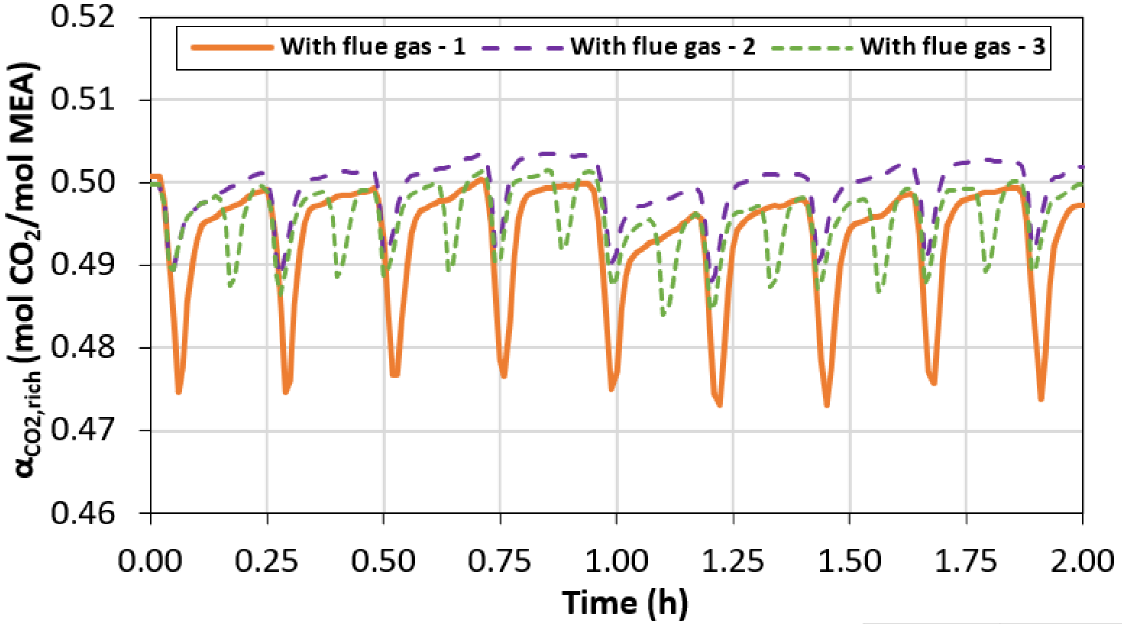
Flue gas n°	FF	FT	FA
1	~15 min	~4 min	~25%
2	~15 min	~2 min	~50%
3	~9 min	~2 min	~50%

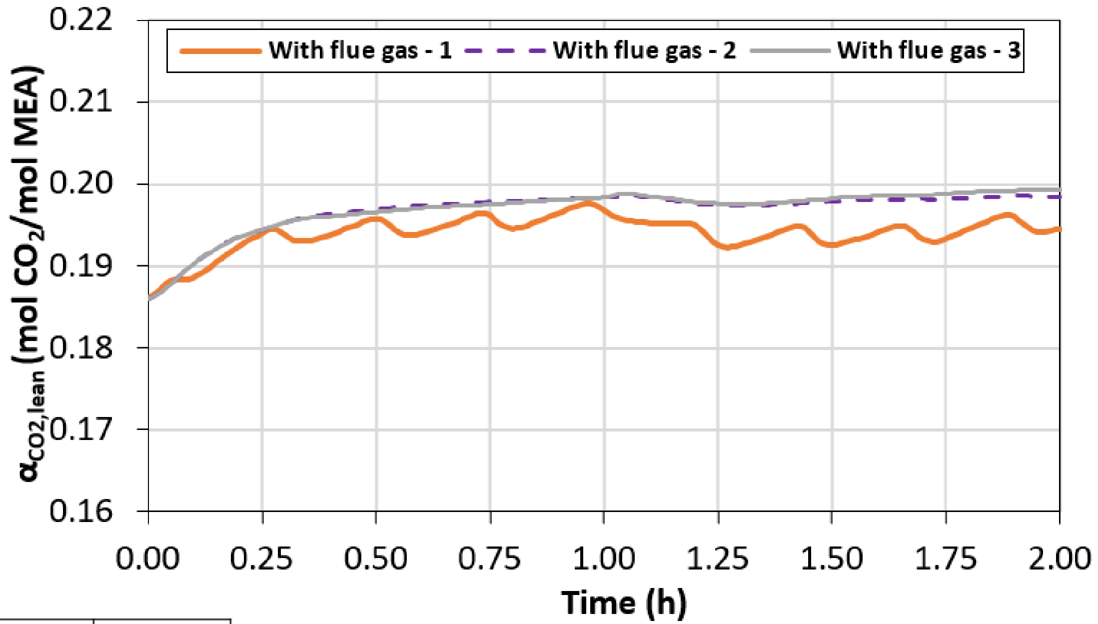
→ When FA ↓ → CO_2 production fluctuation amplitude ↓

→ When FT ↓ → Duration at nominal CO_2 production ↑

→ When FF ↓ → More fluctuating produced CO_2 flow BUT with a smaller variation amplitude

Dynamic simulations results





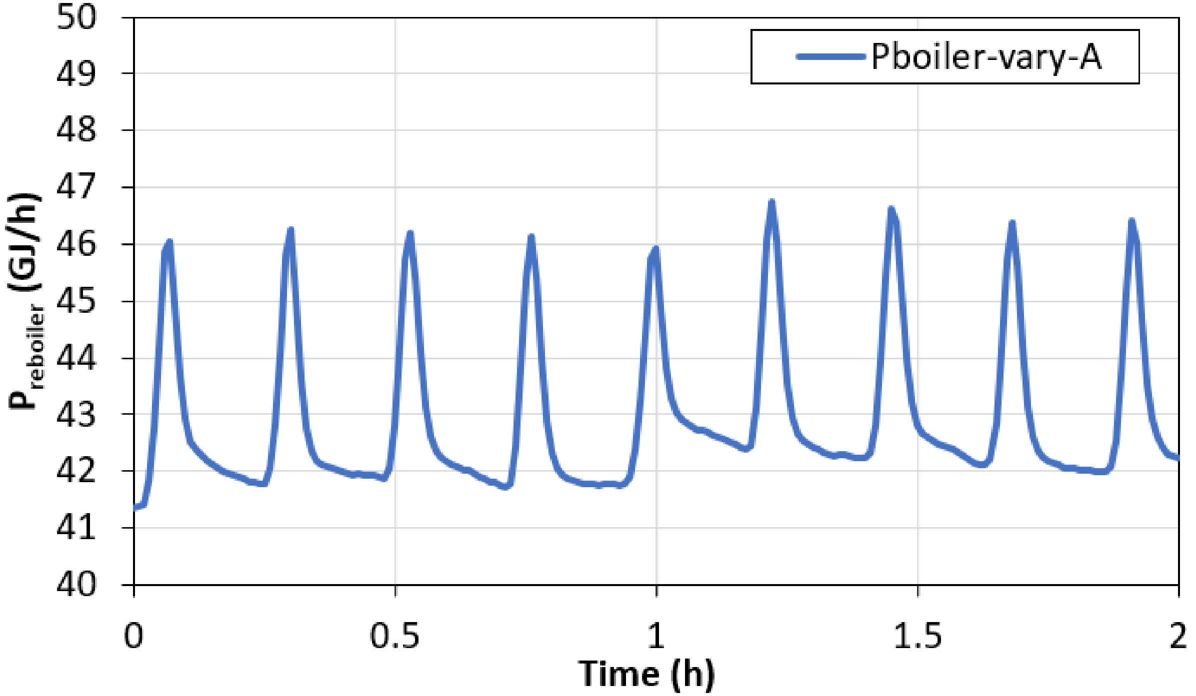
Flue gas n°	FF	FT	FA
1	~15 min	~4 min	~25%
2	~15 min	~2 min	~50%
3	~9 min	~2 min	~50%

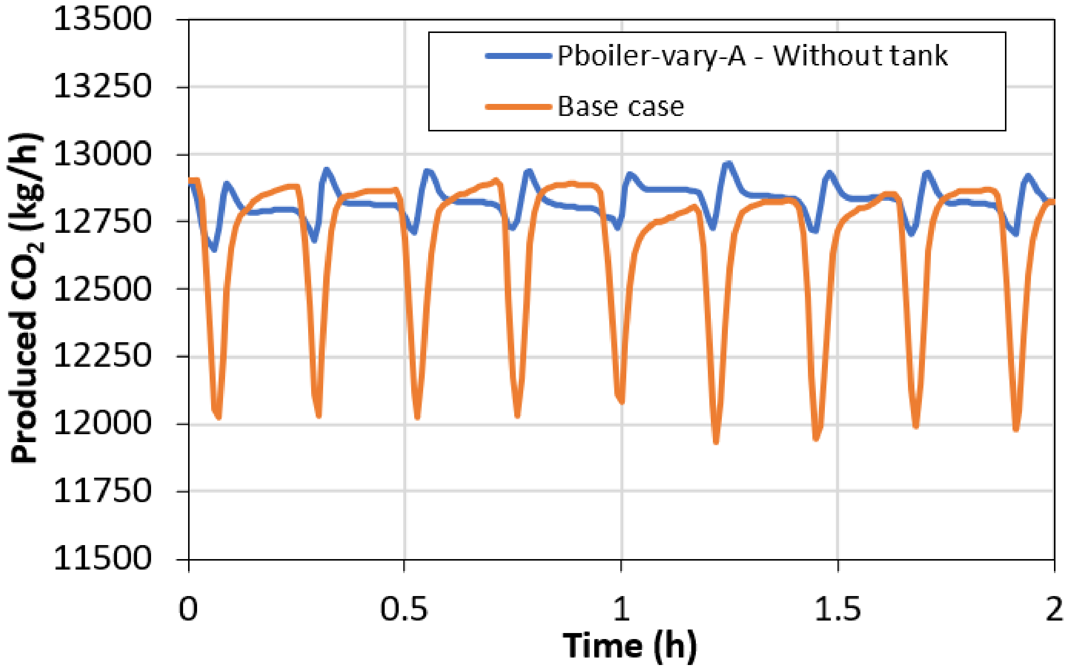
→ Effects on the CO_2 production flow related to the solvent CO_2 loading value, especially the rich solution one

Reboiler duty regulation

Example with Flue gas n°1:

Flue gas n°	FF	FT	FA
1	~15 min	~4 min	~25%
2	~15 min	~2 min	~50%
3	~9 min	~2 min	~50%





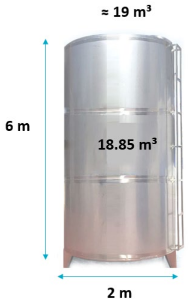
Thanks to reboiler heating regulation:

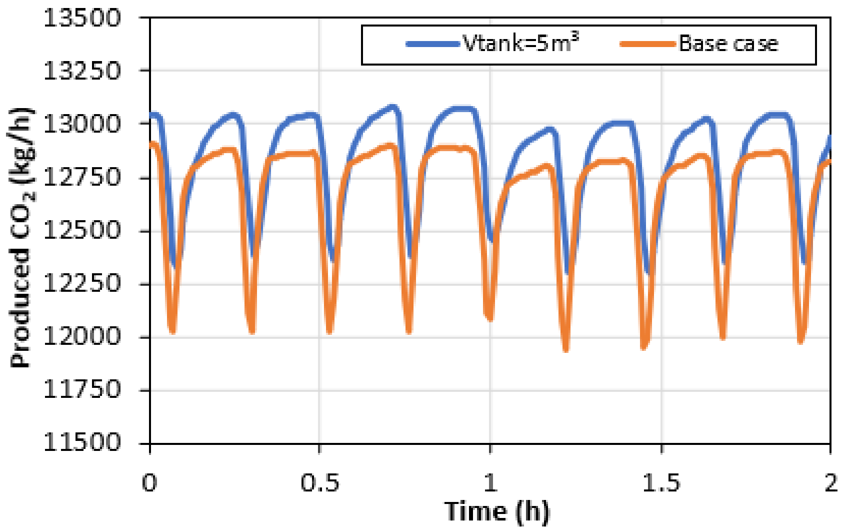
maximum **9.5%** temporary increases of the nominal heating power,
maximum **1.5%** of variation of the CO_2 production flow

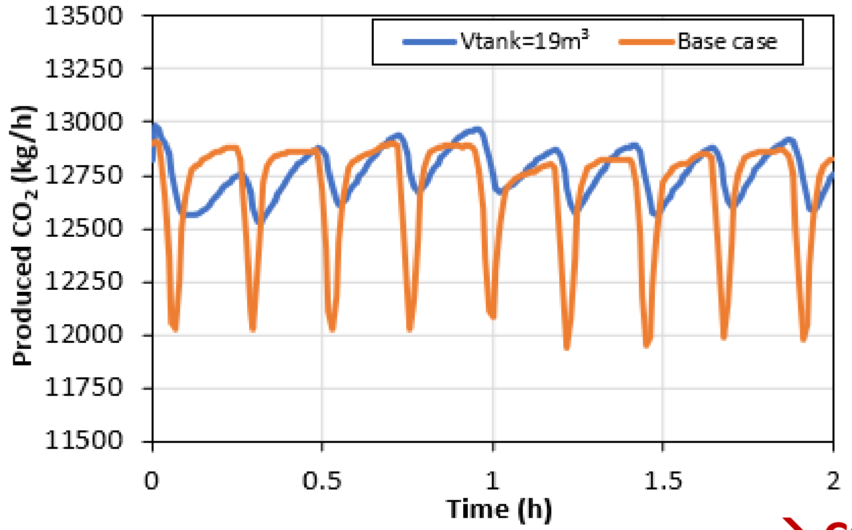
Rich solution buffer tank

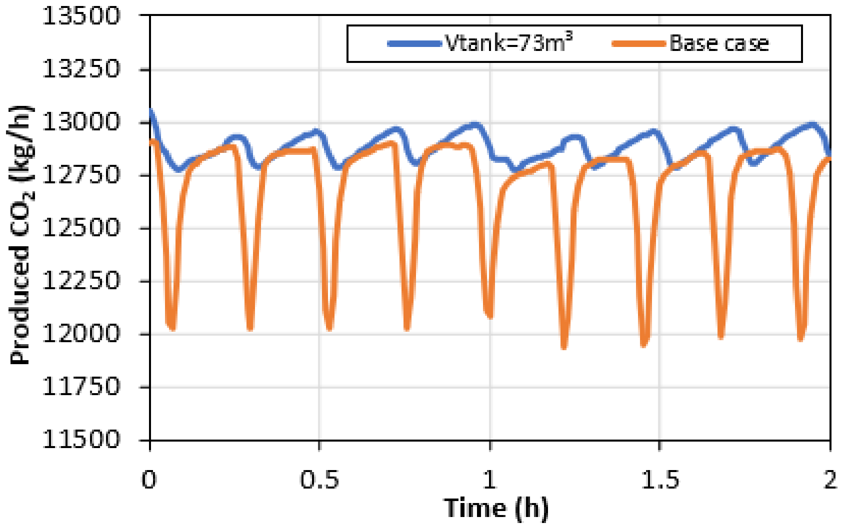
Example with Flue gas n°1:

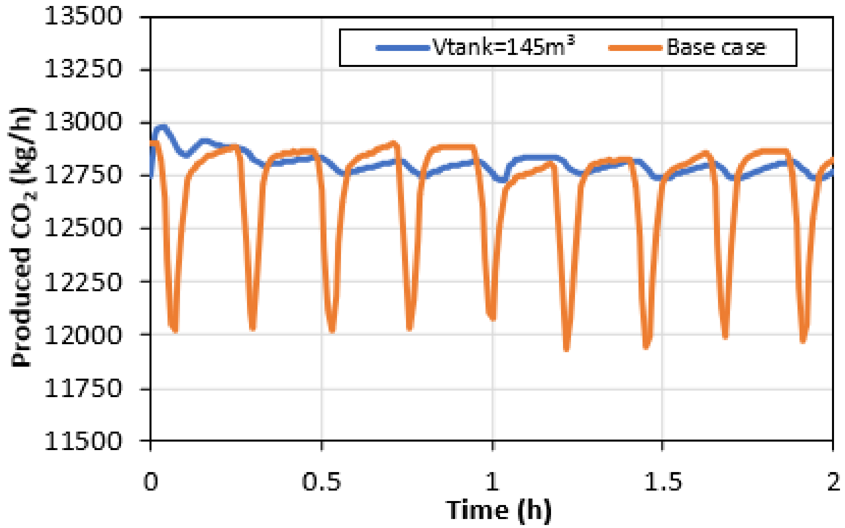
Flue gas n°	FF	FT	FA
1	~15 min	~4 min	~25%
2	~15 min	~2 min	~50%
3	~9 min	~2 min	~50%



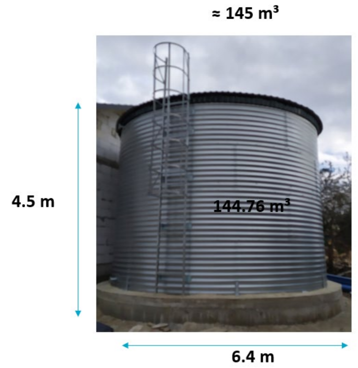








V_{tank} ↑
→ CO_2 production more stable

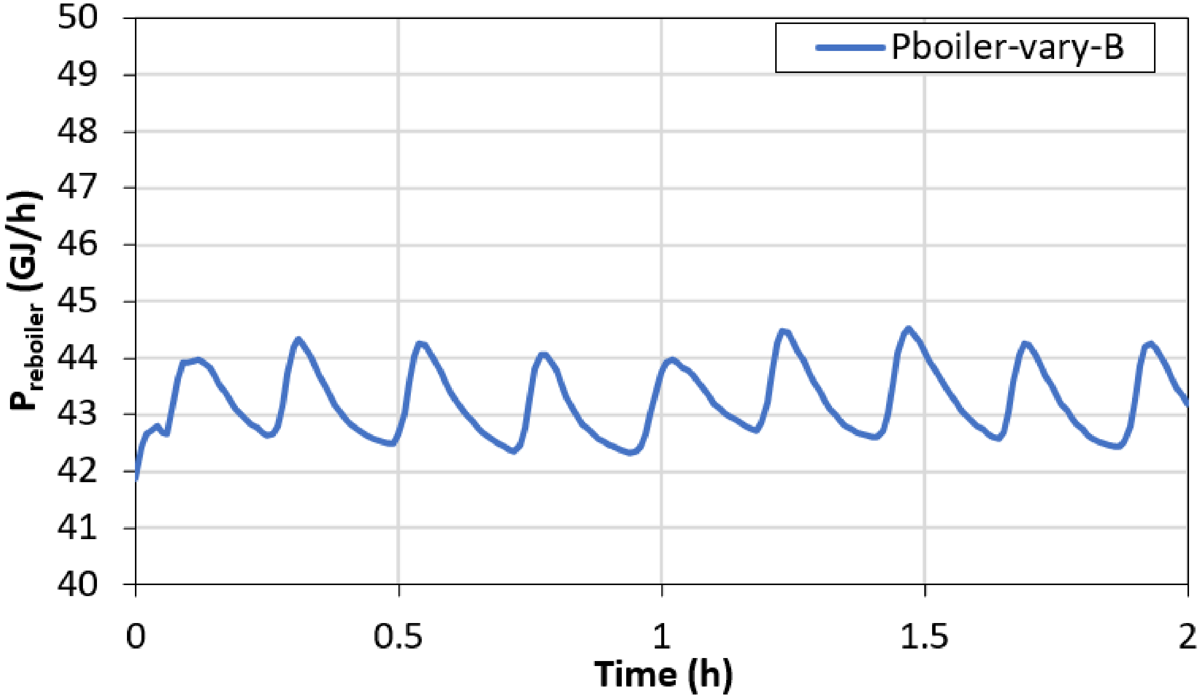


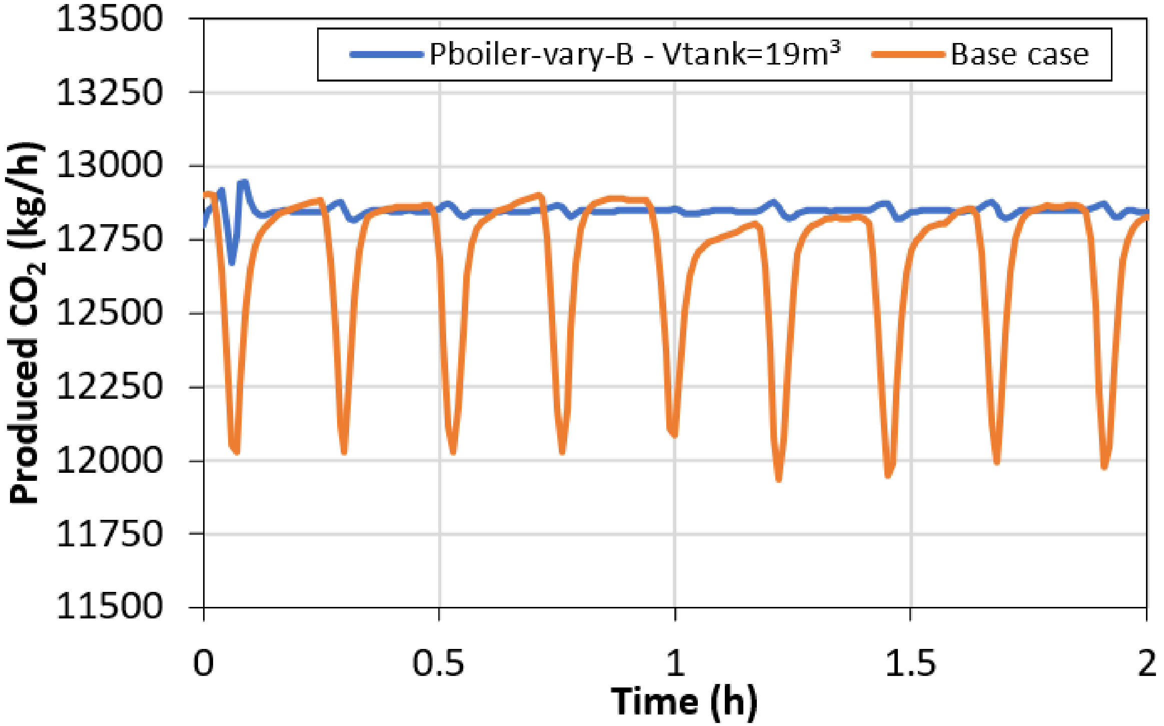
(D_{tank} x H_{tank}):
V_{tank} = 5 m³
(2 m x 1.6 m)
V_{tank} = 19 m³
(2 m x 6 m)
V_{tank} = 73 m³
(3.4 m x 8 m)
V_{tank} = 145 m³
(6.4 m x 4.5 m)

Reboiler duty regulation & tank

Example with Flue gas n°1:

Flue gas n°	FF	FT	FA
1	~15 min	~4 min	~25%
2	~15 min	~2 min	~50%
3	~9 min	~2 min	~50%





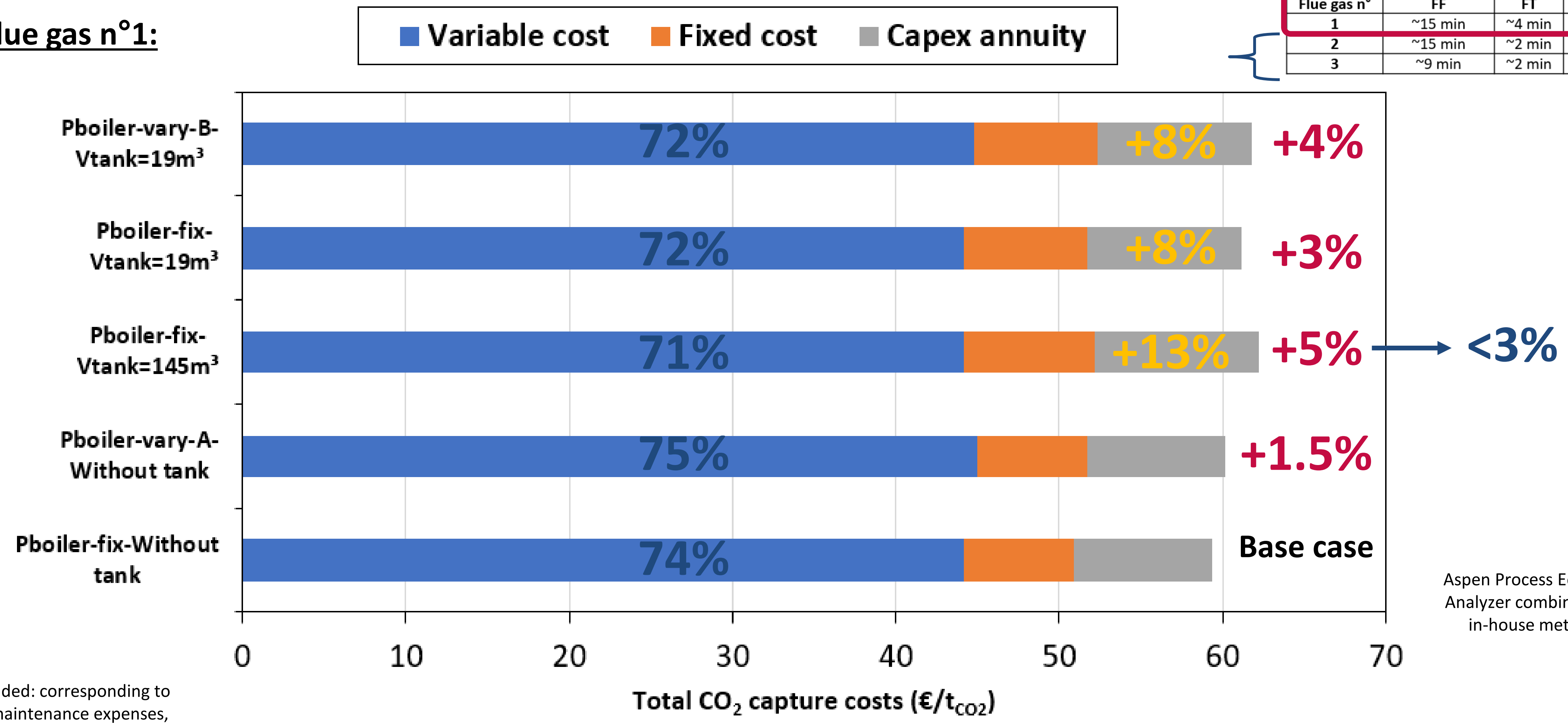
Thanks to reboiler heating regulation and rich solution tank (19 m³) implementation:

maximum **5%** temporary increases of the nominal heating power,
maximum **0.3%** of variation of the CO_2 production flow

Techno-Economic Analysis (TEA)

With Flue gas n°1:

Flue gas n°	FF	FT	FA
1	~15 min	~4 min	~25%
2	~15 min	~2 min	~50%
3	~9 min	~2 min	~50%



Aspen Process Economic Analyzer combined with in-house methods

CEPCI = 797.9

Fixed costs included: corresponding to operation and maintenance expenses, fixed to 7% of the CAPEX.

Annualized CAPEX included:
lifetime of 25 years, 8232 hours of annual effective operations,
interest rate corresponding to a straight-line depreciation of 6.5%.

Limited increase of the total CO_2 capture costs

Even more limited (<3%) with flue gases n°2 & 3 (smaller fluctuations)

Conclusions & Perspectives

- **Lime plant flue gas fluctuations** can be managed for carbon capture application.
- Key aspects are the **costs and availability** of the **steam** for such industrial plants (see electrification options…).
- **Reboiler duty regulation** and/or **implementation of a rich solution buffer tank** are good solutions to "smooth" the recovered CO_2 flow with limited cost increase (<5%).
- **IF** technical measures can be taken **to reduce the fluctuation time and amplitude**, that could be potentially **beneficial in view of smoothing the CO_2 production flow**.
- Future steps: **other solvents (CESAR-1)**, process **configurations**, **other CO_2 capture technologies**.

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THANKS VERY MUCH FOR YOUR ATTENTION!

QUESTIONS?

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