Optimal Control of Industrial Solvent-Based CO$_2$ Capture Plants

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ESCAPE34, June 4th 2024

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ÅURORA

CYBERNETICA

Cybernetica at a glance

- Est. 2000, SINTEF spin-off

- Tailor-made model-based solutions

- Unique NMPC technology
  - Industrially proven
  - Increases profitability for our customers

Application areas

- Polymerization processes:
    - Phenolic resins, amino resins
    - PVC (S-PVC, Paste-PVC)
    - Emulsion polymerization
    - Polyolefins

- Metallurgical processes
    - Aluminum electrolysis
    - Silicon and ferrosilicon
    - Ferromanganese refining
    - Steel refining
    - Extrusion

- Energy and CCUS
    - Offshore production
    - Onshore processing plants
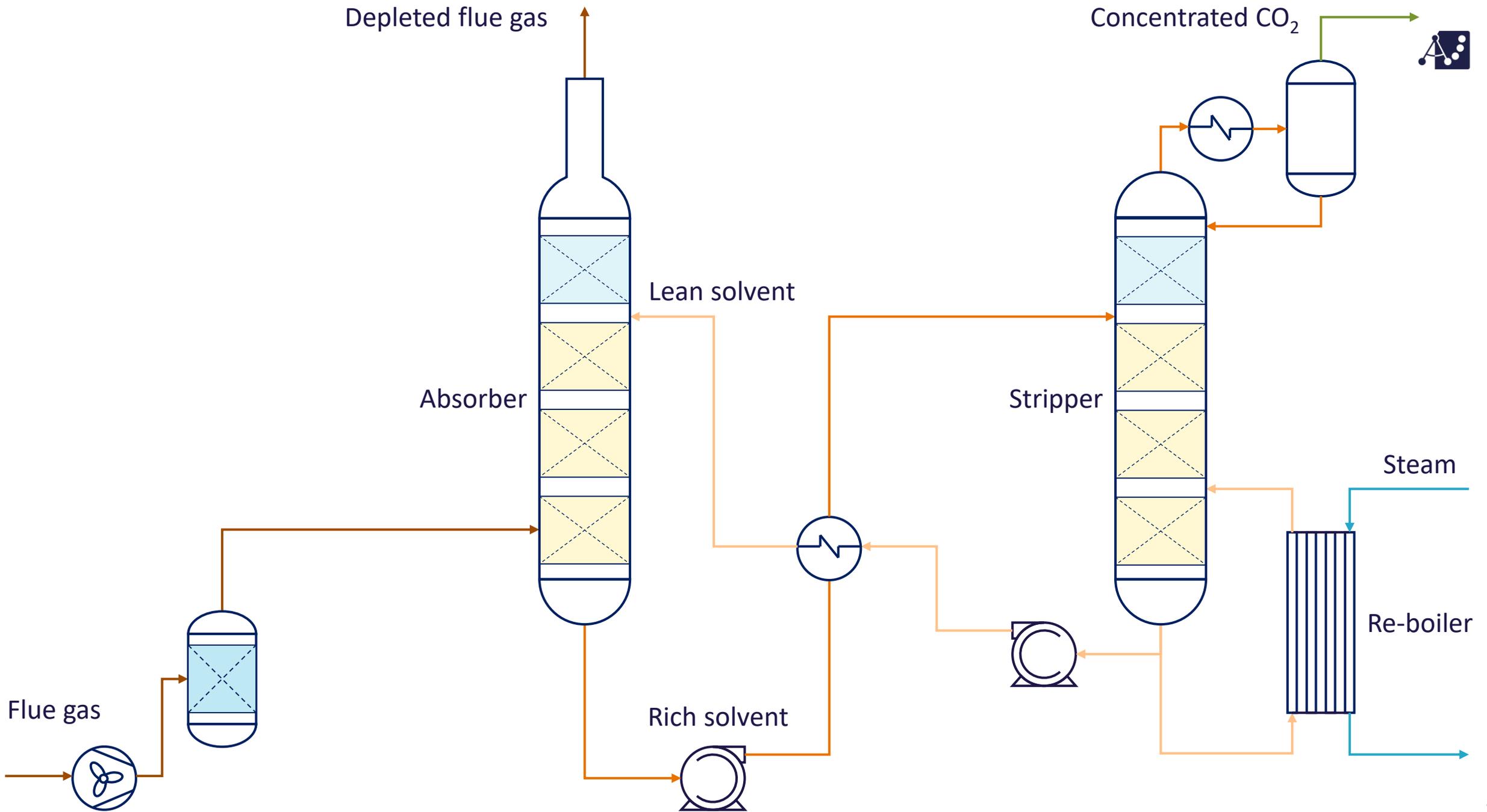   - **CO_2 capture**
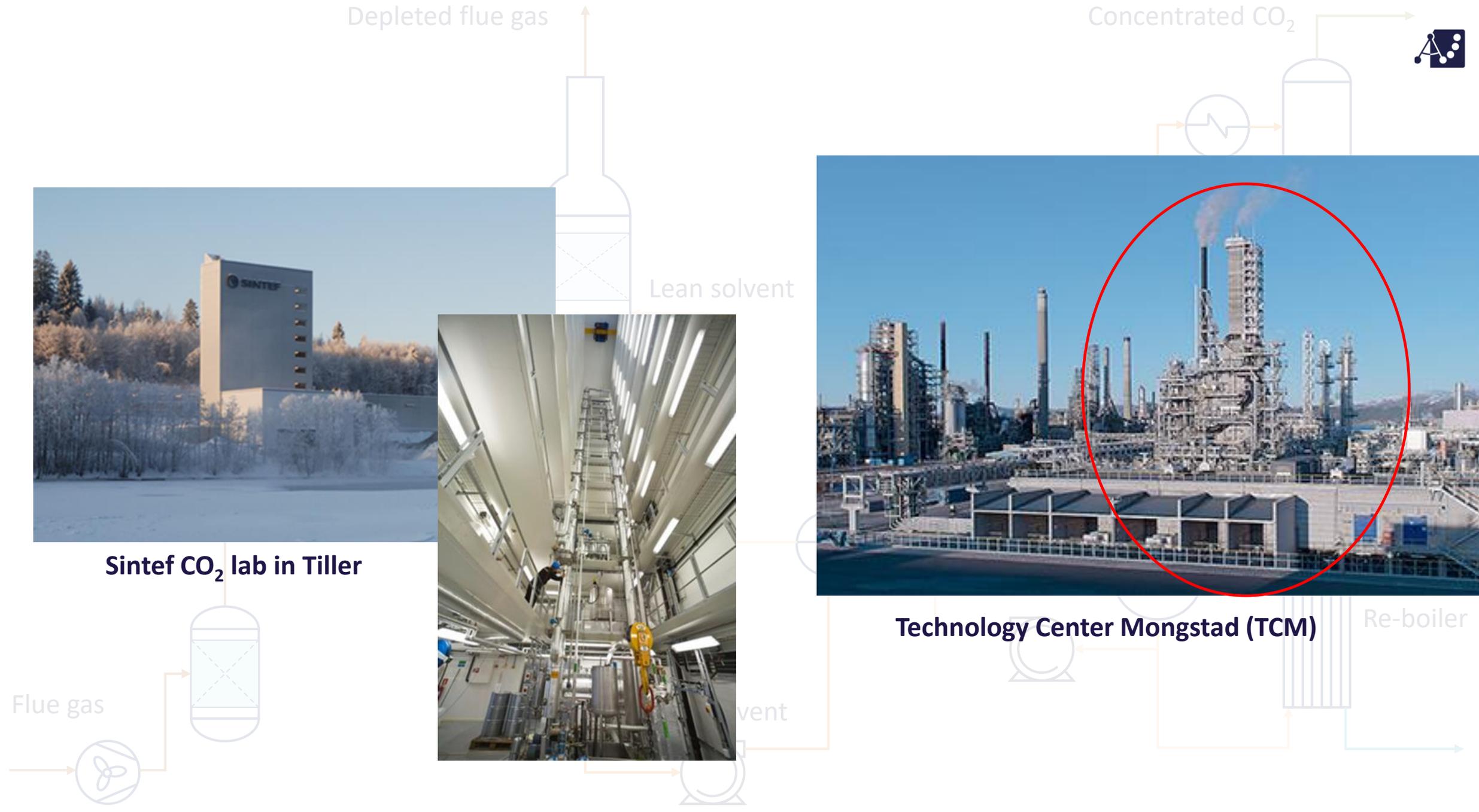
POLYMER

METALLURGICAL
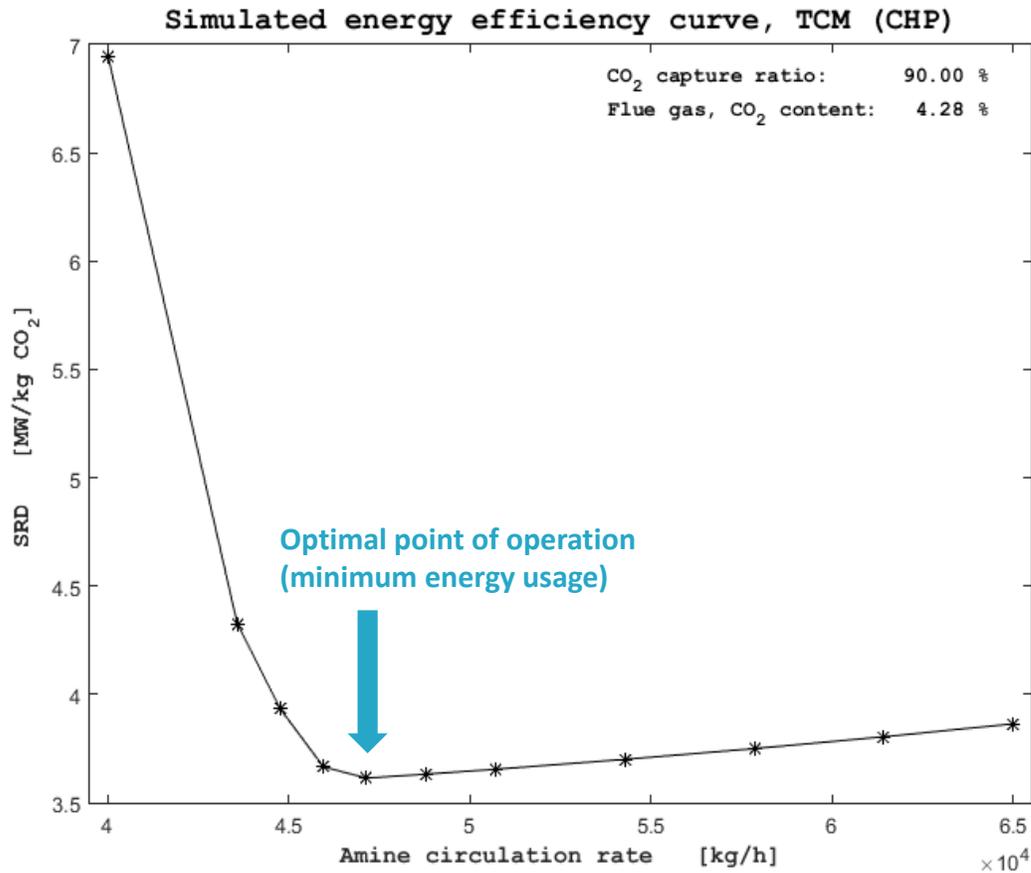
ENERGY

Depleted flue gas

Concentrated CO_2

Lean solvent

Absorber

Stripper

Steam

Re-boiler

Flue gas

Rich solvent

Sintef CO$_2$ lab in Tiller

Technology Center Mongstad (TCM)

Depleted flue gas

Concentrated CO$_2$

Lean solvent

Re-boiler

Flue gas

Simulated energy efficiency curve, TCM (CHP)

CO_2 capture ratio: 90.00 %
Flue gas, CO_2 content: 4.28 %

Optimal point of operation (minimum energy usage)

SRD [MW/kg CO_2]

Amine circulation rate [kg/h] $\times 10^4$
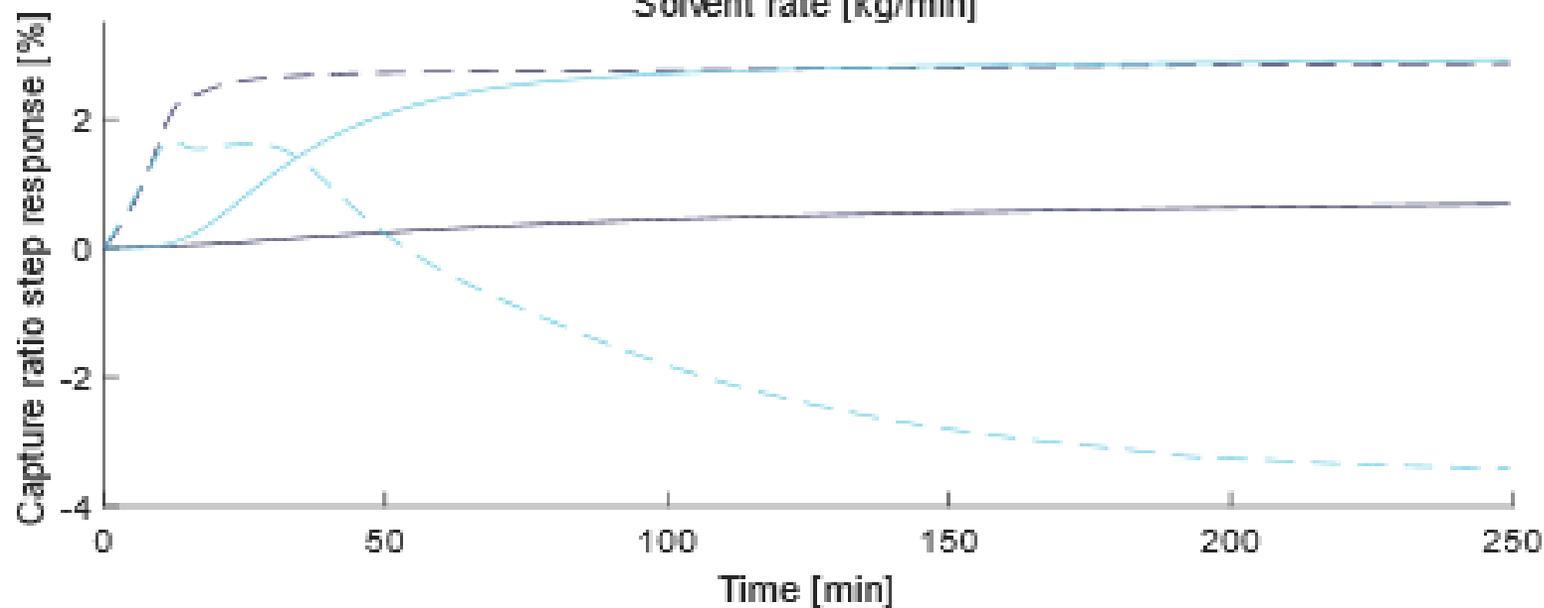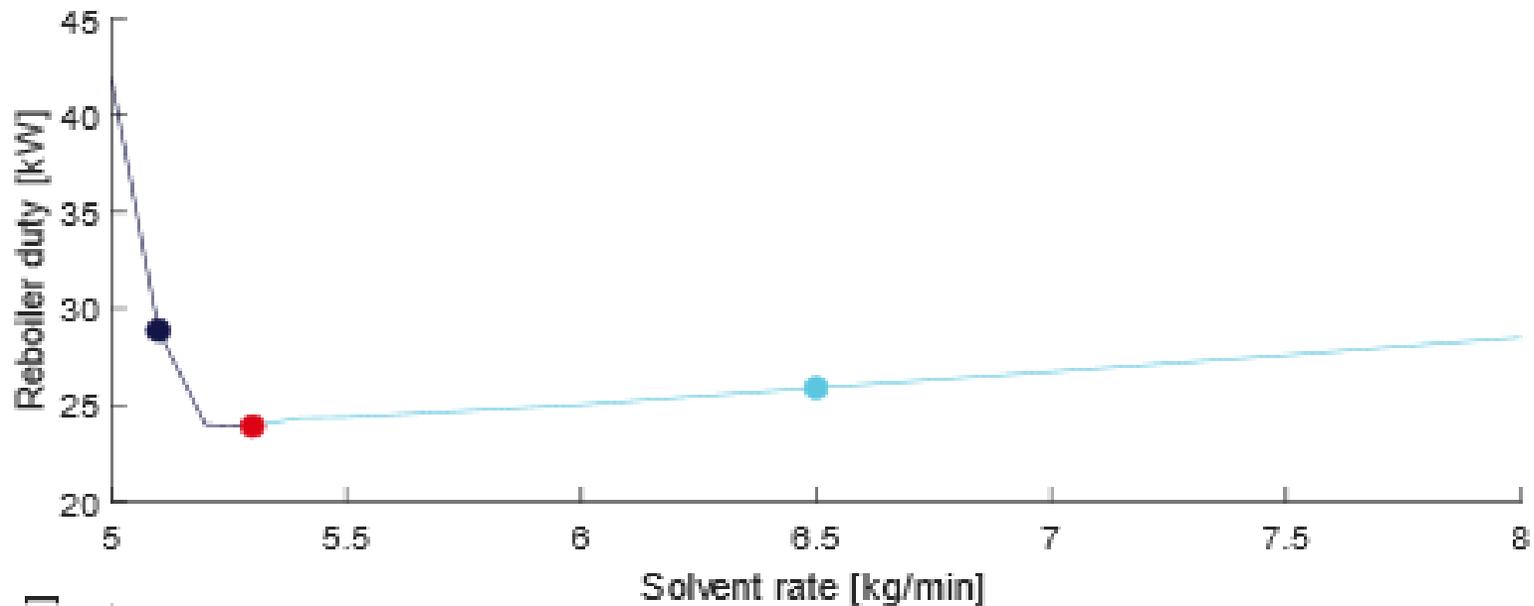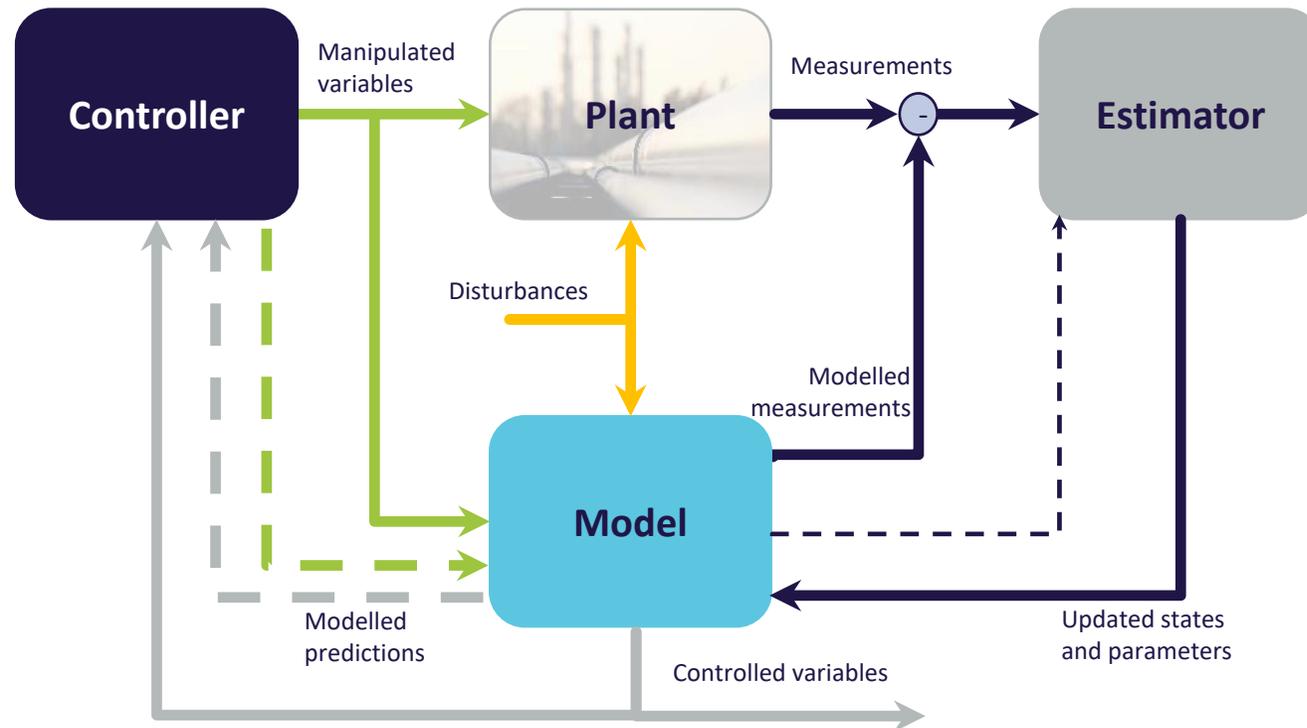
- A solvent-based CO_2 capture is a complex, nonlinear process with both fast and slow dynamics

- Optimal conditions change with
  - desired capture ratio
  - solvent concentration and degree of degradation
  - flue gas flow rate
  - flue gas composition

Controlling the process optimally will be hard using traditional (PID) control!

Model-based Predictive Control

Mathematical description

$$\min_{\Delta \mathbf{U}} J = \frac{1}{2}(\mathbf{Z} - \mathbf{Z}_{\mathrm{ref}})^{\mathrm{T}}\mathbf{Q}(\mathbf{Z} - \mathbf{Z}_{\mathrm{ref}}) + \frac{1}{2}(\Delta \mathbf{U}^{\mathrm{T}}\mathbf{S}\Delta \mathbf{U}) + \mathbf{r}_1^{\mathrm{T}}\boldsymbol{\varepsilon} + \frac{1}{2}\boldsymbol{\varepsilon}^{\mathrm{T}}\mathrm{diag}(\mathbf{r}_2)\boldsymbol{\varepsilon}$$

Subject to

$$\mathbf{x}_{k+j} = \mathbf{f}(\mathbf{x}_{k+j-1}, \mathbf{u}_{k+j-1}, \mathbf{v}_k)$$

$$\mathbf{z}_{k+j} = \mathbf{h}(\mathbf{x}_{k+j}, \mathbf{u}_{k+j})$$

$$\mathbf{Z}_{\min} - \boldsymbol{\varepsilon} < \mathbf{Z} < \mathbf{Z}_{\max} + \boldsymbol{\varepsilon}$$
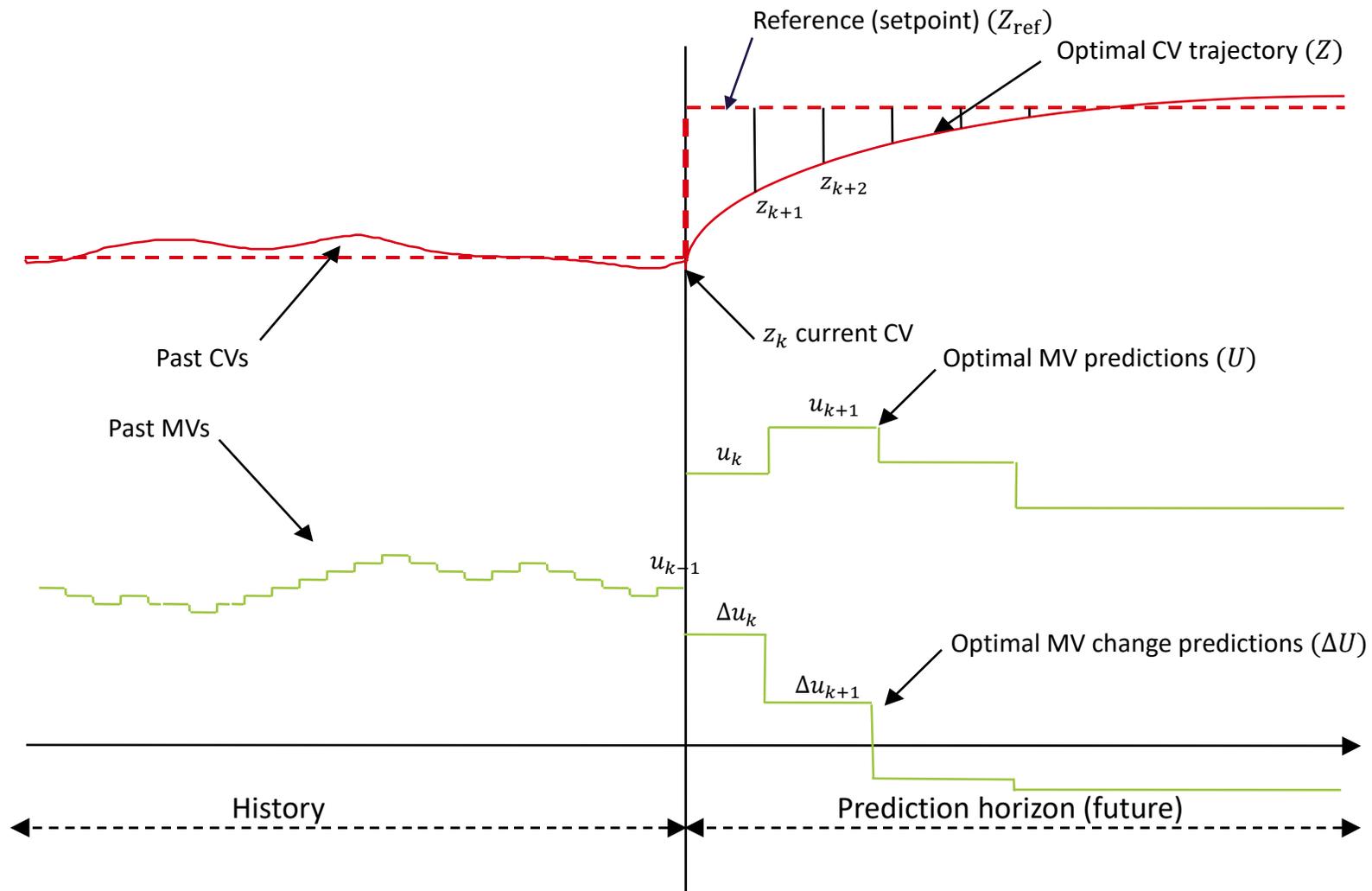
$$\mathbf{0} \leq \boldsymbol{\varepsilon} \leq \boldsymbol{\varepsilon}_{\max}$$

$$\mathbf{U}_{\min} \leq \mathbf{U} \leq \mathbf{U}_{\max}$$

$$\Delta \mathbf{U}_{\min} \leq \Delta \mathbf{U} \leq \Delta \mathbf{U}_{\max}$$

NMPC – Simplified graphical description

Augmented Extended Kalman Filter

- Augmented state vector

- Parameters modelled as integrated white noise

- Process noise covariance ($\mathbf{V}_{k-1}$) also defined for the parameters

Model prediction

$$\bar{\mathbf{x}}_k = \mathbf{f}\big(\hat{\mathbf{x}}_{k-1}, \widehat{\boldsymbol{\theta}}_{k-1}, \mathbf{u}_{k-1}, \bar{\mathbf{v}}_{k-1}\big)$$

$$\overline{\boldsymbol{\theta}}_k = \widehat{\boldsymbol{\theta}}_{k-1} + \bar{\mathbf{v}}_{k-1}$$

$$\bar{\mathbf{y}}_k = \mathbf{g}\big(\bar{\mathbf{x}}_k, \widehat{\boldsymbol{\theta}}_k, \mathbf{u}_{k-1}\big) + \bar{\mathbf{w}}_k$$

Measurement correction

$$\begin{bmatrix} \hat{\mathbf{x}}_k \\ \widehat{\boldsymbol{\theta}}_k \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{x}}_k \\ \overline{\boldsymbol{\theta}}_k \end{bmatrix} + \mathbf{K}(k)\big(\mathbf{y}_{\mathrm{M},k} - \bar{\mathbf{y}}_k\big)$$

CV1: Absorber capture rate (CR) – **Target**

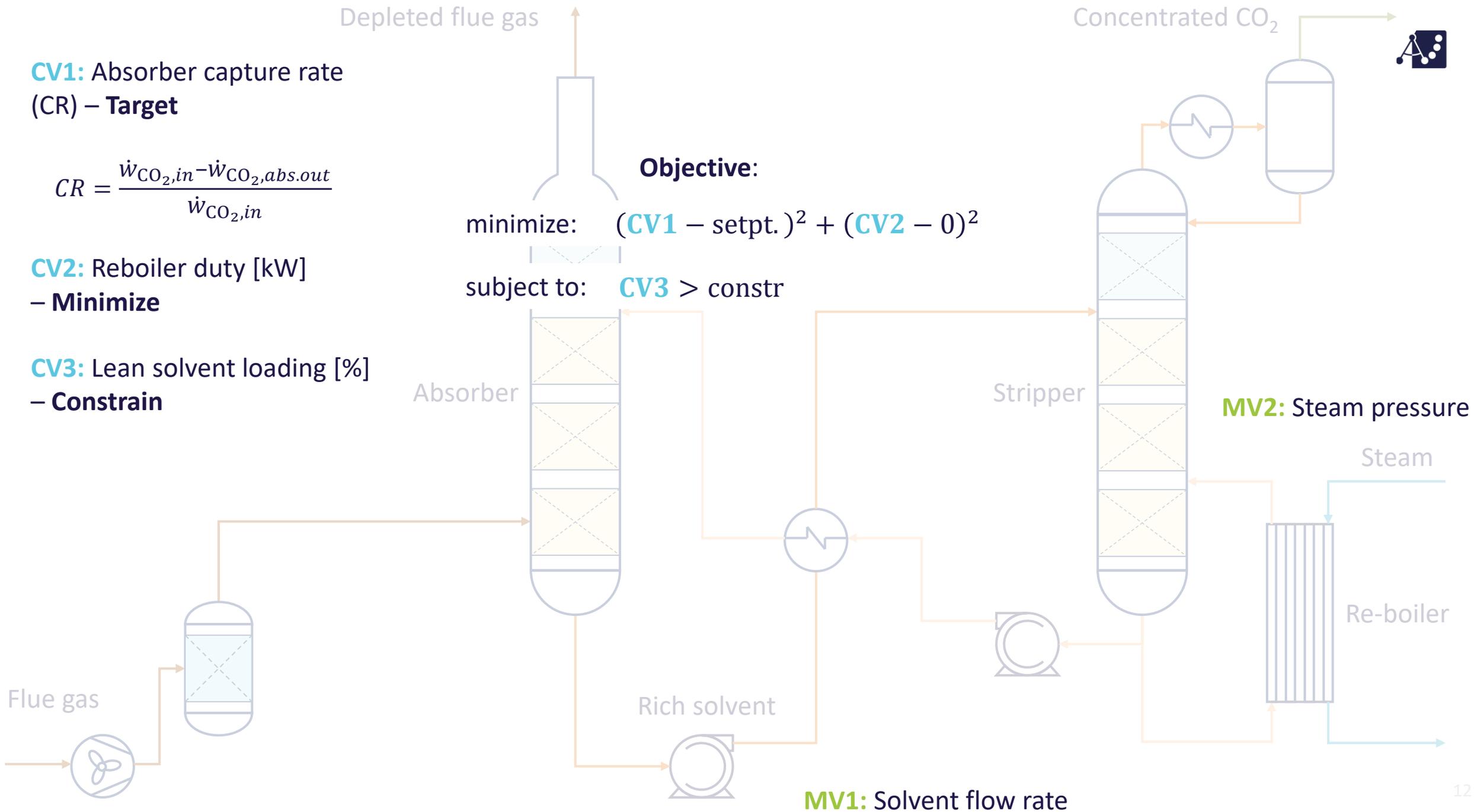$$CR = \frac{\dot{w}_{CO_2,in} - \dot{w}_{CO_2,abs.out}}{\dot{w}_{CO_2,in}}$$
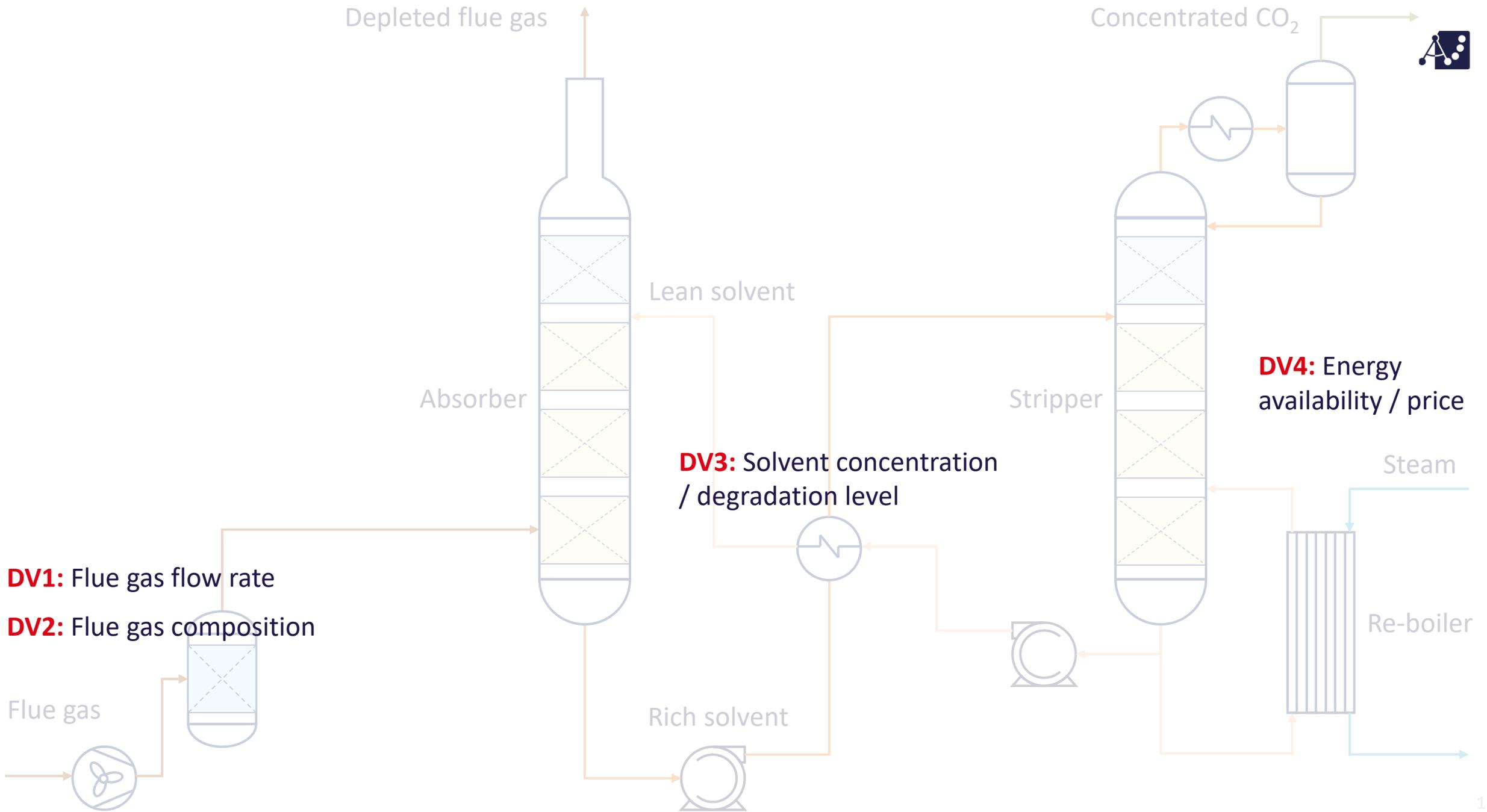
CV2: Reboiler duty [kW] – **Minimize**

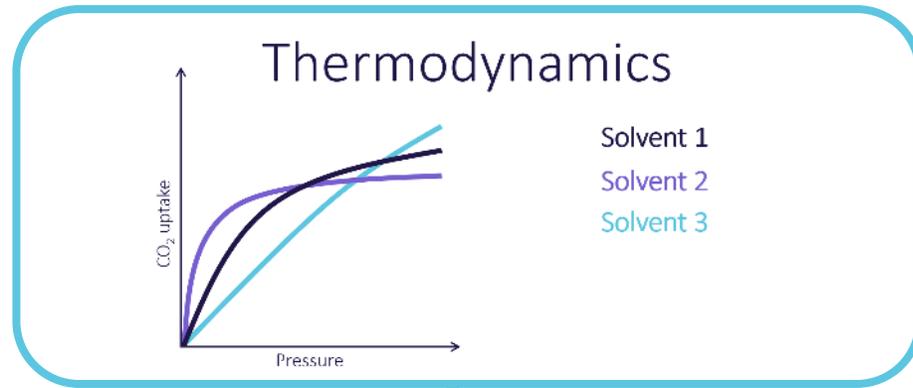CV3: Lean solvent loading [%] – **Constrain**

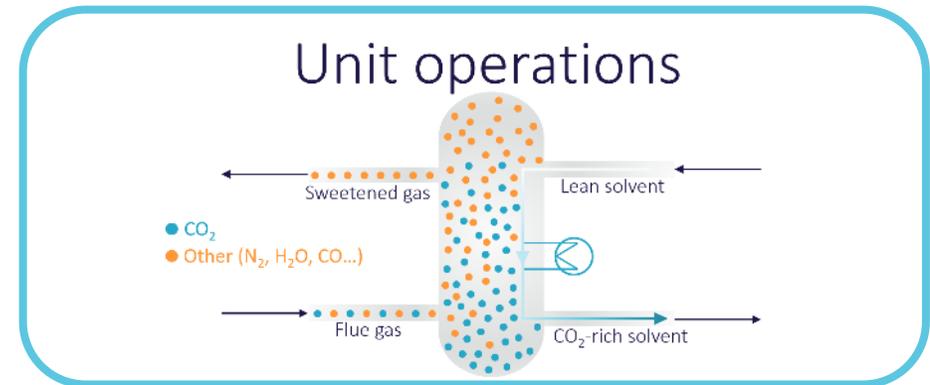**Objective**:

minimize: $(CV1 - setpt.)^2 + (CV2 - 0)^2$

subject to: $CV3 > constr$

Depleted flue gas
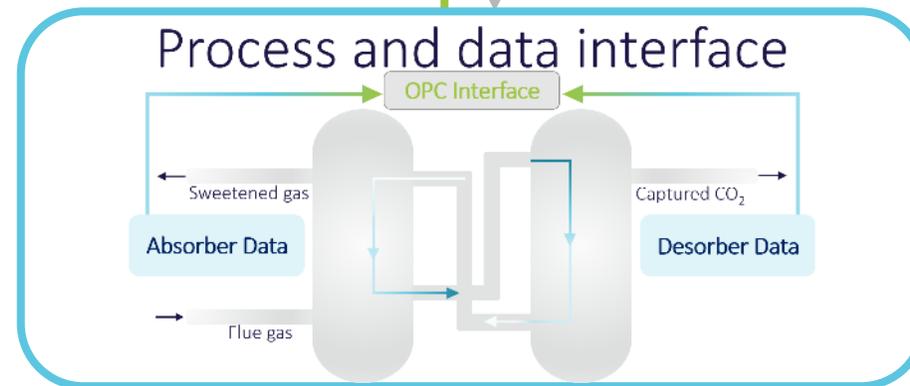
Concentrated CO_2

Absorber

Stripper

MV2: Steam pressure

Steam

Re-boiler

Flue gas

Rich solvent

MV1: Solvent flow rate

12

Depleted flue gas

Concentrated CO₂

Lean solvent

Absorber

Stripper

DV4: Energy availability / price

DV3: Solvent concentration / degradation level

Steam

DV1: Flue gas flow rate

DV2: Flue gas composition

Re-boiler

Flue gas

Rich solvent

Thermodynamics

Solvent 1
Solvent 2
Solvent 3

CO$_2$ uptake

Pressure

(Solvent-specific code)

Unit operations

Sweetened gas

Lean solvent

• CO$_2$
• Other (N$_2$, H$_2$O, CO...)

Flue gas

CO$_2$-rich solvent

(Common, generic code)

CENIT PCC
model

(Plant-specific code)

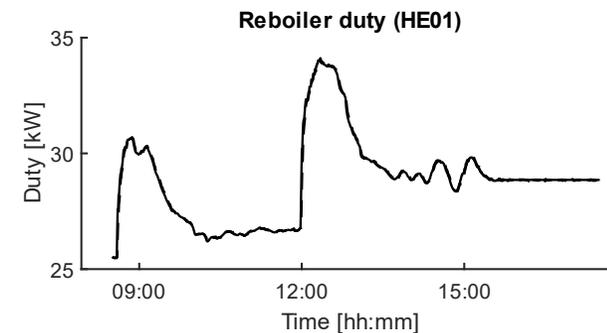Process and data interface

OPC Interface

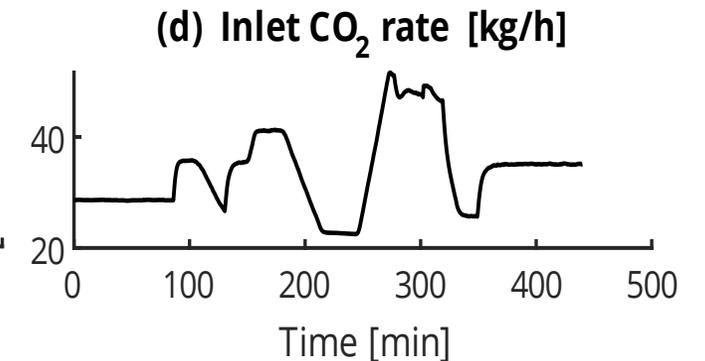Sweetened gas

Captured CO$_2$

Absorber Data

Desorber Data

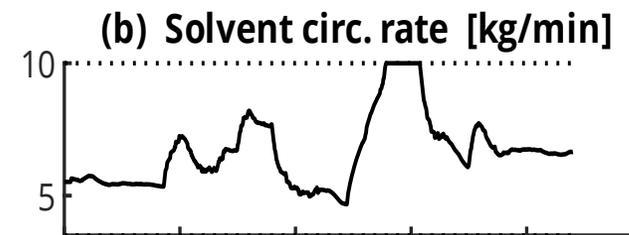Flue gas
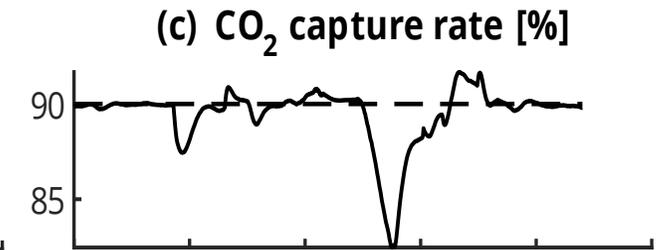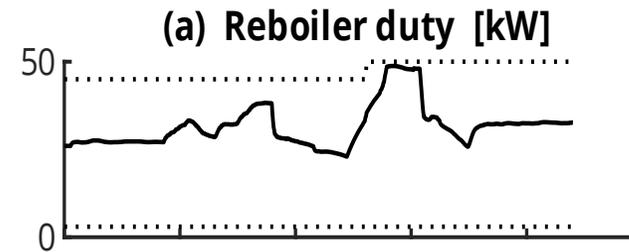
Capture rate, setpoint changes

- Step in capture ratio setpoint

- Controller responds quickly
  - Obeys capture rate setpoint
  - Approaches the point of energy-optimal operation
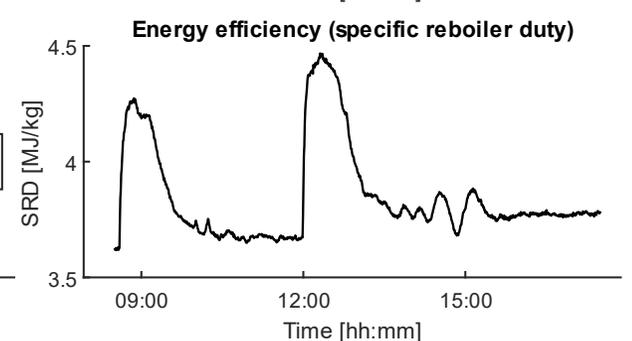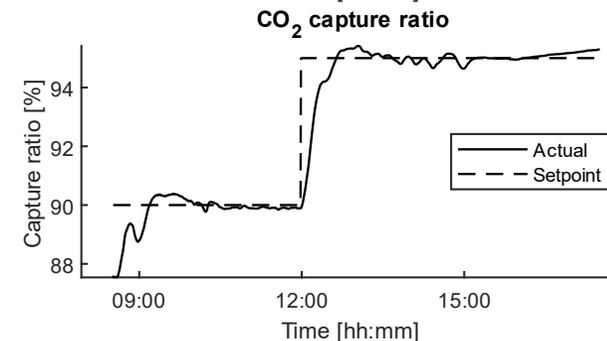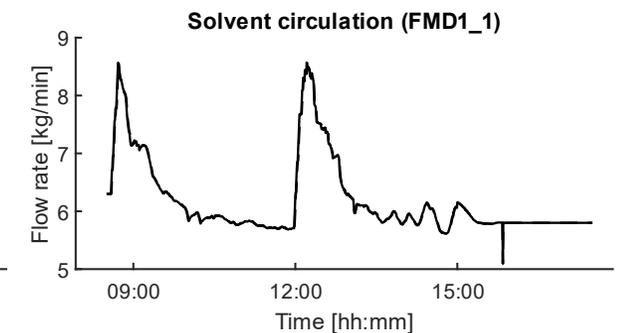
Disturbance rejection

- Changing flue gas conditions
  - Flue gas CO_2 concentration
  - Flue gas inlet flow rate

- Rapid controller response
  - Stays at the prescribed capture rate, while minimizing reboiler duty

(a) Reboiler duty [kW]

(b) Solvent circ. rate [kg/min]

(c) CO_2 capture rate [%]

(d) Inlet CO_2 rate [kg/h]

Time [min]

Special control cases: Energy availability

- Reboiler duty constraint tests

- Lean loading constraint
  - The controller will prioritize to maintain the loading rather than obeying the instantaneous capture rate setpoint

(a) Reboiler duty [kW]

(b) Solvent circ. rate [kg/min]

(c) CO$_2$ capture rate [%]

**(d) Lean loading [-]**

Time [min]
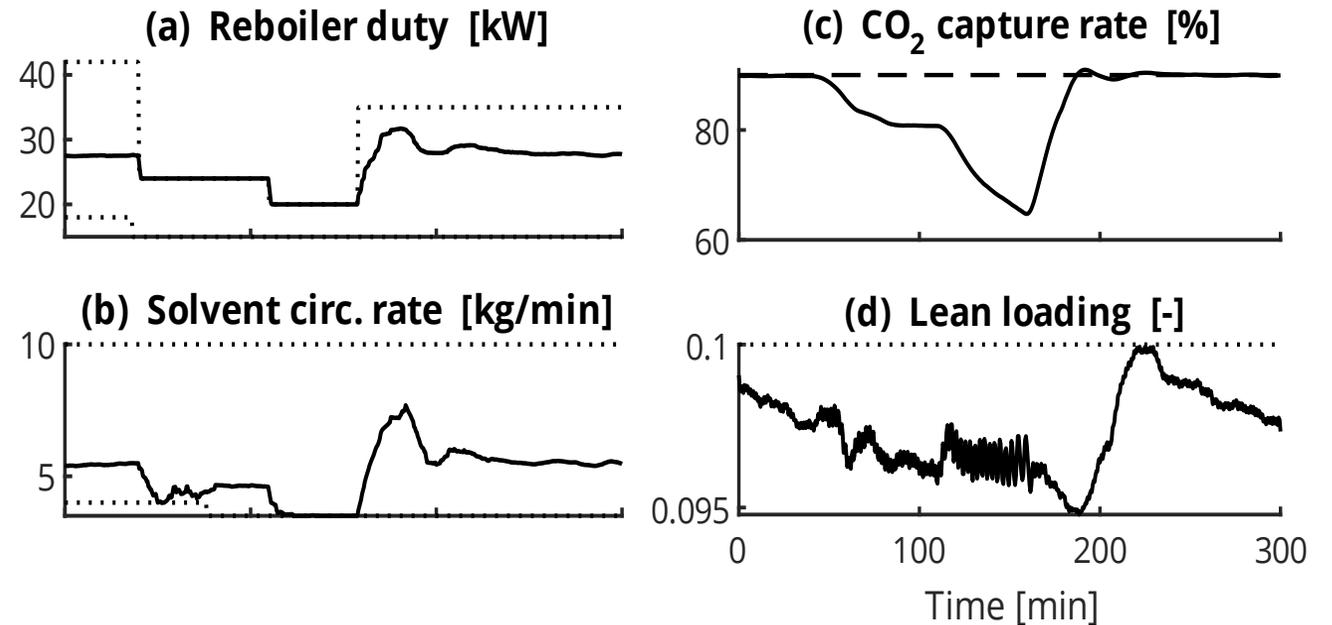
Special control cases: Economic optimization

- Day-to-day (24h) cost optimization, using DRTO

- Varying energy price
    - Energy cost savings in the range of 12%[1]

- Flexible operation using storage tanks
    - Energy cost savings in the range of 33%[1]

[1] For a proposed price regime

Implementation

- Close dialogue with end-user (production engineers & control room operators)

- Close cooperation with DCS supplier

- FAT / SAT on "digital twin" (high fidelity simulator for operator training)

- Remote monitoring of application during commissioning phase
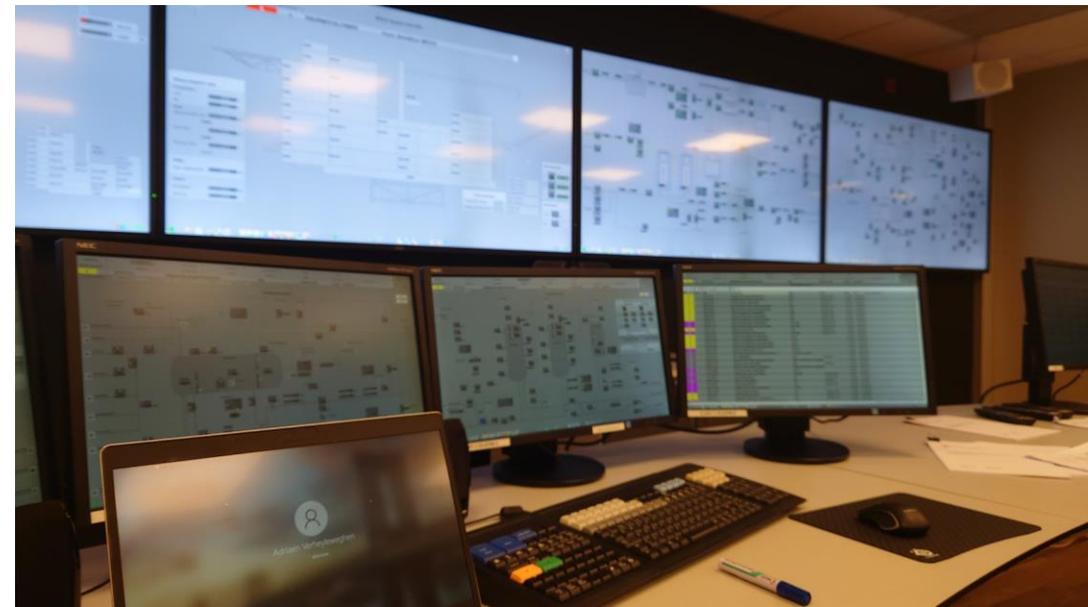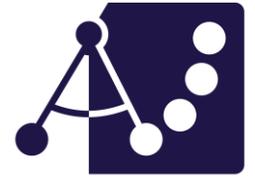
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Scientific papers

- S. O. Hauger, N. E. Flø, H. M. Kvamsdal, F. Gjertsen, T. Mejdell, M. Hillestad:
Demonstration of non-linear control of post-combustion CO_2 capture processes,
Computers and Chemical Engineering 123 (2019) 184-195

- H. M. Kvamsdal, S.O. Hauger, F. Gjertsen, N.E. Flø, K.E. Colombo, T. Mejdell, M. Hillestad:
Demonstration of two-level nonlinear model predictive control of CO_2 capture plants,
14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, 21st – 25th October 2018, Melbourne, Australia.

- T. Mejdell, H. M. Kvamsdal, S. O. Hauger, F. Gjertsen, F. A. Tobiesen, M. Hillestad:
Demonstration of non-linear model predictive control for optimal flexible operation of a CO2 capture plant, **International Journal of Greenhouse Gas Control 117 (2022) 103645, 2022.**

- F. Gjertsen, A. Verheyleweghen, S. O. Hauger, V. Tjessem, T. Mejdell, H. M. Kvamsdal:
Optimal Control of Industrial Solvent-Based CO2 Capture Plants, **Computer Aided Process Engineering / 15th International Symposium on Process Systems Engineering (ESCAPE34/PSE24), 2024.**