



# Demonstration of economic nonlinear model predictive control of CO2 capture plant with CESAR1

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Adriaen Verheyleweghen,<sup>(a)</sup> Fredrik Gjertsen,<sup>(a)</sup> Thor Mejdell,<sup>(b)</sup> Hanne M. Kvamsdal<sup>(b)</sup>

(a) Cybernetica  
(b) SINTEF Industry





# AURORA consortium

|                                     |                                                                                     |                                                                                       |                                                                                     |                                                                                     |                                                                                     |
|-------------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|                                     |                                                                                     |                                                                                       |                                                                                     |                                                                                     |                                                                                     |
| Research/<br>Academia               |    |      |  |  |  |
|                                     | Norway                                                                              |                                                                                       | United Kingdom                                                                      |                                                                                     | Italy                                                                               |
| Industry/<br>Technology<br>provider |    |     |  |  |  |
|                                     | France                                                                              | Norway                                                                                | Greece                                                                              |                                                                                     | Belgium                                                                             |
| SME                                 |  |  |                                                                                     |                                                                                     |                                                                                     |
|                                     | Norway                                                                              | France                                                                                |                                                                                     |                                                                                     |                                                                                     |



## Cybernetica at a glance

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- Est. 2000, SINTEF spin-off
- Tailor-made model-based solutions
- Unique NMPC technology
  - Industrially proven
  - Increases profitability for our customers
- Our employees are experts in advanced control and process modelling with strong engineering backgrounds





# Application areas

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POLYMER

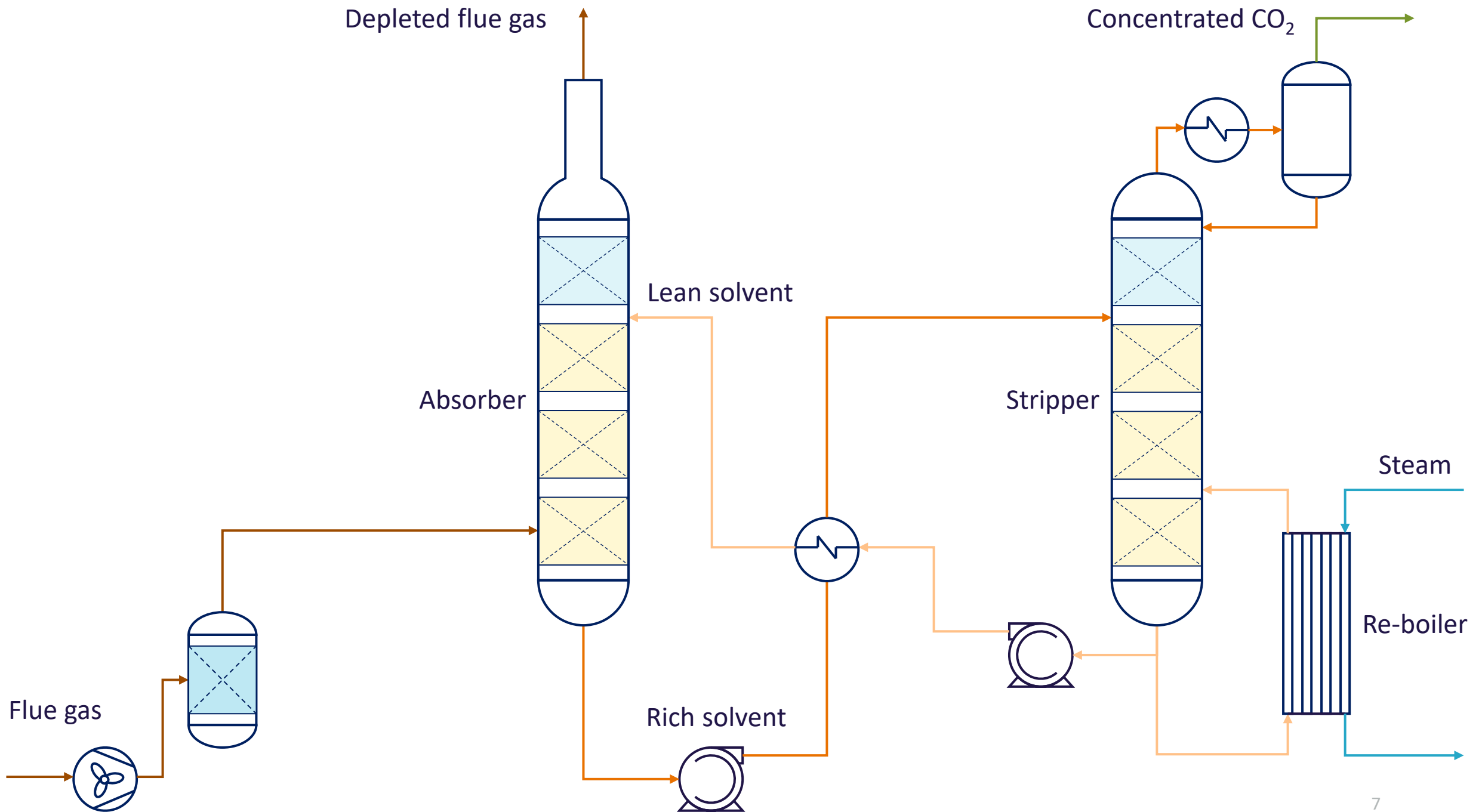


METALLURGICAL



ENERGY





Depleted flue gas

Concentrated CO<sub>2</sub>



Sintef CO<sub>2</sub> lab in Tiller



Lean solvent

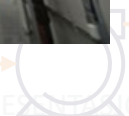
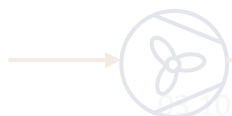


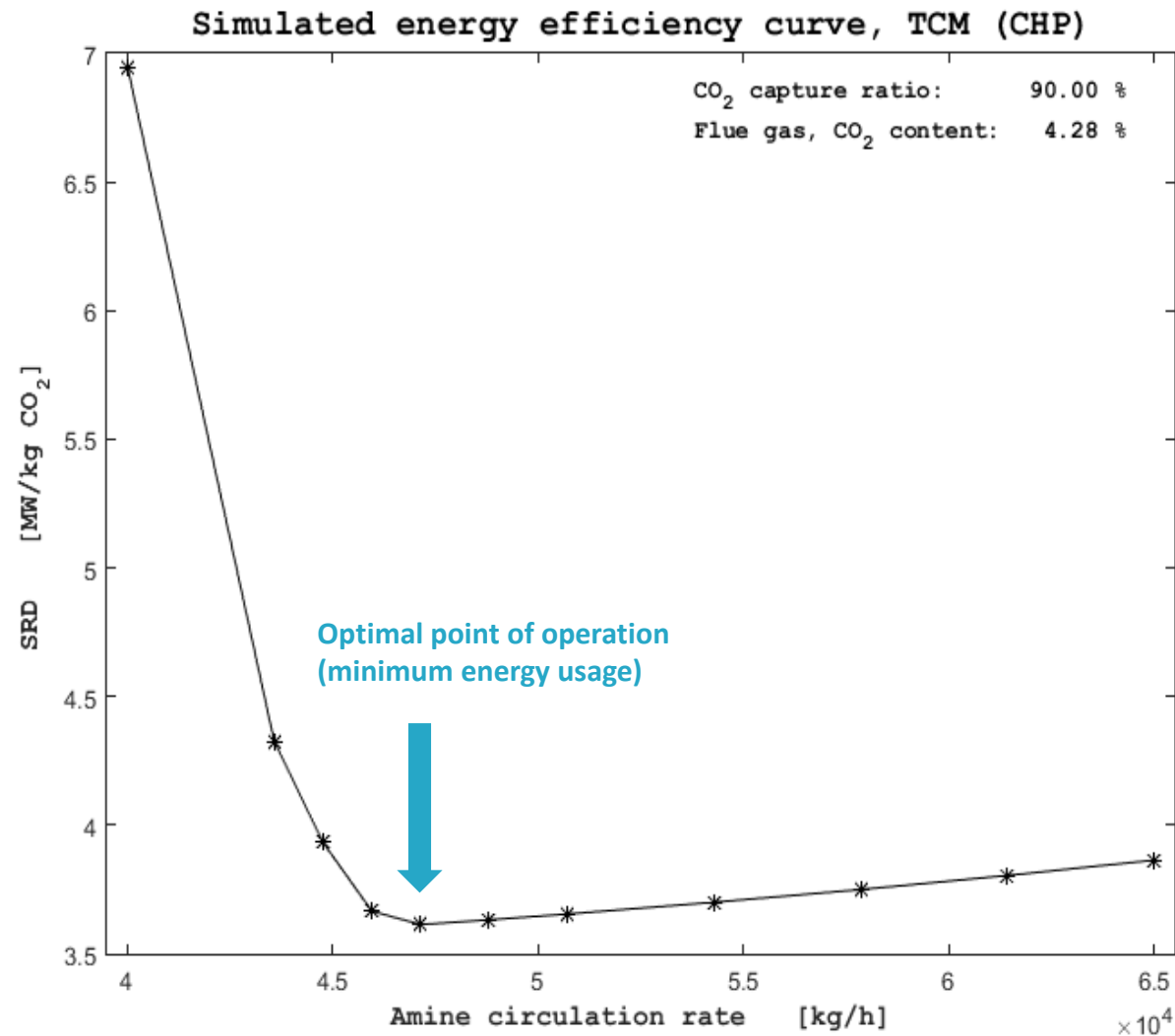
Technology Center Mongstad (TCM)

Re-boiler

Flue gas

Solvent



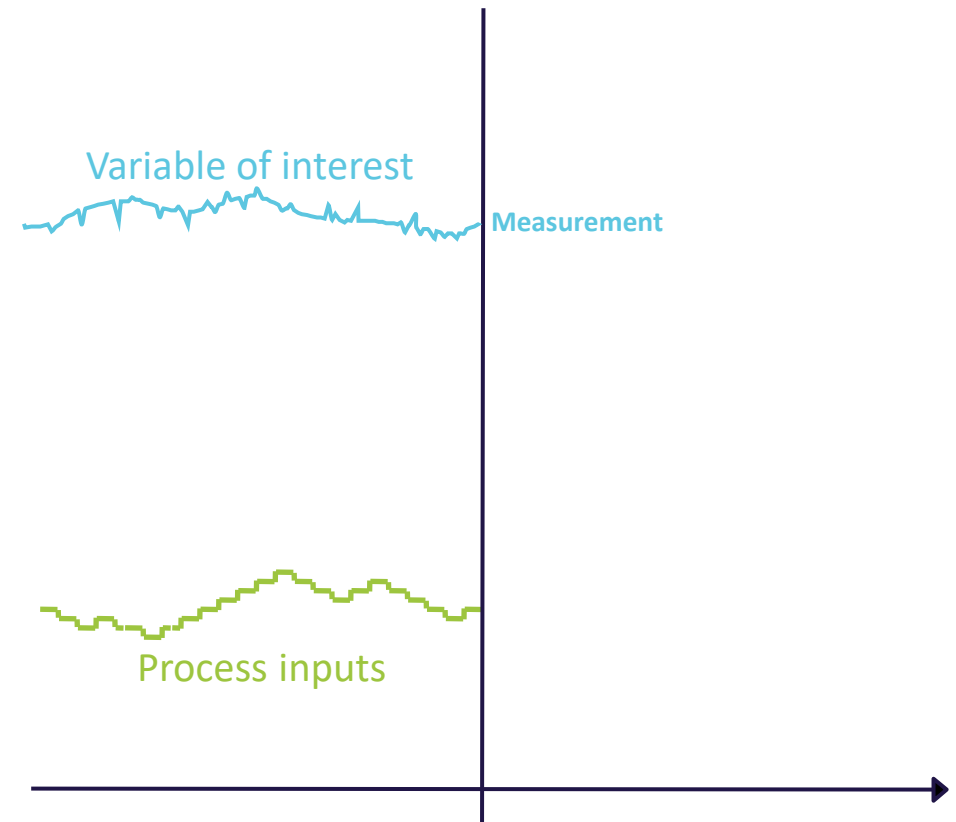


- A solvent-based CO<sub>2</sub> capture is a complex, nonlinear process with both fast and slow dynamics
- Optimal conditions change with
  - desired capture ratio
  - solvent concentration and degree of degradation
  - flue gas flow rate
  - flue gas composition



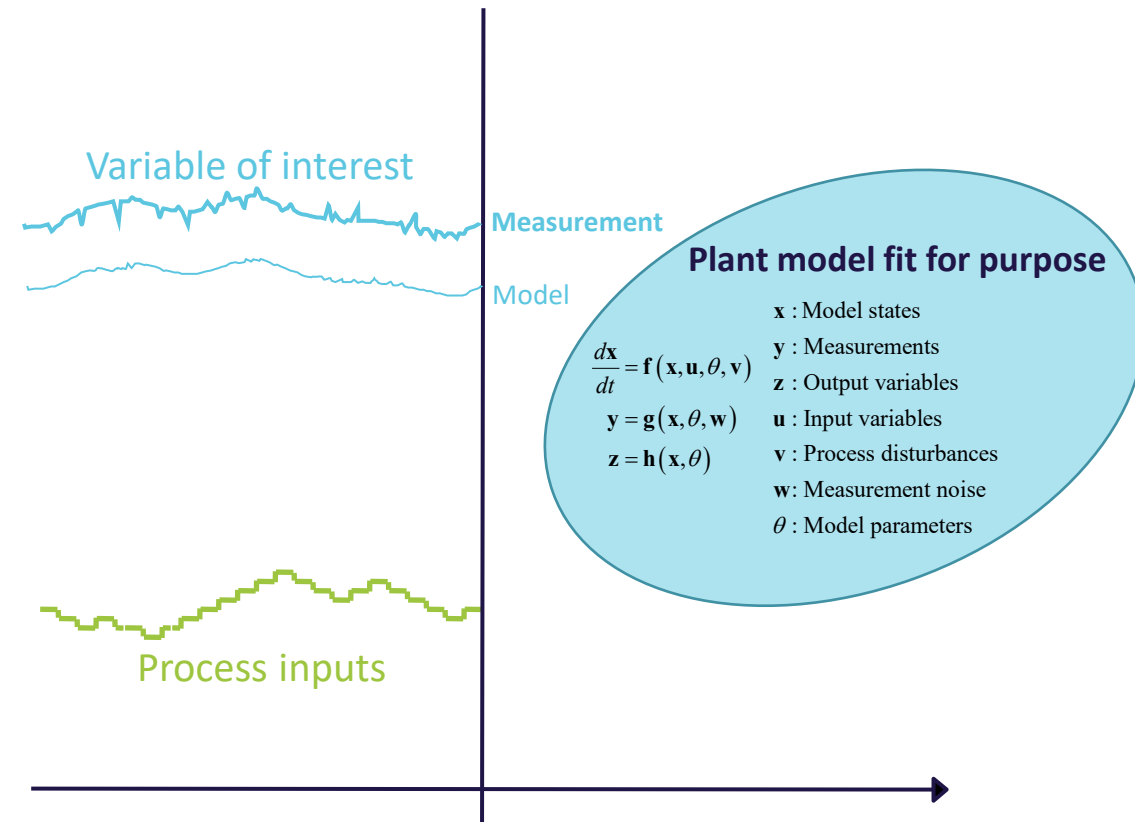
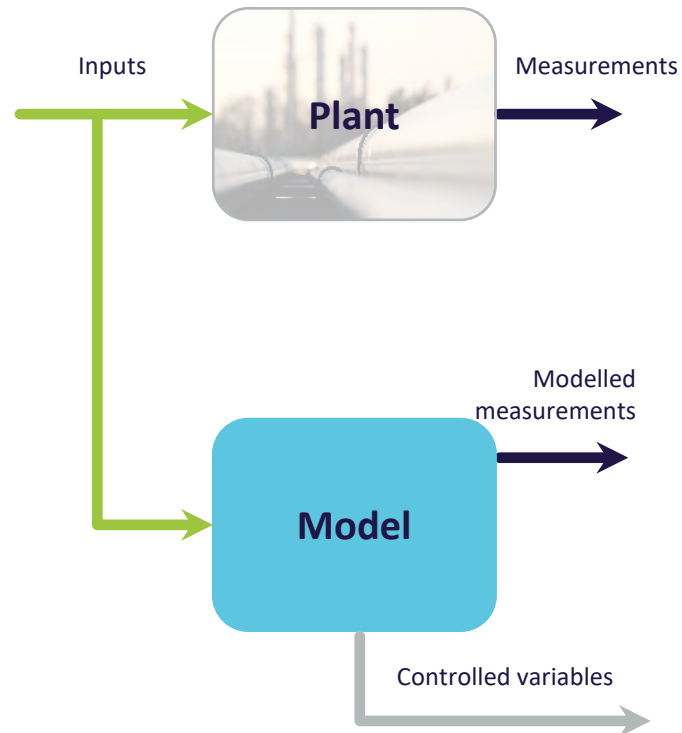
# Target process w/instrumentation

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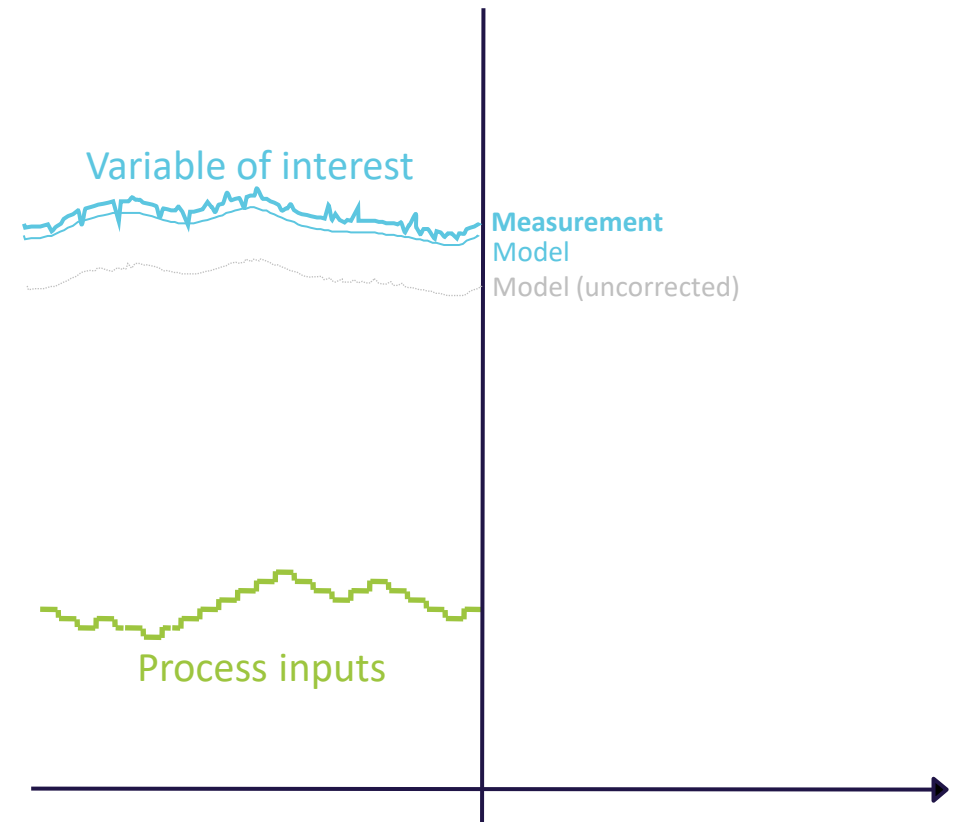
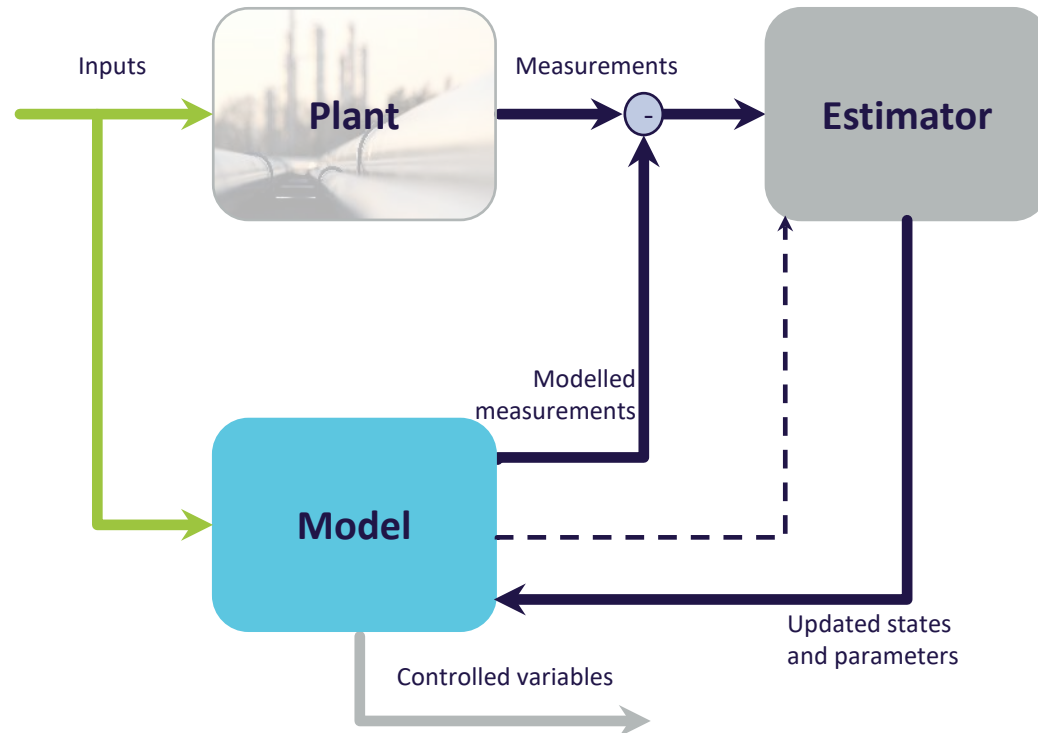


# Numerically efficient plant model



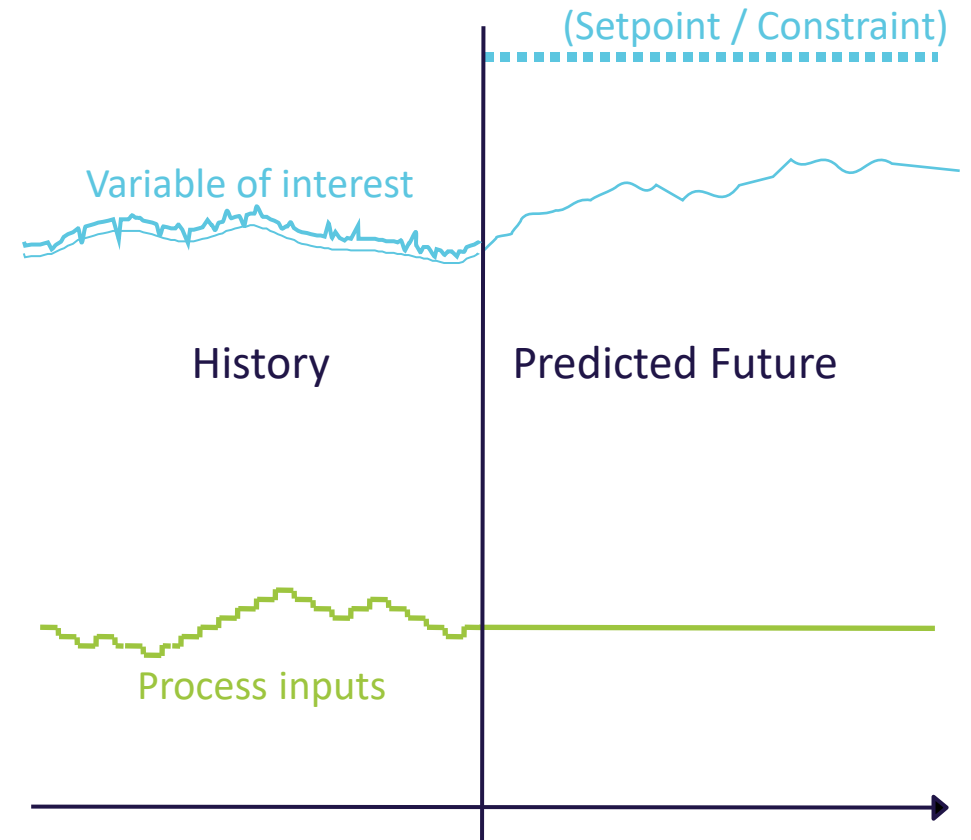
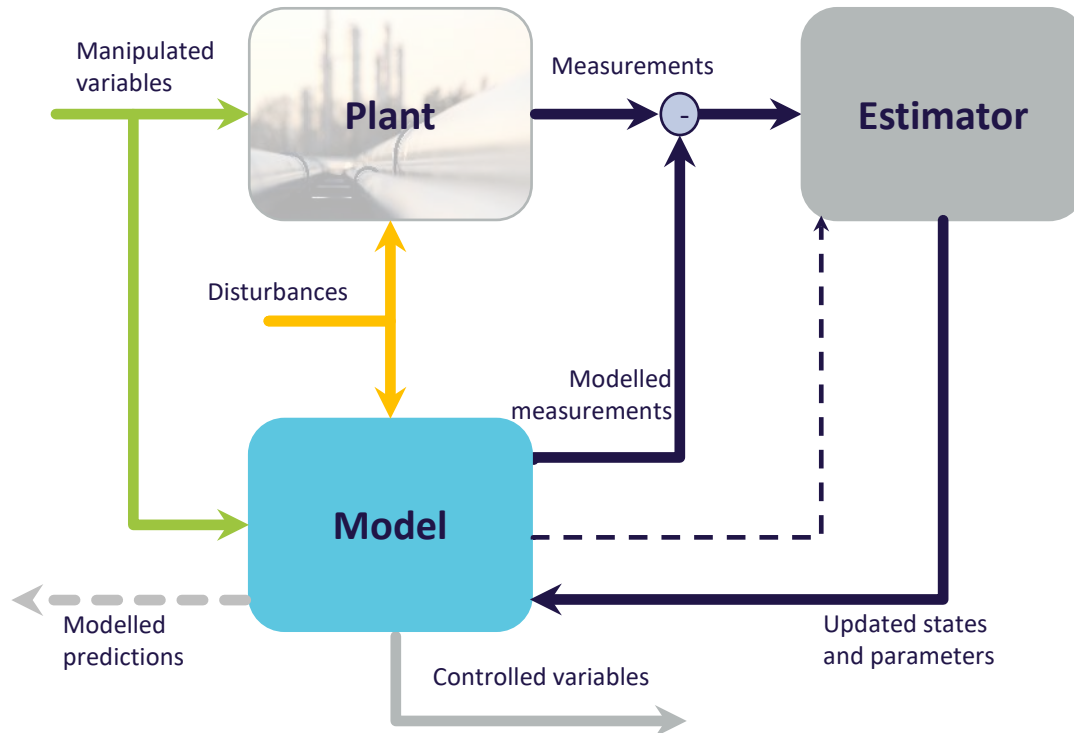


# Model-based State Estimation



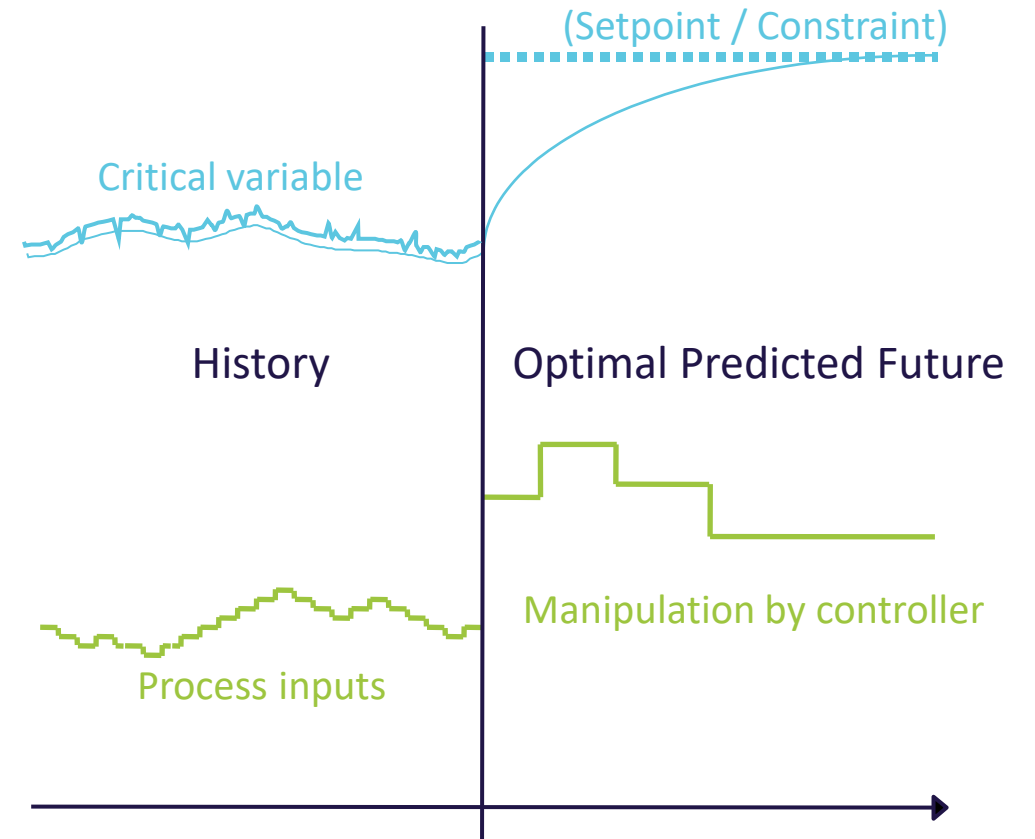
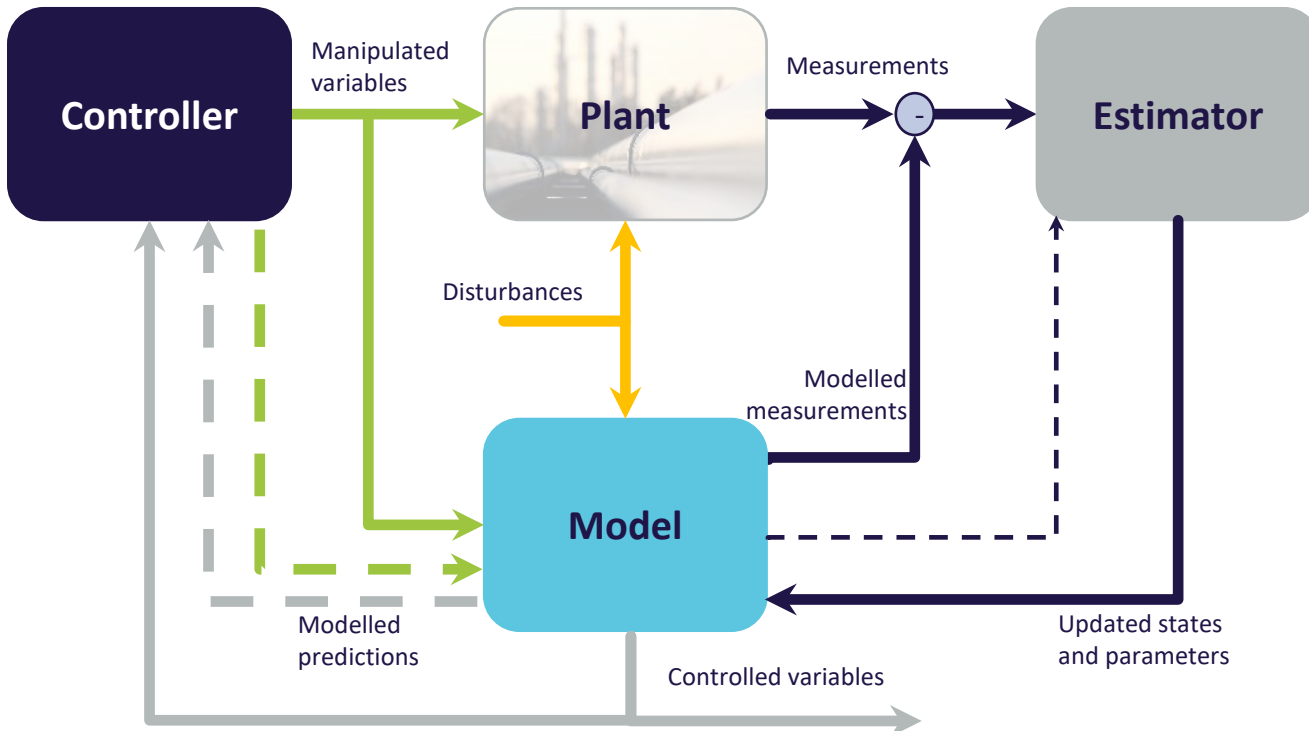


# Model-based Predictions





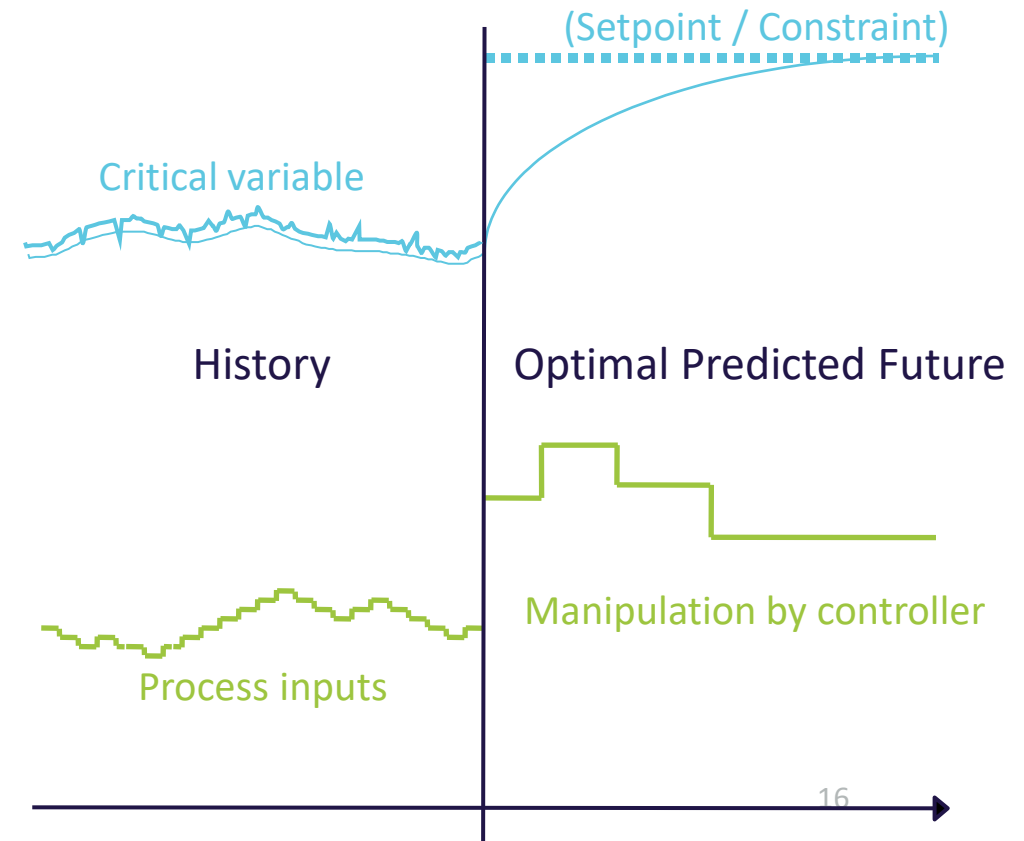
# Model-based Predictive Control



# Advantages

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- Handles process interactions (the fact that each MV influences each CV)
- Handles constraints (min- and max values) in both MVs and CVs
- Controls measured and unmeasured variables
- Performs explicit dynamic optimization
- Reduces operator intervention
- **Flexibility!**
- **Gray / white -box**



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

$$CR = \frac{\dot{W}_{CO_2,in} - \dot{W}_{CO_2,abs.out}}{\dot{W}_{CO_2,in}}$$

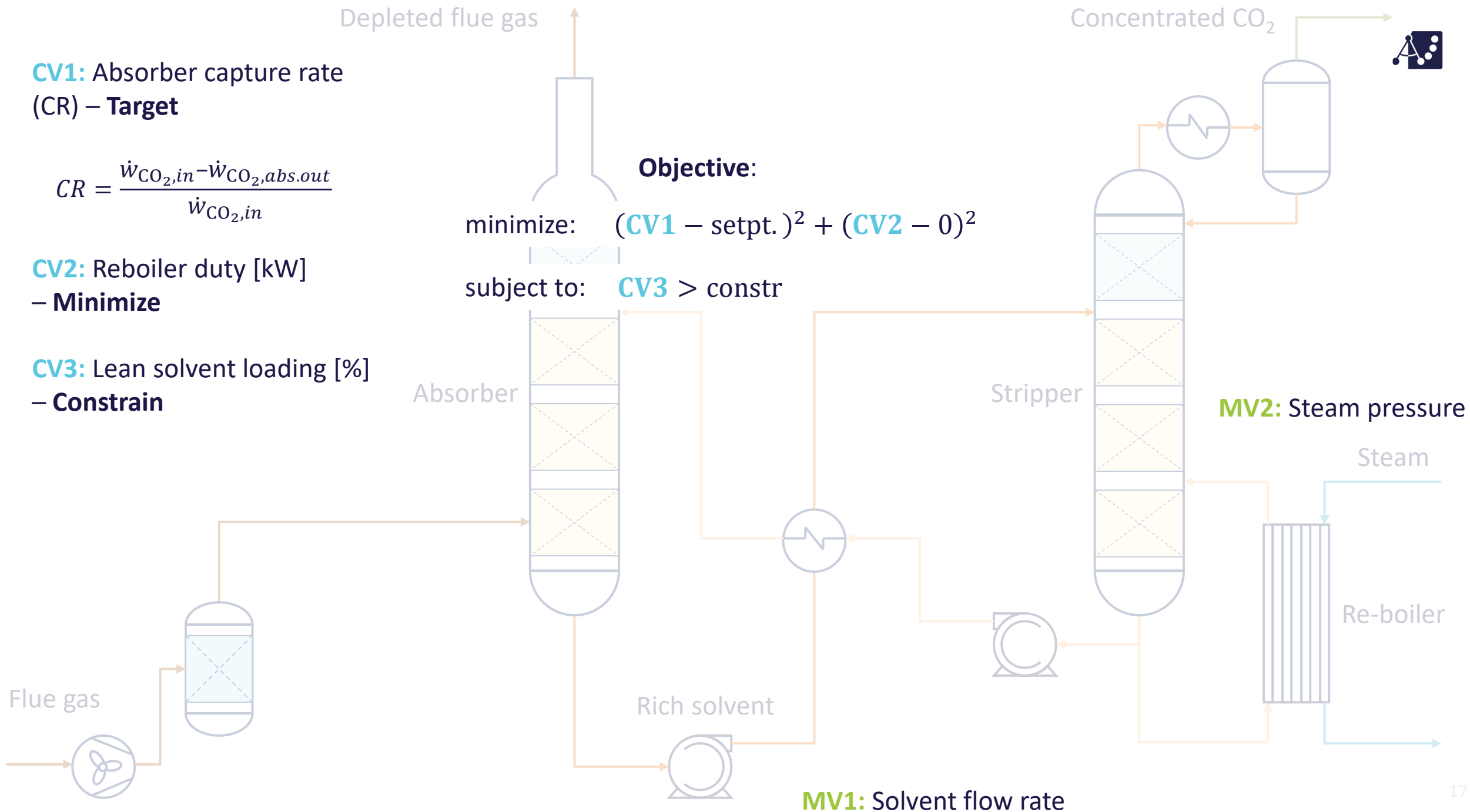
**CV2:** Reboiler duty [kW]  
– **Minimize**

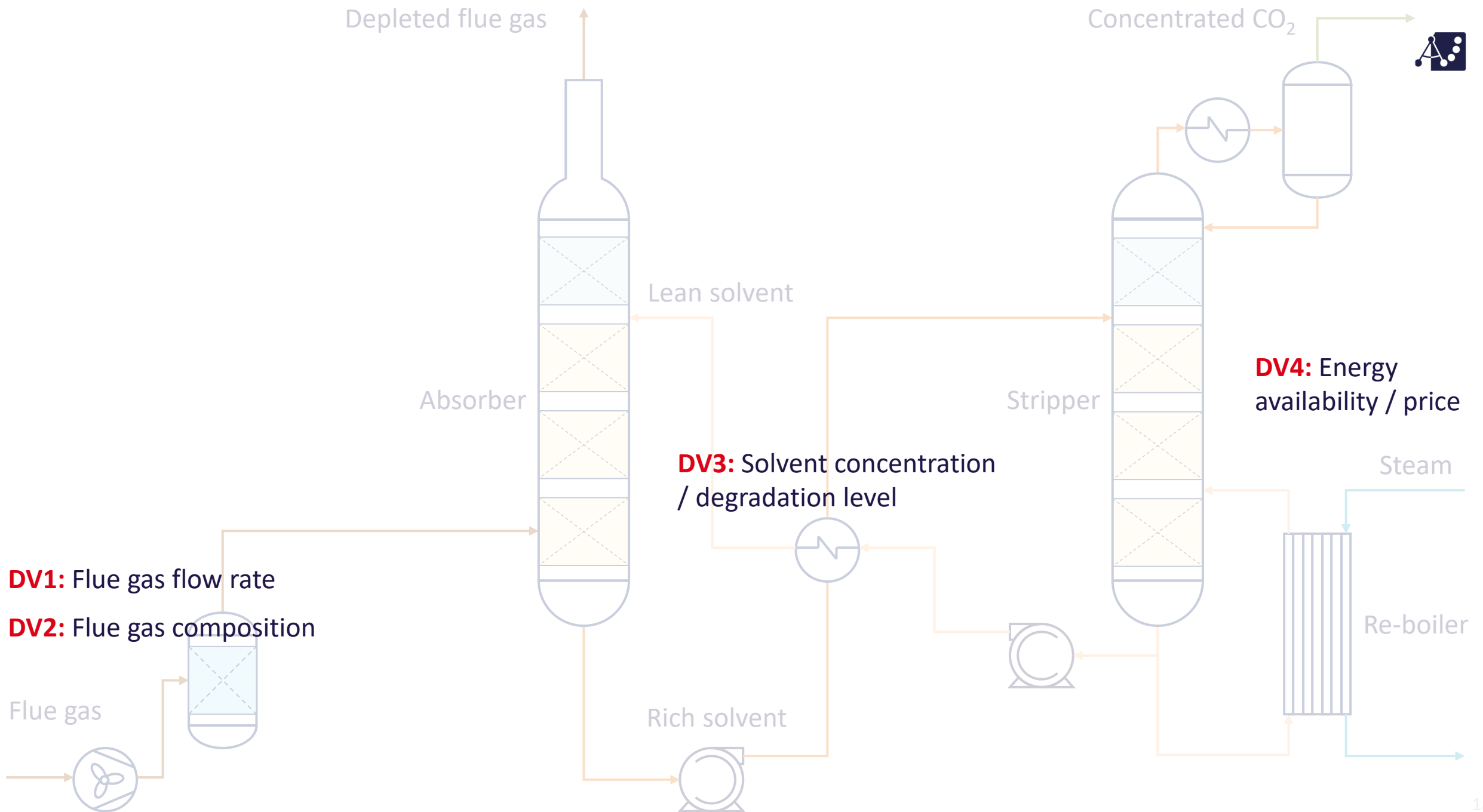
**CV3:** Lean solvent loading [%]  
– **Constrain**

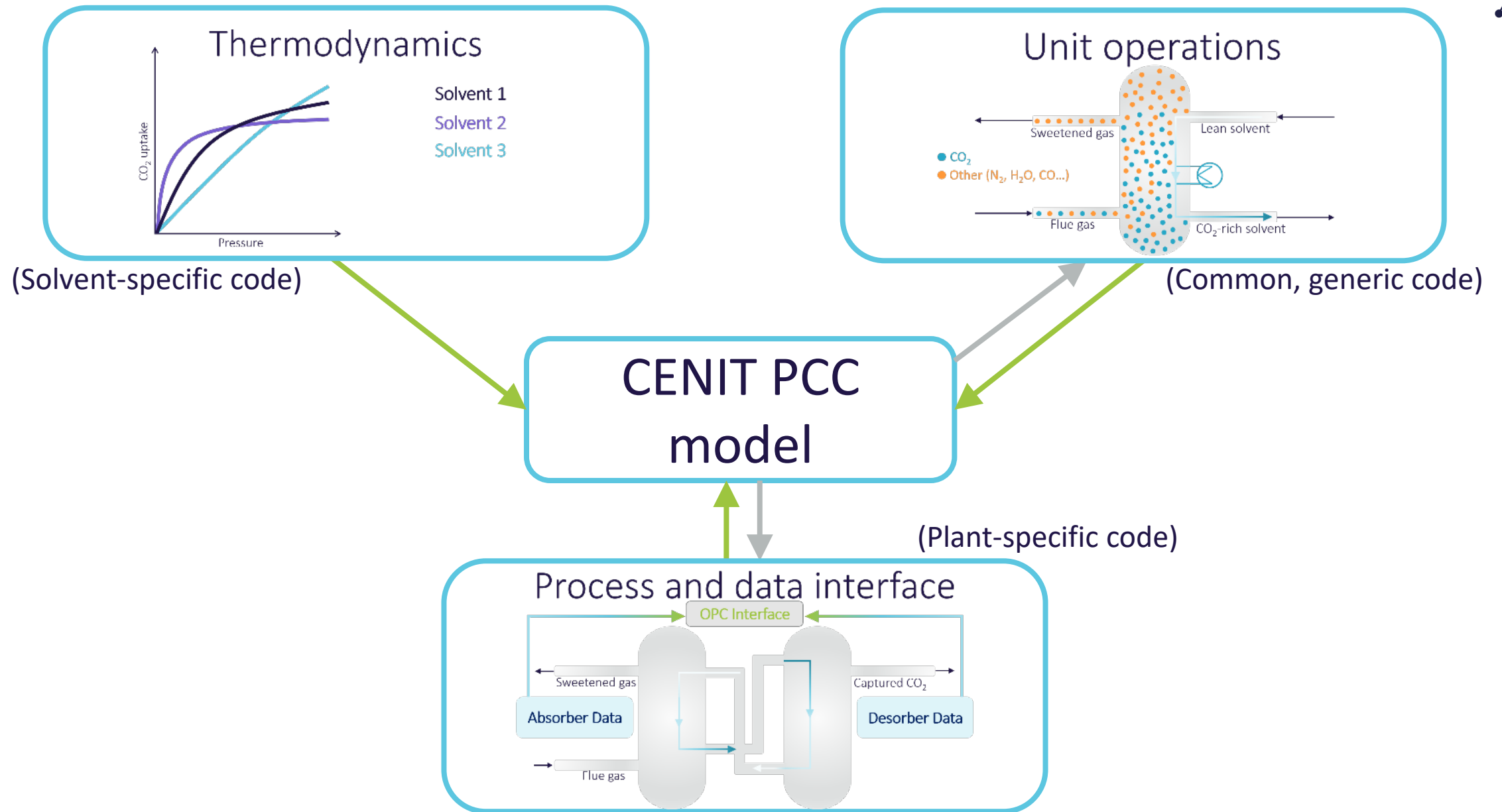
**Objective:**

minimize:  $(\text{CV1} - \text{setpt.})^2 + (\text{CV2} - 0)^2$

subject to:  $\text{CV3} > \text{constr}$

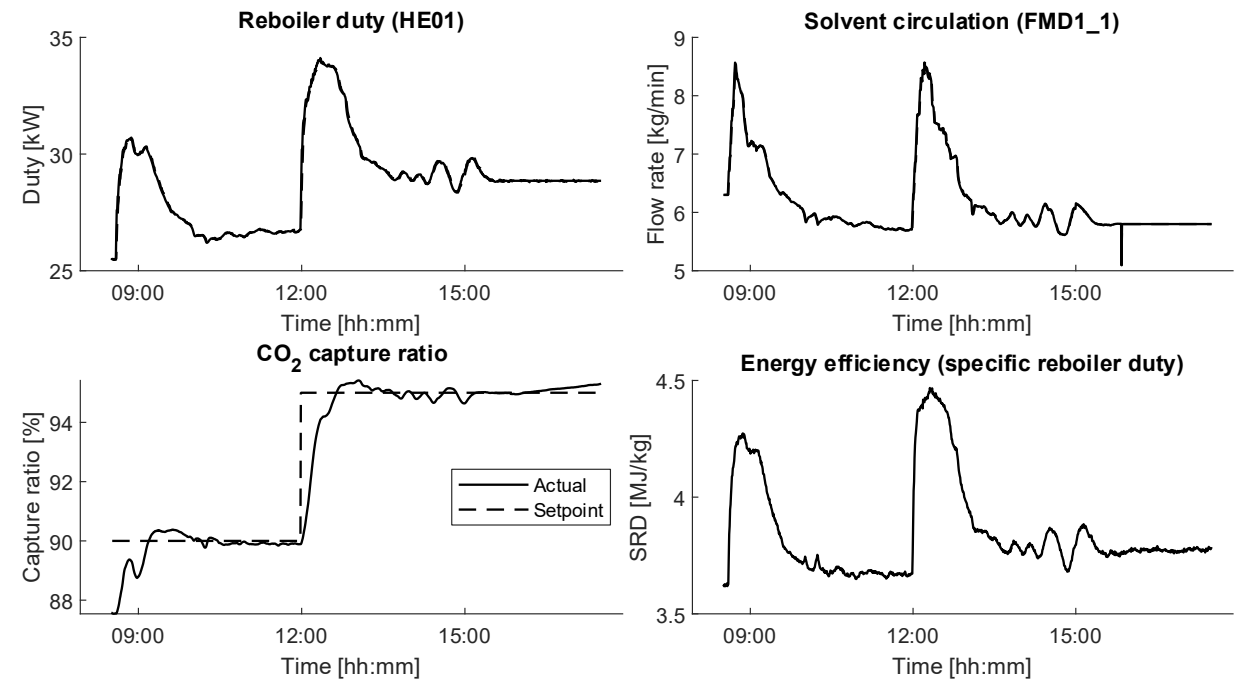






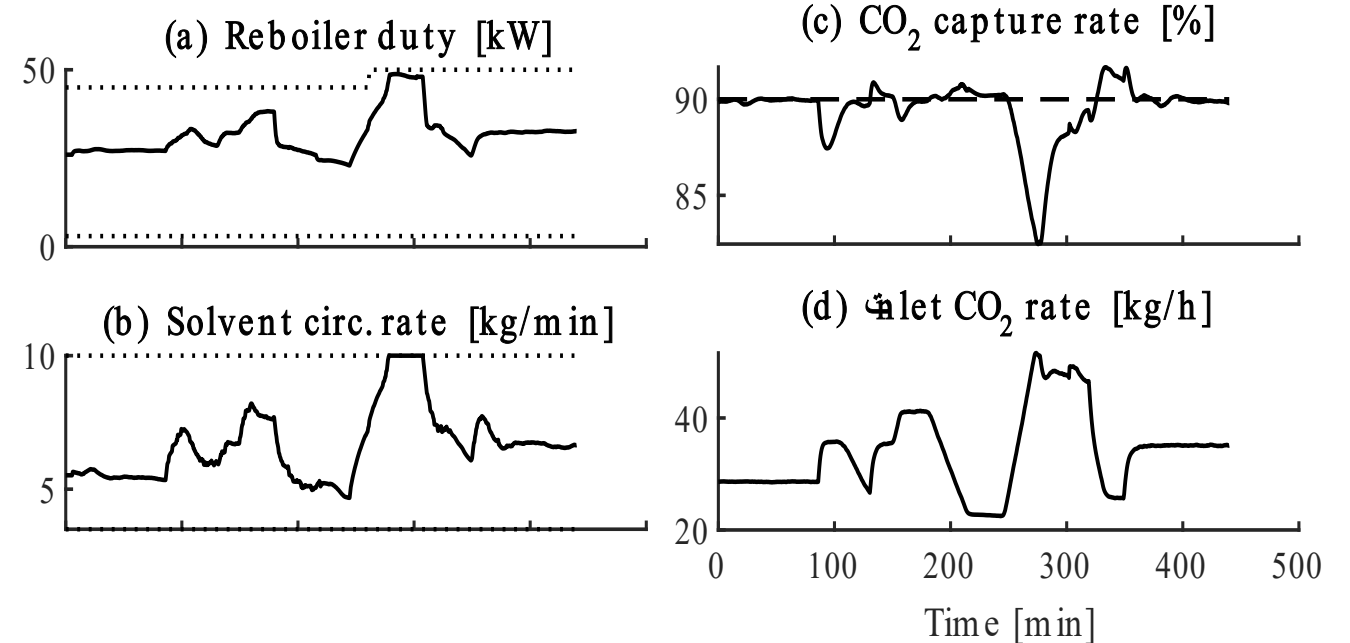
# Capture rate, setpoint changes

- Step in capture ratio setpoint
- Controller responds quickly
  - Obeys capture rate setpoint
  - Approaches the point of energy-optimal operation



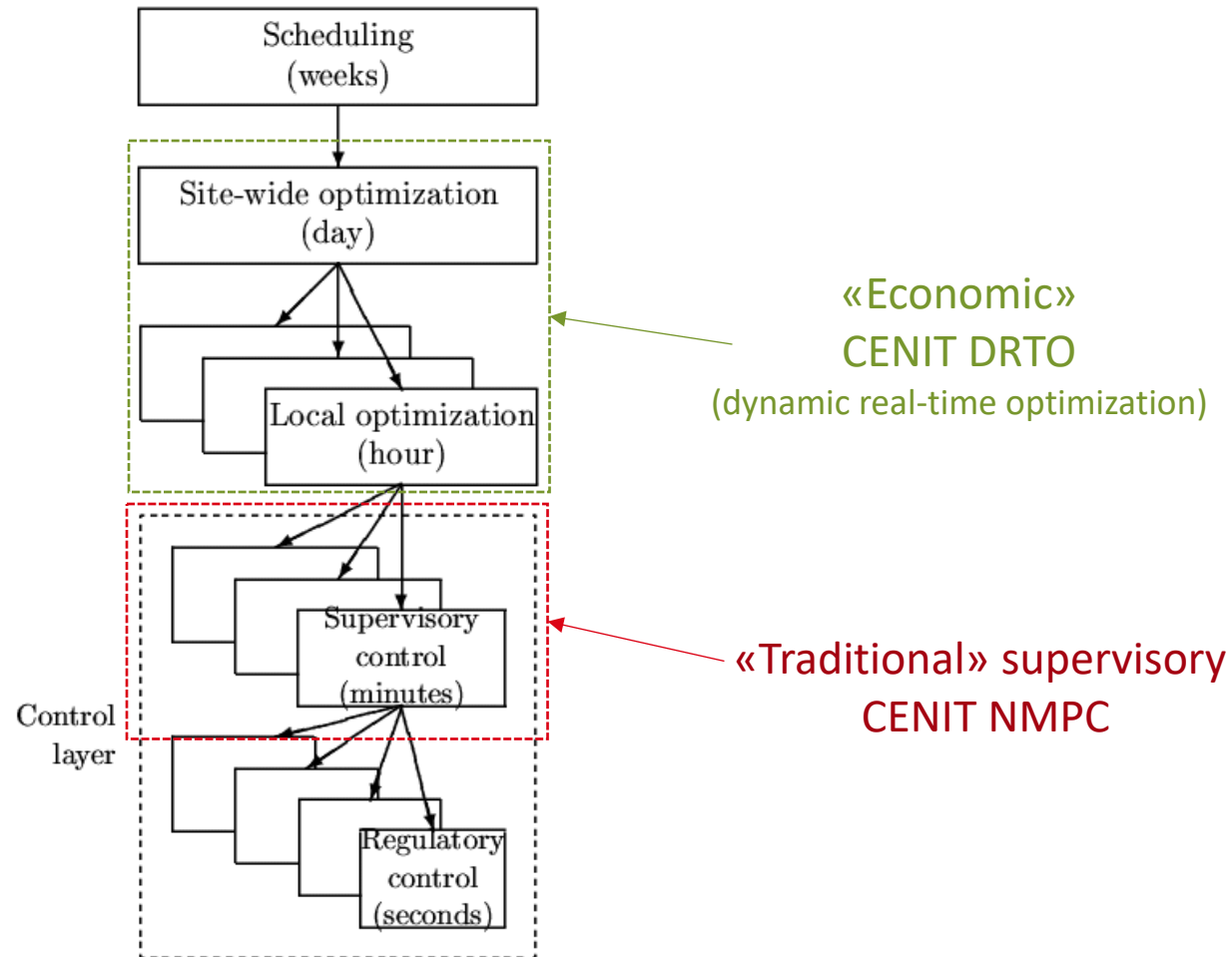
# Disturbance rejection

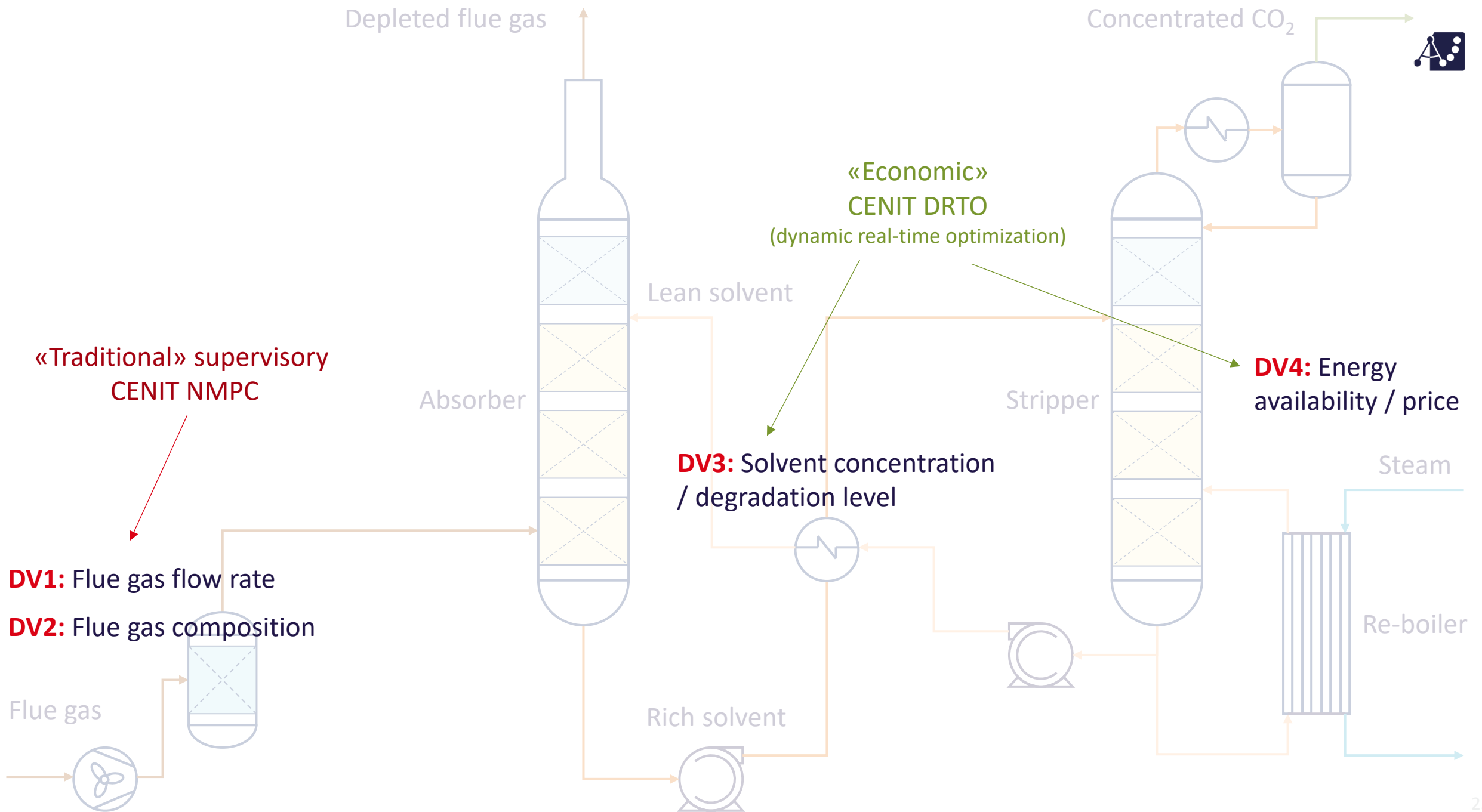
- Changing flue gas conditions
  - Flue gas CO<sub>2</sub> concentration
  - Flue gas inlet flow rate
- Rapid controller response
  - Stays at the prescribed capture rate, while minimizing reboiler duty





# Hierarchical control and optimization





# «Traditional» supervisory CENIT NMPC

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

$$CR = \frac{\dot{W}_{CO_2,in} - \dot{W}_{CO_2,abs.out}}{\dot{W}_{CO_2,in}}$$

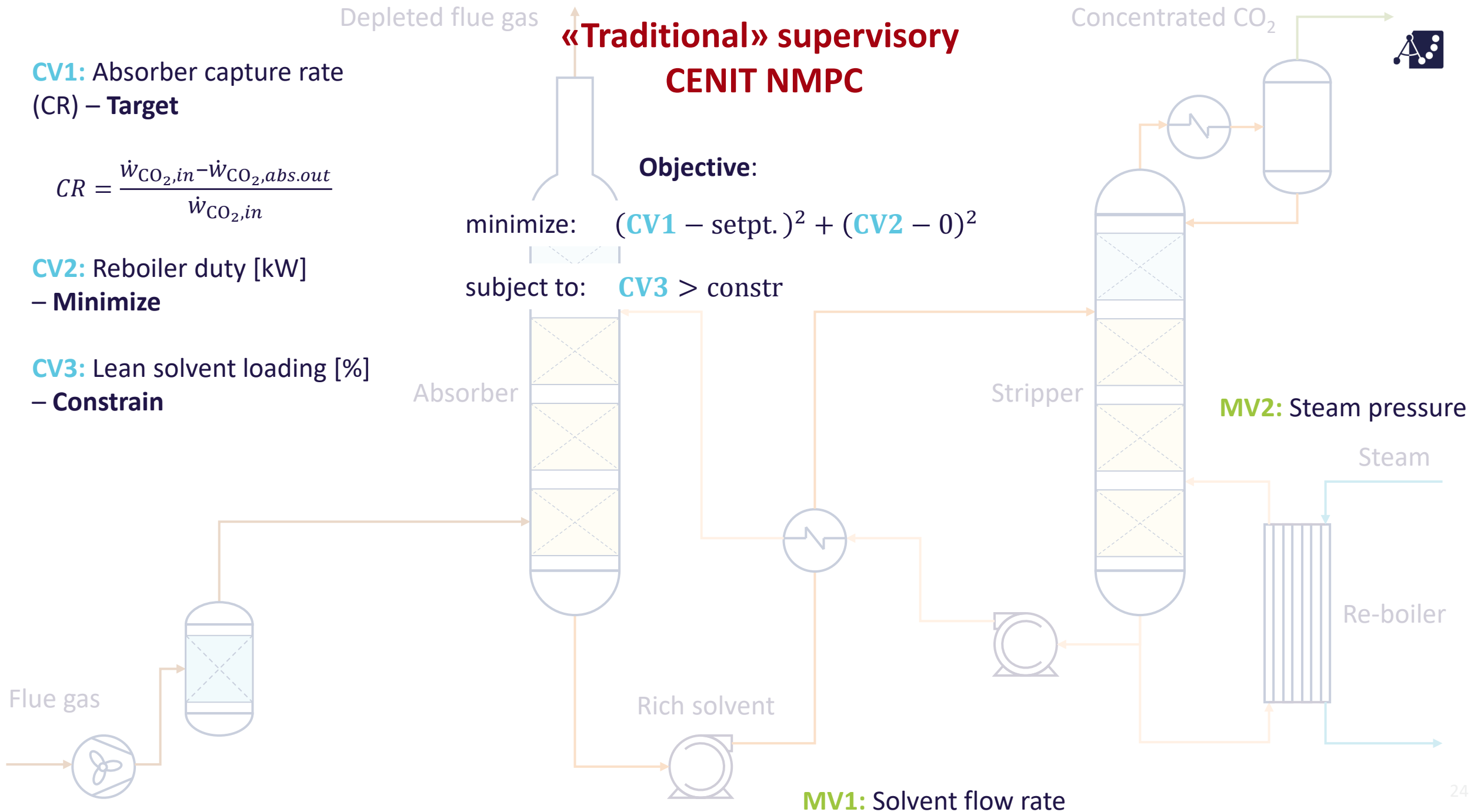
**CV2:** Reboiler duty [kW]  
– **Minimize**

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

**Objective:**

minimize:  $(\text{CV1} - \text{setpt.})^2 + (\text{CV2} - 0)^2$

subject to:  $\text{CV3} > \text{constr}$



**CV1:** CO2 emissions times  
emission prize – **Minimize**

**CV2:** Energy  
consumption throughout  
a 48H period – **Minimize**

**CV3:** Average capture rate  
[%] – **Constrain**

Depleted flue gas

## «Economic» CENIT DRTO

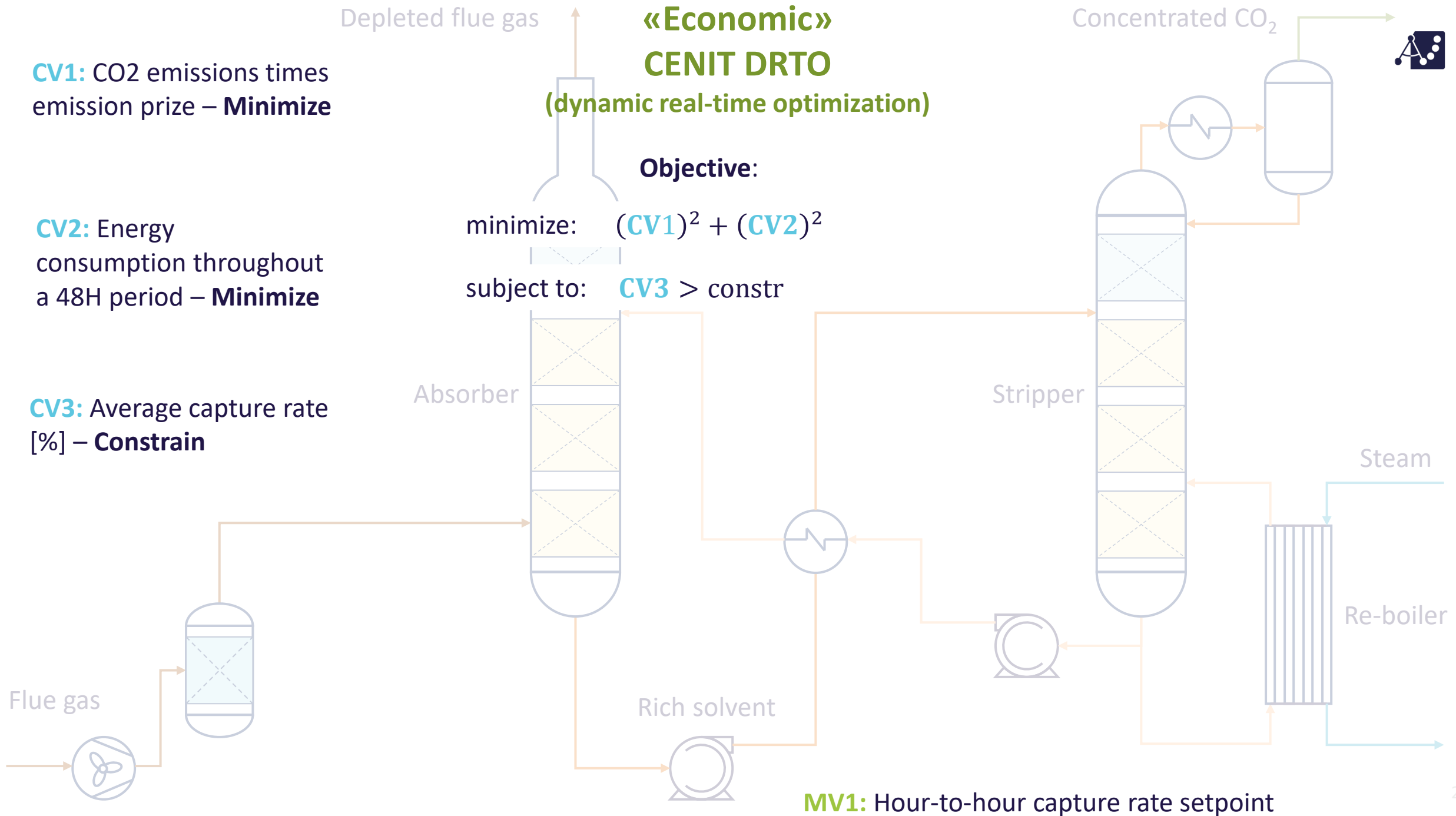
(dynamic real-time optimization)

**Objective:**

minimize:  $(\text{CV1})^2 + (\text{CV2})^2$

subject to:  $\text{CV3} > \text{constr}$

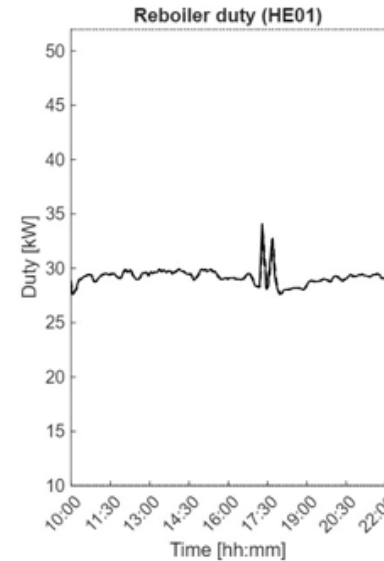
Concentrated CO<sub>2</sub>



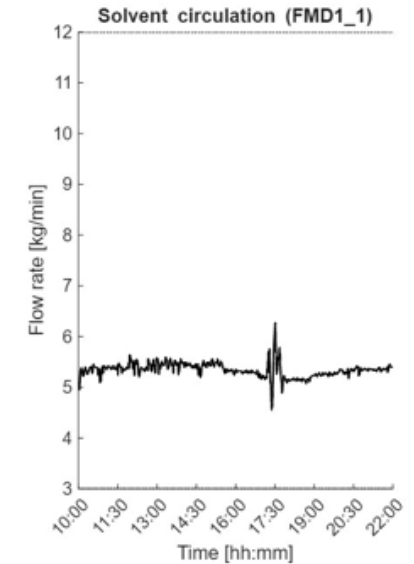
**MV1:** Hour-to-hour capture rate setpoint

# Economic DRT0+NMPC

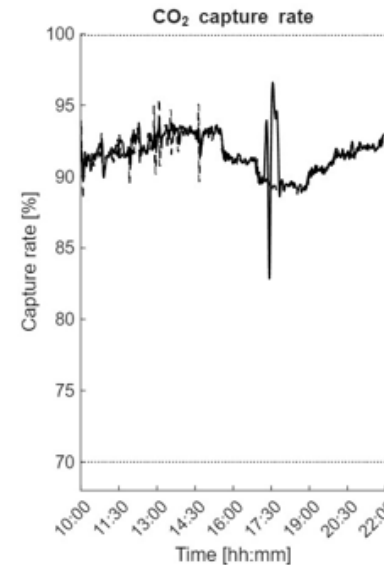
- Pulls day-ahead prices from web API
- DRT0 uses surface model of SRD as a function of MVs
- DRT0 Captures CO<sub>2</sub> when energy is cheap (night)



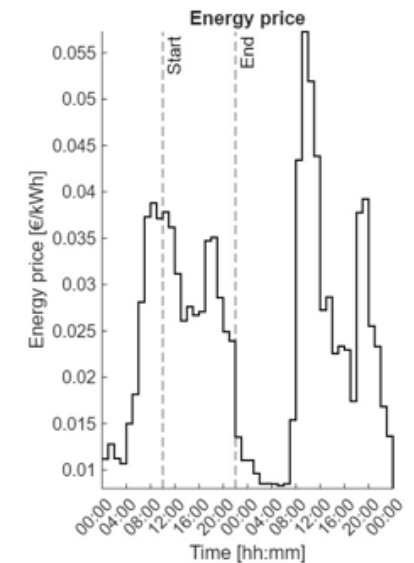
1: Reboiler duty [kW], as controlled by the NMPC



2: Solvent circulation rate [kg/min], as controlled by the NMPC



3: Capture rate setpoint [%], as controlled by the DRT0 and read by the NMPC



4: Energy prices [€/kWh] for a 48-hour period, as read by the DRT0



[www.aurora-heu.eu](http://www.aurora-heu.eu)

# QUESTIONS?

## Thank you!

Adriaen Verheyleweghen – Cybernetica AS

Contact: [adriaen.verheyleweghen@cybernetica.no](mailto:adriaen.verheyleweghen@cybernetica.no)



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# Scientific papers

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- S. O. Hauger, N. E. Flø, H. M. Kvamsdal, F. Gjertsen, T. Mejdell, M. Hillestad:  
Demonstration of non-linear control of post-combustion CO<sub>2</sub> 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<sub>2</sub> capture plants,  
**14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, 21<sup>st</sup> – 25<sup>th</sup> 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 CO<sub>2</sub> 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 CO<sub>2</sub> Capture Plants, **Computer Aided Process Engineering / 15th International Symposium on Process Systems Engineering (ESCAPE34/PSE24), 2024.**